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Changes in climate and UV in the Arctic will have far-reaching impacts, affecting aquatic species of varying trophic levels, the physical environment that makes up their habitat, the chemical properties of that environment, and the processes that act on and within freshwater ecosystems. Interactions of climatic variables, such as temperature and precipitation, with freshwater ecosystems are highly complex and can be propagated through the ecosystem in ways that are difficult to predict. This is partly because of our poor understanding of arctic freshwater systems and their basic interrelationships with climate and other environmental variables, as well as by a paucity of long-term freshwater monitoring sites and integrated hydro-ecological research programs in the Arctic.

The chapter begins with a broad overview of the general hydrological and ecological features of the various freshwater ecosystems in the Arctic, including ACIA-regional descriptions, followed by a review of historical changes in freshwater systems during the Holocene and recent past. Climate-change effects on broad-scale hydroecology; aquatic biota ecosystem structure and function; and arctic fish, fisheries and aquatic wildlife are next reviewed. Of special focus are changes to: runoff, water levels and river/lake-ice regimes; biogeochemical processes, including carbon dynamics; rivers, lakes, ponds and wetlands; aquatic biodiversity and adaptive capacities; fish populations, fish habitat, anadromy and fisheries resources; aquatic mammals and waterfowl. Potential synergistic and cumulative effects are also discussed, as well as the special role of ultraviolet radiation and contaminants.

To illustrate the nature and complexity of many of the effects, case studies are used from around the circumpolar north and discussion provided about important threshold responses (i.e., those that produce step-wise and/or non-linear effects). The chapter concludes with a summary of key findings, a list of science-knowledge gaps and recommendations for policy-related issues.
7.1. INTRODUCTION

The Arctic, which covers a significant area of the northern hemisphere, has a number of prominent and unique climatic, geological and biophysical features. The region is typified by extreme variability in climate and weather, prolonged darkness in the winter to continuous daylight in the summer, the prevalence of vast areas of permafrost, and the dominance of seasonal ice and snow cover. The Arctic also contains a diversity of terrains containing a significant number and diversity of freshwater ecosystems

The region has some of the world’s largest rivers such as the Yenisey, Lena and Mackenzie, numerous permanent and semi-permanent streams and rivers draining mountains, highlands and glaciated areas, large lakes such as Great Bear, Great Slave and Taymyr, a myriad of smaller permanent and semi-permanent lakes and ponds, vast areas of wetlands/peatlands, and coastal estuarine and river delta habitats. In turn, these freshwater systems contain a wide diversity of organisms that have developed adaptations to cope with the extreme environmental conditions they face. Examples include life-history strategies incorporating resting stages and diapause, unique physiological mechanisms to store energy and nutrients, an ability to grow and reproduce quickly under often short growing seasons, and extended life spans relative to more temperate species.

Thus, given the regional complexity of climate and landscape and the diversity of freshwater ecosystems and their associated biota, projecting the potential impacts of future climate change and ultraviolet (UV) radiation exposure presents significant challenges. What is certain is that the responses will be likely quite variable and highly specific to particular freshwater ecosystems, their biota and ecological and biophysical circumstances in which they occur.

7.1.1 Challenges in Projecting Freshwater Hydrologic and Ecosystem Responses

The first and most significant challenge in projecting responses of freshwater systems to climate change is related to our limited understanding of how the climate system is coupled to, and influences key physical and biophysical processes pertinent to aquatic ecosystems, and in turn how these affect ecological structure and function. Figure 7.1 summarizes the complex and often hierarchical interactions between climatic variables (radiation, precipitation, temperature, etc.), their influence on the biophysical features of freshwater ecosystem habitat, subsequent effects on biological structure and function, and the interaction of feedbacks within and between components. Freshwater ecosystems are complex entities which consist of groups of species at various trophic levels, the hydrological/physical environment that makes up their habitat and the chemical properties of that environment, and the multiple physical, biogeochemical, and ecological processes that act on and within the system. Hence, any change in these attributes and processes through changes in climate and UV radiation will ultimately contribute to variable and dynamic responses within the freshwater systems. Even in ecosystems containing only simplified food webs (e.g., those having no predators such as fish or predatory macroinvertebrates), the interactions of environmental parameters such as temperature and precipitation with the system are still complex and may be propagated in ways that are not readily projectable (i.e., non-linear or
step-wise threshold responses in population/community dynamics and stability - see Section 7.4.1). Also, because freshwater systems receive major inputs from terrestrial systems (Chapter 6) and provide major outputs to marine systems (Chapter 8), altered states and processes within the freshwater system are intimately linked through feedback and transfer mechanisms to these arctic ecosystems.

**Figure 7.1. Climate/Ecosystem Interactions.** Interactions among and within components tend to be sequential but complex. However, complex feedbacks also exist both within major classes of components (e.g., trophic structure linkages with biogeochemical cycling), as well as between components (e.g., ice duration and timing feeding back to the regional climate system), but are not illustrated above for visual clarity.

In addition, potential levels where climate/ultraviolet radiation change may interact with various ecosystem components themselves include:

- those within an individual (e.g., changes in physiological processes affecting thermoregulation) or effects on life processes (e.g., growth/reproductive rates), and/or the whole individual (e.g., behaviour);
- those at a population level (e.g., life-history traits, rates of immigration and emigration, migrations, intra-specific competition);
- those at the community level (e.g., changes in trophic structure and in the levels/magnitudes of food web interactions such as inter-specific competition, predation, parasitism); and,
- those at the ecosystem level that affect the nature of the environment which the organisms occupy (e.g., altered biogeochemical processes and hydrologic regimes).

Hence, in assessing the effects of a change in climate or ultraviolet radiation upon freshwater ecosystems, a number of considerations must be kept in mind. First, the simple changes in the environmental parameters themselves may occur in a variety of ways. Second, these may be input to the various aquatic ecosystems in a variety of ways. Third, the effects within the ecosystem may be manifested at a variety of levels and components within the system. Fourth, the effects may be propagated through the ecosystem and affect different components or processes differently within the ecosystem. Thus, the ability to make accurate and reasonable projections regarding such effects within arctic freshwater ecosystems with high levels of certainty is greatly hampered by the inherent complexity of such interactions. Finally, this internal complexity in potential response also lessens our ability to predict output effects upon key linking ecosystems such as deltas and estuaries that form the interactive zones between terrestrial, marine and freshwater systems.

While our general knowledge of how the hydrology, structure and function of arctic aquatic ecosystems are responding to past (e.g., paleolimnological and paleoclimatic studies – See Section 7.3 below) and to relatively recent climate and UV radiation change is gradually improving (e.g., overviews by Hessen, 2002; Prowse et al., 2001; Rouse et al., 1997; Vincent
and Hobbie, 2000; IPCC, 1996, 1998, 2001; CAFF, 2001; AMAP, 1997, 1998, 2002), much of our process and mechanistic understanding of potential impacts continues to be largely based on studies in aquatic systems residing outside of the Arctic (e.g., overviews by Antle et al., 2001; Carpenter et al., 1992; Meyer et al., 1999; Scheffer et al., 2001; Schindler et al., 1996a; Schindler, 2001). Hence, the development of detailed expectations for climate change impacts on arctic freshwater ecosystems is still somewhat limited by our lack of understanding of how these impacts will cascade through these cold regions ecosystems and create second and higher order changes.

With these limitations in mind, using the approach outlined in 7.1.2 below, projected changes in the hydrology and ecology of arctic freshwater ecosystems are identified and discussed in response to future climate and UV scenarios as defined by three future time slices (2020, 2050, 2080) generated by the ACIA modeling and scenarios group (See Chapter 4 for details). Where possible, attempts are made to identify similarities and/or differences in projected impacts in relation to the four ACIA (Arctic Climate Impact Assessment)-defined arctic regions (Region I – Arctic Europe, E. Greenland, Russian European North, N. Atlantic; Region II – Siberia, Region III – Chukotka, Bering Sea, Alaska, W. Arctic Canada; Region IV – N.E. Canada, Labrador Sea, Davis Strait, W. Greenland) (Figure 7.2).

Figure 7.2. ACIA delineated boundary and regions, and the major river systems flowing through these regions to the Arctic Ocean (adapted from AMAP, 1998; discharge data from R-ArcticNet database (www.r-arctinet.sr.unh.edu)).

7.1.2 ‘Quantifying’ Impacts and Likelihood

The confidence level associated with projecting potential impacts of climate/UV change is greatly hampered by our still rather rudimentary level of understanding of arctic freshwater hydrology and ecology, and their direct and indirect linkages, responses and feedbacks to present and future climate. Moreover, the rather coarse spatial resolution of global GCM’s compounded with the uncertainty associated with complex, multi-layered and poorly understood interactions of climate variables, greatly contribute to uncertainty about projected future climates. This is exacerbated by other complexities such as inter- and intra-regional variation driven by, for example, latitude or proximity to marine ecosystems. When combined with uncertainties about how individual species and biological communities will respond to climate and UV-radiation change, our ability to forecast future hydro-ecological impacts and resulting cascading effects is significantly compromised. This makes precise quantification of climate change impacts difficult and often tenuous.

To address the issue of uncertainty and to recognize the substantial inter-regional and latitudinal differences in understanding and coverage of arctic aquatic ecosystems, “quantification” of climate change and ultraviolet radiation impacts has been conducted using a “weight-of-evidence” approach. Following the ACIA prescribed lexicon (see http://www.acia.uaf.edu/), this approach uses a hierarchy of classes that represent the range of likelihood of the impact(s)/outcomes(s) occurring based on a compilation of information available from historical data, published literature, model predictions and the authors’ expert judgement. Projected likelihoods thus follow a progression from “very unlikely” (i.e., little
change of occurring) through to “unlikely” (some chance), “possible”, “likely/probable” and “very likely/very probable”.

Although not strictly quantifiable in a numeric sense (e.g., exact probabilities), this approach provides a comparative and relative measure of likelihood of the impact(s) occurring. Hence, a greater weight-of-evidence indicates a greater confidence in the findings (i.e., an increasing convergence of evidence from a number of independent, comprehensive empirical and/or experimental studies, model projections, etc.) that allows for particular impact(s)/outcome(s) to be classified as either “very unlikely” or “very likely”. Moreover, the designation of particular impacts as only “possible” or “likely” further implies the presence of significant gaps in our current knowledge. It is precisely these gaps which require addressing to achieve a better understanding of impacts at the level of the ecosystem and its components.

This weight of evidence-based lexicon is directly applied in the conclusions/key findings section of the chapter (Section 7.8), thereby providing a relative “quantification” of the expected outcomes/responses of freshwater ecosystems to climate/UV change.

### 7.1.3 Chapter Structure

Section 7.2 provides a broad overview of the general hydrological and ecological features of the various freshwater ecosystems in the Arctic, including ACIA-regional descriptions. Section 7.3 discusses how understanding past climate regimes using the paleolimnological and paleoclimatic records helps to better understand present and future responses of freshwater ecosystems. In the subsequent impact section, the general projections attained from the ACIA climate scenarios are discussed and projections made about potential impacts on the hydrology and ecology of the various major types of arctic freshwater ecosystems (Section 7.4), their major components (Section 7.5), ultraviolet impacts (Section 7.6), and the interactions of these with contaminants (Section 7.7). A key feature of arctic freshwater ecosystems is the biota of direct relevance to humans especially waterfowl, mammals and fishes that provide the basis for harvests. Species within these groups are of special interest in that they also provide direct biotic linkages between major arctic ecosystems, thus either potentially input or output effects from, or to, terrestrial and marine systems. Fish are of particular relevance since two major ecological groups are present; those wholly associated with freshwaters and those which pass parts of their life history in both fresh and marine waters (i.e., diadromous fishes further sub-divisible into catadromous species such as eels that rear in freshwater and breed in the sea, and anadromous species such as salmon that do the converse). Anadromous fish provide major nutrient transfers from marine systems back into freshwater systems, thus are of particular significance. A logical extension of this treatment is to also consider global change impacts upon fisheries for freshwater and diadromous forms, thus Section 7.5.4 parallels treatment in Chapter 12 for marine fisheries. The final section (Section 7.8) summarizes key findings and identifies major knowledge gaps and future research needs.

### 7.2. FRESHWATER ECOSYSTEMS IN THE ARCTIC
7.2.1 General Features of the Arctic Relevant to Freshwater Ecosystems

The nature and severity of climate and weather have a strong influence on the hydrology and ecology of arctic freshwater ecosystems (e.g., Murray et al., 1998a; Pielou, 1994; Prowse and Ommaney, 1990; Prowse et al., 1994; Woo, 1996, 2000). Arctic climate is characterized by several prominent features that show extensive variation along strong latitudinal gradients. These include, extreme seasonality and severity in temperature extremes (i.e., long, cold winter and relatively short, warm summer that persist long enough to limit biota because of physiological thresholds), high intra- and inter-annual variability in temperature and precipitation, and strong seasonally driven latitudinal gradients in incident and UV radiation, to name a few. Extended low temperatures result in extensive ice-cover for long periods of the year, significantly affecting physical, chemical and biological processes in aquatic ecosystems. Extreme seasonality of incident radiation and low levels of that radiation also have profound effects for aquatic ecosystems – much of this radiation may be reflected due to high albedo effects of ice and snow especially during the critical early portions of the spring and summer. In addition, the thermal energy of a substantive portion of this incoming energy is used to melt ice, rendering it unavailable to biota. The timing of radiation is also important for some high-latitude aquatic systems that receive a majority of their annual total prior to the melting of their ice cover. Low levels of precipitation generally occur throughout the Arctic and most of this falls as snow, resulting in limited and highly episodic local runoff.

The ecological consequences of these environmental extremes are profound. For instance, overall annual productivity of freshwater systems generally tends to be low because of low levels of nutrient inputs, low temperatures, prolonged periods of ice presence compared to temperate aquatic ecosystems, and short growing seasons (Murray et al., 1998b). In most cases, this results in slower growth and some longer-lived organisms. The annual cyclicity of processes in arctic aquatic ecosystems is relatively high, which in turn has resulted in various adaptations in the organisms that thrive there. In animals, such adaptations include high rates of consumption of food when it is available, rapid conversion of food to lipids for energy storage, then later metabolism of stored lipids for overwinter maintenance, growth and reproduction (Craig, 1989). Additionally, some groups (e.g., fish) exhibit highly migratory behaviour to optimize life-history functions resulting in movements among different habitats triggered by environmental cues (e.g., dramatic temperature decreases) which usually coincide with transitions between particular seasons (Craig, 1989). Migratory organisms such as waterfowl are exposed to a variety of habitats both seasonally and during their entire life (CAFF, 2001). Hence, aquatic biota display a wide range of adaptation strategies to cope with the severe environmental conditions to which they are exposed (CAFF, 2001; Pielou, 1994). A critical question is whether future changes in key climatic variables will be occurring at a rate and magnitude to which current freshwater species may have sufficient phenotypic or genetic plasticity to adapt and survive.

7.2.2 Freshwater Inputs into Arctic Aquatic Ecosystems

The source, timing and magnitude of freshwater inputs to arctic freshwater ecosystems has important implications to the physical, chemical and biological properties, as well as the structure, function and distribution of river, lake, pond and wetland ecosystems in the Arctic.
Rainfall is a substantial freshwater source for ecosystems at more southerly latitudes, occurring for the most part during the protracted summer season. Further north, snowfall dominates the majority of the annual freshwater budget. High latitude polar deserts receive low levels of precipitation and as such have a pronounced moisture deficit. In contrast, maritime locations generally receive greater quantities of snow and rain than continental regions.

The most important input of freshwater into aquatic ecosystems is often snowfall. It accumulates over autumn, winter and spring in the Arctic, creating important conditions for the occurrence of significant spring freshets. Snowpack duration, away from the moderating influences of coastal climates, has been documented to range from ~180 days to more than 260 days (Grigoriev and Sokolov, 1994). In the spring, elevated levels of solar radiation often result in rapid snowmelt. Consequently, this rapid melt of the snowpack translates into spring runoff that can comprise a majority of the yearly annual total flow, and be of very short-term duration – as little as only two to three weeks (Linell and Tedrow, 1981; Rydén, 1981; Marsh, 1990). In addition, at higher latitudes, infiltration of this spring flush of water is constrained by the permafrost. Thus, spring meltwater may flow over land and enter rivers, or accumulate into the many muskegs, ponds and lakes characteristic of low lying tundra areas (van Everdingen, 1990). Meltwater can also have major impacts on the water quality entering into lakes and rivers. Where highly acidic, it can produce “acid shock” in receiving waters. However, because the incoming meltwater is usually warmer than the lake water, it tends to pass through the lake with little mixing. The potential acid spring pulse is therefore transient without any marked biological consequences, as documented by paleolimnological investigations (e.g., Korhola et al., 1999; Michelutti et al., 2001).

During the summer, sources of water not only include rain, but late or perennial snow patches, glaciers, melting of permafrost, and groundwater discharges (Rydén, 1981; van Everdingen, 1990). As temperatures rise in response to climate change, these sources of water may be expected to become more pronounced contributors to the annual water budgets of freshwater ecosystems, or at least until their ice-based water reserves are depleted.

Groundwater can also play an important role in influencing the annual water budgets of arctic surface water ecosystems. Levels and distribution of groundwater within the Arctic are greatly influenced by permafrost. Groundwater movement through aquifers is restricted by permafrost year-round and by the frozen active layer for up to ten months of the year (Murray et al., 1998a). Three general types of groundwater systems are found in the Arctic: supra-permafrost, intra-permafrost and sub-permafrost. Supra-permafrost groundwater lies above the permafrost table in the active layer during summer, and year-round under lakes and rivers that do not freeze. Intra-permafrost water resides in unfrozen sections within the permafrost, such as tunnels called (by a Russian word) ‘taliks’, located under alluvial flood plains and under drained or shallow lakes and swamps. Sub-permafrost water is located beneath the permafrost table. The thickness of the permafrost will determine the availability of sub-permafrost water to freshwater ecosystems, acting as a relatively impermeable upper barrier. These three types of groundwater systems, which may be located in bedrock or in unconsolidated deposits, may interconnect with each other or with surface water (Mackay and Løken, 1974; van Everdingen, 1990; Woo and Xia, 1995; Woo, 2000) as outflows via springs,
baseflow in streams, and icings. Icings (also known as aufeis or naleds) are comprised of groundwater that freezes when it reaches the streambed during winter. Groundwater interactions with surface water systems greatly influence water quality characteristics such as cation, anion, nutrient and dissolved organic matter concentrations, and even the fate and behaviour of “fossilized” toxic pollutants.

7.2.3 Structure and Function of Arctic Freshwater Ecosystems

Arctic freshwater ecosystems are quite varied with respect to their type, physical and chemical characteristics and their associated biota. Thus, the potential impacts of climate change and increased ultraviolet radiation will be variable and highly specific to particular freshwater ecosystems, their biota and processes. Additionally, in some areas of the Arctic which span a wide latitudinal range (e.g., the arctic regions of Canada and Russia), similar types of freshwater systems exhibit a wide range of characteristics driven in part by latitudinal differences in the environment. These, in turn, will also respond differently to the impacts of global change. Furthermore, the nature of connections between the various regions of the Arctic and non-arctic areas of the globe differ. Consequently regional differences within the same type of aquatic system will likely exist, despite these being at the same latitude. Also, historical differences in the development during recent geological time and geomorphic processes which have affected different regions (e.g., extent of Pleistocene glaciations, age, and connectivity to southern areas), will contribute to regional, sub-regional and local variability in ecosystem structure and function.

Two major categories of freshwater ecosystems can be defined as lotic (running water) and lentic (standing water), but large variation in size, characteristics and location is exhibited within each. Thus, large differences in response to climate change can be expected. For the purposes of this assessment, lotic or flowing water ecosystems include rivers, streams, deltas and estuaries, where flow regimes are a dominant hydrologic feature shaping their ecology. Lentic or standing water ecosystems include lakes and ponds and wetlands (including bogs and peatlands). Although some wetland types may not have standing surface water at all times, for the purposes of this chapter, they will be considered lentic ecosystems.

The Arctic generally contains a relatively low number of aquatic bird and mammal species as compared to more temperate ecozones, it is home to most of the world’s geese and calidrid sandpipers (Zockler, 1998). Migratory birds, including geese, ducks, swans and gulls, can be particularly abundant in arctic coastal and inland wetlands, lakes and deltas (Zhadin and Gerd, 1961; Bellrose, 1980; Godfrey, 1986; for comprehensive review see CAFF, 2001). Most taxonomic groups within the Arctic are generally not very diverse at the species level, though some taxonomic groups (e.g., arctic freshwater fish; see Box 7.5) have high diversity at and below the species level (e.g., display a large number of ecological morphs). In addition, strong longitudinal gradients in biodiversity are generally found in arctic freshwater systems, ranging from extremely low in high latitude, low productivity systems to very diverse and highly productive coastal, delta-estuarine habitats (AMAP, 1998; CAFF, 2001; IPCC, 2001). Very little is still known about the biological and functional diversity of taxa such as bacteria/virus, phytoplankton and zooplankton/macroinvertebrate communities that reside in
arctic aquatic ecosystems, despite their undoubted importance as key components of freshwater foodwebs (Vincent and Hobbie, 2000; Vincent et al., 2000).

7.2.3.1 Rivers and Streams, Deltas and Estuaries

Rivers and Streams

Rivers and streams of the Arctic are most densely distributed in lowlands, including those in Fennoscandia (Region I) and the Interior Plain of Canada (Region III), and are often found in association with lakes and wetlands. Lotic ecosystems (Figure 7.2) include large northward flowing rivers such as the Mackenzie River in Canada (see Chapter 5 for further discussion), high-gradient mountain rivers, and slow flowing tundra streams which may be ephemeral and flow only during short periods in the early spring. Flowing water systems represent a continuum, from the smallest to largest, and although sub-dividing them at times is arbitrary, river systems of different sizes do vary in terms of their hydrology, water quality, species composition, and direction and magnitude of response to changing climatic conditions. This is particularly relevant in the Arctic where river catchments may be wholly within the Arctic or extend southward to more temperate locations.

In general, the large rivers of the Arctic have headwaters well south of the area defined herein as arctic (see Chapter 5 for review of major arctic rivers and their historical trends in flow), and as such act as conduits of heat, water, nutrients, contaminants, sediment and biota northwards (see e.g., Degens et al., 1991 for information on basic geochemistry). For such systems, not only will local effects of climate change be important, but basin-wide effects especially those from the south will also be critical in determining cumulative effects (e.g., see Cohen 1994, 1997). Five of the world’s ten largest rivers fall into this category and have substantive effects on the entire Arctic such as the freshwater budget of the Arctic Ocean and the hydroecology of coastal deltas and related marine shelves: Lena, Ob and Yenisey (Region II–Russia), Mackenzie (Region III–Canada), Yukon (Region III–United States). Various portions of these rivers are regulated (Dynesius and Nilsson, 1994), the most affected being the Yenisey River, which is also the largest of the group and the one predicted to experience significant further impoundment (~+50%) over the next few decades (Shiklomanov et al., 2000). The effects of impoundment on water quantity and quality are wide ranging for northern aquatic systems and are expected to be exacerbated by the effects of climate change (Prowse et al., 2001, 2004).

Numerous, smaller but still substantive rivers also drain much of the Arctic and also may arise from headwaters outside of the Arctic – e.g., rivers such as the Severnaya Dvina and Pechora that drain much of arctic Scandinavia and the Russian European North (Region I), the Khatanga of Siberia (Region II), the Kolyma of eastern Siberia (Region III), and the Churchill and Nelson rivers that drain much of central Canada and supply water to the Arctic Ocean via Hudson Bay (Region IV). Although much smaller than the first group, these rivers are more numerous and in many cases are affected by a similar suite of anthropogenic factors which include agriculture, hydro-electric impoundment, industrialization, mining and forestry, much of which occurs outside of the Arctic and, which as climate change progresses, may become
more prominent. Still smaller types of lotic systems include medium to small-sized rivers which arise wholly within the Arctic. Examples include the Thelon in Canada, Colville in Alaska, Anadyr in northeastern Siberia, many throughout Siberia, and the Tana of Scandinavia. In many cases these rivers do not presently have the same degree of local anthropogenic impacts as the above two types. Despite some levels of anthropogenic impacts, many of these medium-sized to large arctic rivers harbour some of the largest and most stable populations of important and widely distributed arctic freshwater species. For example, many of the best remaining wild populations of Atlantic salmon are extant in northern systems such as the Tana River of northern Norway, despite widespread declines in southern areas (e.g., Parrish et al., 1998).

Virtually all of the rivers noted above share an important characteristic – their main channels continue flowing throughout the winter, typically beneath ice cover, due to some type of continuous freshwater input either from warm southern headwaters, lakes, and/or groundwater inflows. As such, they typically have higher levels of productivity and biodiversity than rivers that do not flow during winter. This latter group consists of rivers that are numerous, still smaller, and found throughout the Arctic. Fed primarily by snowmelt, they exhibit high vernal flows dropping to low base flows during the summer with perhaps small and ephemeral flow peaks during summer-autumn precipitation events prior to freeze-up. Many of these smaller arctic rivers are also fed by glaciers (e.g., Alaska and Greenland), thus initial vernal flows are fed by snow melt and flows are maintained at a relatively high level throughout the summer by glacial melt. Most of these small arctic rivers stop flowing at some point during winter and freeze to the bottom throughout large reaches. Such is the case for many small rivers of Region I, those to the east in Region II, and coastal rivers of Chukotka, northern Alaska and northwestern Canada (Region III). This hydrology has important implications to the biota present (e.g., habitat and productivity restrictions), and climate change has important ramifications for such ecosystems (e.g., cascading effects of changes in productivity, migratory routes).

Although the difference between rivers and streams is somewhat arbitrary, as a class local streams are numerous and found throughout the Arctic in association with all types of terrestrial landforms. Streams feed water and nutrients to lacustrine environments and also act as the first-order outflows from many tundra lakes, thus providing connectivity between different aquatic environments and also between terrestrial and aquatic systems.

The general ecology of arctic rivers and streams is as diverse as are the systems themselves, and is driven in part by size, location, catchment characteristics, nutrient loads and sources of water. Correspondingly, biotic food webs of arctic rivers (Figure 7.3) will vary with river size, geographic area and catchment characteristics (e.g., benthic algae and mosses and finesediment associated benthic invertebrate fauna are more common in smaller, slower flowing rivers and streams, and fish populations being limited in small rivers that freeze over winter (Steffan, 1971; Jørgensen and Eie, 1993; Milner and Petts, 1994; Hobbie, 1984)). Rivers fed primarily by glaciers are physically dynamic and nutrient poor, and as such offer challenging environments for primary production and invertebrate communities (Murray et al., 1998a). Spring-fed streams with stable environments of clear water, year-round habitat and higher winter temperatures exhibit greater diversity in primary producers, including mosses and
diatoms, and lower trophic levels such as insects (Hobbie, 1984). Tundra streams tend to be ephemeral, and low in pH and nutrients, with correspondingly low productivity. Medium-sized rivers, especially those draining lakes, typically have moderate to high levels of productivity and associated diversity in invertebrate fauna, which in turn are affected by such things as suspended sediment loads. For example, clear flowing rivers of the Canadian Shield in Region IV, have higher biodiversity of lower trophic levels, such as invertebrates, than very turbid rivers of the lowlands of Siberia (Region II) and Interior Plains of Canada (Region III) (Murray et al., 1998a). In general, fish diversity in arctic rivers appears to be related primarily to the size of the river and its associated drainage basin; thus similarly sized rivers differing greatly in suspended sediment loads tend to have a similar overall diversity of fish species (Reist, unpublished data). However, the suite of species present differs between clear (e.g., preferred by chars) and sediment-rich (e.g., preferred by whitefishes) rivers. Historical factors such as deglaciation events and timing also figure prominently in determining biodiversity at higher trophic levels in these systems (Bodaly et al., 1989).

Figure 7.3. Representative Arctic river and stream food web. Changes to river ecology, whether they are bottom-up (e.g., changes to nutrient-loading from catchments will affect primary productivity) or top-down (e.g., predatory fish removal with habitat loss will affect lower-level species productivity and abundance), will affect not only river systems, but also receiving waters.

Another ecological feature of arctic rivers and one which will likely be significantly affected by climate change is that of anadromy or sea-run life histories of many of the fish species present (See Section 7.5). That is, most of the salmonid fishes found in the Arctic and several species of other families extensively use marine environments for summer feeding and, in some instances, for extensive portions of their life history (e.g., much of salmon life history occurs in marine waters). These fish, and to some extent waterfowl, provide a fundamental ecological linkage between freshwater systems, estuarine systems and marine systems of the Arctic. For such organisms, the effects of climate and ultraviolet change on each environment will be integrated throughout the life of the individual and hence be cumulative in nature.

Deltas and Estuaries

Deltas are highly diverse ecosystems that lie at the interface between rivers and lakes or oceans, providing a variety of freshwater habitats that are highly seasonal in nature. The most notable deltas in the Arctic are those of the Lena and Ob rivers in Russia (Region II) and the Mackenzie River in Canada (Region III), where easily eroded sedimentary landscapes contribute to heavy sediment-loading of rivers and deltas. Habitats include extensive wetlands, which cover up to 100% of the Mackenzie Delta (Zhulidov et al., 1997), and many ponds and lakes that are frequented by small mammals, fish and waterfowl. Arctic deltas are beneath ice-cover for the majority of the year, although flows continue in their major channels throughout the year. A critical hydrologic feature of these systems is the occurrence of ice-jams and associated ice-jam floods, both of which are paramount in the maintenance of delta ecosystems (Prowse and Gridley, 1993; Prowse, 2001a). Spring overland floods are critical to the recharge of delta lakes, such as those of the North American Yukon, Colville (Dupre and Thompson, 1979; Walker andMcCloy, 1969), Mackenzie (Marsh and Hey, 1989, 1991) and
Slave rivers (Peterson et al., 1981b), and the Siberian Yenisey, Lena, Ob, Kolyma and Indigirka rivers (Antonov, 1969; Burdykina, 1970). Flooding with spring break-up also provides sediments and nutrients to deltas (e.g., Lesack et al., 1991), which in turn helps sustain unique and highly productive habitats for plant and animal species, including fish, waterfowl and small mammals, such as muskrats (e.g., Marsh and Ommanney, 1989). The drastic changes in delta hydrology with seasonal and inter-annual shifts in flow regimes and the effect of wind-related disturbance on delta waters have important implications for delta hydroecology. Hence, given the somewhat transient and sensitive nature of delta hydroecology, climate changes can be expected to have significant impacts in these areas of the Arctic.

River hydrology not only affects the hydroecology of deltas, but also that of estuaries. Examples of large delta and associated estuaries include the Mackenzie River in Canada (Region III), and the Yenisey, Ob and Lena rivers in Russia (Region II). Arctic estuaries are distinct from those at more southerly latitudes in that their discharge is highly seasonal and ice-cover is again a key hydrologic variable influencing the ecology of the systems. Winter flows are typically between 5 and 10 % of the annual average (Antonov, 1970), and estuarine waters are often vertically stratified beneath the ice-cover. This may promote the formation of frazil ice at the freshwater-saltwater boundary. Freshwaters that flow into estuaries over winter typically retain their chemical loads until stratification deteriorates with loss of ice cover. In estuaries that are less than 2 m deep, river discharges in late winter may be impeded by ice and diverted offshore through erosional channels or with tidal inflows (Reimnitz and Kempena, 1987). High magnitude freshwater discharges in spring carry heavy sediment loads and flow beneath the ice, gradually mixing with saltwater as break-up progresses in the estuary. High magnitude freshwater discharges will dominate estuarine waters if landward fluxes of seawater are less pronounced.

Freshwater inflows from large arctic rivers carry sediment, nutrients and biota to coastal areas, thereby contributing to the highly productive nature of estuaries and related marine shelves. Furthermore, this production is fostered by the complex nearshore dynamics associated with mixing of water masses differing in density, which in turn, increase complexity of biological communities (Carmack and Macdonald, 2002). Hence, estuaries provide a significant food source for anadromous species compared to what is available to them from adjacent freshwater streams (Craig, 1989). This productivity typically results in large populations of fish that are important to local fisheries (e.g., Arctic char, Atlantic salmon) and integral to the food web supporting other arctic organisms such as waterfowl, shorebirds and marine mammals, and keystone components affecting energy transfer (Figure 7.4). Shorebirds and seabirds that utilize freshwater and/or estuarine habitats, linking freshwater and marine environments, include species such as the red phalarope, parasitic jaeger, red knot, dunlin, long-tailed jaeger, northern fulmar, glaucous gull, white-rumped and western sandpiper, lapland longspur, parasitic jaeger, the red-necked stint, black-bellied and semi-plamated plover, and ruddy turnstone. Another important feature of estuarine ecosystems is the potential for transfers (by e.g., waterfowl and anadromous fishes) of significant nutrient loads from marine to freshwater habitats (Bilby et al., 1996). Deltas and estuaries also have high rates of sedimentation and as such can be important sinks of terrestrial organic carbon (e.g., Macdonald et al., 1995) and contaminants (e.g., Milburn and
Prowse, 1998) thereby being capable of producing both positive and negative impacts on the aquatic biota in these systems.

**Figure 7.4.** A stylized portrayal of the use of estuaries and keystone role of anadromous fish in trophic dynamics in arctic nearshore estuarine and marine ecosystems (after Carmack and Macdonald, 2002). Many anadromous fishes in these systems (e.g., Arctic cisco, Dolly Varden, rainbow smelt) overwinter in coastal and estuarine waters that are often used for feeding and rearing during the summer. Fishes migrate upstream in freshwater systems to spawn, and in some cases to overwinter. Given the intimate interaction of anadromous fishes with freshwater and marine environments in these delta/estuary systems, changes in freshwater and marine ice and hydrology with climate change, will significantly impact the life-histories of these fishes.

### 7.2.3.2 Lakes, Ponds and Wetlands

Lentic ecosystems of the Arctic are similarly diverse and include an abundance of lakes of varying size, shallow tundra ponds that may contain water only seasonally, and wetlands such as peatlands that are notable stores and sources of carbon. These freshwater systems provide a rich diversity of habitats that are highly seasonal and/or ephemeral.

#### Lakes and Ponds

Arctic lakes are typically prevalent on low-lying landscapes, such as coastal and interior plains (e.g., Canadian Interior Plain – Region III, Finnish Lowlands – Region I). There are many kettle lakes (a product of the melt of buried glacial ice), moraine and ice-scour lakes on undulating terrain of post-glacial, arctic landscapes (e.g., Canadian Shield – Region IV, Fennoscandia and Kola Peninsula – Region I) (Mackay and Løken, 1974; Korhola and Weckström, in press). Thermokarst lakes are also quite common in the Arctic (e.g., along Alaskan coast – Region III, Siberia – Region II), developing in depressions formed by permafrost melt. Small ponds also dominate portions of the Arctic landscape (e.g., low-lying terrain of Fennoscandia – Region I) and typically being <2 m deep, freeze solid over the winter.

Local catchments are typically the primary source of water for arctic lakes (Hartman and Carlson, 1973; Woo et al., 1981; Woo and Xia, 1995). Spring runoff originates from snow accumulation on lake ice, hillslope runoff (Woo et al., 1981), and lateral overflow from wetlands and streams (Marsh and Hey, 1989). Outlets of small lakes may be snow-dammed, and eventually release rapid and large flows downstream (Heginbottom, 1984; Woo, 1980). Arctic lakes also experience considerable evaporative water loss, sometimes resulting in the formation of athalassic saline systems. Water loss may also occur through seepage, which is common in lakes underlain by taliks in the discontinuous permafrost zone (Woo, 2000; Kane and Slaughter, 1973).

The hydroecology of the many small lakes of the Arctic is intimately linked with climatic conditions. The timing and speed of lake ice melt depend on the rate of temperature increase in late spring and early summer, wind, and inflow of basin meltwater and terrestrial heat.
exchanges (e.g., groundwater inflow, geothermal input, heat loss to maintain any underlying talik) (Welch et al., 1987; Doran et al., 1996). Some lakes of the High Arctic retain ice cover throughout the year, while some thermal stratification can occur in arctic lakes where ice-out occurs more quickly. In northern Fennoscandia, for example, lakes >10 m are usually stratified during the summer and have well-developed thermoclines (Korhola et al., 2002a). In contrast, many high-arctic lakes mix vertically thereby reducing thermal stratification (Mackay and Løken, 1974; Welch et al., 1987). Similarly, small shallow lakes do not stratify because they warm quickly and are highly wind mixed. Heat loss from arctic lakes tends to be rapid in late summer/early autumn and often results in complete mixing. Shallow lakes and ponds consequently will freeze to the bottom over winter. The duration and thickness of lake-ice cover in larger lakes increases with latitude, reaching thicknesses of up to 2.5 m and can even be perennial over some years in extreme northern Arctic Canada and Greenland (Adams et al., 1989; Doran et al., 1996). In addition to temperature, the insulating effect of snow also inversely affects ice thickness. Any shifts in amounts and timing of snowfall will be important determinants of future ice conditions, which in turn will affect the physical and chemical dynamics of these systems.

The abundance and diversity of biota, productivity and food web structure in arctic lakes varies regionally with environmental conditions and locally with the physical characteristics of individual lakes (Figure 7.5). For example, lakes across the Russian European North vary from small, oligotrophic tundra systems (having moderate phytoplankton diversity, low primary productivity/biomass and relatively high zoobenthos abundance) to larger taiga lakes (displaying greater species diversity and higher primary and secondary productivity/biomass). Mountain lakes of the region tend to have very low phytoplankton diversity, but substantial primary and secondary productivity and biomass, similar to that of taiga lakes. In general, the abundance and diversity of phytoplankton and invertebrates such as rotifers, copepods and cladocera increase with lake trophic status (Hobbie, 1984), which often is a function of latitudinal constraints on resources for productivity. For example, some Icelandic lakes have phytoplankton production levels of >100 g C/m²/y (Jónasson and Adalsteinsson, 1979; Jónasson et al., 1992), contrasting extremely oligotrophic high-arctic lakes having production at levels <10 g C/m²/y (Hobbie, 1984). Although zooplankton are generally limited and at times absent in arctic lakes due to temperature and nutrient limitations, they may be quite abundant in shallow lakes where there is a lack of predators. For example, >30 Cladocera species have been documented from certain Finnish Lapland lakes, although in general most contain <10 species (Korhola, 1999; Rautio, 2001). Benthic invertebrate species diversity and abundance also displays high latitudinal and inter-lake variability and may be quite prominent in shallow lakes and ponds (Hansen, 1983; Hobbie, 1984; Jørgensen and Eie, 1993; Chapin and Körner, 1994; Vadeboncoeur et al., 2003). For example, in lakes of the Svalbard region, chironomid larvae are often numerically dominant but display low diversity (approx. 10 species) (Styczynski and Rakusa-Suszczewski, 1963; Hirvenoja, 1967; Planas, 1994), while >49 species have been identified in more southern Norwegian lakes. Fish species in arctic lakes are generally not very diverse, ranging from a few species (one to three) in lakes of Greenland (Riget et al., 2000), Iceland (Jónasson, 1992), Faeroe Islands, northwest Scandinavia and the Kola Peninsula, up to several tens of species near the Pechora River in Russia (Reist, unpublished data). These fish may be anadromous or landlocked, depending on life-histories and lake-river networks.
In general, tundra ponds tend to have very low annual primary productivity, which is
dominated by macrophytes and benthic bacteria and algae (Hobbie, 1980). The detrital food
web is highly important in these systems and phytoplankton have nutrient- and light-limited
growth. Zooplankton are abundant because fish are mostly absent in these shallow systems;
therefore, such algal turnover is rapid in response to heavy grazing by herbivorous zooplankton
(Hobbie, 1980). Vegetation of ponds typically includes horsetail, water smartweed, duck
weeds and pond weeds (Zhadin and Gerd, 1961) and the resulting plant detrital material tends
to be mineralized rather than grazed upon. Figure 7.6 illustrates a typical tundra pond food
web.

Ponds, as well as lakes and wetlands (discussed below), provide habitat that is critical to a
wide variety of waterfowl, as well as small mammals. Typical waterfowl in the Arctic include
the Canada, bean and snow goose, the black brant, eider, oldsquaw duck, red-throated and
yellow-billed loon, Arctic loon, tundra swan, ring-necked and canvasback duck, greater scaup
and king eider. Some of the world’s most severely endangered species, including the once
abundant Eskimo curlew (Numenius borealis), and the Steller’s (Polysticta stelleri) and
spectacled eider (Somateria fishceri), are dependent on arctic freshwater systems
(Groombridge and Jenkins, 2002). These and other bird species have been impacted by a
combination of factors such as over-harvesting and changes in terrestrial habitat
quality/quantity or some perturbation at-sea related to climate variability and/or change
(CAFF, 2001; Groombridge and Jenkins, 2002). Coastal and inland wetlands, deltas and
ponds are common feeding and breeding grounds for many species of waterfowl in the spring
and summer months. Some more southerly or sub-arctic ponds, small lakes and wetlands can
also contain thriving populations of aquatic mammals such as muskrat and beaver.

Wetlands

Wetlands are among the most abundant and biologically productive aquatic ecosystems in the
Arctic, and occur most commonly as marshes, bogs, fens, peatlands and shallow open waters
(Mitsch and Gosselink, 1993; Moore, 1981). Approximately 3.5 million km$^2$ of boreal and
sub-arctic peatlands exist in Russia, Canada, the USA and Fennoscandia Gorham (1991).
Arctic wetlands are densely distributed in association with river and coastal deltas (e.g.,
Mackenzie River Delta – Region III, Lena River Delta – Region II), and low-lying landscapes
(e.g., the Finnish lowlands of Region I, the Siberian lowlands of Region II, substantive
portions of the Canadian Interior Plain in Region III). Wetlands are generally less abundant in
Region IV (up to 50% in isolated areas).

Wetlands are a common feature in the Arctic due in large part to the prominence of
permafrost and the low rates of evapotranspirative water loss. Aside from rainfall and melt
waters, wetlands may also be sustained by groundwater, such as is the case for fens, which are
more nutrient-rich, productive wetland systems than bogs, which are fed solely by rainfall.
Arctic wetlands may have standing water in the ice-free season or, as in the case of peatlands,
may have sporadic and patchy pools. The occurrence of these is highly variable seasonally and inter-annually, with heat and water fluxes, and spatially, with peatland microtopography. As such, arctic wetlands often have a diverse mosaic of microhabitats with different water levels, flow characteristics, and biota. Arctic wetlands are also generally distinct from other freshwater systems in their biogeochemistry, having lower dissolved oxygen concentrations, more extreme reducing conditions in their sediments, and more favorable conditions for biodegradation (Wetzel, 2001).

Arctic wetlands are inherently highly productive and diverse systems, as they often are important transition zones between uplands and more permanent freshwater and marine waterbodies. They are typically dominated by hydrophytic vegetation, with a few species of mosses and sedges, and in some instances terrestrial species such as lichens, shrubs and trees (e.g., forested bogs in the mountains of Siberia - Region II). Insects such as midges (chironomids) and mosquitos are among the most abundant fauna in arctic wetlands (Marshall et al., 1999). Peatland pools in arctic Finland for example, host thriving populations of midges that are more abundant and of greater biomass in areas of standing water than in semi-terrestrial sites, and are an important food source for many peatland bird species (Paasivirta et al., 1988).

Aside from habitat provision, river flow attenuation and a number of other ecological functions, wetlands also store and potentially release a notable amount of carbon, with potential positive feedbacks to climate change (e.g., radiative forcing of methane and carbon dioxide). It is estimated that northern peatlands store approximately 455 Pg of carbon (Gorham, 1991), which is nearly one-third of the global total carbon pool contained in terrestrial soils. As well, northern wetlands contribute between 5 and 10% of total global methane emissions (UNEP, 2003). The role of arctic and sub-arctic wetlands as net sinks or sources of carbon (Figure 7.7) is highly dependent on: seasonal water budget and levels; the protracted and intense period of summer primary productivity (during which photosynthetic assimilation and respirative release of carbon dioxide, and bacterial metabolism and creation of methane, may be most active); soil type, active layer depth and extent of permafrost. Methane and carbon dioxide production can occur beneath the snow pack and ice of arctic wetlands. Winter and particularly spring emissions can account for a significant proportion of annual total efflux of these gases (e.g., West Siberia; Panikov and Dedysh, 2000). (A more detailed treatment of carbon cycling and dynamics in Arctic terrestrial/aquatic landscapes can also be found in Chapter 6).

Figure 7.7. Carbon cycling in aquatic ecosystems. Arctic wetlands typically represent net sources of carbon during spring melt and as plants senesce in autumn, shifting to net carbon sinks as leaf-out and growth progresses (e.g., Joabsson and Christiensen, 2001; Laurila et al., 2001; Nordstroem et al., 2001; Aurela et al., 1998, 2001). The future source/sink status of wetlands will therefore depend on changes in vegetation, temperature and soil conditions. Similarly, carbon cycling in lakes, ponds and rivers will be sensitive to direct (e.g., rising temperatures affect rates of carbon processing) and indirect effects of climate change (e.g., changes in catchments affect carbon-loading).
7.3. HISTORICAL CHANGES IN FRESHWATER ECOSYSTEMS

Analysis of the stability, sensitivity, rate and mode of response of freshwater ecosystems to past climate changes has proven to be a valuable tool for scoping potential responses to future climate changes. Preserved records of ecosystem variations, e.g., trees, fossils and sedimentary deposits, combined with dating techniques such as carbon-14, lead-210 or ring/varve counting, have been a primary source of information for unravelling past environmental changes that predate the age of scientific monitoring and instrumental records. The application of climate-change proxies in paleoclimatic analysis has traditionally relied on identification of systematic shifts in ecosystem patterns known from modern analogues or by comparison with independent instrumental or proxy climate records to reflect perturbations in climate-driven environmental conditions such as length of growing season, solar insolation, temperature, humidity, ice cover extent and duration, or hydrologic balance. Such ecosystem-based climate proxies may include presence, distribution, or diversity of terrestrial, aquatic or wetland species or assemblages, changes in water or nutrient balances recorded by chemical or isotopic changes, changes in growth rates/characteristics of individual plants and animals, or changes in physical environments (e.g., lake levels, dissolved oxygen content) that are known to be linked to freshwater-ecosystem productivity and health.

Reliability and confidence in these ecosystem indicators of climate change has been enhanced through development of spatial networks of paleo-data, and where available, by comparison with instrumental climate records, and through concurrent examination of abiotic climate-change proxies in nearby locations. Such abiotic proxy records include: shifts in the isotopic composition of glacial deposits (and to some extent permafrost or porewater), which provide regional information about changes in origin, air-mass evolution, and condensation temperature of precipitation (or recharge); changes in summer melt characteristics of glacial deposits, or sedimentary and geomorphological evidence such as presence of laminated lake sediments (varves), which are indicative of depths of water great enough to produce stratified water columns and meromixis; and variations in varve thicknesses in lakes, and fining/coarsening sequences or paleoshoreline mapping that can be used to reconstruct shifts in lake or sea levels.

7.3.1 Ecosystem Memory of Climate Change

Accumulation of ecosystem records of environmental changes relies on preservation of historical signals in ice caps, terrestrial deposits (soils, vegetation, permafrost), and aquatic deposits (wetlands, rivers, lakes, ice), and is manifestly coupled with methods for reconstructing the timing of deposition. As continuity of deposition and preservation potential is not equal in all environments, there is a systematic bias in the paleo-record toward high-preservation lentic environments, and to a lesser extent wetlands, as compared to lotic systems. A description of common archives and basis of key memory mechanisms is given below.

7.3.1.1 Lentic Archives
Biological indicators of environmental changes that are preserved in lake sediments include pollen and spores, plant macrofossils, charcoal, cyanobacteria, algae including diatoms, chrysophyte scales and cysts, and other siliceous microfossils, biogenic silica content, algal morphological indicators, fossil pigments, bacteria, and invertebrate fossils such as Cladocera, chironomids and related Diptera, ostracods, and fish (Smol, 2002). In general, the best biological indicators are those with good preservation potential, e.g., siliceous, chitinized or (under neutral to alkaline pH conditions) carbonaceous body parts. They also must be readily identifiable in the sedimentary record, and exist within assemblages that have well-defined ecosystem optima or tolerances. Lentic records commonly extend to the time of deglaciation in the Circumpolar Arctic, reflecting 6000 to 11000 years of record.

In general, fossil pollen and spores, plant macrofossils and charcoal are used to determine temporal shifts in terrestrial ecosystem boundaries, notably past fluctuations in northern treeline and fire history. Pollen and spores from emergent plants may also be useful indicators for presence and extent of shallow-water environments. Preserved remains of aquatic organisms, such as algae and macrophytes provide additional information on the aquatic-ecosystem characteristics and lake-level status. Such indicators, which are used to reconstruct ecological optima and tolerances for past conditions, are normally applied in conjunction with surface-sediment calibration data sets to quantitatively relate present-day ecosystem variables or assemblages with others preserved in the sediment record (Smol, 2002; Birks, 1995, 1998). Details on application of diatoms as environmental indicators in the High Arctic are given in Douglas and Smol (1999) and a general treatment for all algal indicators of climate changes are given in Smol and Cummings (2000). Biological indicators useful for lake-level reconstructions include the ratio of planktonic to littoral cladocera as an index of relative size of littoral zone or water depth of northern lakes (MacDonald et al., 2000a; Korhola and Rautio, 2001). Chironomids and diatoms may also be used in a similar manner. While such information allows for quantitative reconstruction of lake levels, errors in projecting lake-water depth from cladocera, chironimid, and diatoms may be large (+1.6-4.6 m; Korhola et al., 2000a; Moser et al., 2000; see also MacDonald et al., 2000a). Cladoceran remains may also provide evidence of changes in trophic structure including fish (Jeppesen et al., 2001a, b, 2003), and chironomids may be used to reconstruct changes in conductivity mediated by variations in runoff and evaporation (Ryves et al., 2002).

Due to their small volume and minimal capacity to buffer climate-driven changes, shallow lakes and ponds, which are characteristic of large parts of the Arctic, may also be well suited for study of hydrological and climate reconstructions. Past shifts in diatom assemblages have been used to track habitat availability for aquatic vegetation, extent of open-water conditions, shifts in physical and chemical characteristics and water levels (Moser et al., 2000).

Further quantitative information can be gleaned from isotopic analysis (e.g., $^{13}$C, $^{18}$O, $^{15}$N) of fossil material, bulk-organic sediments or components such as cellulose or lignin. For example, carbon- and oxygen-isotope analysis of sediment cellulose has been applied in many parts of the circumpolar Arctic (MacDonald et al., 2000a). It relies on the key assumptions that fine-grained cellulose in offshore sediments (excluding woody material etc.) is derived from aquatic plants/algae and that the cellulose-water fractionation is constant (Wolfe et al., 2001). Often the source of material (aquatic versus terrestrial) can be confirmed from other tests such as C/N ratios (Wolfe et al., 2001), although these criteria may not always be met in
all arctic systems (Sauer et al., 2001). Under ideal conditions, the $^{18}$O signals in aquatic cellulose are exclusively inherited from the lake water and therefore record shifts in water balance of the lake (i.e., input, throughflow, residency and catchment runoff characteristics; Gibson et al., 2002). Interpretation of $^{18}$O isotopic signals and other climatic proxies across the circumpolar Arctic is supported by nearby studies of Greenland and arctic-island ice cores (Smol and Cumming, 2000). Ice-core records of past precipitation ($^{18}$O, $^2$H) can help to isolate climatically- and hydrologically-driven changes observed in lake-sediment records.

Stratigraphic reconstructions using $\delta^{13}$C, $^{14}$C, or $^{15}$N measured in aquatic cellulose and fossil material can likewise be used to examine changes in the ecosystem carbon and nitrogen cycles and ecosystem productivity. Trends in chemical parameters such as DIC (Dissolved Inorganic Carbon), DOC (Dissolved Organic Carbon), and TN (Total Nitrogen) can also be reconstructed from fossil diatom assemblages as demonstrated for lakes in the treeline region of the central Canadian Arctic (Ruhland and Smol, 2002), Fennoscandia (Seppä and Weckström, 1999) and elsewhere.

While lakes are nearly ideal preservation environments, the lake-sediment record may not always offer unambiguous evidence of climate-induced ecosystem changes. Other non-climate driven factors, including selective preservation of some organisms (Rautio et al., 2000), erosion or deepening of outlets, damming by peat accumulation, or subsequent permafrost development, can alter lake records (Edwards et al., 2000). Such problems are overcome to some extent by using multi-proxy approaches, by comparing multiple lake records and by using spatial-archive networks. Further research on modern ecosystems, especially processes controlling preservation and modification of proxy records is still required in many cases to reconcile present and past conditions.

7.3.1.2 Lotic Archives

Sedimentary deposits in lotic systems are often poorly preserved compared to lentic systems due to the relatively greater reworking of most riverine deposits. However, preservation of at least partial sediment records can occur in fluvial lakes, oxbow lakes, estuaries and artificial reservoirs. Past river discharge can also be studied by tracking abundance of lotic diatoms in the sediments of lake basins, such as demonstrated for a lake in the High Arctic (Douglas et al. 1996; Ludlam et al. 1996).

7.3.1.3 Terrestrial and Wetland Archives

Tree rings are a traditional source of climate-change information although there are obvious difficulties in applying the method in tundra environments with sparse vegetation. There are however, abundant conifers occurring within the circumpolar Arctic (particularly in northwestern Canada, Alaska and Eurasia), with the northernmost conifers in the world located poleward of 72°N on the Taymyr Peninsula, northern Siberia (Jacoby et al., 2000). Tree-ring widths increase in response to warm-season temperatures and have been used to reconstruct climate changes, in many cases for over 400 years (Jacoby et al., 2000; Overpeck et al., 1997).
Diatoms, chrysophytes, and other paleolimnological indicators are also preserved in peatlands and may be used to reconstruct peatland development and related water balance and climatic driving forces (Moser et al., 2000). Isotope records of $\delta^{13}$C and $\delta^{18}$O from peat cellulose also provide information on climatic variability (Hong et al., 2001), although this method has not been widely applied to date in the Arctic. Selective use of porewater from within peat and permafrost has also been utilized to reconstruct isotopic composition of past precipitation (Wolfe et al., 2000; Allen et al., 1988) although dating control is often imprecise.

7.3.2 Recent Warming: Climate Change and Freshwater Ecosystem Response during the Holocene

The Earth’s climate has continuously varied since the maximum extent of ice sheets during the late Pleistocene (e.g., Gajewski et al., 2000). The most recent climate-warming trend during the industrial period overprints Holocene climate shifts that have occurred due to orbital-induced variations in solar insolation, as well as oscillations produced by local to regional shifts in sea-surface temperatures, atmospheric and oceanic circulation patterns and land-ice cover extent (MacDonald et al., 2000a). During the early Holocene (10,000-8000 y BP), orbital variations (Milankovitch’s theory of a 41,000 year cycle of variation in orbital obliquity) resulted in approximately 8% higher summer insolation and 8% reduced winter insolation poleward of 60°N (Kutzbach et al., 1993). This directly altered key factors controlling arctic freshwater systems, including precipitation, hydrology and surface energy balance. Sea level was also 60-80 m below present-day levels providing an expanded zone (up to several hundred kilometres in width) of near-shore freshwater environments.

During the Holocene, rapidly melting ice sheets presented a shrinking barrier to major air flows, and variations in insolation altered the geographic distribution of atmospheric heating (MacDonald et al., 2000a). Several climate-cooling episodes between 11000 and 7700 y BP are attributed to catastrophic drainage of Lake Agassiz and the Laurentide glacial lakes in North America. Paleogeographic data from this time suggest that the Laurentide ice sheet was almost completely gone with the possible exception of residual ice masses in northern Québec. In general, most of the Arctic experienced summers warmer than today (1-2°C) during the early to middle Holocene (Overpeck et al., 1997). A common assumption is that decreases in summer insolation resulted in cooler summers in the late Holocene, which culminated in the Little Ice Age (ca. 1600). This cooling trend ended sometime in the 18th century. Detailed climatic-ecosystem reconstructions of North America at 6000 y BP (Gajewski et al., 2000) confirm that the Holocene was also a time of increased moisture, resulting in the spreading of peatlands. In the European Arctic, depletion of oxygen-isotope concentrations in parallel with declining pollen-inferred precipitation, cladoceran-inferred lake-levels, diatom-inferred lake-water ionic strength, and erosion intensity as suggested by elemental fluxes into lakes all suggest more oceanic conditions in the region during the early phase of the Holocene than today, with a shift towards drier conditions between ~ 6000 and 4500 BP (Hammarlund et al., 2002; Korhola et al., 2002c). In the late-Holocene, there is a general tendency towards increased moisture, resulting in more effective peat formation (Korhola, 1995).

Despite pervasive orbital-driven forcings, climate changes during the Holocene were strongly variable among regions of the Arctic due to differences in moisture sources (Overpeck et al.,
In general, Arctic Europe, Eastern Greenland, the Russian European North, and the North Atlantic (Region I) were dominated by Atlantic moisture sources; Siberia (Region II) was dominated by Nordic Seas moisture; Chukotka, the Bering Sea region, Alaska, and the Western Arctic of Canada (Region III) were dominated by Pacific moisture; and Northeastern Canada, the Labrador Sea region, Davis Strait region, and Western Greenland (Region IV) were dominated by Labrador Sea and Atlantic moisture. Significant regional differences in climate-ecosystem evolution during the Holocene are described below and depicted in Figure 7.8. Much of the subsequent discussion focuses on historical changes in hydro-climatology (e.g., atmospheric moisture sources) and terrestrial landscape features (e.g., vegetation) in the context that they are primary controls of the water cycle affecting freshwater ecosystems. More details about such changes can be found in Chapters 2 and 6.

Figure 7.8. Pollen record of regional arctic climate change (adapted from http://www.sfu.ca/~ianh/geog415/lectures/polar/sld035.htm)

7.3.2.1 Region I: Arctic Europe, Eastern Greenland, Russian European North, N. Atlantic

The present-day climate in Northern Fennoscandia is dominated by westerly airflow that brings cyclonic rains to the area, especially during winter (see Seppa and Hammarlund, 2000). The Scandes Mountains of mid-central Sweden mark the boundary between oceanic climate conditions to the west and more continental conditions to the east, especially in northern Finland and Russia which are strongly influenced by the Siberian high pressure cell that allows easterly air flow into northern Fennoscandia during winter. Climate and freshwater-ecosystem changes during the Holocene have been attributed largely to fluctuations in the prevailing air-circulation patterns in the region. Pollen, diatom, chironomid, and oxygen-isotope records from lake sediments have been used to reconstruct climate conditions and ecosystem responses during the Holocene (e.g., Seppa and Hammarlund, 2000; Korhola et al., 2000b, 2002c; Rosén et al., 2001; Seppa and Birks, 2002). These studies suggest that northern Fennoscandia was a sparse, treeless tundra environment following final disintegration of the Scandinavian Ice Sheet (10000-9000 y BP) until spread of *Betula* forests to the shores of the Arctic Ocean and to an altitude of at least 400 m in the mountains between 9600 and 8300 y BP (see Chapter 6 for more detailed discussion regarding terrestrial-vegetation changes). Increased moisture during this period has been attributed to strengthening of the Siberian High which may have enhanced sea-level pressure gradients between the continent and the Atlantic, strengthened the Icelandic Low and produced greater penetration of westerly winter storms and increased snowfall over western Fennoscandia (see also Hammarlund and Edwards, 1998). Associated strengthening of westerlies and northward shifts in the Atlantic storm tracks may also have produced higher snowfall in Greenland during this period (MacDonald et al., 2000a).

The decline of *Betula* forests was accompanied by rapid increases in *Pinus* between 9200-8000 y BP in the extreme northeast to 7900-5500 y BP in the western and southwestern parts of the region, which signals a shift toward drier summers and increased seasonality (Seppa and Hammarlund, 2000). Pollen evidence suggests that the late-Holocene treeline retreat in northern Norway and Finland started at about 5000 y BP, and included recession of both *Pinus* and *Betula*, which were subsequently replaced by tundra vegetation. This retreat has
been attributed to decreased summer insolation during the latter part of the Holocene. It has also been suggested that later snowmelt and cooler summers gradually favoured Betula at the expense of Pinus along the boreal treeline. Similar climate changes may explain peatland expansion in the late Holocene both within boreal and tundra ecozones (Seppa and Hammarlund, 2000).

The response of aquatic ecosystems to the climate-induced changes during the Holocene has been inferred from lake sediment and peat stratigraphic records. The very dry period corresponding to shifts from Betula to Pinus corresponds to increasing frequency of diatom and cladoceran taxa indicating lake-level reduction and growing over of numerous lakes (Seppa and Hammarlund, 2000). Likewise, diatom and cladoceran evidence suggest dry warm summers during the period dominated by Pinus (~7000 to 3500 y BP).

There have been a variety of recent quantitative reconstructions of Holocene changes and variability in climatic and environmental variables through analysis of isotopic records and sedimentary remains of pollen, diatom assemblages and/or chironomid head capsules from arctic and sub-arctic lakes in northern Sweden (Rosen et al., 2001; Shemesh et al., 2001; Bigler et al., 2002; Bigler and Hall, 2002, 2003; Bigler et al., 2003; Korhola et al., 2000b; 2002c; and Seppä et al., 2002). Comparative analyses revealed that the timing and scale of development of the historical biotic assemblages were attributable to local geology, site-specific processes such as vegetation development, climate, hydrological setting and in-lake biogeochemical and ecological processes. Several general climate-related trends were deduced for the region: a decreasing average temperatures of approximately 2.5–4°C since the early Holocene; summer temperatures of 1.7-2.3 °C above present-day estimates; winter temperatures 1-3 °C warmer during the early Holocene; and, a corresponding decreasing lake-water pH trend since the early Holocene.

Collectively, proxy records for closed basin lakes seem to suggest that water levels were high during the early-Holocene, declining during the mid-Holocene dry period (~6000-4000 BP), and rising again during the latter part of the Holocene. During the culmination of the Holocene dryness, many shallower water bodies of the region decreased greatly in size or may have dried up entirely (Korhola and Weckström, in press).

In contrast to often quite distinct changes in physical limnology, changes in chemical limnological conditions have been relatively moderate during lake development in the Fennoscandian Arctic and on the Kola Peninsula (Solovieva and Jones, 2002; Korhola and Weckström, in press). As a result of changing climate and successional changes in surrounding vegetation and soils, lakes close to the present tree-line are typically characterized by a progressive decline in pH, alkalinity and base cations, and a corresponding increase in DOC. In contrast, lakes in the barren arctic tundra at higher altitudes manifest remarkable chemical stability throughout the Holocene. Excluding the initial transient alkaline period following deglaciation evident in some sites, the long-term natural rate of pH decline in the arctic lakes of the region is estimated to be ~0.005-0.01 pH units in 100 y. This is generally less than in more southerly sites in boreal and temperate Fennoscandia where rates between 0.01-0.03 pH units per 100 y have been observed. No evidence of widespread recent “industrial acidification” can be found on the basis of quite extensive paleolimnological assessments in Arctic Europe (Korhola et al., 1999; Sorvari et al., 2002; Weckström et al.,...
2003; Korhola and Weckström, in press). However, fine-resolution studies from a number of remote lakes in the region demonstrate that aquatic bio-assemblages have gone through distinct changes that parallel the post-19th century Arctic warming (Sorvari et al., 2002).

7.3.2.2 Region II: Siberia

Siberian climate was similarly affected by increased summer insolation during 10000-8000 y BP, which likely enhanced the seasonal contrast between summer and winter insolation and strengthened the Siberian High in winter and Low in summer (Kutzbach et al., 1993). Following final disintegration of the Scandanavian ice sheet about 10000-9000 y BP, cool easterlies were replaced by predominantly westerly flows from the North Atlantic which now could penetrate western Russia and Siberia (Wohlfarth et al., 2002). Warm, wet summers and cold, dry winters likely dominated the early to mid-Holocene, with more northerly Eurasian summer storm tracks, especially over Siberia (MacDonald et al., 2000a). Warm periods were generally characterized by warmer, wetter summer conditions rather than by pronounced changes in winter conditions that remained cold and dry. Pollen reconstructions from peatlands across Arctic Russia suggest warmer than present conditions (1-2°C) during the late glacial-Holocene transition, which was the warmest time for sites in coastal and island areas. The warmest times for non-coastal areas (accompanied by significantly greater precipitation) occurred between 6000 and 4500 y BP, with notable secondary warming events occurring at about 3500 and 1000 y BP (Andreev and Klimanov, 2000).

Pollen evidence from perennially-frozen soil and peat sequences suggests that boreal-forest development commenced across northern Russia and Siberia by 10000 y BP, reaching the current arctic coastline in most areas between 9000 and 7000 y BP, and retreating to its present position by 4000 to 3000 y BP (MacDonald et al., 2000b). Early forests were Betula dominated but Larix (with lesser Picea) became prevalent between 8000 to 4000 y BP. The expansion of the forest was facilitated by increased solar insolation conditions at the conclusion of the Scandanavian glaciation, and by treeline warming due to enhanced westerly air flow (MacDonald et al., 2000b). Eventual retreat of the treeline to its present day position is likewise attributed to declining summer insolation towards the late Holocene, as well as cooler surface waters in the Norwegian, Greenland and Barents Seas (MacDonald et al., 2000b).

Increases in precipitation in some portions of northern Russia occurred during the interval from 9000-7000 y BP followed by gradual drying to 6000 y BP (Andreev and Klimanov, 2000; Wolfe et al., 2000). This has also been attributed to strengthening of the sea-level pressure gradients that also affected climate and ecosystems in Region I at this time (see MacDonald et al., 2000a).

Northward migration of treeline also had a systematic impact on ecosystem characteristics of some Siberian lakes. For a lake in the Lena River area, diatom assemblages dating prior to treeline advance were found to be dominated by small benthic Fragilaria species, and diatom indicators also suggested high alkalinity and low productivity at this time (Liang et al., 1999). Following treeline advance, lakes shifted to stable diatom assemblages dominated by Achnanthes species and low alkalinity, which are attributed to the influence of organic runoff.
from a forested landscape (Liang et al., 1999). Re-establishment of Fragilaria-dominated
assemblages and higher alkalinity conditions accompanied the subsequent reversion to shrub
tundra (Liang et al., 1999). The authors attributed recent declines in alkalinity and minor
changes in diatom assemblages to influx of humic substances from catchment peatlands.

7.3.2.3 Region III: Chukotka, Bering Sea, Alaska, W. Arctic Canada

Early Holocene (10,000-9000 y BP) climate in northwestern North America was strongly
influenced by the presence of the Laurentian Ice Sheets, particularly in downwind areas.
High albedos, cold surface conditions and height of ice apparently disrupted westerly airflows
(or may possibly have maintained a stationary surface high-pressure cell with anticyclonic
circulation), which promoted dry, warm air penetration from the southeast (MacDonald et al.,
2000a). Dry conditions were also prevalent at this time in unglaciated areas such as
northwestern Alaska and portions of the Yukon where a 60 to 80 m reduction in sea level
increased distances to marine moisture sources by several hundred kilometers. Biological
indicators from Alaskan lakes suggest dry, higher productivity conditions, with lower lake
levels between 11,000 and 8000 y BP, followed by a gradual shift to modern moisture levels
by 6000 y BP (Edwards et al., 2000; Barber and Finney, 2000).

Terrestrial vegetation (and the northern tree limit) clearly indicates a warmer-than-present
early Holocene (e.g., Spear, 1993). Vegetation shifts reconstructed mainly from fossil pollen
evidence reveal the advance and retreat of the boreal forest in Western North America which
has been attributed mainly to short-term changes in atmospheric circulation and associated
storm tracks, i.e., shifts in the mean summer position of the Arctic Frontal Zone (MacDonald
et al., 1993). Higher temperatures and increased moisture during the mid-Holocene
(especially between about 5000 and 3500 y BP) also produced episodes of treeline advance of
250-300 km northward that are recorded in the isotopic, geochemical, diatom and fossil pollen
records of lakes near present-day treeline in the central Canadian treeline region (Yellowknife
area) (MacDonald et al., 1993). Additional evidence for significant changes in diatom
community structure (shifts from planktonic to benthic forms), and increased productivity is
recorded in lake sediments during this mid-Holocene warming interval (ca 6000 to 5000 y
BP) in the central Canadian Subarctic (Pienitz and Vincent, 2000; Wolfe et al., 2001). This
period was also accompanied by significant increases in DOC in lakes, less water
transparency, and less exposure to PAR (Photosynthetically Active Radiation) and UV in the
water column. For the Tuktoyaktuk Peninsula (near Mackenzie Delta) forest limits were at
least 70 km north of the current treeline between 9500 and 5000 BP (e.g., Spear, 1993).
Permafrost zones were also presumably located north of their present day distribution during
this period. In general, modern forests were established in Alaska by 6000 y BP and
northwestern Canada by approximately 5000 y BP.

Prolonged development and expansion of peatlands in North America commencing at
between 8000 and 6000 y BP has been attributed to progressive solar-insolation driven
moisture increases towards the late Holocene (MacDonald et al., 2000a).
7.3.2.4 Region IV: NE Canada, Labrador Sea, Davis Strait, West Greenland

The climate change and ecosystem response in northeastern Canada is distinguished from northwestern regions by generally colder conditions during early Holocene because of delayed melting of ice sheet remnants until close to 6000 y BP. Consequently, tundra and taiga with abundant alder covered more of Labrador and northern Québec than the present day (Gajewski et al., 2000). Other distinct differences in forest ecozones are also apparent (Richard, 1995). Shrub tundra and open boreal forest were also denser than present day (Gajewski et al., 2000). Warming in the eastern Arctic reached a maximum shortly after 6000 y BP, with higher sea-surface temperatures and decreased sea ice extent. Peatland expansion was apparently similar to that of northwestern Canada, and is likewise attributed to insolation driven increases in moisture and cooler conditions in the late Holocene. In contrast with other parts of the circumpolar north, this region has had a relatively stable climate over the last few thousand years but may experience significant warming in the future (see Box 7.1 and details on future warming in Chapter 4).

BOX 7.1. Northern Québec – Labrador: Long-term Climate Stability

7.3.3 Climate Warming and Freshwater-Ecosystem Response During the Industrial Period

Distinctive changes occurred in the magnitude of ecosystem changes at approximately 1840 that distinguish these impacts from climate changes observed during the preceding Holocene period. A compilation of paleoclimate records from lake sediments, trees, glaciers and marine sediments (Overpeck et al., 1997) suggests that in the period following the Little Ice Age, approx. 1840 until the mid-20th century, the Circumpolar Arctic has experienced unprecedented warming to the highest temperatures observed in the past 400 years. Effects include retreat of glaciers, melting of permafrost, and sea ice and alteration of terrestrial and aquatic ecosystems. These climate changes are attributed to increased greenhouse-gas concentrations, and to a lesser extent solar irradiance, decreased volcanic activity and internal climate feedbacks. Examples of profound responses to the recent climate warming relevant to freshwater systems are numerous. Selected examples are given below.

Sorvari and Korhola (1998) studied the recent (~150 years) environmental history of Lake Saanajärvi, located in the barren tundra at 679 m a.s.l. in the northwestern part of Finnish Lapland. They found distinctive changes in the diatom community composition with increasing occurrences of small planktonic diatoms starting about 100 years ago. Since no changes in lake-water pH could be observed, and because both airborne pollution and catchment disturbances are known to be almost non-existent in the region, they postulated that recent arctic warming has been the main reason behind the observed ecological change.

To test the climate warming hypothesis further, Korhola et al. (2002b) analyzed additional sedimentary proxy indicators from Lake Saanajärvi. The biological and sedimentological records were contrasted with a 200-year long climate record specifically reconstructed for the region using a compilation of measured meteorological data and various proxy sources. They found synchronous changes in lake biota and sedimentological parameters that seemed to occur in parallel with the increasing mean annual and summer temperatures starting around
the 1850s. It was hypothesized that the rising temperature had increased the metalimnion steepness and thermal stability in the lake, which in turn supported increasing productivity by creating more suitable conditions for the growth of plankton.

Sorvari et al. (2002), using high-resolution (3-10 ys) paleolimnological data from five remote and non-polluted lakes in Finnish Lapland, found a distinct change in diatom assemblages that parallels the post-19th century arctic warming detected by examination of regional long-term instrumental series, historical records of ice cover and tree-ring measurements. The change was predominantly from benthos to plankton and affected the overall diatom richness. A particularly strong relationship was found between spring temperatures and compositional structure of diatoms as summarized by principal components analysis. The mechanism behind the change is most probably associated with decreased ice-cover duration, increased thermal stability, and resultant changes in internal nutrient dynamics.

Douglas et al. (1994) using diatom indicators in shallow ponds of the High Arctic (Ellesmere Island), found relatively stable diatom populations over the past 8,000 years, but striking successional changes over the past 200 years. These changes probably indicate a climate warming related to decreased ice- and snow-cover duration, and length of growing season (Douglas et al., 1994). Although temperature changes are difficult to assess, the changes were sufficient to change the pond communities. In these ponds there are no diatoms in the plankton; however a shift occurs from a low diversity, perilithic diatom community to a more diverse periphytic community living on mosses.

Diatom indicators in lakes also show shifts in assemblages, most likely caused by climate warming over the past 150 years. Ruhland et al. (2003) document changes in 50 lakes in western Canada between 62°N and 67°N, spanning the treeline. Shifts in diatoms from Fragilariopsis to high abundance of the planktonic Cyclotella forms, is consistent “with a shorter duration of ice cover, a longer growing season and/or stronger thermal stratification patterns”, such as a shift from unstratified to stratified conditions.

Char Lake (Cornwallis Island Canada, 74°N) is the best-studied high-arctic lake. Recent studies (Michelutti et al., 2002) show no change in water quality over time but do show a subtle shift in diatom assemblage as evidenced in the paleorecord. These changes are consistent with recent climate changes (1988-1997) and are likely caused by “reduced summer ice cover and a longer growing season”. Chapter 5 reviews recently documented observations of the general, although not ubiquitous, decline in duration of lake and river ice cover in the Arctic and Subarctic.

Chrysophyte microfossils show changes that parallel diatom changes (Wolfe and Perren, 2001) and are also probably related to reduced ice-cover duration. For example, Chrysophyte microfossils have been absent or rare in Sawtooth Lake (79°N on Ellesmere Island) over the past 2500 years but suddenly became abundant 80 years ago. Similarly, in Kekerturnak Lake (68°N Baffin Island), planktonic chrysophytes increased greatly in the upper sediments corresponding to the latter part of the 20th century. In contrast, lakes in regions without warming show no change in sediment-based indicators. For example, Paterson et al. (2003)
found no change in the last 150 years of chrysophyte and diatom indicators in the sediment of Saglek Lake (Canada, northern Labrador).

The above section has provided documented changes about some aspects of freshwater ecosystems driven by shifts in climate in the recent past. As such, it provides a baseline against which future effects of climate change can be both projected and measured.

7.4. CLIMATE CHANGE EFFECTS

7.4.1 Broad-Scale Effects on Freshwater Systems

Arctic freshwater systems are particularly sensitive to climate change because numerous hydro-ecological processes respond to even small changes in climate. These processes may adjust gradually to changes in climate, or abruptly as environmental or ecosystem thresholds are exceeded (Box 7.2). This is especially the case for cryospheric components that significantly affect: the water cycle of lakes, rivers and ponds; the habitat characteristics of these freshwater systems, and the flora and fauna that occupy them. In the case of large arctic rivers (e.g., Yenisey, Lena, Ob, Mackenzie), evaluations of the effects of climate change must be made well outside the Arctic. The dynamics of such large systems depend on hydrologic processes prevailing within their relatively water-rich headwaters found in more temperate southern latitudes. Also, many of these headwater areas are regulated in some way, a factor that may interact in some way with downstream, arctic climate-change impacts.

BOX 7.2. Thresholds of Response: Freshwater System Step Changes with the Advance Climate Change

Prior to considering the specific effects of climate change on arctic freshwater systems, it is useful to place the ACIA 5-AOGCM (Atmosphere-Ocean General Circulation Model) projections for the overall Arctic into a more suitable freshwater context. For the most part, this requires focusing on model projections for the major arctic terrestrial landscapes, including some extra-arctic headwater areas, since these are the domains of freshwater systems. The following reviews the AOGCM simulation results (primarily on the final time interval of 2070-2089 to illustrate the most pronounced changes) and, through additional processing of the modeled data, provides: a) a perspective on how such changes can be important to broad-scale features of arctic freshwater ecosystems, and b) a background template for the subsequent discussions of specific effects.

Chapter 4 concluded that the 5-model annual mean warming for the areas north of 60°N to 2070-2089 is expect to be 3.7°C, or approximately twice the global mean. It was further noted that it is very likely that nearly all land areas, which includes the freshwater systems, will warm more rapidly than the global average and this effect will be particularly evident during the cold season at northern high latitudes. Within the Arctic, however, it is also important to point out that the regional geography of much of the warming experienced on the land is linked to even larger warming over the central Arctic Ocean. For example, the 5-model mean warming for large areas of the Arctic Ocean reaches above 9°C by 2070-2089.
during the autumn (October-December). Adjacent to this, extensive areas of land also experience pronounced warming, the largest increases in air temperature being closest to the coastal margins and decreasing southwards. An example of this is illustrated in Figure 7.9a, which displays the 5-model composite mean surface air temperature for the month of October. Areas of particular autumn warming are northern Siberia of Region II and the western portions of the Canadian Archipelago in Region IV. Notably, however, air temperature increases here are no more than about 5°C in the extreme compared to the almost two-fold greater increases in temperature over the ocean. Such pronounced potential warming of freshwater systems in October is particularly important because this is typically the month in which freshwater lake and river systems along the coastal margins currently experience freeze-over. Employing a typical rate of change for freeze-up of 1-day/+0.2°C (Magnuson et al., 2000), such warming would cause delays of up to 25 days but importantly, this would most greatly affect the higher latitude, near-coastal freshwater systems. This is further discussed below and in Chapter 5.

Figure 7.9. Changes to arctic mean air temperature for the months of a) October and b) November, 2070-2089, derived from the ACIA 5-AOGCM simulations. Note effect of ocean warming on adjacent arctic coastal zone and extent to more southerly latitudes.

Even more dramatic temperature increases are experienced in coastal land areas in the subsequent month of November for 2070-2089 (Figure 7.9b). Significant warming now also extends to most coastal areas of Region III and to more southerly latitudes of Region II, including the headwater regions of the major Siberian Arctic rivers below 60°N. Latitudinal gradients in warming for arctic freshwater systems are especially important because of the influence of extra-arctic basins on the timing and magnitude of flow in the major northward flowing arctic rivers. In the case of Region II, warming in November south of 60°N is significant because this is typically the month that marks the beginning of major snow accumulation. Similar to the delay in freeze-up, such higher temperatures would effectively decrease the length of period available to accumulate a winter snowpack. This would be subsequently reflected in the magnitude of the spring snowmelt that forms the major hydrologic event of the year at northern latitudes and is known to significantly affect downstream arctic river and delta systems. The effect of a reduced winter snow-accumulation period on the freshet magnitude, however, could be offset by the projected increase in winter precipitation. As noted in Chapter 4, the terrestrial regions of North America and Eurasia are among the areas where the percentage increases in precipitation will be greatest and, similar to temperature, the largest increases are expected in the autumn and winter. Although caution must be used in interpreting regional trends from the simulated precipitation patterns because of large variations in model projections, the 5-model ensemble projections also show winter increases in precipitation for the extra-arctic headwater regions of the large northern rivers (Figure 7.10). The degree to which this would compensate for the reduced length of the winter accumulation period, however, requires detailed regional analysis.

Figure 7.10. Composite map of November to April precipitation changes (2070-2089) from the ACIA 5-AOGCM simulations. Four major arctic rivers (Yenisey, Lena, Ob and
Over the terrestrial regions of the northern latitudes, it is the cold season (defined here as October to May - the current period of dominant snow and ice cover for freshwater systems) that is characterized by the strongest latitudinal gradients in warming. Figures 7.11a and b display the changes in average temperature over terrestrial areas for the four ACIA regions broken into three latitudinal bands of 70-85°, 60-70° and 50-60°N, the latter representing the higher precipitation zones that feed the major arctic rivers in Regions II (Lena, Ob and Yenisey rivers) and eastern Region III plus western Region IV (Mackenzie River). The strongest latitudinal warming gradients in the cold season are evident for Regions I and III, becoming particularly magnified in the latter by 2070-2089, whereas Region IV shows a slight reversing trend. Hence, except for Region IV, it appears that with continued warming the higher-latitude zones will continue to experience the relatively highest degree of warming. This would lead to a reduction in the thermal gradient along the course of some of the major arctic rivers. If such reductions prevail during particular parts of the cold season, they could have major implications for the dynamics of particular hydrologic events such as the spring freshet/ice-breakup. In general, the most severe spring floods on cold-regions rivers are associated with a strong climatic gradient between the headwaters and the downstream reaches – typically from south to north on most large arctic rivers (e.g., Gray and Prowse, 1993). In such cases, the spring flood wave produced by snowmelt must “push” downstream into colder conditions, and hence towards a relatively competent ice cover that has experienced little thermal decay. Changes to the strength of this climatic gradient would alter the severity of breakup and the associated flooding. Figure 7.12a illustrates the changes in air temperatures expected for April, 2070-2089. This is currently the month of freshet initiation, with May being the primary month of freshet advance, in the southern headwaters of the major arctic rivers. With forecasted advances in ice and flow conditions (see also Chapter 5) April should become the primary month of freshet advance by 2070-2089. Of particular note in Figure 7.12a is the high degree of warming in the downstream areas of the major Russian rivers. Such high-latitude warming should therefore lead to less severe ice breakups and flooding as the spring floodwave pushes northward. A comparable degree of high-latitude warming is absent for the Mackenzie River. Of additional note from Figure 7.12a and b is the degree of warming that occurs in the headwater regions of the three large Russian rivers during April and March. This will result in an early advance of snowmelt along these rivers. Again, however, a comparable degree of headwater warming and hence snowmelt runoff is not forecast for the Mackenzie basin. This regional dichotomy could produce future differences in the spring timing of lake/river-ice breakup and associated freshet, including the ultimate export of freshwater to the Arctic Ocean.

Figure 7.11. Changes to mean air temperature for land areas in three latitudinal bands for the four ACIA arctic regions and three time intervals from the ACIA 5-AOGCM simulations. Error bars represent standard deviation from the mean. Cold season (a: October-May) and warm season (b: June-September) were selected based on dominance of ice-covered and open-water period that approximate conditions prevailing in current climate for the zone of major freshwater systems located in latitudinal band 60-70°N. Longer (shorter) duration ice-covered periods prevail at the more northern (southern) latitudinal band.
Figure 7.12. Changes to arctic mean air temperature for the months of a) April and b) March, 2070-2089, derived from the ACIA 5-AOGCM simulations. Note relatively greater headwater and downstream warming of the Russian rivers as compared to that of the Mackenzie.

Although the smallest degree of warming is expected for the open-water warm season in all Regions and at all latitudes (Figure 7.11b), even the forecast ~1-3°C warming could significantly increase evaporative losses from freshwater systems, especially with a shortened ice season, and via evapotranspiration from the terrestrial landscape that feeds them. As for changes in winter snowpack, such temperature-induced losses could be offset by increases in precipitation but the 5-model ensemble indicates that these are expected to be smallest during the summer. More detailed consideration of the changes and effects on freshwater ecosystems that could result from the ACIA AOGCM simulated changes in climate are provided in Chapter 5 and below.

7.4.2 Effects on Hydro-Ecology of Contributing Basins

The regional patterns in forecasted temperature and precipitation reviewed above are useful to understand some broad-scale effects that may occur. Specific effects, however, will be much more diverse and complex, even within regions of similar temperature and precipitation changes because of intra-regional heterogeneity in the freshwater systems and the surrounding landscapes that affect them. For example, elevational difference is one physical factor that will produce a complex altered pattern of snow storage and runoff. Although warmer conditions will generally reduce the length of winter, snow accumulation could either decrease or increase, the latter most likely to occur in higher elevation zones where enhanced storm activity combined with orographic effects would increase winter snowfall. Increased accumulation would be most pronounced at very high elevations above the increased freezing level, and where the summer season would remain devoid of major melt events. Furthermore, with reduced melt at high elevations due to greater storminess, more semi-permanent snowpacks at high altitudes are also expected to be preserved (Woo, 1996). By contrast, warming at lower elevations, especially in the more temperate maritime zones, is likely to increase rainfall and rain-on-snow runoff events. Snow patterns will be affected by a number of other factors, including vegetation, which is also forecast to be altered by climate change (see Chapter 6 for discussion of changes in arctic vegetation regimes). For example, shifts from tundra vegetation to trees may lead to greater snow interception and subsequent losses to sublimation (e.g., Pomeroy et al., 1993), whereas shifts from tundra to shrubs have been shown to reduce snow losses (Liston et al., 2002), thereby affecting the magnitude of the snowpack available for spring melt.

Advancement of the spring warming period means that snowmelt will occur in a period of lower radiation receipts which, other things being equal, will lead to a more protracted melt and less intense runoff. Traditional ecological knowledge indicates that through much of northern Canada, including the Western Canadian Arctic and Nunavut, spring melt is already occurring at an earlier date than in the past, and spring air temperatures are higher (Krupnik and Jolly, 2002), although observations near Eastern Hudson Bay indicate a delay in the initiation of spring melt (McDonald et al., 1997). See Chapter 9 for local accounts of such
changes in the Arctic. The effects of early and less intense spring melt will be most dramatic for catchments wholly contained within the northern latitudes and where snowmelt forms the major and sometimes only flow event of the year. Reductions in the spring peak will be accentuated where the loss of permafrost through associated warming increases the capacity to store runoff, although there will also be a compensating increase in summer baseflow. Overall, the magnitude and frequency of high flows will decline while low flows will increase, thereby flattening the annual hydrograph. This impact is similar to that observed as a result of regulation of rivers hence will tend to compound such effects generally.

Loss of permafrost or deepening of the active layer (seasonal melt depth; see Chapter 5 for changes in permafrost) will also reduce the peak response to rainfall events in summer, increase infiltration and promote groundwater flow. This is consistent with the analog of northern basins where those with less permafrost but receiving comparable amounts of precipitation, are characterized by a lowered and smaller range of discharge (Rouse et al., 1997). Stream runoff from permafrost basins will also be directly affected by changes in the rate of evapotranspiration and its seasonal duration. As modeled by Hinzman and Kane (1992) for areas of Alaska, the greatest reduction in summer runoff will occur in years experiencing light, uniformly spaced rainfall events whereas in years characterized by major rainfalls comprising most of the season’s precipitation, total runoff volume will be affected least.

Changes to the water balance will vary by regional climate and surface conditions but particular areas and features are believed to be especially sensitive to such alterations. Such is the case for the unglaciated lowlands of many arctic islands where special ecological niches, such as found at Polar Bear Pass on Bathurst Island or Truelove Lowland on Devon Island, are produced by unique hydro-climatic regimes and are largely dependent on ponded water produced by spring snowmelt. On a broad scale, arctic islands and coastal areas may experience significant changes to local microclimates that could affect water balance components, especially evaporation rates. Here, longer open-water seasons in the adjacent marine environments will lead to enhanced fog and low clouds, and an associated reduction in solar radiation. Increased water vapour and lower energy flux would thereby offset any potential increase in evaporation from higher air temperatures (Rouse et al., 1997).

Large regional differences in water-balance will also occur because of differences in plant communities (see also Chapter 6). For example, surface drying of open tundra is restricted when overlain by non-transpiring mosses and lichens. Over the longer term, a longer growing season combined with a northward expansion of more shrubs and trees will increase evapotranspiration. Quite a different situation can exist over the multitude of wetlands that occupy so much of the northern terrain. Although evaporation is inhibited after initial surface drying on those covered by sphagnum moss or lichen, evapotranspiration continues throughout the summer in wetlands occupied by vascular plants over porous peat soils, and only slows as the water table declines. Higher summer temperatures have the ability to dry such wetlands to greater depths but their overall storage conditions will depend on changes to other water balance components, particularly snowmelt and rainfall inputs.
As the active layer deepens and more unfrozen flow pathways develop in the permafrost, there will be an enhancement of geochemical weathering and nutrient release (e.g., phosphorus; Hobbie et al., 1999; see also Chapter 5). This will ultimately affect productivity in arctic freshwater systems such as Toolik Lake, Alaska (Box 7.3). As a more immediate result, the chemical composition of surface runoff and groundwater flows will be altered. In addition, suspended sediment loads can be expected to increase as a result of thermokarst erosion, particularly in ice-rich locations. Suspended sediment and nutrient loading of northern freshwater systems will probably also increase as land subsidence, slumping and landslides increase with permafrost degradation, as traditional ecological knowledge has documented in the Western Canadian Arctic where the depth of the active layer has increased (Krupnik and Jolly, 2002). Thermokarst erosion will continue until at least the large near-surface deposits are depleted and new surface flow patterns are stabilized. Such fluvial-morphological adjustment is likely to be very lengthy, bordering on the order of hundreds of years, considering the time that has been estimated for some northern rivers to reach a new equilibrium after experiencing a major shift in their suspended-sediment regime (e.g., Church, 1995). A major reason for such a protracted period is the time it takes for new vegetation to colonize and stabilize the channel landforms. The stabilization that will occur in the Arctic under climate change is further complicated by the expected change in vegetation regimes, particularly by the northward advance of shrubs and trees (see Chapter 6). Such vegetation shifts will cause further changes to stream water chemistry by altering the DOC concentrations. Current data indicate DOC is negatively correlated with latitude (Rühland and Smol, 1998; Fallu and Pienitz, 1999) and, because of the same controlling effects, decreases with distance from treeline (Pienitz and Smol, 1993; Korhola et al., 2002b) and along boreal forest to tundra gradients (Vincent and Hobbie, 2000). Hence, as vegetation shifts from mosses and lichens to grasses and woody-stem species, runoff will contain increasing concentrations of DOC and particulate detrital material. Verification of enhanced DOC supply being associated with northward treeline advance is provided by various paleo studies (e.g., Seppä and Weckström, 1999; Solovieva and Jones, 2002; Korhola and Weckström, in press). Although such increases will be over the long term given the slow rates of major vegetation shifts (see also Chapter 6), earlier increases in DOC and DIC can be expected from the earlier thermal and mechanical erosion of the permafrost landscape (see also Chapter 5). More comprehensive reviews of the projected interactive effects of changes in UV radiation and climate change on DOC and DIC and related aquatic biogeochemical cycles are provided by Zepp et al. (2003) and Häder et al. (2003a).

BOX 7.3. Ecological Transitions in Toolik Lake, Alaska, in the Face of Changing Climate and Catchment Characteristics

Changes in freshwater catchments with climate change will affect not only loadings of nutrients, sediments, DOC and DIC to freshwater systems but also the transport and transformation of contaminants. Contaminant transport from surrounding catchments to freshwaters will increase as permafrost degrades and perennial snow melts (McNamara et al., 1999; Blais et al., 1998, 2001). The contaminants released from these frozen stores, and those originating from long-range transport and deposition in contributing basins, can then be stored in sediments or metabolized and biomagnified through the food web. This topic is discussed in more detail in Section 7.7.
7.4.3 Effects on General Hydro-Ecology

7.4.3.1 Streams and Rivers, Deltas and Estuaries

Lakes and rivers will be affected by a number of hydrologic shifts related to climate change including seasonal flow patterns, ice cover thickness and duration, and the frequency and severity of extreme flood events. Under the present climate, most streams and rivers originating within the Arctic are characterized by a nival regime in which high flows are produced by snowmelt and negligible flow occurs in winter. In areas of significant glaciers, such as on some Canadian and Russian islands, Greenland and Svalbard, ice melt from glaciers can sustain flow during the summer, whereas many other streams produce summer flow only from periodic rainstorm events unless they are fed by upstream storage from lakes and ponds.

A much broader range of hydrologic regimes is found within the Subarctic varying from cold interior continental, comparable to those of the Arctic, to maritime regimes fed moisture directly from open-seas even during winter. Overall, a warmer climate will lead to a shift towards a more pluvial runoff regime as a greater proportion of the annual precipitation is delivered by rain rather than snow; the magnitude of the peak of spring snowmelt declines; runoff peaks are reduced as near-surface storage is increased with melting permafrost; and base flows are augmented by a more active groundwater system.

Enhancement of winter flow will lead to the development of a floating ice cover in some streams that currently freeze to the bed. This could prove beneficial to the biological productivity of arctic streams and fish survival where winter freshwater habitat becomes limited to unfrozen pools (Craig, 1989; Prowse, 2001a, b). For other arctic streams and rivers, generally warming is expected to result in a shortened ice season and thinner cover (see Chapter 5 for further details on expected changes in ice cover). Since river ice is such a major controller of the ecology of northern streams and rivers, there are likely to be numerous significant impacts.

Under conditions of overall annual warming, the duration of river-ice cover would be reduced by a delay in the timing of freeze-up and an advancement of break-up. Data compiled over the last century or more indicates that changes in timing of these events will be at a rate of approximately one day per 0.2°C increase in air temperature (Magnuson et al., 2000). (See Section 7.4.1 and Chapter 5 for details about observed and predicted changes to lake and river ice.) For freeze-up, it is higher water and air temperatures in the autumn that combine to delay the time of first ice formation and eventual freeze-up. If there were also a reduction in the rate of autumn cooling, the interval between these two events would increase. Although all major ice types would continue to be formed, unless there were also significant changes to the flow regime, the frequency and magnitude of, for example, major frazil-ice growth periods could be reduced. This has implications for the types of ice that constitute the freeze-up cover and for the creation of unique under-ice habitats such as air cavities and those influenced by frazil concentrations (Brown et al., 1994; Cunjak et al., 1998; Prowse, 2001b).
Changes in the timing and duration of river ice formation will also alter the dissolved oxygen regimes of arctic lotic ecosystems. Following freeze-up and the elimination of direct water-atmosphere exchanges, dissolved oxygen (DO) concentrations steadily decline sometimes to near-critical levels for river biota (e.g., Chambers et al., 1997; Prowse, 2001a, b; Power et al., 1993). Reductions in ice cover duration and a related increase in the number of open-water re-aeration zones will reduce the potential for this biologically-damaging oxygen depletion. Such benefits will, however, be offset by the projected enhanced input of DOC and its subsequent oxidation (e.g., Whitfield and McNaughton, 1986; Schreier et al., 1980), the rate and magnitude of which would also be increased as a result of the above-noted higher nutrient loading. Worst case scenarios would develop on rivers where the flow is already comprised of poorly-oxygenated groundwater, such as supplied from extensive bogs and peatlands. Some rivers in the West Siberian Plain offer the best examples of this situation. Here, the River Irtysh drains large quantities of de-oxygenated water from vast peatlands into the River Ob resulting in DO levels of only about 5% of saturation (Hynes, 1970; Harper, 1981).

The greatest ice-related ecological impacts of climatic warming on arctic lotic systems will result from changes to break-up timing and intensity. As well as favouring an earlier occurrence of break-up, higher spring air-temperatures can affect break-up severity (Prowse and Beltaos, 2002). While thinner ice produced by a warmer winter would tend to promote a less severe break-up, this could be counteracted to some degree by the earlier timing of the event. Break-up severity also depends on the size of the spring flood wave. While greater and more rapid snowmelt runoff would favour an increase in break-up severity, the reverse is true for smaller snowpacks and more protracted melt. Hence, changes in break-up severity will regionally vary according to the variations in winter precipitation and spring-melt patterns.

For regions that experience more “thermal” or less dynamic ice break-up (Gray and Prowse, 1993), the magnitude of the annual spring flood will be reduced. For the many northern communities that historically located near river floodplains for ease of transportation access, reductions in spring ice-jam flooding would be a benefit. By contrast, however, reductions in the frequency and severity of ice-jam flooding would have a serious impact on river ecology since it is the physical disturbances associated with break-up scouring and flooding that are so important to nutrient and organic matter dynamics, spring water chemistry, and the abundance and diversity of river biota (Scrimgeour et al., 1994; Cunjak et al., 1998; Prowse and Culp, 2003). Specifically, it is ice-induced flooding that supplies the flux of sediment, nutrients, and water that is essential to the health of the riparian system, river deltas being particularly dependent (e.g., Marsh and Hey, 1989; Lesack et al., 1991; Prowse and Conly, 2001). More generally, given that the magnitude and recurrence interval of water levels produced by ice jams often exceed those for open-water conditions, break-up is probably the main supplier of allochtonous organic material in cold-regions rivers (Scrimgeour et al., 1994; Prowse and Culp, 2003). In the same manner, breakup serves as an indirect driver of primary and secondary productivity through the supply of nutrients - a common limiting factor to productivity in cold-regions rivers. Even the meso-scale climate of delta ecosystems and spring plant growth is known to depend on the timing and severity of break-up flooding (Gill, 1974; Hirst, 1984; Prowse, 2001a).
River-ice is also a key agent of geomorphologic change: responsible for the creation of numerous erosional and depositional features within river channels and on channel floodplains (e.g., Prowse and Gridley, 1993; Prowse, 2001a). Since most geomorphological activity occurs during freeze-up and break-up, changes to the timing of these events should not have any significant effect. If, however, climatic conditions alter the severity of such events, then particular geomorphologic processes are likely to be affected. Furthermore, break-up events affect the general processes of channel enlargement, scour of substrate habitat, and the removal-succession of riparian vegetation. All such major river-modifying processes would be altered by any climate-induced shift in break-up intensity.

In summary, if climate change alters the long-term nature of break-up dynamics, the biological template for rivers and related delta ecosystems could be significantly altered with direct effects on in-channel and riparian biological productivity. If, for example, dynamic breakups and the related level of disturbance are significantly reduced, there will be a change to lower overall biological diversity and productivity, the effects being most pronounced on floodplain and delta aquatic systems.

As a result of the reduced ice-covered season and increased air temperatures during the open-water period, summer water temperatures will rise. This combined with greater DOC and nutrient loadings should lead to a general increase in total stream productivity, although it is unclear whether temperature will have a significant direct effect on the rate of processing of additional particulate detrital material. Irons et al. (1994), for example, found a comparable rate of litter processing by invertebrates in Michigan and Alaska and concluded that temperature was not a main factor. The effect of increased temperature on processing efficiency by ‘cold-climate’ species of invertebrates, however, has not been evaluated. The effect of enhanced nutrient loading to arctic streams is more projectable. The current nutrient limitation of many arctic streams is such that even slight increases in available P, for example, will produce a significant increase in primary productivity (Flanagan et al., 2003). Where productivity responses by stream biota are co-limited by P and N (e.g., as suggested by the experimental results of Peterson et al., 1993), increased loadings of both nutrients would be required to sustain high levels of enhanced productivity.

Climate change impacts on the dynamics of arctic estuaries are summarized in Table 7.1 (Carmack and Macdonald, 2002). The major factor affecting arctic estuarine systems from the projected ACIA levels of climate change will be the increase in freshwater discharge (see Chapter 5 for review of changes in discharge of major arctic rivers). For some arctic basins, such as the Chukchi Sea, there is presently very little freshwater runoff and consequently no estuarine zones. Increased river discharge may create estuarine areas, providing new habitat opportunities for euryhaline species. In established estuarine systems, such as the Mackenzie River system and the Yenisey and Ob rivers, increased freshwater input in summer (e.g., Peterson et al., 2002) will increase stratification, making these habitats more suitable for freshwater species and less suitable for marine species. There will likely be shifts in species composition to more euryhaline and anadromous species. The increased freshwater input will also deposit more organic material, changing estuarine biogeochemistry and perhaps increasing primary productivity.
Table 7.1. A synthesis of the potential effects of climate change on arctic estuarine systems from both the bottom-up and top-down ecological perspectives (adapted from Carmack and Macdonald, 2002). Assessment of cascading consequences from a human perspective can be generally positive (+), negative (-), neutral (0), or unknown (?).

A secondary impact of increased freshwater discharge that is of serious concern, particularly for Siberian rivers that traverse large industrialized watersheds, is the potential increased input of contaminants. The Ob and Yenisey rivers, for example, have high levels of organochlorine contamination as compared to the Lena River (Zhulidov et al., 1998), which is considered to be relatively pristine (Guieu et al., 1996). Larsen et al. (1995) note that arctic fishes have a life strategy that involves intensive feeding in spring and summer, allowing for the build up of lipid stores and the coping with food shortages in winter. The high body lipid content of arctic fishes may make them more vulnerable to lipid-soluble pollutants like PAHs (Polycyclic Aromatic Hydrocarbons) or PCBs (Polychlorinated Biphenyls). Additionally, increased availability of open water will lead to increased marine traffic with cascading negative consequences in terms of pollution and risk of oil spills on estuarine systems.

Arctic deltas provide overwintering habitat for many species that tolerate brackish waters. These areas are maintained as suitable habitat by a combination of continuous under-ice freshwater flow, and the formation of the nearshore ice barrier in the stamukhi zone (area of grounded, near-shore ice pressure-ridges). As temperatures rise, the seasonal ice zone of estuaries will expand, and the ice-free season will extend (Carmack and Macdonald, 2002). Disruption of either the flow regime or the ice barrier may have profound effects on availability of suitable overwintering habitat for desired fish species. Given that such habitat is likely limited and hence, in turn, limits population abundance, the consequences of this for local fisheries may be significant. Additionally, in early winter, subsistence and commercial fisheries target fish that overwinter in deltas. Thinning ice may limit access to these fisheries.

Similar to freshwater systems, ecological control of marine systems can be viewed from bottom-up (i.e., nutrients-production-biota linkages) and/or top-down (i.e., human activities-predators-keystone biota) perspectives (Parsons, 1992). The special role of ice as both a habitat and a major physical force shaping the estuarine and nearshore arctic environment suggests climate change as working in both modes to impact the systems (Carmack and Macdonald, 2002). Of example, is the loss of the largest epishelf lake (fresh and brackish water body contained behind ice shelf) in the northern Hemisphere, with the deterioration and break up of the Ward Hunt ice shelf (Mueller et al., 2003). The loss of this near-shore water body has affected a unique community of marine and freshwater planktonic species, as well as communities of cold-tolerant microscopic algae and animals that inhabited the upper ice shelf.

7.4.3.2. Lakes, Ponds and Wetlands

Lentic systems north of the Arctic Circle contain numerous small to medium lakes and a multitude of small ponds and wetland systems. Relatively deep lakes are primarily contained within alpine or foothill regions such as those of the Putorana Plateau in the lower basin of the Yenisey River. One very large and deep lake, Great Bear Lake, is found partly within the Arctic Circle. Variations in its water budget primarily depend on flows from its contributing catchment that is comprised largely of interior plains lowlands and exposed bedrock all
contained north of 60°N. Its southern counterpart, Great Slave Lake, provides a strong hydrologic contrast to this system. Although also part of the main stem Mackenzie River basin and wholly located north of 60°N, its water budget is primarily determined by inflow that originates from Mackenzie River headwater rivers located much further to the south. Moreover, its seasonality in water levels reflect the effects of flow regulation and climatic variability in one of its major tributaries, the Peace River, located some 2000 km upstream in the Rocky Mountain headwaters of western Canada (Gibson et al., 2004; Peters and Prowse, 2001). As such, it offers the best example of a northern lentic system that will be only marginally affected by climate-change hydrologic processes operating within the north (e.g., direct lake evaporation and precipitation) but be dependent principally on changes in water-balance processes operating well outside the Arctic.

The other major arctic landscape-type that contains large, although primarily shallower, lakes is the coastal plains region found around the circumpolar north. As earlier mentioned, these shallow systems depend on snowmelt as their primary source of water, with rainfall gains often negated by evapo-transpirative losses of water during summer. Evaporation from these shallow water bodies will increase as the ice-free season lengths. Hence, the water budget of most lake, pond and wetland systems will depend more heavily on the supply of spring melt water to produce a positive annual water balance and are more likely to dry out during the summer. Another possible outcome of climate change is a shift in vegetation from non-transpiring lichens and mosses to vascular plants as temperatures rise and the growing season extends (Rouse et al., 1997), thus potentially exacerbating water losses. Factors such as increasing cloud cover and summer precipitation may, however, mitigate these effects.

The potential for many northern shallow lotic systems to dry out under a warming climate is increased by the loss of permafrost. Ponds may be coupled with the groundwater system and drain if losses due to downward percolation and evaporation are greater than resupply by spring snowmelt and summer precipitation. Patchy arctic wetlands are particularly sensitive to permafrost degradation, which may link surficial waters to the suprapermafrost groundwater system. Those along the southern limit of permafrost, where increases in temperature are most likely to eliminate the relatively warm permafrost, are at the highest risk of drainage (Woo et al., 1992). Traditional ecological knowledge from Nunavut and Eastern Arctic Canada indicates that recently there has been enhanced drying of lakes and rivers, as well as swamps and bogs, so much so that access to traditional hunting grounds and, in some instances, migration of fish, have been impaired (Krupnik and Jolly, 2002). (See Chapter 9 for detailed discussion of a related case study).

Warming of surface permafrost, however, could enhance the formation of thermokarst wetlands, ponds and drainage networks. This would be particularly true for areas characterized by concentrations of massive ground ice. Thawing of such ice concentrations, however, would also lead to dramatic increases in terrain slumping and subsequent sediment transport and deposition in rivers, lakes, deltas and nearshore marine environments. It would produce distinct changes in channel geomorphology on systems, where sediment-transport capacity is limited, and have significant impact on the aquatic ecology of the receiving water bodies. Catastrophic drainage of permafrost-based lakes that are now in a state of thermal instability could also occur, such as those found along the western arctic coast of Canada.
(Mackay, 1992; Marsh and Neumann, 2001; 2003). Losses of thermokarst lakes within low-lying deltaic areas are also likely to result due to rising sea levels. Lakes in the outer portion of the Mackenzie Delta (northern Richards Island) are commonly drained by marine inundation resulting from continually rising sea level (Dallimore et al., 2000). Moreover, it has been estimated that one lake per year has drained in the Tuktoyaktuk Coastlands of northern Canada over the last few thousand years (Mackay, 1992). Future, more pronounced rises in sea level are likely to accelerate this process.

Changes to the water-balance of northern wetlands are especially important because most wetlands in permafrost regions are peatlands, which can act as a source or sink of carbon and methane depending on the depth of the water table (see also Section 7.4.4.4 below). Analysis by Rouse et al. (1997) for sub-arctic sedge fens under a 2xCO₂ climate suggests that increases in temperature (+4°C) would reduce water storage in northern peatlands even with a small and persistent increase in precipitation. While acknowledging storage changes depend on variability in soil moisture and peat properties, projected declines in the water table were 10 to 20 cm over the summer.

As the ice cover of northern lakes and ponds becomes thinner, forms later and breaks up earlier (see further details in Chapter 5), concomitant changes will occur in their limnology. Thinner ice covers with less snow cover will increase the under-ice receipt of solar radiation thereby increasing under-ice algal production and oxygen (e.g., Prowse and Stephenson, 1986), and reducing the potential for winter anoxia and fish kills. This could be countered somewhat by lower water levels, which reduce water volumes under the ice and increase the likelihood of winterkill. Similarly, greater winter precipitation on a thinner ice cover could promote the formation of more highly reflective snow and white-ice layers. Such layers would reduce radiation penetration well into the spring because they also tend to delay breakup compared to covers comprised of only black ice. Notably, incident radiation will decline according to the ACIA 5-model AOGCM simulations. Reductions are likely to be relatively small (i.e., 10-12 W m⁻² for May-June of 2070-2089, Chapter 4), however, compared to the major reductions that could result from even modification of surface ice type as a result of greater reflective loss from enhanced white-ice formation.

A longer ice-free season will also increase the length of the stratified season and generally increase the depth of mixing (Box 7.4), although the magnitude and duration of the effects depend on factors such as basin depth and area. This could also potentially lead to lower oxygen concentrations in the hypolimnion and an increased stress on cold-water organisms (Rouse et al., 1997). Furthermore, such an enhancement of mixing processes and reduction in ice cover will increase the potential for many northern lakes and ponds to become contaminant sinks (see Section 7.6 for further details).

**BOX 7.4. Lake Ice Duration and Water Column Stratification: Lake Saanajärvi, Finnish Lapland**

With a longer and warmer ice-free season, total primary production should increase on all arctic lakes and ponds, and especially for the oligotrophic high-arctic ponds that are currently frozen for a majority of the year (Douglas and Smol, 1999). Similar to the situation for arctic lotic systems, an enhanced supply of nutrients and organic matter from the more biologically
productive contributing basins should boost primary productivity (Hobbie et al., 1999). Again, however, there may be offsetting effects because of reductions in light availability resulting from enhanced turbidity due to higher inputs of DOC and suspended sediment. Analogous factors have been noted to cause a switch from nutrient to light limitation of primary production, which more commonly controls the primary production of northern lakes (Hecky and Guildford, 1984).

7.4.4 Changes in Aquatic Biota, Ecosystem Structure and Function

Climate change is expected to have both direct and indirect consequences on the biota and the structure and function of arctic freshwater ecosystems. Changes in key physical/chemical parameters described above will affect community and ecosystem attributes such as species richness and biodiversity, species range and distribution, and consequently alter corresponding food web structures and primary and secondary production levels. The magnitude and extent of the ecological consequences of climate change in arctic freshwater ecosystems will depend largely on the rate and magnitude of change of three primary environmental drivers, namely; 1) the timing, magnitude and duration of the runoff regime, 2) temperature, and 3) alterations in water chemistry such as nutrient levels, DOC and particulate organic matter loadings, etc. (Poff et al., 2002; Vincent and Hobbie, 2000; Rouse et al., 1997).

7.4.4.1. Effects on Biological Communities, Biodiversity/Adaptive Responses

Climate change will significantly affect the biodiversity of freshwater ecosystems across all regions of the Arctic and possibly initiate varying adaptive responses. The magnitude, extent and duration of the impacts/responses will be system and geographically dependent, and difficult to separate from other environmental stressors. Biodiversity is related to, or affected by factors, such as:

- the variability of regional and local climate,
- the availability of local resources (e.g., water, nutrients, trace elements, energy, substrate) affecting the productivity potential,
- the nature, timing and duration of disturbance regimes in the area (e.g., floods, catastrophic water loss, fire),
- the original local and regional “stock” of species and their dispersal opportunities/barriers,
- the physiological capacity of individuals and populations to cope with new environmental conditions (e.g., physiological thresholds and tolerances),
- the levels of spatial heterogeneity (habitat fragmentation) and inter-connectiveness between aquatic systems,
- the intensity of biotic interactions such as competition, predation, disease, parasitism,
- phenotypic/genotypic flexibility in reproductive and life-history strategies (e.g., facultative vs. obligatory anadromony for certain fish; plasticity in sexual vs. asexual reproductive strategies in aquatic invertebrate and plant species, and;

Many arctic freshwater systems are exposed to multiple environmental stressors / perturbations occurring from, for example: point and/or non-point pollution (e.g., long-range aerial transport of contaminants; see section 7.7), altered hydrologic regimes related to impoundments/diversions; water quality changes from landscape alterations (e.g., mining, oil & gas exploration); biological resource exploitation (e.g., subsistence and commercial fisheries and harvesting of waterfowl and mammals; see Section 7.5); to name a few. These stressors, along with climate change, will synergistically contribute to the degradation of biological diversity at the species, genetic, and/or habitat-ecosystem levels (Pimm et al., 1995; CAFF, 2001; IPCC, 2001; UNEP, 2003). There is little evidence to suggest that climate change will slow species loss. There is growing evidence, however, that: a) climate change will contribute to accelerated species losses at regional and global levels (UNEP, 2003); and, b) the effects of alterations of biodiversity of ecosystem structure and function are likely more dependent on given levels of functional diversity rather than on the total number of species (Chaplin et al., 2000). Moreover, both the number and type of functional units present in a community largely affect ecosystem resilience and resistance to change (UNEP, 2003).

While, for the reasons stated above, large uncertainties remain in predicting species- and system-specific responses and impacts of climate-UV radiation change on biodiversity at local and regional spatial scales, several broad predictions can still be made.

First, it is likely that locally adapted, arctic species may be extirpated from certain areas as environmental conditions begin to exceed their physiological tolerances and/or ecological optima. Hence, species with limited climatic ranges and/or restricted habitat requirements (related to particular physiological or phenological traits) will be vulnerable to climate-change effects. Species whose population numbers are already low and/or reside in restricted, patchy and highly-specialized environments will be particularly at risk (UNEP, 2003). While it is unlikely that wholesale extinctions of entire arctic species will occur, some highly valued species (e.g., certain fish species) may become geographically or ecologically marginalized. For example, pronounced north-south gradients are observed in the taxonomic composition of stream macroinvertebrate communities in the Arctic, with decreasing species diversity and an increasing importance of taxa such as dipterans with distance northwards (Oswood, 1997). Moreover, many of the high-latitude filamentous algal species have temperature optima well above their low-ambient water temperatures, and are therefore likely to be highly sensitive to climate warming (Tang et al., 1997; Tang and Vincent, 1999). Hence, many high-latitude species are currently at their physiological limits and could therefore be very sensitive to future shifts in climate (Danks, 1992). Projected changes in regional runoff patterns and temperature regimes will impact river/stream environments, possibly reducing severity of disturbance events that are an integral component of their current hydro-ecology (see Section 7.4.2). Specifically, Scrimgeour et al. (1994) suggest that if these disturbances play a role in maintaining habitat complexity and associated species richness and diversity, then climate-related changes in the severity of these events will further affect macroinvertebrate and aquatic algal species distribution and associated biodiversity patterns (see also Prowse and Culp, 2003).
In estuarine habitats, there will likely be shifts in species composition to more euryhaline and anadromous species (e.g., fourhorn sculpin, ninespine and threespine sticklebacks and Arctic flounder, salmonids and coregonines). Such shifts in species composition will have cascading effects through competition for food resources with marine species, such as Arctic cod, currently inhabiting many estuarine zones. The follow-on effects of this on higher trophic levels (e.g., the impact of potentially decreased Arctic cod abundance on marine mammals and birds) remains unknown (see also Chapter 8).

For other fish species (e.g., Arctic char), alterations of the environmental conditions could shift or reduce the availability of preferred habitats of certain morphs, leading, in the extreme case, to the extirpation of particular morphs from certain locations. For example, pelagic forms of Arctic char in Thingvallavatn, Iceland occupy portions of the water column that experience summer heating. Should such heating ultimately exceed thermal preferences for this morph, its growth will likely decrease with a concomitant reduction in reproduction and productivity. Ultimately, exclusion from the habitat during critical times can occur and that morph could be permanently extirpated from such areas.

Changes in habitat characteristics driven by climate change will also likely differentially affect specific populations of fish. For example, some aspects of life-history variation of Dolly Varden on the Yukon north slope appear to be particularly associated with inter-river variation in groundwater thermal properties (e.g., egg size is larger and development time shorter in rivers, and sea access, thus earlier feeding, reduces the periodicity of reproduction to annually in rivers with warmer spring water vs. ≥ 2 years in colder rivers; Sandstrom, 1995). Thus, climate change effects that mimic this natural local, spatial (among-population) variability would be expected to result in similar shifts in populations presently occupying colder habitats.

A second major effect of climate change will be the alteration of the geographic range of species, thereby affecting local and regional biodiversity. This will likely occur through a combination of compression or loss of optimal habitat for “native” arctic species, and allowance for the northward expansion of “non-native”, southern species. For instance, the large number of northward flowing arctic rivers provide pathways for colonization of the mainland by freshwater species, which due to climatic limitations, are presently restricted to sub-arctic or non-arctic portions of the drainage basins. As climate-change effects become more realized (e.g., degree-day boundaries or mean temperature isotherms shift northward), the more ecologically vagile species should extend their geographic ranges northward (Oswood et al., 1992). In North America, for example, the distribution of yellow perch is expected to expand northward where its current distribution is primarily subarctic. Traditional ecological knowledge from the western Canadian Arctic has identified new species of fish (Pacific salmon and least cisco) that were not previously present in aquatic systems of the area (Krupnik and Jolly, 2002; see also Chapter 9). The complete consequences of such new colonizations are unknown, but could include: the introduction of new diseases and/or parasites, population reduction or extirpation through competition for critical resources, increased predation, increased hybridization of closely related taxa, and others. (see also Box 7.5, 7.8 for more detailed discussions on climate-related range extensions for select fish species and their potential ecological consequences).
BOX 7.5  Freshwater and Diadromous Fishes of the Arctic

Aquatic emergent plants are also expected to expand their distribution northwards and thus alter the overall levels of primary production of ponds and small lakes in the Arctic. Alexander et al. (1980) reported a total primary production of 300-400 g C m\(^{-2}\) y\(^{-1}\) in Barrow ponds of emergent Carex (covered 1/3 of pond) as compared to a total primary production of 1 g C m\(^{-2}\) y\(^{-1}\) for phytoplankton and 10 g C m\(^{-2}\) y\(^{-1}\) for epilithic algae. Traditional ecological observations by trappers on the Peace-Athabasca Delta of the Mackenzie River system, Canada, suggest that muskrat abundance will correspondingly increase in high-latitude lakes, ponds and wetlands as emergent aquatic vegetation become more prominent (Thorpe, 1986). While the potential northern limit for emergent aquatic macrophytes is not fully known, their projected increased presence will clearly influence overall productivity and structural complexity of arctic pond and lake habitats.

An overarching issue affecting the responses of arctic aquatic biota and related biodiversity to rapid climate change is ‘adaptive capacity’. The magnitude of change in arctic climate for the next 100 years does not exceed that seen previously, at least over a geological time scale. The future rate of change however, will be unprecedented. To survive such a challenge, arctic aquatic biota, especially those that are truly arctic in nature, must have the inherent capacity to: a) adapt (i.e., sufficient genetic capacity at the population level to evolve at the required rate); b) acclimate (i.e., phenotypic ability at the population and/or individual level to survive in the new conditions); and/or, c) move (i.e., emigrate to more optimal situations). High levels of diversity below the species level present in many arctic organisms implies that some evolutionary compensation to rapid climate change may be possible. Taxa with short generation times (e.g., zooplankton) will be able to evolve more rapidly than those with longer generation times (e.g., fish). Furthermore, assessment of genetic variability for some taxa (e.g., mitochondrial DNA in Arctic char; Wilson et al. 1996) suggests that previous genetic bottlenecking events may have a truncated capacity for such rapid evolution. This will further hamper responses by such taxa and, with the high rate of climate change and other factors (e.g., competition from new colonisers), may result in an increased risk of extinction.

Many arctic taxa may already be pre-adapted to acclimate successfully to rapid change. For example, many organisms already have enzymes with different thermal optima to allow them to cope with changing environmental conditions. Such capacity, which is presumed but not demonstrated to exist for most arctic taxa, could counterbalance the tendency for extinction noted above. Taxa that are capable of moving or emigrating to new areas have additional options to cope with rapid climate change, although access issues may preclude such movements to suitable conditions.

Clearly, significant changes in aquatic biodiversity will very likely result from climate change and biota have varying capacities to cope with the rate of this change. Ecologically speaking, any change will have significant ramifications in that adjustments in the ecosystem will follow (see Sections 7.4.4.2, 7.4.4.3, 7.4.4.4 and 7.5 below). However, from the human perspective, important questions surround the perceived significance of such changes from economic, cultural and value perspectives (see Chapters 9, 10 and 11 for discussions of possible socio-economic implications).
7.4.4.2. Effects on Food Web Structure and Dynamics

The impacts of climate change on the structure and dynamics of aquatic food webs remains poorly understood. To date, many of the insights to how arctic food webs will directly or indirectly respond to climate change effects have been obtained from either descriptive studies or a select few manipulative/experimental studies where ecosystem-level or food web manipulations have been made and response variables measured. Stream processes and biotic populations of Kuparuk River and Oksrukuyik Creek of Alaska have been shown to be controlled by the geomorphology of the systems (i.e., input of nutrient-rich springs; Craig and McCart, 1975), climate (i.e., precipitation affects discharge which affects insect and fish production (Deegan et al., 1999; Hershey et al., 1997)), resource fluxes from the surrounding catchments (Peterson et al., 1993) and corresponding biotic interactions. For instance, nutrient enrichment manipulations of the streams resulted in greater primary and fish production, and a corresponding increase in abundance of benthic macroinvertebrates (Peterson et al., 1993; Harvey et al., 1998). In addition, after seven years of artificial enrichment of the Kuparuk River, the dominant primary producer changed from diatoms to mosses (Bowden et al., 1994), which subsequently altered the abundance, distribution and taxonomic composition of the macroinvertebrate community (Bowden et al., 1999).

Other recent studies of arctic systems have identified the structural and functional importance of the microbial freshwater food web (Figure 7.13). Work in this area has shown that the microbial food web can comprise a significant fraction of the total community biomass in arctic rivers and lakes and that energy flow is routed through a diverse trophic network of microbial species displaying a wide array of nutritional modes (heterotrophic bacteria, phototrophic bacteria, phagotrophic protozoa, and mixotrophic flagellates) (Vincent and Hobbie, 2000). How climate change will influence the response of the microbial food web is not entirely certain, but work on temperate systems might help provide insight. Interestingly, research on microbial food webs of more temperate aquatic systems shows that in the absence of heavy grazing pressure on bacteria by macrozooplankton or benthic macroinvertebrates, the principal role of the microbial food web is in the degradation (respiration) of organic matter (Kalff, 2002). Hence, the microbial food web is primarily an energy sink in the plankton, being largely responsible for recycling nutrients in the water column and thereby helping to sustain planktonic and benthic primary production and ultimately higher secondary and tertiary consumers in the food chain (Kalff, 2002). With projected increases in water temperature and inputs of DOC, particulate organic carbon (POC), and DIC arising from climate change, this will certainly impact the structural and functional dynamics of the microbial food web, likely increasing the rates of carbon processing. Correspondingly, Pienitz et al. (1995) have shown that the same abiotic parameters, along with lake morphometry explains the greatest percentage of variance in diatom community composition in northwestern Canada and that diatom community structure was also highly correlated with DOC gradients in Siberian and sub-arctic Québec lakes (Lotter et al., 1998; Fallu and Pienitz, 1999). Hence, concomitant changes in the phytoplankton component of the food web will also probably cascade through the ecosystem.
Increasing temperature has the potential to alter the physiological rates of individuals, the vital rate parameters of populations, and the resultant dynamics of populations (Beisner et al., 1997; McCauley and Murdoch, 1987). Mesocosm studies investigating the influence of increasing temperature and food chain length on plankton predator-prey dynamics have shown that the predator-prey system is destabilized at higher temperatures (i.e., the macrozooplankton herbivore *Daphnia pulex* always went extinct), irrespective of the complexity of the food web (whether a 2 or 3 level food web is involved (Beisner et al., 1996, 1997). Long-term studies in Toolik Lake, Alaska project that a warmer future will likely cause elimination of lake trout populations in this lake, with concomitant impacts on the food web. The bioenergetics model used by McDonald et al. (1996) projects that a 3°C rise in July epilimnetic (surface mixed layer) temperatures could cause young-of-the-year lake trout to need to consume eight times more food than is currently necessary just to maintain adequate condition. This requirement greatly exceeds the current food availability in the lake, although it is probable that food availability will increase under warming conditions (See Box 7.2). Furthermore, the oxygen concentrations projected by the lake model (Hobbie et al., 1999) show that a future combination of higher temperatures and increased loading of total phosphorus will greatly reduce the hypolimnetic habitat (bottom waters) available for lake trout.

An example of top-down control through size-selective predation in ponds and lakes at Barrow, Alaska is provided: the lakes with fish had small and transparent *Daphnia longiremis* while lakes without fish and all ponds had large and pigmented *Daphnia middendorffiana* and *D. pulex* as well as fairy shrimp and the copepod *Heterocope* (Stross et al., 1980). Rouse et al. (1997) conclude that since top predators (fish) in arctic systems tend to be long-lived, population changes owing to recruitment failure may not be reflected in the adult populations for many years. However, the eventual loss of top predators from these systems will most likely cascade through the food-web, also affecting the structure and function of both the benthic and planktonic communities (Hershey, 1990; Goyke and Hershey, 1992; Hanson et al., 1992; O’Brien et al., 1992; Carpenter et al., 1992; Jeppesen et al., 2003).

Given the above, it is evident that it is very probable that biological interactions, including trophic structure and food chain composition will be substantially impacted by climate change. With both top-down and bottom-up processes operating simultaneously in ecosystems, (McQueen et al., 1989; Hansson, 1992; Golden and Deegan, 1998; and references therein), the degree to which each process influences producer biomass varies (McQueen et al., 1989). The well-established relationship between phosphorus and algal biomass may, consequently, differ for systems with different levels of productivity. For instance, in a 2-level trophic system (relatively unproductive), grazing zooplankton may control the algal biomass and the expected positive *Chl a*-TP (Total Phosphorous) relationship would not be observed. Therefore, one explanation for the discrepancy in the *Chl a*-TP relationship between the temperate and arctic lakes is that differences in the productivity accounts for differences in the relationship through trophic level interactions (Figure 7.14). The low productivity that has been observed in many arctic lakes may limit the presence of...
predators (fish) (i.e., more closely represent a 2-level system) and may result in systems where algal biomass is controlled by extensive zooplankton grazing (Flanagan et al., 2003).

**Figure 7.14.** – (a) A comparison of Chlorophyll $a$ – total phosphorus relationships between temperate and arctic freshwater systems. The difference in the slope is statistically significant. Solid circles represent temperate lakes ($r^2 = 0.28$, $n = 316$, $P < 0.05$) and open circles represent arctic lakes ($r^2 = 0.07$, $n = 113$, $P < 0.05$). The difference in the slope is statistically significant ($P < 0.05$). (b) Graphical representation of the observed nonlinear response of Chlorophyll $a$ in relation to log (total phosphorus) concentration and latitude (from Flanagan et al., 2003).

The importance of top-down control of food web structure in stream/river arctic ecosystems has also been recently shown. Golden and Deegan (1998) found that young Arctic grayling have the potential to produce top-down cascading trophic effects in arctic streams in areas where nutrients are not limited. The grayling were found to affect trophic structure through consumption, nutrient excretion and the modification of prey behaviour. Epilithic chlorophyll $a$ increased with increased fish density in both reference (P-limited) and fertilized zones (P-enriched) of the Kuparuk River, Alaska, while mayfly density decreased with increasing fish density in the fertilized zone only. These results further illustrate that projection of climate-change impacts will not be straightforward.

### 7.4.4.3. Effects on Primary and Secondary Production

Primary and secondary productivity relationships in arctic aquatic ecosystems are highly susceptible to structural and functional alterations due to changes in climate, although the direction and absolute magnitude of the responses will likely be complex (Laurion et al., 1997; Hobbie et al., 1999; Rouse et al., 1997; Vincent and Hobbie, 2000).

For instance, while in general, constituents of microbial food web (e.g., the picocyanobacteria, heterotrophic bacteria, etc.; Figure 7.13) will respond positively to temperature increases, the photosynthesis rate in the picoplankton fraction (0.2-2 µm) is strongly stimulated by increased temperature to a greater extent than nanoplankton (2-20 µm) and microplankton (20-200 µm) fractions (Rae and Vincent, 1998b).

In general, lake primary productivity is expected to increase as higher temperatures correlate with higher primary productivity (longer ice-free season and more sunlight before summer solstice should result in higher primary production of plankton (Box 7.6). Brylinsky and Mann (1973) analyzed lake productivity for 55 lakes and reservoirs from the tropics to the Arctic and found the best non-biological variables for estimating productivity to be latitude and air temperature. A closer examination of the relationship between TP, TN, latitude and algal biomass ($n = 433$ lake years) also reveals that average algal biomass during the ice-free season is significantly negatively related to the latitude of the system, independent of the nutrient concentration (Flanagan et al., 2003). This strong latitudinal effect on algal biomass yield suggests that arctic lakes could take a significant leap in productivity if these systems increase in temperature and nutrient loadings as projected from the future climate change scenarios. While it has previously been shown that arctic lakes have lower primary
productivity than temperate lakes (Shortreed and Stockner, 1986), Flanagan et al. (2003) show that at a given level of phosphorus, the productivity of arctic lakes is significantly less than lakes in the temperate zone, with the lower producer biomass not simply being accounted for by lower nutrient concentrations in the Arctic. Further examination of detailed phytoplankton community structure observations from arctic LTER (Long-Term Ecological Research) sites indicates that there is no fundamental shift in taxonomic group composition between temperate and arctic phytoplankton communities. This suggests that the difference in the Chlorophyll a-TP relationship between temperate (Watson et al., 1997) and arctic lakes is not an artifact of changes in the Chl a: biomass ratio resulting from a taxonomic shift in algal communities (Flanagan et al., 2003). Hence, the observed difference in the Chl a-TP relationship for temperate and arctic lakes may provide insight to the future effects of climate change (Figure 7.14).

BOX 7.6. Productivity of North-East Greenlandic Lakes: Species Composition and Abundance with Rising Temperatures

Primary productivity may also be expected to increase as climate conditions at high latitudes become more suitable for industrial development, and as the associated pollution of currently nutrient-poor aquatic systems increases. For example, mountain lakes of the Kola Peninsula (e.g., Imandra Lake), and lakes and ponds of the Bolshezemelskaya tundra, are currently stressed by heavy loadings of organic matter, heavy metals and crude/drilling fluid from anthropogenic sources, as well as thermal pollution. Phytoplankton structure (e.g., species) in these systems has changed, and primary as well as secondary productivity and biomass have increased significantly.

Arctic lakes, although currently relatively unproductive, will probably experience a significant increase in productivity. If temperature and nutrient loads increase as projected, phytoplankton may no longer experience temperature-induced photosynthetic rate inhibition and growth rates may become more similar to the temperate zone, thus allowing for a greater accumulation of algae. If algae are currently being heavily grazed because of a lack of predation on the herbivores, higher-level predators should invade as the productivity of the system increases. Subsequent increased predation on the grazer community would permit an increase in algal biomass. In addition, the projected increase in nutrient concentration would augment these changes making the increase in productivity even more drastic.

Several empirical studies support this hypothesis. One study compared Swedish lakes (known 3-level system) to unproductive antarctic lakes (known 2-level system). The slope of Chl a-TP relationship for the antarctic lakes was significantly less than the Swedish lakes. This was hypothesized to be a consequence of the different trophic structures of the lakes since productive (3-level) Swedish lakes showed a similar Chl a-TP relationship as temperate lakes, suggesting that climatic-based abiotic factors were not simply causing the differences between the Swedish and unproductive antarctic lakes (Hansson, 1992). Other empirical evidence supporting this hypothesis comes from sub-arctic lakes in the Yukon Territory, which showed higher levels of zooplankton biomass with respect to phosphorus concentrations than in temperate regions, suggesting a 2-level system. The high abundance of zooplankton was attributed to the low abundance of planktivorous fish and this lack of zooplankton predators...
was thought to lead to a trophic bottleneck and the over consumption of algae (Shortreed and Stockner, 1986).

However, a significant factor further complicating the possible productivity response in arctic systems is the interaction with DOC. High DOC levels can differentially impact measured primary productivity by influencing light penetration (more DOC-water darker), affecting turbidity, but also adding enhanced carbon sources for processing. For example, benthic diatoms and total diatom concentrations increased significantly during conditions of high DOC concentrations and low water transparency, whereas planktonic forms decreased (Pienitz and Vincent, 2000). Hecky and Guildford (1984) found in Southern Indian Lake (northern Manitoba), analogous factors decreased light penetration sufficiently to cause a switch from nutrient to light limitation of primary production. In shallow tundra ponds, over 90% of algal primary production was by benthic algae (Stanley, 1976), although this level of productivity will clearly decline if there is appreciable DOC-related light reduction. However, increased DOC will reduce harmful UV-B, so will be a countervailing factor (Vincent and Hobbie, 2000).

Changes in primary productivity with climate change, whether they are attributed to warming of waters or increased DOC loading, will affect secondary production in arctic freshwaters. Productivity of lake zooplankton will increase in response to increases in primary production. At Toolik Lake, a 12-fold increase in primary production yielded a <2-fold increase in secondary production (O’Brien et al., 1992). This production may result in a rise in the abundance of secondary producers, as observed in Alaska, where the abundance of microplankton (rotifers, protozoans) rose with increased primary production (Rublee, 1992). Though larger zooplankton showed little shift in species with increasing productivity, microzooplankton increased both in terms of number of species (i.e., biodiversity) and trophic levels (i.e., productivity). Observations by Kling et al. (1992a) indicate that zooplankton abundance and diversity are more sensitive to changes in primary productivity with latitude, with species number and types declining northward, than to changes in lake primary productivity at any given latitude. As such, lake productivity and species abundance and diversity may be expected to shift in favor of zooplankton as primary production increases in a progressively northward direction with climate warming.

Bacterial species assemblages will likely be changed little by the impact of climate change. Bahr et al. (1996) found that the species occurring in the plankton of Toolik Lake, Alaska, were identical to species found in other lakes in temperate regions. Overall productivity of the lake did not appear to be related to the species of bacteria involved, rather the total bacterial biomass in the plankton is affected by overall primary production and to the amount of allochtonous organic matter entering the lake from the drainage basin. Crump et al. (2003) and O’Brien et al (1997) report that over half of the bacterial productivity in Toolik Lake is based on DOC from land. As a result, the bacterial numbers, biomass, and productivity for this lake are many-fold higher than they would be if it were a plankton-based microbial food web. In contrast, protozoa and rotifer communities are expected to change with increasing primary productivity that may result from climate change. For example, major changes were also observed in protozoa, algal, and rotifer assemblages and production as a result of significant, artificial nutrient additions (4X ambient loading rates; Bettez et al., 2002).
7.4.4.4. Effects on Carbon Dynamics

The ACIA AOGCM climate scenarios project that by 2080 the majority of the Arctic will experience increases in air temperatures, precipitation, evaporation, available degree-days for biological growth and, as detailed in Chapter 5.5, major changes in the extent and nature of permafrost. Although there are variations among model predictions, permafrost degradation will occur most actively at more southerly latitudes of the circumarctic, with regional west-east gradients existing across North America and Eurasia (for comparison to ACIA Regions consult figures in Chapter 5.5 and Figure 7.2). Overall (based on a “median” model prediction; Chapter 5.5), total permafrost area is forecast to decrease by 11, 18 and 23% by 2030, 2050 and 2080, respectively. As further outlined in Chapter 5.5, loss of permafrost and deepening of the active layer will be greatest in western and southern areas of North America and Eurasia because: a) of their initial temperatures being closer to 0°C than in more easterly and northern areas, and b) it is these warmer areas that are more likely to become snow-free in the spring months permitting enhanced soil warming (e.g., Groisman et al., 1994; Chapter 5.3). Growing degree days (Figure 7.15) are projected to increase over the Arctic, for the most part in Regions I and IV, with exception in Greenland where available degree-days are expected to remain the same or decrease. This degradation of high-latitude permafrost and extension of growing season duration with rising arctic temperatures will have a number of likely impacts on carbon cycling in freshwater ecosystems.

Figure 7.15. Projected changes in the length of the growing season defined as number of days where Tmin > 0°C derived from; (a) NCAR Climate System Model, (b) Canadian Climate Centre GCM; (c) Hadley Climate Centre GCM 3. On average, a 20-30 day increase in growing season is projected for areas north of 60° latitude. As the number of degree days increases in the Arctic, carbon cycling in arctic wetlands will not only be affected by changes to rates and magnitudes of primary and microbial productivity, but also to the quantity and quality of organic material that may accumulate in these systems. This in turn will affect carbon loading to, and processing within, arctic lakes and rivers.

Wetlands are a very prominent feature of the Arctic, and are particularly sensitive to climate warming. The structure of these systems, and their function as net sources or sinks of carbon, will respond drastically to changes in: 1) permafrost melt, 2) peatland distribution, and 3) air temperatures and water budgets. The effects are described below.

1) Thaw of perennially frozen wetland soil and ice will likely result in a substantial efflux of carbon gases initially upon melt, as perennial stores of carbon dioxide and methane are released to the atmosphere. Such an effect has been estimated to account for a 1.6 to 3 fold increase in carbon-gas emissions from degrading permafrost, along the 0°C-isotherm in Canada (Region IV; Turetsky et al., 2002). Permafrost thaw and warming has also accounted for a 100-fold acceleration of carbon-dioxide production as well accelerated methane production in the Ob River basin (Region II; Panikov and Dedysh, 2000), and is responsible for drastically increased effluxes of these two gases from a high-latitude mire in Sweden (Region I; Friborg et al., 1997; Svensson et al., 1999). This initial increase in carbon-dioxide and methane emissions with permafrost thaw has potential, positive climate feedbacks. The
effect, however, is anticipated to decline over time as gas stores are depleted, and as wetland vegetation, hydrology, and carbon sink/source function progressively change with climate.

2) Permafrost melt and increased growing degree days will result in increased distribution and biomass of wetland vegetation, essentially increasing carbon storage in arctic and subarctic landscapes. Projections based on 2xCO$_2$ changes (Gignac and Vitt, 1994; Nicholson and Gignac, 2000) indicate a likely 200-300 km northward migration of the southern boundary of peatlands in western Canada, and a significant change in their structure and vegetation all the way to the Arctic Coast. Increases in carbon accumulation have been associated with peatland expansion, along with treeline shift, northward during Holocene warming, a process that slowed and eventually recessed with onset of the Little Ice Age (all ACIA Regions – See Section 7.3.2; Gajewski et al., 2000; Vardy et al., 1997). Similar expansion of peatlands and enhanced biomass accumulation have been recorded in North America (Regions III, IV) over more recent times (Robinson and Moore, 2000; Vitt et al., 2000; Turetsky et al., 2000). Hence, as temperatures rise, wetland/peatland distribution will likely increase at high latitudes, and arctic landscapes will generally represent greater carbon sinks. Carbon accumulation at high latitudes will, however, be limited by loss due to disturbance, e.g., increased occurrence of fire as temperatures and evapotranspiration increase in some areas (Turetsky et al., 2002; Robinson and Moore, 2000), and will result in greater carbon loading to lakes and rivers (Liang et al., 1999).

3) Changes in available degree days, along with energy and water balances of high-latitude wetlands, will have variable effects on rates and magnitudes of photosynthetic assimilation of carbon dioxide, and anaerobic and aerobic production of carbon dioxide and methane in existing arctic and subarctic wetlands:

- Rates and magnitudes of primary productivity, and hence carbon sequestration, will increase in arctic wetlands as air and soil temperatures rise, growing season lengthens (e.g., Greenland - Christensen et al., 2000; Finland – Laurila et al., 2001), and as vegetation changes (as discussed above in the context of permafrost degradation). Carbon fixation in arctic and subarctic wetlands will, however, be potentially limited by UV effects on vegetation (Niemi et al., 2002; see also Chapter 6).

- Carbon dioxide accumulation in high-latitude wetlands will be limited by warming and drying of wetland soils, and the associated production and loss of carbon dioxide through decomposition (e.g., Alaska – 3 fold increase, Funk et al., 1994; Finland – Aurela et al., 2001). This effect will likely lead to substantial losses of carbon dioxide and potential climate feedbacks.

- Methane production and emission will decline as high-latitude wetland soils dry with rising temperatures and increased evapotranspiration, and with regional declines in precipitation (e.g., Finland – Minkinnen et al., 2002; Greenland – Joabsson and Christensen, 2001). Moore and Roulet (1993) have suggested that only a 10-cm deepening of the water table in northern forested peatlands results in their conversion from a source to a sink of atmospheric CH$_4$. Methanotrophy will be most pronounced in drier wetlands that tend toward aerobic conditions. Methane release to the
atmosphere may not only be limited by lowering of the water table, but also by the
projected shift in vegetation toward woody species (see Chapter 6; Liblik et al., 1997).

- Methane production in some wetlands will increase as temperatures and rates of
methanogenesis increase, and as water tables rise in response to regional increases in
water availability (e.g., Finland – estimate 84% increase in methane release from wet
fen with 4.4°C warming, Hargreaves et al., 2001; Alaska – 8 to 33 fold increase in
methane emission with high water table, Funk et al., 1994). Methane production will
increase in those wetlands that have highly saturated soils and standing water, and
those that may become wetter under future climate warming, potentially having
climate feedbacks.

Overall, arctic and subarctic wetlands will likely become greater sources of carbon dioxide
(and in some instances methane) initially, as permafrost melts, and over the long-term, as
wetland soils dry (Moore et al., 1998; Gorham, 1991). Although wetlands will generally
experience a net loss of carbon to the atmosphere under future climate change, the expansion
of wetland (e.g., peatland) distribution in the Arctic, and the increase in carbon accumulation
with permafrost degradation, will offset this loss. See Chapter 6, Section 5 for further
treatment of this topic.

In addition to wetlands, wholly aquatic systems (rivers, lakes and ponds) are also important to
carbon cycling in the Arctic. High-latitude lakes of Alaska have been shown to be net
producers of dissolved organic carbon, whereas streams were typically net consumers (Kling
et al., 2000). Many arctic lakes and rivers are supersaturated with carbon dioxide and
methane, often emitting these gases to the atmosphere via diffusion; increases in productivity
(e.g., primary and secondary) deplete carbon in surface waters, resulting in diffusion of
carbon dioxide into the water (see Figure 7.7; Schindler et al., 1997; Kling et al., 1992b).
Coastal freshwater systems have been found to release carbon in amounts equivalent to
between 20 and 50% of the net rates of carbon accumulation in tundra environments (Kling et
al., 1992b). Enhanced loadings of carbon to arctic lakes and rivers as permafrost degrades
(surface and groundwater flows contribute dissolved carbon dioxide and methane, as well as
particulate organic carbon) will affect carbon cycling in these systems in a number of ways.

DOC loading of lakes and rivers will likely result in increased primary productivity and
associated carbon fixation. This increase in photosynthetic carbon dioxide consumption by
aquatic vegetation (e.g., algae, macrophytes) will reduce emissions of this gas from lake
waters to the atmosphere. This effect has been noted in experimental fertilizations of lake
waters in both temperate and arctic lakes (Schindler et al., 1997; Kling et al., 1992b).
Nutrient-loading of high-latitude rivers, however, will likely not have a similar effect, as these
waters have a rapid rate of renewal.

Although DOC loading of surface waters will cause a decline in carbon-dioxide emission
from some lakes, increased inputs of DOC, as well as particulate organic carbon (POC) may
offset this effect and, in some cases, increase production of this gas. Enhanced DOC and POC
loads will increase turbidity in some lakes, reducing photosynthesis (see Section 7.4.4.4.).
This rise in availability of organic matter will probably result in a concomitant increase in
benthic microbial respiration; a process that produces carbon dioxide (Ramlal et al., 1994). These effects will be less pronounced or absent in flowing-water systems.

Increased nutrient loading and water temperature in high-latitude freshwater bodies will also enhance methanogenesis in sediments. Slumping of ice-rich Pleistocene soils has been identified as a major source of methane release from thermokarst lakes, such as in extensive areas of north Siberian lakes (e.g., Zimov et al., 1997), and may explain high wintertime concentrations of atmospheric methane between 65-70°N (Semiletov, 2001; Zimov et al., 2001). Methane produced in such systems will be released to the atmosphere via ebullition, a process that will increase as the open-water season lengthens. Emission of this gas to the atmosphere will also be enhanced in lakes, ponds and streams that experience an increase in macrophytic growth, and an associated increase in vascular transport of methane (see Section 7.4.4.1.).

7.5. CLIMATE CHANGE EFFECTS ON ARCTIC FISHES, FISHERIES AND AQUATIC WILDLIFE

Fishes and wildlife intimately associated with arctic freshwater and estuarine systems are of great significance to local human populations (See Chapter 9) as well as significant keystone components of the ecosystems (See Section 7.2 and elsewhere in this chapter). Accordingly, interest in understanding the impacts of climate change on these components is very high. However, in addition to the problems outlined in section 7.1.1, detailed understanding of climate change impacts to these higher-order biota is compromised by a number of additional circumstances:

- Such components will experience first-order effects (e.g., increased growth in arctic taxa due to warmer conditions and higher productivity) of climate change as well as large numbers of second order effects (e.g., increased competition with species extending their distribution northward). The responses of such biota will integrate these sources in complex and not readily discernible ways; further, responses to climate change will be embedded within those resulting from other impacts such as exploitation and habitat alteration, and it may be impossible to differentiate these. These multiple impacts will likely act cumulatively or synergistically to affect arctic taxa.

- Higher-level ecosystem components affect lower levels in the ecosystem (i.e., so-called top-down control) and in turn are affected by changes in those levels (i.e., bottom-up control). The balance in such controlling influences may shift in undiscernible ways in response to climate change.

- Higher-level ecosystem components typically migrate seasonally between habitats or areas key to their life histories – arctic freshwater fishes and aquatic mammals may do so locally, and aquatic birds tend to do so globally between arctic and non-arctic areas. Thus, the effects of climate change upon such organisms represent the integrated impacts across numerous habitats that indirectly affect the species of interest.
These biotic circumstances increase the uncertainty associated with developing understanding of species-specific responses to climate change, particularly to key fish and other aquatic species that are of economic and ecological importance to arctic freshwater ecosystems and the communities of northern residents that depend on them.

7.5.1 Understanding for Projecting Responses of Arctic Fishes

Implicit in much of the text developed above is the linkage between atmospheric climate parameters and habitat parameters present in aquatic ecosystems, and the follow-on linkage of these to effects manifested in organisms and populations. It follows from this logic that changes in climate regimes, however they may be manifested, will only indirectly affect aquatic organisms of interest. That is, the aquatic environment itself will be directly affected by changes in climate, but will modify and then transmit the influences in some fashion. Thus, for example, substantive shifts in atmospheric temperature regimes will affect water temperatures but given the density differences between water and air and the influence of hydrodynamic factors, the effects on aquatic systems will be modified to some degree. In turn, the effects of changes in atmospheric parameters will be indirect on biota present in aquatic systems and thus may be ameliorated or partially buffered (e.g., thermal extremes or seasonal timing shifted). In some instances, however, climate change effects may be magnified or exacerbated, increasing the multiplicity of possible outcomes resulting from these changes. For example, stream networks amplify many environmental signals that occur at the watershed level, and that are concentrated in the stream channel (Dahm and Molles, 1992). This added level of complexity and uncertainty in the magnitude and direction of climate change manifestations in arctic freshwater ecosystems is not as acute for terrestrial environments. It results in greater uncertainty for projecting potential impacts on aquatic organisms. An example of the logical associations and both direct and indirect effects of climate parameters on anadromous fish and the various aquatic environments used is provided in Figure 7.16.

Figure 7.16. A stylized portrayal of some potential direct effects on climate parameters on aquatic environments and some potential indirect effects upon aquatic organisms such as anadromous fish.

7.5.1.1. Fish and Climate Parameters

Fish are ectotherms thus, for the most part, their body temperature is governed by that of the surrounding waters. Additionally, individual fish species can behaviourally choose specific thermal preferenda (Beitinger and Fitzpatrick, 1979) at which physiological processes are optimal (i.e., greatest net benefit is achieved for the individual). This is typically a thermal range which may be fairly narrow; temperatures outside this are sub-optimal (i.e., net benefit is still attained but it is not the greatest possible), grading to detrimental (i.e., non-lethal but net energy is expended while in such conditions), and ultimately to lethal conditions (i.e., death ensues after some level of exposure). Furthermore, within a species, local northern populations often have such preferenda set lower than do southern representatives which presumably represents differential adaptation to local conditions. Also, individual life stages
(e.g., egg, alevin, juvenile, adult) differ in their thermal preferenda linked to optimizing criteria specific to their developmental stage. For most species only limited understanding of such thermal optima is available, and then typically only for some life stages of southern species. Fish control body temperatures behaviourally, i.e., sensing and moving into appropriate, or from inappropriate, zones (Coutant, 1987). Aquatic thermal regimes are spatially and temporally heterogeneous and availability of water of preferred temperature may be limited, thus, be an important resource for which competition may ensue. This may be particularly important in species found in Alaskan and Yukon north slope rivers (e.g., Dolly Varden and Arctic grayling) during winter when physical habitat is limited due to rivers freezing to the bottom over long reaches (Craig, 1989). Thus, the thermal niche of individual fish species can be defined (see Box 7.5). Temperate species have been grouped into three thermal guilds defined by similar thermal niches: Warmwater (preferred summer temperatures centred upon 27-31°C), Coolwater (21-25°C) and Coldwater (11-15°C) (Magnuson et al., 1979). Many sub-arctic species with distributional centres in southern temperate areas but which extend into the Arctic such as northern pike, walleye and yellow perch are coolwater species (Schlesinger and Regier, 1983). Fishes of the Coldwater Guild (e.g., lake whitefish, lake trout) have narrow thermal tolerances but usually are widely distributed due to the availability of colder habitats in water bodies (e.g., deeper layers in lakes; higher elevation reaches in streams) (Schelsinger and Regier, 1983). Following this approach, Reist (1994) defined an Arctic Guild as fish distributed wholly or primarily in northern areas and adapted to relatively colder waters (<10°C) and related aspects of the habitat such as short growing seasons, extensive ice presence and long periods of darkness. Species such as Arctic char and broad whitefish are members of this guild.

As noted above, thermal preferenda presumably optimize all internal physiological processes (i.e., benefits outweighs costs) in individual fish associated with digestion, growth, muscle (hence swimming) efficiency, gas exchange across gills, cellular respiration, reproduction, and so on. The relationship of temperature to such processes is perhaps most easily seen with respect to growth (e.g., increase in size or weight over time) (Figure 7.17). In addition to exhibiting higher growth rates at lower temperatures, arctic fish species also exhibit narrower ranges of temperature preference and tolerance (i.e., stenothermic); (Figure 7.17) which has profound effects for productivity. Stenothermic tolerances also imply the species may have little capacity to accommodate thermal impacts of climate change. Conversely species exhibiting eurythermic or wide thermal tolerances or responses likely have a much wider capacity to accommodate climate changes (see Box 7.5 also).

Figure 7.17. Specific-growth rates of fish species for varying temperatures determined from laboratory studies. Stenothermic northern species (e.g., A,B,C,F; Arctic char, lake cisco, lake trout, brook trout, respectively) are grouped towards the lower temperatures on the left, whereas mesothermic southern species (e.g., G,I,J; bluegill, smallmouth bass, walleye, respectively) are grouped towards the right. Stenothermic species tend to have a more peaked curve indicating only narrow and typically low temperature ranges over which optimal growth is achieved. Wide ranging eurythermic species (e.g., D,E,H; northern pike, lake whitefish, emerald shiner, respectively) likely exhibit the greatest possibilities for adapting rapidly to shifting thermal regimes driven by climate change.
Population-level influences of thermal regimes are also apparent. That is, effects upon individuals such as temperature impacts on mortality, feeding, parasitism and predation are integrated into consequences upon fish populations through the various processes which connect fish populations to their ecosystems. As noted previously, environmental parameters such as temperature may affect various life stages differently hence can be modeled separately, but it is important to remember that the ultimate effects of all these influences are integrated throughout the fish population of interest. Similarly, environmental changes also have specific effects upon other organisms relevant to fish such as predators, parasites and food organisms. Hence a single environmental parameter may exert both indirect and direct effects at many levels which influence the fish population, but the actual effect of this may be indiscernible from the effects of other natural and anthropogenic influences. Examples of connections of environmental parameters which affect key processes at the population level in fishes are provided in Figure 7.18 (Sibley and Strickland, 1985). The ultimate effects of these in turn affect sustainability of the populations and human uses in a fishery context.

Figure 7.18. The major biotic processes affecting the dynamics of a freshwater or anadromous arctic fish population and some of the aquatic abiotic environmental parameters that affect these processes. Migratory aspects of life history especially for anadromous fish are not shown but will also be significantly affected by abiotic processes. Salinity will also be a factor for sea-run phases of life history of adults. Change in aquatic abiotic parameters will be driven by climate change and increased variability in climate parameters. Such impacts will affect the fish directly as well as indirectly via impacts on their prey, predators and parasites. This cascade of effects and synergies and antagonisms amongst effects greatly complicate the projection of climate change impacts on valued fish populations in the north. In addition, other parameters not shown such as groundwater inflows on spawning beds will affect the survival of various life history stages. Adapted from Sibley and Strickland (1985). Abbreviations: temp – temperature, turb – turbidity, curr – current, sal – salinity.

Temperature relationships with individual fish and fish populations are perhaps the most easily understood ones, however, other climate parameters such as precipitation (amounts and types) will directly affect particular aquatic environmental parameters such as productivity (e.g., see Box 7.7) and flow regimes (amounts and timing). For example, flattening hydrographs and shifts in water sources (Sections 7.4.2 and 7.4.3) will alter availability of arctic rivers as migratory routes for anadromous fish – increased and earlier vernal flows will enhance fish survival during out-migration and lengthen the potential summer feeding period at sea (both positive effects at the levels of the individual fish and the population). However, autumnal flows are required in many smaller rivers to provide access to returning fish (Jonsson, 1991) – reduction in amounts and shifts in timing will have negative effects. Additional secondary environmental factors that may change in response to direct changes in basic climate parameters will also be important in their effects upon aquatic biota – these include, for example, nature and duration of freeze-up, ice types, ice-on periods, and break-up; and, the nature and penetration of incident radiation into aquatic systems. Similarly, terrestrial impacts of climate change may influence aquatic habitat hence indirectly affect biota there – e.g., permafrost alteration and run-off influences on sediment loads, pH and related water chemistry, etc. Another potential class of indirect effects of climate change are
those affecting the behaviour of the aquatic biota. For example, fish use thermal regimes and spatio-temporal shifts in these, at least in part, as behavioural cues of thresholds to trigger critical life history functions. Water mass boundaries defined by temperature act as barriers to movement and may define feeding areas (Coutant, 1987). Final gametic maturation in fall-spawning species is likely triggered by decreasing water temperatures and perhaps also photoperiod in arctic whitefishes. There is anecdotal evidence that final upstream movements by broad whitefish from holding areas to spawning sites are triggered by decreased sediment loads precipitated in turn by freezing of river banks (Reist and Chang-Kue, 1997), an adaptation to ensure eggs are not smothered. Water temperature integrated over time (e.g., as degree days) affects rate of egg development. Thus, aquatic thermal regimes affect ecotherms such as fish in two basic ways – influencing physiology and as cues for behavioural changes. Although typically less understood, similar effects likely result from other physical (e.g., currents, flows, turbidity, ice dynamics) and chemical (e.g., pH, oxygen) parameters in the aquatic habitat (e.g., Sibley and Strickland, 1985). Climate-change induced alteration of these habitat characteristics will significantly affect arctic fish populations, although substantive research is required to quantify such effects.

Box 7.7. Effects of Changes on Life-History and Population Characteristics of Arctic Char

7.5.1.2. Ecosystems, Habitat and Fishes – Climate Change in the Context of Multiple Stressors

Aquatic ecosystems are highly structured and complex entities consisting of both abiotic and biotic elements, and functional relationships within and between those elements. Similarly, individual components of ecosystems, such as a single fish species, exhibit a unique but complex structure. From the perspective of an individual or even a population, climate parameters and change in them may be viewed as either a stressor (i.e., that which perturbs homeostatic systems; Adams, 1990), or as a promoter (i.e., that which promotes homeostasis). Stressors and promoters directly and indirectly influence underlying physiological processes and their outcomes at both the level of the individual and that of the population. Points of action within individuals range from the molecular to the organismal level; those affecting whole individuals overlap with effects on populations and communities (Adams, 1990). The various organizational levels are also influenced by events occurring at other levels of the hierarchy. Levels within the individual tend to have short-term responses and limited overall ecological relevance, whereas those at the population/community/ecosystem level tend to be longer-term responses with higher ecological relevance (Adams, 1990). Given the structured complexity inherent in a fish population, the effect of any particular stressor or promoter can be: manifested at many levels simultaneously; interact with others in an additive or cumulative fashion; and, typically observed (if at all) in wild populations only at the more general population or community level.

For example, the effect of a temperature change may induce a short-term physiological response in an individual (e.g., processes occurring outside of the zone of optimal enzyme performance), a medium-term acclimatization response such as expression of new enzyme alleles optimal for the new temperature, and a somewhat longer-term response of changed
biological condition. Concomitant expressions at the population level might be a shift in age structure, lower overall abundance and ultimately local extirpation or adaptation to new conditions.

Another important point is that at least locally, the impacts of climate change on fish populations will be but one of several stressors. Other stressors affecting arctic fish both now and in the future include exploitation, local habitat change due to industrial development or river regulation, contaminant loadings, and incident ultraviolet radiation changes. These stressors will result in similar effects at individual and population levels as described for climate change. However, all these stressors will also interact additively and multiplicatively upon individual fish and fish populations hence the effects will likely be cumulative (Reist, 1997b). Perhaps the greatest future challenge associated with climate change will be to effectively recognize and manage in an integrated fashion all potential and realized impacts on arctic fish populations so as to ensure their conservation and sustainability.

7.5.1.3. Some General Effects of Climate-Induced Changes on Physical Habitat

Physical changes in aquatic habitats will affect arctic fishes as climate change takes hold in the north. Some examples are developed in the following to show the linkages and various potential effects on biota, but the underlying absence of data precludes quantification of causal linkages in most cases. Rectifying these and similar gaps is a major future challenge.

Groundwater and Fish – Groundwater flows sustain fish habitat and are extremely important during periods of low flow in many arctic rivers (Power et al., 1999) and perhaps some lakes (see Sections 7.2 and 7.4 above). For stream-dwelling salmonids, inflows along stream bottoms clear fine-grained sediments from spawning areas, supply thermally regulated and oxygenated water to developing eggs and larval fish, and in many cases provide physical living space for juvenile and adult fishes. In highly channelized shallow arctic rivers which characterize many areas of the North American Arctic and Chuktoka (Regions III, IV), groundwater inputs are critical to migrations of fish and preventing strandings (Power et al., 1999). In winter many Alaskan and western Canadian north slope rivers (Region III) cease flowing and freeze to the bottom over large stretches, and groundwater provides refugia which support entire populations of Arctic grayling and Dolly Varden as well as any co-occurring species (Craig, 1989). Overwintering mortality, especially of adults weakened from spawning activities, is suspected as a primary regulator of the populations of Dolly Varden in this area and a major factor in such mortality is the quality and amount of wintering habitat maintained by groundwater. Possible increases in groundwater flows discussed earlier as a potential effect of climate change would positively affect overwinter survival, especially if coupled with shorter duration and thinner ice cover. However, increased nutrient loadings in groundwater may have more complex impacts – e.g., increases in in-stream primary and secondary productivity would promote growth and survival of larval fish, but increases in winter oxygen demand associated with decomposition of vegetation may decrease overwinter survival of larger fish. How these various effects will balance in specific situations to result in an overall net effect on particular fish populations is unknown.
In summer, ground and surface water inflows ameliorate summer temperatures and provide thermal refugia especially along southern distributional margins (Power et al., 1999). This is likely especially relevant for fish belonging to the arctic and coldwater thermal guilds. However, even small increases in water temperatures of 2-4°C likely to result from climate change (e.g., warmer surface flows) may preclude some species from specific aquatic habitats (e.g., temperature in higher elevation cold water stream reaches determines habitat occupancy of bull trout; Paul and Post, 2001). Increased ambient conditions above physiological thermal optima will further stress populations and combined with other possible effects such as competition from colonizing southern taxa, such impacts will likely exacerbate range contractions for arctic species.

Ice and Fish - The influence of ice on arctic fish and fish habitat is significant especially in smaller lotic systems important to salmonids (Craig, 1989; Cunjak et al., 1998; Power et al., 1999; Prowse, 2001a,b) with effects ranging from possible physical damage (e.g., frazil ice), to probable limitation of access to habitat (e.g., decreasing water volumes in winter due to ice growth), to annual recharge of habitat structure during dynamic breakup (e.g., cleansing of interstitial spaces in gravel). Shifts in the timing and duration of ice-related events will affect the survival and success of fish, with some effects being advantageous and others disadvantageous. In the north, these effects will be superimposed upon a poorly known but complex biological and environmental situation. Limited knowledge precludes accurate forecasting of many of these potential effects, and novel approaches are required to redress this (Cunjak et al., 1998).

Decoupling of Environmental Cues due to the Differential Influence of Climate Change – A speculative issue which may present surprises and unanticipated effects is the potential for decoupling of various types of environmental drivers due to some being differentially affected by climate change. Fish and other organisms use progressive and/or cusp-like changes in environmental parameters as cues to trigger key life-history functions such as migration, reproduction, and development. For example, although quantitative linkages are lacking change in photoperiod (e.g., declining light period) is probably coupled with declining water temperatures in the autumn and together these trigger final gonadal maturation and reproductive activities in many northern fishes (especially salmonids). Environmental cues that drive major life-history events are especially critical to migratory species and in the Arctic particularly to the anadromous species. This coupling is likely especially strong in the north where both parameters change rapidly on a seasonal basis. Although not explored to date in a climate change context, as seasonal photoperiod shifts remain unchanged but coincident cues such as declining temperatures occur later in the autumn such decoupling may have profound impacts on population processes. The initial impact of such decoupling may be quite subtle (e.g., lowered fecundity, fertilization success, and/or egg survival in the example above), not readily discernible, and almost certainly not directly linkable to climate change. However, a critical threshold will likely be reached at some point at which impacts become significant – e.g., total reproductive failure in one year resulting in a failed year class, ultimately leading to population extirpation if it occurs over successive years approaching the generation time of the population. Investigation of coupling among cues, their influence upon population processes in fish and other aquatic organisms, and their potential for decoupling due to climate change in the Arctic should be of priority.
The above are but a few examples of likely or probable physical habitat influences upon fish populations and the potential effects of climate-induced change in them which will have cascading effects upon the integrity, sustainability and future productivity of northern fishes. These serve to illustrate the general lack of knowledge that exists regarding associations between physical habitat and biology in northern aquatic biota, and thus how climate change impacts will be manifested. Redress of this knowledge gap is required on a community- and/or species-specific basis to account for local and historical influences and filters which greatly affect the present-day structure and function of these aquatic ecosystems (Tonn, 1990).

7.5.1.4. Issues at the Level of Fish Populations

As implied above, projecting climate change impacts at the population level for most species is complex and fraught with uncertainty. This is especially so when attempting to do so for arctic species, for which there is a dearth of fundamental biological information. A variety of approaches to address this problem are available (Box 7.8) and most have been applied in one way or another to develop some understanding of climate change impacts on northern fish populations.

BOX 7.8. Approaches to Predicting Climate Change Effects on Arctic Fish Populations

In North America, much of the focus of climate change effects on freshwater fish populations and communities has been in the south, for example, on the Great Lakes region and associated fisheries (e.g., Meisner et al., 1987; Magnuson et al., 1990; Regier et al., 1990, 1996; Hill and Magnuson, 1990; Shuter and Post, 1990; Assel, 1991; Smith, 1991; Minns and Moore, 1992) where climate warming is expected to result in effects similar to those predicted for the Arctic (e.g., significant reductions in the duration and extent of ice cover, an earlier seasonal disappearance of the 4°C depth isotherm, measurable declines in dissolved oxygen and slight hypolimnetic anoxia in shallower basins; Blumberg and Di Toro, 1990; Schertzer and Sawchuk, 1990). Loss of suitable cool-water habitat associated with lake warming is also expected and will differentially affect species within lacustrine fish communities, e.g., promote growth and survival in lake whitefish but negatively affect these in lake trout (Magnuson et al., 1990). Preliminary consideration for northern areas has occurred for European systems (e.g., Lehtonen, 1996). Relatively less attention has been paid to the possible effects of climate change on resident fish communities in other ecosystems, in particular the Arctic. With respect to freshwater fish populations, the IPCC concluded that fish populations in streams and rivers on the margins of their geographic distributions (e.g., arctic and sub-arctic species), which have a high rate of heat transfer from air, will be the first to respond to the effects of climate change. Some of these effects are:

• Nutrient level and mean summer discharge explained 56% of the variation in adult Arctic grayling growth over a 12 year period in two Alaskan rivers (Deegan et al., 1999). Summer temperature added to these variables explained 66% of variation in young-of-the-year growth. Correlation with discharge was positive for adults and
negative for young, thus grayling life history appears able to respond to variability in the arctic environment by balancing adult growth with year-class strength. How this balance shifts under climate warming is uncertain at present.

- Temperature effects on growth appear to be greatest at the extremes of the geographic range of the species (Power and van den Heuvel, 1999), and local effects will be species-specific (King et al., 1999). Generally, young-of-the-year fish appear to grow better in warmer summers reaching relatively larger sizes thus predisposing them to higher over-winter survival, which, in turn determines year-class strength and population abundance (Shuter et al., 1980); potentially a positive result of climate warming assuming food is not limiting.

- Northern lake cisco populations along the coast of Hudson Bay exhibited reduced growth and later maturity due to lower temperatures and shorter growing seasons (Morin et al., 1982). Individual fecundity did not change but the most northerly populations skipped reproduction more frequently (hence overall population productivity was lower). This latitudinal gradient represents responses to temperature stresses whereby further trade-offs in energy allocation between reproduction and growth currently are not possible (Morin et al., 1982); a common circumstance for most arctic fish populations and one that will probably be ameliorated under warming scenarios potentially resulting in increased population abundances.

- Countergradient variation (Levins, 1969) whereby genetic influences of growth in brown trout vary inversely with annual mean water temperatures (Jensen et al., 2000) suggest trout in the coldest rivers are specifically adapted to low temperatures and short growing seasons. Thus, climate warming will likely negatively affect growth rates, age/size structure, and abundances of such species.

### 7.5.2 Climate Change Effects on Arctic Freshwater Fish Populations

The ability of fish to adapt to changing environments is species specific. In case of rapid warming associated with climate change there are three possible outcomes for any species: local extinction due to thermal stress, a northward shift in the geographic range where dispersive pathways and other biotic and abiotic conditions allow, and genetic change within the limits of heredity through rapid natural selection. It is likely that all three will occur, depending on the species (Lehtonen, 1996). Local extinctions are typically difficult to project without detailed knowledge of critical population parameters (e.g., fecundity, growth, mortality, population age-structure, etc.). Dispersal and subsequent colonization will undoubtedly occur, but will inevitably be constrained by watershed drainage characteristics, and ecological and historical filters (Tonn, 1990). In watershed systems draining to the north, increases in temperature will allow some species to shift their geographic distribution northward (see Box 7.5). In watershed systems draining to the east or west, increases in temperature may be compensated for by altitudinal shifts in riverine populations where barriers to headwater movement do not exist. Lake populations needing to avoid temperature extremes will be confined to the hypolimnion during the warmest months provided anoxic conditions do not develop. Patterns of seasonal occurrence in shallower littoral zones will
almost certainly change, with consequent effects on trophic dynamics. Changes in species dominance will also occur because species are adapted to specific spatial, thermal and temporal characteristics that will inevitably be altered by climate-induced shifts in precipitation and temperature.

Before successful range extensions can occur habitat suitability, food supply, predators and pathogens must be within the limits of species’ niche boundaries. In addition, routes to dispersal must exist. Physiological barriers to movement such as salinity tolerances or velocity barriers (current) may act to restrict range extensions where physical barriers to migration (e.g., waterfalls, non-connected drainage basins) do not exist. Against this background of dynamic physical and biotic changes in the environment some regional and species-specific climate change projections have been made.

Region I: European Percids - Under climate-warming scenarios, spawning and hatching of spring and summer spawning populations is likely to occur earlier in the year. For example, European perch will advance spring spawning by as much as a month (Lehtonen, 1996) and juveniles will experience longer growth periods and reach larger sizes at the end of the first summer. The potential benefits of increased size, however, may not be realized if higher egg incubation temperatures are associated with smaller larvae having smaller yolk-sacs and increased metabolic rates (e.g., Peterson et al., 1977; Blaxter, 1992). Small larvae are more susceptible to predation, have higher mortality rates and are confronted with a shorter period during which they must adapt to external feeding to survive (Blaxter, 1992). In addition, increased over-winter survival will be associated with increased demand for prey resources and may lead directly to population stunting.

The zander is an eurythermal species distributed widely in Europe whose growth and recruitment success is correlated to temperature (Colby and Lehtonen, 1994). The present northern distribution coincides with the July 15°C isotherm and is likely to shift northwards with climate warming. Successive year-class strengths and growth rates in northern environments are also likely to increase as temperatures warm. Increases in both abundance and size will hold obvious consequences for the competitiveness of resident coldwater guild fishes if concomitant increases in lake productivity fail to yield sufficient ration to meet the needs of expanding populations of pikeperch and other percids. Evidence that northward colonisations are already occurring comes from the Russian portion of Region I. Over the last 10-15 years northern pike, ide and roach have become much more numerous in the Pechora River delta and the estuary Sredinnaya Guba (i.e., ~68°N) of the Barents Sea (A. Kasyanov, Institute of Inland Waters, Russian Academy of Sciences, pers. comm.).

Region II: Fishes in Siberian Rivers – Many species of fish in the large northward flowing rivers of Siberia have the potential for significant northward range extensions and/or responses to climate change. Several species in the Yenisey and Lena rivers that prefer warmer boreal-plain habitats (e.g., roach, ide, common dace, European perch and ruffe) will likely move into the northern mouth areas of these rivers which are currently dominated by whitefishes and chars. Overall the fish species diversity will likely increase but this probably will be at the expense of the coldwater salmonids. The speed at which this process might occur is uncertain, however, it may already be occurring and is likely to be similar to that
noted above for Region I (i.e., ~10 years or so). Additionally, as environments change other species (e.g., carp bream and zander) are likely to be intentionally stocked in the area – a factor likely to result in additional pressures upon native arctic fish populations.

Region III: Alaskan Game Fish - Food availability and lotic productivity are often determined by nutrient availability and believed to be a major controlling factor in riverine fish production. Several studies have found fish density and growth correlate with nutrient status and food availability in streams, with larger standing crops in nutrient-rich streams (McFadden and Cooper, 1962; Murphy et al., 1981; Bowlby and Roff, 1986). In particular, salmonid biomass in nutrient-poor environments varies with nutrient levels, habitat type and discharge (Gibson and Haedrich, 1988). The bottom-up propagation of nutrients through algal and invertebrate production to fish has been projected as a possible result of climate-induced increases in nutrient additions associated with permafrost breakdown. The premise, however, has rarely been tested, with the result that the relationship between nutrient loading and fish production is poorly understood (Peterson et al., 1981a). Shifts in stable carbon and nitrogen isotope distributions have demonstrated a coupling between the stimulation of benthic algal photosynthesis and accelerated growth in stream-resident insect and fish populations (Peterson et al., 1992). In addition, experimental fertilization of Alaskan tundra rivers has demonstrated increased growth rates for adult and young-of-the-year Arctic grayling, with the strongest response being seen in the latter (Deegan and Peterson, 1992).

Temperature increases associated with climate warming are also likely to be associated with lower flows to which growth of adult Arctic grayling is also highly correlated. At low flows adult growth is low, whereas young-of-the-year continue to grow well (Deegan and Peterson, 1992). As Arctic grayling in many Alaskan systems are already food limited, the associated increases in metabolic costs are likely to be associated with decreased survival unless nutrient loading associated with permafrost breakdowns offset the increased metabolic costs of low-flow conditions (Rouse et al., 1997).

Lake trout are a keystone predator in many Alaskan lakes. Low food supply and temperatures, however, keep the species near physiological limits for survival with the result that lake trout may be particularly sensitive to changes in either temperature or food supply initiated by climate warming (McDonald et al., 1996). Increases in temperature will increase metabolic demands. Unless met by sufficient increases in ration, increased metabolic demands will lead to lower realized growth rates.

The fact that many populations are already food limited suggests further increases in temperature will have significant effects on population abundance. Bio-energetic modeling of juvenile populations in the epilimnion of Toolik Lake has suggested that they will not survive a 3°C increase in mean July epilimnetic temperatures given existing ration, and would require >8-fold increase in food to achieve historical end-of-year sizes (McDonald et al., 1996). Documented increases in epilimnetic temperatures, however, have not been associated with increased food availability. If recent changes in the lake foreshadow long-term trends, results suggest that young lake trout will not over-winter successfully and the associated changes in mortality patterns may lead to local extinction and the disruption of lake trout control of the trophic structure in many arctic lakes (McDonald et al., 1996).
Region IV: Northern Québec and Labrador Salmonid and Pike Populations - Among the salmonids of northern Québec and Labrador the response to temperature changes will track physiological preferences for warmer waters. Several species will extend their ranges northward such as native Atlantic salmon and brook trout and introduced brown trout and rainbow trout. While the warmer water percid and cyprinid species are restricted to the southwest and unlikely to extend their range to the north because of dispersal barriers unless moved northwards by humans (Power, 1990b), the euryhaline salmonids are able to move from estuary to estuary as conditions allow. For example, Dumont et al. (1988) have documented the successful movement of rainbow and brown trout and exotic salmon species in the estuary of the Gulf of St. Lawrence and there is some indication that brown trout dispersal in Newfoundland has been temperature limited (Crossman, 1984). As a result of probable range extensions, Arctic char will be reduced or replaced by anadromous Atlantic salmon and/or anadromous brook char throughout much of the southern portion of the region and brook trout will become a more important component of native subsistence fisheries in rivers now lying within the tundra zone (Power, 1990b). Lake trout are likely to disappear from rivers and the shallow margins of many northern lakes and behave as currently observed in temperate regions (Martin and Olver, 1980).

Northern pike habitats in much of sub-arctic North America and Europe are projected to sustain some of the most severe consequences of global warming. Adult northern pike actively avoid surface temperatures in excess of 25°C, which will become more frequent as air temperatures increase throughout much of the distributational range. In shallower lakes, lake chemistry changes associated with warming may result in cooler bottom waters becoming anoxic and a restriction of suitable habitat (e.g., Schindler et al., 1990). Studies in Ohio impoundments have shown that although northern pike show summer seasonal growth, there is an associated weight loss during the periods of habitat restriction (Haedrick and Carline, 1993). Accordingly, northern pike throughout much of their current range are expected to be restricted in both numbers and size as a result of climate change.

Attempts to relate fish yields and mean annual air temperatures have been coupled with geographic information techniques to predict both shifts in distribution and in yields of important freshwater fishes in this region (Minns and Moore, 1992). In general throughout subarctic Quebec, yields for lake whitefish are predicted to increase 0.30 to >1.0 kg per hectare per year; northern pike yields in southern portions of the Hudson Bay drainage are predicted to rise 0.03-0.10 kg, and those in northern portions marginally by 0.01-0.03 kg; walleye yields found in the southern drainage basin of Hudson Bay are predicted to rise 0.01-0.10 kg. These changes result from occupancy of new, presently unsuitable, areas in the northern areas, as well as, increased overall productivity throughout the entire area. The total overall productivity may be offset due to declining production in southern areas that become unsuitable due to sub-optimal thermal regimes for these species or to local population extirpation.

7.5.3 General Effects of Climate Change on Arctic Anadromous Fish

There are about 30 species within the arctic regions belonging to the families Petromyzontidae, Acipenseridae, Anguillidae, Clupeidae, Osmeridae, Salmonidae, and
Gasterosteidae (Table 1 in Box 7.5) that exhibit diadromous behaviour, i.e., spend part of their lives in the marine environment and migrate to freshwater to spawn, or the converse. Most arctic diadromous species are actually anadromous (i.e., use estuarine and/or marine environments for feeding and rearing, and freshwater environments for spawning, early life-history, and in the case of most arctic species overwintering); only freshwater eels (Anguillidae) and some lampreys (Petromyzontidae) are catadromous (i.e., breed at sea and rear in freshwaters). Most anadromous species in the Arctic are facultatively anadromous (Craig, 1989) in that, although accessible many individuals in a population do not necessarily migrate to sea. Typically, anadromous behaviour is most prevalent at northern latitudes (McDowall, 1987) because the ocean is more productive than adjacent freshwater habitats in temperate and also arctic zones (Gross et al., 1988). For a number of facultative anadromous species (e.g., Arctic char, Dolly varden, brook trout, brown trout, threespine sticklebacks), anadromous behaviour ceases towards the southern portion of the species distributional range (several references in McDowall, 1987). Anadromy in Arctic char also declines or ceases towards the extreme northern geographic limits likely because access and time at sea, hence benefits are limiting. Facultative anadromous species exhibit such behaviour in polar regions to take advantage of marine coastal productivity and escape extreme oligotrophic conditions that typify arctic lake systems. Generally, individuals of a population that exhibit anadromous behaviour have a larger maximum size and higher maximum age indicating some benefit to seaward migration and feeding.

Diadromous fishes will integrate climate change effects that impinge upon freshwater, estuarine and marine areas, hence the total impact on these will be significant (e.g., see Friedland, 1998; Fleming and Jensen, 2002). This has major follow-on impacts since these fishes support important fisheries in all arctic regions (see Section 7.5.4 below and Chapter 9). Consequences of climate change for diadromous fishes include:

- Projected impacts of climate change on arctic lakes overall suggests that productivity of these limited systems will increase due to a longer ice-free, growing season and higher nutrient loads. Anadromous fish populations should initially benefit with increases in survival, abundance and size of young freshwater life-history stages, and these may cascade to older, normally anadromous stages. Thus, facultative anadromous species may actually exhibit progressively less anadromous behaviour if the benefits for migrating to coastal areas for summer feeding are outweighed over time by the benefits of remaining in freshwater systems. Nordeng (1983) reported that when the freshwater food was experimentally increased, the incidence of anadromous migration by Arctic char decreased. However, any tendency to reduce facultative anadromy in response to increased freshwater production may also be offset by increased estuarine production discussed earlier. The exact balance and circumstances of how such scenarios will unfold are ecosystem specific and depend upon the details of present productivity, accessibility and ease of migration by fish, as well as the nature and degree of any climate-related effects.

- The variability associated with projected changes in productivity is uncertain. The anadromous species listed in Box 7.5, Table 1 are typically long-lived (15-50 years) compared to other fish species. Longevity benefits species living in variable
environments by ensuring a relatively long reproductive cycle, thus minimizing the risk that prolonged, environmentally unfavourable periods (5-15 years) will result in the loss of a spawning stock (Leaman and Beamish, 1981). Anadromous forms of arctic fish species are relatively long-lived (>10-15 years) and are likely suited to cope with increased variability that might accompany climate change. Initially as environmental conditions improve, successful spawning episodes will increase in frequency. Anadromous fish that are short-lived (<10-15 years) will likely exhibit more variability in abundance trends with increased variability in environmental conditions.

- Anadromous species (Box 7.5, Table 1) also inhabit streams or rivers when in freshwater in addition to lakes. Projected climate impacts on arctic hydrology (see 7.4) suggest that runoff will be driven by increased precipitation and will not be as seasonally variable; winter flows will be enhanced and summer flows reduced. Also, warmer conditions will reduce the length of winter and shorten the ice season along with a reduction in the thickness of ice. Thus, streams that were previously frozen solid will retain water beneath ice thereby benefiting anadromous species that utilize streams for winter habitat (e.g., Dolly Varden). Overwintering habitat is critical for arctic species and is typically limited in capacity (Craig, 1989). However, the shortened ice season and thinner ice will reduce the severity of ice-jamming. This will have implications for productive river deltas that require flooding. There are several anadromous species, such as Arctic cisco, that rely on deltas as feeding areas, particularly in spring (Craig, 1989).

- Anadromous fish are by definition highly migratory and tolerant of marine conditions. Thus as limiting environmental factors are ameliorated, a number of sub- or low-arctic anadromous species will likely extend their northern limits of distribution to include areas within the Arctic. Pacific salmon species will likely colonise northern areas of Region III. Sockeye and pink salmon have already been incidentally recorded from Banks Island, Northwest Territories, Canada outside their normal range of distribution (Babaluk et al., 2000). Similarly, anadromous species such as Atlantic salmon, alewife, brown trout and brook trout could also extend their northern range of distribution in Regions I and IV. Invasion of new anadromous species to arctic regions will also likely have negative impacts on species already present. However, for many of these sub-arctic species climate change will likely have negative impacts upon southern populations thereby offsetting any positive benefits that may be accrued in the north (e.g., Welch et al., 2002). Catadromous species such as European eel (Region III) are primarily warm-water species limited by colder arctic temperatures (e.g., Nordkappe, Northern Norway) is the present limit (Dekker, 2003). Eastward colonization of Russian areas of Region II, and possibly also increased abundances are likely in some areas where it presently occurs but where populations are insufficient for fisheries (e.g., Iceland).

Two arctic anadromous species are particularly important in northern fisheries – Arctic char (all Regions) and Atlantic Salmon (Regions I, IV). To indicate the range of possible responses
by these to climate change, they are treated separately in more detail as specific boxes (Box 7.7 and Box 7.9, respectively).

Box 7.9. Projecting the Effects of Climate Change on a Stock-specific Basis of the Atlantic Salmon

7.5.4 Impacts on Fisheries for Arctic Freshwater and Anadromous Species

As for all previous discussion, the potential and realized impacts of changes in climate and ultraviolet radiation parameters on arctic fisheries must be viewed in terms of direct impacts upon the fish and fisheries as well as indirect impacts mediated through the aquatic environment. However, for fisheries the human context is of great importance and must be considered, also. Fisheries are managed to have a sustainable harvest. Harvests (i.e., quantity) in fisheries affect different species and their life stages differently. Fisheries must also be viewed from the perspective of quality of the product which affects its suitability for human consumption as well as its economic value. Finally, success of a fishery implies that the fishers themselves have suitable access and success in the fishery, typically the result of experience and local knowledge. This also means that fishers are able to return high quality catch in good condition to points of consumption or transport to market. All these components of fisheries conducted in arctic freshwaters, quantity, quality, and access are subject to both direct and indirect impacts of climate change and increased ultraviolet radiation to a greater or lesser extent. Similarly, climate change will affect aquaculture operations conducted in arctic freshwaters. The implications of this will be explored in the following for fisheries conducted in fresh-, estuarine- or nearshore coastal waters.

7.5.4.1. Nature of Fisheries in Arctic Freshwaters

Fisheries for arctic freshwater and diadromous fish are conducted in all polar countries including Canada, Denmark (Greenland), Faeroes, Finland, Iceland, Norway, Russia, Sweden and the United States of America (Alaska). Freshwater fisheries as described here include those on species that live their entire lives in freshwater, such as lake trout and those conducted on diadromous species such as Atlantic salmon. Offshore marine fisheries conducted upon anadromous species and the relevant impacts of climate change on these in marine waters are dealt with in Chapter 12.

Arctic freshwater fisheries generally involve mostly local indigenous peoples, although some may also involve non-indigenous local people as well as visitors to the Arctic. (See Chapter 9 for traditional accounts of changes in fishes and fishing in recent years.) Although details vary locally at least three semi-distinct types of freshwater fisheries can be distinguished:

- Commercial – fisheries in which the product is sold commercially either locally or often in markets far removed from the sources;
- Recreational – fisheries in which non-indigenous people participate primarily from the experiential perspective rather than from the perspectives of economic, cultural or nutritional value of the product; and,
• Domestic or subsistence – fisheries conducted by indigenous or local peoples primarily from a cultural and sustenance perspective (See also Chapter 11).

Arctic freshwater fisheries can be quite substantial but generally never achieve the same economic significance that marine fisheries do, in part due to abundances and in part due to lack of fishery infrastructure (e.g., absence of processing plants on lower Lena River, extremely long distances to markets). For the nine arctic countries in 2000, reported commercial catches for northern fishes (8-350,000 metric tonnes) represented 0.002-32% of total commercial catches for all species within those countries (FAO, 2002), although ~10% or less of this was truly arctic in location as defined herein (J.D. Reist, unpublished data). Rather, arctic fisheries are diverse, locally widely dispersed, and target a variety of species that are locally abundant. Such fisheries are extremely important in meeting the needs of the local peoples and contribute significantly to the economy and society of northern peoples (see also Chapter 11), thus their value must be measured in more than simple economic terms and understood in the context of climate impacts.

7.5.4.2. Impacts on Quantity and Availability of Fish

Over the short-term future projected general productivity increases for arctic freshwater ecosystems, increased summer survival and growth of young fish, and increased overwinter survival of fish will probably result in increased biomass and yields for many fished species. Production shifts will depend upon local conditions such as faunal composition of the fishes and food species, tolerances and reactions of individual species to climate change, and on general productivity shifts in aquatic ecosystems (Lehtonen, 1996). However, there will be much regional and local variation and responses will likely be primarily species- or ecosystem-specific (Tonn, 1990). Thus, for wholly freshwater species shifts in productivity are more likely to occur in lakes along the southern fringe of the Arctic, and less likely to be observed in flowing water ecosystems. For anadromous species, increased summer nearshore productivity may similarly enhance growth rates, hence biomass and potential fishery yields. Furthermore, recent work conducted on Atlantic salmon while in marine waters suggests that warmer sea surface temperatures (8-10°C) enhance survival both in winter (Friedland et al., 1993) and early summer (Friedland et al., 2003). Both effects will enhance fish returns to freshwaters. Shifts in river-flow regimes critical to upstream migrations of anadromous fish especially in the late summer may act negatively thus counter-balance this generality to some degree. Arctic freshwater-fisheries production will probably show some increases over the next decade or two. The greatest manifestation of this increase will likely occur at the southern boundary of the Arctic as defined herein, and will involve species that are primarily subarctic (i.e., occurring throughout northern temperate regions and extending into the Arctic). Fisheries yields for such subarctic fish species (i.e., northern pike, lake whitefish, walleye from eastern North America, and northern pike, European whitefish, perch in northern Europe) have been linked with species-specific (and perhaps region-specific) optimality in habitat (e.g., Christie and Regier, 1988; Lehtonen, 1996; Schlesinger and Regier, 1983). Such yield relationships have been further examined in the context of GCM-projections of temperature increase for the area (Minns and Moore, 1992; Shuter and Post 1990). This regional approach suggests, at least for deeper lakes and perhaps larger rivers,
substantial re-distribution of fishery potential driven by population productivity as well as by re-distribution of species will occur.

As thermal optima are exceeded locally and perhaps as ecosystems re-equilibrate and nutrient limitations occur, reductions in biomass and yields may occur. For example, climate change will affect species individually owing to differential colonisation, extinction and productivity rates (Tonn, 1990). This could lead to substantive ecological reorganisation (Peterson et al., 1997). These effects will likely be most severe for true arctic species such as broad whitefish and Arctic char, which may also be affected by increased competition from more southerly species extending their geographic distributions northwards. Thus, in the longer term, the effects of climate change on arctic fisheries yields of true arctic fish species are likely to be negative, whereas those of subarctic and northern temperate species, are likely to be positive.

As freshwater productivity increases, the frequency of anadromy may decrease within populations that exhibit facultative anadromy (e.g., Arctic char, Dolly Varden and broad whitefish). Given that anadromy and feeding at sea results in larger size at a given age and also in larger populations (Gross et al., 1988), a switch away from anadromy will likely result in decreased productivity. To ensure sustainability, this may necessitate lower harvests of native anadromous species; shifts in harvesting of alternate species, if available; and/or a change in location or timing of fisheries. The consequences of these changes to fisheries of local indigenous people who rely on the autumn upstream runs of anadromous fish will be substantial from economic (i.e., protein replacement and increased costs to travel to new fishing areas for smaller catches), social and cultural perspectives.

As noted previously one of the hall-marks of climate change in the Arctic is likely to be increased inter-annual variability in climate parameters. Although it may be partially lost in the background noise of typically high inherent variability in arctic climate, this in turn may possibly increase the variability of good and poor year-classes in arctic fish. The consequence of this to fisheries will probably be increased variability in fishing success and unstable yields for targeted species. Such increased variability will exacerbate problems discussed above which affect the biomass and yields of fisheries. Consequences include those associated with domestic sustenance if the local people rely heavily on the fished species, as well as difficulties with developing stable commercial or recreational fisheries that are economically viable and sustainable. As warming becomes more pronounced, southern fish species will colonise newly available areas, enhancing the possibility of negative impact from competition. They may however, also represent opportunities for new fisheries. Hence, flexible, adaptive management will be key to the success of future fisheries (Peterson et al., 1997), particularly in responding to uncertainties associated with available data; an attribute not currently present in many fishery management regimes in the Arctic (e.g., Reist, 1997a; Reist and Treble, 1998).

Availability of fish species to fisheries will probably change as a result of several factors. For example, most fished arctic species are salmonids which tend to prefer cool or cold thermal regimes especially as adults (e.g., lake trout), thus they seek summer refuge in colder waters below thermoclines in lakes. As the thermocline depths deepen, the availability of these species to fisheries may change because deeper waters are more difficult to fish. This will be
especially true for larger, deeper arctic lakes (e.g., Great Slave Lake in Canada) and may necessitate gear changes for fisheries and/or re-education of fishers in new techniques. Questions as to how this might occur and how costs can be covered are currently not being addressed. In addition, the optimal temperature habitats of salmonids (e.g., European whitefish and brown trout) will change in northern Europe and summer temperatures might be too high in shallow arctic lakes (Lappalainen and Lehtonen, 1997), with consequent effects on local fisheries.

### 7.5.4.3. Impacts on Quality of Fish

Quality of fish captured in a fishery refers to its suitability for marketing (e.g., locally or distantly by trade, cultural exchange and/or sale) and for consumption by humans. This suitability is affected by factors inherent to the fish itself resulting from environmental conditions experienced prior to capture, as well as factors that affect the fish product after capture. Factors influencing fish quality before capture include ‘fish condition’ (e.g., typically an index of weight and length which measures fatness or nutritional state or ‘well-being’) (Busacker et al., 1990), flesh firmness which is typically influenced by water temperatures immediately prior to capture (i.e., with warmer waters generally resulting in poorer quality flesh), general appearance (e.g., colour and lack of imperfections) of both the fish itself and perhaps key consumed organs such as livers, parasite loads and disease, and contaminant burdens. Factors influencing fish quality after capture include preservation (e.g., cooling or freezing), and the ease, conditions and time associated with transport to the consumption site, market or processing facility. As for all other impacts of change in climate parameters or ultraviolet radiation, both direct and indirect impacts will influence fish quality.

Indirect and direct impacts on quality of fish before capture are primarily those considered in previous sections of the chapter. That is, for example, impacts on ecosystem structure and trophic pathways will affect the availability of food (both amount and quality) to the fish and thus will influence fat levels and condition, those which may affect migratory patterns or access will influence growth and condition, and additionally, impacts such as higher late-season water temperatures may decrease flesh firmness of cold and cool water fishes such as salmonids, hence lower either perceived or real quality. There is evidence that the colour, size and firmness of livers and flesh in some species is affected by nutritional state of the fish – for example, burbot livers appear to be affected by fat content and presumably nutritional state of the fish (Lockhart et al., 1989). This appears to be related in part to seasonal variance in nutrition rather than specifically to environmental impacts such as contamination. Thus, climate change impacts that affect nutrition of fished species will result in follow-on effects on fish quality, but these may be difficult to distinguish from ongoing typical seasonal effects. However, some additional potential impacts are worth noting or emphasizing. In general, increased contaminant burdens present in fish flesh will result from climate change with a concomitant decrease in fish quality and acceptability for human consumption and may exceed safe ingestion limits. This may be particularly acute for some contaminants such as heavy metals (e.g., mercury) and also for some areas of the Arctic. Thus cautions and caveats associated with arctic contaminants as embodied in the Arctic Monitoring Assessment Programme report (AMAP, 1998) may be substantially exacerbated by climate change (see also Section 7.7 below).
Furthermore, the potential impacts of climate change on fish parasites and hence on fish quality have been poorly addressed but appear to represent major higher-order impacts (Marcogliese, 2001). Potential direct impacts on the aquatic parasites themselves include many of the same ones noted for fish species, for example, both biological challenges and opportunities associated with parasite physiology either as a direct effect of the environment on the parasite (e.g., higher temperatures and/or shorter durations of low temperatures accelerating development) or as mediated through the host fish (e.g., shifts in fish feeding affecting parasite development). Higher developmental rates of parasites suggest increased burdens upon fish hosts, which, in turn will result in decreased productivity of the population and/or condition of individuals (Marcogliese, 2001). A further potential impact of parasites on arctic freshwater fishes is that associated with the introduction of new parasites to new host species or new areas (i.e., those not presently colonized) via the mechanism of host colonisation of such areas through range extension. This will be complicated by a tendency to higher levels of eutrophication in arctic water bodies associated with a general increase in temperature. Similarly, disruption of normal developmental synchronicities between parasites and host fish such as seasonal migrations within a water body may result in shifts in rates of transmission to various hosts necessary to the parasites life cycle, but may also result in switching to different hosts. Thus, parasites typically found in temperate fishes may switch to arctic fishes, affecting the latter both biologically and from the perspective of quality. Shifts in thermal regimes that result in increased local densities of hosts especially intermediate ones, such as planktonic or benthic invertebrates, will also theoretically increase parasite diversity (Marcogliese, 2001 and references therein). Conversely, activities such as fishing (which for relatively pristine fish populations reduce the density of larger and older fish and replace this with increased densities of younger and smaller fish) can result in the ‘re-packaging’ of parasites and a net overall increase in parasite density within individual fish (T. Dick, University of Manitoba, Winnipeg, 2001 pers. comm.). This reduces fish quality and marketability. The nature and timing of water delivery and potential shifts in overall amounts of precipitation may also affect parasite levels – a general decrease in water levels is likely to be accompanied by a general increase in parasites and associated problems. Although poorly studied at present, the potential impact of fish diseases must also be addressed – climate change is likely to result in increased incidence and spread of diseases, and perhaps increased intensity locally as fish populations are stressed. Furthermore, effects such as those associated with parasites, disease and contaminants are part of the cumulative effects scenario impacting local populations thus must be considered when addressing issues of impacts on fish quality.

Many of these effects will be most likely seen and present major problems in fish quality for areas of the southern Arctic which are presently characterized by both reasonably high levels of exploitation and also by large southern catchments that flow north to the Arctic Ocean (see Section 7.2.3). Thus, problems which may be small at present and confined marginally to the southern Arctic may be expected to increase in intensity and also spatially as climate change becomes more pronounced throughout the Arctic.

Impacts of increased ultraviolet radiation on some fish parasites may actually be beneficial in that infection rates are slowed and/or the spread of some parasites may be inhibited (Marcogliese, 2001). However, immunosuppression as a consequence of increased ultraviolet exposure may increase the consequences of parasitism, disease and contaminant loading for
individual fish. This will possibly lower population productivity by decreasing survival. Also, any obvious physical damage such as lesions or growths resulting from ultraviolet exposure will decrease fish condition and quality.

7.5.4.4. Impacts on Access and Success of Fisheries

From the perspective of the fishers, climate change will have substantive impacts on how, when and where fisheries may be conducted. That is, access to and from fishing sites, as well as local knowledge associated with fish presence, migratory timing, and species composition will all be affected. The success of the fisheries, especially as measured by transportation of high-quality product to market or point of consumption, will similarly be affected. Some aspects of the latter impact such as transportation and infrastructure issues are dealt with elsewhere in this volume (Chapter 15). Most arctic freshwater fisheries are small in scale, conducted locally and seasonally, and often use limited and relatively simple gear. Climate change impacts that fishers will have to accommodate include: increased frequency of extreme events such as high intensity storms and increased winter precipitation and stronger water flows that may imperil the fishers, restrict their access to fishing sites or result in the loss of fishing gear (hence economic burden). Generally arctic freshwaters are characterized by long periods of winter during which ice provides a stable platform for transportation across lakes and rivers and for deploying some types of fishing gear such as gill nets. Decreased length of the ice season, concomitant increases in the duration of freeze-up and break-up, and increased ice roughness from storms will result in substantive changes in timing, duration and methods by which fisheries are conducted in the future.

Success of fisheries often depends upon the experience of the fishers, and for domestic fisheries is intimately connected with traditional knowledge of where and when to fish for particular species. The projectability associated with this will possibly decrease as climate-change impacts are realized. The timing of migratory runs, the typical keystone event in many northern domestic fisheries, will exhibit increased variability and decrease the ability of the fishers to know when to best begin fishing. Such circumstances will potentially result in decreased success of fisheries. Furthermore, such variability is likely to become the norm as ecosystems undergo shifts, at least until new equilibriums are established. Because the changes wrought by climate change are likely to be protracted and depend in large part upon local ecological circumstances and the nature of the biota present, new equilibriums are unlikely to be quickly established. Thus, fishers may have to tolerate highly variable and unstable conditions in freshwater and coastal ecosystems. This will result in highly variable successes in freshwater and anadromous fisheries, at least over longer time frames.

Another aspect that deserves consideration is the shifting of species composition as new species colonize an area. If the new colonizer is similar to existing species (e.g., Pacific salmon as another salmonid present in an area), the existing experience and interest of fishers will likely be applicable. Alternatively, if the new species represents an unfamiliar taxon, fishers may have to build the experience base for capture and marketing, assuming the species is desirable. Undesirable species (defined by local needs and wants such as, for example, spiny rayed species) may prove to be pests by clogging nets and reducing capture efficiency. Such species may also be considered to be substandard for local use based upon either
tradition or physical characteristics. Although highly adaptable, northern peoples will still require time and experience to modify existing practices and develop necessary adaptations for continuing successful fisheries.

Fishing as an industry carries relatively high inherent risks associated with the environment and with the tools employed. These include loss of equipment (i.e., both fishing gear and boats), injury and death of the fishers themselves. Along with the expected change and projected increased variability in climate systems, and thus decreased projectability associated with forecasts and environmental conditions, the incidence and severity of catastrophic climatic events such as severe storms will increase. Such circumstances will imperil fishers who are exposed to the elements. For example, protracted break-up or freeze-up periods will make ice conditions more unpredictable. Travel over ice is essential to arctic life and especially to early winter fisheries conducted through the ice; the choice facing fishers will be increased risk or decreased fishing time, hence decreased catch.

This general summary of impacts of climate change and ultraviolet radiation changes on arctic freshwater and anadromous fisheries is by no means comprehensive. Numerous additional potential impacts are summarized in Table 7.2.

Table 7.2. Summary of possible, likely and very likely effects on fished species and freshwater and anadromous fisheries.

Detailed regional and local analyses of particular types of fisheries (e.g., commercial, recreational or domestic) and of specific arctic freshwater and anadromous fisheries are required to more fully elucidate all impacts, understand their consequences to the local fisheries, and to stimulate the development of appropriate short- and long-term adaptive responses by fishery managers and related constituents of the fishery infrastructure. Failure to address these issues in a timely fashion will undermine coherent and comprehensive preparedness to meet challenges both climate change and ultraviolet radiation increase present for arctic freshwater and anadromous fisheries.

7.5.4.5. Impacts on Specific Fishery Sectors: Commercial, Domestic, Sport

In addition to the general impacts discussed above, climate change will have impacts specific to the various types of fisheries conducted in the Arctic.

Commercial Fisheries – Perhaps the most significant challenge facing commercial fisheries will be development of appropriate adaptive management strategies that deal with complex, synergistic and cumulative effects of climate change on fish populations and their environment, particularly in the context of sustainable use and long-term conservation.

For example, the conundrums of how to manage both declining and increasing populations of two fishable species in a particular location, how to understand and integrate climate change impacts through functional ecosystem pathways to project future states, and how to balance the needs of local peoples and competing demands, all represent real problems for northern
fishery management. Clearly some sort of adaptive or heuristic approach that incorporates elements of both fishery and ecosystem management is required (Reist and Treble, 1998). Generally this is either unavailable or not being applied presently, a situation which must be rectified in order to adapt to climate change as it unfolds in the north.

Furthermore, the research necessary to underpin both the management approaches and to elucidate ecosystem linkages to fisheries must be undertaken for the north to fill gaps in our understanding. Clearly, the best approach would be to leave sufficient resilience and compensatory capacity within fished populations and their supporting ecosystems, so as to account for all impacts, and to provide sufficient buffers for increased variability and surprises associated with climate change. Current management practices incorporate such buffers in a limited way, especially in the Arctic. The development and application of such buffers (e.g., through risk analysis or other techniques) needs to be extended. This presents a significant challenge both in terms of developing or modifying appropriate tools for use in arctic fisheries.

Domestic Fisheries – The subsistence sector in the arctic portion of the Canadian northern economy is estimated at approximately CAN $15,000 per year per household (Fast and Berkes, 1998). This represents one-quarter to one-half of the total local economy, and this portion may even be growing. Similar values are likely for domestic fisheries in other arctic countries especially in more remote regions where the portion of total economy, hence value, may be even higher. Furthermore, replacement of this sector by wage or industrial economies is generally unlikely. Fisheries, which in the Canadian Arctic include marine mammals in coastal areas, comprise as much as 20% of the overall subsistence harvest in some areas (Fast and Berkes, 1998). Thus, climate-mediated impacts as noted above upon fish habitat, fish themselves and fish populations will have significant effects on availability, use and sustainability of domestic fisheries. In addition to those already enumerated, the following effects will likely be observed within domestic fisheries.

Traditional ecological knowledge developed over hundreds or thousands of years of direct environmental contact may be compromised (Fast and Berkes, 1998). This may be more intense regionally in particular areas where climate change effects are acute. Also, the impacts of this would be exacerbated for extreme events which are unprojectable. Thus, increased climate variability and concomitant unprojectability of environmental conditions will possibly be more significant than will change in the trends of such conditions. As noted above, this may alter access to traditional fishing areas, increase risk associated with travel on the land or ice, and also change fishery success. Loss of a significant portion of fish from the household economy will, in turn, mean replacement by some other means – perhaps increased reliance upon food transported from the south and/or upon other northern country foods (e.g., terrestrial mammals) further stressing those populations. The former solution, i.e., a dietary shift to southern transported foods may contribute to dietary problems and increased health costs (Fast and Berkes, 1998). Increased transportation costs for such foods would likely be covered in some manner by subsidies from southern portions of the national economies, but this feedback from the north would increase the economic impact of climate change on southern areas. However, the availability of new fish species in some areas may mitigate these problems, yet as noted above, may not provide immediate solutions.
Recreational Fisheries – Impacts similar to those outlined above will also affect sport or recreational fisheries. Additionally altered management demands and economic implications associated with such fisheries may occur. For example, recreational fishing for Atlantic salmon in eastern North America is regulated in part through river closures driven by higher temperatures and low water levels. The rationale is that under such conditions fish are environmentally stressed and catch-and-release angling (the norm for the area) would further stress individuals thus impact populations (Dempson et al., 2001). Annually about 28% of 158 rivers were closed on average between 1975 and 1999 with up to 70% affected in some years. This resulted in 35-65% loss of potential fishing days with the warmest period (1995-1999) being impacted most. In part this stress was the result of increased upstream migratory energy demands associated with lower water levels and higher water temperatures. Although this study was conducted in Newfoundland, it represents a possible future situation for arctic sport fisheries based upon riverine migrating fishes such as Atlantic salmon and Arctic char. Such fishes support significant local tourist economies in many areas of the Arctic, hence this potentially represents a substantive economic impact by increasing the frequency and duration of closures (Dempson et al., 2001).

7.5.4.6. Impacts on Aquaculture

Aquaculture of fish in northern areas of arctic countries tends to focus upon cold-water species with high economic value such as Atlantic salmon and Arctic char. In general, such culture appears to be presently located in areas south of the Arctic as defined herein, but this will likely change as demand and opportunity increase. Aquaculture can be conducted wholly in freshwter using locally available or exotic species either indoors or out, or in protected nearshore marine areas primarily using anadromous species. Aspects of the latter are also considered in Chapter 12. Climate change will result in a number of possible shifts in this industry, however, similar to those described earlier for fisheries dependent upon wild populations, these may be complex and interactive with both positive and negative consequences. The details will be specific to the local situations. Possible changes include production increases especially in northern locations due to temperature-driven increased growth rates of cultured fish and also decreased times necessary for culture to marketable sizes (Lehtonen, 1996), but increased need for food is obviously likely. This will depend upon other factors not becoming limiting; especially available volumes of freshwater needed for inland operations. Knowledge of expected shifts in precipitation and evaporation with concomitant impacts on ground water levels will be important for the viability of such endeavours. Production increases may be offset by increased costs associated with oxygenating warmer waters, especially those for summer use, and increased loss to disease or costs associated with prevention (Lehtonen, 1996).

As warmer conditions extend northwards, the areas in which aquaculture is economically viable (i.e., revenue exceeds costs) will possibly increase opening new areas to this activity. However, increased climate variability and frequency of extreme events may also increase engineering costs. This will present both opportunities as well as potential negative impacts on local native species, especially if the cultured species is exotic to the area (e.g., a non-native southern species). As climate-change effects are realized, the suite of southern species
potentially viable for aquaculture will increase and pose new economic opportunities. This will increase the need for regulatory scrutiny of such development, especially if the risk of escape and naturalization of such species is high. A related issue will be increased risk of intentional but unauthorized introductions of exotic species into natural systems already impacted to some degree by climate change. Escape and naturalization of Atlantic salmon along the Pacific Coast of North America (Volpe et al., 2000) serves as a valuable model for potential negative effects. Appropriate management and control of such activities will be required; such activities may add significant additional stress to native populations already highly stressed by climate change. Strategies to deal with such possibilities are presently lacking or extremely limited especially for potential transfers within countries.

7.5.5 Impacts on Aquatic Birds and Mammals

Given our increasing understanding of the critical role of climate in driving waterfowl and aquatic wildlife population dynamics, it seems highly likely that progressive, rapid change in climate will trigger substantial fluctuations in endemic fauna and flora. Population and community-level responses of aquatic birds and mammals would probably result from combinations of direct and indirect impacts. Some of these include: changes in winter severity; seasonal snow and ice distribution and depths; timing and peaks of lake, pond and wetland productivity; predator-prey dynamics; parasite-host interactions; habitat quality and distribution; and fire frequency, intensity and distribution.

As discussed in section 7.4.1, projections from the ACIA 5-AOGCM simulations show that coastal land areas (and associated estuarine and freshwater habitats) are likely to experience more dramatic temperature increases and changes in their hydrologic regimes. Such changes will significantly alter the quantity and quality of existing coastal estuarine and delta habitats, thereby affecting associated bird and aquatic mammal communities.

It is therefore probable that changes in freshwater and estuarine habitat will result in altered routes and timing of migration. Emigration of aquatic mammals and waterfowl will likely extend northward as more temperate ecosystems and habitats develop at higher latitudes (See Chapter 6, Section 3.6). Migration may occur earlier in the spring with the onset of high temperatures, and later in the fall if high temperatures persist. Breeding-ground suitability and access to food resources will be the primary driving forces in changes to migration patterns. However, many species living in these areas are adapted and even dependent on extreme natural fluctuations in climate and associated impacts on water resources. Hence, their responses to such changes will likely be species-specific and quite varied.

A number of direct and indirect effects will likely occur in shallow arctic lakes and ponds that lack a thermocline. Summer maximum temperatures will likely climb above physiological preferences or thresholds of algae, plankton, and benthic invertebrates, which in turn would produce substantial shifts through time in diversity and/or abundance at these lower trophic levels. Such shifts could result in earlier or reduced seasonal peaks in abundance of key foods, thereby creating mismatches between resource availability and timing of breeding. This would lead to a lowering of reproductive success of higher-level consumers such as waterfowl.
Changes in water regimes could also dramatically alter the quantity and quality of in-water and riparian habitat, leading to local changes in the distribution of birds and mammals, and at larger scales, could affect overall habitat availability, carrying capacity and reproductive success. Aquatic mammals and waterfowl are highly dependent on the availability and quality of aquatic habitats for successful breeding, and in the case of waterfowl, nesting. Northerly species may have diminished reproductive success as suitable habitat either shifts northward, declines in availability and access. Northward colonization of southern species may result in competitive exclusion of “northern” species for habitat and resources. Many of the expected responses are likely to result from simple changes in temperature and precipitation. For example, water depths have been shown to have a significant positive effect on the annual production of juvenile whooping cranes (Boyce and Miller, 1985). It has also been suggested that increased summer temperatures will likely yield drier conditions in the whooping crane nesting marshes over the long-term, decreasing production of young and slowing annual population growth rate (Boyce and Miller, 1985).

Many shorebirds (e.g., sandpipers, plovers, snipe, godwits, curlews) are also known to be dependent on water levels and persistence of shallow wetlands. For instance, most North American species of shorebirds breed in the Arctic, with ten species common to the outer Mackenzie Delta (Gratto-Trevor, 1994; 1997). These species are dependent on invertebrate prey during laying of clutches, and hatchlings are highly dependent on mosquitoes/chironomids, the preferred foods of developing young. Any changes in timing and availability of food at staging sites in the Arctic, let alone the availability of wetland habitat, could have detrimental effects on the success of hatchlings. As such, most species will be adversely affected by loss of shallow wetland habitat as areas of ponded water dry in response to rising temperatures, potential decline in precipitation and degradation of permafrost. On the other hand, melting of permafrost and increases in precipitation may increase the occurrence and distribution of shallow wetlands, and the success of shorebirds in the Arctic.

Long-term survey data are available for a limited number of wetland-dependent migratory birds in Canada which demonstrate some of the possible effects of climate-related change. This information clearly indicates dramatic declines in abundance of several waterfowl species (e.g., scoters, lesser scaup) with core breeding areas located in northwestern boreal forest of Canada. Several hypotheses have been proposed to explain these patterns, including changes in wetland systems (e.g., food resources for breeding birds or their offspring). It is difficult to identify causes of decline because changes have also occurred simultaneously on each species’ wintering, migration and breeding areas; however, breeding ground changes seem quite possible because indices of productivity (i.e., a clear breeding ground signal) have decreased during the past 20 years (Afton and Anderson 2001; Austin et al. 2000).

The dynamics and stability of aquatic mammal populations have also been linked to observed variability and extremes in hydrologic conditions. Thorpe (1986) found that in the Peace-Athabascan delta, Canada, years that were associated with observed spring ice-jam flooding (and associated re-flooding of perched basins) saw high success in local trapping of muskrats. A decade with low water levels in the delta resulted in dryer perched basins and fewer
muskrats, followed by a decade of higher water levels and high muskrat harvesting. In this case, perched-basin water levels and the extent of emergent vegetation development seemed to be the controlling factors in muskrat occurrence and abundance. Independent Traditional Ecological Knowledge studies of the area also provided corroborative evidence of this trend (NRBS, 1986). Hence, projected decreases in the frequency and intensity of ice-jam flooding under future climate scenarios would probably cause decreases in the re-flooding of perched basins thereby negatively affecting these populations in low-water level years.

It is also possible that projected climate change in the Arctic will produce an increased incidence of mortality from disease/parasites in bird and aquatic mammal populations. As temperatures rise, southerly species of mammals and waterfowl will shift northward. These species may carry with them new diseases and/or parasites to which northerly species are not adapted.

7.6. UV IMPACTS ON FRESHWATER ECOSYSTEMS

7.6.1 Introduction

Ultraviolet radiation (UVR) is the most reactive waveband of solar energy reaching the surface of the Earth and has a broad range of effects on aquatic biogeochemistry, biota and ecosystems. As a result of anthropogenic impacts on the Earth's atmosphere, UV exposure in arctic environments is changing substantially, and there is likely to be much greater change over the course of this century. To provide the necessary context for the assessment, an overview is provided on how underwater UV exposure is linked to climate, followed by a discussion of general principles concerning UV impacts in aquatic ecosystems, including natural protection mechanisms. This is followed by a systematic analysis of potential UV impacts on arctic freshwater habitats.

7.6.2 Climate Effects on Underwater UV Exposure

To understand the overall impact of UV radiation, the synergistic and antagonistic processes resulting from climatic warming have to be considered since they have the potential to modify the UV underwater regime and consequently the stress on aquatic organisms. Climate change will be accompanied by shifts in biological UV exposure in arctic river, lake and wetland environments via three mechanisms (Vincent and Belzile, 2003): changes in stratospheric ozone, changes in snow and ice cover duration, and changes in the colored materials dissolved in natural waters that act as sunscreens against UV radiation.

Although it is projected that the downward ozone trends may reverse in the near future as a consequence of reduced anthropogenic emissions of chlorofluorocarbons (CFCs) and related compounds, some of the longer-lived ozone-depleting substances are still accumulating in the stratosphere and climate change may prolong the effects of depletion. The warming of the troposphere will be accompanied by a cooling of the lower stratosphere, and there is already
some evidence of this effect in the polar regions. This will increase the frequency and extent of polar stratospheric clouds (PSCs) that catalyse CFC-ozone reactions and result in a strengthening of the polar vortex, which in turn could lead to longer-lasting conditions for ozone loss (Staehelin et al., 2001). The minimum winter temperatures of the arctic stratosphere are very close to the threshold for the chlorine reactions that lead to ozone loss, and the Arctic remains vulnerable to large-scale ozone depletion (Dahlback, 2002). It is also possible that greenhouse warming could lead to increased zonal flow in mid-latitudes causing the polar vortex to be more stable, again favoring ozone loss and a delay in the eventual recovery from CFC emissions (Shindell et al., 1998). Furthermore, as greenhouse-gas concentrations increase, the tropical tropopause might get warmer resulting in more water vapor being transported into the stratosphere, which in turn may lead to the formation of PSCs at higher temperatures (Kirk-Davidoff et al., 1999). Therefore, the ozone in the arctic stratosphere would be at greater risk of depletion (see Chapter 3 for further discussion).

The underwater UVR environment can change dramatically with a decrease of the snow- and ice-cover duration, especially if this occurs during periods of highest UV flux and ozone depletion. Analyses of the effects of arctic sea ice and lake ice melting show that this process will result in order-of-magnitude increases in biological UV exposure that greatly exceed those caused by moderate ozone depletion (Box 7.10; Vincent and Belzile, 2003). Lake and river ice are relatively transparent to UV radiation because of Coloured Dissolved Organic Matter (CDOM) exclusion (Belzile et al., 2002a). Small changes in snow cover and white ice, however, can radically influence the below-ice UV radiation field in arctic waters (Belzile et al., 2001).

**BOX 7.10. Changing Snow and Ice Cover – Implications for UV Exposure**

In aquatic environments of the Arctic, transmission of UV is affected by variations in suspended particulates, and especially CDOM (see Box 7.11). These variations can be more important than ozone depletion in determining the UV exposure in the water column of freshwater systems.

**Box 7.11. CDOM : The Natural UV-Sunscreen in Arctic Lakes and Rivers**

For some areas of the Arctic, climate change will be accompanied by increased vegetation, a concomitant increase in CDOM loading (Freeman et al., 2001), and reduced exposure to underwater UV. These positive effects may, however, be offset by reduced availability of light in the visible waveband (Photosynthetically Active Radiation, PAR) (Arrigo and Brown, 1996; Pienitz and Vincent, 2000; Neale, 2001). Marked south-north gradients in current CDOM concentrations in waters of the Arctic are associated with the distribution of terrestrial vegetation over the latitudes. CDOM loading of freshwater systems is less pronounced at higher latitudes. Lakes of the tundra and polar desert biomes contain low amounts of these materials; small variations in CDOM concentration in these systems can cause major changes in underwater UV exposure (Vincent and Pienitz, 1996; Laurion et al., 1997). Freshwaters in northern Scandinavia are low in dissolved colour similar to water bodies in North America; the median DOC concentration for 25 lakes above the treeline in Finnish Lapland was 1.8 mg C L^{-1} (Rautio and Korhola, 2002b). Although acid precipitation enhances underwater UVR by reducing the concentrations of DOC in the water, increased melting of permafrost with
climate warming may increase soil runoff and levels of DOC (or CDOM) in arctic freshwater systems. This will be accompanied by an increase in water turbidity, which will not only decrease PAR penetration but also increase UVR wavelength ratios, thereby hindering repair processes in aquatic organisms (stimulated by longer wavelengths). Increased physical turbulence may also expose planktonic organisms to unfavorable irradiance conditions (e.g., exposure to bright surface UVR plus PAR), the effects of which may be especially severe for species that cannot migrate.

7.6.3 UV Impacts on Aquatic Biota and Ecosystems

The impacts of UV radiation in the aquatic environment range from molecular to whole-ecosystem (see below). Photobiological damage includes the direct effects of UVR in which photons are absorbed by biomolecules such as nucleic acids and proteins that then undergo photochemical alteration. An alternative damage pathway is via the interaction of UV and organic compounds or other photosensitizing agents to produce reactive oxygen species such as superoxide and hydroxyl radicals. These can then diffuse away from the site of production and cause oxidative damage to enzymes, lipid membranes and other cellular constituents.

Aquatic biota have four main lines of defence against UV damage: escape, screening, quenching and repair. The net stress imposed by the UV environment reflects the energetic costs of protection and repair in addition to the rate of photochemical degradation or alteration of cellular components (Vincent and Neale, 2000). These defences are well illustrated by arctic zooplankton (see Box 7.12), but despite this protection these organisms remain vulnerable to UV radiation (Zellmer, 1998), particularly in the cold, shallow, CDOM-poor waters that characterize many arctic lakes and ponds.

Box 7.12. UV Protection and Recovery Mechanisms in Arctic Freshwaters

Changes in underwater UV exposure have the capacity to impact directly on the species composition of aquatic biota at each trophic level, as well as cause effects that cascade throughout the benthic (e.g., Bothwell et al., 1994) or pelagic (e.g., Mostajir et al., 1999) food webs and the coupling between them. Some trophic responses may be ‘bottom-up effects’ in that UV exposure reduces the quantity or quality of prey and thereby impairs the next level of consumer organisms. This could occur, for example, via shifts towards inedible or less digestible algal species (Van Donk and Hessen, 1995; Van Donk et al., 2000) or by reducing the nutritional value of food organisms (Scott et al., 1999). The effects of UV-B on the quality of phytoplankton photosynthetic products have received little attention compared to its quantification (except for studies at the pigment level; e.g., Buma et al., 1996; Zudaire and Roy, 2001). Any alteration in the biochemical composition of primary producers may change the nutritional value of food consumed by grazers (thus influencing energy flow throughout the food web) as well as deter the possibility of producing photoprotective compounds against UVR. Short-term exposure to enhanced UV-B levels in phytoplankton populations of various lakes from the Canadian High Arctic influenced the carbon allocation of newly fixed carbon into the major macromolecular classes (Perin, 2003). Generally, both the protein and polysaccharides syntheses were inhibited by UV-B and the photosynthate would remain or accumulate in the low molecular weight pool. Lipid synthesis was insensitive to UV-B and represented the most conservative and uniform class that accounted for about 20% of total
carbon fixed. Overall, these results were similar to those observed for Lake Ontario (Smith et al., 1998). However, the various classes of lipid may respond differently to UV-B. For example, exposure to UVR influenced the fatty acid composition in algal cultures (Goes et al., 1994; Wang and Chai, 1994). Also, other studies observed that the effect of UV-B on the major lipid classes is species-specific (De Lange and Van Donk, 1997).

Higher trophic levels are dependent on phytoplankton either directly as their food or indirectly via trophic cascades. Possibly inhibition of growth and cell division in phytoplankton will most often affect the food quality of these cells by causing stoichiometric constraints on the grazer (Hessen et al., 1997). Hessen and Alstad Rukke (2000) have also recently showed that water hardness could be a major determinant to UV susceptibility among calcium demanding species like *Daphnia*. They suggested that Ca, which is an important element to invertebrates with calcified exoskeletons, could in low concentrations (low pH lakes, acidification) reduce the stress tolerance of organisms. Although several studies have reported increased mortality for different freshwater invertebrate species, especially on zooplankton (Siebeck and Böhm, 1994; Williamson et al., 1994; Hurtubise et al., 1998; Vinebrooke and Leavitt, 1999; Leech and Williamson, 2000; Rautio and Korhola, 2002a), the variation in UV tolerance is high among species and life-stages (Leech and Williamson, 2000). In general, small zooplankton (small rotifers) are considered to have a high UV tolerance while large species vary in their tolerance both among and within species. Leech and Williamson (2000) found that cladocerans had the lowest UV tolerance and exhibited high variability among species. *Daphnia* was one of the most sensitive groups of organisms while adult calanoid and cyclopoid copepods had high UV tolerances. In a comparison of lakes across a successional gradient of catchment vegetation and thus CDOM content, three zooplankton species (*Asplanchna priodonta*, *Ceriodaphnia quadrangula* and *Bosmina longirostris*) were absent from low-CDOM, UV-transparent waters, and perished when transplanted from a CDOM-rich lake in the series and held at 0.5 m under full UV exposure in a clear lake. In contrast, two species that avoided high UV exposure in the near-surface waters (*Daphnia pulicaria* and *Cyclops scutifer*, a highly UV-tolerant species) occurred in even the clearest lakes (Williamson et al., 2001). Morphotypic and biochemical differences among populations of a given species may also play an important role. Pigmented clones of *Daphnia* were more tolerant to UV than transparent clones (Hessen et al., 1999) and pigmentation appears to increase in response to UV exposure (Rautio and Korhola, 2002b; see protection strategies Box 7.12). Studies on the effects of natural UV radiation to fish are rare but laboratory experiments have shown that high-latitude species of trout have sunburns, increased fungal infections and higher mortalities when exposed to UV (Litle and Fabacher, 1994).

Other trophic responses may be ‘top down effects’ in which some species are released from grazing pressure or predation by UV effects on the consumers and thereby achieve higher population densities (Bothwell et al., 1994). This complex combination of direct and indirect effects will make any future shifts in aquatic ecosystem structure extremely difficult to project. Also, the deleterious effects of UV-B at the community level are difficult to assess since they are generally species-specific. For example, the responses of the planktonic microbial communities of ponds from Greenland to ambient UV-B levels were shown to vary greatly between species especially for rotifers and ciliates (Wickham and Carstens, 1998).
Multiple factors seem to negatively affect amphibians. These factors include both site-specific, local effects (such as pesticide deposition, habitat destruction, and disease) as well as global effects (such as increased UV-B exposure and global warming) (e.g., Häder et al., 2003b). Amphibians have been the focus of special interest at temperate latitudes because of the recent, widespread decline in many frog populations and the recognized value of these organisms as sensitive indicators of environmental change. Although many amphibians can be relatively resistant to UV-B radiation it can cause deformities, delays in development, behavioural responses, physiological stress and death in frogs. As well, the rise in UV-B radiation associated with stratospheric ozone depletion has been widely promoted as one of several hypotheses to account for their decline (Collins and Storfer, 2003, and references therein). However, the effects are controversial and in many habitats where the frogs are declining, the animals are well protected by coloured dissolved organic matter (CDOM, Box 7.11). A small number of frog species occur in the Subarctic and Arctic, for example the Common Frog (Rana temporaria) and the Wood Frog (Rana sylvatica – North America), whose distributions extend north of the Arctic Circle. Contrary to expectation, however, these populations may experience higher UV exposures, and therefore be more pre-adapted (under natural conditions relative to temperate regions) because of 1) lower concentrations of UV-screening CDOM in high latitude waters (cf. Palen et al., 2002), and 2) their life cycle characteristics (phenology - higher UV-B doses during the breeding season at higher latitudes) (Merilä et al., 2000). There is considerable variation between amphibian strains and species in UV tolerance; for example a latitudinal comparison in northern Sweden found that R. temporaria embryos were relatively tolerant of UV-B, with no clear latitudinal differences (Pahkala et al., 2002). The positive and negative effects of climate change on Arctic habitats (e.g., duration of ice-free water conditions, extent of wetlands) are likely to have much greater impacts on amphibians than UV exposure.

### 7.6.4 Impacts on Physical/Chemical Attributes

#### 7.6.4.1 Rivers and Streams

The large arctic rivers are relatively protected from UV exposure given their high CDOM contents (Gibson et al., 2000). On the other hand UV may be important for photochemical loss of carbon from these systems. There is evidence that the duration of ice free conditions has increased for example in the Mackenzie River, Canada (Magnuson et al., 2000) and the River Tornio, Finland. The resultant increased exposure may favour increased annual rates of UV-degradation of riverine DOC, with possible impacts on the inshore coastal waters that receive these inputs.

#### 7.6.4.2 Lakes, Ponds and Wetlands

In addition to low CDOM concentrations and the resultant deep UVR penetration, many arctic freshwaters are shallow systems. The mean measured depth for > 900 lakes in northern Finland was less than 5 m (Blom et al., 1998), and about 5 m for 31 lakes in the arctic region of Tuktoyaktuk (Northwest Territories; Pienitz and Smol, 1993) and 46 lakes of Ellesmere Island (Nunavut; Hamilton et al., 1993). As a consequence, all functional groups, including the benthos, are often exposed to UV radiation throughout the entire water column. In
addition, many aquatic species stay in the offshore pelagic zone. Even species that are more benthic or littoral are protected minimally by macrophytes, as arctic waters, especially those in barren catchments, often contain little aquatic vegetation.

Changes in exposure of these northern ecosystems are amplified by the low CDOM concentrations. Most have concentrations of DOC below the 4 mg DOC L\(^{-1}\), the threshold below which there are marked changes in UV penetration through the water column, and also the ratio of wavebands controlling the damage-repair balance, with only minor changes in CDOM (Laurion et al., 1997).

First impacts will be associated with the loss of permanent ice covers in the far northern lakes - this appears to have already recently taken place in the Canadian High Arctic (Belzile et al., 2002a). These effects will be amplified by prolongation of open-water conditions in the lakes and ponds. However the other physical changes in these environments (e.g., wind-induced mixing) are likely to have greater perturbation effects than those associated with increased UV exposure. Although increases in CDOM will mitigate the effects of increased UV, decreases in PAR will hamper photosynthesis. Furthermore increased turbidity associated with permafrost melting may further reduce the exposure of organisms to damaging UV radiation (for turbidity effects on UV, see Belzile et al., 2002b).

The photochemical effects of UV may also influence the toxicity of contaminants (also see Section 7.7 below). Mercury is the principal toxic chemical of concern in the Arctic and elsewhere. Methyl mercury (MeHg) is the most toxic form and the only form that biomagnifies in food chains. It was recently shown that: 1) UVR exposure photoreduces divalent mercury (Hg\(^{2+}\); the soluble form in lakes) to elemental mercury (Hg\(^{0}\); the form that can volatilize from lakes; Amyot et al., 1997); 2) UVR can also influence photooxidation (the conversion Hg\(^{0}\) to Hg\(^{2+}\); Lalonde et al., 2001); 3) The formation of MeHg in arctic wetlands is very temperature sensitive; 4) UVR photodegrades MeHg; and 5) Most of the mercury in recently fallen snow moves back to the atmosphere within a few days exposure to solar radiation (Lalonde et al., 2004). Not only is photochemical reduction of mercury important in the Arctic but microbial reduction and oxidation may also occur as shown previously in temperate lake waters. Microbial oxidation is turned on by a hydrogen peroxide dependant enzyme no doubt triggered by the activity of photochemical production of hydrogen peroxide (Scully et al., 1997). The interactions of UVR, temperature and pH can alter mercury mobilization and speciation and regulate the levels of mercury on organisms at the base of the food web. Photochemical events during spring may be especially sensitive to rising UV-B levels. Large quantities of mercury are photochemically oxidized and precipitate out of the Arctic atmosphere at first light each spring resulting in a rapid rise in mercury concentrations in snow; diel variations in these atmospheric Hg-depletion events correlate with fluctuations in UV-B irradiance (Lindberg et al., 2002). Increasing spring levels of UV radiation through stratospheric ozone depletion would probably enhance this so-called ‘mercury sunrise’ phenomenon.
Wetlands and peatlands are rich in CDOM and the aquatic biota are therefore well protected. Early loss of snow and ice, however, may increase exposure during a critical growth phase. Photochemical processes may be especially active in these shallow waters, and this mechanism of loss may accelerate with warming (snow cover loss) and ozone depletion.

7.6.5 Impacts on Biotic Attributes

Mild increases in UV could stimulate biological processes via photochemical release of low molecular weight organic carbon substrates and nutrients. More severe increases will cause damage and or a shift towards tolerant species with a potential loss of diversity or other unique ecosystem attributes (see Box 7.13).

Box 7.13. UV Effects from Molecules to Ecosystems

7.6.5.1. Rivers and Streams

Benthic mats and films are a common feature of high latitude streams as well as many ponds and lakes, and wetlands and are often dominated by cyanobacteria, especially the N₂-fixing genus *Nostoc* and filamentous species of the order Oscillatoriales (Vincent, 2000). These communities commonly occur in shallow water systems where UV exposure is likely to be high. Ultraviolet radiation is known to have a broad range of deleterious effects on benthic cyanobacteria including on their pigment content, nitrogenase activity, photosynthesis and respiration (Vincent and Quesada, 1994; Garcia-Pichel and Castenholz, 2000). Much of the literature, however, is based on experiments that have been conducted under unrealistically high UV dosages provided by artificial lamps, and many of the effects are likely to be much less apparent or absent in natural ecosystems, even under conditions of severe ozone depletion (Vincent and Neale, 2000). Periphyton and benthic invertebrates are well protected given their avoidance and sunscreen capacities. Zooplankton and phytoplankton communities are well developed in large arctic rivers (e.g., Rae and Vincent, 1998a), however they are generally protected by high CDOM concentrations in these waters.

7.6.5.2. Lakes, Ponds and Wetlands

In the Arctic, lake organisms have to cope with low nutrients conditions/low food availability; low temperatures and short growing seasons (3-5 months). The UV damage-repair balance may be especially sensitive to features of the arctic freshwater environment. Most of these ecosystems are oligotrophic and the phytoplankton is therefore commonly limited by nutrient supply (Bergeron and Vincent, 1997) in addition to low temperatures (Rae and Vincent, 1998a). As a result, the photosynthetic rates per unit biomass tend to be extremely low, even by comparison with other low temperature systems such as sea ice, polar oceans and low temperature cultures (Markager *et al*., 1999). Because of the low temperatures and low nutrients, photosynthetic rates of phytoplankton are extremely low in Canadian high-arctic lakes (usually less than 1.5 µg C µg Chl a⁻¹ h⁻¹) and phytoplankton perform very poorly under high light regimes (Kalff and Welch, 1974; Rigler, 1978; Perin, 2003). There have been few explicit tests of the effect of temperature on UV damage of planktonic systems (Rae and Vincent, 1998a). However, since enzymatic processes are temperature-dependent (whereas damage induction is not), the slow metabolic rates of northern phytoplankton are likely to
have a direct effect on the net stress imposed by UV exposure by reducing all cellular processes including the rate of repair of photochemical damage. In the Antarctic Ocean, for example, low temperatures drastically reduce repair to the extent that algal cells failed to show any photosynthetic recovery for at least five hours after UV exposure (Neale et al., 1998). The low nutrient conditions that characterize northern lakes may further compound this effect by reducing the availability of elemental resources for building enzyme systems involved in the functioning of the cell, including the repair of UV-damage, and may also limit the investment in photoprotective mechanisms. Moreover, the lower temperatures likely reduce the affinity of the phytoplankton cells for nutrient uptake by membrane transport processes (Nedwell, 2000), thereby increasing nutrient limitation.

The paleo-record has also provided insights into the possible effects of past climate change on UV exposure on aquatic ecosystems. For instance, analyses of fossil diatom assemblages in northern and alpine lake sediments have indicated that variations in underwater UV irradiance during the Holocene had major impacts on algal community structure and productivity (Pienitz and Vincent, 2000; Leavitt et al., 1997). Paleo-optical studies from subarctic lakes have revealed large fluctuations in biologically-damaging, underwater UV irradiance over the last 6000 years. These variations were accompanied by pronounced shifts in algal species composition and changes in the balance between benthic and pelagic primary producers (Pienitz and Vincent, 2000). Similar effects have been observed in low-CDOM mountain lakes (Vinnebrooke and Leavitt, 1999).

There are only a few studies of temperature-dependent UV damage to zooplankton (Borgeraas and Hessen, 2000). In general, it is assumed that low temperatures would slow down the UV damage repair mechanisms such as DNA (Deoxyribose Nucleic Acid) repair and detoxification of reactive oxygen species. However, contrary to expectations, Borgeraas and Hessen (2000) found that reduced temperatures increased survival among UV-irradiated Daphnia. They argued that although repair mechanisms are slower in the cold, UV-triggered activation processes (such as reactive oxygen species metabolism and lipid peroxidation) also slow down with decreasing temperature, thereby increasing Daphnia survival.

At ambient levels, UV-B can contribute up to 43% of the photoinhibition of photosystem II function in phytoplankton populations of Canadian high-arctic lakes as measured by both \textit{in vivo} and DCMU (dichlorophenyldimethyl urea)-enhanced fluorescence as well as decreasing (up to 40%) phytoplankton productivity rates near the water surface (Perin, 1994). The smallest size fraction i.e., picoplankton (0.2 –2 µm) usually represents more than 50% of total phytoplankton productivity in high-arctic lakes (Perin, 1994). Oligotrophic conditions tend to select for small cells with a high surface-to-volume ratio that favours nutrient transport at low substrate concentrations. Small cells are known to be especially sensitive to UV because they have a high illuminated surface to volume ratios, little self-shading and small effectiveness of screening pigments (Karentz et al., 1991; Raven, 1998). Even the production of UV-sunscreens is unlikely to confer much protection given the short pathlength in these cells (Garcia-Pichel, 1994), and studies on a variety of organisms have shown that larger cells are favoured under UV exposure (Karentz et al., 1991). The size-dependence of UV effects on photosynthesis was evaluated in sub-arctic lakes in a series of short-term photosynthetic experiments. These assays showed that in contrast to expectation the smaller cells were more
resistant to UVR than larger cells (Laurion and Vincent, 1998). This smaller cell fraction was dominated by cyanobacteria, a group known to have a broad range of effective UV-protective mechanisms (Vincent, 2000). Kaczmarska et al. (2000) also found low UV susceptibility of a picocyanobacteria-dominated phytoplankton assemblage from a clear lake in southern Canada. On the other hand, short-term experiments on several high-arctic lakes showed that the relative contribution of picoplankton (0.2 – 2 µm) to phytoplankton production generally decreased with UV-B exposure while the larger cells (> 20 µm) were more UV-B tolerant and their contribution to productivity usually increased after UV-B exposure. Assays on arctic lakes at Spitsbergen also indicated a greater sensitivity of the picocyanobacteria relative to larger colonial species to UV-B exposure (Van Donk et al., 2000). A study by Boelen et al. (2001) showed for the marine tropical plankton that UV-B-induced DNA damage was not significantly different between two size classes (0.2 - 0.8 µm and 0.8 – 10 µm). Given the variability in results between studies, other aspects such as species-specific sensitivity, repair capacities or cell morphology might be more important than cell size (Boelen et al., 2001).

The level of photoinhibition by UVR in phytoplankton can be modified by many factors that influence the extent of exposure within the water column. For instance, vertical mixing can affect the time and duration of phytoplankton to UV exposure and diminish or aggrivate projected inhibition of photosynthesis done under simulated conditions (continuous UVR exposures). In a well-mixed water column, the planktonic community can seek refuge from UV-B and photorepair in the deeper portion. However, the formation of near-surface thermoclines caused by bright solar irradiance, calm winds and solar heating of the surface water can retain the phytoplankton under high irradiances for longer periods of times (Milot-Roy and Vincent, 1994) and result in UVR damages that can exceed what can be repaired (Xenopoulos et al., 2000). During the spring and summer months in the Arctic, the climatic conditions (e.g., clouds, rain, snow, fog and wind) that change tremendously between days in arctic regions can also affect the amount of UVR exposure as well as the ratios of UVR to longer wavelengths reaching the earth’s surface. In the coastal areas of northern Norway, variation in cloudiness was demonstrated to influence the UVR levels. The relative amount of UV-A and UV-B to PAR increased during periods of heavy cloud cover (Eilertsen and Holm-Hansen, 2000) because radiation is reflected and returned from clouds (Madronich et al., 1995).

Ultraviolet may impair the transfer of carbon from the microbial food web to higher trophic levels, including zooplankton and fish. However, increased photochemical activity associated with UV radiation also has the potential to stimulate some heterotrophic species by causing the breakdown of high molecular weight organic compounds into a more available form (Wetzel et al., 1995; Lindell et al., 1996; Reche et al., 1998; Bertilsson et al., 1999) that can then be taken up for bacterial and protist growth. A study using large enclosures in a high-arctic lake with high levels of dissolved organic compounds showed that after long-term exposure to enhanced UV-B, the heterotrophic bacterial production and zooplankton density increased a little, which may have resulted from an increase in nutrients availability caused by photodegradation of organic compounds and the stimulation of heterotrophic pathways (Perin, 2003).

Some wetland biota such as amphibians are known to be highly sensitive to UVR, although sensitivity varies greatly among populations, and other factors such as climate effects on
habitat extent may have much greater impacts on northern species (see Section 7.6.3). A variety of complex responses have been observed to date on wetland plants. For example, UV-B effects on the growth of high latitude mosses appear to be a function of water supply as well as species. Field irradiation (15% increased UV-B) of *Sphagnum fuscum* caused a 20% inhibition of growth, however growth of the moss species was stimulated by up to 31% by the enhanced UV-B. This stimulatory effect, however, ceased or was reversed under conditions of reduced water supply (Gehrke *et al.*, 1996). Further information on UV effects on these semi-aquatic ecosystems is given in Chapter 4.

### 7.7. GLOBAL CHANGE - CONTAMINANTS

During the past 50 years, persistent organic pollutants (POPs), metals and radionuclides have been widely distributed into northern freshwater ecosystems through long-range atmospheric transport (Macdonald *et al.*, 2000). Within some catchments, deposition from the atmosphere may be augmented locally by industry or agriculture (AMAP, 1998) or bio-transport (de Wit *et al.*, 2003; Ewald *et al.*, 1998; Zhang *et al.*, 2001). Contaminant pathways, transfers and exchanges in freshwater systems are illustrated in Figure 7.19. Briefly discussed here is how projected global change might alter these pathways, focusing especially on POPs and Hg because they have the greatest potential for climate-related change in risk to freshwater ecosystems (Macdonald *et al.*, 2003a,b).

Figure 7.19. Contaminant pathways, transfers and exchanges in freshwater systems: land-atmosphere-water interactions (adapted from AMAP, 1998)

#### 7.7.1 Contaminant Pathways and Arctic Freshwater Ecosystems

There are two components of long-range transport pathways: transport to arctic freshwater catchments, and processes within the catchments (Figure 7.20). Transports and transfers within each of these two components of the pathways can be altered by climate change manifested in such things as wind fields, precipitation (amount, timing, form), snow cover, permafrost, extreme events, UV exposure, the hydrological cycle, ice cover, the organic carbon cycle and food webs, and may result in enhanced bioaccumulation of contaminants (e.g., Box 7.14).

Figure 7.20. A schematic diagram highlighting the processes involved in transporting POPs to the Arctic and depositing them into terrestrial ecosystems. Transport, deposition, and exchange can occur anywhere along the transport pathway. Contaminants can also be transported within aquatic and terrestrial food chains. Climate change can alter the physical couplings between the systems, for example by changing rain or snowfall patterns, or alter the biological couplings by changing trophic structure or migratory pathways ($K_{AW}$ is the air/water partition coefficient, $K_p$ - particle/air, $K_{OA}$ - octanol/air, $K_{OW}$ - octanol/water, $K_{AS}$ – air/snow; VP is vapor pressure, $k_{deg}$ - degradation coefficient).
Box 7.14. Temperature Induced Metal Accumulation and Stress Responses in Fish from Canadian Arctic Lakes

Before describing specifically how global change may alter contaminant pathways, it is important to understand how contaminants become concentrated in the environment. Macdonald et al. (2002) suggest that there are two distinct concentrating processes, which they term solvent switching and solvent depletion. Solvent switching can, for example, lead spontaneously to concentration amplification of hexachlorocyclohexanes (HCHs) in water because HCH partitions strongly out of air (Li et al., 2002), or high concentrations of PCBs in phytoplankton due to strong partitioning out of water and into lipids (Mackay, 2001). Solvent depletion involves a reduction in the mass of solvent in which the contaminant is held, a process that can lead to fugacity amplification – that is, POPs concentrations exceeding thermodynamic equilibrium with the surrounding media. Examples include inefficient fat transfers in aquatic food webs (i.e., biomagnification, Kidd et al., 1995c), the loss of organic carbon in settling particles or during sediment diagenesis (Jeremiason et al., 1998; Larsson et al., 1998), the decrease of snow surface area as crystals become more compact during aging or the entire loss of snow surface during melting (Macdonald et al., 2002; Wania, 1998) or cryoconcentration during the formation of ice (Macdonald et al., 2003b) (Figure 7.21). Many of the consequences of climate change for the solvent-switching processes are relatively easy to project and model because the effect of temperature on partition coefficients is known. For example, contaminants that presently exhibit saturation in arctic surface waters, warming will generally lead to net gas evasion (Harner, 1997) and the ocean will become a net source of those contaminants to the atmosphere. McKone et al. (1996) concluded that, with warming, the risk hexachlorobenzene (HCB) presents to aquatic biota will likely decrease slightly because HCB will partition less into water (McKone et al., 1996). The solvent-depleting processes, however, provide a much greater challenge to projection and have not yet been incorporated realistically into models.

Figure 7.21. In the illustrated solvent-depleting processes, POPs are concentrated beyond thermodynamic equilibrium through the removal of solvent by organic carbon metabolism in (a) aquatic and (b) terrestrial carbon cycles, by (c) inefficient lipid transfer in aquatic food webs, by (d) exclusion into a dwindling layer of water during the growth of ice, by (e) the loss of snow surfaces during aging or melting, by (f) the loss of surface area through condensation of fog into water droplets or onto surfaces and (g) through loss of lipid pools during periods of starvation.

7.7.2 Persistent Organic Pollutants in Arctic Catchments

Arctic lakes are likely to provide sensitive sentinels of change in their freeze, melt and hydrological cycles and, as a consequence, in their organic-carbon cycles. As discussed in more detail in sections above and related chapters, changes that are probable to occur through projected warming are: reduction in the thermal contrast between winter and spring; reduction in duration of snowmelt (later freeze-up, earlier melting); reduction in ice formation; increased annual precipitation; melt out of permafrost producing a deeper active layer, enhanced erosion of soil, mobilization of organic carbon and reduction in pond areas through
drainage; more frequent extreme events; change in the catchment vegetation toward leaf-bearing plants; change in availability of nutrients; warming of lakes and; increase in the frequency of wild fires (e.g., Hinzman et al., 2003; Schindler, 1997; Schindler et al., 1996a; Schindler et al., 1997; Vörösmarty et al., 2001). For some lakes, permafrost degradation together with reduced ice cover may result in enhanced nutrient and organic carbon loadings and higher productivity. On the other hand, if dry summer conditions produce extensive fires, affected lakes may receive reduced spring melt, fewer nutrients from the catchment and reductions in productivity (Schindler et al., 1996a) not to mention higher burdens of combustion PAHs.

Most arctic lakes receive their contaminant burdens atmospherically with the catchment acting as a receptor through snow, rain and dry deposition especially during winter, and a conveyor through snow and ice melt and runoff in spring (e.g., see Larsson et al., 1998; Macdonald et al., 2000). The following describes the stages from contaminant release to its final emergence in top freshwater predators (Figure 7.20), noting especially those components of the pathway likely to be altered through climate change.

Upon release, contaminants are transported through the atmosphere either as gases or adsorbed onto particles. During atmospheric transport, washout and air-surface exchange remove some of the contaminant to the surface where it may become permanently sequestered or re-volatilized through, for example, seasonal heating cycles, eventually arriving in the Arctic through a number of ‘hops’ (Barrie et al., 1998). Accordingly, POPs undergo a hemispheric-scale chromatographing with surfaces (soil, water, vegetation) providing the stationary phase and the atmosphere, the moving phase. Global warming will generally accelerate this cycling. Processes that are effective at capturing contaminants into arctic drainage basins (e.g., strong partitioning onto particles, into precipitation, into vegetation) are also effective at removing contaminants during transport. For example, Li et al., (2002) suggest that air-water partitioning alone restricts the entry of _-HCH into the Arctic by removing it to surfaces through rain and air-sea exchange. In the case of _-HCH, and in the case of contaminants that partition strongly onto particles (e.g., many PAHs, DDT (C_{14}H_{9}Cl_{5}) and highly chlorinated PCBs), change in rainfall patterns (amount and location) will alter the efficiency of transport to arctic locations and capture within the Arctic. Heavy metals provide an instructive example that will likewise apply to many of the POPs. Presently, <20% of particulate metal entering the Arctic is captured there (Akeredolu et al., 1994). Since the ACIA 5-model AOGCM simulations (Chapter 4) confirm that the Arctic will become a ‘wetter’ place (Manabe et al., 1992; Serreze et al., 2000), the capture for particulates and contaminants that partition strongly into water are likely to significantly increase by a factor that could more than offset efforts to reduce global emissions.

Because much of the contaminant delivery to the Arctic occurs during late winter as ‘arctic haze’ or as ‘brown snow’ events (Hileman, 1983; Welch et al., 1991), it is clear that sequestering by snow is an important process. Hence, careful consideration must be given to any changes in arctic snow conditions. Newly-formed snow has a large surface area (as much as 0.4 m\(^2\)/g, Hoff et al., 1998) that scavenges both particulate and gaseous POPs, eventually sequestering them into the snowpack (Gregor, 1990). Precipitation form (snow, rain, fog) is therefore important and, considering the seasonal modulation in atmospheric concentrations of contaminants (Heintzenberg, 1989; Hung et al., 2001; Macdonald et al., 2000), so is
timing. For example, snowfall during a period of arctic haze would be much more important for transferring contaminants to ground than at other times of the year.

As snow ages or melts, it depletes its surface thereby removing the solvent that captured the POPs (see, for example: Wania, 1997). Macdonald et al. (2002) estimated that this process could lead to fugacity amplification of ~2,000 times that of the air – clearly an enormous thermodynamic forcing. Depending on the exact circumstances under which snow loses its surface area, the POPs will be vaporized back to the air or partitioned into particles, soil, vegetation or the meltwater. Changes in the frequency and timing of snowfall or unusual events like freezing rain, or the rate and timing of snowmelt, have the potential to effect large changes in the proportion of POPs that enter the Arctic’s hydrological cycle.

Terrestrial organic carbon in soils and vegetation has a large capacity to store many POPs (Simonich and Hites, 1994), with PCBs, DDT, HCH and chlorobenzines figuring prominently (de Wit et al., 2003). Wania and McLachlan (2001) have shown that forests “pump” OCs from the atmosphere into foliage and thence to a long-term reservoir in soils. Accordingly, increased proportions of leaf-bearing plants in arctic catchments will enhance this ‘pump’. Increased metabolism of soil organic carbon due to temperature increase, change in soil moisture or reduced snow cover will force POPs associated with soil organic carbon to redistribute, probably into groundwater or meltwater.

Climate variation has the ability to archive contaminants in perennial snow and ice or in soils and vegetation during periods of cold climate (years to decades). This archive may then release stored contaminants during a period of warming and, although this process may not be sustainable, it could produce episodes of high contaminant loadings into water (Blais et al., 1998; Blais et al., 2001). During permafrost destruction a shift toward dendritic drainage patterns (e.g., see McNamara et al., 1999) will allow a more complete transport of contaminants into ponds and lakes and possibly also re-mobilize contaminants archived in soils. Simultaneously, reduced pond areas due to drainage channels in permafrost (Hinzman et al., 2003) will likely enhance contaminant transport into remaining surface water.

After POPs enter the hydrological cycle by the above set of transfers, a proportion of them will be stored in lakes and lake sediments. Evidence from a limited number of studies (Diamond et al., 2003; Helm et al., 2002; Macdonald et al., 2000) suggests that meltwater currently enters arctic lakes when they are thermally stratified beneath an ice cover. Therefore, much of the annual snowmelt traverses under the ice to exit at the outflow carrying with it its contaminant burden; that is, arctic lakes are not efficient at capturing POPs entering via streamflow. It is probable that many of the previously described climate-change induced changes to freshwater systems (such as reduced ice cover, increased mixing and primary production, and increased loading of organic carbon and sediment from the contributing catchments) will also enhance contaminant capture in lakes (e.g., see Hinzman et al., 2003).

Because most arctic lakes tend to be oligotrophic, only a small proportion of POPs is transported by vertical flux of organic particles and buried in sediments (e.g., Diamond et al., 2003; Muir et al., 1996; Stern and Evans, 2003). A second solvent-depletion process occurs due to organic carbon metabolism during particle settling and within bottom sediments (Figure 7.21a). The loss of organic carbon can provide exceptionally strong thermodynamic forcing to drive the POPs back off solid phases and into sediment porewater where they may then diffuse into bottom waters or partition into benthos (Gobas and MacLean, 2003;
Jeremiason *et al.*, 1994; Macdonald *et al.*, 2002). Increase in the vigor of the organic carbon cycle (e.g., increased primary production, organic carbon loadings and microbial activity) will enhance this thermodynamic pump. Cryoconcentration (Figure 7.21d) could work together with organic carbon metabolism in sediments during winter to produce exceptionally high concentrations of POPs in bottom water. Although relatively poorly studied, contaminants are believed to be excluded from ice as it grows. For shallow water that freezes nearly to the bottom, dissolved contaminants may be forced into a very small volume of remaining water and the resultant high water concentrations will promote partitioning into remaining organic material including sediment surfaces, benthos, plankton and larger animals. As noted earlier, such under-ice zones are often a critical winter refuge for biota (e.g., Hammar, 1989).

Intuitively, a general reduction in the depth of ice formed during warmer winters should reduce cryoconcentration. However, cryoconcentration interacts with water level, and this will likely decrease during permafrost destruction (Hinzman *et al.*, 2003).

The transfer of lipid-soluble POPs upward in aquatic foodwebs provides one of the most important routes of exposure to apex feeders including humans. In this solvent-depleting process, much of the lipid is metabolized at each trophic level while the organochlorines are retained with the result that the higher trophic levels exhibit OC (Organic Carbon)-biomagnification factors in their lipids of 3 to 100, and a net bioaccumulation from the water by as much as $10^7$ to $10^9$ (Braune *et al.*, 1999; Kidd *et al.*, 1995a; Kidd *et al.*, 1995c; Macdonald *et al.*, 2003b). Change in aquatic trophic structure – either through alteration of the number of foodweb steps or the size distribution of predatory fish – will likewise change contaminant burdens. With warming, widely distributed shifts in zoogeographic distributions have the potential to impact every step in freshwater food chains (Hinzman *et al.*, 2003; Schindler, 1997).

There are several other ways that global change can alter contaminant pathways in arctic aquatic ecosystems. As noted in Section 7.7.4.5, recent evidence suggests that salmon migrations undergo large, climate-related variation (Finney *et al.*, 2002; Finney *et al.*, 2000) and that Pacific salmon may respond to change by invading arctic rivers (Babaluk *et al.*, 2000). Given that these salmon biomagnify and bioaccumulate contaminants in the Pacific Ocean, they provide important vectors to transport contaminants into particular arctic catchments. For selected lakes, fish may supply more POPs than atmospheric deposition (Ewald *et al.*, 1998). Similarly, bird migrations that may change in location and intensity have the potential to concentrate, transport and focus contaminants on particular catchments (Braune *et al.*, 1999; de Wit *et al.*, 2003; Hinzman *et al.*, 2003). For instance, detailed work by Norwegian researchers on Lake Ellasjoen found that seabirds can serve as important biological pathways carrying contaminants (in this case POPs) from marine to freshwater environments (AMAP, 2002). Climate change or human intervention may also lead to the introduction of exotic species to the Arctic. Although probably not a risk to arctic lakes, the zebra mussel’s invasion into the Great Lakes provides an instructive example of just how disruptive an exotic species can be to organic carbon and POPs cycles (Morrison *et al.*, 1998; Morrison *et al.*, 2000; Whittle *et al.*, 2000).

Changes within arctic catchments that cause apex feeders (e.g., humans, bears, mink, birds) to switch their diet from aquatic to terrestrial foodwebs or vice versa have a large potential to alter contaminant exposure. Whereas arctic aquatic foodwebs exhibit endemic contamination from biomagnifying chemicals, land-based foodwebs are among the world’s cleanest (de Wit
Dietary changes can be forced by fluctuations in the populations of prey species or by changes in access to the species due to early melt or permafrost degradation (see, for example: Fast and Berkes, 1998; Riedlinger, 2001).

As conditions more suitable for domestic crops develop, agriculture or silviculture within arctic drainage basins, and associated use of chemicals, may expand. Demographic shifts and population increases in northern regions could then lead to increased local release of contaminants. South of the Arctic, global warming and alteration of hydrological cycles will probably result in insect and other pest outbreaks (e.g., West Nile virus or Malaria) provoking the re-introduction of banned pesticides (Harnar, 1997). Finally, contaminants in dumps or sumps presently contained by permafrost may be released through permafrost degradation (Anonymous, 2001).

For PAHs, there are likely to be increased fluxes due to erosion of peat-rich soils (Yunker et al., 1993) or drying trends leading to increase in wild fires. Associated increases in PAH flux will likely have a greater impact on small rivers which presently receive most of their PAH from combustion sources (Yunker et al., 2002).

7.7.3 Mercury in Arctic Catchments

Mercury exhibits a natural global cycle which has been enhanced by human activities such as coal burning, soft and ferrous metal smelting, cement production and municipal waste with the consequence that two to three times as much mercury is now cycling through the atmosphere and surface waters than was before the rise of industry (Lamborg et al., 2002). Pacyna and Pacyna (2001) estimated worldwide emissions of mercury from human activities in 1995 to be 2235 tonnes with fossil fuel consumption contributing over half of that. This value may be compared to 2500 tonnes estimated for natural emissions (Nriagu, 1989). The largest emitter of mercury from fossil fuel consumption is China (495 tonnes in 1995), which is directly upwind from the Bering Sea, Alaska and the western Arctic. By comparison, Russia released about 54 tonnes in 1995. Many of the concentrating processes discussed for POPs (Figure 7.21) apply equally to mercury. However, atmospheric mercury depletion events (MDEs) after polar sunrise, provide a unique, climate-sensitive pathway to deposit mercury into arctic catchments (Figure 7.22, Lindberg et al., 2002; Lu et al., 2001; Macdonald et al., 2000; Schroeder et al., 1998; Steffen et al., 2003). The process requires snow surfaces, solar radiation and the presence of sea salts (bromides and chlorides). Although MDEs are initiated over the ocean, and especially over the marginal seas where halides are more available from frost flowers or first-year ice (Shepson et al., 2003), atmospheric advection can then deposit reactive mercury in arctic catchments (Steffen et al., 2003). As was the case for POPs, mercury can be transferred and concentrated during snow aging and snow melting, such that a large pulse of mercury is released to terrestrial and freshwater environments during spring melt (e.g., see Stanley et al., 2002; Diamond et al., 2003; AMAP, 2004). The mercury deposited through the MDE mechanism has been shown to be in a form that can readily be taken up by biota (Scott, 2001). Once mercury enters the hydrological cycle, it can be concentrated and transferred through the carbon cycle and foodwebs, both of which are vulnerable to change and, finally, the efficiency of arctic lakes for capturing mercury can be altered by changing the timing of freshet, ice melt and productivity (Braune et al., 1999; Diamond et al., 2003; Kidd et al., 1995b; Macdonald et al., 2000).
Figure 7.22. A schematic diagram illustrating the production of particulate and reactive gaseous mercury over the ocean after polar sunrise (right side) and the advection of reactive and bioavailable forms of mercury into catchments where it deposits. After deposition, the mercury enters lakes through meltwater and is then subject to reduction and methylation processes. Methyl mercury is the most toxic form. See Folt et al. (2002) for discussion of mercury accumulation at higher trophic levels.

Once mercury has been deposited into arctic catchments, a number of processes may lead to elevated concentrations in old, predatory fish (Table 7.3). The coupling between deposition of mercury to surfaces and its entry into lakes will likely be enhanced by projected changes in the hydrological and organic carbon cycles (Diamond et al., 2003; Stanley et al., 2002). Apex feeders will be most vulnerable to any change in the mercury cycle considering that bio-accumulation and bio-magnification factors are 1000 – 3000 (Atwell et al., 1998; Kidd et al., 1995b; Muir et al., 1999). Because methyl mercury presents a far greater health hazard than inorganic or elemental mercury, the process of methylation is a crucial point upon which climate change can operate. Wetlands and wetland sediments are net producers of methyl mercury (Driscoll et al., 1998; Suchanek et al., 2000) and mercury observed in fish from small lakes appears to correlate with the amount of watershed occupied by wetlands (Greenfield et al., 2001). Flooding of terrestrial landscape has the well-known consequence of releasing mercury from submerged soils (Bodaly et al., 1984). Therefore, alteration of wetland distribution or area as a result of permafrost melting in the Arctic (see Section 7.4.4.4) has the potential to release mercury – all the more serious if arctic soils contain an inventory of contaminant mercury accumulated during the past century or two.

Table 7.3. Environmental factors affecting mercury concentration in aquatic top predators.

7.8. KEY FINDINGS, SCIENCE GAPS and RECOMMENDATIONS

In general, changes in climate and UV in the Arctic will have far-reaching impacts, affecting aquatic species of varying trophic levels, the physical environment that makes up their habitat and the chemical properties of that environment, and the processes that act on and within freshwater ecosystems. Interactions of climatic variables such as temperature and precipitation with freshwater ecosystems are highly complex and can be propagated through the ecosystem in ways that are not readily projectable. This reduces our ability to accurately forecast specific effects of climate and ultraviolet-radiation change upon freshwater systems. This is particularly the case when dealing with threshold responses, i.e., those that produce step-wise and/or non-linear effects. Our ability to forecast is further hampered by our poor understanding of arctic freshwater systems and their basic interrelationships with climatic and other environmental variables, as well as by a paucity of long-term freshwater monitoring sites and integrated hydroecological research programs in the Arctic.
A significant amount of our understanding of potential impacts is based on historical analogues, i.e., historical evidence from past periods of climate change, as well as from a limited number of more recent studies of ecosystem response to environmental variability. Paleo-reconstructions indicate that during the most recent period of climatic warming, which followed the Little Ice Age, the Arctic warmed to its highest temperature observed in the past 400 years, causing glacier retreat, permafrost melt, and major shifts in freshwater ecosystems. Examples of ecosystem effects included altered water chemistry, changes in species assemblages, altered productivity, and an extended length of the growing season. Importantly, however, past natural changes in the Arctic occurred at a rate much slower than that forecasted to occur under anthropogenically-induced climate change over the next 100 years. In the past, organisms had considerable time to adapt; their responses may therefore not provide good historical analogues for what will result under much more rapid climate change. In many cases, the adaptability (i.e., adapt, acclimate or move) of organisms under rapidly changing climate conditions is largely unknown. Unfortunately, no large-scale attempts have been made to study the effects of rapid climate change on aquatic ecosystems using controlled experiments, as has been attempted for terrestrial systems (e.g., see International Tundra Experiment (ITEX) regarding tundra plant response in Chapter 6). Important knowledge, however, has been gained from field studies in areas that have recently experienced rapid changes in climate. Information about ongoing climate-change impacts are provided by results from long-term environmental monitoring and research sites in the Arctic. Example case studies around the circumpolar north include: Northern Québec-Labrador, Canada (Box 7.1), Toolik Lake, Alaska (Box 7.3), Lake Saanajarvi, Finnish Lapland (Box 7.4), and Zackenberg Valley in North-East Greenland (Box 7.6).

The following sections list a number of broad-scale findings for major components of arctic freshwater ecosystems. Although it was possible within the chapter to evaluate meso-scale regional differences in, for example, timing and severity of freshet/break-up amongst large rivers, difficulties in ecological downscaling of most climatic and related hydrological changes precluded regional discrimination of variations in impacts. Hence, most of the following statements are broad-scale and not regionally specific. To indicate the probability of each impact occurring, the ACIA lexicon regarding the range of likelihood of outcome (Section 7.1.2.) has been applied (i.e., the bolded statement(s) of each bullet) to the findings. Each assigned probability ranking is a product of a multi-author scientific judgement made on the basis of knowledge synthesized from the scientific literature, including the above noted case-studies, and the interpretation of effects deduced from the ACIA 5-AOGCM simulations. The same level of likelihood of occurrence is applied to the subsequent, more detailed descriptions following each major finding.

**Ecological Impacts of Changes to Runoff, Water Levels and River-Ice Regimes**

- A probable shift to a more pluvial system with smaller and less intense freshet and ice breakup, will very likely decrease the natural disturbance regime and reduce the ability of flow systems to replenish riparian ecosystems, particularly river deltas. As rainfall becomes a more prominent component of high-latitude river-flow regimes, and as temperatures rise, freshets will be less intense and ice breakup less dramatic.
Furthermore, differential changes in streamwise climatic gradients in the large arctic rivers will produce varying responses in freshet timing and break-up severity. Decreased frequency and intensity of physical disturbance regimes will result in declined species richness and biodiversity in riverine, deltaic and riparian habitats.

- **Reduced climatic gradients along large northern rivers will likely alter ice-flooding regimes and related ecological processes.** Projected differential rates of warming across major latitudinal ranges of some large northern rivers and the corresponding reduction in the north-south, spring temperature gradient will likely reduce the frequency and magnitude of dynamic river ice break-ups and lead to more placid thermal events. Because such disturbances play a major role in maintaining habitat complexity and associated species richness and diversity, this will have significant implications to ecosystem structure and function.

- **A very probable increase in winter flows and reduced ice-cover growth will very likely increase availability of under-ice habitat.** High-latitude rivers that typically freeze to the bottom during the winter will experience increased flow in response to increasing precipitation and winter temperatures, rises in baseflow and declining ice thickness. The subsequent presence of year-round flowing water in these river channels will increase habitat availability, ensuring survival of species previously restricted by the limitation of under-ice habitat. Migration and the geographical distribution of aquatic species (e.g., fish) may also be affected.

- **A probable decrease in summer water levels of lakes and rivers will very likely affect quality and quantity of, and access to, aquatic habitats.** For areas where combinations of precipitation and evaporation lead to reductions in lake and/or river water levels, pathways for fish movement and migration will be impaired including access to critical habitat. In addition, declining water levels will affect physical and chemical processes, such as stratification, nutrient cycling and oxygen dynamics.

**Changes to biogeochemical inputs from altered terrestrial landscapes**

- **Enhanced permafrost melting will very likely increase nutrient, sediment and carbon loadings to aquatic systems.** This will very probably have a mixture of positive and negative effects on freshwater chemistry. As permafrost and peat warm and active layers deepen with rising temperatures, nutrients, sediment and organic carbon will be flushed from soil reserves and transported into aquatic systems. Increased nutrient and organic carbon loading will enhance productivity in high latitude lakes, as well as decrease UV exposure of biota. On the other hand, heavily nutrient-enriched waters (i.e., systems with enhanced sediment and organic matter loads), may result in increased light-limitation and reduced productivity.

- **An earlier phase of enhanced sediment supply will probably be detrimental to benthic fauna.** As soils warm in high-latitude permafrost landscapes and become more susceptible to erosion, surface runoff will transport larger sediment loads to lakes and rivers. Aerobes in lake and river bottom sediments will initially be threatened by oxygen-
deprivation due to higher biological oxygen demand associated with sedimentation. Larger suspended sediment loads will also negatively affect light penetration and consequently primary-production levels. Similarly, negative effects such as infilling of fish spawning beds associated with increased sediment loads are also likely in many areas.

- **Increases in DOC loading through permafrost melting and increased vegetation will very probably have both positive and negative effects. The balance will be ecosystem- or site-specific.** For example, as DOC increases, there will be reduced penetration of damaging UV radiation and a decline in photochemical processing of organic material. Alternatively, decreases in light availability (quantity and quality) will also negatively affect primary production.

*Alterations to Ponds/Wetlands*

- **Freshwater biogeochemistry will very likely be altered by changes to water budgets.** As permafrost soils in pond and wetland catchments warm, nutrient and carbon loading to these freshwater systems will rise. Nutrient and carbon enrichment will enhance nutrient cycling and productivity, and alter the generation and consumption of trace carbon-based gases.

- **The source/sink status for carbon and methane will very probably be altered.** High-latitude aquatic ecosystems function as sinks or sources of carbon and methane, depending on temperature, nutrient status and moisture levels. Initially arctic wetlands (e.g., peatlands) will act as sources of carbon as permafrost melts, soils warm, and accumulated organic matter decomposes. Decomposition rates in aquatic ecosystems will also increase with rising temperatures and increases in rates of microbial activity. Increases in wetland water levels could enhance anaerobic decay and production/release of methane.

- **Permafrost melt in ice-rich environments will very likely lead to catastrophic lake drainage; increased groundwater flux will drain others.** As permafrost soils warm, freshwater bodies will become increasingly coupled to groundwater systems and experience drawdown. Lake drawdown will result in a change in the limnology and the availability and suitability of habitat for aquatic biota. Over the long-term, aquatic habitat will be replaced with terrestrial habitat.

- **New wetlands, ponds and drainage networks will very likely develop in thermokarst areas.** Permafrost and ground ice melt in thermokarst areas will result in the formation of depressions where wetlands and ponds may form, interconnected by new drainage networks. These new freshwater systems and habitats will allow for the establishment of aquatic species of plants and animals in areas formerly dominated by terrestrial species.

- **Peatlands will probably dry due to increased evapotranspiration.** As temperatures increase at high latitudes, rates of evapotranspiration in peatlands will rise. Drying of peat soils will promote the establishment of woody vegetation species, and increase rates of peat decomposition and carbon loss.
Effects of Changing Lake-ice Cover

- **Reduced ice thickness and duration, plus changes to timing and composition, will very likely alter thermal and radiative regimes.** Rising temperatures will reduce the maximum ice thickness for lakes and increase the length of the ice-free season. Reduced lake-ice thickness will increase the availability of under-ice habitat, winter productivity and associated dissolved-oxygen concentrations. Extension of the ice-free season will increase water temperatures and lengthen the overall period of productivity.

- **A longer open-water season will very probably affect lake stratification and circulation patterns.** Earlier ice-out will lead to rapid stratification and a reduction in spring circulation. In certain types of lakes this will cause a transfer of under-ice oxygen-depleted water to the deep water of stratified lakes in the summer (i.e., lakes will not get a chance to re-aerify in the spring). A longer open-water season will result in an increase in primary production over the summer that will lead to increased oxygen consumption in deeper waters as algae decompose. Correspondingly, fish habitat will become much reduced by the combination of upper water warming and the deeper water low-oxygen conditions. As a result certain fish species (e.g., lake trout), may become severely stressed.

- **Reduced ice cover will probably have much greater effect on underwater UV exposure than the projected levels of stratospheric ozone depletion.** A major increase in UV will cause enhanced damage to organisms (biomolecular, cellular and physiological damage, and alterations to species composition). Allocations of energy and resources by aquatic biota for protection from UV will increase, likely decreasing productivity of trophic levels. Elemental fluxes will increase via photochemical pathways.

Aquatic Biota, Habitat, Ecosystem Properties and Biodiversity

- **Climate change will very likely affect the biodiversity of freshwater ecosystems across most regions of the Arctic.** The magnitude, extent and duration of the impacts/responses will be system and geographically dependent, and will produce varying outcomes, including: local/regional extinctions or species loss; genetic adaptations to new environments; and alterations to species ranges and distributions, including invasion by southern species.

- **Microbial decomposition rates will likely increase.** Rates of microbial decomposition will rise in response to increasing temperatures, and soil drying and aeration. Enhanced decomposition of organic materials will increase the availability of dissolved organic carbon and the emission of carbon dioxide, which has implications for the carbon balance of high latitude lakes and rivers and, in particular, wetlands, which are significant carbon reserves.

- **Increased production will very likely result from a greater supply of organic matter and nutrients.** Organic matter and nutrient loading of rivers, lakes and wetlands will increase as temperatures and precipitation rise. Melt of permafrost and warming of frozen
soils with rising temperature will result in the release of organic matter and nutrients from catchments. Rising temperatures will increase rates and occurrence of weathering and nutrient release. Organic matter contributions may also increase with the establishment of woody species. Primary productivity will rise, the effects of which may be translated through the food chains of aquatic systems, increasing freshwater biomass and abundance. In some instances high loading of organic matter and sediment may be photo-inhibiting and result in a decline in productivity in some lakes and ponds.

- **Shifts in invertebrate species’ ranges and community compositions will likely occur.** Temperature-limited species from more southerly latitudes will extend their geographic range northward. This will result in new invertebrate species assemblages in arctic freshwater ecosystems.

**Fishes and Fisheries**

- **Shift in species range, composition and trophic relations will very probably occur.** Southerly species will shift northward with warming of river waters, and likely compete with northern species for resources. Anadromous species may shift as oceanic patterns shift. The geographic ranges of northern or arctic species will contract in response to habitat impacts as well competition. Changes in species composition at northern latitudes will likely have a top-down effect on the composition and abundance of species at lower trophic levels. The broad whitefish, Arctic char complex and the Arctic Cisco are particularly vulnerable to displacement as they are wholly or mostly northern in their distribution. Other species of fish, such as the Arctic grayling of northern Alaska, thrive under cool and wet summer conditions, and may be less reproductively successful with warming of waters, potentially causing elimination of populations.

- **Spawning grounds for cold-water species will likely diminish.** As water temperatures rise, the geographic distribution of spawning grounds for northern species will shift northward, and likely contract. Details will be ecosystem-, species- and site-specific.

- **Increased incidence of mortality and decreased growth and productivity from disease/parasites will likely occur.** As southern species of fish migrate northward with warming river waters, they could introduce new parasites and/or diseases to which arctic fish species are not adapted, and hence have a higher risk of earlier mortality and decreased growth.

- **Subsistence, sport and commercial fisheries will possibly be negatively affected.** Changes in the species range and distribution of fish in northern lakes and rivers in response to changing habitat and the colonisation of southerly species has implications for the operation of commercial fisheries and potentially devastating effects on subsistence fishing. Changes in northern species will diminish opportunities for current fisheries on such species, calling for regulatory and managerial changes that promote sustainable populations. Subsistence fisheries may be at risk in far northern areas where vulnerable species, such as the broad whitefish, Arctic char complex and Arctic Cisco, are often the only fish species present. Fisheries will have to change to secure access, and ensure that
fishery function and duration of operation are effective, given a change in fish species and habitat. Alternatively, new opportunities to develop fisheries may occur.

Aquatic Mammals and Waterfowl

• Probable changes in habitat will likely result in altered migration routes and timing of migration. Migration of aquatic mammals and waterfowl will likely extend northward in geographic extent as more southerly ecosystems and habitats develop at higher latitudes with warming. Migration may occur earlier in the spring with the onset of high temperatures, and later in the fall if high temperatures persist. Breeding-ground suitability and access to food resources will be the primary driving forces in changes to migration patterns. As an example, wetlands are important feeding and breeding grounds for waterfowl, such as geese and ducks, in the spring. As permafrost landscapes degrade at high latitudes, the abundance of thermokarst wetlands may increase, promoting the northward migration of southerly wetland species, or increasing the abundance and diversity of current high-latitude species.

• An increased incidence of mortality and decreased growth and productivity from disease/parasites will possibly occur. As temperatures rise, southerly species of mammals and waterfowl will shift northward. These species may carry with them new diseases and/or parasites to which northerly species are not adapted, which will likely result in both an increased susceptibility to disease and parasites, and an increased result in mortality.

• Probable changes in timing of habitat availability, quality and suitability will very likely alter reproductive success. Aquatic mammals and waterfowl are highly dependent on the availability and quality of aquatic habitats for successful breeding, and in the case of waterfowl, nesting. Northerly species may have diminished reproductive success as suitable habitat either shifts northward or declines in availability and access. Northward migration of southern species may result in competitive exclusion of “northern” species for habitat and resources.

Climate-Contaminant Interactions

• Warming and increased precipitation will very likely increase contaminant capture in the Arctic. Projected increases in temperature and changes in the timing and magnitude of precipitation will affect the deposition of contaminants at high latitudes. Warming will accelerate rates of contaminant transfer. Climate scenarios currently project a “wetter” Arctic; hence, increasing the probability of wet deposition of contaminants such as heavy metals and persistent organic pollutants.

• Episodic releases of high-contaminant loadings from perennial snow and ice will very probably increase. As temperatures rise at high latitudes, snow and ice accumulated over a period of years to decades will melt, and associated stored contaminants will be released in meltwater. This will increase episodes of high-contaminant loadings into water, which may have toxic effects on aquatic organisms.
Permafrost degradation may also mobilize contaminants. The impacts of pond and lake contamination upon high-latitude freshwater bodies will be amplified by lowering of water levels.

- **Arctic lakes will very likely become more prominent contaminant sinks.** Spring melt waters and associated contaminants typically pass through thermally stratified arctic lakes without transferring their contaminant burden. Contaminant capture in lakes will increase with reduced lake-ice cover (decreased stratification), increased mixing and primary production, as well as with greater organic carbon and sediment loading. Contaminants in bottom sediments may dissociate from the solid phase with a rise in the rate of organic carbon metabolism and, along with contaminants originating from cryo-concentration, may reach increasing levels of toxicity in lake-bottom waters.

- **The nature and magnitude of contaminant transfer in the food web will probably change.** Changes in aquatic trophic structure and zoogeographic distributions will alter biomagnification of contaminants, including persistent organic pollutants and mercury, and potentially impact freshwater food webs, especially top-level predatory fish (e.g., lake trout) that are sought by all types of fisheries.

### Cumulative, Synergistic and Overarching Interactions

- **Decoupling of environmental cues used by biota will likely occur, but the significance of this to biological populations is uncertain.** Photoperiod, an ultimate biological cue, will not change, whereas water temperature, a proximate biological cue, will change. For arctic species, decoupling of environmental cues will probably have significant impacts on population processes (e.g., the reproductive success of fish, hatching/feeding success of birds, and the migratory timing and success of birds and anadromous fish may be compromised).

- **The rate and magnitude at which climate change takes place and affects aquatic systems will likely outstrip the capacity of many aquatic biota to adapt or acclimate.** Evolutionary change in long-lived organisms such as fish cannot occur at the same rate as the anticipated change in climate. Ability to acclimate and emmigrate to more suitable habitats will be limited, thus effects on some native arctic biota will be significant and detrimental. Shorter-lived organisms (e.g., freshwater invertebrates) may have a better genetic and/or phenotypic capacity to adapt, acclimate or emmigrate.

- **Climate change will likely act as a multiple stressor leading to synergistic impacts on aquatic systems.** For example, predicted increases in temperature will (a) enhance contaminant influxes to aquatic systems, and (b) independently increase susceptibility of aquatic organisms to contaminant exposure and effects. The consequences to the biota will in most cases be additive (cumulative) and multiplicative (synergistic). The total result will be higher contaminant loads and biomagnification in ecosystems.

- **Climate change as an impact will very likely act cumulatively and/or synergistically with other stressors to affect physical, chemical and biological aspects of aquatic


**ecosystems.** For example, resource exploitation (e.g., fish or bird harvesting) and climate change impacts will both negatively impact population size and structure.

### 7.8.1 Key Science Gaps Arising from the Assessment

In conducting this assessment a number of science gaps became evident. These are noted throughout the text and succinctly itemized below. Filling these gaps would greatly improve understanding of the effects of climate and UV change on arctic freshwater ecosystems. Furthermore, comprehensive monitoring programmes to outline the nature, regionality and progress of climate change and related impacts require development and rapid implementation for representative locations, aquatic ecosystems and regions throughout the Arctic. Coupling such programmes with ongoing and new research will greatly facilitate the meeting of challenges sure to result from climate change and increased UV radiation in the Arctic.

- Limited record of long-term changes in physical, chemical and biological attributes throughout the Arctic
- Circumpolar disparity of available biophysical and ecological data (e.g., extremely limited information about habitat requirements of arctic species)
- Existing data among various countries and disparate programmes has been rarely integrated in a circumpolar context
- General lack of integrated, comprehensive monitoring and research programs, at regional/national and especially circumpolar scales
- Need for standardized and networked international approaches for monitoring and research
- Paucity of representative sites for comparative analyses, either by freshwater ecosystem type (e.g., small rivers, wetlands, lakes) or by regional geography (ecozone, latitude, elevation)
- Unknown synergistic impacts of contaminants and climate change on aquatic organisms
- Limited understanding of the cumulative impacts of multiple environmental stressors on freshwater ecosystems (e.g., land use, fisheries, forestry, flow regulation and impoundment, urbanization, mining, agriculture, poleward transport of contaminants of invasive/replacement species)
- Unknown effect of extra-arctic large-river transport on freshwater systems induced by southern climate change
- Limited knowledge of UV-temperature interactions on aquatic biota
- Deficient knowledge about the linkage between structure (i.e., biodiversity) and function of arctic aquatic biota
- Elementary level of coupling among physical/chemical and biotic processes
- Lack of coupled cold regions hydro-ecological theory and related projective models

### 7.8.2 Science/Policy Implications and Recommendations

A number of the above science gaps could be addressed by the following policy/programme-related adjustments:
• Funding and mechanisms for the establishment of a coordinated network of key long-term, representative freshwater sites for comparative monitoring and assessment studies among arctic regions – e.g., establishment of a Circumpolar Arctic Aquatic Research and Monitoring Programme
• Based on the results of this synthesis, establishment of a Science Advisory Board (preferably at international level) for targeted funding of arctic freshwater research
• Security of long-term funding sources, preferably by an international cooperative programme, for integrated arctic freshwater research
• Adjustments to current northern fisheries management policies and coordination with First Nations resource use and consumption
• Establish post-secondary education programmes focused on freshwater arctic climate change issues at both intra- and extra-arctic educational institutions, preferably involving a circumpolar educational consortium
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**Appendix Table 1. Formal scientific names of arctic fishes alphabetically listed by common name used in the text and boxes.**

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*Ch07 - Freshwater Arctic Ecosystems*  
*ACIA Scientific Report*  
*External Review January 2004*  
*7–133*  
*DO NOT CIRCULATE OR CITE*
Northern Québec-Labrador in the eastern Canadian Low Arctic is a landscape dominated by lakes, wetlands and streams. Few studies have addressed the effects of recent climate change in this region, but a variety of paleolimnological studies have provided insights into long-term change.

This region comprises four terrestrial ecozones: 'taiga shield' with bands and patches of wetland forest, forest-tundra and lichen-woodland vegetation; 'southern arctic' consisting of shrub tundra; 'northern arctic' of true tundra; and a mountainous region of 'arctic cordillera' (the Torngat Mountains). There are major changes in the chemical and biological characteristics of lakes associated with the transition between these different vegetation types, notably changes in alkalinity and (especially) coloured dissolved organic matter (CDOM; see Box 7.11). Highest water colour (highest CDOM concentrations) is associated with the heavily vegetated wetland-forest catchments, while much lower values occur in lakes completely surrounded by drier lichen woodland and tundra (Figure 1). Given the broad range of effects of dissolved organic matter on high-latitude aquatic ecosystems (Vincent and Pienitz, 1996), this implies that any climate-related shift in catchment vegetation would have major impacts on the limnology of these eastern Canadian lakes.

Figure 1. Variations in CDOM (as measured by water colour, in units of relative colour (Platinum Units - Pt)) among lakes from different vegetation zones in Labrador. Each value is the mean for 7-20 lakes. Plotted from the data in Fallu et al. (2002).

In the western Canadian Subarctic, variations in climate over the last 5000 years caused large shifts in the position of the northern treeline, in turn resulting in substantial changes in water colour, the underwater light regime (including biological UV exposure) and in the relative importance of benthic versus pelagic production (as indicated by their diatom communities; MacDonald et al., 1993; Pienitz et al., 1999; Pienitz and Vincent, 2000). In contrast, the eastern Canadian Subarctic seems to have experienced relatively little change in vegetation structure over the millennial timescale, and the stable forest-tundra of northern Québec-Labrador has been referred to as 'an ecological museum' (Payette et al., 2001), in part a consequence of the extremely slow pace of northward migration and colonization by black spruce during periods of warming. Québec-Labrador also appears to be less prone to temperature change as a result of the strong arctic marine influence on this region resulting from the Hudson Strait and Labrador current outflows from the Arctic. Like much of the eastern Canadian Arctic and southern Greenland, this region has shown little change or even cooling from the mid-1960s to mid-1990s while most other sectors of the circumpolar Arctic have shown strong warming trends over the same period (Weller, 1998; Capellen and Vraae Jørgensen, 2001).

This long-term stability in climate and vegetation is also reflected in the paleolimnology of the region. Diatom assemblages in the sediment cores taken from Labrador lakes show very little change over the last 200 years while there were major shifts in community structure elsewhere in the Arctic (Laing et al., 2002). Similarly, in a lake at the northern Québec...
treeline, CDOM and other inferred limnological variables remained relatively stable over the last 3000 years; e.g., the mean inferred dissolved organic carbon concentration over this period is 5 mg L\(^{-1}\), with a coefficient of variation (SD/mean) for 107 strata of only 8% (Ponader et al., 2002.) Coastal lakes of this region have shown major changes associated with plant succession immediately after deglaciation, and isostatic uplift causing the severing of connections with the sea, but relatively constant conditions over the last 1000 years (Pienitz et al., 1991; Saulnier-Talbot and Pienitz, 2001; Saulnier-Talbot et al., 2003).

This remarkable stability at timescales of decades, hundreds of years and thousands of years suggests that northern Québec-Labrador lakes may experience less short-term climate change relative to other sectors within the circumpolar region. ACIA climate models, however, imply that these east-west differences in climate change may largely disappear by 2080 (see Chapter 4) by which time the lakes, rivers and wetlands of Northern Québec-Labrador will be subjected to the climate impacts that are well advanced in other regions.

**BOX 7.2. Thresholds of Response: Freshwater System Step Changes with the Advance Climate Change**

Some changes expected in arctic freshwaters will result in small, slow responses in the environment; other changes will exceed an environmental or ecosystem threshold and cause a dramatic switch in organisms or a change of state of the system. Thresholds may be: physical, for example, permafrost will begin a slow thaw when the yearly average air temperature rises above –2°C (J. Brown, personal communication); chemical, for example, the bottom waters of a lake may lose all oxygen when lake productivity increases or allochtonous carbon increases; or biological, for example, insect larvae frozen in the bottom of tundra ponds will die when their temperature falls below –18°C (Scholander et al., 1953). While thresholds are only a part of the whole picture of response, they are critical in the understanding and assessment of the full scope of climate change impacts.

One obvious physical threshold is the amount of heat necessary to melt the ice cover of a lake. At the northern edge of the Arctic, such as on Ellesmere Island, there are lakes that have only recently begun to have open water during the summer; other lakes are now open for more summers every decade than in the past. Sediment records of algae, in particular diatom species and chrysophyte abundance, show that in Finland and northern Canada, lakes were ice-bound for thousands of years but conditions began to change some 150 years ago. With open water, the algal community shifts from a predominance of benthic diatoms associated with a surface to planktonic forms and chrysophytes begin to occur. The link to climate change is the increase in summer air-temperatures and the earlier onset of melt. Some scientists believe that the increase in the length of the growing season may also be important in controlling algal species. Shifts in species composition at the level of primary producers will then have follow-on consequences for higher trophic levels through the alteration of food
Another physical threshold is the onset of stratification in lakes. Once lakes begin to have open water, water circulation driven by wind becomes one of the controls of biological processes. Almost all lakes have a period of total circulation of the water column immediately after the ice cover disappears. Very cold waters may continue to circulate for the entire summer so that each day algae spend a significant amount of time in deep waters where there is not enough light for growth. When a lake stratifies, that is, when only the uppermost waters circulate, then algae have better light conditions and primary production increases. The higher temperatures in the upper waters increase all biotic processes. There is a threshold, probably tied to increased primary production, when whole new trophic levels appear. For example, the sediment record from a lake in Finland shows that cladocera, a type of zooplankton, begin to appear around 150 years ago. Most lakes in the Arctic already have summer stratification so this threshold applies mostly to lakes in the far north.

When air temperatures increase above an average yearly air temperature of −2°C, permafrost will begin to thaw. When the upper layers of ice-rich permafrost thaw, the soil is disturbed; lakes may drain, and ponds form in depressions. In eastern Siberia, newly thawed soils that are rich in organic matter slump into lakes. Microbial action depletes the oxygen in the lake allowing the bacteria to produce so much methane that the lakes and ponds are a significant source of this greenhouse gas, and enhance an important feedback to the climate system. This threshold affects lakes in the more southern regions of the Arctic.

It is well known that lakes surrounded by shrubs and trees contain much more coloured dissolved organic matter (CDOM; Box 7.11) than lakes in the tundra zone. The CDOM comes from the organic matter produced by plants and modified by soil microbes. The CDOM strongly absorbs light, so much so that the algae of the upper waters become light limited and the primary production is reduced. This may also be accompanied by a shift towards increasing primary production by attached algae in the shallow inshore zone relative to offshore planktonic production. The threshold described here is related to the treeline, often demarcated by patches rather than a continuous zone of vegetation. As air temperatures increase over the next century these patches will grow, fuse and move further northwards. As a result, the impact will take the form of a slowly moving band of affected lakes. Extreme polar desert catchments in the High Arctic may experience their first arrival of higher plants, and a sudden increase in the transfer of organic materials from land to water.

As lakes warm, some species or populations of species may reach a temperature threshold for survival. This threshold is linked to increases in the rate of metabolism and growth. For example, a bioenergetic model based on laboratory studies predicts that the young-of-the-year lake trout in northern Alaska will not obtain enough food for growth if their metabolic rate rises in response to a temperature increase of a degree or so. Evidence from field studies of a stream fish, the Arctic grayling, also suggest that a population at the northern limit of the distribution may not survive an increase of only a few degrees in the summer temperatures. Both these examples are of fish species at the northern limit of their distribution. It is likely
that other types of widely-distributed fish, such as whitefish and Arctic char, will be less affected unless new competing species arrive from southerly regions.

A different type of threshold involves a shift in the ecological behavior of migratory fish such as the Arctic char. In many arctic rivers, char migrate to the sea for some months every year; the productive marine food web allows them to grow to a large size. Many of these sea-run fish are harvested in the rivers by local fishermen each time the fish congregate and migrate. It is predicted that when the freshwaters become more productive, migrations to the sea will decrease and may eventually cease, thus the char will remain in freshwater rivers and lakes for the entire year. These freshwaters are much less productive than the marine ecosystems; therefore adult freshwater char will be much smaller than migrating char. As a result of climate change, a valuable food resource for arctic peoples will change with respect to sizes available, and may also be lost.

**BOX 7.3. Ecological Transitions in Toolik Lake, Alaska, in the Face of Changing Climate and Catchment Characteristics**

Toolik Lake (depth$_{max}$ 25 m, 1.5 km$^2$) lies in the foothills north of the Brooks Range, Alaska, at 68ºN, 149ºW. The river study site is the headwaters of the Kuparuk River. Project and publications details are given at [http://ecosystems.mbl.edu/ARC/](http://ecosystems.mbl.edu/ARC/). Average annual temperature of the area is -9ºC, and precipitation nears ~300-400 mm. Permafrost is 200 m thick with an active layer up to 46 cm deep. Acidic tussock tundra covers the hill slopes. A small area of wetlands in the study site is dominated by sedges, while the dry uplands have a cover of lichens and heaths. Lakes and streams are ultra-oligotrophic, and are ice-free from July to September with strong summer stratification and oxygen saturation. Stream flow is nival, and carries dissolved organic carbon (DOC)-enriched spring runoff from peaty catchments to Toolik Lake. Primary producers in Toolik Lake consist of 136 species of phytoplankton, dominated by chrysophytes with dinoflagellates and cryptophytes, as well as diatoms. Annual primary productivity averages 12 g C m$^{-2}$ and is co-limited by nitrogen and phosphorus. Zooplankton are sparse. Fish species are lake trout, Arctic grayling, round whitefish, burbot and slimy sculpin, and feed on benthic chironomid larvae and snails, the latter of which control epilithic algae in the lake. DOC drives microbial productivity (5-8 g C m$^{-2}$ y$^{-1}$).

The average air temperature of northern Alaska has warmed in the past 30 years by nearly 2ºC. Warming of Alaskan waters may have a detrimental effect on adult grayling, which grow best during cool and wet summers and which may actually lose weight during warm and dry summers (Deegan et al., 1999). Some 20 km from Toolik (Hobbie et al., 2003), permafrost has warmed as well, increasing from –5.5ºC to –4.5ºC between 1991 and 2000 at a depth of 20 m. This warming of frozen soils likely accounts for recent increases in stream- and lake-water alkalinity.

Climate has been shown to have a significant control on the vegetation of the site, which in turn has affected aquatic resources for productivity. Runoff from melting soils within Toolik
Lake’s catchment have affected lake productivity in a number of ways. DOC from excretion, leaching, and decomposition of plants in the catchment, along with associated humics, have been found to reduce photosynthesis in the lake and absorbs 99% of the UV-B light in the upper 20 cm (Morris et al., 1995). In spring, meltwaters for the lake contain up to 3 mM DOC and abundant nutrients. Upon reaching the lake, meltwater flows cause a two-week high in bacterial productivity (~50% of the annual total) beneath the lake ice cover (Figure 1). This peak in production, which takes place at 2°C illustrates that bacteria are carbon and energy limited, not temperature limited, and as such, will be indirectly affected by climate change. Phytoplankton biomass and primary production peak soon after the ice leaves the lake, and as solar radiation peaks. The lake stratifies so rapidly that no spring turnover occurs, causing oxygen-depleted bottom waters to persist over summer. This effect will be amplified with higher temperatures, and will reduce habitat available to fish species such as lake trout that require these areas.

Figure 1. Bacterial productivity and chlorophyll over the spring and summer in Toolik Lake (adapted from Crump et al., 2003).

Future increase in average air temperature and precipitation will further affect freshwater systems at Toolik. Lakes will have early ice-out and higher water temperatures. Stream waters will warm as well, and runoff will increase, though evapotranspiration may offset increased precipitation. As waters warm, primary production in lakes and rivers at the site will increase, though most species of aquatic plants and animals will not change during the climate changes that have been predicted. Lake and river productivity will also increase in response to changes in the catchment, in particular, warming of permafrost soils and increased weathering and release of nutrients. Increased precipitation will also affect nutrient supply to freshwater systems. This will likely result in increased decomposition of organic matter in soils (Clein et al., 2000), formation of inorganic nitrogen compounds, and increased loss of nitrogen from land to water. The shift in terrestrial vegetation to predominantly shrubs will cause greater DOC and humics loading of streams and lakes, and a reduction in ultraviolet-B (UV-B) penetration. Increases in organic matter will, however, likely have detrimental effects on the stream population of Arctic grayling at this site, resulting in their disappearance in response to high oxygen depletion. Lake trout, on the other hand, will survive but their habitat will be slightly reduced by the combination of reduced deep water oxygen and warmer surface waters.

**BOX 7.4. Lake Ice Duration and Water Column Stratification: Lake Saanajärvi, Finnish Lapland**

Lake Saanajärvi (depth_{max} 24 m, area 0.7 km^2; 69°05’N, 20°87’E) is the key Finnish site in the European-wide research projects “Mountain Lake Research” (MOLAR) and “European Mountain Lake Ecosystems: Regionalization, Diagnostics and Socio-economic Evaluation” (EMERGE). Lake Saanajärvi has been intensively monitored since 1996. Project details are given at [http://www.helsinki.fi/science/ecru/](http://www.helsinki.fi/science/ecru/). The data presented here have been published in
several papers, such as Sorvari and Korhola, 1998, Sorvari et al., 2000, Rautio et al., 2000, Sorvari et al., 2002, Korhola et al., 2002a. Mean annual temperature is ~2.6°C, and precipitation ca. 400 mm. The catchment area is mostly covered by bare rocks and alpine vegetation. Lake Saanajärvi is a dimictic, ultra-oligotrophic, clear-water lake. The lake is ice-free for nearly four months of the year, with highly oxygenated waters, and is strongly stratified for two months after spring overturn. Phytoplankton biomass and densities are low (Forsström, 2000; Rautio et al., 2000; Forsström, unpublished data), consisting predominantly of chrysophytes and diatoms. Bacterial biomass is low as well, and zooplankters are not very abundant. Freshwater shrimp (Gammarus lacustris) are common and form an important food source for fish, which include Arctic char and brown trout (Salmo trutta m. lacustris).

Changes in water temperature and stratification of Lake Saanajärvi have been associated with climate changes in Finnish Lapland over the past 200 years (Alexandersson and Eriksson, 1989; Tuomenvirta and Heino, 1996; Sorvari et al., 2002). Mean annual air temperatures in Finnish Lapland, as in much of the Arctic, rose 1 to 2°C following the Little Ice Age. During this period of warming, diatom communities changed from benthic-periphytic to pelagic, cladocera increased in abundance, and chrysophytes became less numerous. These changes have been shown to be associated with increased rates of organic matter accumulation and increased concentrations of algal pigments during the climatic warming (Sorvari and Korhola, 1998; Korhola et al., 2002a; Sorvari et al., 2002; Figure 1). After a period of cooling from the 1950s to the 1970s, air temperatures in the Arctic continued to rise. More recently, inter-annual variability in temperatures has been shown to account for changes in the thermal gradient and mixing of Lake Saanajärvi surface waters. For example, Lake Saanajärvi normally stratifies two weeks after ice break-up, and retains a clear, steep thermocline at 10-12 m over summer. In 2001, this summer stratification was broken after a period of slight cooling, after which the lake was only weakly stratified. In 2002, on the other hand, spring and summer temperatures were extremely warm. Spring ice break-up was early and waters warmed quickly, resulting in a very sharp thermocline that was stable during the entire summer stratification period.

Figure 1. Comparison of the diatom assemblage changes with the regional and Arctic-wide temperature anomalies. Principal components analysis (PCA) primary axis scores derived from the correlation matrices of the diatom percentage counts of the five study sites (A). Spring (MAM) temperature anomalies (°C) for NW Finnish Lapland, smoothed using a 10-year low-pass filter (B). Annual air-temperature trend (°C) for NW Finnish Lapland, smoothed using a 10-year low-pass filter (C). Standardized proxy Arctic-wide summer-weighted annual temperature, plotted as sigma units (D) (from Overpeck et al., 1997).

Future warming of climate will, therefore, affect the thermal structure of lakes in Finnish Lapland, and throughout the Arctic, which will have dramatic consequences to lake biota. Rising mean annual temperatures will surely influence the length of the summer stratification, and the stability and depth of the thermocline in Finnish lakes. As such, many of the presently isothermal lakes may become dimictic with climate warming. As well, the prolonged thermal stratification that may accompany climate warming may lead to lower oxygen concentrations...
and increased phosphorus concentrations in the hypolimnion, benefiting nutrient-limited primary production. As spring temperatures rise and the ice-free period extends, not only may thermal stratification stabilize, but production of many high latitude lakes may peak twice rather than once during the open-water season (e.g., Lepistö, 1999; Pechlaner, 1971; Hinder et al., 1999; Medina-Sánchez et al., 1999; Lotter and Bigler, 2000; Rautio et al., 2000; Catalan et al., 2002). On a broader scale, changes to lake stratification and water mixing may affect species composition (e.g., diatoms) (Agbeti et al., 1997).

BOX 7.5. Freshwater and Diadromous Fishes of the Arctic

The Fishes – There are approximately 99 species in 48 genera of freshwater and diadromous (i.e., anadromous or catadromous forms moving between fresh and marine waters) fishes present in the ACIA area. These represent 17 families (Table 1). Ninety-nine species is a conservative estimate because some groups (e.g., chars and whitefishes) in fact contain complexes of incompletely resolved species. Many species are also represented by local polymorphic forms that biologically act as species (e.g., four morphs of Arctic char in Thingvallavatn, Iceland). The most speciose family is the Salmonidae with more than 33 species present, most of which are important in various fisheries. The next most speciose family is the Cyprinidae with 23 species, few of which are fished generally, although some may be locally. All remaining families have six or fewer species, and five families are represented in the Arctic by a single species. These generalities hold true for individual ACIA Regions as well (Table 1). All the families represented in the Arctic are also present in lower latitude temperate and sub-temperate regions. Most have a southern centre of distribution as do many of their associated species (Berra, 2001). Individual species may be confined to the Arctic, or may penetrate northwards to varying degrees.

Table 1. Freshwater/diadromous fish present in the Arctic and ACIA Regions.

Regional Differences – Substantial differences in the number of species present are apparent between the ACIA Regions (Table 1). Region III (essentially unglaciated Beringia and the western Canadian Arctic) contains 58 nominate taxa, followed by Region I (Arctic Europe and Russia) with 38, and Regions II (Siberia) and IV (eastern North America) are about equal at 29 and 32 respectively. This likely represents a combination of historical effects (e.g., glacial events, postglaciation re-colonization routes and access), as well as present-day influences such as local climate, diversity of habitats, and ecological processes such as competition and predation. Arctic char is the only species that is truly Holarctic, being present on all landmasses in all Regions, occurring the farthest north to the extremes of land distribution (~84°N), and also exhibiting the widest latitudinal range (about 40 degrees) of all true arctic species (i.e., south in suitable lakes to ~45°N latitude). A few additional species are distributed almost completely across the Holarctic but are absent from one or more areas within an ACIA Region – e.g., burbot ~75% of a complete circumpolar distribution, northern pike ~85%, lake/European/Siberian whitefish ~85%, and, ninespine stickleback ~90%. With the exception of the stickleback, all are fished extensively where they occur (Table 1) and represent the mainstays of food fisheries by northern peoples as well as supporting significant commercial fisheries in most areas. These species are often the only ones present in extremely...
remote areas, inland areas, and higher latitude areas, thus are vital for local fisheries. Where they are regionally present, many other species are exploited to a greater or lesser degree.

**Fish Distribution in Relation to Climate and Climate Change** – The ACIA area includes high, low, and sub-arctic areas defined by climate, geography and physical characteristics. Additionally, many of the areas included (e.g., southern Alaska, northern Scandinavia and Russia) are significantly influenced by nearby southern maritime environments and/or large north-flowing rivers. Moreover, this area includes many different climatological zones. Thus, given that the distribution of many freshwater and anadromous fish species is controlled or significantly influenced either directly or indirectly by climate variables (particularly temperature), it follows that primary associations of fish distribution with climate variables will be important. Three types of distribution of arctic fishes can be defined, and within some, further sub-division based upon the nature of distribution can be made. Within the generalities discussed below, the impacts of climate change will definitely be species- and ecosystem-specific, thus the following should be viewed as the range of possibilities only. Also, although thermal regimes are emphasized below the influence of other climate parameters may be equally or more important to specific species in particular areas.

1) Species of the Arctic Guild have their centre of distribution in the Arctic with the southern limits defined by, for example, high temperatures and associated ecological factors including competition from southern fish species. Fish such as broad whitefish, or Arctic cisco, and many char taxa are examples of such taxa. The pervasive and ultimate impacts of climate change upon such species are likely to be negative. These generally will be exhibited as a: range contraction northwards driven by thermal warming that exceeds preferences or tolerances; by related habitat changes; and/or by increased competition, predation or disease resulting from southern taxa extending their range northwards. These may also be preceded by local reductions in growth, productivity and perhaps abundance. Many of these effects may be driven by or exacerbated by shifts in life-history of some species (e.g., from anadromy to freshwater only). Other than conceptual summaries, no detailed research has been conducted to outline such impacts for most fish species of this guild.

2) Second, fish that are southern-arctic in distribution are northern members of the Coldwater Guild. This group includes species such as the lake/European/Siberian whitefish complex and lake trout. Two distributional subtypes can be differentiated – a) those exhibiting a wide thermal tolerance as implied, for example, by a wide latitudinal distribution often extending well outside the Arctic (i.e., eurythermal) with lake whitefish being a good example; and, b) those exhibiting a narrow thermal tolerance (i.e., stenothermal) implied by occupying very narrow microhabitats (e.g., lake trout occupy deep lakes below thermoclines in the south but a much wider variety of coldwater habitats in the north) and/or narrow latitudinal distribution centered in northern areas (e.g., pond smelt). The overall impacts of arctic climate change on these groups of species will likely be quite different. Thus, eurythermal species likely have the capacity for reasonably quick adaptation to changing climate and, all other things being equal, may exhibit increases in growth, reproduction and overall productivity. Such species also may extend the northern edge of their distribution further northwards where this is presently limited thermally, but this is likely to be a secondary, relatively small response. Alternatively, stenothermal coldwater species will likely experience generally negative
impacts. Lake trout in northern lakes, for example, may be forced into smaller volumes of suitable summer habitat below deeper lake thermoclines and may have to enter such areas earlier in the season than at present. Concomitant follow-on impacts on such species will generally be negative as well. Northern-centered coldwater species will likely experience the same general impacts as described above for wholly arctic species to some degree, that is, reductions in productivity characters, increased stress, local extirpation, and/or range contractions. As for the arctic-guild species described above, little or no detailed research assessing impacts on northern coldwater-guild fishes has been conducted to date.

3) The third type of distribution includes Coolwater Guild species (such as perches) that have southern, temperate centres of distribution but which range northwards to occur in the southern areas of the Arctic as defined herein. As above, these species also can be differentiated into eurythermal and stenothermal species. Thus, the perches have a wide latitudinal range and occupy a number of ecological situations extending outside temperate regions, and hence can be described as eurythermal. Northward range extensions of ~2-8 degrees of latitude are predicted for yellow perch in North America under a +4°C climate warming scenario (Figure 1; Shuter and Post, 1990). Shuter and Post (1990) found that the linkage between perch distribution and climate was indirect, that is, the first-order linkage was direct dependency of overwinter survival (and related size at the end of the first summer of life) with food supply, which limited growth. The food supply, in turn, was dependent upon climate parameters. Alternatively, many northern minnows (e.g., northern redbelly dace in North America) and some coregonines (e.g., vendace in Europe) are likely stenothermal as implied by their limited latitudinal range and habitat associations. Range contraction along southern boundaries is likely for these. Because of their stenothermal tolerances, however, their northward extension is not likely to be as dramatic as that described for perch. Northward penetration by such species will be promoted to some degree by the presence of many of these species in the large northward-flowing arctic rivers such as the Lena, Mackenzie, Ob, and Yenisey. The associated effects of heat transfer by such systems will facilitate northward colonization by these species as well as eurythermal species also present in the systems. Knowledge of ecological associations with climate parameters and research quantifying potential impacts of climate change for coolwater-guild species, although inadequate overall, generally tends to be more comprehensive than for the previous two guilds. However, it is often focused upon southern populations. Hence, its applicability to arctic populations of the species may be limited.

Figure 1. The North American distributional limit of yellow perch: present (south-solid black line), and predicted in the future under a 4°C warming scenario (north – black line). Northward displacements (arrows and P’s) are based upon overwintering survival (adapted from Shuter and Post, 1990). The solid red line portrays the approximate present-day 10°C July isotherm; the blue line portrays the approximate southern boundary of ACIA’s definition of the Arctic.

Summary – Freshwater and diadromous fishes of the Arctic exhibit high diversity in their associations with various climate parameters. This, together with the more complex indirect effects climate may have upon their habitats, implies a wide range of responses to climate change. Other than logical extrapolations, most responses to climate change are impossible to
quantify due to the absence of basic biological information for most arctic fish species and the incomplete understanding of overall associations with present-day climate parameters.

BOX 7.6. Productivity of North-East Greenlandic Lakes: Species Composition and Abundance with Rising Temperatures

The Danish-Greenlandic “Biobasis” monitoring programme initiated in 1997 includes two lakes located in the Zackenberg Valley, North-East Greenland (74° N). The monitoring at Zackenberg is expected to continue for at least 50 years. The area is situated in a high-arctic, permafrost area in North-East Greenland National Park. More information about the area and the monitoring programme can be found in Meltofte and Thing (1997) and Christoffersen and Jeppesen (2000), as well as at [http://biobasis.dmu.dk](http://biobasis.dmu.dk). The two lakes, Sommerfuglesø and Langemandsso, are 1.7 and 1.1 ha in size, with maximum depths of 1.8 m and 6.1 m, respectively. Lakes and ponds of the area are covered by ice for most of the year, except from the end of July to the beginning of September. Most water bodies likely freeze solid during the late winter and spring. Primary producers in these nutrient-poor lakes are dinophytes, chlorophytes and diatoms. Zooplankton grazers are sparse, consisting of *Daphnia*, copepods, and protozoans. Benthic invertebrates include *Lepidurus*. There are no fish in Sommerfuglesø. Dwarf Arctic char in Langemandsso prey on *Daphnia*, therefore, copepods and rotifers dominate zooplankton populations in this lake.

Plants and animals in Sommerfuglesø and Langemandsso are active prior to ice-melt, hence phytoplankton biomass becomes substantial as incoming solar radiation increases (Rigler, 1978). Primary productivity slows, however, as nutrients are consumed. As such, phytoplankton density varies annually with nutrient abundance. For example, in warmer years, nutrient concentrations and, as such, productivity are higher due to increased loading of nutrients and humus from catchments as the active layers melts.

Monitoring of planktonic species in the two lakes over 1999 (a year of late ice melt; low water temperatures) and 2001 (a year of early ice melt; high water temperatures) has shown that not only does biomass and abundance change with temperature, but species composition changes as well (Figure 1). In 1999, when water temperatures were lower, Chrysophytes and dinophytes represented 93% of total phytoplankton abundance in Sommerfuglesø, while dinophytes dominated phytoplankton (89%) in the deeper and colder Langemandsso. In 2001, when ice broke early and water temperatures were higher, phytoplankton in both lakes was completely dominated by chrysophytes (94-95% of total phytoplankton abundance). Total phytoplankton abundance was approximately twice as high in 2001, when nutrient levels were higher as well. Zooplankton abundance, in turn, was 2.5 times higher in 2001 than in 1999 in both lakes (Figure 2), likely in response to greater phytoplankton abundance. *Daphnia* and copepods were more abundant in 2001, while rotifers were less abundant than in 1999, perhaps in response to competition for food resources.

Figure 1. Composition of phytoplankton (average of three samples per year) in Langemandsso and Sommerfuglesø in 1999 and 2001. In both years total biovolume is twice as high in
Langemandssø as in Sommerfuglesø. Chrysophyte dominance was considerably lower in both lakes when ice melt-out was later (1999) rather than earlier (2001).

Figure 2. The relationship between biomass (dry weight) of different zooplankton groups in mid-August 1999 and 2001 in Langemandssø and Sommerfuglesø. Total zooplankton biomass was ca. 2.5 higher in 2001 in both lakes and approximately twice as high in Sommerfuglesø as in Langemandssø in both years. Only few Daphnia occur in Langemandssø where they are preyed upon by Arctic char – in contrast, there are more small-sized cladocerans (chydroids) and rotifers.

A more maritime climate has been predicted to occur in North-East Greenland. Based on the 5 years of monitoring at Zackenberg thus far, increasing temperature and precipitation are predicted to have major impacts on physico-chemical and biological variables in the lakes. As snowfall increases, ice cover duration will be prolonged, shortening the growing season and productivity, and as such, possibly lowering food availability to the top predator of arctic lakes, the Arctic char. Greater runoff will increase nutrient loading and primary productivity, which may result in oxygen depletion and winter fish kill. Thus, one expectation of climate change will be the extirpation of local fish populations in shallow lakes in similar ecological situations. Increased particulate loading will likely limit light penetration for photosynthesis. Increased humus input with spring melt will also limit light penetration, and in doing so reduce UV damage to biota.

BOX 7.7. Effects of Environmental Changes on Life-History and Population Characteristics of Labrador Arctic Char

Present-day relationships between environmental and biological parameters must be understood to provide the foundation for assessing future climate change effects on fish populations. The general lack of such understanding for most arctic fishes currently precludes in depth development of comprehensive and accurate qualitative scenarios of impact, and limits quantification of effects under those scenarios. Development of such understanding requires significant long-term data which are relatively sparse for most arctic fish; a circumstance that demands redressing. A notable exception is the availability of data for Arctic char. The distribution and life-history patterns of Arctic char are complex, and few attempts have been made to relate fluctuations in abundance, catch rates and stock characteristics to environmental variables such as temperature and precipitation. Table 1 lists associations between biology and environmental variability in environmental parameters for Arctic char from northern Labrador, Canada (Region II).

Table 1. Nain Arctic char – Environmental Associations

Long-term (1977-1997) monitoring of the char fishery at Nain, Labrador (56° 32' N, 61° 41' W) has produced data both on anadromous fish and environmental variables, that have been applied in assessment of long-term variability in catch biometrics (Power et al., 2000). Climate variability in particular years and seasons was found to have effects at critical life-history stages, and to affect average stock age, weight and length characteristics, thus determining the
dynamics of exploited Arctic char populations several years later as well as the eventual spawning success (Power et al., 2000). Aspects of these and the likely effects on the population are also summarized in Table 1.

Mean age-at-catch and weight of Arctic char from the Nain fishery declined significantly, with a lag of four years, in response to high summer precipitation. This change with high precipitation is likely due to fluctuations in river flow and nutrient dynamics during the initial migration of Arctic char to nearshore marine areas. First-time migrants tend to stay in the nearshore areas (Bouillion and Dempson, 1989; Berg, 1995) and are most likely to be immediately affected by changes in nutrient inputs resulting from variability in river flow. High precipitation years increase nutrient and particulate organic carbon exports from river and lake catchments (Meyer and Likens, 1979; Allan, 1995), and as such increase nutrient inputs to near-shore marine feeding areas, hence likely increasing productivity of all trophic levels.

The significance of increased winter precipitation is related to events occurring in the first critical winter of life for char. Heavier, more frequent snowfalls in Labrador maintain ice cover in an isothermal state and limit ice thickness (Gerard, 1990). Deeper snowpack maintains taliks, or unfrozen areas, in lake and river beds (Prowse, 1990; Allan, 1995), improving winter refugia conducive to fish survival (Power and Barton, 1987; Power et al., 1999; Allan, 1995).

The possible effects of temperature on Arctic char are complex. Mean fish length increased with rising summer temperatures and the persistence of optimal growth temperatures (12-16 °C) over a longer period of time (Johnson, 1980; Baker, 1983). High spring temperatures and accelerated ice break-up, however, can have negative effects on populations migrating with ice breakup (Nilssen et al., 1997). In the Fraser River (Labrador), breakup typically occurs in late April or early May (Dempson and Green, 1985) and would be well advanced, as would seaward migration, in years experiencing above normal May temperatures. Although temperature rises can advance preparatory adaptations for marine residency (i.e., smoltification), they also result in a more rapid loss of salinity tolerances and a shortening of the period for successful downstream migration (McCormick et al., 1997). Rapid increases in temperatures are likely to impinge on the development of hypo-osmoregulatory capabilities in migrants and decrease growth due to the increased energetic costs of osmoregulatory stress, increase the probability of death during migratory transitions to the sea, and decrease average growth through a reduction in average marine residency.

Several conclusions arise from this study:
• long-term and comprehensive biological and environmental datasets are critical to assess and monitor climate change impacts on fish populations.
• for long-lived arctic fish, the effects of particular environmental conditions are often lagged by many years, which cascades to fishery production and management.
• effects of the environment are manifested in the fish population in the same way that other effects such as exploitation are (e.g., in terms of individual growth that translates into survival, fitness, reproduction and ultimately into population dynamic parameters such as abundance), thus distinguishing specific effects of climate change from other proximate drivers may be problematic.
particular environmental effects tended to reinforce each other with respect to their effect on the fish; although generally positive in this study, effects from several environmental parameters could presumably act antagonistically resulting in no net effect, or could synergistically act in a negative fashion to substantially impact the population.

**BOX 7.8. Approaches to Predicting Climate Change Effects on Arctic Fish Populations.**

Uncertainty in projections for temperature, hydrology, precipitation and their associated cascade consequences for vegetation and nutrient patterns in arctic aquatic ecosystems makes predicting the specific effects of climate change for a fish species difficult. To date fisheries literature has suggested three approaches to this problem: [1] use of regionally specific climate projections that can be coupled directly to knowledge of the species’ physiological limits; [2] use of empirical relationships relating local climate (weather) to measurements of species’ or stock dynamics (e.g., abundance, size, growth rate, fecundity) and comparison of population success temporally (e.g., from a period of climatically variable years) or spatially (e.g., locales representing the extremes of variation in weather conditions such as latitudinal clines); and, [3] use of current distributional data and known or inferred thermal preferences to shift ecological residency zones into geographic positions that reflect probable future climate regimes.

1. **Physiological Approaches to Predicting Climate Change Effects**

Temperature is typically regarded as a factor affecting individual physiological and behavioural processes, but it is also a key characteristic of an organism's habitat. Hutchinson (1957) considered an animal's niche to be defined by the complete range of environmental variables to which it must be adapted for survival. At the fringes of the distributional range, abiotic niche axes are likely to exert a greater influence over the physiological responses (e.g., growth) of the species to its environment than elsewhere. Growth rates and population dynamics of fish living at the limits of their distribution will usually differ from those of the same species living in the optimum temperature range (Elliott, 1994). For example, in studies of northern populations of yellow perch, Power and van den Heuvel (1999) noted that although heterogeneous thermal environments allow fish opportunities to compensate for temperature fluctuations by selecting for preferred temperatures, such opportunities will be limited in the portion of the geographic range where temperatures do not typically exceed those that define the optimum scope for growth. Accordingly, unless future temperatures increase above the point where the maximum scope for growth is realized, northern fish will be limited in their abilities to select for optimal growth temperatures and, as a consequence, will more strongly reflect the influence of temperature on growth than southern populations. This also suggests that analogues of climate warming derived from lower latitude populations will not be accurate guides to probable climate warming impacts on sub-arctic and arctic fishes. Nevertheless, the effects of climate change in the north will include faster, temperature-driven growth and maturation rates, reductions in winter mortality and expanded habitat availability for many species (Regier *et al.*, 1996). However, somatic gains could be offset by increased maintenance ration demands to support temperature-induced increases in metabolism. Ration demands for lacustrine fish are likely to be met as warming occurs since
warm water lakes are generally more productive than cold water lakes (Regier et al., 1996). Basic knowledge of temperature-growth relationships and temperature-dependent energy demands is lacking for many key arctic fish species, thus accurate physiologically based predictions of climate change impacts cannot be made.

2. Empirical Approaches to Predicting Climate Change Effects
Empirical approaches to predicting the possible effects of climate change on fish populations can be sub-divided into two groups. The first group examines the integrated responses of a population measured by yield or production over time. The second group examines the population characteristics spatially and uses inherent variability across latitude to make inferences about how they will change under climate warming scenarios.

Temporal Yield/Production Predictions - There are numerous models for predicting freshwater fish production in lakes (see Leach et al., 1987). Models disagree about the lake characteristics that most significantly influence productivity. Comparative studies based on lakes covering a wide range of geographic areas and trophic status, however, have suggested that fish production in oligotrophic to hyper-eutrophic lakes of moderate depth is better correlated with primary production than the morphoedaphic index (Downing et al., 1989). Limitations surrounding such modelling centre on the deficiencies in fish distribution data and knowledge of the interactive effects of climate-induced changes in key environmental variables (Minns and Moore, 1992). Together with limited fishery databases covering long enough time frames, these limitations in most cases preclude this approach for predicting productivity changes for arctic populations.

Spatial Latitudinal Predictions - Organism life-history characteristics often vary with latitude because of predictable changes in important environmental factors (e.g., Leggett and Carscadden, 1978; L’Abée-Lund et al., 1989; Fleming and Gross, 1990; Rutherford et al., 1999). Among the most important environmental factors which may vary with latitude is temperature, which for fish populations is known to influence growth rate (Wotton, 1990; Elliott, 1994) and thereby indirectly affect life-history attributes that determine population dynamics (e.g., longevity, age-at-maturity and fecundity). Among salmonids, temperature has been shown to influence movement and migration (Jonsson, 1991), habitat occupancy (Paul and Post, 2001); migration timing (Berg and Berg, 1989), smolting (Power, 1981; McCormick et al., 1998); growth rate (Brett et al., 1969; Jensen et al., 2000), age-at-maturity (Power, 1981; Scarneccia, 1984; L’Abée-Lund et al., 1989), fecundity (Fleming and Gross, 1990) and the proportion of repeat spawners (Leggett and Carscadden, 1978). Many studies have demonstrated latitudinally separated disparate populations of the same species with distinctive metabolic rates, thermal tolerances, egg development rates and spawning temperature requirements consistent with a compensatory adaptation to maximize growth rates at a given temperature (Levinton, 1983). Animals living in low temperature, high latitude locales would, therefore, be expected to compensate by increasing metabolic and growth rates at a given temperature relative to animals in high temperature, low latitude locales. There are two generalizations which may be made from studies on latitudinal variation in growth rates: [1] high latitude poikilotherm populations often attain larger maximum body size than conspecifics at lower latitudes, and [2] although lower temperatures often reduce activity and constrain individuals to grow more slowly, they compensate by
accelerating growth rate or larval development time relative to low latitude conspecifics when raised at identical temperatures. Although adaptation to low temperature probably entails a form of compensation involving relative growth acceleration of high latitude forms at low temperature, the shift in metabolism increases metabolic costs at higher temperatures, leaving cold-adapted forms with an energetic disadvantage in the higher temperature environments (Levinton, 1983) likely to result from with climate change. Accordingly, it is likely that fish populations are locally adapted for maximum growth rate and that they sacrifice metabolic efficiency at temperatures rarely experienced to maximize growth efficiency at temperatures that are commonly experienced. This suggests that possible effects of climate warming for northern fish may include decreased growth efficiency and associated declines in length-dependent reproductive success. Thus particular responses to climate warming are likely population specific, a consequence that greatly complicates our predictive ability and accuracy over large areas of the Arctic.

3. Distributional Approaches to Predicting Climate Change Effects

Many attempts to predict the biological responses to climate change rely on the climate envelope approach whereby the current species’ distributions are mapped with respect to key climate variables (e.g., temperature, precipitation) and the distributions shifted in accordance with climate change predictions (e.g., Minns and Moore, 1992). For example, Shuter and Post (1990) have argued that weight-specific basal metabolism increases as size decreases with no associated increase in energy storage capacity, resulting in smaller fish being less tolerant of the starvation conditions typically associated with over-wintering. Size-dependent starvation endurance requires young-of-the-year fish complete a minimum amount of growth during their first season of life. Growth opportunity, however, is increasingly restricted on a south-north gradient and the constraint has been demonstrated to effectively explain the northern distributional limit of yellow perch in central and western North America (see Box 7.5), European perch in Eurasia, and the smallmouth bass in central North America. If winter starvation does form the basis for the geographic distributions of many fishes (e.g., 11 families and 25 genera of fish within Canadian waters (Shuter and Post, 1990)), then climate-induced changes in growing season length, and consequent reductions in the period of winter starvation, will be associated with significant range extensions of many species. Species already well established within low arctic watersheds are likely to show the greatest potential for range extensions. Associated changes in species assemblages will shift patterns of energy flow in many aquatic systems. For example, increasing the number of cyprinids (e.g., emerald shiner, northern lake chub) in northern waters that consume plankton may divert energy from existing planktivores (e.g., ciscoes) reducing the latter’s population abundances. In turn, top-predators (e.g., lake trout) will have altered diets and the changes in the ratio of pelagic and benthic sources of carbon in piscivore diets will, in turn, alter Hg tissue concentrations (Power et al., 2002; Section 7.7), thus linking general climate change impacts with local contaminant loadings.

The dominant result of simulations used to predict the impact of climate change on the distribution and thermal habitat of fish in north temperate lakes is an increase in available warmer habitat. Temperature influences on thermal habitat use are strong enough that Christie and Regier (1988) were able to develop measures of thermal habitat volume during the summer period by weighting the amount of lake bottom area and pelagic volume with water
temperatures within species’ optimal thermal niches. Thermal habitat volume explained variations in total sustained yield of four commercially important species: lake trout, lake whitefish, walleye, and northern pike.

Although distributional changes provide a convenient and easy means of assessing possible range extensions, the flaw in the approach is that the distribution of species often reflects the influence of interactions with other species (Paine, 1966; Davis et al., 1998) or historical effects (Tonn, 1990). Predictions based on changes in single-species climate envelopes will, therefore, be misleading if interactions between species are not appropriately considered when predictions are made. Microcosm experiments on simple assemblages showed that as the spatial distribution of interdependent populations changed as a result of temperature increases, the pattern and intensity of dispersal also changed. Thus, warming can produce unexpected changes of range and abundance in situations incorporating dispersal and species interaction (e.g., competition and predator-prey dynamics). Feedbacks between species are likely to be even more complex than simple experiments allow (Davis et al., 1998); e.g., distributions of stream-resident salmonids are not simple functions of either temperature or altitude (Fausch, 1989). Accordingly, whenever dispersal and interactions operate in natural populations, climate warming is likely to provoke similar phenomena and predictions based on extrapolation of the climate envelope may lead to serious errors (Davis et al., 1998).

In theory, the temperature signal should be strong enough to project long-term changes in the availability of fish thermal habitat and use available empirical relationships to project sustainable yields. However, until the results of such research attempts are available for arctic fishes, year-to-year variability and latitudinal differences in climate will provide the best tests for hypotheses about the importance and effects of climate change on arctic fish species (Magnuson and DeStasio, 1997).

**BOX 7.9. Predicting the Effects of Climate Change on a Stock-specific Basis for Atlantic Salmon**

Differences in stock characteristics, local geography and year-to-year variations in spawning escapement of Atlantic salmon confound attempts to apply the results of specific field studies (e.g., Egglishaw and Shackley, 1977, 1985; Buck and Hay, 1984; Chadwick, 1987) in predicting the effects of changes in climate (Power and Power, 1994). Further complications arise as a result of the ongoing debate regarding whether environmental variation and population effects are greatest in fresh or marine waters (Friedland, 1998), and how these act to determine survival of various life stages and population abundance. Knowledge of Atlantic salmon biology, however, is sufficient to describe the range of temperature conditions required for optimal growth and reproductive success, and thus to allow inferences of climate change effects. Atlantic salmon life-history stages all occur within optimal temperature ranges (Wankowski and Thorpe, 1979; Dwyer and Piper, 1987; Peterson and Martin-Robichaud, 1989; Power, 1990a).
However, variation in the required range of optimal temperatures for salmon at different life-
stages makes predicting the effects of climate change difficult. To date three approaches to
tackling the problem have been proposed in the scientific literature (see Box 7.8).

Firstly, regional climate scenarios and projections can be coupled directly to knowledge of the
physiological limits within which salmon operate. For example, winter discharges and
associated overwintering habitat will respond to precipitation changes (Power, 1981). Low
summer discharge on the east coast of Newfoundland and in Southern Québec, which limits
parr territory and hampers upstream adult migration, will change as well, affecting population
abundances in many rivers (Power, 1981). Problems with this approach include inaccuracy of
precipitation and extreme events forecasts, and coupling of climate models with ocean
circulation models.

A second approach to understanding the possible impacts of climate change on Atlantic
salmon is to apply what we know about the relationships between weather and salmon
population dynamics. For example, historical records of the salmon fisheries in the Ungava
Region of northern Québec show a correlation between ice conditions, the late arrival of
salmon and poor catches that suggest an improvement in salmon abundances may occur in the
future associated with a climate-induced reduction in the extent and duration of sea-ice cover
(Power, 1976; Power et al., 1987). The correlation between stock characteristics and latitude
(Power, 1981) suggests that smolt mean ages will decrease in association with increases in
average temperatures and growing season length. Power and Power (1994) found that
temperature increases and decreases have varying effects on populations distributed across
latitudes (Table 1). Where temperatures are currently at the upper end of the optimal
temperature range for growth, increases in temperature reduced growth, increased average
riverine residency and associated riverine mortalities, decreased smolt production and
increased parr densities. The reverse (increased smolt production and decreased parr
densities) occurred when temperatures at the lower end of the temperature range optimal for
growth were raised. Modest changes in precipitation, and thus available habitat, were found to
have no significant direct effect or interaction effect with changes in temperature on either
smolt production or parr density under any of the considered temperature scenarios. Thus,
depending upon the exact location and characteristics of the salmon population, the precise
impact of a given environmental change under a future climate scenario may be positive or
negative relative to present conditions. This makes regional differences in fish biology, local
climate and in regional scenarios of climate change extremely important in predicting future
situations.

Table 1. Results of modelling experiments measuring the possible effects of climate
change on populations of Atlantic Salmon. No change is denoted by x, a decrease by > and an
increase by <.

A third approach to predicting the effects of climate change involves attempting to shift
ecological zones into more appropriate geographic positions to reflect probable future climate
regimes and the known physiology of potentially affected species. The present distribution of
many fish is limited by the position of the summer isotherms which either directly limit the fish
due to thermal relationships or indirectly do so through effects on critical resources such as food (Shuter and Post, 1990). Using this approach, it appears Atlantic salmon will disappear from much of their traditional southern range in both Europe and North America as temperatures rise, and find more suitable habitat in cold rivers that experience warming. In the eastern Atlantic the overall area occupied by salmon will shrink simply due to a lack of land masses northward that would be expected to have suitable environments. In the western Atlantic, rivers in the Ungava Bay area could become more productive and may experience increases in the numbers of salmon (e.g., Koroc and Arnaux rivers). Rivers which currently have large salmon runs are also likely to become more productive (e.g., George, Koksoak and Whale rivers) and experience associated increases in salmon abundances (Power, 1990a). There will also be rivers on Baffin Island and Greenland that may become warm enough for Atlantic salmon to colonize. Such colonization, however, would likely come at the expense of Arctic char populations that currently inhabit the rivers, driven by competition between these species. Constraints on redistribution northward with warming include reductions in spawning substrate availability with increased sediment loading of rivers, changes in stream and river hydrology, and delay in the establishment of richer terrestrial vegetation and trees known to be important for the allochtonous inputs that provide important sources of carbon for salmon (Doucett, 1999).

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**BOX 7.10. Changing Snow and Ice Cover – Implications for UV Exposure**

The warming northern climate is causing prolongation of open water conditions. The loss of ultraviolet (UV)-attenuating snow and ice cover earlier in the season, when water temperatures are still low but UV irradiances are maximal, may be especially stressful for aquatic biota. As shown here, white ice (ice with air inclusions) has a strong attenuating effect.

Figure 1. The UV-attenuating effect of ice and snow over the plume of the Great Whale River, in Hudson Bay, Northern Québec, immediately offshore from the river.
on PAR (Photosynthetically Active Radiation – visible light) and an even greater effect on UV-A and UV-B. This snow-clearing experiment on Hudson Bay showed that only 2 cm of snow reduced the below-ice exposure to UV as well as to PAR by about a factor of three, with slightly greater effects at the shorter wavelengths.

Box 7.11. CDOM : The Natural UV-Sunscreen in Arctic Lakes and Rivers

Colored dissolved organic matter (CDOM) is composed of humic and fulvic materials that are derived from terrestrial soils, vegetation and microbial activities. CDOM is known to be an effective protective screen against UV (ultraviolet) radiation for freshwater biota (e.g., plankton, Vincent and Roy, 1993; amphibians, Palen et al., 2002). These compounds absorb UV-B (ultraviolet-B), UV-A (ultraviolet-A) and short wavelength visible light, and in high concentrations such as in arctic rivers they stain the water yellow or brown. CDOM is now known to be the primary attenuator of underwater UVR (Ultraviolet Radiation) in sub-arctic and high-arctic lakes (Laurion et al., 1997); Toolik Lake Alaska (Morris et al., 1995); arctic ponds (Rautio and Korhola, 2002a); and arctic coastal seas influenced by river inflows (Gibson et al., 2000; Vincent and Belzile, 2003). The concentrations of CDOM in natural waters are influenced by pH (acidification can cause a severe decline; Schindler et al., 1996b), catchment morphology, runoff and the type and extent of terrestrial vegetation. The latter aspects are especially dependent on climate. The paleo-ecological record has been helpful in examining past impacts of climate on biological underwater UV exposure, specifically by using fossil diatoms in lake sediments as quantitative indicators of variations in CDOM. This record also underscores the large regional differences in the magnitude and direction of change in underwater UV (Saulnier-Talbot et al., 2003; Ponader, 2002). Shifts in vegetation and hydrology caused by warming or cooling

Figure 1. UV and blue-light absorption by CDOM in the Mackenzie River (Inuvik, October 2002). The lower curves are for surface samples near the same date in the Beaufort Sea showing the CDOM influence at 1, 90 and 120 nautical miles offshore from the mouth of the river (W.F. Vincent and L. Retamal, unpublished data).
trends will affect the quantity of CDOM that is exported from catchments to their receiving waters, which in turn affects underwater UV. For example, an analysis of the past underwater climate (paleo-optics) of sub-arctic treeline lakes indicated that neo-Holocene cooling from about 3500 years ago to the present was accompanied by a southward retreat of the treeline and a large decrease in CDOM concentrations in lake waters. This decreasing CDOM resulted in an increase in biological UV exposure that was two orders of magnitude greater than that associated with moderate (30%) ozone depletion (Pienitz and Vincent, 2000). Saulnier-Talbot et al. (2003) reported large decreases in biological UV exposure during the Holocene in sub-arctic Québec associated with the gradual increase in terrestrial vegetation.

Box 7.12. UV Protection and Recovery Mechanisms in Arctic Freshwaters

Aquatic organisms have varying abilities to counter the effects of ultraviolet radiation (UVR). Photoprotective and repair processes are particularly important in preventing and reversing UVR damage to photosynthesis. A range of potential repair processes is stimulated by longer wavelengths to counteract the damaging effects of UV radiation. The relative importance of repair versus protection will vary depending on specific conditions and the physiological characteristics of the assemblage (Banaszak and Neale, 2001). Organisms living in arctic lakes have evolved several strategies to cope with UV radiation, which play an important role in shallow and highly UV transparent arctic lakes and ponds. Some species of algae and zooplankton have an ability to reduce their exposure to solar UV by vertical migration, which may be a response to UV (Huntsman, 1924). More recently, Leech and Williamson (2001) and Rhode et al. (2001) have provided further evidence that organisms avoid the highly irradiated areas by escaping the brightly-lit surface zone.

In addition to avoidance, aquatic organisms can escape from UV by reducing the effective radiation that penetrates the cell. A variety of UV-protecting compounds have been described; the three major types are carotenoids, mycosporine-like amino acids (MAAs), and melanin. The photoprotective properties of carotenoids are mainly associated with anti-oxidant mechanisms and inhibition of free radicals, as opposed to direct UV-screening (Hessen, 1994). They absorb wavelengths in the visible light spectrum and do not therefore provide direct protection from UV. Mycosporine-like amino acids have absorption maximum ranging from 310 to 360 nm, within the UV range. MAAs are present in alpine phytoplankton and zooplankton (Sommaruga and Garcia-Pichel, 1999; Tartarotti et al., 2001) and most probably also occur in arctic freshwater organisms although there is no research on this. Animals are unable to synthesize MAAs and carotenoids and must therefore acquire these compounds from their diet.

Melanin, with absorption maximum between 250 and 350 nm is produced in cladocera and fish. Its synthesis seems to be a direct response to UV radiation that acts by absorbing radiation before it enters the body tissues (Hobæk and Wolf, 1991). Melanic zooplankton are typically found in clear arctic waters where the absorbance of UV is low, and in shallow ponds where high dissolved organic carbon (DOC) may not provide enough protection from UV (Hebert and Emery, 1990; Rautio and Korhola, 2002b). It has also been shown recently that melanin synthesis followed the annual change in UV radiation; i.e., synthesis peaked at
the time of maximum underwater UV irradiance. Aquatic organisms can also repair damage from UV by nucleotide excision repair or by photoreactivation mechanisms, such as photoenzymatic repair (Leech and Williamson, 2000).

Brief exposure to UVR gives only the initial UV stress response. However, responses over long periods of time may show that organisms can acclimate to the UV stress and/or recover growth rates with the development of UV photoprotective strategies (e.g. the synthesis of photoprotective compounds). A long-term enclosure experiment conducted in a high-arctic lake on Ellesmere Island (Nunavut) showed an initial decrease in phytoplankton productivity with enhanced ultraviolet-B (UV-B) exposure, with recovery after 19 days (Perin, 2003). Long-term acclimation and recovery to UVR were also observed in a cultured marine diatom (Zudaire and Roy, 2001). Antecedent light conditions, temperature, nutrient availability and/or variations between species are all factors that can affect acclimation of organisms to UV-B (Zudaire and Roy, 2001).

**Box 7.13. UV Effects from Molecules to Ecosystems**

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Ultraviolet radiation is the most reactive waveband in the solar spectrum and has a wide range of effects, from molecular to whole ecosystem (Vincent & Roy, 1993)
High-altitude and high-latitude lakes are very sensitive ecosystems, where even slight environmental changes may substantially affect ecosystem function (Köck and Hofer, 1998; Köck et al., 2001). These changes could severely impact fish populations in terms of their habitat and their rate of toxicant accumulation from water and diet. Long-range transport of pollutants also tends to endanger fish populations by leading to highly elevated metal accumulation (Köck et al., 1996). Water temperature has been shown to be the driving force of excessive metal accumulation in these fish. A multi-year project, which is centred around small sensitive lake ecosystems in the Canadian Arctic Archipelago (Cornwallis Island, Somerset Island, Devon Island), was designed to explain the interactions between short- or longer-term climatic variation, the bioaccumulation of metals, and various biochemical stress indicators in land-locked populations of Arctic char.

Arctic char were collected at monthly intervals from Resolute Lake (Cornwallis Island, Nunavut, 74°41´N, 94° 57´W) during summers from 1997 to 2001. Fish were dissected and liver tissue subsampled for analysis of metal content (Cd, Zn) and biochemical stress indicators (glutathione - GSH, glutathione disulfide - GSSG, glycogen, Vitamin-C). GSH is an antioxidant, which is reduced to GSSG in the presence of reactive oxygen species. The GSSG/GSH ratio is a sensitive indicator of oxidative stress in cells (Lackner, 1998). Stress response was indicated by a decrease of GSH accompanied by an increase of GSSG.

Similar to Arctic char from Austrian high-mountain lakes, concentrations of Cd and Zn in the liver of high-latitude char exhibited a marked seasonal change during summer, and were significantly higher at the end of the ice-free period. A similar pattern could be found for concentrations of metallothione (an inducible metal-binding protein) in the liver. Concentrations of Cd and Zn in the liver of char collected in August 1998 were significantly higher than those in fish collected during the same period in 1997, 1999, 2000 and 2001, which coincides with much higher lake water temperatures in the El Niño year 1998 (Köck et al., 2002). Cd concentrations in the liver were positively correlated with frequencies of high temperatures (4 - 12 °C) and negatively with those of lower temperatures (< 0 - 4 °C).

Interannual variation of GSSG/GSH ratio, glycogen and Vitamin-C levels in the char studied indicate a higher level of stress in 1998 than in 1997 and 1999: GSSG/GSH ratio in the liver from fish collected in 1998 was significantly higher than in 1997 and 1999 (Köck et al., 2002; Figure 1). Furthermore, concentrations of glycogen and Vitamin-C were significantly lower in 1998. The severe depletion of glycogen energy reserves indicates that atypically high lake temperatures could enhance metal bioaccumulation and detoxification responses, diverting energy resources from other important physiological functions.

Figure 1. Interannual variation of GSSG/GSH ratio in the liver of Arctic char (N = 20 individuals per group) from Resolute Lake. Means ± SD are given. * denotes significant differences between 1998 and the other groups.

These results illustrate that Arctic char are extremely susceptible to even slight changes in lake water temperatures. Rising water temperatures lead to increased metabolic rates and thus pumping of higher volumes of water across the gills, which in turn results in increased uptake of dissolved metals from the water. It is speculated that the rapid increase in temperatures, as
predicted by various Global Circulation Models, could be a serious threat to the stability of Arctic char populations in high latitude lakes.

Table 7.1. A synthesis of the potential effects of climate change on arctic estuarine systems from both the bottom-up and top-down ecological perspectives (modified from Carmack and Macdonald, 2002). Assessment of cascading consequences from a human perspective can be generally positive (+), negative (-), neutral (0), or unknown (?).

<table>
<thead>
<tr>
<th>Bottom-up: nutrients/production/biota etc.</th>
<th>Top-down: humans/predators/biota etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>• More open water, more wind mixing, upwelling and greater nutrient availability for primary producers (+)</td>
<td>• Shifting water masses and currents will affect biotic cues for habitat use and migrations of biota such as fish and marine mammals (?)</td>
</tr>
<tr>
<td>• More open water, more light penetration especially seasonally hence more primary production (+); potential for increased UV issues (-/?)</td>
<td>• Re-distribution of grazers will impact underlying trophic structure (-/?)</td>
</tr>
<tr>
<td>• Decreased ice cover, decreased ice-associated algal production, follow-on impacts on pelagic and benthic foodwebs (-)</td>
<td>• Changed habitats seasonally in freshwater, estuarine and marine zones will affect anadromous fish distribution and use, with follow-on consequences to their prey communities and possibly also availability to humans (-/?)</td>
</tr>
<tr>
<td>• Increased basin rainfall, increased export of carbon to nearshore (+)</td>
<td>• Physical absence or alteration of seasonality or characteristics of ice platform will affect ice-associated biota (e.g., polar bears, seals, algae) (-), with cascading consequences to fish (+/-)</td>
</tr>
<tr>
<td>• Increased storms and open water, increased coastal erosion (-), increased sediment loads, nutrients and mixing (+), possibly increased productivity especially in late season (?) but offset by decreased light penetration (-)</td>
<td>• Increased open water will facilitate whale migrations (+) but increase predator risk to calves (-); shifts in whale populations may cascade through the trophic structure (e.g., shifted predation on fish by belugas; increased predation on plankton by bowhead whales) with unknown trophic consequences for anadromous and marine fish (?)</td>
</tr>
<tr>
<td>• Potential positive feedback on climate change processes – e.g., permafrost melting, release of methane and acceleration of global warming from this greenhouse gas. Contaminant inputs, mobilization or increase fluxes driven by temperature changes will increase availability and biomagnification in food chains (-).</td>
<td></td>
</tr>
</tbody>
</table>
Table 7.2. Summary of possible, likely and very likely effects on fished species and freshwater and anadromous fisheries.

<table>
<thead>
<tr>
<th>Climate Change or Ultraviolet Radiation Effect</th>
<th>Potential Impact on Fisheries</th>
<th>Consequences/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Impacts on Quantity of Fish in Arctic Fisheries</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased productivity of lower trophic levels:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Very likely increased growth, recruitment and survival of freshwater species</td>
<td>- Biomass and yields increased</td>
<td>- Short-term management for increased fishery yields especially for temperate species in the southern Arctic</td>
</tr>
<tr>
<td>- Likely increased growth in early years for facultatively anadromous species promotes shift to wholly freshwater life histories</td>
<td>- Shifts in balance of anadromy vs. non-anadromy decreases yields overall (i.e., smaller fish and perhaps more fish)</td>
<td>- Long-term management for change in type, locations of fisheries, and for decreased fishery yields</td>
</tr>
<tr>
<td>Local water temperature increases will at some point exceed thermal optima for individuals, possibly decreasing growth</td>
<td>- Biomass and yields decreased</td>
<td>- Especially true for arctic species and for cool water species in the southern Arctic; population declines and local extirpation; synergistic effects from other factors such as competition from southern taxa; management issues associated with declining fisheries</td>
</tr>
<tr>
<td>Duration of ice cover reduced for arctic lakes especially in northern arctic areas, increased and more rapid stratification, earlier and increased primary production, decreased oxygenation at depth possibly will result in reduction in quality and quantity of habitat for species such as lake trout</td>
<td>- Survival, biomass and ultimately yields of preferred species generally decreased</td>
<td>- Management for decreased fishery yields; potential management for declining fisheries and loss of populations</td>
</tr>
<tr>
<td>Improved quality of winter habitat possibly results in increased survival (but this would also be affected by summer conditions, stratification and overturns)</td>
<td>- Biomass and yields increased</td>
<td>- Short-term management for increased fishery yields; long-term implications unknown</td>
</tr>
<tr>
<td>Increased water temperatures generally and seasonally, but ultimately a decrease in summer habitat (e.g., deeper thermoclines in lakes; shrunken hypolimnia in lakes, reduced colder waters in rivers) likely reduces available habitat and decrease fish productivity, results in fish movements to deeper areas, and/or fatally stresses some fish species (e.g., Arctic grayling)</td>
<td>- Short-term increase in biomass and yields (e.g., several to 10’s of years)</td>
<td>- Short-term management for increased fishery yields – e.g., limit growth of fishery</td>
</tr>
<tr>
<td>- Long-term decrease in biomass and yields (e.g., &gt;10’s of years)</td>
<td></td>
<td>- Long-term decrease in traditional fisheries, switch to alternative fisheries if available</td>
</tr>
<tr>
<td>- Decreased availability of traditionally targeted species and/or loss of key populations</td>
<td></td>
<td>- Long-term re-tooling of fisheries to new areas such as deeper portions of lakes, possible cost issues to support re-tooling</td>
</tr>
<tr>
<td>Geographic ranges shift:</td>
<td>- Decreased availability or local loss of native species; increased opportunity to fish new species (especially in southern</td>
<td></td>
</tr>
<tr>
<td>- southern arctic and sub-arctic fish species very likely extend geographic ranges northwards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Likely with some significant negative effects on native species, northern (wholly arctic) species very likely experience range contraction and/or local extirpation</td>
<td>Arctic areas</td>
<td>and education in new ways of fishing if needed</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>--------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Decreased water flows in summer decreases habitat availability and possibly denies or shifts access to migrating fish</td>
<td>- Decreased availability of arctic species to local fisheries, potential for replacement by other species low or uncertain</td>
<td>- Management issues for declining fisheries, and ultimately addressing rare or endangered species; in Canada this also has implications under land claim legislation for basic needs provisions</td>
</tr>
<tr>
<td>Increased ultraviolet radiation in surface waters likely disrupts development and/or causes damage to young fish consequently decreasing survival, or forcing fish deeper thus slowing growth</td>
<td>- Decreased biomass and yields</td>
<td>- Management for declining fisheries</td>
</tr>
<tr>
<td>Increased inter-annual variability in climate, aquatic habitats, productivity and fish growth and production characters very likely occurs</td>
<td>- Unknown, some arctic species are relatively long-lived indicating an ability to withstand prolonged periods of poor year-class success - Increased frequency of good and poor year classes</td>
<td>- Variability in fishing success; conservative management for median (at best) or low-yield year classes to ensure sustainability; management for highly unpredictable fisheries - Instability in yields for targeted species results in uncertainty of product for fisheries</td>
</tr>
<tr>
<td>Increased water flows in winter</td>
<td>- Increased runoff in winter, decreased spring flood, changes in migratory runs</td>
<td>- Revision of management issues</td>
</tr>
</tbody>
</table>

### Impacts on Quality of Fish in Arctic Fisheries

<table>
<thead>
<tr>
<th>As water temperatures increase:</th>
<th>- Individual fish condition is reduced, thus quality is lower - Biomass and yields are reduced</th>
<th>- Especially true for arctic species and arctic-adapted coolwater species requiring thermal refugia; value of individual fish and total amount landed is reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>- thermal optima for individual growth are likely exceeded, resulting in negative effects on individuals</td>
<td>- Flesh quality reduced</td>
<td>- Value is reduced; preservation compromised</td>
</tr>
<tr>
<td>- flesh firmness is possibly decreased due to capture in warmer waters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Decreased availability due to changes in migratory runs | - Replacement of protein and potential social issues for peoples which heavily rely on traditional fishing; switch to other wildlife | |

- Decreased availability of arctic species to local fisheries, potential for replacement by other species low or uncertain
- Management issues for declining fisheries, and ultimately addressing rare or endangered species; in Canada this also has implications under land claim legislation for basic needs provisions
- Management for declining fisheries
- Variability in fishing success; conservative management for median (at best) or low-yield year classes to ensure sustainability; management for highly unpredictable fisheries
- Instability in yields for targeted species results in uncertainty of product for fisheries
- Revision of management issues

Especially true for arctic species and arctic-adapted coolwater species requiring thermal refugia; value of individual fish and total amount landed is reduced
- Value is reduced; preservation compromised
As air temperatures increase, fisheries may occur under warmer conditions which will very likely increase problems of preserving and transporting the product.

- Problems with immediate preservation increased (e.g., on-board refrigerators required)
- Transportation costs increased (i.e., faster method or more return trips to fish plants) or impossible
- Quality of product is decreased
- Costs of production are increased

- Low-value marginal fisheries will not be economically viable; northern fishery development compromised; and some fisheries may be abandoned if transportation is not possible
- Consumption of lower quality or poorly preserved product may increase human health risks

Climate change and/or ultraviolet radiation change possibly results in:
- Physical disfiguration of fish (e.g., discolourations, lesions, growths, etc.);
- Increased parasitism, and new parasites and/or diseases in traditionally fished arctic species

- Perceived and real quality and value of fish decreased
- Decreased interest in fisheries especially those based upon high quality fish (e.g., recreational fisheries)

- Increased concern voiced by local peoples requiring appropriate investigation and response from management agencies, e.g., ruling out potential proximate causes other than climate or ultraviolet radiation changes
- Increased inspection and addressing of real and perceived health concerns required
- Economic development compromised

Persistent contaminants mobilised from natural sources (e.g., Hg liberated by permafrost melting or flooding), or fluxes from anthropogenic sources to arctic ecosystems increased and likely results in:
- Higher body burdens in arctic fish
- Cascade effects on other higher trophic levels

- Real and perceived quality of fish decreased
- Compromised fish health reduces growth, decreases biomass and fishery yields

- Increased inspection and monitoring required
- Health concerns for fish consumption especially for domestic fisheries which typically are not routinely monitored

**Impacts on Success of Arctic Fisheries**

Increased climate variability and frequency of extreme events (e.g., storms affecting fishing to catastrophic winter fish kills) possibly results in biological consequences on fish populations, follow-on synergistic effects on biotic systems (e.g., parasites) and synergistic effects from other impacts (e.g., local industrialisation)

- Increased unpredictability in places, times and amounts of fish present in an area, and amounts captured and transported to processing, distribution or consumption points

- Increased risk of gear and boat loss
- Increased personal risk to fishers

- Extreme unpredictability in fish volumes has significant consequences for local peoples relying on fish for sustenance, on infrastructure development to support fisheries (e.g., fishing supplies, fish processing plants, transportation) and on development of markets for products from commercial and sport fisheries.
- Loss of gear decreases success, economic viability and persistence of fishery
- Need for search and rescue increased; fishing as an occupation falls from favour with a societal cost

Shifted environmental regimes likely affect time and difficulty of transportation to fishing sites and of product from sites to distribution or consumption points

- Decreased economics of many arctic fisheries remote from communities or without permanent access
- Costs associated with fishing are

- Marginal fisheries not economically viable, fishery development compromised; increased reliance on local easily accessible domestic fisheries raises the probability of over-exploitation with follow-on
| Changes in the distribution and abundance of traditionally harvested fishes will cause traditional fishing sites to have fewer fish available | increased sustainability and management issues  
- As/if domestic fisheries fail, then issues with protein replacement from other sources increase |  
- Decreased harvests and fewer fish available for communities  
- Aboriginal fishermen are tied to location and particular species by tradition and may not be able to adapt |
Table 7.3. Environmental factors affecting mercury concentration in aquatic top predators.

<table>
<thead>
<tr>
<th>Projected change</th>
<th>Effect on mercury concentration in predatory fish</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooding of soil</td>
<td>Increase</td>
<td>(Bodaly and Johnston, 1992)</td>
</tr>
<tr>
<td>Increased primary production</td>
<td>Reduce</td>
<td>(Pickhardt et al., 2002)</td>
</tr>
<tr>
<td>Increased number of trophic levels</td>
<td>Increase</td>
<td>(Kidd et al., 1995b)</td>
</tr>
<tr>
<td>Shift toward larger fish</td>
<td>Increase</td>
<td>(Sherwood et al., 2001)</td>
</tr>
<tr>
<td>Reduced lake size</td>
<td>Increase</td>
<td>(Bodaly et al., 1993)</td>
</tr>
<tr>
<td>Increased anadromous fish migration</td>
<td>Increase</td>
<td>(Zhang et al., 2001)</td>
</tr>
</tbody>
</table>

Box 7.5 Table 1

Table 1: Freshwater/Diadromous fish present in the Arctic and ACIA Regions (Reist, unpublished data).

<table>
<thead>
<tr>
<th>Family Name</th>
<th>Common Names</th>
<th>Arctic Forms in ACIA Area</th>
<th>Nspecies in ACIA Regions</th>
<th>Thermal Guild¹</th>
<th>Exploitation in ACIA Regions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ngenera</td>
<td>Nspecies</td>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>Petromyzontidae lampreys</td>
<td></td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Acipenseridae sturgeon</td>
<td></td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Hiodontidae goldeyes</td>
<td></td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Anguillidae freshwater eels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clupeidae shads²</td>
<td></td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Cyprinidae minnows</td>
<td></td>
<td>14</td>
<td>23</td>
<td>11</td>
<td>4</td>
<td>13</td>
</tr>
</tbody>
</table>
### Freshwater Arctic Ecosystems

<table>
<thead>
<tr>
<th>Family</th>
<th>Region I</th>
<th>Region II</th>
<th>Region III</th>
<th>Region IV</th>
<th>ACIA area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catostomidae</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>Warm/Cool/Cold Limited in Region II and western Region IV.</td>
</tr>
<tr>
<td>Catostomidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobitidae</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Warm Not fished.</td>
</tr>
<tr>
<td>Cobitidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Esocidae</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Cool/Cold Extensively fished in all Regions.</td>
</tr>
<tr>
<td>Esocidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umbridae</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>Cold/Arctic Limited at most where they occur.</td>
</tr>
<tr>
<td>Umbridae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Osmeridae</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>Cool/Cold Limited at most, where they occur.</td>
</tr>
<tr>
<td>Osmeridae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salmonidae</td>
<td>10</td>
<td>33+</td>
<td>9</td>
<td>14</td>
<td>Cool/Cold/Arctic Most species extensively fished in all Regions.</td>
</tr>
<tr>
<td>Salmonidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percopsidae</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Cool/Cold Not fished.</td>
</tr>
<tr>
<td>Percopsidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gadidae</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Cool/Cold Extensively fished in all Regions.</td>
</tr>
<tr>
<td>Gadidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasterosteidae</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>Warm/Cool/Cold Not fished.</td>
</tr>
<tr>
<td>Gasterosteidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cottidae</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>Cool/Cold Not fished.</td>
</tr>
<tr>
<td>Cottidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percidae</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>Warm/Cool Fished where they occur, especially Region I. Mostly temperate species, but enter ACIA area via warmer north-flowing rivers.</td>
</tr>
<tr>
<td>Percidae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td>48</td>
<td>99</td>
<td>38</td>
<td>29</td>
<td>58 32</td>
</tr>
</tbody>
</table>

---

1. **Catostomidae** suckers
2. **Cobitidae** loaches
3. **Esocidae** pikes
4. **Umbridae** Blackfish
5. **Osmeridae** smelts
6. **Salmonidae** salmon, char, whitefishes, ciscoes
7. **Percopsidae** troutperches
8. **Gadidae** cods
9. **Gasterosteidae** sticklebacks
10. **Cottidae** sculpins
11. **Percidae** perches

---

**Notes:**
- **Catostomidae** suckers are not exploited or limited elsewhere.
- **Cobitidae** loaches are not fished. **Noemacheilus barbatulus** only. Subarctic only; very southern edge of ACIA Region I.
- **Esocidae** pikes are extensively fished in all Regions. **Esox lucius**, northern pike, only, and widely distributed.
- **Umbridae** Blackfish are limited at most where they occur. **Dallia** spp., blackfishes, only.
- **Osmeridae** smelts are limited at most, where they occur.
- **Salmonidae** salmon, char, whitefishes, ciscoes are the most widely distributed and abundant arctic group and fisheries mainstay.
- **Percopsidae** troutperches are not fished. **Percopsis omiscomaycus**, trout perch, only.
- **Gadidae** cods are extensively fished in all Regions. **Lota lota**, burbot, only, and widely distributed.
- **Gasterosteidae** sticklebacks are not fished.
- **Cottidae** sculpins are not fished.
- **Percidae** perches are fished where they occur, especially Region I. Mostly temperate species, but enter ACIA area via warmer north-flowing rivers.
### Total Families

|   | 17 | -- | 12 | 10 | 14 | 12 |

2. Only Alosinae, the shads, are arctic representatives.
3. Only Dallia, the blackfish, are arctic representatives.

### Box 7.7

Table 1. Nain Arctic char – Environmental Associations

(see next page)
## Nain Arctic char – Environmental Associations

<table>
<thead>
<tr>
<th>Timing</th>
<th>Significant Environmental Parameters</th>
<th>Likely Environmental Effect</th>
<th>Observed Biological Effect on Individual Fish</th>
<th>Observed Biological Effect on Fish Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within Year</td>
<td>Summer air Temperature</td>
<td>Increased Marine Productivity</td>
<td><em>Increased</em> weight</td>
<td>Better condition</td>
</tr>
<tr>
<td></td>
<td>Sea Surface Temperature</td>
<td><em>Within Limits</em></td>
<td><em>Increased</em> length</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Increased</em> growth</td>
<td></td>
</tr>
<tr>
<td>First Summer of Life</td>
<td>Winter Precipitation</td>
<td>Increased snow pack</td>
<td><em>Increased</em> survival overwinter</td>
<td>More fish</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decreased seasonal freezing</td>
<td></td>
<td>Earlier recruitment to the fishery (i.e., lower age at catch)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>More Overwintering habitat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fourth year of life (first year at sea)</td>
<td>Summer air Temperature</td>
<td>Increased nutrient loading to nearshore productivity</td>
<td><em>Increased</em> growth</td>
<td>Increased weight at catch</td>
</tr>
<tr>
<td></td>
<td>Summer Precipitation</td>
<td></td>
<td></td>
<td>Decreased age at catch</td>
</tr>
</tbody>
</table>

- Climate variables are very important in understanding year-to-year variability in stock characteristics.
- Causative relationships appear to exist between life history and environment but precise roles played, timing of the effect and limits to the effects need to be investigated more thoroughly.
Box 7.9
Table 1. Results of modelling experiments measuring the possible effects of climate change on populations of Atlantic Salmon. No change is denoted by x, a decrease by > and an increase by <.

<table>
<thead>
<tr>
<th>Latitude/Longitude</th>
<th>Temperature Increase</th>
<th></th>
<th>Temperature Decrease</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Smolt Production</td>
<td>Parr Density</td>
<td>Smolt Production</td>
</tr>
<tr>
<td>47° 01’ N / 65° 27’ W</td>
<td>&gt;</td>
<td>&lt;</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>50° 11’ N / 61° 49’ W</td>
<td>&lt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&lt;</td>
</tr>
<tr>
<td>53° 42’ N / 57° 02’ W</td>
<td>&lt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&lt;</td>
</tr>
</tbody>
</table>
## Appendix Table 1: Formal scientific names of arctic fishes alphabetically listed by common name used in the text and boxes (see Fishbase [http://www.fishbase.org/home.htm](http://www.fishbase.org/home.htm) or other references for further details on species). See also Box 7.9 Table 1.

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Scientific Name or Group</th>
<th>Family</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alewife</td>
<td><em>Alosa sp.</em></td>
<td><em>Alosidae</em></td>
</tr>
<tr>
<td>Arctic char</td>
<td><em>Salvelinus alpinus</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>Arctic cisco</td>
<td><em>Coregonus autumnalis</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>Arctic cod</td>
<td><em>Boregadus saida</em></td>
<td><em>Gadidae</em></td>
</tr>
<tr>
<td>Arctic grayling</td>
<td><em>Thymallus arcticus</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>Arctic flounder</td>
<td><em>Pleuronectes glacialis</em></td>
<td><em>Pleuronectidae</em></td>
</tr>
<tr>
<td>Atlantic salmon</td>
<td><em>Salmo salar</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>bluegill</td>
<td><em>Lepomis macrochirus</em></td>
<td><em>Centrarchidae</em></td>
</tr>
<tr>
<td>broad whitefish</td>
<td><em>Salvelinus fontinalis</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>brook trout</td>
<td><em>Salmo trutta</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>brown trout</td>
<td><em>Salvelinus confluentus</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>burbot</td>
<td><em>Lota lota</em></td>
<td><em>Gadidae</em></td>
</tr>
<tr>
<td>carp bream</td>
<td><em>Abramis braha</em></td>
<td><em>Cyprinidae</em></td>
</tr>
<tr>
<td>chars</td>
<td><em>Salvelinus spp.</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>chum salmon</td>
<td><em>Onchorhynchus keta</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>cisco</td>
<td><em>Coregonus (Leucichthys) subgenus</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>coho salmon</td>
<td><em>Onchorhynchus kisutch</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>common dace</td>
<td><em>Leuciscus leuciscus baicalensis</em></td>
<td><em>Cyprinidae</em></td>
</tr>
<tr>
<td>coregonids</td>
<td><em>Salvelinus namaycush</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>cyprinids</td>
<td><em>Notropis atherinoides</em></td>
<td><em>Cyprinidae</em></td>
</tr>
<tr>
<td>emerald shiner</td>
<td><em>Salvelinus malma</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>Dolly Varden</td>
<td><em>Anguilla anguilla</em></td>
<td><em>Anguillidae</em></td>
</tr>
<tr>
<td>European eel</td>
<td><em>Perca fluviatilis</em></td>
<td><em>Percidae</em></td>
</tr>
<tr>
<td>European perch</td>
<td><em>Coregonus lavaretus</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>European whitefish</td>
<td><em>Myoxocephalus quadricornis</em></td>
<td><em>Cottidae</em></td>
</tr>
<tr>
<td>ide</td>
<td><em>Leuciscus idus</em></td>
<td><em>Cyprinidae</em></td>
</tr>
<tr>
<td>lake cisco</td>
<td><em>Coregonus artedi</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>lake trout</td>
<td><em>Salvelinus namaycush</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>lake whitefish</td>
<td><em>Coregonus clupeaformis</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>lampreys</td>
<td><em>Lampetra, Petromyzon spp.</em></td>
<td><em>Petromyzontidae</em></td>
</tr>
<tr>
<td>least cisco</td>
<td><em>Coregonus sardinell</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>ninespine stickleback</td>
<td><em>Pungitius pungitus</em></td>
<td><em>Gasterosteidae</em></td>
</tr>
<tr>
<td>northern pike</td>
<td><em>Esox lucius</em></td>
<td><em>Esocidae</em></td>
</tr>
<tr>
<td>northern redbelly dace</td>
<td><em>Chrosomus eos</em></td>
<td><em>Cyprinidae</em></td>
</tr>
<tr>
<td>Pacific salmon</td>
<td><em>Onchorhynchus spp.</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>percs</td>
<td><em>Hypomesus olidus</em></td>
<td><em>Percidae</em></td>
</tr>
<tr>
<td>pink salmon</td>
<td><em>Onchorhynchus gorbuscha</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>pond smelt</td>
<td><em>Osmerus mordax</em></td>
<td><em>Osmeridae</em></td>
</tr>
<tr>
<td>rainbow smelt</td>
<td><em>Onchorhynchus mykiss</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>rainbow trout</td>
<td><em>Rutilus rutilus lacustris</em></td>
<td><em>Cyprinidae</em></td>
</tr>
<tr>
<td>roach</td>
<td><em>Gynnocephalus cernus</em></td>
<td><em>Percidae</em></td>
</tr>
<tr>
<td>ruffe</td>
<td><em>trouts, chars, salmons</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>salmonids</td>
<td><em>Osmerus mordax</em></td>
<td><em>Cottidae</em></td>
</tr>
<tr>
<td>sculpins</td>
<td><em>Microperus dolomieu</em></td>
<td><em>Centrarchidae</em></td>
</tr>
<tr>
<td>Siberian whitefish</td>
<td><em>Ocorhynchus nerk</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>smallmouth bass</td>
<td><em>Pungitius, Gasterosteus spp.</em></td>
<td><em>Gasterosteidae</em></td>
</tr>
<tr>
<td>sockeye salmon</td>
<td><em>Cottus spp.</em></td>
<td><em>Salmonidae</em></td>
</tr>
<tr>
<td>sticklebacks</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Notes

1. Marine species found in nearshore, brackish and estuarine areas.
2. Freshwater species found freshwater or freshened brackish water areas only.
3. Anadromous species primarily (although freshwater forms are also present).
4. Catadromous species primarily (although freshwater forms may be present).