Canadian Water Quality Guidelines for the Protection of Aquatic Life

TEMPERATURE
(Marine)

Water temperature, along with salinity, is one of the most important physical factors affecting marine and estuarine organisms. Temperature affects almost every physical property of seawater. The ionization constant, surface tension, and latent heat of vaporization decrease in a near-linear fashion as temperature is raised. The compressibility, viscosity, and specific heat of water all decrease nonlinearly with increasing temperature. Vapour pressure and thermal conductivity, the speed of sound in seawater, its electrical conductivity, and osmotic pressure, however, increase in magnitude as temperature increases. The solubility of gases, such as nitrogen, hydrogen, carbon dioxide, and oxygen, in contrast, all decrease as water temperatures rise (Cox 1965; Houston 1982).

Temperatures in the Canadian Pacific and Atlantic coastal and estuarine waters vary considerably depending on location, depth, freshwater inputs, extent of ice formation, upwellings, and currents (Dera 1992). For both coasts there is a pronounced seasonal variability in nearshore surface temperatures. Temperature measurements along the Canadian Atlantic coast have shown that winter water temperatures often range between -2 and 6ºC, while summer temperatures vary between 7 and 18ºC (Petrie and Jordon 1993). In the Straits of Georgia and Juan de Fuca, along the Canadian Pacific coast, winter temperatures between 5 and 8ºC have been measured, while summer temperatures have been between 12 and 15ºC (Thomson 1981). These general water temperature ranges are often exceeded in localized areas, such as certain fjords in British Columbia (e.g., Pendrell or Hotham Sound), where summer stratification has caused surface temperatures to exceed 20ºC (Valiela 1979; Thomson 1981). Temperatures in the Arctic Ocean also exhibit geographical, seasonal, and annual variations, but fluctuations are smaller than those experienced in the Pacific or Atlantic Canadian coastal waters. In areas with drifting ice, surface waters usually remain at about -1.8ºC, year-round. In the summer, ice-free areas may reach temperatures that rise several degrees above 0ºC (Heimdal 1989). In northern Baffin Bay, average monthly temperatures over a 2-year period changed only marginally from a low of -1.53ºC to a high of 0.19ºC (Ross 1991). Ice and water transport patterns, winter air temperatures, and freshwater inputs can contribute to considerable local variability in recorded Arctic marine water temperatures (Drinkwater 1986; Prinsenberg 1986; Hopky et al. 1990).

Most of the human activities that affect the temperatures of marine and estuarine waters in Canada are associated with the release of waste heat. The major sources of these inputs include the processes of the chemical, petrochemical, and pulp and paper industries; municipal sewage; and thermal generating stations (Swiss 1984). Thermal generating stations account for over 75% of the total heat discharged into the marine environment. For example, the six thermal stations in Nova Scotia have been observed to raise the temperature of their effluent between 6.1 and 14.4ºC over natural levels (Swiss 1984).

Other disturbances of aquatic temperature regimes may be related to the physical alteration of a water body. For instance, such processes as river diversions, water withdrawals from coastal areas, retaining walls in estuaries, large jetties, breakwaters, and causeways in coastal areas may significantly alter water temperatures. The construction of a tidal barrage in the upper regions of the Bay of Fundy, for example, increased the local tidal range and resulted in an overall lowering of the area's surface sea temperatures (Greenberg 1984).

Biological Effects

Summary

Temperature affects many chemical and biological processes. Chemical equilibrium constants, solubilities, and the rates of chemical reactions are temperature-dependent (Whitehouse 1984). Most marine and estuarine organisms are poikilotherms (i.e., cannot regulate their internal temperatures). As a result, biological processes, such as photosynthetic and respiration rates, spawning, uptake of toxic substances, and behavioural patterns of organisms, are all responsive to changes in temperature (Strickland 1965; Houston 1982; Aiken and Waddy 1990).

Kinne (1963) conducted a comprehensive review of the effects of water temperature on marine and brackish water animals. The results of this review indicated that biological processes may be greatly affected by water temperature fluctuations, gradients, ranges, and averages, as well as by the frequency and intensity of changes, duration of patterns, and accumulated heat units. Most marine and estuarine species, or populations within species, have characteristic tolerable temperature ranges that include specific high and low lethal temperatures. Eurythermal species, i.e., species that can tolerate wide ranges of temperatures, are characteristic of aquatic environments with fluctuating temperatures. Stenothermal species, i.e., species that can only exist in a narrow range of temperatures, are characteristic of environments with near-constant temperatures. Gradual water temperature changes are usually better tolerated by all species than sudden changes (Kinne 1963).

Many marine and estuarine organisms can adjust to alterations in ambient water temperatures through an array of biological responses. This process, termed acclimation, can include behavioural, morphological, physiological, or biochemical responses. The length, frequency, and severity of exposure, as well as thermal history, are all-important determinants of an individual organism's response to temperature changes (Fry 1971; Hochachka and Somero 1971; Thompson and Newell 1985).

Potential effects of extremely low water temperatures on aquatic organisms include insufficient integration of nervous and metabolic processes, insufficient rates of energy liberation, changes in water and mineral balance, increase in osmoconcentration resulting from extracelluar freezing followed by the dehydration of cells, liquefaction of cortical protoplasm, and gelation of the cell interior (Kinne 1963). Many species of marine fish have body fluids with lower osmotic pressure than seawater, causing such species to freeze at temperatures above the freezing point of seawater. Most species of marine fish avoid freezing by either avoiding ice-laden seawater and/or by increasing the osmotic concentration of their blood (DeVries 1971).

The effects of extremely high temperatures include insufficient supply of oxygen, failures in process integration, desiccation (intertidal organisms), enzyme inactivation, change in lipid state, increase in protoplasmic viscosity, increase in cell membrane permeability, protein denaturation, and release of toxic substances from damaged cells. Death can result from exposure to either extremely high or extremely low water temperatures (Kinne 1963).

Water temperature changes that are not lethal can produce a wide variety of significant sublethal effects. For example, temperature changes can significantly affect photosynthesis; respiration; susceptibility to disease; osmoregulation; uptake of pollutants; susceptibility to the toxic effects of pollutants; various behavioural patterns, including physical activity, reproduction, feeding, growth, migration, distribution, intra- and inter-specific competition, predator–prey relationships, community composition, and parasite–host relationships; and many other biological processes (Kinne 1963). Selected examples of some water temperature effects in marine and estuarine ecosystems follow. Wherever possible, examples dealing with Canadian marine or estuarine systems were selected.

Specific Effects

Lüning and Freshwater (1988) studied the water temperature tolerance (−1.5–30ºC) of marine algae (49 species) and seagrass (two species) near Vancouver Island. All species studied showed high levels of cold tolerance, with all surviving at 0ºC and only six species dying at −1.5ºC. Heat tolerance was much more variable; most subtidal species showed survival limits lower than 20ºC; intertidal species survived at higher ranges of 20–28ºC. Only one species, the seagrass *Zostera marina*, survived at 30ºC. The authors characterized the northeast Pacific seaweeds as "cold-stenothermal", indicating a narrow range of temperature tolerance at the low end of the range of global marine temperatures.

Different organisms will exhibit different productivity levels at a given water temperature range. In Newfoundland coastal waters, Pomeroy and Deibel (1986) measured low levels of bacterial growth and respiration during the spring phytoplankton bloom, when surface temperatures were −1–2ºC. It was suggested that in very cold environments, low bacterial activity (i.e., decomposition) during a period of high primary production could result in greater food availability for herbivores, thereby enhancing secondary production. Temperature-related control of bacterial activity may therefore be important in influencing production at higher trophic levels (Pomeroy and Deibel 1986; Pomeroy et al. 1991).

Water temperature plays a limiting role on the feeding and recruitment success of fish and crustacean larvae. The eggs of the walleye pollock *(Theragra chalcogramma)* in the Bering Sea generally hatch at temperatures ranging between 3 and 6ºC, and the larvae feed on copepod nauplii. It was found that the larvae reared at 5.5ºC were more successful at capturing copepod nauplii when the prey was at low concentrations, than the larval fish cohorts reared at 3ºC. Conversely, larvae hatching at 5ºC required 8% more calories than those hatching at 3ºC (Paul 1983 and references therein). Paul and Nunes (1983) reported that northern pink shrimp larvae *(Pandalus borealis)* that hatched during a warm year (i.e., at 6ºC) required 63% more calories to meet their metabolic requirements than larvae of the same weight that hatched in a cooler year (i.e., at 3ºC). If this increased metabolic requirement were to exceed their ability to find and ingest food, the survival of that year's recruits could be compromised.

Increasing water temperature generally causes increases in the respiratory rates of aquatic animals and vascular and nonvascular plants (Kinne 1963; Dawson 1966). Beyond a given temperature, thermal stress is induced (Kinne 1963; Paul and Nunes 1983; Paul 1986; Paul et al. 1988). As respiratory rates increase, so do the organism's metabolic energy needs (feeding or photosynthesis). This relationship has important implications for the overall productivity and survival of marine and estuarine organisms that thrive in habitats with varying temperature regimes. Commercially important pacific fish species were investigated for their metabolic oxygen requirement. In the linear portion of the oxygen consumption-temperature relationship, the nonfeeding metabolic requirement increased by 11%, 7–12%, 9%, and 18% per ºC for Pacific cod, Atlantic cod, saffron cod, and juvenile walleye pollock, respectively (Paul 1986; Paul et al. 1988, 1990, and references therein).

Water temperature may also affect the reproductive capacity of marine organisms. Tanasichuk and Ware (1987) found that for Pacific herring the mean sea temperature in overwintering habitats during the three months before spawning (December to March) best accounted for variations in size-specific fecundity. The range in mean monthly sea surface temperature during the three months before spawning for the five years studied was 5.6–8.1ºC. This range is relatively narrow, considering that the data purposely included one year that was very strongly influenced by an El Niño episode, and that herring came from seven sites extending close to 700 km along a north–south axis (Tanasichuk and Ware 1987).

All the relationships previously described demonstrate that relatively small changes in the extent and timing of temperature phenomena in high-latitude coastal waters can significantly alter biological processes.

Temperature and Toxic Substances

In general, the sensitivity of aquatic organisms to toxic substances increases with increasing water temperature (Cairns et al. 1975). The interactions between temperature and toxicity, however, are very complex because temperature generally affects the chemistry and availability of toxic substances, the survival and function of organisms, and the responses of organisms to toxicants. In water, ammonia exists in two forms, a non-ionic species (NH_3) and an ionic species (NH_4^+). The toxicity of ammonia to aquatic organisms is largely determined by the concentration of the non-ionic species, which is partly temperature dependent. A decrease in temperature will lead to an increase in the proportion of NH_3 in water (Whitfield 1974; Miller et al. 1990).

Some criteria or guideline documents state different maximum or average toxicant concentrations allowed or recommended for different temperatures. The British Columbia ambient water quality criteria for ammonia for the protection of marine life (Nordin 1992, adopted from USEPA 1989) give maximum and average concentrations of total ammonia nitrogen that vary with water temperature.

According to Voyer and Modica (1990), insufficient data exist to permit the development of relationships between either water temperature or salinity and the toxicity of heavy metals in marine water. However, the authors also stated that evidence is available that indicates that survival, bioconcentration, and sublethal effects of pollutants on estuarine organisms are often related to ambient salinity and temperature conditions. Generally, as water temperature increases, the rate of metabolic processes increases, resulting in enhanced uptake and toxicity of metals to marine and estuarine organisms (Phillips 1976; Waldichuk 1985; McLusky et al. 1986; Voyer and Modica 1990).

Interim Guideline

Human activities should not cause changes in ambient temperature of marine and estuarine waters to exceed ±1ºC at any time, location, or depth. The natural temperature cycle characteristic of the site should not be altered in amplitude or frequency by human activities. The maximum rate of any human-induced temperature change should not exceed 0.5ºC per hour (CCME 1996).

Rationale

Many biological processes that occur in marine and estuarine waters are sensitive to temperature changes. The interim guideline of ±1ºC for induced temperature change is recommended to ensure that adverse effects on these processes are minimized. The variability of coastal and estuarine waters is such that this temperature alteration is probably a minor proportion of the total variability to which organisms are exposed in these environments. Furthermore, the recommended rate of temperature change of 0.5ºC per hour, which is adopted from the Alaskan guideline for temperature (BNA 1986; State of Alaska 1989), should reduce the impact of sudden induced temperature changes on the Canadian marine environment.

Site-specific diurnal, seasonal, and annual water temperature regimes are intended to be maintained through the recommendations of the interim temperature guideline. In recognition of this intention, a clause, adapted from the USEPA (1986) and Alaskan (BNA 1986; State of Alaska 1989) guidelines, which calls for the preservation of the amplitude and frequency of ambient temperature cycles, has been included as part of the Canadian interim temperature guideline.

It is recognized that, in implementing the recommended interim guideline for temperature, allowance may be made for the existence of mixing zones. Definitions of mixing zones are generally site-specific and consider the requirements of the jurisdiction or jurisdictions responsible for a particular activity.

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