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Canadian Coastal Seas and Great Lakes Sea Surface Temperature Climatology and Recent Trends

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Abstract. 28 years of satellite data were used to calculate sea surface temperature (SST) climatologies covering Canada's 3 surrounding oceans and the Great Lakes. Results show the imprint of major circulation features on the spatial distribution of the SST. Together with the Gulf Stream, the Labrador Current generates a strong spatial variability of SST on the east coast. Most of the Canadian Arctic, with the exception of Hudson Bay and the coastal Beaufort Sea region, is characterized by very small seasonal SST amplitude. Lake Erie is the water body having the largest seasonal SST amplitude, but for the oceanic regions, it is the southern Gulf of St. Lawrence and the adjacent Scotian Shelf.
A trend analysis showed that many regions are undergoing rapid warming of the sea surface. However, warming is not spatially uniform. The strongest warming was detected in Baffin Bay and appears to result from the decreasing ice cover. Lake Superior is also showing a strong warming trend.
These results have important implications for fisheries management because SST affects many species. Regions with small yearly amplitudes and warming trends might act as future cool water oases for some species.

Résumé. 28 années de données satellitaires ont été utilisées afin de calculer des climatologies des températures de surface de la mer «sea surface temperature» (SST) pour les 3 océans entourant le Canada ainsi que pour les Grands Lacs. Les résultats montrent l'empreinte des principaux courants océaniques sur la distribution spatiale des SST. Avec le Gulf Stream, le courant du Labrador génère une forte variabilité spatiale des SST sur la côte est. La plupart de l'arctique canadien, avec l'exception de la Baie d'Hudson et la zone côtière de la mer de Beaufort, est caractérisé par une très faible amplitude annuelle des SST. Le lac Érié est la masse d'eau montrant la plus grande amplitude saisonnière, mais pour les régions océaniques, ce sont le sud du Golfe du Saint-Laurent et le plateau Néo-Écossais adjacent.
Une analyse de tendances a montré que plusieurs régions sont soumises à un accroissement rapide des températures de surface. Toutefois, le réchauffement n'est pas spatialement uniforme. Le plus fort réchauffement a été détecté dans la baie de Baffin et semble relié à la décroissance de la couverture de glace. Le lac Supérieur montre aussi une forte tendance au réchauffement.
Ces résultats ont d'importantes implications pour la gestion des pêches puisque la SST affecte plusieurs espèces. Les régions ayant une faible amplitude annuelle et un faible taux de réchauffement pourraient agir dans le futur comme des oasis froides pour certaines espèces.

INTRODUCTION

Canada is surrounded by 3 oceans: Atlantic, Pacific, and Arctic, each with very distinct characteristics. The Atlantic region is characterized by the presence of major currents (Labrador and Gulf Stream), a complex bathymetry, and a large seasonal cycle from freezing point to more than 25°C. The Pacific Ocean has a simpler bathymetry and current system but its coastal regions are affected by seasonal upwellings due to a shift of dominant winds (Cummins and Masson 2014). Finally, despite a strong trend toward a longer open-water season, the Arctic Ocean still experiences the presence of a complete ice cover during most of the year. These 3 marine ecosystems, thus, exhibit spatial and temporal variability at various scales resulting from the interactions of tides, bathymetry, winds, freshwater runoff, etc.

The Canadian coastal ecosystems support a variety of commercial fish stocks belonging to many species (herring, capelin, shrimps, salmon, crab, lobster, etc.) that are temperature dependent for parts of their life cycle. Climate scenarios have shown that atmospheric warming should occur everywhere over Canada's surrounding oceans, with the more significant changes predicted for over the Arctic. Surface layer heating could thus influence fisheries' yields by strengthening the vertical stratification (Taboada and Anadón 2012) that has a direct impact on primary production, moving the spatial window of optimum temperatures (Khan et al. 2013) or affecting the marine food web (Sherman et al. 2009). Sea surface temperature (SST) is also an important parameter to consider for ocean acidification (Sun et al. 2012). In the Arctic, the gradual increase in the

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duration of the open-water season is profoundly changing the dynamics of phytoplankton production from a polar to a more temperate mode with the addition of a fall bloom (Ardyna et al. 2014). Impact of such changes on the marine food chain is still unknown. In the Pacific, climate change could affect survival, growth, and distribution of salmon species, some of which are at the southern limit of their range (Beamish et al. 2009; Malick et al. 2015).

SST is an essential climate variable and a key indicator of changes in the marine ecosystems. Oceanic SST variability results from a combination of atmospheric and oceanic processes due to either surface energy fluxes (e.g., North Atlantic Oscillation, Arctic Oscillation), coupled ocean-atmosphere interactions such as the El-Nino–Southern Oscillation, or intrinsic oceanic modes such as the Atlantic Multidecadal Oscillation or Pacific Decadal Oscillation (Deser, Alexander, et al. 2010). Many studies addressed the SST variability over the oceans (Belkin 2009; DelSole et al. 2013; Deser, Alexander, et al. 2010; Deser, Phillips, et al. 2010; Guan and Nigam 2009; Park, Lee, Chang, et al. 2015; Taboada and Anadón 2012; Ting et al. 2014) using either observations or models and found correlations with major atmospheric drivers (North Atlantic Oscillation, etc.). For Canadian waters, Deser, Phillips, et al. (2010), using long-term (1900–2008) datasets, indicated that the warming trends on the eastern side of the continent were higher than those in the Pacific. Using shorter (1982–2006) remote sensing datasets, Belkin (2009) found the same difference, with the Newfoundland–Labrador Shelf Large Marine Ecosystem having the 5th fastest SST increase in the world (1.04°C over 25 years) and the Scotian Shelf the 7th (0.89°C), whereas the Gulf of Alaska SST increased by only 0.37°C. The yearly amplitude of SST is also predicted to increase in the future over eastern Canada (Khan et al. 2013; Taboada and Anadón 2012). Estimating trends in the Arctic is more difficult due to the presence of an ice cover for most of the year. Belkin (2009) indicated that warming rates for the Beaufort Sea were moderate with a change of 0.35°C over 25 years.

In the coastal regions, other processes affect SST variability, such as wind-driven upwellings, freshwater runoff, coastal currents, and tidal mixing in shallow zones. These processes add variability to the SST that would otherwise be driven only by large-scale atmospheric processes. They often have a limited spatial scale, but because most of the primary production occurs in the coastal regions, they can have very significant effects on the global biological production because they directly affect the mixed-layer depth and nutrient resupply in the euphotic zone.

To date, existing SST climatologies covering Canada's 3 oceans based on in situ or remote sensing measurements such as HadSST1, HadSST2, ERSST, NCEP/NOAA and Kaplan have a relatively low spatial resolution (1° × 1° at best), preventing their use in coastal, regional, or local applications. In the present study, we use a 28-year time series of high-resolution (1 km) SST data generated from remote sensing methods to describe the oceanic/coastal environment, evaluate seasonal variability, and calculate recent trends for the 3 coastal regions surrounding Canada and the Great Lakes.

MATERIAL AND METHODS

Satellite remote sensing has often been used to estimate climate variability in the open ocean (Good et al. 2007; Lawrence et al. 2004), in the coastal regions (Barale et al. 2004; Galbraith et al. 2012; Ginzburg et al. 2004; Gómez-Gesteira et al. 2008; Relvas et al. 2009), and in inland waters (Schneider and Hook 2010). For this work, we used SST covering the period June 1985 to May 2013 (28 years), calculated by using the National Oceanic and Atmospheric Administration (NOAA) and MetOp Advanced Very High Resolution Radiometer (AVHRR) satellite images available from the Department of Fisheries and Oceans (DFO) Maurice Lamontagne Institute (MLI) remote sensing laboratory.[1] The raw data (day and night) acquired by 3 DFO and 4 NOAA satellite receiving stations were processed using the Terascan software. SST was calculated using the split-window Multi-Channel Sea Surface Temperature algorithm (McClain et al. 1985). Sensor specific algorithm coefficients published by the NOAA were used. Daytime data were processed using a 2-channel algorithm and a 3-channel algorithm was used for night-time data. The Terascan software was also used to detect clouds, correct navigation errors, and project the results onto a national georeferenced grid of 1 km. Further data screening includes a +/− 3-day temporal variability filter, an ice mask filter based on satellite microwave data products, and a climatological filter that has been shown to greatly improve the quality of SST retrievals (Pettigrew et al. 2011). Mean SST at each grid node are then calculated for averaging periods of 1, 3, 5, 7, and 15 days, as well as monthly. According to a recent study, the 15-day composites are within a range of −0.3°C to −0.1°C to in-situ thermograph readings (Pettigrew et al. 2011). Galbraith et al. (2012) showed that the MLI SST was, on average, 0.33°C colder than the Pathfinder V5.2 SST for the Gulf of St. Lawrence, but that seasonal means were highly correlated ($R^2 = 0.83$). The trends calculated using both time series were also similar and within confidence intervals.

In the current study, due to the high cloud cover over certain regions, full-resolution (1 km) monthly composites have been used. Seasonal averages were calculated over the months of December–January–February (winter), March–April–May (spring), June–July–August (summer), and September–October–November (fall) using all the available data during the period. To increase the spatial coverage for the Arctic, no minimum number of data was imposed to calculate the mean

[1] http://ogsl.ca/en/remotesensing/data.html

values. So, even if only a single SST datum was available during the entire 28 years of monthly averages, it has been incorporated into the seasonal composites leading to observed SSTs, even in the winter time for some areas that are often ice-covered (e.g., Great Lakes).

Physical forcings responsible for long-term trends operate at large spatial scales, and SST exhibits a strong spatial coherence, even in areas affected by physical processes such as upwellings (Ouellet et al. 2003). The trend analysis was thus done using averages of 4 × 4 pixels in order to reduce computation time while maintaining a good spatial resolution.

RESULTS

Spatial and Seasonal Variability

Considering the wide geographical extent of the study (Figure 1), results were used to highlight global and regional features only. Readers are invited to zoom into the images if they are interested in more local details. Using climatologies to discuss dynamical features also implies that only permanent or quasi-permanent features having an SST signature will be apparent in the results. For all regions, results are coherent with other climatologies based on satellite/in situ data or models (such as the Extended Reconstructed Sea Surface Temperature or the World Ocean Atlas Climatology), but with a much higher spatial resolution, allowing observations of smaller-scale oceanographic features.

Eastern Canada

The Labrador Current, which takes its source at the exit of Hudson Strait and flows along the Labrador coast, is the most important oceanographic feature on the Canadian east coast (Urrego-Blanco and Sheng 2012), bringing cold Arctic waters and ice toward the southern regions (Figure 2). The main core of the Labrador Current flows along the shelf edge, but a smaller inshore branch also exists (Lazier and Wright 1993; Wang et al. 2015). The cold water advected by the Labrador Current has major impacts on the Canadian east coast SST, including the entire Grand Banks region during all seasons. The smaller inshore branch that flows along the Newfoundland coast is more visible in the summer and fall seasons, corresponding to times when its velocities are higher (Wang et al. 2015). In the summer, waters observed along the Labrador and Newfoundland coastlines are warmer than those further offshore. Banks located along the path of the Labrador Current also exhibit slightly warmer SST than the surrounding waters in the summer. The high SST difference between the main Labrador Current and the offshore Labrador Sea waters generates strong temperature fronts (Cyr and Larouche 2015).

Further south, in the Grand Banks region, the imprint of bathymetry is clearly visible on the seasonal SST maps where the main core of the Labrador Current divides in two branches, with the main branch flowing through Flemish Pass while the 2nd one flows around Flemish Cape (Han et al. 2008). At the end of its southern extension, the Labrador Current meets with the much warmer waters transported north by the Gulf Stream. Due to the strong SST contrast between both currents, the region where they meet is characterized by a large frequency of SST fronts (Cyr and Larouche 2015).

The Gulf of St. Lawrence is a large coastal sea strongly affected by the freshwater outflow from the St. Lawrence River and to a lesser degree by numerous rivers along its northern coast. Because of the seasonal ice cover (December to March), water is near the freezing point during a large portion of the year. Seasonal warming starts in April after the ice has melted (Galbraith et al. 2012) and strongly affects the shallow (<50 m) southern Gulf of St. Lawrence where averaged summer water temperatures reach 16°C–18°C. The large freshwater influx from the St. Lawrence River generates a strong buoyancy-driven current that flows along the Gaspé Peninsula, transporting freshwater toward the southern Gulf region (Benoit et al. 1985). Colder waters can be seen during the summer along the northern shore of the Gulf, resulting from the presence of wind-driven coastal upwellings (Bourque and Kelley 1995; Lacroix 1987) and from tidal mixing in the Jacques Cartier Passage. Cold water observed along the northern shore near the Strait of Belle Isle can also result from Labrador waters entering the Gulf of St. Lawrence (Urrego-Blanco and Sheng 2014). These areas have higher chlorophyll concentrations (Cyr and Larouche 2015) and are known to host different marine mammal species (Doniol-Valcroze et al. 2007). The St. Lawrence estuary is characterized by cold water temperatures throughout the year that result from the presence of a strong tidal-driven upwelling that brings waters from the cold intermediate layer to the surface (Cyr et al. 2015; Gratton et al. 1988) at its head, located near the Saguenay River.

The Scotian Shelf is characterized by the year-round presence of cold waters at the southwestern tip of Nova Scotia. Tidal mixing (Garrett et al. 1978; Loder and Greenberg 1986) and topographic upwelling (Tee et al. 1993) explain the presence of cold water in this area where higher chlorophyll concentrations are also observed (Cyr and Larouche 2015). In the Bay of Fundy, the large semidiurnal tide is the main factor explaining the presence of cold water observed during the summer and fall. A band of cooler waters running along the coastline of Nova Scotia corresponds to the location of the Nova Scotia Current that carries water from the Gulf of St. Lawrence to the Gulf of Maine (Urrego-Blanco and Sheng 2014). An area with warm water is also observed year-round, extending over Emerald Basin and Emerald Bank bounded to the east by the cooler waters of the Shelf Break Jet. The mean seasonal surface currents and the tides in these areas are characterized by low speeds that reduce mixing (de Margerie and Lank 1986; Urrego-Blanco and Sheng 2014) and allow the sea surface to retain more heat. Further south, the imprint of Georges Bank is clearly visible during the

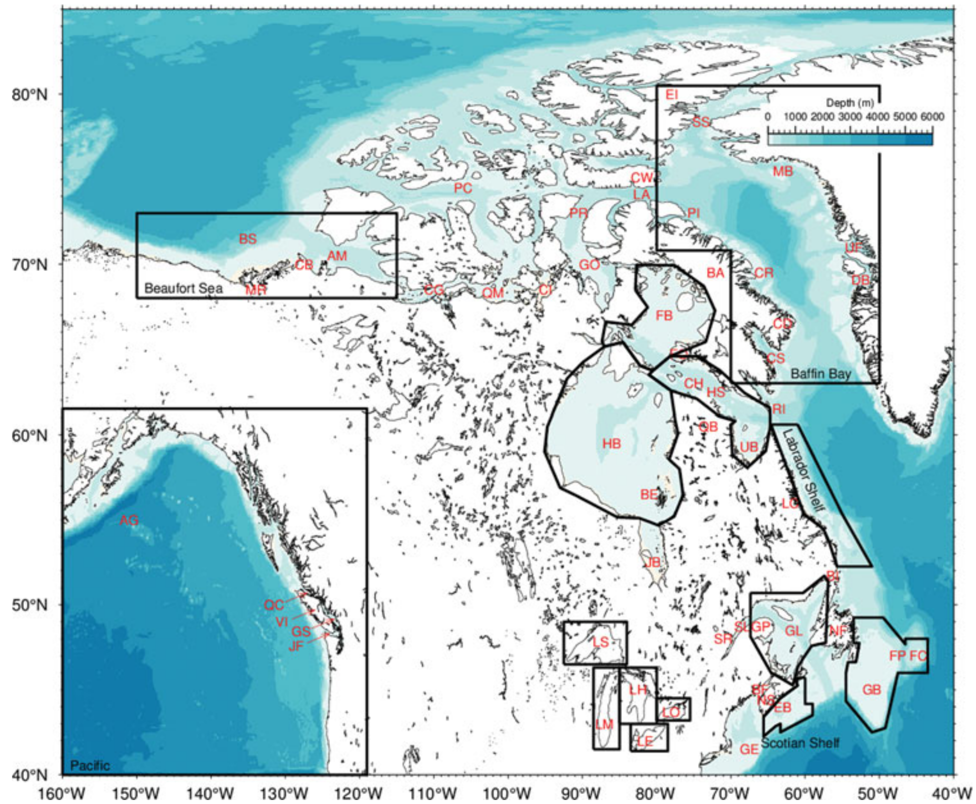

FIG. 1. Map showing the Canadian coastal seas. Bathymetry is in metres. The boxes are the areas that were used to calculate mean trends. Place names are: AG (Alaska Gyre), AM (Amundsen Gulf), BA (Baffin Island), BE (Belcher Islands), BF (Bay of Fundy), BI (Belle Isle Strait), BS (Beaufort Sea), CB (Cape Bathurst), CD (Cape Dyer), CH (Charles Island), CI (Chantrey Inlet), CG (Coronation Gulf), CR (Cape Raper), CS (Cumberland Sound), CW (Cape Warrender), DB (Disko Bay), EB (Emerald Basin), EI (Ellesmere Island), FB (Foxe Basin), FC (Flemish Cape), FP (Flemish Pass), FO (Foxe Peninsula), GB (Grand Banks), GE (Georges Banks), GL (Gulf of St. Lawrence), GP (Gaspe Peninsula), GS (Georgia Strait), HB (Hudson Bay), HS (Hudson Strait), JB (James Bay), JF (Juan de Fuca Strait), LC (Labrador Coast), LA (Lancaster Sound), LE (Lake Erie), LH (Lake Huron), LM (Lake Michigan), LO (Lake Ontario), LS (Lake Superior), MB (Melville Bay), MR (Mackenzie River), NF (Newfoundland), NS (Nova Scotia), PC (Parry Channel), PI (Pond Inlet), PR (Prince Regent Inlet), QB (Quebec), QC (Queen Charlotte Strait), QM (Queen Maud Gulf), RI (Resolution Island), SL (St. Lawrence estuary), SR (Saguenay River), SS (Smith Sound), UB (Ungava Bay), UF (Uummannaq Fjord), VI (Victoria Island).

summer and fall seasons, with a ring of colder water surrounding a central warm core.

Hudson Bay, Hudson Strait, Foxe Basin and Ungava Bay

Hudson Bay is a large interior sea that is almost totally ice covered between December and May. Figures 2c and 2d show that the central portion of the Bay is colder than the more coastal regions during the open-water season. An exception to this is the cold surface-water observed around the Belcher Islands, already described by Galbraith and Larouche (2011). Because tidal amplitude is small in that area, it is not clear if the observed cold water results from tidal or wind mixing (Cyr and Larouche 2015). Mixing around the Belcher Islands is thought to be responsible for the higher chlorophyll levels observed in that area (Harvey et al. 1997). Cold surface-water is also observed along the western shore of Hudson Bay, an area known for wind-driven upwellings (Gunn 2014). The southern tip of James Bay is where the maximum temperatures are observed, with summer values reaching 15°C resulting from the very shallow water depth in that area.

Foxe Basin does not show much spatial structure and is characterized by the presence of very cold waters throughout the year. A patch of near-freezing water is always observed northwest of Foxe Peninsula where strong tidal mixing occurs (Drinkwater and Jones 1987), while warmer SSTs are limited to small areas along the western coast of Baffin Island.

Hudson Strait and Ungava Bay are also characterized by low SST. Ungava Bay, where strong tidal mixing is expected to keep the surface waters cold, does not show any prominent features except at its southern end where some higher temperatures are

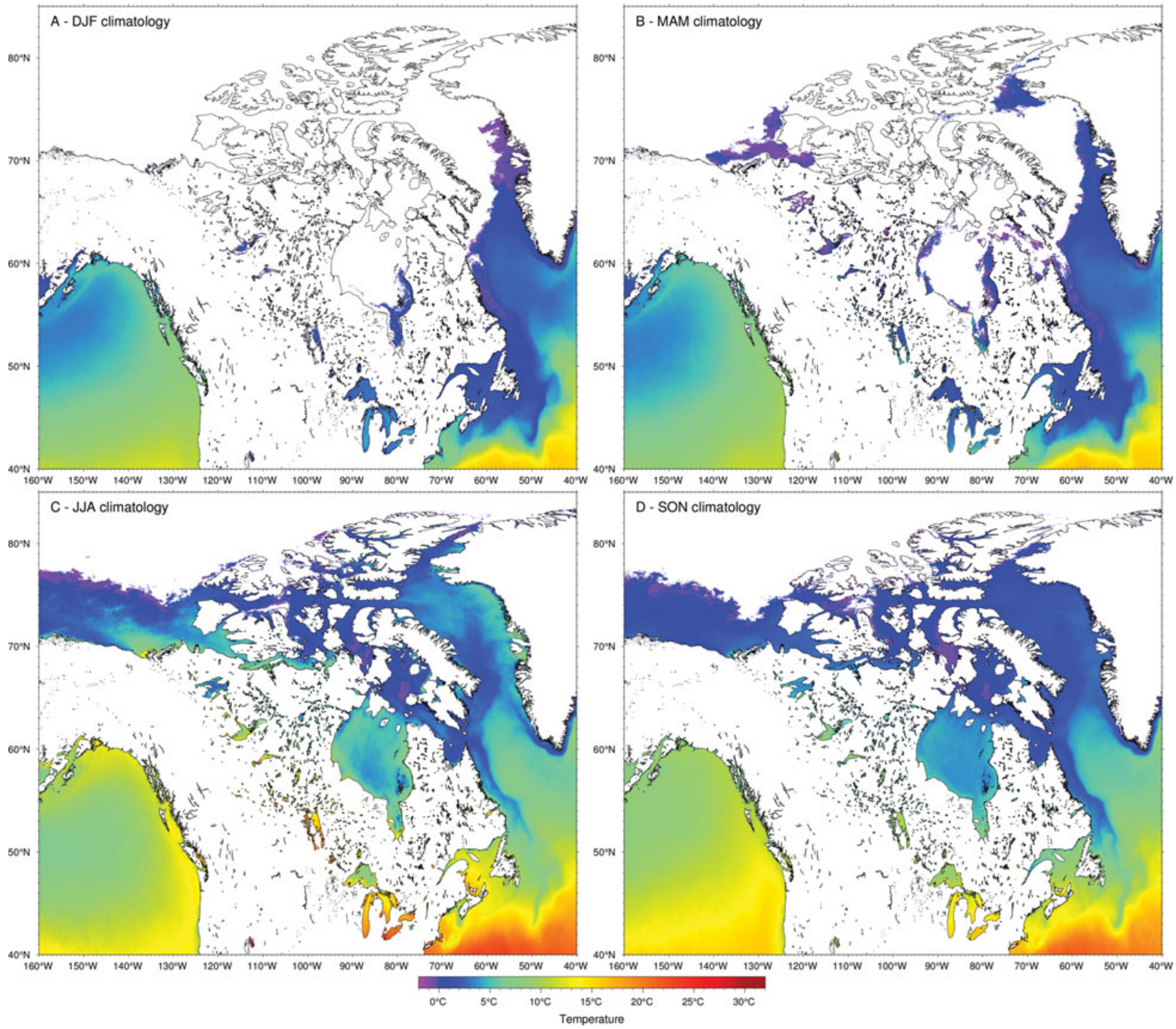

FIG. 2. Seasonal sea surface temperature climatologies (1985–2013). (a) December–January–February, (s) March–April–May, (c) June–July–August, (d) September–October–November.

observed during the summer season. These warmer SSTs might partially result from the freshwater flux (~ 4,500 m^3s^{-1}; Déry et al. 2005) of rivers emptying into that area. The central portion of Hudson Strait shows slightly higher temperatures than the waters near the coasts in the summer. This results from the presence of a current flowing west along the shore of Baffin Island, bringing cold Baffin Bay waters into that area (Straneo and Saucier 2008). On the southern side, a strong density-driven coastal current flows along the Quebec coast (Saucier et al. 2004). Despite this current, the influence of the relatively warm SST exiting Hudson Bay appears limited to the area west of Charles Island. Strong tidal mixing near that island (Drinkwater and Jones 1987) is probably responsible for the disappearance of the surface signature of the coastal current. At the eastern end of Hudson Strait, the area around Resolution Island is characterized by near-freezing temperatures year-long, confirming high tidal mixing in that area (Griffiths et al. 1981) that generates persistent SST fronts (Cyr and Larouche 2015).

Baffin Bay

Baffin Bay is connected to the Arctic through Smith, Jones, and Lancaster Sounds and to the Atlantic through Davis Strait and is seasonally ice covered. The winter and spring SST distribution patterns clearly indicate the impact of the West Greenland Current on the eastern side of the Bay that limits ice formation and/or accelerates its degradation. The North Water Polynya in northern Baffin Bay is also visible in the spring. More features become apparent during the summer season as the sea surface begins to warm along the west Greenland coast, in particular in Disko Bay and Uummannaq Fjord where seasonal heating is more intense (Figure 2c). The West Greenland Current is clearly seen flowing NNW along the shelf break until it turns west, following bathymetry to join the outflow along Baffin Island (Wu et al. 2012). In the northern portion of Baffin Bay, low SSTs are observed along the coast of Melville Bay, an area known for its large number of melting glaciers that influence surface-water properties (Lobb et al. 2003; Valeur et al. 1996). Further north, in Smith Sound, near-freezing water flowing south maintains low SST throughout the year, with some heating taking place on the eastern side of the Sound. This cold Arctic water is advected south along Ellesmere Island until it reaches Lancaster Sound. In situ measurements indicate that this current makes an incursion into the Sound before recirculating cyclonically and exiting on the southern side of Lancaster Sound (De Lange Boom et al. 1982; Fissel et al. 1982; Wang et al. 2012). Despite its weak SST signature, that circulation pattern is apparent in the summer climatology extending west to Cape Warrender. In the summer, SSTs on the western side of Baffin Bay are slightly higher (4°C–5°C) between Pond Inlet and Cape Raper than they are further south, where SSTs remain low year-long except in Cumberland Sound. By fall, most surface features have disappeared in Baffin Bay.

Beaufort Sea and the Canadian Archipelago

The ice cover in the Beaufort Sea normally starts to disappear in the spring from the south due to the dominant wind patterns that push the ice out of the Amundsen Gulf (Galley et al. 2008), creating a large shore lead polynya. Over time, the ice edge moves northward, freeing a large open-water area. The Beaufort Sea is characterized by the presence of a large, shallow continental shelf that is strongly affected by the freshwater outflow of the Mackenzie River. Not surprisingly, the highest SST observed during the summer and fall periods are all located near the mouth of the Mackenzie River and roughly correspond to the area influenced by its freshwater plume. The spreading of the plume depends on the local winds (Mulligan et al. 2010) but in a climatological sense, the plume appears to extend toward the northwest in response to the dominant wind pattern. The high summer SSTs (∼15°C) observed around the Mackenzie delta are consistent with in situ observations (Mulligan et al. 2010) and are the warmest Arctic waters at this latitude and higher.

At the eastern end of the Mackenzie shelf, the area directly northwest of Cape Bathurst is known for the presence of relatively cold waters. Evidence of upwellings in that area has been observed in the past (Lanos 2009; Sévigny et al. 2015; Williams and Carmack 2008). The main process generating these upwellings is the presence of northeasterly winds that, combined with isobath divergence, result in stronger mixing (Williams and Carmack 2008). Strong tidal mixing is also present in that area (Kulikov et al. 2004). These cold waters are nutrient rich, sustaining enhanced primary production (Tremblay et al. 2014).

In the Amundsen Gulf, summer surface warming happens mainly in bays and inlets with the central, deeper portion remaining colder throughout the summer period. In the Canadian Archipelago, SST remains low all the time except in the more southern area of Coronation Gulf, Queen Maud Gulf, and Chantrey Inlet, where averaged summer SST can reach 7°C–8°C, and in some inlets and fjords on the west side of Ellesmere Island. In the southern Gulf of Boothia, SST is at the freezing point even in the summer. It is also worth noting that the Northwest Passage seaway that runs through Parry Channel and directly links Baffin Bay to the Beaufort Sea remains cold all year.

Northeastern Pacific

The main dynamical feature observed in the northeastern Pacific SST climatologies (Figure 2) is the Alaska Gyre that is clearly visible during the winter and the spring seasons as an area with SST of 3°C–4°C. The Alaska Gyre is bounded to the south by the North Pacific Current and to the east and north by the Alaska Current. This cyclonic gyre is known to be an area of low biological production despite the presence of high nutrients brought to the surface by the gyre (Gargett 1991). The northeastern Pacific region is also characterized by a latitudinal gradient of SST and the presence of warmer temperatures along the coast. Maximum temperatures are reached during the summer season when stronger coast to offshore SST gradients exist. In other seasons, temperatures are much more homogeneous over a large coastal extent. Maximum SST (∼ 18°C) are observed in the summer, covering much of the Strait of Georgia. The impact of coastal upwellings on the SST spatial structure can be observed along Vancouver Island during the summer and fall seasons due to a shift of dominant winds (Cummins and Masson 2014; Thomson et al. 2014). Relatively low SST can also be observed in Queen Charlotte Strait and Juan de Fuca Strait. This latter region is characterized by strong tidal mixing (Cummins and Masson 2014; Masson 2006) and a seasonal eddy (Freeland and Denman 1982) and is known for the presence of whales (Dalla Rosa et al. 2012).

Great Lakes

The Great Lakes represent 18% of the world's surface freshwater and play a significant role as a source of freshwater to the Canadian marine coastal ecosystem. They also compose a major seaway and influence regional climate (Lofgren 1997). Extending over 1,000 km in a north–south direction, the principal characteristic of the Great Lakes SST is a strong latitudinal gradient clearly visible at all seasons (Figure 2). During the summer, the SST difference between Lake Superior and Lake Erie reaches ∼ 15°C. Lakes Ontario and Erie show a small spatial SST variability in the summer. The central deeper portion of Lake Michigan shows slightly cooler SST than its southern and northern ends and a patch of cooler water (∼ 13°C) is observed

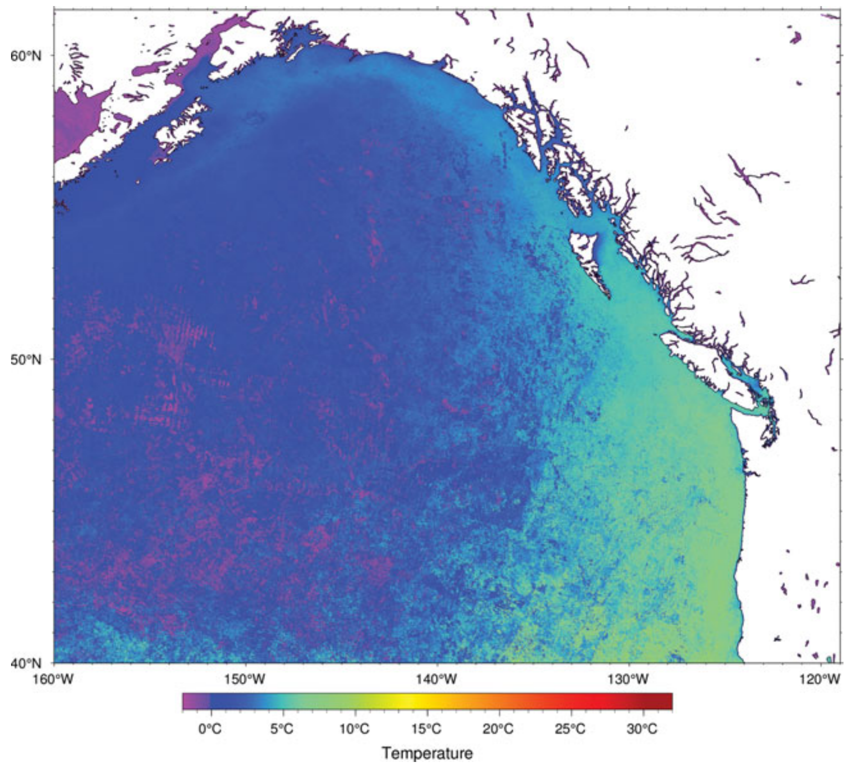

FIG. 3. Minimum monthly sea surface temperature for the northwestern Pacific region.

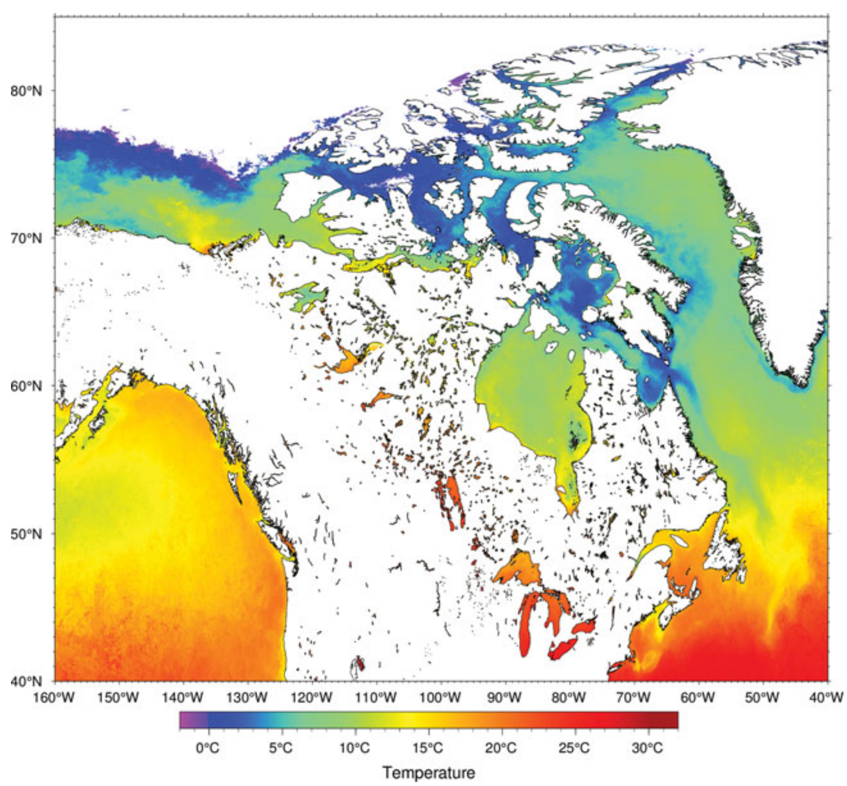

FIG. 4. Maximum monthly sea surface temperature map.

over the deeper central portion of Lake Huron in summer and fall, leading to higher latent heat flux in these areas (Lofgren and Zhu 1999). The nearshore shallow areas of Lake Superior get relatively warm (∼ 15°C) in the summer while the offshore region remains cool (8°C–10°C) leading to the presence of SST fronts aligned with the coastline (Ullman et al. 1998). In the fall, SSTs are lower on the Canadian side of Lake Ontario, indicating that wind-driven upwellings (Gächter et al. 1974; Simons and Schertzer 1987) have a more profound impact on the surface temperature during that season, and/or that seasonal cooling happens faster in that shallower portion of the lake. Lake Superior has approximately the same SST in the fall as in the summer indicating a strong buffer effect due to the large heat capacity of the deep waters. The presence of upwelling along the western shore of Lake Michigan (Plattner et al. 2006) is not evident in the summer SST climatology but becomes apparent in the fall.

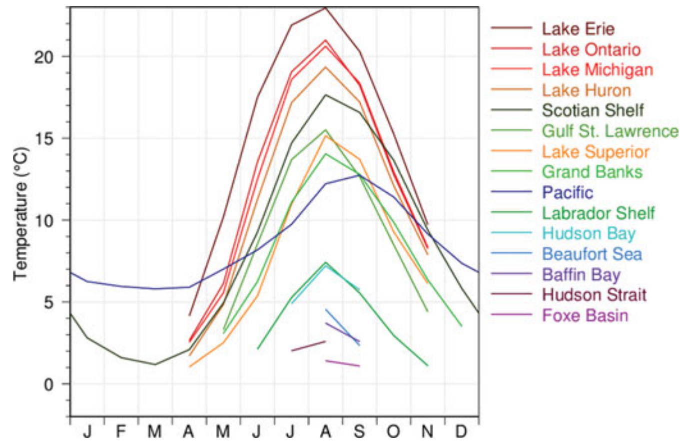

FIG. 5. Sea surface temperature annual cycle for the regions defined in Figure 1.

SST Extremes and Amplitude

Because many fishes and invertebrates are affected by temperature during some part of their life cycle, knowledge of extreme temperatures recorded at specific locations is important for coastal waters fisheries management. As seen in the previous section, the Canadian coastal waters are characterized by large seasonal amplitude of their SST, resulting from the impact of a cold winter climate. As a consequence, during the winter, most coastal waters are at the freezing point of seawater (−1.8°C). Minimum monthly temperature recorded over the 28 years of data is, thus, similar everywhere except in the northeastern Pacific region (Figure 3) and in the Gulf of Maine (1°C–3°C). More interesting is the maximum monthly SST observed over the 28-year period that provides an indication of extreme values that can be reached in a specific location (Figure 4). Because our analysis is based on monthly composites, daily SST extremes will be higher. Figure 4 shows that in the northeastern Pacific, extreme SSTs are ∼ 18°C over a region extending far from the coast. Localized zones such as the northwest tip of Vancouver Island, with lower extreme SSTs, correspond to permanent high-mixing or upwelling areas that greatly limit the seasonal warming of the sea surface. Maximum values are similar across the Great Lakes except for Lake Superior, which shows cooler extreme SST, and Lake Erie, which shows higher extremes. The Labrador Current shows its imprint over the eastern Canadian coastal waters with extreme values that are less than those of the surrounding waters. As in the Pacific, areas where upwellings and high mixing occur, such as the Bay of Fundy and the southern tip of Nova Scotia, are characterized by lower extreme SST. Going further north, extreme SST become lower. The west side of Baffin Bay can reach temperatures that are lower than on the east side, resulting from the presence of the cold Arctic water flowing along the Ellesmere and Baffin Islands. Hudson Bay is characterized by extreme SSTs that are similar (∼ 10°C) over much of the bay except near the coast, in river plumes, and in southern James Bay. Much of the Canadian Archipelago shows very low extreme SST indicating that these waters never warmed above ∼ 3°C–4°C, at least, over monthly averages. Despite its northern location, the coastal Beaufort Sea (including the Amundsen Gulf) can reach extreme SST of ∼ 10°C, with the mouth and plume of the Mackenzie River reaching higher values.

Another interesting piece of information with biological consequences is contained within the SST data. Figure 5 shows the climatological mean of the annual SST cycle for the different regions defined in Figure 1. The warmest month of the year is August, except in the northwest Pacific where the maximum occurs in September. Because of the presence of an ice cover, the span of the yearly SST cycle is reduced while moving to northern regions. Only the Pacific and the Scotian Shelf regions have an SST cycle that covers the full year. The yearly SST cycle amplitude also varies greatly with location. Figure 6 shows the mean annual SST amplitude recorded over 28 years. Except at some small coastal locations where upwelling and mixing limit the yearly range of SST, the average seasonal warming for the entire northeast Pacific is quite spatially homogeneous at ∼ 8°C. Another exception is the Georgia Strait where the amplitude is ∼ 14°C. This is probably a result of the high vertical stability induced by the Fraser River freshwater outflow that keeps the heat in the surface layer. This area has been shown to have the highest annual chlorophyll concentration of the entire west coast, also possibly resulting from the stratification enhancement (Jackson et al. 2015).

The coastal ecosystems most affected by seasonal warming are all located in eastern Canada. The Gulf of St. Lawrence, the Scotian Shelf, the Newfoundland Shelf, the Grand Banks and the Great Lakes all experience a large yearly SST excursion. The relatively shallow (19 m) Lake Erie experiences the largest seasonal heating of the 5 Great Lakes with a range of more than 25°C. For the Canadian marine coastal waters, the highest mean yearly SST amplitudes are located in the southern Gulf of St. Lawrence and adjacent Scotian Shelf, confirming model

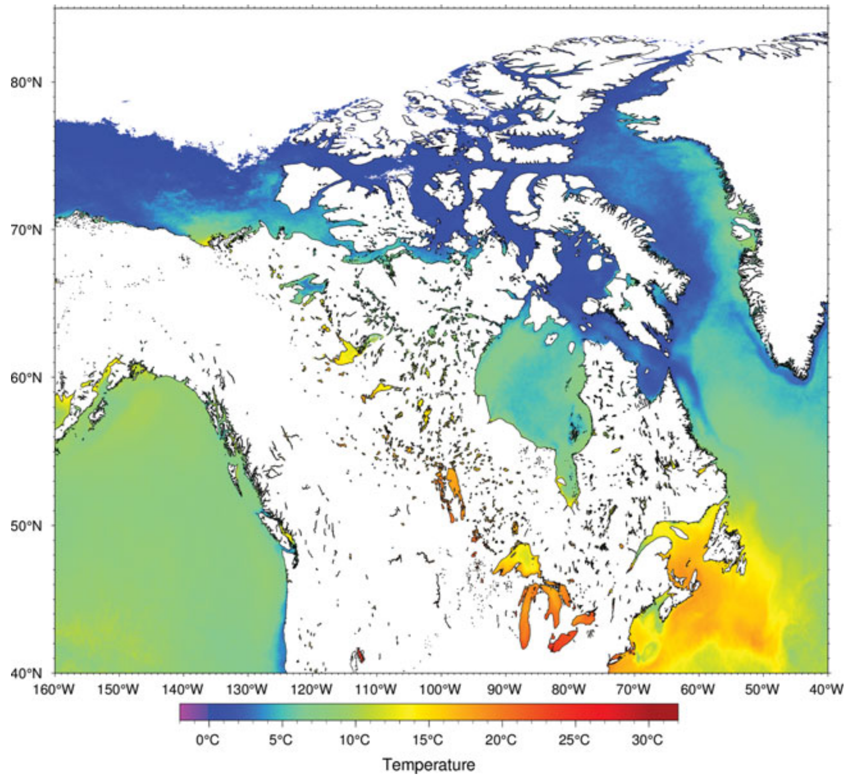

FIG. 6. Climatological sea surface temperature annual amplitude.

results (Geshelin et al. 1999) and the coherence of SST over these areas (Urrego-Blanco and Sheng 2014). The effect of tidal mixing is clearly visible at the southern tip of Nova Scotia, in the Bay of Fundy, and in the St. Lawrence estuary where SST does not increase much during the summer season. The mean seasonal range of SST in these areas is similar to the range observed at much higher latitudes such as Hudson Bay and Baffin Bay, providing these waters with year-long sub-Arctic surface temperatures. Another feature is the quasi absence of a seasonal cycle in most of the Canadian Archipelago, including Hudson Strait, Foxe Basin, Ungava Bay, the western side of Baffin Bay, and the northern Labrador shelf, consistent with model results (Carton et al. 2015). Hudson Bay has a mean seasonal cycle of $\sim$ 6°C–8°C with indications that the amplitude is less in its central part and around the Belcher Islands. Finally, most of the Beaufort Sea coastal waters and the southern half of Amundsen Gulf are, considering their high latitude, characterized by a relatively large mean seasonal SST amplitude ($\sim$ 6°C–8°C) that can reach 13°C near the Mackenzie River mouth. This particularity of the Canadian coastal arctic is not seen in the results of the low-resolution models (Carton et al. 2015), showing the importance of using high spatial-resolution data for the observation of the coastal regions. Further offshore, and despite a constantly decreasing sea ice cover in the Beaufort Sea, the SST seasonal amplitude is still very small.

Recent Sea Surface Temperature Trends

Figure 7 shows the map of SST temporal trends of annual maximal monthly SST for the Canadian coastal waters based on 4 km x 4 km averages. Table 1 shows the spatially averaged trend over the regions shown in Figure 1. As previously shown, the SST maximum generally occurs in August, except for the Pacific region where it occurs in September. Using the maximum yearly SST integrates the seasonal warming to a single accumulated value. In order to make sure that this method did not induce biases in the trend calculations, an alternate method of estimating warming trends was also done over each region. First, only those months with 90% or more of available pixel data were included in the average, except for the northwest Pacific (for lower returns in 1985–1988), and the sea-ice covered areas of Baffin Bay, Beaufort Sea, Foxe Basin, Hudson Bay, and Hudson Strait, for which a lower threshold of 50% was used. Then, for each region, an anomaly time series was created for each month and seasonal means were calculated by averaging available anomalies in each year for the range of months selected (all months of the year, when possible, and summer months in sea-ice covered areas; see Table 1). Finally, the seasonal average of the monthly climatological means was added. This procedure yields identical results to those obtained by calculating the mean of monthly average temperatures, except that it allows for some missing monthly means. The resulting time series for each

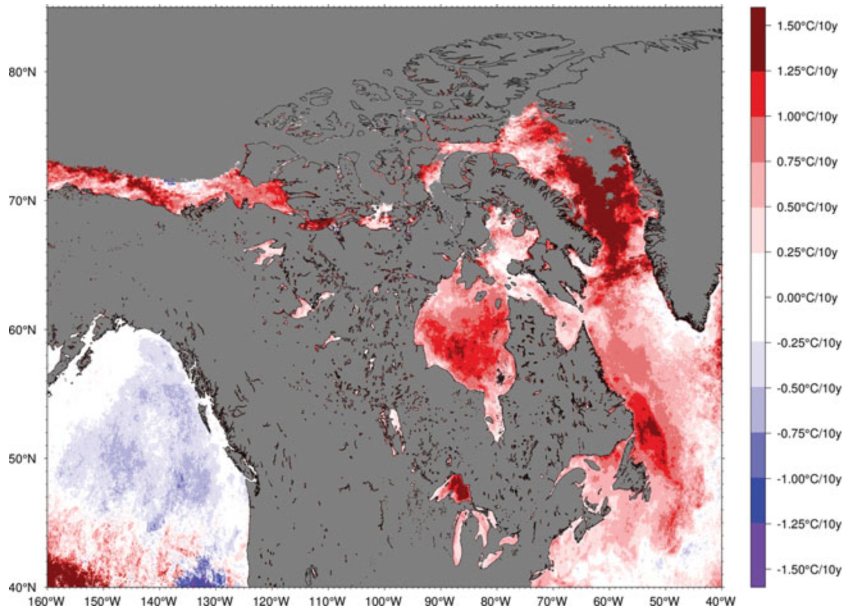

FIG. 7. Trend of the annual maximal monthly sea surface temperature (1985–2013).

region are shown in Figure 8. Linear trends were then computed for each time series. Table 1 shows that calculated trends are similar using both methods, in spite of the fact that the 1st method documents the warming trend of the warmest month of the year and the 2nd deals with averages over many months of the year. Because of their higher spatial resolution, we will, thus, use the results of the 1st method for the following description.

These trends were calculated using 28 years of recent data, so they are not representative of longer (∼ 100 years)

TABLE 1
Warming trends over Canadian coastal seas using 2 alternate methods: average (standard deviation) of all 4 km × 4 km trends computed using the interannual time series of maximum monthly temperature for specific areas; trend (95% confidence interval) of interannual seasonally averaged temperature over the same areas. The months used for the seasonal average are also shown.

Area	Years spanned	Warming trend using the annual monthly SST maximum (°C per decade)	Warming trend using the seasonally averaged SST (°C per decade)
Pacific northwest	1985–2012	−0.05 (0.54)	0.21 (0.30) Jan–Dec
Beaufort Sea	1985–2012	0.81 (0.41)	0.14 (0.57) Jul–Sep
Baffin Bay	1993–2012	1.08 (0.51)	0.82 (0.34) Aug–Sep
Hudson Bay	1985–2012	0.87 (0.23)	0.85 (0.47) Jul–Sep
Hudson Strait/Ungava Bay	1985–2012	0.51 (0.25)	0.55 (0.25) Jul–Aug
Foxe Basin	1985–2012	0.56 (0.42)	0.29 (0.37) Aug–Sep
Labrador Shelf	1985–2012	0.90 (0.22)	0.80 (0.27) Jun–Nov
Grand Banks	1985–2012	0.68 (0.19)	0.69 (0.36) May–Dec
Scotian Shelf	1985–2012	0.46 (0.10)	0.59 (0.26) Jan–Dec
Gulf of St. Lawrence	1985–2012	0.67 (0.24)	0.57 (0.24) May–Nov
Lake Superior	1985–2012	0.94 (0.45)	0.81 (0.50) Apr–Nov
Lake Michigan	1985–2012	0.54 (0.26)	0.61 (0.40) Apr–Nov
Lake Huron	1985–2012	0.50 (0.30)	0.61 (0.36) Apr–Nov
Lake Erie	1985–2012	0.44 (0.25)	0.49 (0.28) Apr–Nov
Lake Ontario	1985–2012	0.55 (0.31)	0.59 (0.32) Apr–Nov
All oceans (IPCC 2014)	1971–2010	0.11	0.11

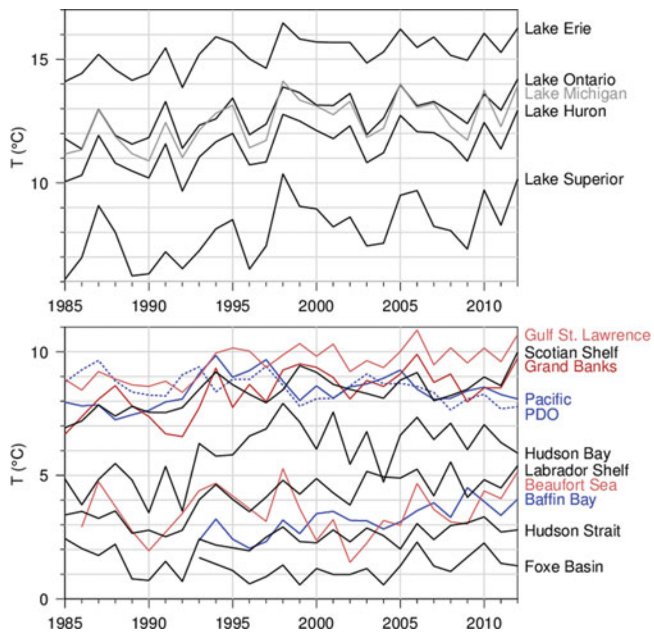

FIG. 8. Seasonally-averaged sea surface temperature over regions defined in Figure 1. Months used in the seasonal averaging are listed in Table 1. An index of the Pacific Decadal Oscillation is also shown for comparison with the northwest Pacific time series.

climatic trends. Trends calculated using yearly SST maximums (Figure 7) are, however, statistically significant (95%) everywhere except in the Beaufort Sea and a small portion of the Grand Banks. The lack of significance for these 2 areas reflects a strong interannual variability of the annual maximal SST. Trends from seasonally averaged temperatures are significant everywhere except for the Beaufort Sea, Foxe Basin, and the northwest Pacific regions.

Figure 8 shows that the April–November averaged SST time series for the Great Lakes are very similar, with cross-correlation coefficients ranging from $R^2 = 0.73$ (between the farthest separated Lakes Erie and Superior) to 0.96 (between Lake Huron and Lake Michigan). Figure 7 shows that the strongest SST trend is observed over the deeper portion of Lake Superior, with values reaching between 1°C to 2°C per decade, although no trend is observed in the western portion of the lake. These values are higher than those evaluated using in situ weather buoys (∼ 1°C/10 years; Austin and Colman 2007). Austin and Allen (2011), using a 1-dimensional model, showed that summer SSTs result from the combined effect of air temperature, wind speed, and previous winter ice cover for Lake Superior. The observed difference with previous results can, thus, be explained not only by the different period covered by the buoy data (1979–2006) but also by the fact that trends calculated using the buoy data were based on summer (July–August–September) data only while our calculations reflect the annual monthly maximal SST. Trends are smaller and not spatially homogeneous for the other 4 Great Lakes. A small positive trend (0.5°C–1°C/10 years) is observed along the western shore of Lake Michigan. Because this is an area of wind-driven upwellings (Plattner et al. 2006), this could indicate a decreasing strength of upwelling-favorable winds or a warming of the upwelled waters. In lakes Huron and Erie, small positive trends were observed above the deeper portion of the lakes. This is consistent with values evaluated using in situ measurements that showed the shallower western Lake Erie to have either no significant or very small SST trends (Austin and Colman 2007; Burns et al. 2005). No spatial patterns are visible in Lake Ontario, with the entire water body experiencing a small positive trend of 0.55°C/10 years. Altogether, the trends in the Great Lakes are consistent with other studies that showed values of 0.5°C–0.6°C/10 years (Schneider and Hook 2010).

In eastern Canada, some high positive trends (0.5°C–1.5°C/10 years) occur along the Labrador and Newfoundland coasts, extending into Flemish Pass and over Flemish Cape, confirming that this area is experiencing one of the highest large marine ecosystems warming (Sherman et al. 2009). The area located between the inshore and offshore Labrador Current, which consists of a series of banks, is characterized by stronger positive trends. In the Gulf of St. Lawrence, there is a spatial gradient of trends with smaller positive values (0.25°C–0.75°C/10 years) observed over most of the Gulf and higher values (0.75°C–1.5°C/10 years) observed in the northeastern portion. The calculated values are generally consistent with previous estimates of summer SST trends for that area (Galbraith et al. 2012). SST in the Gulf has been shown to be highly correlated to air temperatures and atmospheric forcing (Galbraith et al. 2012; Urrego-Blanco and Sheng 2014). The trend in the St. Lawrence estuary might be due to a combination of both direct air temperature effect and an increase of the cold intermediate layer temperature that is upwelled at the head of the estuary (Galbraith et al. 2014). The Scotian Shelf is characterized by small positive trends (0.25°C–0.5°C/10 years) located mostly over Emerald Basin. This area is characterized by complex interactions between the cold waters advected from the north and the movement of the Gulf Stream (Urrego-Blanco and Sheng 2012). The cross-correlation coefficient between the Gulf of St. Lawrence and Scotian Shelf time series ($R^2 = 0.70$) indicates a strong link between the 2 regions in spite of different ranges of months used for the analysis (Table 1).

Small to medium warming trends (0.5°C–1.5°C/10 years) are observed in Hudson Bay with the higher values located in the central part of the bay. In Hudson Strait, the strongest trends (0.5°C–1°C/10 years) are located along the central axis of the strait. Trends in most of Ungava Bay are smaller (0.25°C–0.5°C/10 years). These values for both Hudson Bay and Hudson Strait are consistent with results from a previous study done using only the warmest week of the year for the period 1985–2009 (Galbraith and Larouche 2011), which also showed a strong relation between SST and air temperature.

The largest warming trends (1.5°C–2.5°C/10 years) over all Canadian waters are located in the central portion of Baffin

Bay along a line extending from Cape Dyer to Melville Bay, while the northwest part of Baffin Bay shows very small trends (< 0.25°C/10 years). Caution must, however, be used because most 4 km x 4 km groups of pixels have a much shorter time series than other regions, as the period from 1985 to 1992 had much lower data availability due to heavy sea-ice cover. The entrance of Lancaster Sound, Prince Regent Inlet, and Coronation Gulf areas all show trends between 0.5°C and 1.5°C/10 years. For the rest of the Arctic region (Canadian Archipelago, Foxe Basin), trends are very small except in localized coastal areas.

For the northeastern Pacific region, the results show that most of the area experienced neither positive nor negative trends over the 1985–2012 period, including the coastal regions. Some small negative trends (0.25°C–0.75°C/10 years) are observed in the offshore regions, consistent with the shift from a positive to a negative Pacific Decadal Oscillation in the late 1990s (Ding et al. 2013). Indeed, the cross-correlation between the Pacific Decadal Oscillation annual average (Figure 8) and the SST seasonal time series for the time period 1993–2012 explains 50% of the variance.

DISCUSSION

Results showed that there is a strong spatial coherence of SST for the 3 coastal regions surrounding Canada. The use of the full-resolution remote sensing data provided much higher spatial information about many regional features such as coastal upwellings, high mixing areas, etc. The results confirmed that the eastern Canadian shelves are the most variable (Thompson et al. 1988), with the Labrador Current affecting the entire region. The Pacific is the least variable water body, characterized by small yearly SST amplitudes and no significant trends over the recent 28 years. In general, the results are coherent with other studies on SST variability in the Canadian coastal regions (Brand et al. 2014). The trends calculated by using the recent remote sensing data are higher than those that were calculated using long-term in situ databases (Geshelin 1999), reflecting the impact of the recent ocean warming.

SST variability in the oceans results from a combination of atmospheric and oceanic processes (Deser, Alexander, et al. 2010). Previous research showed that the main factors affecting SST trends in the Atlantic sector are a combination of the North Atlantic Oscillation, the Atlantic Multidecadal Oscillation, the Arctic Oscillation and anthropogenic forcing acting on different time scales (Greene et al. 2013; Guan and Nigam 2009; Head and Sameoto 2007; Ting et al. 2014). In the Pacific, the North Pacific Oscillation and the El-Niño Southern Oscillation all contribute to the observed SST variability (Bond et al. 2003; Deser, Alexander, et al. 2010; Kumar et al. 2014; Linkin and Nigam 2008). The observed interannual variability in the record shown here for the northwest Pacific is partly consistent with the Pacific Decadal Oscillation, at least in later years.

The trend analysis showed that Baffin Bay, followed by Lake Superior, Labrador coast, and Hudson Bay are the areas that are changing the more rapidly. The area average trend for the Beaufort Sea is also very high (0.81°C/10 years), which is consistent with the decrease of sea-ice over the last few decades (Wang and Overland 2012). Trends in the Gulf of St. Lawrence and Hudson Bay have already been discussed elsewhere (Galbraith and Larouche 2011; Galbraith et al. 2012) and indicate a clear link between air temperatures and SST. In Baffin Bay, there appears to be a good spatial association between the SST change and the reduction of sea ice that results from an increase in downward infrared radiation (Park, Lee, and Feldstein 2015). Interestingly, this is also an area where a strong seasonal salinity cycle exists (Sena Martins et al. 2015), possibly indicating an increase in stratification due to seasonal ice loss. The Canadian trends are much higher than the mean warming rate of the global oceans' surface layer (0.11°C/10 years) over the period 1971–2010 (IPCC 2014), except for the northwest Pacific. This implies that changes are expected to occur faster than the global average and generate a more significant impact on the Canadian coastal marine ecosystems.

Because they are limited to a relatively short period (28 years), these values are biased toward the more recent warming period as shown by Galbraith et al. (2012) for the St. Lawrence Gulf and Ting et al. (2014) for the North Atlantic. This also explains why the calculated trends in the northeastern Pacific are different from previous estimates done using longer time series that showed some small heating trends in the Alaska Gulf (Freeland 2013) or from models that predict much warmer SSTs in the future (IPCC 2014). Also, our time series does not include the strong positive SST anomaly observed since the winter of 2013–2014 over the northeastern Pacific (Bond et al. 2015). In the east, except in some areas such as the southern tip of Nova Scotia, which show relative SST stability and might, thus, become oases to some species, there are clear indications that profound changes are happening in the surface coastal waters. These changes can lead to impacts on primary production and the upper trophic levels that are difficult to evaluate because temperature is not the sole factor regulating fisheries, due to the complex nature of food webs (Heath et al. 2012). Potential impacts include longer ice-free seasons that could lead to higher SSTs and an enhanced primary production (Arrigo and van Dijken 2015), a reorganization of the seasonality of the plankton food web (Reygondeau et al. 2015; Villarino et al. 2015), a change of dominant zooplankton species (Kjellerup et al. 2015; Kjellerup et al. 2012) enhanced grazing on phytoplankton biomass (Paul et al. 2015) and changes in body conditions of marine vertebrates (Harwood et al. 2015). Changes in the thermal habitat can also lead to northward migrations of species (Beaugrand et al. 2009; Taboada and Anadón 2012; Villarino et al. 2015) and affect their spawning grounds (Basilone et al. 2013). Finally, temperature is also a factor in the regulation of CO_2 absorption by the oceans that leads to acidification and impacts the oceanic carbon cycle (Lefebvre et al. 2012).

CONCLUSION

Significant changes of the sea surface temperature have occurred along the Canadian coasts during the last 28 years. The trends calculated in this study are, however, only representative of the recent years and should thus be used with caution when making future projections because the values are highly dependent on the length of the time series that cannot resolve interdecadal variability. Despite these limitations, the information provided is considered important for fisheries/aquaculture management and the development of climate adaptation strategies because some regions with small seasonal amplitudes and warming trends might become oases for specific species.

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REFERENCES

Ardyna, M., Babin, M., Gosselin, M., Devred, E., Rainville, L., and Tremblay, J.-É. 2014. "Recent Arctic Ocean sea ice loss triggers novel fall phytoplankton blooms." *Geophysical Research Letters*, Vol. 41(No. 17): pp. 2014GL061047. doi: 10.1002/2014gl061047.

Arrigo, K.R., and van Dijken, G.L. 2015. "Continued increases in Arctic Ocean primary production." *Progress in Oceanography*, Vol. 136, pp. 60–70. doi: 10.1016/j.pocean.2015.05.002.

Austin, J.A., and Allen, J. 2011. "Sensitivity of summer Lake Superior thermal structure to meteorological forcing." *Limnology and Oceanography*, Vol. 56(No. 3): pp. 1141–1154. doi: 10.4319/lo.2011.56.3.1141.

Austin, J.A., and Colman, S.M. 2007. "Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: a positive ice-albedo feedback." *Geophysical Research Letters*, Vol. 34(No. 6): p. L06604. doi: 10.1029/2006gl029021.

Barale, V., Schiller, C., Villacastin, C., and Tacchi, R. 2004. "The Adriatic sea surface temperature historical record from advanced very high resolution radiometer data (1981–1999)." *International Journal of Remote Sensing*, Vol. 25(No. 7–8): pp. 1363–1369.

Basilone, G., Bonanno, A., Patti, B., Mazzola, S., Barra, M., Cuttitta, A., and McBride, R. 2013. "Spawning site selection by European anchovy (*Engraulis encrasicolus*) in relation to oceanographic conditions in the Strait of Sicily." *Fisheries Oceanography*, Vol. 22(No. 4): pp. 309–323. doi: 10.1111/fog.12024.

Beamish, R.J., Riddell, B.E., Lange, K.L., Farley Jr., E., Kang, S., Nagasawa, T., Radchenko, V., Temnykh, O., and Urawa, S. 2009. *The Effects of Climate on Pacific Salmon—A Summary of Published Literature*. Vancouver, Canada: North Pacific Anadromous Fish Commission.

Beaugrand, G., Luczak, C., and Edwards, M. 2009. "Rapid biogeographical plankton shifts in the North Atlantic Ocean." *Global Change Biology*, Vol. 15(No. 7): pp. 1790–1803. doi: 10.1111/j.1365-2486.2009.01848.x.

Belkin, I.M. 2009. "Rapid warming of large marine ecosystems." *Progress in Oceanography*, Vol. 81(No. 1–4): pp. 207–213. doi: 10.1016/j.pocean.2009.04.011.

Benoit, J., El-Sabh, M.I., and Tang, C.L. 1985. "Structure and seasonal characteristics of the Gaspe current." *Journal of Geophysical Research*, Vol. 90(No. C2): pp. 3225–3236.

Bond, N.A., Cronin, M.F., Freeland, H., and Mantua, N. 2015. "Causes and impacts of the 2014 warm anomaly in the NE Pacific." *Geophysical Research Letters*, Vol. 42(No. 9): pp. GL063306. doi: 10.1002/2015gl063306.

Bond, N.A., Overland, J.E., Spillane, M., and Stabeno, P. 2003. "Recent shifts in the state of the North Pacific." *Geophysical Research Letters*, Vol. 30(No. 23): pp. 2183. doi: 10.1029/2003gl018597.

Bourque, M.-C., and Kelley, D.E. 1995. "Evidence of wind-driven upwelling in Jacques-Cartier strait." *Atmosphere-Ocean*, Vol. 33(No. 4): pp. 621–637.

Brand, U., Came, R.E., Affek, H., Azmy, K., Mooi, R., and Layton, K. 2014. "Climate-forced change in Hudson Bay seawater composition and temperature, Arctic Canada." *Chemical Geology*, Vol. 388: pp. 78–86. doi: 10.1016/j.chemgeo.2014.08.028.

Burns, N.M., Rockwell, D.C., Bertram, P.E., Dolan, D.M., and Ciborowski, J.J.H. 2005. "Trends in temperature, Secchi depth, and dissolved oxygen depletion rates in the central basin of Lake Erie, 1983-2002." *Journal of Great Lakes Research*, Vol. 31 (Supplement 2): pp. 35–49.

Carton, J.A., Ding, Y., and Arrigo, K.R. 2015. "The seasonal cycle of the Arctic Ocean under climate change." *Geophysical Research Letters*, Vol. 42(No. 18): pp. 7681–7686. doi: 10.1002/2015gl064514.

Cummins, P.F., and Masson, D. 2014. "Climatic variability and trends in the surface waters of coastal British Columbia." *Progress in Oceanography*, Vol. 120: pp. 279–290. doi: 10.1016/j.pocean.2013.10.002.

Cyr, F., Bourgault, D., Galbraith, P.S., and Gosselin, M. 2015. "Turbulent nitrate fluxes in the Lower St. Lawrence Estuary, Canada." *Journal of Geophysical Research*, Vol. 120(No. 3): pp. 2308–2330. doi: 10.1002/2014jc010272.

Cyr, F., and Larouche, P. 2015. "Thermal fronts atlas of Canadian coastal waters." *Atmosphere-Ocean*, Vol. 53(No. 2): pp. 212–236. doi: 10.1080/07055900.2014.986710.

Dalla Rosa, L., Ford, J.K.B., and Trites, A.W. 2012. "Distribution and relative abundance of humpback whales in relation to environmental variables in coastal British Columbia and adjacent waters." *Continental Shelf Research*, Vol. 36: pp. 89–104. doi: 10.1016/j.csr.2012.01.017.

De Lange Boom, B.R., MacNeill, M.R., and Buckley, J.R. 1982. "Iceberg motion in Lancaster sound and northwest Baffin Bay, Summer 1978." *Arctic*, Vol. 35(No. 1): pp. 219–233.

DelSole, T., Jia, L., and Tippett, M.K. 2013. "Decadal prediction of observed and simulated sea surface temperatures." *Geophysical Research Letters*, Vol. 40(No. 11): pp. 2773–2778. doi: 10.1002/grl.50185.

de Margerie, S., and Lank, K.D. 1986. *Tidal Circulation of the Scotian Shelf and Grand Banks*. Report. Dartmouth, Canada: ASA Consulting.

Déry, S., Stieglitz, M., McKenna, E.C., and Wood, E.F. 2005. "Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964–2000." *Journal of Climate*, Vol. 18(No. 14): pp. 2540–2557.

Deser, C., Alexander, M.A., Xie, S.-P., and Phillips, A.S. 2010. "Sea surface temperature variability: patterns and mechanisms." *Annual Review of Marine Science*, Vol. 2(No. 1): pp. 115–143. doi: 10.1146/annurev-marine-120408-151453.

Deser, C., Phillips, A.S., and Alexander, M.A. 2010. "Twentieth-century tropical sea surface temperature trends revisited." *Geophysical Research Letters*, Vol. 37: p. L10701. doi: 10.1029/2010GL043321.

Ding, H., Greatbatch, R.J., Latif, M., Park, W., and Gerdes, R. 2013. "Hindcast of the 1976/77 and 1998/99 climate shifts in the Pacific." *Journal of Climate*, Vol. 26(No. 19): pp. 7650–7661. doi: 10.1175/jcli-d-12-00626.1.

Doniol-Valcroze, T., Berteaux, D., Larouche, P., and Sears, R. 2007. "Influence of thermal fronts on habitat selection by four rorqual whale species in the Gulf of St. Lawrence." *Marine Ecology Progress Series*, Vol. 335: pp. 207–216. doi: 10.3354/meps335207.

Drinkwater, K.F., and Jones, E.P. 1987. "Density stratification, nutrient and chlorophyll distributions in the Hudson Strait region during summer and their relation to tidal mixing." *Continental Shelf Research*, Vol. 7(No. 6): pp. 599–607.

Fissel, D.B., Lemon, D.D., and Birch, J.R. 1982. "Major features of the summer near-surface circulation of western Baffin Bay, 1978 and 1979." *Arctic*, Vol. 35(No. 1): pp. 180–200.

Freeland, H.J. 2013. "Evidence of change in the winter mixed layer in the northeast pacific ocean: a problem revisited." *Atmosphere-Ocean*, Vol. 51(No. 1): pp. 126–133. doi: 10.1080/07055900.2012.754330.

Freeland, H.J., and Denman, K.L. 1982. "A topographycally controlled upwelling center off southern Vancouver Island." *Journal of Marine Research*, Vol. 40(No. 4): pp. 1069–1093.

Gächter, R., Vollenweider, R.A., and Glooschenko, W.A. 1974. "Seasonal variations of temperature and nutrients in the surface waters of Lakes Ontario and Erie." *Journal of the Fisheries Research Board of Canada*, Vol. 31(No. 3): pp. 275–290. doi: 10.1139/f74-047.

Galbraith, P.S., Chassé, J., Gilbert, D., Larouche, P., Caverhill, C., Lefaivre, D., Brickman, D., Pettigrew, B., Devine, L., and Lafleur, C. 2014. *Physical Oceanographic Conditions in the Gulf of St. Lawrence in 2013*. Research Document 2014/062. Ottawa, Ontario, Canada: Fisheries and Oceans Canada.

Galbraith, P.S., and Larouche, P. 2011. "Sea-surface temperature in Hudson Bay and Hudson Strait in relation to air temperature and ice cover breakup, 1985–2009." *Journal of Marine Systems*, Vol. 87(No. 1): pp. 66–78. doi: 10.1016/j.jmarsys.2011.03.002.

Galbraith, P.S., Larouche, P., Chassé, J., and Petrie, B. 2012. "Sea-surface temperature in relation to air temperature in the Gulf of St. Lawrence: interdecadal variability and long- term trends." *Deep-Sea Research II*, Vol. 77–80: pp. 10–20. doi: 10.1016/j.dsr2.2012.04.001.

Galley, R.J., Key, E., Barber, D.G., Hwang, B.J., and Ehn, J. 2008. "Spatial and temporial variability of sea ice the southern Beaufort Sea and Amundsen Gulf: 1980–2004." *Journal of Geophysical Research*, Vol. 113: p. C05S95. doi: 10.1029/2007JC004553.

Gargett, A.E. 1991. "Physical processes and the maintenance of nutrient-rich euphotic zones." *Limnology and Oceanography*, Vol. 36(No. 8) pp. 1527–1545. doi: 10.4319/lo.1991.36.8.1527.

Garrett, C.J.R., Keeley, J.R., and Greenberg, D.A. 1978. "Tidal mixing versus thermal stratification in the Bay of Fundy and Gulf of Maine." *Atmosphere-Ocean*, Vol. 16(No. 4): pp. 403–423. doi: 10.1080/07055900.1978.9649046.

Geshelin, Y., Sheng, J., and Greatbatch, R.J. 1999. *Monthly Mean Climatologies of Temperature and Salinity in the Western North Atlantic*. Dartmouth, Canada: Bedford Institute of Oceanography.

Ginzburg, A.I., Kostianoy, A.G., and Sheremet, N.A. 2004. "Seasonal and interannual variability of the Black sea surface temperature as revealed from satellite data (1982–2000)." *Journal of Marine Systems*, Vol. 52(No. 1–4): pp. 33–50.

Gómez-Gesteira, M., deCastro, M., Alvarez, I., and Gómez-Geistera, J.L. 2008. "Coastal sea surface temperature warming trend along the continental part of the Atlantic arc (1985–2005)." *Journal of Geophysical Research*, Vol. 113: p. C04010. doi:10.1029/2007JC004315.

Good, S.A., Corlett, G.K., Remedios, J.J., Noyes, E.J., and Llewellyn-Jones, D.T. 2007. "The global trend in sea surface temperature from 20 Years of advanced very high resolution radiometer data." *Journal of Climate*, Vol. 20(No. 7): pp. 1255–1264.

Gratton, Y., Mertz, G., and Gagné, J.A. 1988. "Satellite observations of tidal upwelling and mixing in the St. Lawrence estuary." *Journal of Geophysical Research*, Vol. 93(No. C6): pp. 6947–6954. doi: 10.1029/JC093iC06p06947.

Greene, C.H., Meyer-Gutbrod, E., Monger, B.C., McGarry, L.P., Pershin, A.J., Belkin, I.M., Fratantoni, P.S., et al. 2013. "Remote climate forcing of decadal-scale regime shifts in Northwest Atlantic shelf ecosystems." *Limnology and Oceanography*, Vol. 58(No. 3): pp. 803–816. doi: 10.4319/lo.2013.58.3.0803.

Griffiths, D.K., Pingree, R.D., and Sinclair, M. 1981. "Summer tidal fronts in the near-arctic regions of Foxe Basin and Hudson Bay." *Deep-Sea Research*, Vol. 28A(No. 8): pp. 865–873.

Guan, B., and Nigam, S. 2009. "Analysis of Atlantic SST variability factoring interbasin links and the secular trend: clarified structure of the Atlantic multidecadal oscillation." *Journal of Climate*, Vol. 22(No. 15): pp. 4228–4240. doi: 10.1175/2009JCLI2921.1.

Gunn, G. 2014. "Polynya formation in Hudson Bay during the winter period." In *Environment and Geography*. Winnipeg, Canada: University of Manitoba.

Han, G., Lu, Z., Wang, Z., Helbig, J., Chen, N., and de Young, B. 2008. "Seasonal variability of the Labrador Current and shelf circulation off Newfoundland." *Journal of Geophysical Research*, Vol. 113(No. C10): p. C10013. doi: 10.1029/2007jc004376.

Harvey, M., Therriault, J.-C., and Simard, N. 1997. "Late-summer distribution of phytoplankton in relation to water mass characteristics in Hudson Bay and Hudson Strait (Canada)." *Canadian Journal of Fisheries and Aquatic Sciences,* Vol. 54(No. 8): pp. 1937–1952.

Harwood, L.A., Smith, T.G., George, J.C., Sandstrom, S.J., Walkusz, W., and Divoky, G.J. 2015. "Change in the Beaufort Sea ecosystem: diverging trends in body condition and/or production in five marine vertebrate species." *Progress in Oceanography*, Vol. 136: pp. 263–273. doi: 10.1016/j.pocean.2015.05.003.

Head, E.J.H., and Sameoto, D.D. 2007. "Inter-decadal variability in zooplankton and phytoplankton abundance on the Newfoundland and Scotian shelves." *Deep-Sea Research II*, Vol. 54(No. 23–26): pp. 2686–2701. doi: 10.1016/j.dsr2.2007.08.003.

Heath, M.R., Neat, F.C., Pinnegar, J.K., Reid, D.G., Sims, D.W., and Wright, P.J. 2012. "Review of climate change impacts on marine fish and shellfish around the UK and Ireland." *Aquatic Conservation: Marine and Freshwater Ecosystems*, Vol. 22(No. 3): pp. 337–367. doi: 10.1002/aqc.2244.

IPCC. 2014. *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.

Jackson, J.M., Thomson, R.E., Brown, L.N., Willis, P.G., and Borstad, G.A. 2015. "Satellite chlorophyll off the British Columbia Coast, 1997–2010." *Journal of Geophysical Research*, Vol. 120(No. 7): pp. 4709–4728. doi: 10.1002/2014jc010496.

Khan, A.H., Levac, E., and Chmura, G.L. 2013. "Future sea surface temperatures in large marine ecosystems of the northwest Atlantic." *ICES Journal of Marine Science*, Vol. 70(No. 5): pp. 915–921. doi: 10.1093/icesjms/fst002.

Kjellerup, S., Dünweber, M., Møller, E., Schiedek, D., Oskarsson, G., Rigét, F., Johansen, K., and Mosbech, A. 2015. "Vertical and horizontal distribution of zooplankton and polar cod in southern Baffin Bay (66–71°N) in September 2009." *Polar Biology*, Vol. 38(No. 5): pp. 699–718. doi: 10.1007/s00300-014-1633-4.

Kjellerup, S., Dünweber, M., Swalethorp, R., Nielsen, T.G., Friis, M.E., Markager, S., and Hansen, B.W. 2012. "Effects of a future warmer ocean on the coexisting copepods *Calanus finmarchicus* and *C. glacialis* in Disko Bay, western Greenland." *Marine Ecology Progress Series*, Vol. 447: pp. 87–108. doi: 10.3354/meps09551.

Kulikov, E.A., Rabinovich, A.B., and Carmack, E.C. 2004. "Barotropic and baroclinic tidal currents on the Mackenzie shelf break in the southeastern Beaufort Sea." *Journal of Geophysical Research*, Vol. 109(No. C5): p. C05020. doi: 10.1029/2003jc001986.

Kumar, A., Jha, B., and Wang, H. 2014. "Attribution of SST variability in global oceans and the role of ENSO." *Climate Dynamics*, Vol. 43(No. 1–2): pp. 209–220. doi: 10.1007/s00382-013-1865-y.

Lacroix, J. 1987. *Étude descriptive de la variabilité spatio-temporelle des phénomènes physiques de surface de l'estuaire maritime et de la partie ouest du golfe du Saint-Laurent à l'aide d'images thermiques du satellite NOAA-7*. Rimouski, Canada: Université du Québec à Rimouski.

Lanos, R. 2009. *Circulation régionale, masses d'eau, cycles d'évolution et transports entre la mer de Beaufort et le Golfe d'Amundsen*. Québec, Canada: Université du Québec.

Lawrence, S.P., Llewellyn-Jones, D.T., and Smith, S.J. 2004. "The measurement of climate change using data from the advanced very high resolution and along track scanning radiometers." *Journal of Geophysical Research*, Vol. 109: p. C08017. doi: 10.1029/2003JC002104.

Lazier, J.R.N., and Wright, D.G. 1993. "Annual velocity variations in the Labrador Current." *Journal of Physical Oceanography*, Vol. 23(No. 4) pp. 659–678. doi: 10.1175/1520-0485(1993)023<0659:avvitl>2.0.co;2.

Lefebvre, S.C., Benner, I., Stillman, J.H., Parker, A.E., Drake, M.K., Rossignol, P.E., Okimura, K.M., Komada, T., and Carpenter, E.J. 2012. "Nitrogen source and pCO2 synergistically affect carbon allocation, growth and morphology of the coccolithophore *Emiliania huxleyi*: potential implications of ocean acidification for the carbon cycle." *Global Change Biology*, Vol. 18(No. 2): pp. 493–503. doi: 10.1111/j.1365-2486.2011.02575.x.

Linkin, M.E., and Nigam, S. 2008. "The North Pacific oscillation–West Pacific teleconnection pattern: mature-phase structure and winter impacts." *Journal of Climate*, Vol. 21(No. 9): pp. 1979–1997. doi: 10.1175/2007jcli2048.1.

Lobb, J., Weaver, A.J., Carmack, E.C., and Ingram, R.G. 2003. "Structure and mixing across an Arctic/Atlantic front in northern Baffin Bay." *Geophysical Research Letters*, Vol. 30(No. 16): pp. 1833, doi: 1810.1029/2003GL017755.

Loder, J.W., and Greenberg, D.A. 1986. "Predicted positions of tidal fronts in the Gulf of Maine region." *Continental Shelf Research*, Vol. 6(No. 3): pp. 397–414. doi: 10.1016/0278-4343(86)90080-4.

Lofgren, B.M. 1997. "Simulated effects of idealized laurentian Great Lakes on regional and large-scale climate. *Journal of Climate*, Vol. 10(No. 11): pp. 2847–2858. doi: 10.1175/1520-0442(1997)010<2847:seoilg>2.0.co;2.

Lofgren, B.M., and Zhu, Y. 1999. *Seasonal Climatology of Surface Energy Fluxes on the Great Lakes*. Report GLERL-112. Ann Arbor, USA: Great Lakes Environmental Research Laboratory.

Malick, M.J., Cox, S.P., Mueter, F.J., and Peterman, R.M. 2015. "Linking phytoplankton phenology to salmon productivity along a north–south gradient in the Northeast Pacific ocean." *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 72(No. 5): pp. 697–708. doi: 10.1139/cjfas-2014-0298.

Masson, D. 2006. "Seasonal water mass analysis for the straits of Juan de Fuca and Georgia." *Atmosphere-Ocean*, Vol. 44(No. 1): pp. 1–15.

McClain, E.P., Pichel, W.G., and Walton, C.C. 1985. "Comparative peformance of AVHRR-based multichannel sea surface temperatures." *Journal of Geophysical Research*, Vol. 90(No. C6): pp. 11587–11601.

Mulligan, R.P., Perrie, W., and Solomon, S. 2010. "Dynamics of the Mackenzie River plume on the inner Beaufort shelf during an open water period in summer." *Estuarine, Coastal and Shelf Science*, Vol. 89(No. 3): pp. 214–220. doi: 10.1016/j.ecss.2010.06.010.

Ouellet, M., Petrie, B., and Chassé, J. 2003. *Temporal and Spatial Scales of Sea-Surface Temperature Variability in Canadian Atlantic Waters*. Report FS97-18/228E. Dartmouth, Canada: Bedford Institute of Oceanography.

Park, K.-A., Lee, E.-Y., Chang, E., and Hong, S. 2015. "Spatial and temporal variability of sea surface temperature and warming trends in the Yellow Sea." *Journal of Marine Systems*, Vol. 143: pp. 24–38. doi: 10.1016/j.jmarsys.2014.10.013.

Park, D.-S.R., Lee, S., and Feldstein, S.B. 2015. "Attribution of the recent winter sea ice decline over the Atlantic sector of the Arctic Ocean." *Journal of climate*, Vol. 28(No. 10): pp. 4027–4033. doi: 10.1175/jcli-d-15-0042.1.

Paul, C., Matthiessen, B., and Sommer, U. 2015. "Warming, but not enhanced CO2 concentration, quantitatively and qualitatively affects phytoplankton biomass." *Marine Ecology Progress Series*, Vol. 528: pp. 39–51. doi: 10.3354/meps11264.

Pettigrew, B., Larouche, P., and Gilbert, D. 2011. *Validation des images composites des températures de surface produites au laboratoire de télédétection de l'Institut Maurice-Lamontagne*. Mont-Joli, Canada: Institut Maurice-Lamontagne.

Plattner, S., Mason, D.M., Leskevich, G.A., Schwab, D.J., and Rutherford, E.S. 2006. "Classifying and forecasting coastal upwellings in lake Michigan using satellite derived temperature images and buoy data." *Journal of Great Lakes Research*, Vol. 32(No. 1): pp. 63–76.

Relvas, P., Luis, J., and Santos, A.M.P. 2009. "Importance of the mesoscale in the decadal changes observed in the northern Canary upwelling system." *Geophysical Research Letters*, Vol. 36: p. L22601. doi: 10.1029/2009GL040504.

Reygondeau, G., Molinero, J.C., Coombs, S., MacKenzie, B.R., and Bonnet, D. 2015. "Progressive changes in the Western English Channel foster a reorganization in the plankton food web." *Progress in Oceanography*, Vol. 137: pp. 524–532. doi: http://dx.doi.org/10.1016/j.pocean.2015.04.025.

Saucier, F.J., Senneville, S., Prinsenberg, S., Roy, F., Smith, G., Gachon, P., Caya, D., and Laprise, R. 2004. "Modelling the sea ice-ocean seasonal cycle in Hudson Bay, Foxe basin and Hudson strait, Canada." *Climate Dynamics*, Vol. 23(No. 3–4): pp. 303–326.

Schneider, P., and Hook, S.J. 2010. "Space observations of inland water bodies show rapid surface warming since 1985." *Geophysical Research Letters*, Vol. 37: p. L22405. doi: 10.1029/2010gl045059.

Sena Martins, M., Serra, N., and Stammer, D. 2015. "Spatial and temporal scales of sea surface salinity variability in the Atlantic Ocean." *Journal of Geophysical Research*, Vol. 120(No. 6): pp. 4306–4323. doi: 10.1002/2014jc010649.

Sévigny, C., Gratton, Y., and Galbraith, P.S. 2015. "Frontal structures associated with coastal upwelling and ice-edge subduction events in southern Beaufort Sea during the Canadian Arctic Shelf Exchange Study." *Journal of Geophysical Research*, Vol. 120(No. 4): pp. 2523–2539. doi: 10.1002/2014jc010641.

Sherman, K., Belkin, I.M., Friedland, K.D., O'Reilly, J., and Hyde, K. 2009. "Accelerated warming and emergent trends in fisheries biomass yields of the world's large marine ecosystems." *AMBIO*, Vol. 38(No. 4): pp. 215–224. doi: 10.1579/0044-7447-38.4.215.

Simons, T.J., and Schertzer, W.M. 1987. "Stratification, currents, and upwelling in Lake Ontario, summer 1982." *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 44(No. 12): pp. 2047–2058. doi: 10.1139/f87-254.

Straneo, F., and Saucier, F. 2008. "The outflow from Hudson Strait and its contribution to the Labrador current." *Deep-Sea Research I*, Vol. 55(No. 8): pp. 926–946. doi: 10.1016/j.dsr.2008.03.012.

Sun, Q., Tang, D., and Wang, S. 2012. "Remote-sensing observations relevant to ocean acidification." *International Journal of Remote Sensing*, Vol. 33(No. 23): pp. 7542–7558. doi: 10.1080/01431161.2012.685978.

Taboada, F., and Anadón, R. 2012. "Patterns of change in sea surface temperature in the North Atlantic during the last three decades: beyond mean trends." *Climatic Change*, Vol. 115(No. 2): pp. 419–431. doi: 10.1007/s10584-012-0485-6.

Tee, K.T., Smith, P.C., and Lefaivre, D. 1993. "Topographic upwelling off southwest Nova Scotia." *Journal of Physical Oceanography*, Vol. 23(No. 8): pp. 1703–1726. doi: 10.1175/1520-0485(1993)023<1703:tuosns>2.0.co;2.

Thompson, K.R., Loucks, R.H., and Trites, R.W. 1988. "Sea surface temperature variability in the shelf-slope region of the Northwest Atlantic." *Atmosphere-Ocean*, Vol. 26(No. 2): pp. 282–299. doi: 10.1080/07055900.1988.9649304.

Thomson, R.E., Heesemann, M., Davis, E.E., and Hourston, R.A.S. 2014. "Continental microseismic intensity delineates oceanic upwelling timing along the west coast of North America." *Geophysical Research Letters*, Vol. 41(No. 19) pp. 6872–6880. doi: 10.1002/2014gl061241.

Ting, M., Kushnir, Y., and Li, C. 2014. "North Atlanticmulti-decadal SST oscillation: external forcing versus internal variability." *Journal of Marine Systems*, Vol. 133: pp. 27–38. doi: 10.1016/j.jmarsys.2013.07.006.

Tremblay, J.É., Raimbault, P., Garcia, N., Lansard, B., Babin, M., and Gagnon, J. 2014. "Impact of river discharge, upwelling and vertical mixing on the nutrient loading and productivity of the Canadian Beaufort Shelf." *Biogeosciences*, Vol. 11(No. 17): pp. 4853–4868. doi: 10.5194/bg-11-4853-2014.

Ullman, D., Brown, J., Cornillon, P., and Mavor, T. 1998. "Surface temperature fronts in the Great Lakes." *Journal of Great Lakes Research*, Vol. 24(No. 4): pp. 753–775.

Urrego-Blanco, J., and Sheng, J. 2012. "Interannual variability of the circulation over the eastern Canadian shelf." *Atmosphere-Ocean*, Vol. 50(No. 3): pp. 277–300. doi: 10.1080/07055900.2012.680430.

Urrego-Blanco, J., and Sheng, J. 2014. "Study on subtidal circulation and variability in the Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine using a nested-grid shelf circulation model." *Ocean Dynamics*, Vol. 64(No. 3): pp. 385–412. doi: 10.1007/s10236-013-0688-z.

Valeur, H., H., Hansen, C., Hansen, K.Q., Rasmessen, L., and Thingvad, N. 1996. *Weather, Sea and Ice Conditions in Eastern Baffin Bay, Offshore Northwest Greenland. A review*. Report 96-12. Copenhagen, Denmark: Danish Meteorological Institute.

Villarino, E., Chust, G., Licandro, P., Butenschön, M., Ibaibarriaga, L., Larrañaga, A., and Irigoien, X. 2015. "Modelling the future biogeography of North Atlantic zooplankton communities in response to climate change." *Marine Ecology Progress Series*, Vol. 531: pp. 121–142. doi: 10.3354/meps11299.

Wang, M., and Overland, J.E. 2012. "A sea ice free summer Arctic within 30 years: An update from CMIP5 models." *Geophysical Research Letters*, Vol. 39(No. 18): p. L18501. doi: 10.1029/2012gl052868.

Wang, Q., Myers, P.G., Hu, X., and Bush, A.B.G. 2012. "Flow constraints on pathways through the canadian arctic archipelago." *Atmosphere-Ocean*, Vol. 50(No. 3): pp. 373–385. doi: 10.1080/07055900.2012.704348.

Wang, Z., Yashayaev, I., and Greenan, B. 2015. "Seasonality of the inshore Labrador current over the Newfoundland shelf." *Continental Shelf Research*, Vol. 100: pp. 1–10. doi: 10.1016/j.csr.2015.03.010.

Williams, W.J., and Carmack, E.C. 2008. "Combined effects of wind-forcing and isobath divergence on upwelling at Cape Bathurst, Beaufort sea." *Journal of Marine Research*, Vol. 66(No. 5) pp. 645–663.

Wu, Y., Tang, C., and Hannah, C. 2012. "The circulation of eastern Canadian seas." *Progress in Oceanography*, Vol. 106: pp. 28–48. doi: 10.1016/j.pocean.2012.06.005.