Sea-surface temperature in relation to air temperature in the Gulf of St. Lawrence: Interdecadal variability and long term trends

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**Abstract**

Monthly average sea-surface temperatures (SST) derived from NOAA-AVHRR remote sensing data are analyzed for the period 1982–2011 for the Gulf of St. Lawrence (Canada) and compared to monthly average air temperature. Results show that SST increased by 1 to 1.5°C during the period when averaging from May to November of each year, a change associated with interdecadal variability rather than a long term trend. SST averaged over the ice-free months of May–November is strongly correlated to an index of the April–November air temperature anomaly, capturing up to 90% of the variance, suggesting strong coupling between air and sea-surface temperatures on seasonal time scales. The air temperature anomaly index series can be used as a proxy for longer term climate variability of SST prior to 1982. Overall warming trends in air temperature of 0.9°C and 0.6°C per century were found using data from weather stations dating back to 1873 and from the National Centers for Environmental Prediction (NCEP) reanalysis that goes back to 1871. The strong co-variations of SST and air temperature indicate that the SST has likely increased by a similar amount. These co-variations will help to predict the response of the Gulf water temperature to changing climate as well as provide a perspective with respect to changes that have occurred in the previous century.

**1. Introduction**

The Gulf of St. Lawrence is a semi-enclosed sea, covering an area of about 235,000 km² and containing 35,000 km³ of water (including the St. Lawrence Estuary), which opens to the Atlantic Ocean through Cabot Strait (104 km wide and 480 m at its deepest) and the Strait of Belle Isle (17 km wide and 60 m at its sill) (Fig. 1). This complex ecosystem supports a variety of commercial species (lobster, crab, shrimps, etc.) that use the surface layer during their life-cycle. These species are thus affected by the surface temperatures encountered that could result in either good or bad recruitment years (e.g., Ouellet et al., 2007). It has also been shown that the distribution of whales is related to the presence of thermal fronts in the north-western part of the Gulf (Doniol-Valcroze et al., 2007). Climate scenarios indicate that Eastern Canada should warm by a few degrees Celsius over the next century which could thus have major implications for these species and the fisheries industry.

Climatologies of the sea-surface temperature (SST) spatial patterns in the Gulf of St. Lawrence were previously documented based on all available temperature and salinity profiles by Petrie et al. (1996) who constructed monthly climatologies, by Han et al. (1999) who derived seasonal climatologies to use as input for diagnostic numerical modeling, and by Doyon and Ingram (2000) who also used limited remote sensing data to construct monthly climatologies with finer spatial features. Interannual variability was investigated by Drinkwater and Gilbert (2004) by using bulk temperatures averaged over large areas of the Gulf.

The aim of this work is to quantify SST during ice-free months in the Gulf of St. Lawrence in terms of monthly climatology, interannual variability and spatial representativeness of a mean index, and to compare a mean annual index to air temperature during the period 1982–2011. The air temperature will then be used as a proxy for SST to examine variability and trends over a longer timescale.

**2. Methodology**

**2.1. Study area**

The water column in the Gulf of St. Lawrence consists of three distinct layers: the surface layer, a cold intermediate layer, and a deeper layer. Only the first two exhibit strong seasonal variability (Fig. 2). Surface temperatures typically reach maximum values...
from mid-July to mid-August; gradual cooling occurs thereafter. Wind mixing during the fall leads to a progressively deeper and cooler mixed layer, eventually encompassing the cold intermediate layer. During winter, the surface layer thickens partly because of buoyancy loss (cooling and reduced runoff) and brine rejection associated with sea-ice formation, but mostly from wind-driven mixing prior to ice formation (Galbraith, 2006). The surface winter layer extends to an average depth of 75 m (e.g. Fig. 2) and up to 150 m in places by the end of March and exhibits near freezing temperatures (–1.8 to 0 °C) (Galbraith, 2006). During spring, surface warming, sea-ice melt waters, and continental runoff produce a lower-salinity and higher-temperature surface layer, below which cold winter waters are partly isolated from the atmosphere and are known as the summer cold intermediate layer. This layer persists until the next winter, gradually warming and deepening during summer (Gilbert and Pettigrew, 1997), more rapidly during the fall as vertical mixing intensifies. The SST is therefore representative of a mixed layer of varying thickness that is minimum in spring and maximum in fall and winter (Fig. 2). Koutitonsky and Bugden (1991) presented a general review of the physical oceanography of the Gulf.

2.2. Air temperature

Average monthly air temperatures were obtained from Environment Canada’s National Climate Data and Information Archive1 for stations around the Gulf of St. Lawrence: Sept-Iles, Natashquan, Blanc-Sablon, Gaspé, Daniel’s Harbour, Charlottetown, Iles-de-la-Madeleine and Port aux Basques (Fig. 1). This dataset was chosen over the Environment Canada Homogenized Surface Air Temperature (HSAT) Data set because data for recent years (2009–2011) were not yet included in the latter dataset. The HSAT dataset has been specifically developed for climate research in Canada which addresses shifts due to changes in site exposure, location, instrumentation, observer and observing program (Vincent, 1998; Vincent and Gullett, 1999; Vincent et al., 2002). A comparison of both datasets for six of the eight stations showed that there were typically no corrections applied to these data since 1981, and, if any, only very small corrections in the order of 0.1 °C were made to data prior to that period.

In order to increase the length of the time series, data from two stations were merged to create a single composite at Gaspé and three stations were combined for Charlottetown. Using all available monthly data sampled at both Gaspé stations between April and November (months chosen for reasons that will be explained later), an average offset of 0.53 °C was calculated between the two stations which was subtracted from the older station data. The same data-overlap method was used to merge data from the three stations at Charlottetown for which the offset was 0.54 °C between the most recent station (Charlottetown A) and the older two (which have nearly identical means over overlapping April–November data). The temporal data coverage for these five stations is shown in Fig. 3(A) (Gaspé) and (B) (Charlottetown). Normalized anomalies are used to display the similarities of the combined stations. A normalized anomaly is the observed value minus the mean over a reference time period, divided by the standard deviation of the timeseries over the same reference period. Here, the anomalies from the older stations at a given location are normalized using the mean and standard deviation of the station with most recent data over the reference period 1981–2010. Fig. 3 shows that the joining of several stations into a longer timeseries is justified by the similarity of the normalized anomalies. Minor differences remain because of spatial separation as well as altitude differences between stations.

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Monthly anomalies were calculated for each of these composite stations and six other weather stations based on the 1981–2010 period, a 30-year (WMO standard) climatological period that closely matches the span of the sea-surface temperature data discussed below. The temporal coverage of these eight stations is shown in Fig. 3(C). All available station anomalies were then averaged together to produce a monthly composite timeseries for the Gulf. April–November values of this composite are averaged to produce a single yearly anomaly index timeseries, termed as the Gulf air temperature anomaly index. The climatological mean air temperature from 1981 to 2010, from April to November, is

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1 http://www.climat.meteo.gc.ca/prods_servs/cdn climate summary e.html.
8.47 °C. The Gulf air temperature anomaly index includes data from seven stations back to 1955, six stations back to 1947 and five to 1945 (Fig. 3), making it robust to that time. Prior to 1945, the index is composed of data from Charlottetown which are available back to 1873, reinforced by the sporadic presence of other station data such as Gaspé, Iles-de-la-Madeleine and Port aux Basques which have mostly similar anomalies for overlapping years. Charlottetown anomalies are well correlated to the Gulf air temperature anomaly index ($R^2=0.71$) for the period 1945–2010, providing confidence that the earlier portion of the air temperature anomaly index is also representative of the climate of the Gulf.

Air temperature from the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al., 1996) and NCEP 20th century reanalysis version 2 (Compo et al., 2011) were also used, as provided by the NOAA/OAR/ESRL Physical Sciences Division (Boulder, Colorado, USA; http://www.esrl.noaa.gov/psd/). All points from the 2.5° (NCEP 1) and 2° (NCEP 20th century) resolution in latitude and longitude databases that overlaid the Gulf (Fig. 1) were averaged into composites. The NCEP 20th century analysis includes results from 56 simulations. In addition to averaging the 56 results at the 7 grid points over the Gulf, the standard deviations of the 56 averages are also computed as a gage of the stability of the result.

2.3. Sea-surface temperature

Satellite remote sensing has often been used in the past to estimate climate variability in the open ocean (Good et al., 2007; Lawrence et al., 2004), in coastal regions (Relvas et al., 2009; Gómez-Gesteira et al., 2008; Ginzburg et al., 2004; Barale et al., 2004) and in inland waters (Schneider and Hook, 2010). For this work, we used weekly average SST (1982–2011) calculated using two products based on National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite images. The first product is the Pathfinder SST dataset Version 5.2 (Casey et al., 2010), a 4-km resolution reanalysis covering 1982–2010. Two world composites are available for each day of the year (daytime and nighttime) which we further averaged into monthly composite by simple averaging of all available data for each cell. The second SST product used is a 1-km resolution dataset available from the Canadian Dept. of Fisheries and Oceans Maurice Lamontagne Institute (MLI) remote sensing laboratory (see Galbraith and Larouche (2011) for details of the processing).

The Pathfinder and the MLI SST products are different. The Pathfinder SST is a 4-km resolution reanalysis product that aims at generating the most accurate SST as compared to simultaneous SST measurements using a single AVHRR sensor at a time. On the other hand, the MLI processor is a 1-km resolution near real-time system with the goal to generate the closest estimate of the mean daily SST using all available satellites to decrease aliasing from the diurnal signal (Fig. 4). Validation of the MLI SST composites over the Gulf of St. Lawrence using in-situ thermograph measurements showed that the mean monthly SST exhibited a cold bias of 0.13 °C (Pettigrew et al., 2011). Therefore we have adjusted the temperatures shown here by this amount.

Sea ice typically starts to form in the Estuary as well as in the southwestern and the northern parts of the Gulf and is advected towards Cabot Strait during the ice season (Drinkwater et al., 1999; Galbraith et al., 2011). Ice formation may occur before January and there were several years since 1982 (when the SST records begin) when sea ice has formed in December. Sea ice also enters the Gulf through the Strait of Belle Isle. Since it tends to be thicker than the locally-formed sea ice and occupies the coolest part of the Gulf, it is usually the last to melt. The ice in the Mécénatina region melts to 5% of the climatological winter maximum volume by May 16 (Galbraith et al., 2011). The months of December through April will thus be excluded from the following
analyses for the following reasons. First, sea-ice prevents the remote sensing of SST with, based on 1998–2010 ice conditions, late December having a median ice cover of 7% and a maximum of 15%, late February having 89% median and 100% maximum, and a drop to 8% median and 22% maximum by April 15th. Second, during the period of May–November, no water temperatures are at the freezing point, consequently any relationship between SST and air temperature found would not be masked by including data close to this limiting temperature. While including the month of May introduces a small bias because colder ice-covered areas that may still be present in the northeast Gulf will not be accounted for in the SST averaging, the bias is small because these areas are small compared to the Gulf as a whole (median cover < 1%).

For the purpose of illustrating the annual cycle of SST in the Gulf of St. Lawrence, shipborne thermosalinograph data are also used. These data were collected between 2000 and 2010 from commercial ships instrumented by MLI. In this system, water is pumped via a through-hull water intake at a depth of approximately 3 m into a debubbling chamber and then circulated into a sampling tank where an SBE 21 from Sea-Bird Electronics, Inc., records temperature and salinity (Galbraith et al., 2002).

3. Results and discussion

3.1. Sea-surface temperature

The Pathfinder and MLI monthly composites for June 2010 illustrate the spatial structure of SST (Fig. 5). Major features include the warmest waters at the western extremity (near to and upstream of the salt wedge of the Upper St. Lawrence Estuary), warm waters located in the southwest Gulf over the relatively shallow Magdalen Shallows, the presence of colder waters along the Gulf North Shore which result from wind-driven upwellings (Bourque and Kelley, 1995), the colder waters in the Lower St. Lawrence Estuary and the inflow of cold water through the Strait of Belle Isle (Petrie et al., 1988).

Fig. 6 shows the climatological seasonal cycle of SST in the Gulf, in the Lower Estuary, and at the head of the Laurentian Channel using 25 years of MLI weekly SST composites. Surface waters in the Lower Estuary are cooler than in the Gulf from late June onwards and reach the annual maximum temperature earlier as well. This results from the estuarine circulation that transports the cold intermediate layer of the Gulf towards the head of the Laurentian Channel (Ingram, 1979; Galbraith, 2006; Smith et al., 2006) where strong tidal mixing and upwelling (Therriault and Lacroix, 1976) maintains the waters much colder than in most parts of the Gulf, barely reaching 7 °C at the head of the Laurentian Channel (Fig. 6). The annual cycle is completed for winter months when ice precludes satellite-derived SSTs by using thermosalinograph data available for the period 2000–2010. In spite of the fact that the ship track only covers parts of the Gulf (Fig. 5), the climatological mean SST is similar to that obtained by AVHRR SST imagery. These data show that, on average, surface
waters in the Gulf reach near-freezing (−1.7 °C) by mid-February and remain so until mid-March. The notable exception is the head of the Laurentian Channel, where waters in winter are kept well above freezing at ≈0 °C, forming a polynia at this mixing hot spot.

The Lower St. Lawrence Estuary surface temperature regime will be excluded from further analysis and from the comparison done with atmospheric temperatures because it is dominated by estuarine circulation as well as mixing and upwelling processes at its head.

Away from coastal upwelling areas, SST anomalies occur on spatial scales of order 100 km and over time scales of a few weeks in response to atmospheric forcing (winds, solar radiation) (Ouellet et al., 2003). Averaging over the time-span of a month removes some of this variability, and averaging over many months yields a single average per year useful for climatic variability studies. Fig. 7 shows the time series of mean SST calculated by averaging all monthly mean SST cells within the limits of the Gulf of St. Lawrence (see Fig. 5) between May and November for both the MLI and Pathfinder datasets. The Pathfinder timeseries does not show any values for 1994 and 1995; there is a documented gap in late 1994 preventing a complete May–November average for that year and several months in 1995 had sparse coverage in the Gulf of St. Lawrence that led to biased SST estimates such that the 1995 average was excluded from further analysis. SST averages were also constructed using Pathfinder data collected only during daytime and, separately, nighttime. The mean difference between the daytime and nighttime time-series was 0.43 °C. The MLI SST are on average 0.20 °C colder than the Pathfinder (all-data) SST but this may in part be due to the exclusion from the Pathfinder data of coastal cells where upwelling is likely to occur. Indeed, there is no statistical difference in the mean temperature of the two SST products within a 60 nm square in the middle of the Gulf, away from the coast. From visual inspection, it appears that the differences between the Pathfinder and MLI May–November means during 1989–1993, a period of NOAA-11 coverage (Fig. 4), are greater than those in other years. Cold biases of around 1 °C have been reported for NOAA-11 for some oceanic regions by Reynolds et al. (1989), but on the other hand a limited validation of NOAA-11 data was done by Topliss (1996) indicating that there was a warm bias of 0.1 °C of the satellite-derived products for the eastern Canadian waters in 1989. The observed difference between the MLI and Pathfinder data sets for these years may result from the SST algorithm used (MCST vs. NLSST) and the fact that Pathfinder products are adjusted on a monthly basis for sensor degradation. In spite of some differences in the Pathfinder and MLI SST timeseries, both products display very similar interannual variability (correlation coefficient $R^2$ of 0.83 overall and of 0.90 excluding the NOAA-11 span of 1989–1994).

Based on the regression trend over the period 1985–2011, the May–November SST increased by 1.4 °C in the MLI timeseries, or 0.5 °C per decade (Table 1). The same trend is found in the

Table 1

<table>
<thead>
<tr>
<th>Trends and correlation coefficients. (Top) overall trends are shown for the entire span of the timeseries shown. (Bottom) correlation coefficients ($R^2$) between all timeseries. The plus and minus numbers for the trends are 95% confidence intervals.</th>
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<td>---------------------------------------------------------------</td>
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<td>0.5 ± 0.2 °C per decade</td>
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$R^2$ Table

| Pathfiner SST (1982–2010) | 0.83 | 0.90 | 0.75 | 0.69 |
|---------------------------------------------------------------|
| MLI SST (1985–2011) | 0.51 | 0.70 | 0.52 | 0.53 |
| Station air T (1873–2011) | 0.80 | 0.70 | 0.52 | 0.53 |
| NCEP V1 (1948–2010) | 0.65 | 0.70 | 0.52 | 0.53 |
Pathfinder timeseries albeit over its slightly different timespan (with an increase of 1.5 °C over 1982–2010), with no statistical difference between daytime and nighttime data sets. This trend is similar to a previous estimate made for an area near Cabot Strait using a shorter time series (1998–2004) by Good et al. (2007). The trend for the Gulf of St. Lawrence compares to trends of 0.5 °C per decade for the Great Lakes estimated over 1985–2009 (Schneider and Hook, 2010), 0.9 °C per decade (1981–2000) for the Black Sea (Ginzburg et al., 2004) and 1.0 °C per decade (1981–1999) for the Adriatic Sea (Barale et al., 2004). Alternatively, the series can be interpreted as a temperature shift occurring in 1994 (1.0 °C difference between 1985–1993 and 1994–2011 averages in the MLI record, and 1.1 °C difference between 1982–1993 and 1996–2010 averages in the Pathfinder record) as part of a broader, regional-scale change also observed on the Labrador and Newfoundland shelves (Colbourne et al., 2011).

The representativeness of these area-averaged SST timeseries with respect to various regions of the Gulf determines the spatial applicability of the results to follow. To quantify this, the SST from each cell of the 4-km resolution Pathfinder monthly composites were averaged from May to November for each year of the 1982–2010 dataset and each of these timeseries was regressed against the Gulf-wide SST average timeseries (Fig. 7). The same was done with the MLI monthly composites for 1985–2011 which were first averaged into 4 km square cells, matching the Pathfinder resolution. Fig. 8 shows the spatial distribution of the correlation coefficients $R^2$. Results show that the average timeseries computed for the entire Gulf is well suited to represent most of the Gulf; 66% of the Pathfinder cells have $R^2 \geq 0.7$ and 42% have $R^2 \geq 0.8$, covering areas of 235,000 and 149,000 km$^2$, while the areas for $R^2 \geq 0.7$ and 0.8 in the MLI dataset are similar at 246,000 and 165,800 km$^2$. Fig. 8 also justifies the earlier decision to exclude the Lower St. Lawrence Estuary where correlations are much weaker. Only some limited areas of the Gulf have very weak correlations with the bulk timeseries. These include some water overlying Mécatina Trough which were previously discussed as affected by the inflow of cold Labrador shelf waters, as well as the head of the Laurentian Channel (visible on the MLI correlations), the Pointe-des-Monts area, the Jacques-Cartier Strait and Northumberland Strait. These last two areas are fairly shallow and had previously been identified as being susceptible to tidal mixing (Lu et al., 2001) while the area off Pointe-des-Monts has been shown to be subject to upwelling (Couture, 1989). The head of the Laurentian Channel is, as previously mentioned, a site of intense tidal mixing and upwelling.

Another test of the representativeness of a single Gulf average to various areas of the Gulf is shown in Fig. 9 with the interannual trend at each 4 km $\times$ 4 km cell. This shows that the southern part of the Gulf experienced very similar SST warming trends as the average and that the trend was within 0.1 °C per decade of the average in most areas, except for a fairly large region in the northeastern Gulf warming at a faster pace.

![Pathfinder SST correlation with average timeseries](image1)

![MLI SST correlation with average timeseries](image2)

**Fig. 8.** Spatial representation of the correlation coefficient $R^2$ between the timeseries of May–November SST average for the Gulf of St. Lawrence and of the same variable computed for each 4 km $\times$ 4 km area. Results are shown for the Pathfinder dataset (top panel) and the MLI SST dataset (bottom panel) for all coordinates that have a minimum of 20 years with data in all months from May to November. The 1-km resolution MLI data were averaged into 4 km $\times$ 4 km cells.
3.2. Air temperature in relation to SST

The 1985–2010 monthly climatology of the eight-station composite air temperature over the Gulf is shown in Fig. 6, delayed by a period of a half-month (i.e. the air temperature average for the month is displayed at the end of the month). Here, the 1985–2010 climatological period is simply chosen to match the SST climatology displayed in the same figure. Our set of weather stations represent sufficiently well the air temperature in the Gulf to arrive at the same climatological values as SST. The agreement of the two climatologies throughout the ice-free months of the year is useful for climate change studies of the Gulf surface waters since a forecasted seasonal increase in air temperature associated with climate change scenarios can therefore be readily applied to SST climatologies in the Gulf of St. Lawrence, at least in a bulk fashion.

On shorter time scales, the half-month offset added to air temperature in Fig. 6 to match the SST annual cycle indicates that air temperature drives SST and not the other way around, the 1985–2010 climatological period is simply chosen to match the SST climatology displayed in the same figure. Our set of weather stations represent sufficiently well the air temperature in the Gulf to arrive at the same climatological values as SST. The agreement of the two climatologies throughout the ice-free months of the year is useful for climate change studies of the Gulf surface waters since a forecasted seasonal increase in air temperature associated with climate change scenarios can therefore be readily applied to SST climatologies in the Gulf of St. Lawrence, at least in a bulk fashion.

On shorter time scales, the half-month offset added to air temperature in Fig. 6 to match the SST annual cycle indicates that air temperature drives SST and not the other way around, although atmospheric–ocean coupling and feedback are important (e.g. fall cooling of air temperature may be delayed by heat flux from the sea; (Faucher et al., 2004)). The half-month lag is in agreement by the results of Yashayaev and Zveryaev (2001) who quantified a lag of about 0.4 months between the annual cycles of air temperature and SST for the Gulf of St. Lawrence. To include such a lag when using only monthly data, SST anomalies for month \( n \) are compared to air temperature anomalies averaged over the same and the previous month, \( n \) and \( n-1 \) (Fig. 10).

The resulting correlation coefficient \( R^2 = 0.52 \) (air temperature versus MLJ SST) and \( 0.60 \) (air temperature versus Pathfinder SST) suggests a relatively strong coupling between air and sea surface temperatures at short timescales. Note that the regression coefficients are higher when comparing two month averages of air temperature anomalies with monthly SST anomalies than those obtained comparing anomalies from only the same month.

In the same manner, to look at anomalies on longer time scales, the yearly April–November air temperature averages are compared to the May–November SST averages. This adds the desired half-month lag and integrated effect of air temperature on SST. The interannual variability of the average April–November air temperature from the eight stations is shown in Fig. 11 as anomalies based on the latest standard climatological 30-year period, 1981–2010, which almost matches the Pathfinder record period. There is agreement between April–November air temperature anomaly and May–November SST timeseries with an overall \( R^2 \) of 0.70 using the MLJ SST dataset and of 0.90 using Pathfinder (Fig. 10). The slopes of the regression lines shown in Fig. 10 are 0.8 and 0.9 for MLJ and Pathfinder respectively. Conventional regressions minimize differences in the ordinate (SST). Doing the opposite and minimizing differences in air temperature yields an increase of the slope from 0.9 to 1.0 with Pathfinder whereas the geometric mean regression yields a slope of 0.95. Although it is anticipated that the factor between changes in air temperature and those of SST might be less than unity for a variety of reasons (e.g. thermal inertia, mixing of surface waters with the cold intermediate layer, coastal upwelling), it may
nevertheless be greater than 0.9 as the geometric mean regression slope suggests. The three largest differences between the air temperature and MLI SST relationship occur in 1989, 1990 and 1993 during NOAA-11 coverage (as before when MLI and Pathfinder SST were compared). If that period is excluded, all differences but those for 1995 and 1996 are within 0.5 °C and the 1995 SST corresponds well with the NCEP 20th century reanalysis air temperature anomaly.

The two NCEP surface air temperature April–November timeseries are also consistent with SST interannual variability, although NCEP correlation to SST is not as high ($R^2=0.75$ and $0.69$ for Pathfinder SST correlations with NCEP 1 and NCEP 20th century respectively and $R^2=0.51$ and 0.52 using MLI SST; see Table 1).

### 3.3. Long-term tendencies

The previous section showed that there was a good agreement between SST anomalies and air temperature anomalies on seasonal timescales, with a correlation coefficient $R^2=0.9$ using the Pathfinder SST dataset. Based on that correlation, it is now possible to go back further in time to estimate the long-term variability of SST using the Gulf air temperature anomaly index and NCEP timeseries as proxies. Fig. 12 shows that the Gulf's climate was quite variable over the last 137 years. Temperatures as high as the ones observed during the last decade were measured in 1889, 1901 and 1930–31 and cool periods also occurred such as 1914–1926. A negative trend observed between 1948 and 1971 has also been noted to occur in southern Canada (Zhang et al., 2000), contributing to the weak trend observed over the span of the NCEP 1 data set (not statistically different from zero; Table 1). The general tendencies noted in the anomaly index time series are in good agreement with more general trends found using global SST hemispheric datasets (Baines and Folland, 2007; Chylek et al., 2011; Thompson et al., 2010). Different explanations have been offered to explain the long-term hemispheric SST variability including variations of the thermohaline circulation and increased sulfate aerosols (Baines and Folland, 2007) or a thermal Rossby ocean mode at 20 years periodicity involving the variability of the Atlantic meridional overturning circulation combined with longer time scale variations (Chylek et al., 2011). Because the Gulf of St. Lawrence is a coastal sea, it is probable that the air (and SST) temperatures are also affected by continental processes leading to differences in timing and intensities between the general hemispheric trends and those observed in the Gulf of St. Lawrence.

Long-term-trends calculated using the entire time series show an air temperature increase of 0.9 °C per century (±0.3 °C at 95% confidence intervals), or 1.3 °C over 138 years (1873–2011). The trend is weaker on the NCEP 20th century reanalysis data, at 0.57 °C per century (±0.26 °C, 95% CI). Obviously, these value are much lower than the ones calculated using only the remote sensing data set which are somewhat biased by the recent (since 1994) increase in air temperature over the Gulf area. This increase is generally in-phase with the 20 years periodicity of the Atlantic Multidecadal Oscillation (Chylek et al., 2011) but corresponds also to a major change in the April–November mean North Atlantic Oscillation index (NAO) that is more negative since the early 1990s which normally corresponds to warmer than normal temperatures in Eastern Canada. However, looking in detail at the past temperature record, such large trends as the recent 0.6 °C per decade have happened before around 1925–35 but at that time the NAO index was becoming more positive. This confirms the complexity of the Gulf's temperature variability that is a combination of long-term change and more periodic patterns.

Looking forward, the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon et al., 2007) projected that summer air temperatures over the Gulf of St. Lawrence may increase by 0.2 °C per decade for the next few decades and by 3 °C over the next century compared to the 1980–2000 period. Our work implies that SSTs would also increase by slightly less than this amount, leading to unprecedented SSTs (compared to the last 140 years) in the Gulf of St. Lawrence within 50 years. This in turn could mean major changes to the biological component of the ecosystem including changes in growth rates for certain species that spend part of their lives in the surface layer, change of the distribution areas of

![Fig. 10. SST anomalies for the Gulf of St. Lawrence versus air temperature anomalies using (top) Pathfinder and (bottom) MLI datasets. Monthly SST anomalies for month $n$ are compared to the average air temperature anomaly for months $n-1$ and $n$, accounting for air temperature leading SST by one half of a month (gray dots). The correlations account for 60% and 52% of the variance using Pathfinder and MLI datasets, respectively. SST anomalies averaged from May to November are compared to air temperature anomalies averaged from April to November (black dots). The correlations account for 90% and 70% of the variance respectively.](image)
temperature-sensitive species such as capelin, and invasion of more exotic species which could expand their ecological niche to the warmer waters.

4. Summary and conclusion

A large SST increase observed between 1982 and 2011 from remote sensing happens to coincide with a cold period near the beginning of the record that amplifies the apparent trend in SST. Moreover, the two warmest years of the air temperature index have occurred recently (1999 and 2006; 2008 is also the third warmest year of the Pathfinder record). These factors combine to give the large positive trend (0.5°C per decade) observed in the SST record. (See Table 1 where all trends and cross-correlations are summarized.)

The monthly climatology for the period 1985–2010 of the average SST in the Gulf of St. Lawrence, measured from AVHRR remote sensing, was shown to coincide remarkably well with the monthly air temperature climatology occurring a half-month earlier. This indicates a relative agreement that can be exploited for climate change issues. Any predicted changes in the air temperature seasonal pattern is expected to be reflected in SST, although such predictions must account for air–sea coupling. Beyond matching climatologies, interannual seasonal variability and even monthly anomalies in SST and air temperature have been shown to be correlated ($R^2 = 0.90$ and 0.60 and slopes of 0.9 ± 0.1 and 0.8 ± 0.1, respectively, using Pathfinder SST and $R^2 = 0.70$ and 0.52 and slopes of 0.8 ± 0.2 and 0.7 ± 0.1 using MLI SST). The interannual variability was quantified using a bulk average of SST averaged from May to November over all the Gulf. This index was shown to be well correlated with the variability at a much smaller scale (4 km × 4 km) over much of the Gulf, and the trend found at smaller scale was similar to that of the bulk average (typically within 0.1 of the 0.5°C per decade recorded on average over the Gulf between 1982 and 2010 for Pathfinder or between 1985 and 2011 for MLI).

To study SST variability over a 100-year time scale, the strong correlation ($R^2 = 0.90$) found here between May–November SST and April–November air temperature anomalies was exploited and air temperature was used as a proxy. A positive (warming) but much reduced trend of 0.9°C per century is found in the weather-station composite proxy between 1873 and 2011. The warming trend is still important since 9 of the 20 warmest years since 1873 have occurred in the last 20 years, 7 of the warmest 15 have occurred in the last 15 years, and 5 of the warmest 10 in the last 10 years. The air temperature anomaly index based on weather station data is consistent with the average surface air temperature anomaly at NCEP 20th century version 2 reanalysis grid points over the Gulf. The trend observed in the NCEP data is weaker at 0.6°C per century but the confidence intervals overlap.
The surface of the Gulf of St. Lawrence has been affected by a warming climate of up to 0.9 °C per century in air temperature that has likely translated to a similar increase in SST according to our results. Past co-variations of SST and air temperature shown here will help to predict the response of the Gulf water temperature to changing climate as well as provide a perspective with respect to changes that have occurred in the previous century. While the 1998–2011 period has been the warmest in over a century, some years in the past have been almost as warm. However an increase in summer air temperature of 0.2 °C per decade for the next few decades and of 3 °C over the next century as predicted by the IPCC, would translate to a roughly similar increase in SST. Such an increase in the mean state within a century would be larger than the minimum-to-maximum interannual variability observed within the last three decades and would bring unprecedented SSTs (in recent history) to the Gulf of St. Lawrence. Assuming the same interannual variability as currently observed, even the coolest years would be warmer than the current warmest year on record (2006), possibly introducing changes to the ecosystem.

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