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INTERACTION BETWEEN ATMOSPHERE AND OCEAN-ICE REGIONAL MODELS OVER THE GULF OF ST LAWRENCE, CANADA

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1. Introduction

The motivation for this study is to understand the regional climate, climate changes and climate variability in Eastern Canada. The climate of Eastern Canada is dominated by the passage of synoptic weather systems traveling from the west through the Great Lakes and from the southwest along the US East Coast. Occasionally, there is a formation of high-pressure system in northern Quebec, pushing cold Arctic air mass southward. However, the evolution of these systems is modified by atmosphere-ocean interactions due to the presence of two large inner seas: the Gulf of St. Lawrence (GSL) and the Hudson Bay. Variable sea-ice and irregular coastlines characterize these basins, giving a complex distribution to surface fluxes (heat, moisture and momentum). In this study, we want to further understand the interactions between the atmosphere, the ocean and the ice in the GSL and their effects on the climate of Eastern Canada by using numerical tools. We choose the GSL because this basin is relatively well documented and because we have an ocean model for its representation.

In order to study the climate in the GSL area, we need a coupled regional climate model. In Canada, we have the Canadian Regional Climate Model developed at the "Université du Québec à Montréal" (CRCM, Caya and Laprise 1999) and the Gulf of St-Lawrence ocean model developed at the "Institut Maurice-Lamontagne" (GOM, Saucier *et al*. 2001). However, these two models have been developed independently and are not coupled yet. The goal of this study is to test the sensitivity of the CRCM and GOM to each other with a series of simulations over Eastern Canada. This sensitivity study is a necessary step toward a fully regional coupled model for our area of interest. The sensitivity of these models has already been investigated for a short simulation by Gachon *et al*. (2001). However, we need to understand the interactions between the atmosphere, the ocean and the sea-ice over the Gulf of St. Lawrence (GSL) using these two models on a longer time scale.

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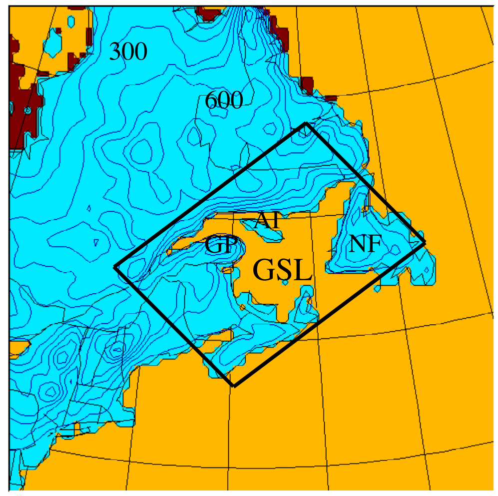


Figure 1. Model domain for the CRCM with land-sea mask and topographical height at every 100 m. The CRCM sponge zone is excluded and GOM's domain is indicated with a black rectangle. The land is in blue, the ocean is in yellow and sea-ice is in brown. Gulf of St. Lawrence: GSL, Anticosti Island: AI, Newfoundland: NF, Gaspé Peninsula: GP.

Research efforts devoted to the coupling of regional climate models (RCMs) with oceanic components are underway in other parts of the world. For example, the atmospheric regional model REMO of the Max-Planck Institute for the Meteorology in Hambourg has been coupled to the Baltic Sea model of the Institute for Marine Research in Kiel (Hagedorn *et al*. 2000). At the University of Colorado, the group of A. Lynch is working on a coupled RCM for the Arctic region (Lynch *et al*. 1995). A regional atmosphere-ocean coupled model is also being developed at the Rossby Centre (Döscher *et al*. 2000).

2. Experimental framework

The atmospheric component (CRCM) is a limited area model based on fully elastic, non-hydrostatic Euler equations (Caya and Laprise 1999). Its physical parameterization of the sub-grid scale processes is described in McFarlane *et al*. (1992). The oceanic component (GOM) is a three-dimensional, high-resolution dynamical ocean model for the GSL and the Estuary of the St. Lawrence, based on hydrostatic and Boussinesq approximation (Saucier *et al*. 2001). This model includes a dynamic-thermodynamic ice component based on a multi-category particle-in-cell method (Flato and Hibbler 1992; Flato 1994).

A series of atmospheric and oceanic simulations are performed iteratively. The CRCM and GOM are run separately and alternatively over a fixed period of 5 months, using variables from the other model to supply the needed forcing fields. Each model computes its own surface budget of momentum, heat and freshwater at the interface between the atmosphere and the ocean-ice system from the exchanged variables. The study period is from November 1st, 1989 to March 31st, 1990, including a spinup of 1 month.

The computational domain of the CRCM is centered over the GSL (Fig. 1). It contains 99 by 99 grid points in the horizontal with grid spacing of 30 km (true at 60˚N) on a polar stereographic projection. There are 30 levels in the vertical between 131 m and 31 953 m. The timestep is 10 minutes. The lateral boundary conditions are obtained from the NCEP (National Center for Environmental Predictions) analyses. The computational domain of GOM extends from the Strait of Cabot to Montréal and at the head of the Saguenay Fjord. The horizontal resolution is 5 km on a rotated-Mercator projection. The ocean is layered in the vertical with a uniform resolution of 5 m down to 300 m depth and 10 m below 300 m. The timestep is 5 minutes, except 30 minutes for the ice component. The boundary conditions are taken from observations and/or climatologic data as described in Saucier *et al*. (2001).

A first simulation begins the iteration with the CRCM (CRCM1) taking observations from the AMIP II database (Atmospheric Models Intercomparison Project, Gates 1992) to provide the initial oceanic forcing fields (Initial O.C.). The AMIP data includes the sea-surface temperature (SST) and sea-ice fraction (SIF) with a spatial resolution of 1 degree. The atmospheric fields of CRCM1 (incident solar radiation at the surface, cloud cover, precipitation, 10-m wind, 2-m temperature and humidity) are archived every 6 hours and are used to prescribe the atmospheric state for a first oceanic simulation with GOM (GOM1) over the same 5-month period. The once-daily archived results of GOM1 (SST, SIF and sea-ice thickness) are used to repeat the atmospheric run (CRCM2); the AMIP data are used to supply the oceanic state outside the GSL. This second atmospheric simulation is used to repeat the oceanic simulation (GOM2) and so on. The process is iterated 3 times to study the evolution of the CRCM and GOM solutions when the atmospheric or oceanic fields are updated from the previous run:

Initial O.C. ⇒ CRCM1 ⇒ GOM1 ⇒ CRCM2 ⇒ GOM2 ⇒ CRCM3 …

A cold bias was introduced in the AMIP data to simulate an extreme winter situation and to study the effect of this anomaly through the iterations.

3. Results

The experiment begins with CRCM1 where low-resolution data provide an initial oceanic surface condition. Figure 2a shows the monthly mean sea-ice concentration (SIC) for December 1989. From this figure, the GSL is completely ice-covered with relatively thick sea-ice in the Estuary of the St-Lawrence (near 46 cm) and thinner sea-ice in the southern part of the gulf (near 5cm). The SIC field is relatively smooth with little details, especially in the Estuary of the St. Lawrence. However, there is a sharp transition in the SIC field around Anticosti Island due to the interpolation of the data. In CRCM2, high-resolution oceanic data from GOM1 provide the oceanic surface condition. Figure 2b shows the GOM1 monthly mean SIC for December 1989. From this figure, the ice-covered area is much reduced with sea-ice only present in the western part of the GSL. The SIC distribution shows more details in better agreement with the climate of the GSL (Koutitonsky *et al*. 1991). However, the CRCM is rather insensitive to differences in the oceanic fields during our study period. For example, the difference in monthly mean temperature at 975 hPa (CRCM2 minus CRCM1) is at most 2.7˚C locally along the West Coast of Newfoundland (Fig. 3). Furthermore, the difference is restricted to the low level of the atmosphere and vanishes at 900 hPa (not shown). Near the surface, the difference in atmospheric forcing fields is more important. For example, the difference in the 2-m air temperature (CRCM2 minus CRCM1) reaches 7.5˚C in the eastern part of the GSL and locally up to 10˚C along the north coast (not shown). The latter is due to the formation of leads in GOM1, reflected in open water grid cells and large upward surface heat flux in CRCM2, as opposed to a fully ice cover and little atmosphere-ocean exchange in CRCM1. The air mass is less stable over the GSL and the 10-m wind is stronger in CRCM2, compared with CRCM1. The difference in wind speed is near 1 to 2 m/s.

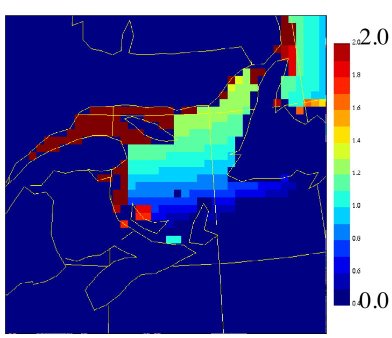
The warming of the near surface air and the increase in wind speed are responsible for changes in the surface conditions from GOM1 to GOM2. For example, there is a warming of the sea-surface over much of the area, further reduction in the ice cover and an increase in the ocean surface circulation from GOM1 to GOM2. The difference (GOM2 minus GOM1) in SST is up to 2˚C warmer along the west coast of Newfoundland (Fig. 4a). On Fig. 4b, the monthly mean sea-ice fraction (values greater than

10%) extends over a large part of the GSL in GOM1, but on Fig. 4c it is restricted to the western half of the GSL in GOM2. The ice fraction is reduced by 10% to 15% and thinner in GOM2, compared with that in GOM1. On Fig. 5a-b, the monthly mean surface currents for December 1989 show relatively large differences from GOM1 to GOM2. In particular, the Gaspé current flows along the Gaspé Peninsula in GOM1 (Fig. 5a), while it is detached from the coast and extends further east in GOM2 (Fig. 5b). This experiment indicates that the position of the Gaspé current follows an area of slightly warmer, less stable atmospheric conditions and stronger winds, in relation with the sea-ice distribution.

The warming trend has continued into the third iteration, but with reduced amplitude. The 975-hPa air temperature difference (CRCM3 minus CRCM2) is smaller, reaching 1.8˚C south of Anticosti Island (not shown). The sea-ice cover in GOM3 is further reduced, with the position of the edge approximately 30 km west of that in GOM2. Three additional iterations have been done for December 1989 to verify and confirm the convergence of the solutions for both, the CRCM and GOM. The results indicate a slight warming trend has continued further for both the atmosphere and the ocean, but with reduced amplitude. Furthermore, the results suggest that most fields tend towards equilibrium at the sixth iteration. An example of this convergence is presented with the 2-m air temperature in Figure 6. The values are domain-averaged (over the GSL), monthly mean 2-m air temperature starting at below –10˚C at iteration #1 rising to –2˚C at iteration #6.

We present the time series of the 2-m air temperature (TA) and sea-surface salinity (SSS) for the period from December 1st, 1989 to show the sensitivity of the models to each other on a longer time scale (Figure 7a-b). The time series are the spatial mean (over the GSL) of daily values for TA and SSS. Figure 7 shows that the differences are most important between iteration 1 and 2, and decrease as the number of iteration increase. Furthermore, the differences are more important in December 1989 during the transition season towards winter. In the ocean, Fig. 7b indicates a persisting SSS anomaly through the entire period due to the inertia of the system.

2a)



2b)

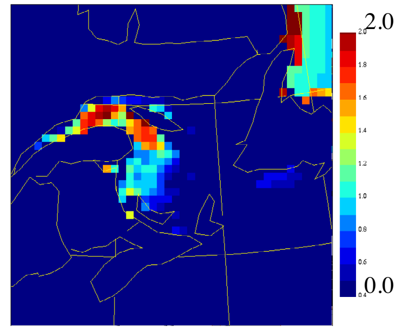


Figure 2. Monthly mean SIC (kg m^{-2} x10^{2}) for (a) CRCM1 and (b) for CRCM2 for December 1989. There is no data over the continent. These figures present a small portion of the CRCM domain to show the difference in the GSL.

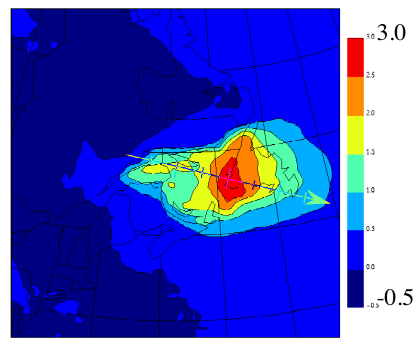


Figure 3. Difference of monthly mean (CRCM2 minus CRCM1) air temperature at 975 hPa (contour every 0.5°C) for December 1989.

4a)

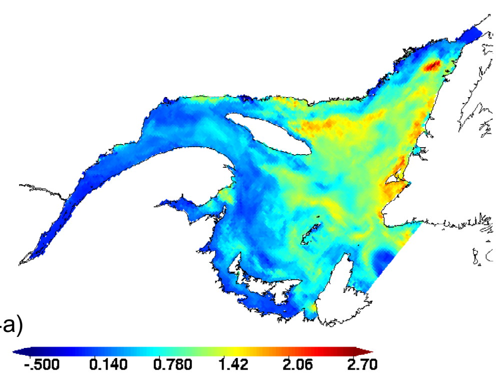


Figure 4. (a) Difference of monthly mean (GOM2 minus GOM1) SST (°C) for December 1989.

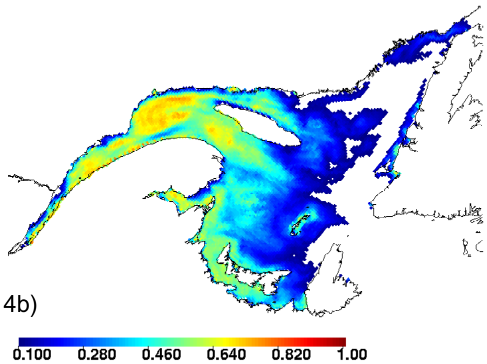


Figure 4 (continued) (b) Monthly mean sea-ice fraction (%) for December 1989 from GOM1. White area in c indicates no ice.

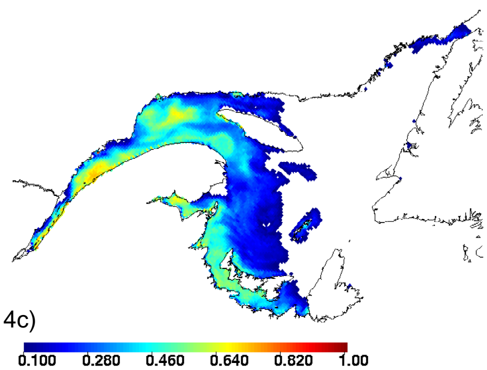


Figure 4. (Continued) (c) Monthly mean sea-ice fraction (%)for December 1989 from GOM2.

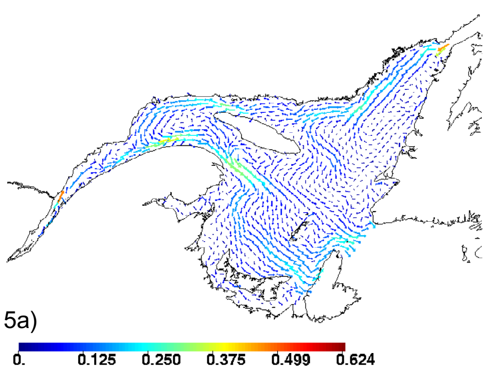


Figure 5. Monthly mean surface current (m s^{-1}) for December 1989 from (a) GOM1.

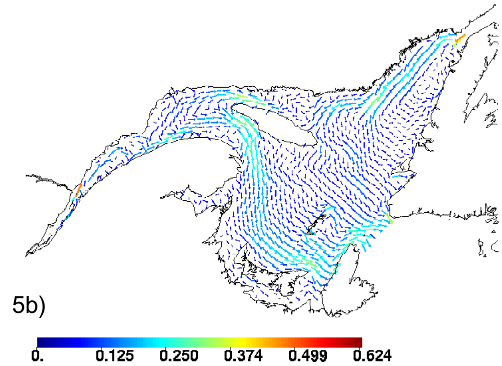


Figure 5. (Continued) Monthly mean surface current (m s^{-1}) for December 1989 from (a) GOM2.

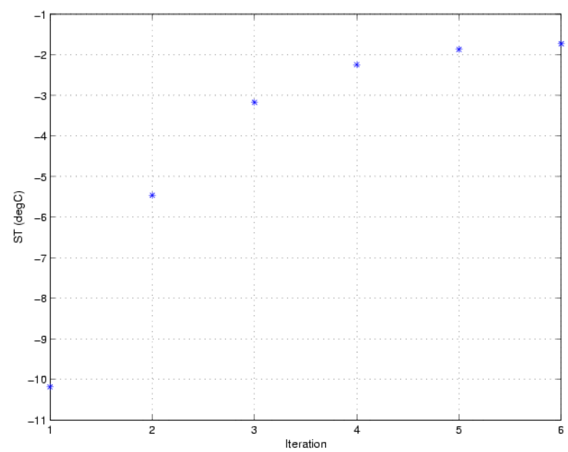


Figure 6. Domain-average (over the GSL), monthly mean 2-m air temperature (˚C) for December 1989 for iteration #1 to #6.

4. Conclusion

The results of this experiment show that, on a monthly or longer time scale, the CRCM is not very sensitive to the oceanic fields from GOM, except locally in the Gulf area and near the surface. However, GOM is relatively sensitive to small differences in the atmospheric forcing from the CRCM. An important result is the convergence of the solutions, indicating that both models are reaching equilibrium with respect to each other. The sensitivity of the models to each other was investigated for a winter season. However, we are now continuing the study over an annual cycle to understand the sensitivity of the models with respect to each other during a summer season while the atmospheric flow is generally weaker. The next step is to make a coupled experiment where both models exchange information on a frequent basis.

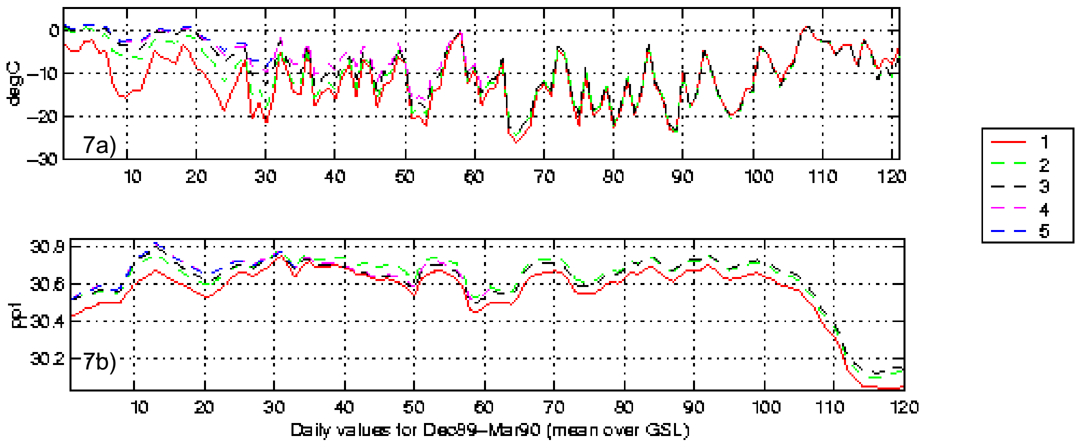


Figure 7. Time series of daily mean, spatially averaged (a) 2-m air temperature (˚C) and (b) SSS (ppt) for simulations (a) CRCM1-5 and (b) GOM1-5. The period is from December 1st, 1989 to March 31, 1990, except for CRCM4 (GOM4) and CRCM5 (GOM5) ending respectively on January 31, 1990 and December 31, 1989. The iteration #6 is not included on the graph for more clarity.

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