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Modeling the formation and circulation processes of water masses and sea ice in the Gulf of St. Lawrence, Canada

François J. Saucier, François Roy, and Denis Gilbert
Fisheries and Oceans, Maurice Lamontagne Institute, Mont-Joli, Québec, Canada

Pierre Pellerin and Harold Ritchie
Meteorological Service of Canada, Recherche en Prévision Numérique, Dorval, Québec, Canada

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[1] The seasonal cycle of water masses and sea ice in the Gulf of St. Lawrence is examined using a three-dimensional coastal ice-ocean model with realistic tidal, atmospheric, hydrologic, and oceanic forcing. The model includes a level 2.5 turbulent kinetic energy equation. A model simulation over 1997–1998 is verified against available data on sea ice, temperature, and salinity. The results demonstrate a consistent seasonal cycle in atmosphere-ocean exchanges and the formation and circulation of water masses and sea ice. The accuracy of radiative, momentum, and sensible heat exchanges at the sea surface, and the production of turbulent kinetic energy from winds and tides, are critical to the accuracy of the modeled circulation. The analysis of the mean error on near-surface temperature and salinity in the late summer and fall using standard bulk exchange coefficients and radiation (about 1°C too cold and 1 salinity unit too fresh) shows the tradeoff between tidal mixing at the head of the Laurentian Channel, and wind-driven circulation and mixing in the surface waters. The results suggest year-long stratification in the estuary and northwestern Gulf, with little mixing except near the head region, where relatively deep warmer waters are mixed to the surface during winter, and cold intermediate waters are efficiently withdrawn during summer. The results suggest that the summer cold waters found at intermediate depths in the estuary and northwestern Gulf are not formed in situ. A significant fraction of these waters enters through the Strait of Belle Isle in wintertime, eventually reaching the estuary within about 6 months. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4243 Oceanography: General: Marginal and semienclosed seas; 4235 Oceanography: General: Estuarine processes; 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; *KEYWORDS:* St. Lawrence, air-sea interactions, circulation, tide, sea ice, numerical modeling, seasonal cycle

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1. Introduction

[2] The Gulf of St. Lawrence (GSL, Figure 1) is a semi-enclosed sea with an area of about 2.4×10^5 km^2 opened to the Atlantic Ocean through Cabot Strait and the Strait of Belle Isle. On timescales ranging from hours to seasons and years, the circulation is controlled by tides, exchanges with the atmosphere, runoff from land, the seasonal ice cover, and inflow through the bounding straits (e.g., see reviews by *Dickie and Trites* [1983] and *Koutitonsky and Bugden* [1991]). The main channels allow Atlantic and Labrador shelf waters to intrude at depth and circulate toward the head region of the lower St. Lawrence Estuary. Continental runoff freshwaters enter the GSL mainly from the estuary and north shore rivers. They partly mix with salt waters, flow through the general cyclonic circulation, and exit through Cabot Strait. The heat, salt, and momentum distributions of the surface 200 m exhibit a strong seasonal cycle wherein the heat and salt contents of the water column remain everywhere strongly influenced by horizontal currents and stratification. During winter, sea ice of the order of half-meter thickness is produced. The surface mixed layer reaches about 100 m depth, and significant inflows of relatively cold and salty Labrador shelf waters take place at intermediate depths. This leaves a cold intermediate layer (CIL), with temperature near 0°C and salinity between 32 and 33, persisting between 30 and 150 m depth beneath the new spring surface layer [e.g., *Lauzier and Graham*, 1958; *Banks*, 1966]. The circulation and fate of the CIL over seasons remain elusive. The waters below the CIL are warmer (2° to 6°C) and saltier (33 to 35). They are slowly advected in the Laurentian Channel (LC) from the continental shelf break toward the estuary [e.g., *Lauzier and Bailey*, 1957; *Lauzier and Trites*, 1958; *Bugden*, 1991]. The sea ice cover, the water mass properties, and the circulation

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Seasonal versus synoptic variability in planktonic production in a high-latitude marginal sea: The Gulf of St. Lawrence (Canada)

V. Le Fouest, B. Zakardjian, and F. J. Saucier
Institut des Sciences de la Mer de Rimouski (ISMER), Université du Québec à Rimouski, Rimouski, Quebec, Canada

M. Starr
Fisheries and Oceans Canada, Maurice Lamontagne Institute, Mont-Joli, Quebec, Canada

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[1] The Gulf of St. Lawrence (Canada) is a subarctic marginal sea characterized by highly variable hydrodynamic conditions that generate a spatial heterogeneity in the marine production. A better understanding of physical-biological linkages is needed to improve our ability to evaluate the effects of climate variability and change on the gulf's planktonic production. We develop a three-dimensional (3-D) eddy permitting resolution physical-biological coupled model of plankton dynamics in the Gulf of St. Lawrence. The planktonic ecosystem model accounts for the competition between simplified herbivorous and microbial food webs that characterize bloom and post-bloom conditions, respectively, as generally observed in temperate and subarctic coastal waters. It is driven by a fully prognostic 3-D sea ice-ocean model with realistic tidal, atmospheric, and hydrological forcing. The simulation shows a consistent seasonal primary production cycle, and highlights the importance of local sea ice dynamics for the timing of the vernal bloom and the strong influence of the mesoscale circulation on planktonic production patterns at subregional scales.

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1. Introduction

[2] General circulation models generally predict that global climate change associated with increased greenhouse gas concentrations in the atmosphere will lead to an amplified warming in the Arctic and its adjacent seas over the next century (5°–8°C in 2070 [e.g., *Holland and Bitz*, 2003]). Among those, the Gulf of St. Lawrence (GSL) is a large semi-enclosed sea of 226,000 km^2 that connects the Great Lakes and the St. Lawrence river with the North Atlantic Ocean [e.g., *Koutitonsky and Budgen*, 1991]. Runoff from the St. Lawrence watershed is the second most important source of freshwater from North America into the North Atlantic Ocean [e.g., *Bourgault and Koutitonsky*, 1999]. The GSL exhibits a subarctic climate with a seasonal sea ice cover present between January and April, and sheds the southernmost extent of sea ice in the Northern Hemisphere. Freshwater runoff, large to moderate tides, and highly synoptic winds drive the gulf's circulation. These physical forcings, coupled with the relatively large dimensions of the gulf (several internal Rossby deformation radii) and an average depth of 150 m, generate a complex hydrodynamics with eddies, coastal upwellings, and fronts superimposed on a mean estuarine-like circulation [e.g., *Koutitonsky and Budgen*, 1991; *Saucier et al.*, 2003]. These hydrodynamic conditions have been shown to have a marked effect on summer primary production in the northwestern Gulf [*Levasseur et al.*, 1992; *Fuentes-Yaco et al.*, 1995, 1996, 1997a, 1997b; *Tremblay et al.*, 1997], and are thought to generate a spatial heterogeneity in the marine production of the GSL [e.g., *de Lafontaine et al.*, 1991]. *Savenkoff et al.* [2001] also suggest that the GSL can be subdivided into distinct subregions on the basis of specific hydrodynamic regimes that affect the nutrient transport and the resulting planktonic production. Recent observations confirm that the high interannual variability in plankton biomass in the Lower Estuary [*Starr and Harvey*, 2000; *Starr et al.*, 2001], the recruitment of fish stocks in the southern gulf [*Runge et al.*, 1999], the aggregation of krill and whales at the head of the Laurentian Channel [*Simard and Lavoie*, 1999; *Lavoie et al.*, 2000], and the water masses properties of the GSL [*Saucier et al.*, 2003] are strongly linked to the influence of climate and freshwater inputs on the mixing and circulation processes. However, it has not yet been possible to quantify together the detailed circulation and the response of the planktonic ecosystem.

[3] Prior to any attempt to predict the effects of global climate variability and change on the GSL system, we must first acquire a better knowledge of the links between the physical environment and the short-term to interannual variations in planktonic production. In order to improve

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