7B.5 Impacts of Air-Sea Fluxes on the Evolution of an Arctic "Bomb"

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1. INTRODUCTION

The Arctic is important because of its unique dynamical-thermo teleconnections and its potential role in global climate change. Intense Arctic storms are examples of "extreme" weather which can impact coastal oceanographic processes in the southern Beaufort Sea and the west Canadian Arctic. This area is important because the coastal marine environment is an integral part of the life style of Canadian Northerners, and because of hydrocarbon exploration and potential development in the near future. Factors such as open water and ice, and the oceanic surface fluxes can modulate storm development and winds. Climate change may endanger coastal settlements and marine environments.

It is well known that hurricane intensity is influenced by factors such as the storm's initial intensity, the spatial extent of the storm, the thermodynamic state of the atmosphere through which the storm moves, the storm propagation speed, and sea surface fluxes along the storm track. Although several of these factors are also known to modulate the strength of low- and mid-latitude cyclone systems, little is known about the impact of atmosphere-ocean-ice interactions on Arctic storms.

The primary focus of this study is to model the oceanic responses to an Arctic "bomb" in September 1999 which made landfall as an unusually intense storm along the southern coast of the Beaufort Sea. We investigate the ability of surface heat fluxes to influence the storm's life cycle and air-ocean-ice dynamics.

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2. BACKGROUND

The Arctic storm from September 1999 is mesoscale in size. It developed over the NE Pacific and western Bering Sea at 1800 UTC on 21 September 1999. It intensified explosively in the Gulf of Alaska, developing into a meteorological bomb at 1800 UTC 22 September 1999. The storm made landfall with surface winds > 25 m s^{-1} at Cape Newenham, Alaska, at 1200 UTC 23 September and rapidly moved north northeastward. Thereafter, it crossed the Rocky Mountains to the Yukon and Northwest Territories and re-intensified over the coastal waters of the southern Beaufort Sea, over a zone of high sea surface temperature gradients, causing extensive damage to coastal communities. After half a day, the system moved northeastward along the coast of the Beaufort Sea and continued to fill. Finally, it dissipated over the northern Canadian Archipelago, just after 1800 UTC on 26 September.

Initially, the storm lay 200 km off the Alaskan coastline at 0000 UTC on 22 September with a central sea level pressure (SLP) of 980 mb as analyzed by the NARR, NCEP and CMC (Canadian Meteorological Centre) datasets. The subsequent 18 h saw it develop as a superbomb tracking northward and re-intensify to 953 mb near the southern shore of Alaska. During with its mature stage, satellite images reveal a mesoscale size and spiral cloud bands of unusual symmetry, that suggest the presence of a strong midlevel trough interacting with the system over this period, contributing to a rapid spinup of the lower level vortex via baroclinic processes. The track of the low pressure center passed over Anchorage, Alaska where observed time series show a pronounced maximum in equivalent potential temperature at the storm's core. Storm tracks and central SLP are given in Fig. 1 from reanalysis data.

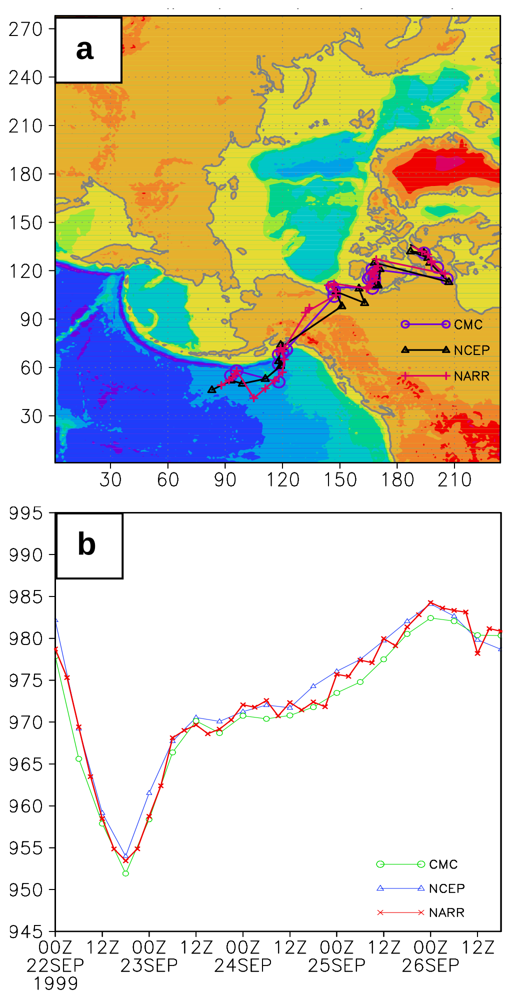

Figure 1: CMC, NCEP and NARR analysis data showing (**a**) storm track and (**b**) central SLP (hPa), from 00 UTC 22 Sep to 18 UTC 26 Sep.

3. MODEL DESCRIPTIONS

All simulations are performed by using Mesoscale Compressible Community (MC2) atmospheric model coupled to the Coupled Ice-Ocean Model (CIOM, Wang et al. 2002), in which the SSTs, ice concentration and thickness from CIOM are passed to MC2, while the surface air temperature, wind, sea level pressure, short-wave radiation, clouds, precipitation and specific humidity (i.e. the momentum, heat, and moisture fluxes) from MC2 are passed back to CIOM.

The MC2 model is a state-of-the-art fully elastic nonhydrostatic model, using a semi-Lagrangian advection and a semi-implicit time-differencing dynamic scheme (Tanguay et al., 1990). As a modeling tool, MC2 is very versatile and has been successfully used in simulations of extratropical cyclones (Benoit et al., 1997; McTaggart-Cowan et al., 2001, 2003; Ren et al., 2004; Fogarty et al., 2006). The MC2 model domain covers the entire Arctic Ocean, its coastal areas as shown in Fig. 1. The number of horizontal grid points is 235 x 279, with horizontal resolution of 30km and 30 vertical layers. The central grid point is located at (76ºN, 170ºW). We use north-polar projection, and the integration time step is 600s. Initial conditions and boundary conditions are determined from the CMC 6-hourly analysis fields (Chouinard et al., 1994).

POM is used to simulate the oceanic component of our coupled model system (Blumberg and Mellor 1987; Mellor, 1998). To accurately represent the cyclone-related mixed layer dynamics, 23 vertical layers are used, with higher resolution in the upper ocean mixed layer (8 levels within the upper 80 m). Ocean topography is determined from the Earth Topography and Ocean Bathymetry Database (ETOPO2V2) at 2-min resolution, interpolated to POM's model grid (U.S. National Geophysical Data Center, http://www.ngdc.noaa.gov/).

The sea ice component of the coupled model is a thermodynamic model based on multiple categories of ice thickness distribution function (Throndike *et al*., 1975; Hibler, 1980) and a dynamic model based on a viscous-plastic sea ice rheology (Hibler, 1979). For Ice-Ocean coupling, heat and salt fluxes at the ice-ocean interface are governed by the boundary processes as discussed by Mellor and Kantha (1989) and Kantha and Mellor (1989).

The coupled ice-ocean model grid size is about 27.5 km with 23 sigma layers. The number of horizontal grid points is 143 x 191. The domain includes the central Arctic Ocean (Canada and Eurasian Basins), the Beaufort Sea coastal areas, Canadian Archipelago and the northern GIN Seas. In this study, eight ice categories are used. Because Bering Strait and the southern boundary are open, the radiation condition is applied at the lateral open boundary of the CIOM model, with specified depth-averaged transport taken from an extension of the CIOM model. The initial conditions and boundary conditions for temperature and salinity are given by monthly averaged profiles from the polar Science Center Hydrographic Climatology (PHC).

4. ANALYSIS OF SIMULATION RESULTS

To investigate the role of air-sea-ice interactions for the superbomb storm the simulated went from 1800 UTC 22 Sep to 1800 UTC 26 Sep 1999. Control runs are simulations in which MC2 is used alone, uncoupled to the ice-ocean model, using CMC analysis data to specify fixed SSTs during the integration period. Coupled runs use the MC2–CIOM model system.

1) STORM TRACK AND SST

Comparisons between the simulation (coupled and uncoupled) tracks and the CMC storm track are shown in Fig. 2. The uncoupled simulation track differs from the coupled simulation after the storm reaches the Beaufort Sea coast and the Archipelago. The coupled simulation is closer to the CMC storm track.

The storm induces a cool wake in the upper ocean. The SST cool wake is weak during superbomb's early stages, as the storm lingers in the Gulf of Alaska. But within 24 hours, the storm moves to the Beaufort Sea and influences the ocean surface by strong winds (> 20 $m \cdot s^{-1}$), so that a cool wake becomes widely distributed around the Beaufort coastal areas as shown in Figure 3b.

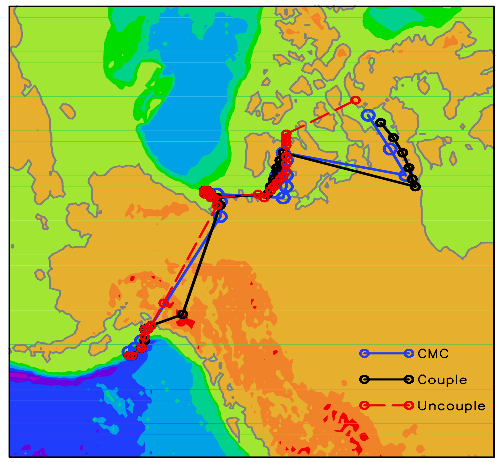

Figure 2: Comparisons between the control storm tracks simulation (uncoupled), with the coupled simulation and the CMC analysis storm track.

During the second day of the simulation (to 48 h), the storm's propagation slows (> 15 $m \cdot s^{-1}$) and it still lingers along the Beaufort Sea southern coast. Thus, the cool wake strengthens in the coastal waters. During the third day of the simulation (to 72 h), the cool wake central area moves eastward, as the storm moves over the Canadian Archipelago. The maximum SST cooling is almost 2°C and occurs in the coastal waters off the Mackenzie Delta.

Because of extensive ice cover in the Arctic Ocean in September 1999, the SST cooling and associated oceanic mixed layer currents, produced by the storm's cyclonic, asymmetric wind fields (Fig. 3a) mainly occur in open waters of the southern Beaufort Sea.

2) UPPER-OCEAN RESPONSES

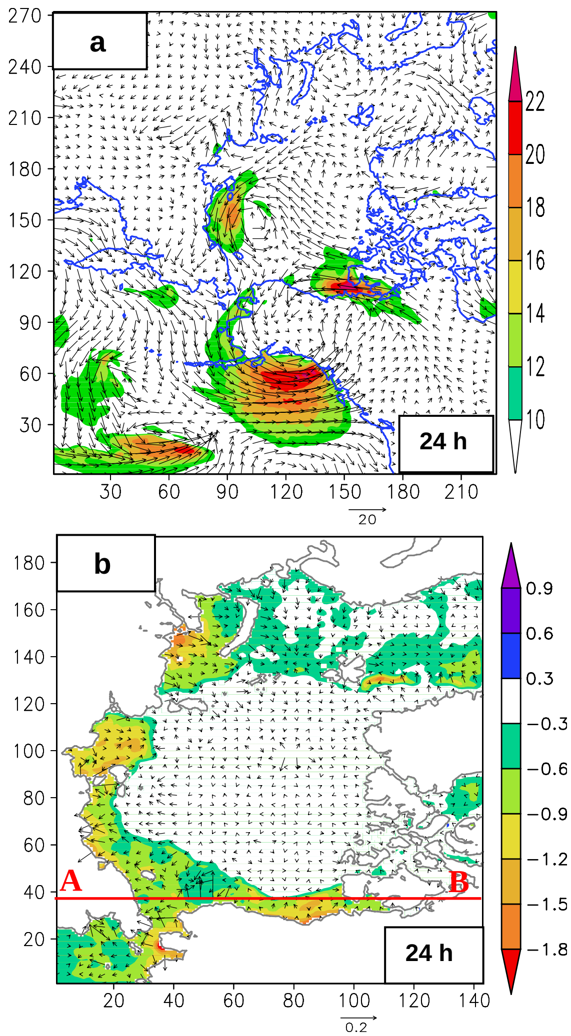

Figure 3: Coupled model results: (**a**) he U_{10} winds ($m \cdot s^{-1}$) at 24h for Superbomb starting at 1800 UTC 22 Sep and (**b**) the SST at 24h, *minus* the initial SST, and surface current ($m \cdot s^{-1}$).

The storm-induced cool wake is not simply an ocean surface feature. In September, there is typically an oceanic autumn sea temperature profile whereby a shallow mixed layer overlays colder water, and a sharp temperature gradient occurs in the upper thermocline. The warmest sea temperatures occur in the southern Chukchi Sea, because of warm currents from the NE Pacific via Bering Strait.

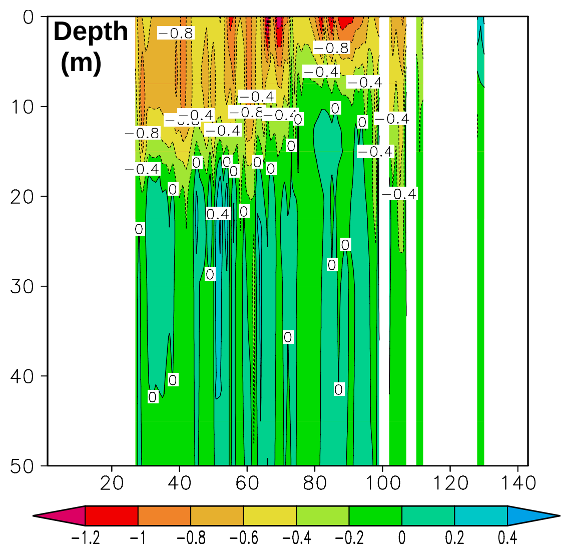

Figure 4: Horizontal–depth section from the coupled simulation along line A–B (Fig. 3a) giving temperature difference (0.2°C contours) after 96-h simulation *minus* the initial state.

Figure 4 shows the storm-induced impacts on the upper-ocean temperature from the coupled simulation. The largest change in sea temperature occurs to along the south Beaufort Sea coast. At this time, the storm is moving northward over the coast. A cooling zone extends over the Chukchi Sea, Barrow, and Beaufort Seas to the Archipelago, to the 10-m depth, with warming in deeper (20 to 50 m) waters, by as much as 1°C (Fig.4). The latter is consistent with Price (1981) and Ren (2004) results whereby entrainment causes cooling in the mixed layer and warming at depths below the initial mixed layer. Storm-induced currents are a dominant mechanism in forming a given storm's SST depression. Because of the asymmetry of the storm's wind fields (Fig. 3a), the storm track and the distribution of ice cover in Arctic, the strongest surface currents are produced in coastal waters. This is shown in the coupled simulation in Fig. 3b, with current speeds up to 1.5 m·s^{-1}, which is similar to currents generated by tropical and extratropical cyclones (Bender and Ginis 2000; Ren et al., 2004).

3) SEA ICE RESPONSES

Arctic storm activity plays important roles at various time and space scales, ranging from the local scale, causing severe erosion along coastal margins of the Beaufort and Alaska and other Arctic regions, to the continental scale, where storm corridor position and strength strongly affect the moisture and heat exchanges between the Arctic and lower latitudes. Sea-ice, specifically the location of the ice edge, plays an important role in the location of storm tracks as well. Its presence can impede storm progression into the Arctic by creating a cold friction zone over which storms lose energy. The ice edge often defines a strong baroclinic zone which can enhance storm activity by both strengthening storms and by acting to preferential guide their trajectory.

A recent NASA study shows that the rising frequency and intensity of Arctic storms over the last half century can be attributed to progressively warmer waters, directly resulting in enhanced acceleration in the rate of Arctic sea ice drift.

For the summer Beaufort, Chukchi, and East Siberian Seas we investigated the response of the ice edge and interior ice to the superbomb storm using the air-ocean-ice coupled model. Specifically, the peak U_{10} winds are about 18 m s^{-1} (Fig. 5b). Figure 5a shows the associated impacts on sea ice drift from the coupled simulation during the storm.

The ice edge currents imply that the storm fractures the large floes into small floes, some of which are advected into the adjacent warm water. The ice interior thickness suggests that the storm caused an increase in the open water amount and a shift in the floe size distribution toward smaller floes.

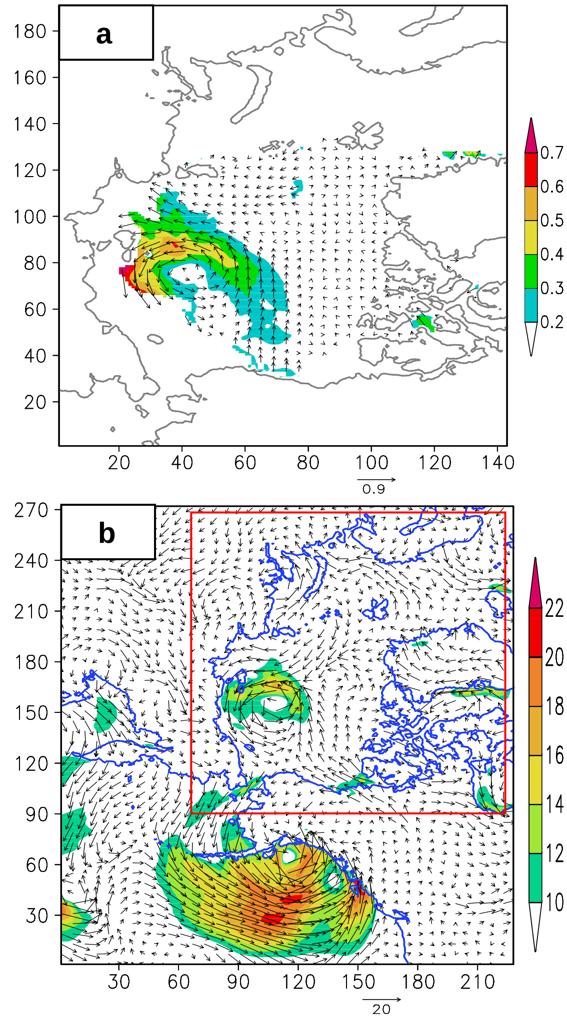

Figure 5: Distribution of the ice current (**a**) and U_{10} winds ($m \cdot s^{-1}$) at 03h for the coupled simulation starting at 1800 UTC 22 Sep., 1999.

4) SEA SURFACE FLUXES CHANGE

Comparisons of the associated sensible and latent heat fluxes from the coupled simulations are shown in Figure 6a and 6b. As expected, latent heat flux constitutes a dominant factor in the coupling of atmosphere and ocean. Moreover, SSTs and the storm's propagation speed are important factors affecting the ocean's impact on latent heat fluxes. While sensible and latent heat fluxes have similar distributions, the Arctic storm propagates rapidly and after 24 h it has moved over cold water and both latent and sensible heat fluxes are negative near the storm-center. Although extensive positive sensible heat fluxes remain, they are confined to the rear of the storm and do not strongly affect further storm development. The reaction of the lower atmosphere to SST cooling is strong. Smaller sensible and latent heat fluxes from the ocean surface tend to cool and dry the atmospheric boundary layer in the coupled simulation. Concomitantly, the U_{10} winds decrease and the cyclone tends to weaken in the coupled simulation. However, because most of the significant interactive processes occur during the peak intensification period, after the initial 96 h in our simulation of the storm, the ocean impact on intensity is not large.

4. CONCLUSIONS

This study is concerned with the implications of using a coupled atmosphere–ocean-ice model to simulate intense arctic storms and upper-ocean responses. To illustrate the impacts of ocean surface processes, we consider an Arctic superbomb that developed over the NE Pacific and western Bering Sea at 1800 UTC on 21 September 1999. The coupled model can realistically simulate the atmosphere-ocean-ice interactions in the storm. Model results were shown to compare well with CMC analysis data. We have shown the role of sea surface fluxes on the storm's explosive re-intensification over the Beaufort coastal waters. We compared these processes to the other factors that modify the storm's development as it passes across the Rockies, to its final decay region in the Arctic.

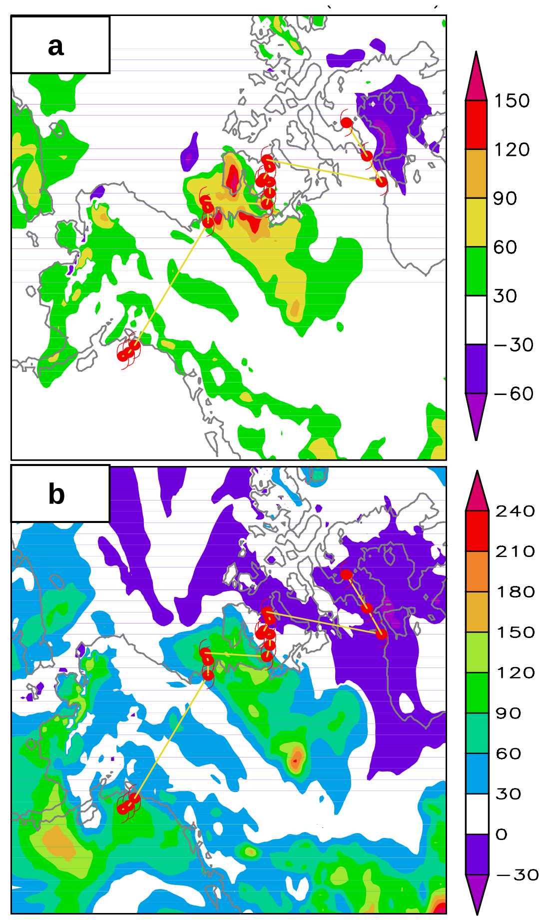

Figure 6: Distribution of sensible heat flux (**a**) and latent heat flux (**b**) at 96h for the coupled simulation starting at 1800 UTC 22 Sep., 1999. (Units: $W \cdot m^{-2}$)

5. ACKNOWLEDGEMENTS

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