Modeling Study of Arctic Storm with the Coupled MM5-Sea Ice-Ocean Model

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1. Introduction

Synoptic activities, such as cyclones, have been intensified in recent decades in the Arctic regions (Serreze and Barry, 1988; Zhang et al. 2003) concurrent with the decreasing sea ice extent (Rothrock et al, 1999) and dropped sea level pressure (Walsh et al., 1996). McCabe et al., 2001 also suggest that the increase in high latitude cyclone frequency, associated with a northward shift of storm tracks, is a regional trend for the Arctic under conditions of global warming. The intensified cyclones apparently result in strengthening of high frequency atmospheric variability, which may cause noticeable changes of sea ice and the upper ocean and leave a lasting imprint to affect climate variability. These have been evidently detected in several studies, such as cyclones increase sea ice export through straits (e.g., Brummer et al, 2000) and the deep mixing produced by intense storms eventually affect the ocean heat and salt budgets (Yang et al. 2001). These imply that interactions between Arctic storms and the sea ice and ocean may play an important role in the evolution of a global warming scenario in high latitudes.

As such, studies of the development processes within Arctic storms, as well as its interaction with the sea ice and ocean, are needed. For those cyclones originating from low latitudes, one important feature is its accompanying advection of warm air, which brings large amounts of energy to result in remarkable dynamic and thermodynamic changes within the atmosphere, sea ice and ocean. Then how do the atmosphere and sea ice/ocean interact during the warm air advection brought by a cyclone system? How do the atmosphere, sea ice and ocean temperatures vary spatially and temporally during the warm air advection? In this work we will investigate these questions with a coupled modeling system denoted the “Arctic MM5”. The Arctic MM5, which is based on the version 3.3 of the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) (Dudhia 1993; Grell et al. 1994), includes land surface, thermodynamic sea ice and ocean mixed layer components coupled to the atmosphere. These features of the Arctic MM5 make it a true earth modeling system for the exploration of the atmosphere / sea-ice / ocean / land-surface interactions and better understanding of the evolution progresses of the Arctic storms and their interactions with the sea ice and ocean.

The Surface Heat Budget of the Arctic ocean (SHEBA) project conducted a year-long field experiment at a drift station on the pack ice of the Arctic ocean from 2 October 1997 to 9 October 1998 beginning at (75°N latitude, 142°W longitude) and ending at (80°N latitude, 162°W longitude). This field experiment provides valuable measurements for studying the atmosphere-ice-ocean interactions. During this SHEBA experiment, a well-developed storm process in the middle May 1998 was captured. This cyclonic system moved slowly northward from the Bering Sea to the Beaufort Sea from 9th through 12th May 1998 and brought about an outstanding warm air advection over the Chukchi Sea and the western Beaufort Sea. In this study we employed the Arctic MM5 modeling system to carry out a modeling study of this storm process. We verified the modeling results with the SHEBA measurements and investigated the storm development and associated atmosphere-ice-ocean interactions.

In section 2 we describe briefly the aspects of the Arctic MM5 system. The Pacific-Arctic storm captured by SHEBA and the modeling design for simulating the storm are introduced in section 3. Section 4 presents the simulation results and its comparisons with SHEBA observations.

2. The Arctic MM5 Model

As noted in the introduction, the Arctic MM5 was developed based on the version 3.3 of the PSU/NCAR MM5 by coupling with a thermodynamic sea ice and ocean mixed layer models to improve the simulations of surface energy flux over the Arctic ocean and sea ice and by modifying several parameterization schemes to better represent the physical processes occurring in the polar regions. A general description of the atmospheric model MM5 is given by Dudhia (1993) and Grell et al. (1994). It is a three dimensional, non-hydrostatic, primitive equation, regional model with a terrain following sigma vertical coordinate and a choice of multiple options of physical parameterization schemes. The thermodynamic sea ice model (Zhang and Zhang 2001) coupled to the Arctic MM5 predicts the changes in sea ice concentration and sea ice temperature and considers the effects of varying sea ice on the surface energy exchange. The ocean mixed layer model (hereafter denoted MLM), developed by Kantha and Clayson (1994) and now employed in the Arctic MM5, predicts the changes of ocean temperature T_o , salinity, as well as heat flux exchanges between the ocean and the sea ice, which play important roles on the sea ice modeling. For the land surface processes, Chen and Dudhia (2001) coupled a modified Oregon State University (OSU) Land Surface Model (LSM) with MM5 and improved the simulation of surface energy flux, boundary layer and associated precipitation processes. In the Arctic MM5, the land surface model OSU-LSM was updated with the NOAH-LSM, a descendant of OSU-LSM, modified by Koren et al. (1999) and Mitchell et al. (2002). The NOAH-LSM included cold season processes such as the spatial and temporal variability of the snowpack as well as frozen soil, which are very important processes over the high latitudes. In addition, cloud and precipitation physics represented by the Reisner explicit microphysics scheme (Reisner et al. 1998) as well as longwave and shortwave radiation represented by the National Center for Atmospheric Research (NCAR) Community Climate Model, version2 (CCM2) radiative transfer scheme (Hack et al. 1993) were modified in the Arctic MM5 follow the Polar MM5 (Cassano et al. 2001) for better representations of the radiative and microphysical processes occurring in the Arctic atmosphere.

The detailed descriptions of the land surface model OSU-LSM and its coupling with the MM5 have been given by Chen and Dudhia (2001). Further modifications to the cold season processes can be found in Koren et al. (1999) and Mitchell et al. (2002). And the detailed improvements made to the microphysics and radiative transfer schemes as in the Polar MM5 can be found in Cassano et al. (2001). We refer the reader to these papers for details.

The thermodynamic sea ice model predicts sea ice concentration, sea ice temperature and surface energy flux. The treatment of sea ice thermodynamics is similar to that in both Hibler (1979) and Parkinson and Washington (1979). Sea ice thickness *h* and concentration *A* at a grid cell are described by the following equations:

$$\frac{\partial h}{\partial t} = F_h \qquad (1)$$

$$\frac{\partial A}{\partial t} = F_A \qquad (2)$$

F_h and F_A are the thermodynamic source/sink functions, parameterized following Hibler (1979):

$$F_A = \frac{F_h}{2h} A + \frac{\left(\partial h / \partial t \right)^0_{therm}}{h_0} (1 - A) \qquad (3)$$

$$F_h = \left(\frac{\partial h}{\partial t} \right)^1_{therm} A + \left(\frac{\partial h}{\partial t} \right)^0_{therm} (1 - A) \qquad (4)$$

where superscript “0” represents new ice forming over open water while superscript “1” represents growth of existing sea ice. $\left(\frac{\partial h}{\partial t} \right)_{therm}$, the local rate of sea ice growth or melt is determined from the sea ice surface energy budget H_n and the turbulent heat flux H_w between the ocean and the sea ice:

$$\left(\frac{\partial h}{\partial t} \right)_{therm} = \frac{1}{q_0} (H_w - H_n) \qquad (5)$$

where H_n has different definitions depending on the surface types:

$H_n = H_{T_o}$ = *net surface energy flux, open ocean*

$H_n = H_{T_i}$ = *net surface energy flux, bare sea ice*

$H_n = G_i$ = *conductive heat flux within snow-covered sea ice*

Details on H_{To}, H_{Ti} and G_i are given in Appendix A. H_w is calculated with the ocean temperature T_o and freezing point T_f following Ebert and Curry (1993):

$$H_w = \rho_o c_{po} C_t (T_f - T_o) \qquad (6)$$

The snow surface temperature T_s and the sea ice surface temperature T_i are calculated with the Newton/Raphson iterative scheme from the surface energy balance. When there is no snow cover on the sea ice, T_i is calculated by linearizing the sea ice surface energy balance:

$$T_i^n = T_i^{n-1} + \frac{H_{T_i}^{n-1} + \frac{C_i}{h}(T_b - T_i^{n-1})}{4\sigma(T_i^{n-1})^3 + \frac{C_i}{h} + \rho C_p C_h V + \rho C_p L_s q_i \frac{a(273.16-b)}{(T_i^{n-1}-b)^2}} \quad (7)$$

When the sea ice is snow-covered, a similar relation is used to obtain T_s:

$$T_s^n = T_s^{n-1} + \frac{H_{T_s}^{n-1} + \frac{C_s C_i}{C_i h_s + C_s h}(T_b - T_s^{n-1})}{4\sigma(T_s^{n-1})^3 + \frac{C_s C_i}{C_i h_s + C_s h} + \rho C_p C_h V + \rho C_p L_s q_s \frac{a(273.16-b)}{(T_s^{n-1}-b)^2}} \quad (8)$$

The interface between snow and sea ice has a balance between the conductive fluxes of snow and sea ice:

$$\frac{C_s}{h_s}(T_i - T_s) = \frac{C_i}{h}(T_b - T_i) \quad (9)$$

Then we have:

$$T_i^n = \frac{C_s h T_s^n + C_i h_s T_b}{C_s h + C_i h_s} \quad (10)$$

Thus from (1)-(10), the changes of sea ice thickness and concentration, sea ice/snow temperatures and flux exchanges between the atmosphere and the surface can be predicted.

The ocean mixed layer model MLM, which predicts the change of ocean temperature T_o, salinity, density, mixed layer depth as well as heat flux exchanges between the ocean and the sea ice, is the second-moment closure model developed by Kantha and Clayson (1994). The MLM is based on Mellor-Yamada's second-order turbulence closure with improved parameterizations of pressure covariance terms and the inclusion of shear instability-induced mixing in the strongly stratified region below the ocean mixed layer. The governing equations of the MLM model include conservation laws for mass, momentum, and scalar mean quantities as well as conservation relations for second-order turbulence quantities, Reynolds stress, turbulent heat fluxes and the temperature variance. We refer the reader to the Kantha and Clayson (1994) paper for details.

3. Case descriptions and modeling design

According to the NCEP/NCAR reanalysis data, an outstanding and steady warm air advection event occurred in the Beaufort Sea from 9th through 12th May 1998. During this period, the SHEBA icebreaker was located around (76°N latitude, 165°W longitude) and was covered by the warm air advection. This event resulted from allocation of weather systems. On 0000 UTC 9th May 1998, a well-developed cyclone moved to the eastern Bering Sea and an anticyclone stood over the Canada Basin and the Canadian Archipelago. A resultant westward warm air advection formed over the Beaufort Sea between these two weather systems. The warm air originally came from the Gulf Alaska. Since then, the cyclone system persisted due to its less motion and due to the combinations of the other two cyclone systems coming from the East Siberia and the Sea of Okhtsk. Consequently, the advection intensified and sustained. At 0000 UTC 11th May 1998, the eastern cyclone system within the linked low systems began to weaken (998 hPa) and moved northeastward. At 0000 UTC 12th May, the well-organized warm air advection event over the Beaufort Sea went to the end when the eastern cyclone system moved northward further.

We employed the Arctic MM5 to perform the simulation of the storm and investigate the air-ice-ocean interactions during the period of the storm event over the SHEBA site. The model domain (Figure 1) is centered at 62.5°N latitude and 172.5°W longitude and has a horizontal coverage of 6825 km (north/south direction) × 7525 km (east/west direction), with a grid resolution of 35 km. We utilized a total of 31 vertically stretched σ sigma levels, of which eight are located within the lowest 500 m of the atmosphere. The sigma levels are closely spaced near the ground and more coarsely spaced with height to the model top at 50 hPa. A model time step of 100s is used.

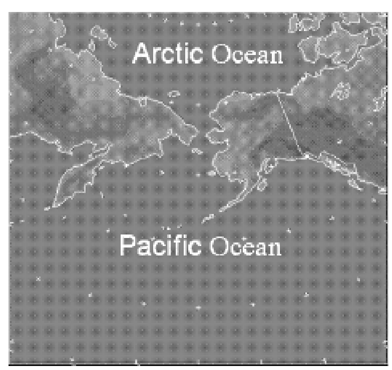

Figure 1 The Model Domain

In the simulation, the following physical parameterizations are used: the modified Reisner explicit microphysics parameterization (Cassano et al. 2001); the Grell cumulus parameterization

(Grell 1993); the MRF planetary boundary layer scheme (Hong and Pan 1996); the modified CCM2 radiative transfer scheme (Cassano et al. 2001); and the land surface model NOAH-LSM (Mitchell et al., 2002, Koren et al., 1999), in which a thermodynamic sea ice model and mixed layer ocean model as described in section 2 are coupled. The NCEP/NCAR reanalysis data are used to initialize the model atmosphere and provide continues lateral boundary conditions for modeling the May 1998 storm. The boundary forcing is archived using linear relaxation, of which outer row and column is specified by time-dependent value, next four points are relaxed towards the boundary values with a relaxation constant that decreases linearly away from the boundary and fields without boundary values (such as some moisture variables) are specified to be zero on inflow boundaries and to have zero-gradient on outflow boundaries. The initial sea ice concentration is from NCEP/NCAR climate data assimilation system (CDAS) in which sea ice concentration grids are constructed from the Special Sensor Microwave Imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP) F-13 (11) satellite, derived with the bootstrap algorithm (Comiso 2002).

4. Simulations and comparisons with SHEBA

Simulations of the May 1998 cyclone systems commenced at 0000 UTC 9 May 1998 and lasted for 72 hours. A well-developed cyclone with intensity of 982 hPa located at the eastern Bering Sea was initialized at 0000 UTC 9 May for the simulation. It then traveled northward slowly and covered the Norton Sound coast areas (with the low center of 995 hPa) at 0000 UTC 10 May (24 simulation hours), which matches the NCEP/NCAR reanalysis very well. Meanwhile the other two cyclone systems originated from the Sea of Okhotsk (with a center low of 993 hPa at the model initial time) and Siberia (with a center low of 984 hPa at the model initial time) traveled eastward and were linked with the cyclone system over the Being Sea at 1200 UTC 10 May. Two cyclones existed within the linked low systems at 0000 UTC 11 May (48 simulation hours). The western cyclone is a bit stronger than the eastern one. Since then the western cyclone moved eastward and the eastern cyclone traversed rapidly northward to the Beaufort Sea coast. Along the northward movement of the eastern system originated over the eastern Bering Sea, a quite amount of warm air was brought to the Beaufort Sea areas. Comparing with the NCEP/NCAR reanalysis, the modeled eastern cyclone is stronger than the reanalysis by 2 hPa and 6 hPa at 48 and 72 simulation hours respectively, the western one is weaker than the reanalysis by 7 hPa and 4 hPa at the above simulation hours. Meanwhile the modeled low systems also moved slower than the reanalysis. These differences between the simulations and the NCEP/NCAR reanalysis are possible since the NCEP/NCAR reanalysis should not capture the details of the storm because of its coarse resolution.

The upper layer wind fields (such as 850 hPa and 500 hPa) steered the cyclone systems from the southern Bering Sea into the northern Beaufort Sea via the prevalent southwest flow over the Bering Sea and the west coast of Alaska. The persisted southwest flow, resulted from the steady low systems over the eastern Siberia and the Bering Sea, helped bringing an amount of warm air to the north. The warm air advection to the Beaufort Sea caused a significant increase in temperature and decrease in sea ice concentration.

Given that the Arctic MM5 simulates adequately the development and moving path of the storm, it is possible to further investigate the air-ice-ocean interactions during this event. Since the SHEBA site was covered by this storm event, we compared the simulation results with observations at the SHEBA site. The surface pressure comparisons between the observation and the modeling at the SHEBA site are very consistent. When the storm system moved northward, surface pressure decreased and there was about 15 hPa drop for 2 days (May 10-May 12). The Model captured the temperature increase as well as that in the observations and the increases are about 11 degree within 24 hours.

Affected by the warm air of the storm system, the modeled sea ice temperature increased and thickness decreased. The air-ocean-ice feedbacks resulted in a noticeable increase in the ocean temperature, which further amplified the sea ice melting, the simulated sea ice thickness at the SHEBA site decreased about 6.5cm within 2 days.

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