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P4.12 MESOSCALE MODELING OF THE WINTERTIME BOUNDARY LAYER STRUCTURE OVER THE ARCTIC PACK ICE

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1. INTRODUCTION

Three-dimensional simulations of the planetary boundary layer (PBL) over the wintertime, 2-m thick, Arctic pack ice have been done with the Penn State/NCAR Mesoscale Model (MM5). The long-range purpose of these simulations is to scale-up the point measurements of surface fluxes obtained during the Surface Heat Flux of the Arctic Ocean (SHEBA) year (Perovich et al 1999; Uttal et al 2002) to the scale of global circulation model grids using the nesting capability of the MM5. In the short range, this requires obtaining accurate simulations of the boundary layer thermodynamic and kinematic structure as revealed by validations of the model output with the extensive observations available near the SHEBA site.

These three-dimensional simulations will need to be done in a variety of environmental conditions. Initially, the simplest conditions are chosen in order to be able to isolate the reasons for the model discrepancies. Hence, the first tests simulate the period Jan. 14-19, 1998, during which the skies were mostly clear and there was no solar radiation. At this time, the SHEBA site was at 75°N and 151°W in the Beaufort Sea. By avoiding the effects of solar radiation and minimizing the impacts of longwave radiation by clouds, and by having measurements of all fluxes, causes for discrepancies could be isolated and improvements made. The tests particularly focused on the effects of the longwave radiative scheme, the snow/ice model, and the boundary-layer scheme. The following discussion highlights the major results so far.

2. VALIDATION DATA

The validation of the model PBL structure and forcing is done with hourly data from the 5-level Atmospheric Surface Flux Group (ASFG) 20-m tower site (Persson et al 2002), the NOAA/ETL minisodar, the 12-hourly rawinsondes, a cloud radar, and a lidar (Intrieri et al 2002). At the lowest heights, the tower data is used in preference over the radiosonde and sodar data. At heights below 150 m where both sounding and sodar wind data exists, the sodar data is assumed to be correct because of excessive smoothing of the low-level sounding winds. Tower humidity data is used to correct each sounding humidity profile. Along with basic meteorological parameters, the validation data include direct covariance measurements of the turbulent fluxes of heat, moisture, and momentum, and the measurements of the four-component near-surface broadband shortwave and longwave radiative fluxes. The processing methods and accuracy of this data are discussed by Persson et al (2002).

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Time-height sections for January 14-19 were produced for the SHEBA site (Fig. 1). These showed a surface-based inversion extending to 0.9-1.4 km. The 2-m temperatures are -33 to -38°C and the 1500 m temperatures are -22 to -25°C. Though a surface-based inversion existed, a layer of enhanced stability (enhanced Brunt-Vaisala frequency) was present 100-150 m above the surface (Fig. 1a and Fig. 3a), and is assumed to mark the top of the boundary layer directly affected by surface friction. The air below this stable layer is the planetary boundary layer (PBL), while the

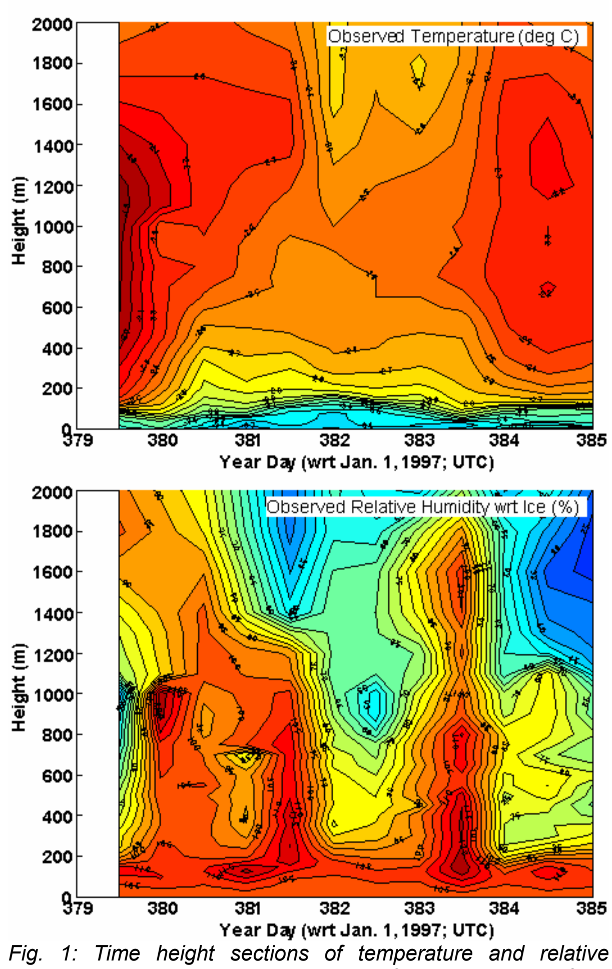

Fig. 1: Time height sections of temperature and relative humidity (wrt ice) in the lowest 2 km of the atmosphere from combined soundings, sodar, and ASFG tower data for January 14-19, 1998, at the SHEBA site. Supersaturated regions are the darker shades in b).

air capped by the inversion at 1.2-1.6 km in Fig. 1a is called the Arctic boundary layer (ABL). The median Monin-Obukov (MO) stability parameter (ζ = z/L) calculated from the tower measurements was less than 1 for most of the week and only greater than 10 for a few isolated hours on Jan. 15, 18 and 19. MO Similarity Theory (MOST) works well for ζ<1 (Grachev et al 2002).

The cloud radar and lidar show that a cloud existed at 0.3-1.0 km height between 22 UTC Jan. 14 to 01 UTC. Jan. 15. The entire period from Jan. 15 at 01 UTC to Jan. 20 at 05 UTC was cloud free, except for a few ice clouds between 00-06 UTC on Jan. 18 (not shown) and some very thin clouds with small particles not detected by the cloud radar but suggested by the lidar during midday on Jan. 16. On January 20, clouds moved over the site changing the radiative and thermal environment. Only the clouds near 00 UTC Jan. 15 and starting at 05 UTC Jan. 20 had a significant impact on the incoming longwave radiation at the surface. Hence, the period between these times can be considered "cloud free", though recognizing the caveats above. Note that the relative humidity with respect to ice suggests supersaturated conditions near 150 m MSL at the top of the PBL throughout the entire period (Fig. 1b), with slightly deeper supersaturated conditions during the periods in which clouds were detected. It is uncertain whether any ice crystals were present in this low supersaturated layer, though the lidar and cloud radar suggest that there were not.

3. THREE-DIMENSIONAL MODEL TESTS

3.1 Model and test description

The MM5 model configuration has been optimized for the Arctic environment with choices of domain boundaries, low-level vertical resolution, and model physics, with development of a more sophisticated surface parameterization shown to be key. The simulations shown here use a horizontal resolution of 81 km and 50 layers in the vertical. Forty of these layers are below 1.6 km (Fig. 2a). The model is initialized at 00 UTC Jan. 15 with the analysis from the European Center for Medium Range Weather Forecasting (ECMWF). At this time, cloud cover existed over the SHEBA site. The domain boundaries, obtained from ECMWF analyses, are located over the continental regions to avoid ingesting errors over the Arctic Ocean that may result from the operational models' poor resolution of the Arctic boundary layer and from the use of model physics not optimized for the Arctic environment (Bretherton *et al.*, 2002). Also note that the 12-hourly SHEBA radiosondes were ingested by the ECMWF operational analysis, mainly impacting the initial conditions.

The model experimentation mainly involves varying the parameterizations for the longwave radiation, the boundary layer, and the surface snow and ice. The longwave radiation parameterizations of Dudhia (DUD; 1989) and Mlawer (1997) were tested. The latter is referred to as the Rapid Radiative Transfer Model (RRTM). The boundary-layer schemes of Blackadar

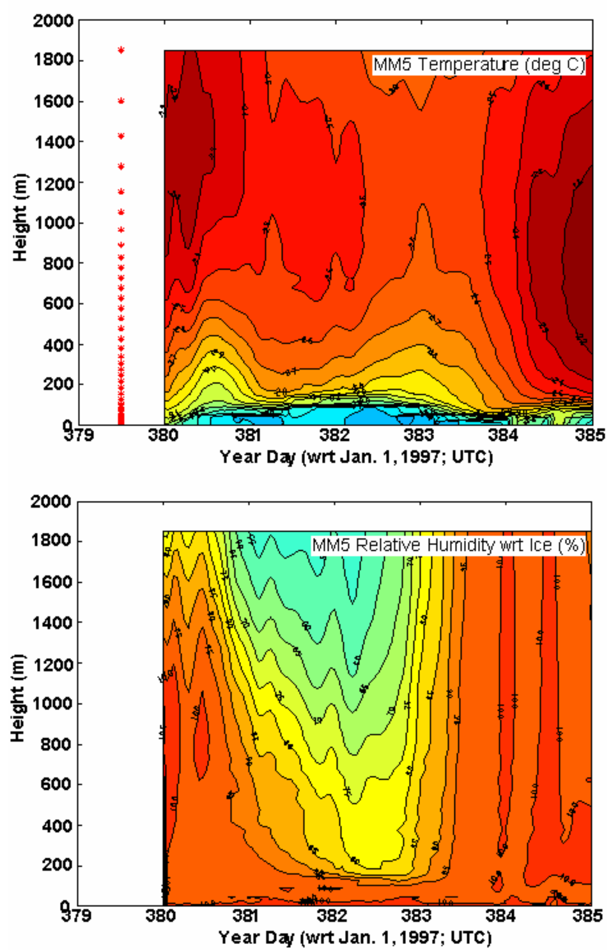

Fig. 2: As in Fig. 1, but for the MM5 simulation 3SNW. The stars in a) indicate the model levels.

(BK; Zhang and Anthes 1982), Burk and Thompson (BT; 1989), Gayno-Seaman (GS; Shafran *et al*, 2000), and the ETA model were tested. The surface layer schemes in each of these parameterizations are based on MOST. Only the results from the first three schemes will be presented here.

The treatment of the surface of the Arctic Ocean was found to be very important for the simulation of the boundary layer. A diffusion model was developed in which various layers could be defined as either snow or ice and their thickness could be varied. During this week at the SHEBA site, the ice was about 2.2 m thick and was covered with 22 cm of snow. The ocean water temperature below the ice was -1.8°C. In the simplest configuration (1ICE), the ice was represented by one layer without any snow cover. In another configuration (1SNW), the ice is represented by two 110 cm ice layers covered by one snow layer 22 cm deep. This is a typical configuration for climate models. A second configuration (3SNW) retains the 2 ice layers, but divides the snow cover into 3 layers with thicknesses of 3, 6 and 13 cm, with the thinnest layer at the top. The third configuration (5SNW) consisted of 5 snow layers (0.5, 2.5, 3, 3, and 13 cm) on top of the ice. The various experiments are summarized in Table 1.

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Table 1: List of MM5 model experiments. The abbreviations are defined in the text.

EXP.	LW RAD	PBL	SURFACE
DUDLW	DUD	BK	1ICE
RRTM	RRTM	BK	1ICE
1SNW	RRTM	BK	1SNW
3SNW	RRTM	BK	3SNW
5SNW	RRTM	BK	5SNW
BTPBL	RRTM	BT	3SNW
GSPBL	RRTM	GS	3SNW

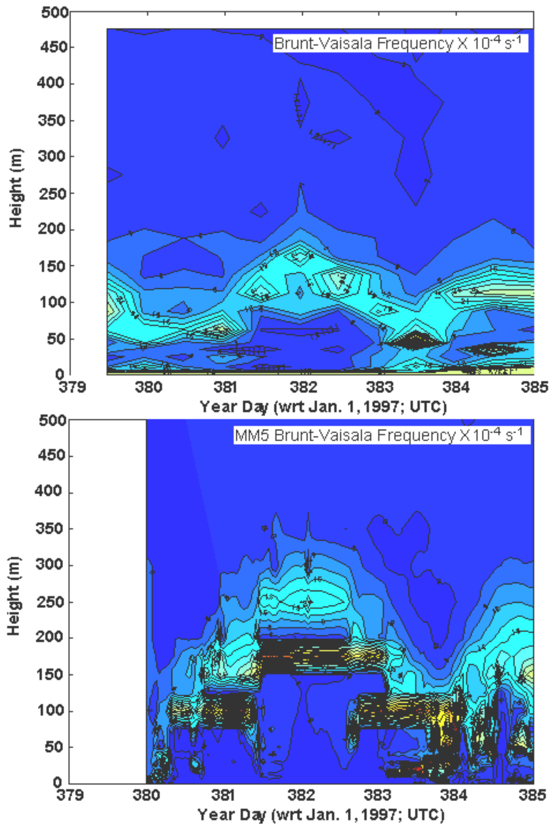

Fig. 3: The Brunt-Vaisala frequency in the lowest 500 m from the a) observations, and b) the MM5 simulation 3SNW. The lighter shades represent larger values.

3.2 Results

Initial tests of the longwave radiative schemes showed that using the RRTM scheme (Mlawer et al 1997) rather than the Dudhia (1989) scheme halved the deficit in the incoming longwave radiation between the model and the observations by increasing the incoming radiation by 5-8 Wm^{-2} (Fig. 4a). However, when a better surface representation is used, resulting in a cooler boundary layer (see below), the incoming longwave radiation from RRTM is seen to be still too low. Tests with a more sophisticated radiative transfer model suggest that this deficit may be due to inadequately representing the effects of aerosols, whose concentration profile is unknown for the SHEBA site.

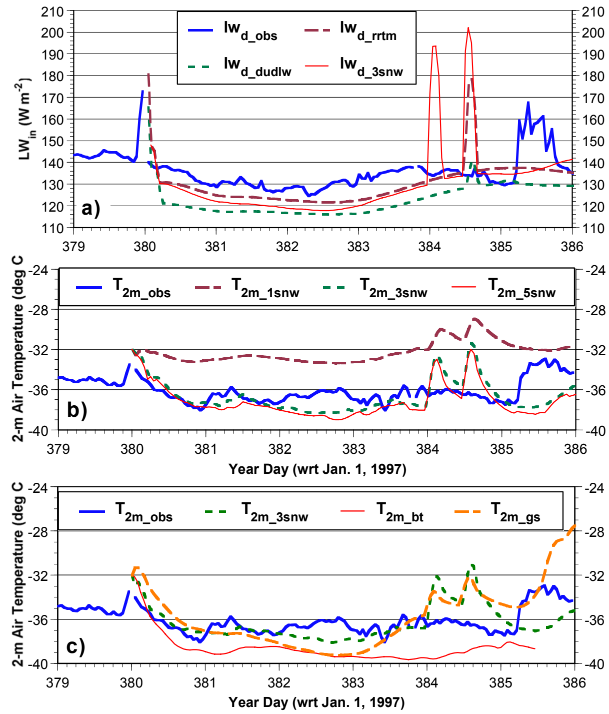

Fig. 4: Time series of a) incoming longwave radiation for the radiation tests (DUDLW,RRTM,3SNW), b) 2-m air temperature for the snow/ice model tests (1SNW,3SNW, 5SNW), and c) 2-m air temperature for the PBL tests (3SNW,BTPBL,GSPBL) for January 14-20, 1998. The heavy solid curves are observed values in all panels.

Figure 4b shows the effect of different treatments of the surface on the surface environment. The simulation with the snow treated with one layer produced too much conductive flux through the surface, not allowing the PBL to cool as the skies cleared immediately after initialization. Using a 3-layer representation of the snow yielded significant improvements (simulation "3SNW"). Additional layers in the snow model only produced minor differences from the one with 3 layers. The key feature in the multi-layered snow simulations was the shallow top snow layer that allowed the surface temperature to respond quickly and with the correct magnitude to changes in radiative and turbulent fluxes. Figure 4c shows that the variations in surface layer temperature obtained by using different PBL schemes are smaller than those seen when changing the snow model from one layer to three.

The atmospheric model structure in simulation 3SNW is generally satisfactory, though some crucial improvements must still be made. The temperature during the first 4 days of the simulation is within 3°C of the observations up to 3 km height (Figs. 1a and 2a). After 4 days, the synoptic conditions in the model differ too much from the observations for valid comparisons. Note that clouds developed on Jan. 19 (JD384) between 200 m and 2300 m (Fig. 2b) but weren't present in the observations (Figs. 1b). These "model" clouds produced a sudden increase of the surface temperature (Fig. 4b) of about the same magnitude as seen in the observations on Jan. 20 (JD 385) when clouds do

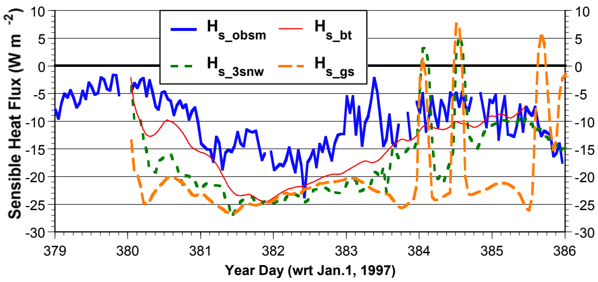

Fig. 5: As in Fig. 4, but of sensible heat flux (H_s). Shown are median observed values (heavy solid) and those from simulations 3SNW, BTPBL, and GSPBL.

appear in the observations, and much greater than the response seen in simulation "1SNW". Hence, the response of the surface temperature to cloud forcing seems to be much improved in 3SNW.

The model also produces an enhanced stable layer near 100-150 m above the surface (Fig. 3b), though this enhanced stability occurs in multiple layers rather than one layer and is stronger in the model than in the observations. The wind speed above the PBL is too strong in the model (not shown) due to a too high surface pressure gradient. The excess pressure gradient appears to be due to excessively cold air temperatures over the Canadian archipelago that advect north of the SHEBA site. The effect of the enhanced surface winds is to produce downward sensible heat flux enhanced by about 10 Wm^{-2} (Fig. 5), counteracting the deficit in longwave radiation, and thereby fortuitously producing the correct surface temperature. The PBL (lowest 150 m) is also not as stratified as in the observations, due either to the stronger winds or to excessive redistribution of heat by the PBL scheme. The lowest layers in the model are supersaturated with respect to ice as observed, but do not reach the degree of supersaturation noted in the observations (Figs. 1b and 2b).

4. CONCLUSIONS

These initial tests show that: 1) the RRTM radiative scheme performs best, but could be improved with information on the aerosol concentration profiles because the moisture profile is less dominant in this dry environment compared to lower latitude environments, 2) the surface parameterization needs to have a multi-level ice and a multi-level snow model in order to insulate the Arctic boundary layer from the warm ocean and provide the proper timescales to the PBL changes in response to changes in the forcing, and 3) a sensitivity to existing PBL schemes is observed but is much less than the sensitivity to the surface model sophistication.

Work in the immediate future on this case will attempt to 1) eliminate the cause for the false rapid cooling in the Canadian archipelago or ameliorate the enhanced pressure gradient by doing incremental reanalyses with the MM5 output as the first guess field, 2) find the reason(s) for the insufficient incoming longwave radiation, and 3) test the ability of different PBL schemes to produce a single and weaker PBL top and a more stable PBL. All of these modifications are probably necessary to obtain a satisfactory simulation, and the effort spent now to obtain an excellent simulation for this relatively simple case will likely be rewarded with easier diagnostics in later more complicated cases. Once a satisfactory simulation is obtained with the 81 km resolution mesh, finer nesting will be done, which will include more detailed surface characteristics (e.g., leads) obtained from satellite images and aircraft data. Runs with this finer nesting will then be used to assess how the scaling-up of the surface fluxes needs to be done during these wintertime conditions.

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