Validation of Surface Fluxes from a New Surface Layer Module in MM5 with SHEBA Observations

J-W. Bao[1] R. D. Pyles[2] S. A. Michelson[1, 2] P. O. G. Persson[1, 2] J. W. Wilczak[1]

[1]NOAA/Environmental Technology Laboratory
[2]Cooperative Institute for Research in the Environmental Sciences, University of Colorado

1. Introduction

In the mainstream of atmospheric modeling related to the forecasts of weather, climate and air quality, the surface momentum and heat fluxes are calculated using bulk parameterization schemes based on the Monin-Obukhov similarity (MOS) theory. The bulk parameterization schemes have been so popular because of its mathematical simplicity, and its root in statistical fluid dynamics. Although extensive research refining the bulk flux parameterization schemes has been carried out for a few decades, uncertainties coming from a variety of sources still remain in the specification of the parameters used in the schemes (e.g., Weidinger et al. 2000). One such uncertainty is the stability function when the vertical stratification is very stable (Marht 1999 and Grachev et al. 2002). The statistics of turbulence within a very stable planetary boundary layer (PBL) are difficult to characterize because the turbulence is often intermittent and coexists with gravity waves.

Since the surface momentum and heat fluxes are the result of turbulent transport, the bulk parameterization schemes based on the MOS theory are, in fact, turbulence models for the surface layer with the first order closure defined by Panofsky and Dutton (1984) and Stull (1988). Attractive alternatives to the bulk parameterization schemes are turbulence models with higher order closure. As a matter of fact, approaches to turbulence simulations using models of high-order closure are well established in geophysical applications (e.g., Mellor 1973, Wyngaard and Coté 1974, Moeng 1984, and Gatski et al. 1996). Although turbulence models of high-order closure have been widely used in numerical weather forecast models for modeling vertical turbulent mixing of the atmospheric PBL above the surface layer (e.g., Mellor and Yamada 1982, Burk and Thompson 1989, and Janjić 1994), they have not been used for flux modeling within the surface layer. It was not until Pyles (2000) coupled a turbulence model with MM5 V2 to simulate the surface-layer physics over western North America that an effort was started to apply a high-order-closure turbulence model for prediction of surface fluxes in numerical weather prediction models.

One advantage of high-order closure models over the parameterization based on the MOS theory is that a prior knowledge about the stability function is not required. Starting in the winter of 2001, a project has been carried out at NOAA/Environmental Technology Laboratory to implement a high-order-closure turbulence model in MM5 V3 as an alternative to the bulk parameterization schemes for surface momentum and heat fluxes. This turbulence model serves as the dynamic core of an advanced canopy-atmosphere-soil algorithm (ETL/ACASA). ETL/ACASA is based on a prototype developed for MM5 V2 by Pyles (2000) at the University of California/Davis. In addition to all the features in the prototype, ETL/ACASA has a thermodynamic sea ice/snow model that makes the module more general for regional climate and weather modeling studies.

In this report, we present results from offline and online surface flux and meteorological comparisons between ETL/ACASA and observations from the Surface Heat Budget of the Arctic Ocean Experiment (SHEBA) Atmospheric Surface Flux Group (ASFG) site from 5 October 1997 through 30 September 1998 (Persson *et al*. 2002). This comparison is our first step toward the establishment of a high-order-closure model in MM5 for modeling surface turbulent transport.

2. Overview of ETL/ACASA

ETL/ACASA incorporates a diabatic turbulence model of third-order closure (Meyers and Paw U 1986, 1987; Pyles 2000) to simulate the turbulent transport of momentum and heat within the surface layer. It also includes parameterizations for the effect of the canopy on the energy exchange between the surface and air. Recently, a thermodynamic sea ice/snow model has been added to it as a new feature to make it applicable over the sea ice/snow surface. In the sea ice/snow model, a revised version of fourth-order surface temperature solution technique of Paw U and Gao (1988) is used to achieve more accurate results for extremely cold situations. The treatment of heat transfer in soil, sea-ice, and snow in ETL/ACASA is adapted from the mesoscale analysis and prediction system scheme (MAPS) (Smirnova *et al*. 2000). Heat transfer is handled using a 1-D thermal diffusion approach, and moisture transport calculations include both vertical diffusional and gravitational effects. Although this treatment only involves thermodynamic effects and is relatively simple, it is able to produce good results in controlled 1-D tests (Smirnova *et al.* 2000).

The number of soil, sea ice layers, or snow layers in ETL/ACASA is variable, and there are 20 atmospheric layers within the surface layer (i.e., the layer between the lowest half-σ surface and the surface when coupled with MM5). In the current version of the coupled ETL/ACASA and MM5, there are 15 layers of soil/sea ice. In ETL/ACASA the number of snow layers depends upon the depth of the snowpack, with 1 layer of snow for each 0.05 m of snow depth in the current configuration. The vertical resolution and grid spacing of the soil/sea ice and snowpack are adjustable.

3. Overview of Observations

The observations of surface conditions and boundary layer structure used in this study is from the multi-institutional and interdisciplinary SHEBA experiment described in Uttal *et al.* (2001) and Persson *et al*. (2002). The data used for the 1-D model input in this study are the observed incoming short-wave and long-wave radiative fluxes, and the air temperature, humidity and wind at the second tower level (nominally 2 m above the surface).

4. Methodology

To validate the surface flux calculation in the coupled ETL/ACASA and MM5, the first step is to run 1-D ETL/ACASA with observed atmospheric mean state as forcing. This step is crucial for obtaining the information on the optimal configuration of ETL/ACASA for coupling with MM5 in the Arctic. The 1-D simulation is also important for the examination of the sensitivity of ETL/ACASA to several parameters (including resolutions of snow and ice layers) used in its setup.

Model simulated fluxes from 1-D ETL/ACASA are compared with the observed ones at the SHEBA site for a multi-month period. Comparisons include all the turbulent fluxes in surface energy exchanges, namely surface temperature, momentum, sensible and latent heat fluxes. In the 1-D simulations, ETL/ACASA is driven with values of air temperature, wind speed, downwelling long- and short-wave radiation, surface pressure, and hourly precipitation rate at 2-m level from 31 October 1997 through 26 September 1998. The depth of the sea-ice is assumed to be 2.2 m, roughly in keeping with observed values (Perovich and Elder 2001) while the snow depth is initialized to the SHEBA value for Jan 15 1998 (0.22 m). Sea-ice temperature as a function of depth was initialized with observed values for 31 October 1997. The sea-ice temperature at the ice-water interface in ETL/ACASA is kept at the climatological value of -1.8^{o}C throughout the entire simulation.

With the information on the optimal configuration of sea ice/snow obtained form the 1-D simulation, ETL/ACASA is then coupled with MM5 to simulate surface-air turbulence fluxes to provide lower boundary conditions for a mesoscale modeling of the wintertime boundary layer structure over the Arctic pack ice. The simulated fluxes are compared again with the observations at the SHEBA site. Since the simulated surface winds, temperature and moisture are not expected to be the same as the observations, the comparison of the fluxes are performed in terms of normalized scattered diagrams to make the comparison meaningful. Daily mean values of predicted short- and long-wave radiative transfer, and surface (skin) temperature are compared with observed values.

5. Results

Figure 1 shows the time series of the magnitudes of friction velocity from the SHEBA observations and the 1-D ETL/ACASA simulation for the time period of 15 January-11 March 1998. It is seen that the results from the 1-D ETL/ACASA are in better agreement with observations than those obtained using a MOS parameterization scheme. Since the wind forcing used in the 1-D ETL/ACASA is the same as that used in the MOS scheme, these results indicate that the momentum flux from the 1-D ETL/ACASA is smaller than that obtained by the MOS scheme. The comparison of the observed and simulated sensible heat fluxes is depicted in Fig. 2. Again, the results from the 1-D ETL/ACASA follow the observational trend better than those from the MOS scheme. Estimates of other parameters such as skin temperature and thermal radiative transfer (not shown) lie within observational uncertainty. A slight overprediction of latent heat flux (not shown), which is most evident during the warm season, may be related to observational error (see Persson *et al*. 2002). Values of sensible heat flux indicate a slight negative bias, which might be due to ETL/ACASA ignoring latent heating of the pack ice due to the freezing of seawater. The sensitivity of the 1-D ETL/ACASA to the number of snow layers (i.e., the vertical resolution of the snow pack) is also shown in Figs. 1 and 2. The results of the sensitivity indicate that the sensible heat flux from the 1-D ETL/ACASA is more sensitive to the vertical resolution of the snow pack that the momentum flux, and the solution appears to converge after the number of snow layers exceeds 3.

The coupled ETL/ACASA and MM5 is only run for eight days, starting from 00Z 15 January 1998. The comparison of the observed momentum fluxes and surface temperature with the counterparts from the coupled ETL/ACASA and MM5 simulations suggests that the results from the ETL/ACASA and MM5 are, if not better, comparable to those from the coupled MOS scheme and MM5.

The preliminary results also indicate that the stability dependence suggested by the ETL/ACASA is different than that described by the MOS scheme. Qualitatively, without prior knowledge about the stability function, ETL/ACASA can deal with very stable stratification, and apparently is able to model reasonably well the surface processes over the Arctic pack ice.

5. References

Burk, S.D., and W.T. Thompson, 1989: A vertically nested regional weather prediction model with second-order closure physics. *Mon. Wea. Rev.*, **117**, 2305-2324.

Gatski, T. B., M. Y. Hussaini, J. L. Lumley, 1996: *Simulations and Modeling of Turbulent Flows.* Oxford University Press, New York, 314 pp.

Grachev, A. A., C. W. Fairall, P. O. G. Persson, E. L. Andreas, and P. S. Guest, 2002: Stable boundary-layer regimes observed during SHEBA experiment. Proceedings, *15th Symposium on Boundary Layer and Turbulence*, Amer. Meteor. Soc. Wageningen, The Netherlands.

Janjic, Z. I., 1994: The step-mountain Eta coordinate model: further development of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927-945.

Mahrt, L. 1999: Stratified atmospheric boundary layers. Bound.*-Layer Meteor.*, **90(3)**, 376-396.

Mellor, G. L., 1973: Analytic prediction of the properties of stratified planetary surface layers. *J. Atmos. Sci.*, **30**, 1061-1069.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.*, **20**, 851-875.

Meyers, T. P., and Paw U, K. T., 1987: Modelling the plant canopy micrometeorology with higher-order closure principles. *Agric. For. Meteor.*, **41**, 143-163.

Meyers, T. P. and Paw U, K. T., 1986: Testing of a higher-order closure model for airflow within and above plant canopies. *Bound.-Layer Meteor.*, **37**, 297-311.

Moeng, C-H., 1984: A large-eddy simulation model for the study of planetary boundary-layer turbulence. *J. Atmos. Sci.*, **41**, 2052-2062.

Panofsky, H.A., and J. A. Dutton, 1984: *Atmospheric Turbulence*. John Wiley & Sons, New York, 397 pp.

Paw U, K. T., and W. Gao, 1988: applications of solutions to non-linear energy budget equations. *Agric. For. Meteorol.,* **43**, 121-145.

Perovich, D. K., and B. C. Elder, 2001: Temporal evolution of Arctic sea-ice temperature. *Annals of Glaciology, in press.*

Persson, O. G., C. W. Fairall, E. L. Andreas, P. S. Guest, and D. K. Perovich, 2002: Measurements near the Atmosphere Surface Flux Group tower at SHEBA: near-surface conditions and surface energy budget. *J. Geophys. Res. – Atmospheres*, in press.

Pyles, R. D., 2000: The development and testing of the UCD advanced canopy-atmosphere-soil algorithm (ACASA) for use in climate prediction and field studies. PhD Dissertation, University of California, Davis.

Smirnova, T. G., J. M. Brown, S. G. Benjamin, and D. Kim, 2000: Parameterization of cold-season processes in the MAPS land-surface scheme. *J. Geophys. Res*., **105(D3)**, 4077-4086.

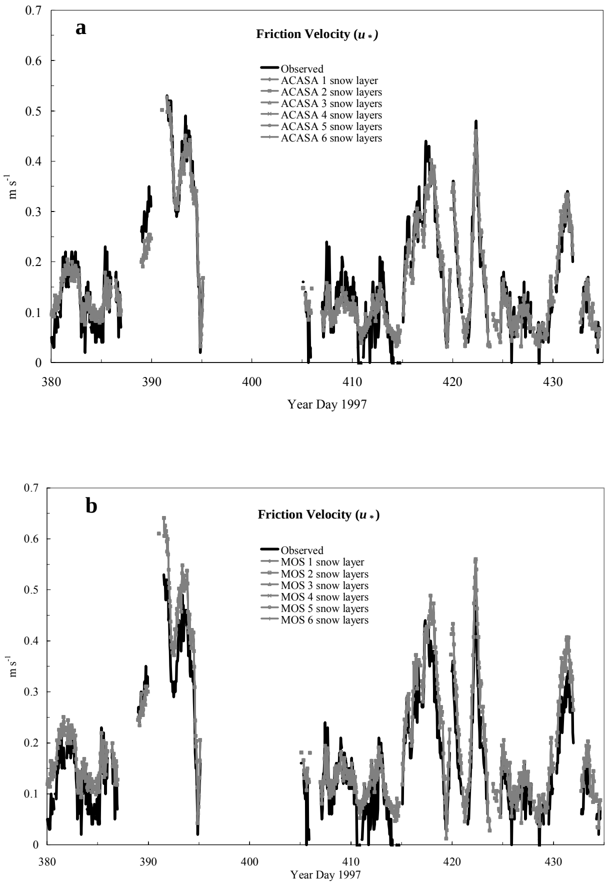
Stull, R. B., 1988: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publishers, Boston, 666 pp.

Uttal, T., J. A. Curry, M. G. McPhee, D. K. Perovich, R. E. Moritz, J. A. Maslanik, P. S. Guest, H. L. Stern, J. A. Moore, R. Turenne, A. Heiberg, M. C. Serreze, D. P. Wylie, P. O. G. Persson, C. A. Paulson, C. Halle, J. H. Morison, P. A. Wheeler, A. Makshtas, H. Welch, M. D. Shupe, J. M. Intrieri, K Stamnes, R. W. Lindsey, R. Pinkel, W. S. Pegau, T. P. Stanton, and T. C. Grenfeld, 2001: The surface heat budget of the Arctic, *Bull. Amer. Meteor. Soc.*, (submitted).

Weidinger, T., J. Pinto, L. Horvath, 2000: Effects of uncertainties in universal functions, roughness length, and displacement height on the calculation of surface layer fluxes, *Meteor. Zeitschrift*, **9**, 139-154.

Wyngaard, J. C. and O. R. Coté, 1974: The evolution of a convective planetary boundary layer- A higher-order-closure model study. *Bound.-Layer. Meteor.*, **7**, 289-308.

.



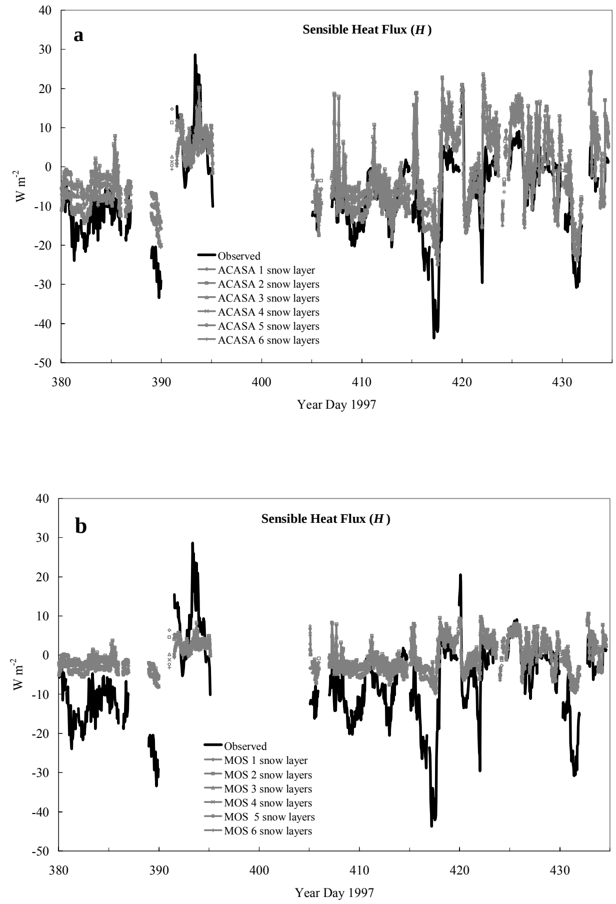


Figure 1 The magnitudes of friction velocity from the SHEBA observations, comparing with the output from (a) the 1-D ETL/ACASA simulation and (b) the 1-D MOS simulation for the time period of 15 January-11 March 1998.

Figure 2 The sensible heat flux from the SHEBA observations, comparing with the output from (a) the 1-D ETL/ACASA simulation and (b) the 1-D MOS simulation for the time period of 15 January-11 March 1998.