Final report

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Interactions of the Cloudy Arctic Boundary Layer with Variable Surface Conditions and Large-Scale Circulations

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1.   Introduction

Our project included a variety of activities, ranging from model development to data manipulation and even participation in the SHEBA and FIRE field experiments. The following sections outline the work accomplished under these tasks. A collection of reprints is attached to this report.

2.   Model development

Higher-order closure (HOC) models have been proposed for parameterization of the turbulent planetary boundary layer (PBL). HOC models must include closures for higher-order moments (e.g., fourth moments in third order closure models), for pressure terms, and for dissipation terms. Mass-flux closure (MFC) models have been proposed for parameterization of cumulus convection and, more recently, the convective PBL. MFC models include closures for lateral mass exchanges and for pressure terms (which are usually ignored).

We have developed a new kind of model that combines HOC and MFC, which we hope will be useful for the parameterization of both the PBL and cumulus convection, in a unified framework. Such a model is particularly well suited to regimes in which the PBL turbulence and the cumulus convection are not well separated, for example, the broken stratocumulus and shallow cumulus regimes. The model makes use of an assumed joint probability distribution for the variables of interest, and the equations typically used in HOC models can be derived by integrating over the distribution. Accordingly, the model is called Assumed-Distribution Higher-Order Closure (ADHOC).

The prognostic variables of ADHOC are the mean state, the second and third moments of the vertical velocity, and the vertical fluxes of other quantities of interest. All of the parameters of the distribution can be determined from the predicted moments; thereafter the joint distribution is effectively known, and so any and all moments can be constructed as needed. In this way, the

usual closure problem of "higher moments" is avoided. The pressure-term parameterizations previously developed for HOC models are used to predict the convective fluxes and the moments of the vertical velocity. In companion papers, parameterizations of lateral mass exchanges and subplume-scale fluxes are presented, and then ADHOC is applied to several observationally based tropical, subtropical, and dry convective boundary layers.

A detailed description of the basic design of the model is given by Lappen and Randall (2001 a).

The dissipation parameterizations developed for higher-order closure have been used to parameterize lateral entrainment and detrainment in a mass-flux model. In addition, a subplume-scale turbulence scheme is included to represent fluxes not captured in the conventional mass-flux framework. The new parameterizations have been tested by simulating trade wind cumulus from the Barbados Oceanographic and Meteorological Experiment (BOMEX). This work is described in detail by Lappen and Randall (2001 b).

3. Participation in field experiments

Graduate student Cara-Lyn Lappen spent over a month on the SHEBA ship. During this time she assisted in the operation of a tethered balloon system. She wrote an operator's manual for the system while she was on the ship (see publications list).

David Randall participated in the FIRE field phase based in Fairbanks, Alaska. He participated in mission planning and flew on the NCAR C-130 several times, on missions out over the sea ice.

4. Testing the models with data

4.1 Subtropical data

The model has been is applied to a variety of clear and cloudy planetary boundary layers

(PBLs) including dry convection from the Wangara Experiment, trade wind cumulus from the Barbados Oceanographic and Meteorological Experiment (BOMEX), and marine stratocumulus from the Atlantic Stratocumulus Experiment (ASTEX). For Wangara, the simulated variances and fluxes match that expected from similarity arguments, while the mean state is a little less mixed than the observations. In the BOMEX simulation, the shape and magnitude of the fluxes and the turbulence kinetic energy budget agree with LES results and observations. However, the liquid water mixing ratio is too large. This is attributed to an underprediction of the skewness. In agreement with observations from the ASTEX experiment, many of the model-simulated fields distinctly reflect a regime in transition between the trade wind cumulus and the classic stratocumulus-topped boundary layers. In general, the simulated entrainment rate tends to be a little underpredicted in regimes where there is little cloud-top radiative cooling (Wangara and BOMEX), while it is overpredicted in regimes where this process is more critical (e.g., ASTEX). Prior work suggests that this may be related to the manner in which the pressure terms are parameterized in the model. Overall, the model is able to capture some key physical features of these PBL regimes, and appears to have the potential to represent both cloud and boundary layer processes. These results are discussed in detail by Lappen and Randall (2001 c).

4.2   Arctic data

Currently, large discrepancies exist between GCM simulations and observed cloudiness in the Arctic (Lappen, 1996). Arctic stratus clouds (ASC) are widespread and persistent and they play an important role in the surface radiation budget of the Arctic. Tsay et al. (1989) found that these clouds increase the downward longwave flux by 130 to 200 W m^{-2}. The net radiative effects of ASCs on the surface is complicated by nonlinear interactions with the sea ice cover that are seasonally dependent.

Up to this point, only higher-order closure (HOC) models have simulated the turbulent

small-scale structure of Arctic stratus. In general, one does not usually consider a mass-flux (MF) model for simulating ASCs because MF models are typically applied to situations in which non-local transport plays a more dominant role (e.g., Cu, Sc). However, because ADHOC uses a combination of MF and HOC, we will se that the simulation of an ASC is possible. The vertical redistribution of turbulence in ASCs is handled nicely with the mass-flux part of the ADHOC model, while the small-scale turbulence handles diffusion well.

The SHEBA case that we chose to simulate to test ADHOC in the Arctic was a fairly simple liquid-only surface-based ASC, which encompassed many of the features that distinguish ASCs from stratus clouds at lower latitudes (e.g., a humidity inversion). On July 23rd, a 200-300 m surface fog layer hovered over the SHEBA base camp. The fog layer was comprised of a single ice-free well-mixed layer with no significant precipitation fluxes. For the ADHOC simulation of this case, we used a vertical resolutions of 15m and a timestep of 0.5 seconds. The model was run for 2 days and 12-hour time averages were taken. The model was forced with the ECMWF horizontal advective tendencies for moisture and temperature and vertical velocity. These tendencies showed large-scale rising motion with low-level moistening and warming throughout most of the lower the lower troposphere. The skin temperature was set to 274 K, which slightly warmer than the freezing temperature in July. The surface pressure remained between 1016 mb and 1019 mb. See Lappen (1999) for a complete description.

We compare the simulation to observations from FIRE/SHEBA and to LES results. However, this particular case was not simulated by LES and so, for the purposes of model evaluation, we use previous observations of an ASC which was qualitatively similar to the current one. The LES case that we choose is discussed in Curry et al. (1988).

Fig. 1 shows a comparison of the evolution of the simulated temperature, mixing ratio, and relative humidity profiles with those measured using rawinsondes at SHEBA. The profiles are
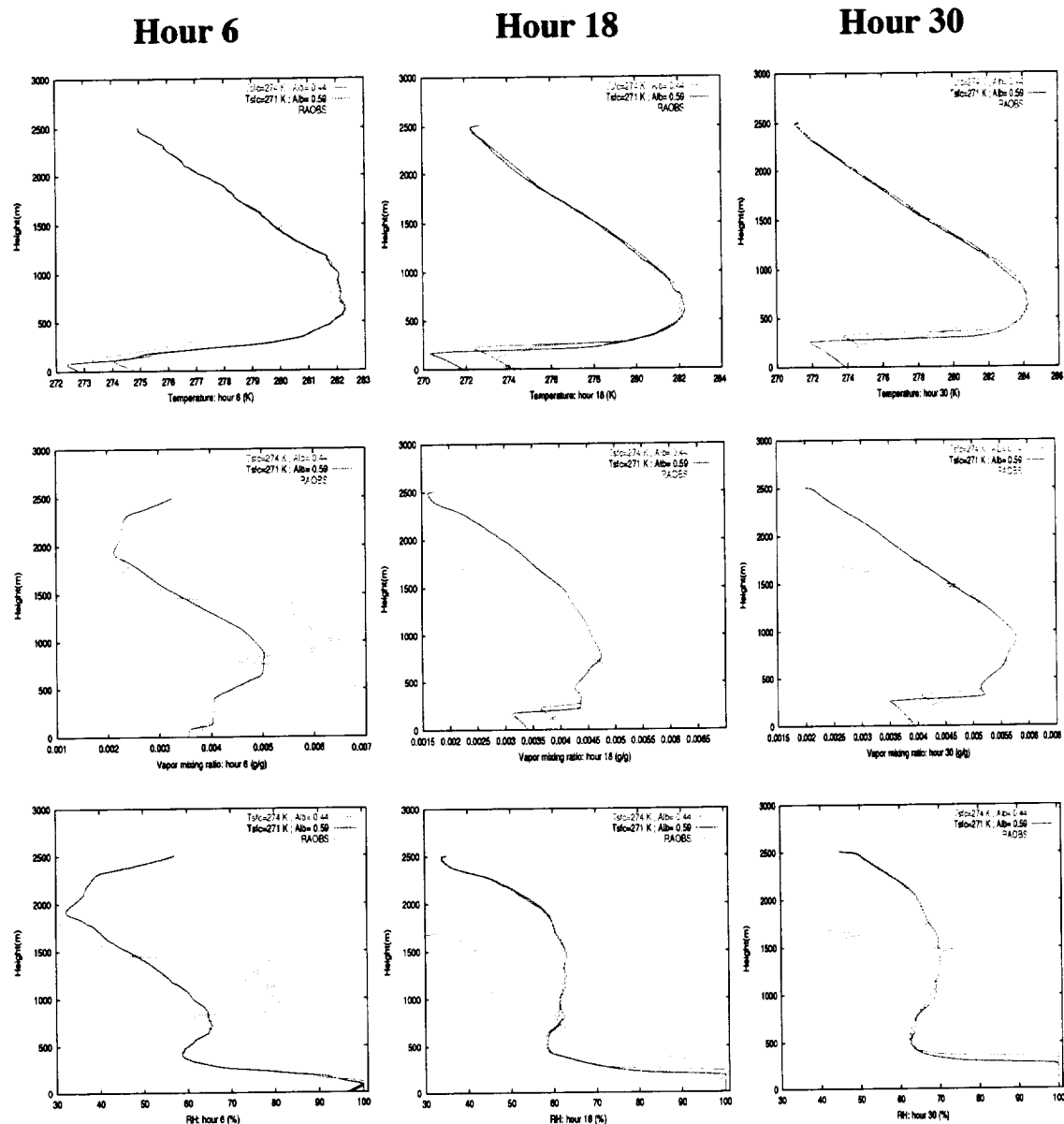
Figure 1: Comparison between simulated and observed temperature (top row), water vapor mixing ratio (middle row), and relative humidity (bottom row). The left column is for 6 hours into the simulation; the middle column is for 18 hours into the simulation; and the right column is for 30 hours into the simulation. The observations are from rawinsondes, which were launched at SHEBA.

shown are for 3 different times (6, 18, and 30 hours into the run). The profile which corresponds to the skin temperature of 274 K (green curves in *Fig. 1*) are discussed here. Overall, the

simulated profiles are agree very nicely with the observations for all three fields. During the first 6 hours, the simulated and observed relative humidity in the lower part of the boundary layer is gradually increasing. By hour 6, the observations show a fog layer which extends to a height of 500 m, while the model is only just beginning to reach saturation near 100 m. Since the simulated and observed temperatures are close, the observed 500 m fog layer is a result of the large mixing ratios measured by the rawinsondes between 200 m and 500 m.

At the beginning of the simulation, the model was initialized with rawinsonde observations (*Fig. 2*). The ADHOC-simulated mixing ratio moistens in response to the forcing (from 3.7 g kg^{-1} to 4.1 g kg^{-1}), but the observations moisten in a burst from (from 3.7 g kg^{-1} to 6.9 g kg^{-1}) between 200-500 m. We feel that the absence of the full moisture "burst" in the simulation is a result of the ECMWF forcing being too coarse to resolve such a feature.

Twelve hours later, there is a cloud in both the ADHOC simulation and the observations, although the observations indicate a cloud-top height which is slightly higher than that simulated by ADHOC. There is a sharp decrease in the RH above cloud top in both profiles. At the surface, the observations show that the fog layer has lifted. However, ship reports from the Des Groseillier indicate that no such lifting occurred. We believe that this is a problem with the humidity sensor on the rawinsonde. From my experiences up at SHEBA, that was not an unusual occurrence in these extremely cold conditions.

The temperature profiles show exceptionally good agreement in the hour-18 profiles. The radiative cooling at cloud top is fairly large, as indicated by the decrease of temperature with height in the cloud layer. In addition, we see signs of entrainment at cloud top; in *Fig. 2*, the total water mixing ratio shows a positive "bump" near cloud top (entrainment *moistening*). The differences between the simulated and observed mixing ratio profiles at hour 6 (due to the
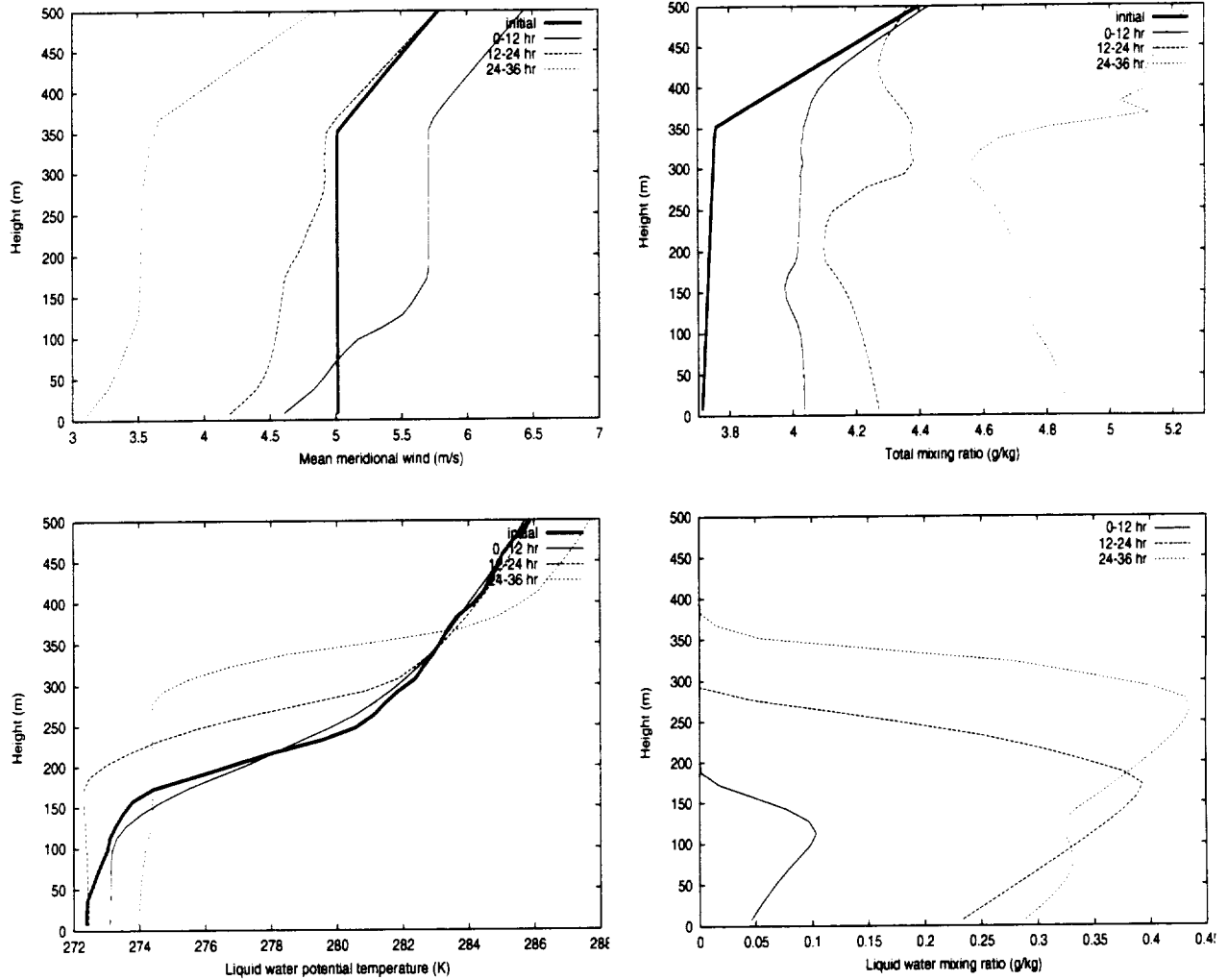
Figure 2: Profiles of the simulated mean meridional velocity (top, left); mean total water mixing ratio (top, right); mean liquid water potential temperature (bottom, left); and mean liquid water mixing ratio (bottom, right). The darkest line is the initial conditions.

unresolved burst) are decreasing.

At hour 30, the ADHOC-simulated profiles still show a good resemblance to those measured by the rawinsondes. However, there are some significant differences. The observed temperature decreased between cloud top and 1500 m by approximately 1 K, while the simulated profiles actually increased at these levels nearly 2 K. In addition, the cloud-layer temperature in

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ADHOC also increased by the same 2 K, while that observed did not change. The fact that the entire ADHOC profile changed by approximately the same value is suspicious. Ironically, the large scale ECMWF forcing was 4 K day^{-1} during this period (see Lappen, 1999; Fig. 58). We have concluded that the ECMWF advective tendencies are too strong, and not representative of the observed conditions (see Lappen, 1999 for a full discussion).

The difference between the simulated and observed mixing ratios by hour 30 have further decreased. In fact, if one were to smooth out the noisy hour-30 observed mixing ratio profile, it would closely resemble that simulated by ADHOC.

Fig. 2 shows the evolution of the mean profiles of the meridional wind ($\overline{V}$), total and liquid water mixing ratios ($\overline{r_T}$ and $\overline{r_L}$ respectively), and liquid water potential temperature ($\overline{\theta_L}$). The simulated $\overline{V}$ profile increases during the first 12 hours, and decreases rather steadily over the following 24 hours. As the magnitude of the wind evolves, the wind profile maintains its shape.

$\overline{\theta_L}$ and $\overline{r_T}$ both evolve in a manner which is consistent with the above discussion. Initially, the profile of $\overline{r_T}$ is well-mixed up to 350 m and *increases* linearly above this. In the first 24 hours, the profile moistens slowly in response to horizontal advection. During the following 12 hours, the moistening is more rapid. We see a negative "bump" just below cloud top in all of the moisture profiles. This is a result of the auto-conversion scheme (Curry, 1983), which acts to redistribute water in areas where it builds up. We also see that the magnitude of the mixing ratio "jump" at cloud top increases with time. This is due to entrainment.

In the bottom left plot in ***Fig. 2***, we show a plot of $\overline{\theta_L}$. This simple plot represents much of the physics of this regime. At the initial time (darkest curve), the profile of $\overline{\theta_L}$ is close to

adiabatic. When the cloud forms, the cloud layer initially become well-mixed and the overall $\overline{\theta}_L$ increases. The former is a result of radiative cooling, which drives turbulence and mixes the layer, while the latter is due to the horizontal advection of temperature (note that the warming effect is less near cloud top; this is a direct result of radiative cooling which is balancing the warming). Between hours 12-24, the cloud layer grows and cools. During this time, the liquid water mixing ratio in the cloud increases by 0.3 g kg^{-1}. The increase in radiative cooling, due to this large increase in $\overline{r}_L$, outweighs the warming due to horizontal advection.

During the subsequent 12 hours (hours 24-36), the "unrealistically large" ECMWF advective warming (see above discussion) is large enough to outweigh the radiative cooling. During this time, $\overline{r}_L$ increases less than 0.05 g kg^{-1}. Another interesting feature of the 24-36 hour $\overline{\theta}_L$ profile is that the layer from the surface to 150 m appears to not be as well mixed as the rest of the profile. What is occurring here is that the unrealistically large warming creates stronger-than-normal downward sensible and latent heat fluxes (see above discussion). This acts to cool the lower layers, decoupling them from the in-cloud turbulence. Thus, we see that ADHOC is responding in a manner which is physically consistent with the "unrealistic ECMWF" forcing.

The magnitude of the liquid water mixing ratios simulated in this case are within the range of those previously observed in these types of ASCs (Tsay and Jayaweera, 1984; McInnes and Curry, 1995; Smith and Kao, 1996).

Fig. 3 shows show the simulated fluxes of total water, and virtual potential temperature. The potential temperature and total water fluxes are fairly typical for ASCs. Next to the corresponding ADHOC-simulated profiles in *Fig. 3* are the simulated profiles from Smith and Kao (1996; SK96) and the observations reported by Curry (1986; C86). The ADHOC-simulated

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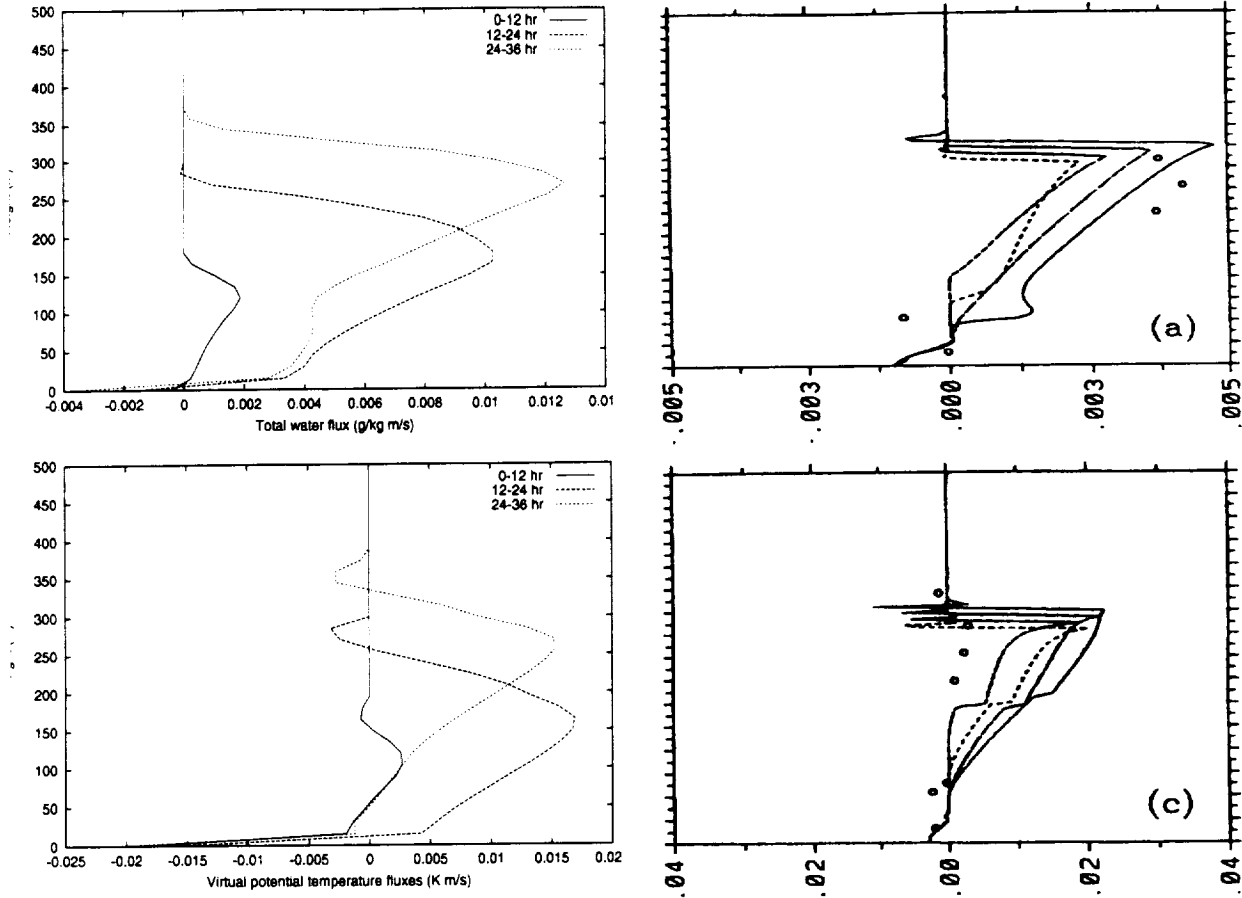
Figure 3: Flux profiles. Top left, simulated total water flux; top right, total water flux from Smith and Kao (1996; lines) and Curry (1986; circles); bottom left, simulated potential temperature fluxes; bottom right, virtual potential temperature from Smith and Kao (1996; lines) and Curry (1986; circles).

fluxes are amazingly similar to the profiles of SK96 and C86 in shape, and are within a reasonable range in magnitude, especially considering that the ASCs are similar but not the same.

The simulated virtual potential temperature fluxes are negative near the surface. In ADHOC, right at the surface, we see a discontinuous jump to very large negative values. This is a

direct result of the unrealistic advective warming (discussed above), and is not a problem with ADHOC. The simulated heat flux, in the absence of this unrealistic warming, is negative, indicative that the turbulence is not driven by buoyant production at the surface. The virtual heat flux increases with height in the cloud to a maximum at cloud top, showing the effects of condensation and radiative cooling. At cloud top, the heat flux decreases sharply with height, as a result of the strong radiative flux divergence which occurs in this layer.

The ADHOC-simulated total water fluxes also agree nicely in shape and magnitude with those of SK96 and C86. The stable, near surface region is characterized by a negative total moisture flux, which indicates that moisture is being removed from the atmosphere and deposited on the ice. Above this, the simulated ADHOC moisture flux profile and those of SK96 and C86 all exhibit the same unusual feature; the flux, which is increasing upwards from the surface, transitions to a near vertical profile, and then resumes a positive slope. This feature in ADHOC is strongest during the 24-36 hour period, but can still be seen during the earlier 12-hour period. This feature is an indicator that the surface and the cloud layers are decoupled (at least partially) for both ASCs. While this region is not cloud-free in the ADHOC simulation, the liquid water mixing ratio is a minimum there (*Fig. 2*).

5.   Concluding remarks

The most important product of this study is the model described by Lappen et al. (2001 a, b, c). We have demonstrated that the model is able to represent the physics of a wide variety of cloudy boundary layers. We are now working to install the model as a parameterization in a general circulation model. In this way we can achieve closure on the ultimate goal of this project, which has been to improve the representation of boundary-layer clouds in general circulation models.

Publications resulting from this research

Dissertation

Cara-Lyn Lappen, 1999: *The Unification of Mass Flux and Higher-Order Closure in the Simulation of Boundary Layer Turbulence.* Ph. D. Thesis, Colorado State University, 329 pp. (Also available as *Atmospheric Science Paper 679*, Colorado State University.)

Refereed publications in chronological order

Randall, D. A.,. Curry, D. Battisti, G. Flato, R. Grumbine, S. Hakkinen, D. Martinson, R. Preller, J. Walsh, and J. Weatherly, 1998: Status of and outlook for large-scale modeling of atmosphere-ice-ocean interactions in the Arctic. *Bull. Amer. Meteor. Soc.,* **79**, 197-219.

Randall, D. A., Q. Shao, and M. Branson, 1998: Representation of Clear and Cloudy Boundary Layers In Climate Models. In *Clear and Cloudy Boundary Layers*, A. A. M. Holtslag and P. G. Duynkerke, Eds., Roy. Neth. Acad. Arts and Sci., Amsterdam, pp. 305-322.

Randall, D. A., and D. G. Cripe, 1999: Alternative methods for specification of observed forcing in single-column models and cloud system models. *J. Geophys. Res.,* **104**, 24527-24545.

Fowler, L. D., and D. A. Randall, 1999: Simulation of upper-tropospheric clouds with the CSU general circulation model. *J. Geophys. Res.,* **104**, 6101-6121.

Curry, J. A., P. V. Hobbs, M. D. King, D. A. Randall, P. Minnis, G. A. Isaac, J. O. Pinto, T. Uttal, A. Bucholtz, D. G. Cripe, H. Gerber, C. W. Fairall, T. J. Garrett, J. Hudson, J. M. Intrieri, C. Jakob, T. Jensen, P. Lawson, D. Marcotte, L. Nguyen, P. Pilewskie, A. Rangno, D. Rodgers, K. B. Strawbridge, F. P. J. Valero, A. G. Williams, and D. Wylie, 2000: FIRE Arctic Clouds Experiment. *Bull. Amer. Meteor. Soc.,* **81**, 5- 29.

Lappen, C.-L, and D. A. Randall, 2001 a: Towards a unified parameterization of the boundary layer and moist convection. Part I. A new type of mass-flux model. *J. Atmos. Sci.,* **58**, 2021-2036.

Lappen, C.-L., and D. A. Randall, 2001 b: Towards a unified parameterization of the boundary layer and moist convection. Part II. Lateral mass exchanges and sub-plume-scale fluxes. *J. Atmos. Sci.,* **58**, 2037-2051.

Lappen, C.-L., and D. A. Randall, 2001 c: Towards a unified parameterization of the boundary layer and moist convection. Part III. Simulations of multiple convective regimes. *J. Atmos.*

Sci., **58**, 2052-207

Randall, D. A., M. E. Schlesinger, V. Galin, V. Meleshko, J.-J. Morcrette, and R. Wetherald, 2002: Cloud Feedbacks. In *"Frontiers in the Science of Climate Modeling,"* J. T. Kiehl and V. Ramanathan, Eds., Cambridge University Press. In press.

Non-refereed publications in chronological order

Lappen, C.-L., 1998: Operator's manual for SHEBA powered tether balloon system. *Atmospheric Science Paper No. 664*, Colorado State University, 20 pp. (D. A. Randall, Principal Investigator).

Lappen, C.-L. and D. A. Randall, 1999: Unification of mass flux and higher-order closure techniques in the simulation of boundary-layer turbulence. Paper presented at the *13th Conference on Boundary Layers and Turbulence of the American Meteorological Society,* Dallas, Texas, 10-15 January 1999.

Cripe, D. G., C.-L. Lappen and D. A. Randall, 1999: Simulation of Arctic weather with a single-column model. Paper presented at the *5th Conference on Polar Meteorology and Oceanography of the American Meteorological Society,* Dallas, Texas, 10-15 January 1999.

Cripe, D. G., Cara-Lyn Lappen, and D. A. Randall, 1999: Simulation of Arctic weather with a single-column model. Paper presented at the *International Union of Geodesy and Geophysics,* Birmingham, England, July 1999.

Randall, D. A., Ed., 2000: *Workshop on cloud processes and cloud feedbacks in large-scale models.* WCRP-110, WMMMO/TD No. 993, 175 pp.

Randall, D. A., and C.-L. Lappen, 2000: New approaches to parameterizing convection. In *Workshop on cloud processes and cloud feedbacks in large-scale models.* WCRP-110, WMMMO/TD No. 993, pp. 92-101.

Randall, D. A., J. Curry, P. Duynkerke, S. Krueger, M. Miller, M. Moncrieff, B. Ryan, D. Starr, W. Rossow, G. Tselioudis, and B. Wielicki, 2000: The GEWEX Cloud Systems Study Second Science and Implementation Plan. *IGPO Publication Series No. 34,* 45 pp.

Fowler, L. D., and D. A. Randall, 2000: The second generation of cloud microphysics and fractional cloudiness in the CSU general circulation model. Paper presented at the *13th*

Randall, D. A., 2001: Parameterization of the planetary boundary layer for large-scale models. Paper presented at the *European Geophysical Society Conference*, Nice, France. (Invited paper)

Randall, D. A., 2001. Parameterization of the boundary layer for climate models. Paper presented at the *Climate Conference 2001*, Utrecht, The Netherlands, August 20-24, 2001.

Randall, D. A., 2001: Boundary layers and climate. Paper presented at the *Climate Conference 2001*, Utrecht, The Netherlands, August 2001. (Invited paper)

Randall, D. A., M. E. Schlesinger, V. Galin, V. Meleshko, J.-J. Morcrette, and R. Wetherald, 2002: Cloud Feedbacks. In *"Frontiers in the Science of Climate Modeling,"* J. T. Kiehl and V. Ramanathan, Eds., Cambridge University Press. In press.

Curry, J. A., P. V. Hobbs, M. D. King, D. A. Randall, P. Minnis, G. A. Isaac, J. O. Pinto, T. Uttal, A. Bucholtz, D. G. Cripe, H. Gerber, C. W. Fairall, T. J. Garrett, J. Hudson, J. M. Intrieri, C. Jakob, T. Jensen, P. Lawson, D. Marcotte, L. Nguyen, P. Pilewskie, A. Rangno, D. Rodgers, K. B. Strawbridge, F. P. J. Valero, A. G. Williams, and D. Wylie, 2000: FIRE Arctic Clouds Experiment. *Bull. Amer. Meteor. Soc.*, 81, 5- 29.

List of Attachments

Randall, D. A.,. Curry, D. Battisti, G. Flato, R. Grumbine, S. Hakkinen, D. Martinson, R. Preller, J. Walsh, and J. Weatherly, 1998: Status of and outlook for large-scale modeling of atmosphere-ice-ocean interactions in the Arctic. *Bull. Amer. Meteor. Soc.*, **79**, 197-219.

Randall, D. A., Q. Shao, and M. Branson, 1998: Representation of Clear and Cloudy Boundary Layers In Climate Models. In *Clear and Cloudy Boundary Layers*, A. A. M. Holtslag and P. G. Duynkerke, Eds., Roy. Neth. Acad. Arts and Sci., Amsterdam, pp. 305-322.

Lappen, C.-L., 1998: Operator's manual for SHEBA powered tether balloon system. *Atmospheric Science Paper No. 664*, Colorado State University, 20 pp. (D. A. Randall, Principal Investigator).

Randall, D. A., and D. G. Cripe, 1999: Alternative methods for specification of observed forcing in single-column models and cloud system models. *J. Geophys. Res.*, **104**, 24527-24545.

Randall, D. A., and C.-L. Lappen, 2000: New approaches to parameterizing convection. In *Workshop on cloud processes and cloud feedbacks in large-scale models*. WCRP-110, WMMMO/TD No. 993, pp. 92-101.

Lappen, C.-L, and D. A. Randall, 2001 a: Towards a unified parameterization of the boundary layer and moist convection. Part I. A new type of mass-flux model. *J. Atmos. Sci.*, **58**, 2021-2036.

Lappen, C.-L., and D. A. Randall, 2001 b: Towards a unified parameterization of the boundary layer and moist convection. Part II. Lateral mass exchanges and sub-plume-scale fluxes. *J. Atmos. Sci.*, **58**, 2037-2051.

Lappen, C.-L., and D. A. Randall, 2001 c: Towards a unified parameterization of the boundary layer and moist convection. Part III. Simulations of multiple convective regimes. *J. Atmos. Sci.*, **58**, 2052-207