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AN EXAMINATION OF A UNIFIED CLOUDINESS-TURBULENCE SCHEME WITH VARIOUS TYPES OF CLOUDY BOUNDARY LAYERS

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1. INTRODUCTION

An improved formulation to represent cloudy boundary layers (BL), appropriate for low-order turbulence models, has been proposed in a series of papers by Bechtold and collaborators (Bechtold et al., 1992; Bechtold et al., 1995; Cuijpers and Bechtold, 1995; Bechtold and Siebesma, 1998). This formulation is based on a unified cloudiness-turbulence approach and allows for a more physical representation of turbulent fluxes under various clear and cloudy conditions and for a more detailed treatment of microphysics in partly cloudy layers. Bechtold et al. developed and tested this approach in a one-dimensional version of a mesoscale model, against a number of marine boundary layer cases, including various regimes of stratocumulus (Sc) clouds in the mid-latitudes and subtropics, trade wind BLs with shallow and deeper cumulus (Cu) clouds, as well as boundary layers characterized by intermediate cloud fraction.

In the present study, this approach is examined using three-dimensional mesoscale simulations and is extended to a wider range of conditions taken from recent field experiments, such as FIRE.ACE (First ISCCP Regional Experiment Arctic Cloud Experiment) (Mailhot et al., 2002) and MERMOZ-II (Mailhot et al., 1999). Three different types of cloudy boundary layers are considered. The first case corresponds to Sc clouds over the Arctic ice pack observed during FIRE.ACE that are characterized by mixed phases. Two other cases, taken from MERMOZ-II, correspond to continental Cu clouds forming at the top of an initially clear convective boundary layer.

2. MODEL DESCRIPTION

We present here a brief description of the features of the physics package that are most relevant to the present study.

2.1 *Surface processes*

The surface processes include a coupled sea ice model and a modified version of the ISBA land surface scheme with special attention to snow physics. The multi-level thermodynamic sea ice model comprises a snow cover on top of ice, heat conduction through snow and ice, and a parameterization of albedo, conductivity and heat capacity. The sea ice concentration and ice thickness are obtained from observational data from the Canadian Ice Service and the U.S. National Ice Center.

2.2 *The cloudy boundary layer*

A unified cloudiness-turbulence scheme along the lines proposed by Bechtold et al. has been developed to replace the current scheme used in the Canadian mesoscale models. Our current approach is based on a TKE turbulence scheme (with the thermodynamic variables of dry potential temperature θ and specific humidity q_v) coupled somewhat artificially with a shallow convection scheme to describe cloud-topped convective boundary layers. This will be referred to as our standard scheme. The improved formulation, referred to as the new scheme, is appropriate for a low-order turbulence model such as our TKE scheme and allows a general description of stratiform clouds and shallow non-precipitating cumulus convection regimes, by using a fractional cloudiness. A treatment for mixed-phase clouds has also been included.

Following the notation of Bechtold and Siebesma (1998; BS), the model now uses conservative thermodynamic variables, the ice-liquid potential temperature $\theta_{il} = \theta\,(1 - Lq_c / c_pT)$ and the total water content $q_w = q_v + q_c$ where q_c is the total cloud content formed of liquid water and ice contents $q_c = q_l + q_i$ and $L = L_v + f\,L_f$ where L_v and L_f are the latent heats of vaporization and fusion, respectively. Here, f is the ice fraction of the cloud condensate, set equal to zero at temperatures above -15°C, to unity at temperatures below -25°C, and with a linear variation in the temperature range between -25°C and -15°C.

BS showed that, in the presence of clouds, the ensemble mean buoyancy flux appearing in the TKE equation can be expressed as

$$F_{\theta v} = (1 + \delta\, q_w - \beta\, b\, f_N\, N)\, F_{\theta il} + (\alpha + \beta\, a\, f_N\, N\,)\, F_{qw}$$

where a, b, α, β and δ are thermodynamic coefficients (derived in Appendix A of BS) and $F_{\theta il}$, F_{qw} are the vertical fluxes of the conservative variables. Statistical relations appropriate to the various boundary-layer cloud regimes were obtained by BS based on observations and large-eddy simulations, that permit to define the subgrid-scale cloud fraction N, the flux enhancement factor f_N and the total cloud content q_c in terms of a single parameter Q_1 representing the normalized saturation deficit (see Appendix B of BS).

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Another improvement to our current BL scheme concerns the inclusion of a nonlocal mixing length formulation (Bougeault and Lacarrère 1989). Based on two clear-sky convective BL cases from MERMOZ-I, Bélair et al. (1999) showed that the inclusion of the nonlocal mixing length together with a consistent dissipation length in the TKE scheme resulted in increased entrainment near the inversion (due to enhanced values for the mixing length), and produced a more realistic evolution of the convective BL depth.

2.3 *The mixed-phase cloud microphysics scheme*

An explicit cloud scheme with mixed-phase (MXP) microphysics (Tremblay and Glazer, 2000) is used to describe clouds resolved at the model grid scale. The MXP cloud scheme was developed to incorporate more detailed microphysics into mesoscale models. The MXP scheme uses only one prognostic variable, the total cloud water content, making it simple enough to be used in an operational environment, yet it discriminates between the solid, warm, and supercooled liquid phases.

The explicit microphysical processes include condensation or evaporation of cloud droplets, evaporation of rain, ice nucleation, deposition or sublimation of ice particles, sedimentation, and ice melting. Sedimentation includes thresholds with values of the liquid water and ice content of 0.1 g m^{-3} and 0.01 g m^{-3}, respectively, to model the onset of precipitation. Homogeneous nucleation freezing of supercooled cloud droplets and raindrops at temperatures below - 35° C is also considered. For mixed-phase clouds in which both warm and cold microphysical processes are active, the partition between liquid and ice is based on a diagnostic equilibrium relation for the ice fraction within saturated updraft in the cloud. This equilibrium solution expresses the steady-state balance between riming, vapor deposition, production of vapor excess by adiabatic cooling, and mixed-phase sedimentation. The adiabatic cooling process depends on the vertical velocity representing an explicit forcing of microphysical processes by the model dynamics.

2.4 *The coupling between the two schemes*

An important aspect in a mesoscale model concerns the coupling between the cloud-turbulence scheme and the explicit cloud scheme. Here, it is desirable to generate the properties of the subgrid-scale boundary-layer clouds, while also being able to switch to the grid-scale clouds described by the explicit detailed microphysical scheme via a smooth transition. For instance, this allows to move from the non-precipitating shallow Cu or stratiform cloud regimes to deeper precipitation-producing Sc clouds. In the model, this is achieved by gradually switching from the moist turbulence scheme to the explicit cloud scheme as soon as the latter generates a cloud water content that exceeds a specific threshold set to $0.01/\rho_a$ (in g kg^{-1} where ρ_a is the air density).

3. MODEL EVALUATION USING FIRE.ACE DATA

Measurements with the Canadian Convair-580 aircraft over a large polynya (wide openings in sea ice) in the Beaufort Sea provided detailed observations of cloud properties during FIRE.ACE.

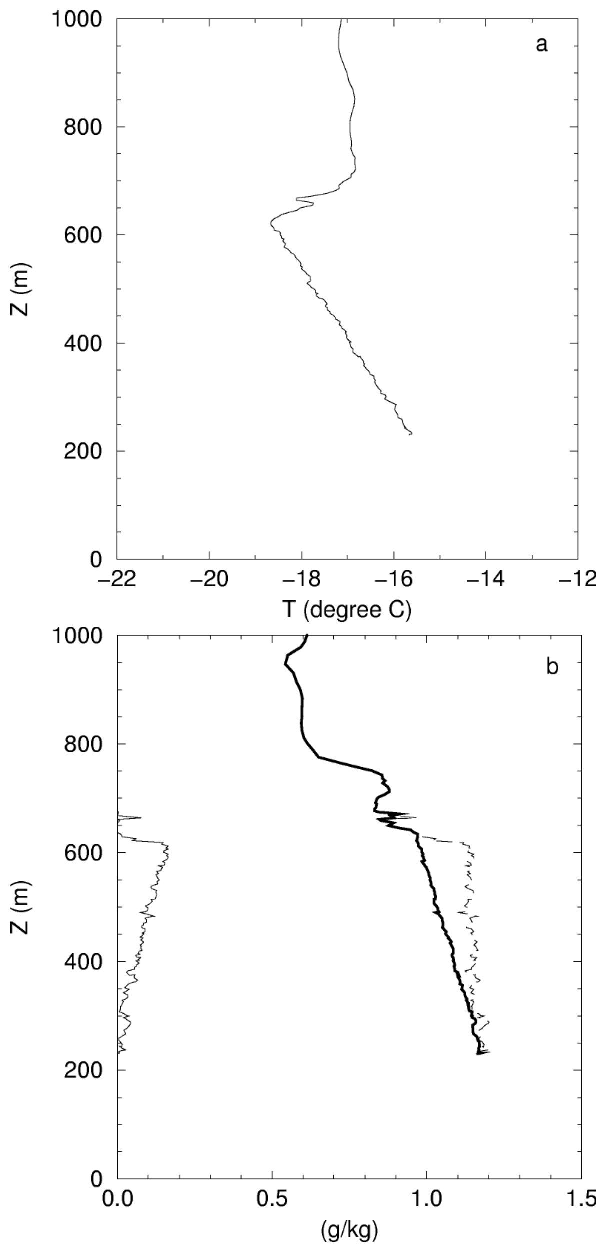

Fig. 1 Vertical profile of the cloudy boundary layer at 2245 UTC 25 April 1998 from vertical sounding by the NRC Convair-580. (a) Temperature (°C); (b) liquid water content (thin solid, g kg^{-1}) from the King probe, specific humidity (thick solid, g kg^{-1}), and total water content (vapor and cloud, dashed line).

An interesting case described in Mailhot et al. (2002) occurred on 25 April 1998, when cold air advection resulted in strong surface heat fluxes over the polynya and in the formation, despite the relatively low temperatures (-19° C), of mixed-phase clouds at the top of the Arctic boundary layer. The Canadian Mesoscale Compressible Community model (MC2) has been used to simulate this case at 2-km resolution, with a detailed treatment of surface processes and the actual observed structure of the large polynya. In order to get a realistic representation of the boundary layer and low-level clouds, 44 levels are used with vertical stretching, resulting in a resolution of about 50 m in the first 0.8 km. The rest of the model setup is similar to that of Mailhot et al. (2002).

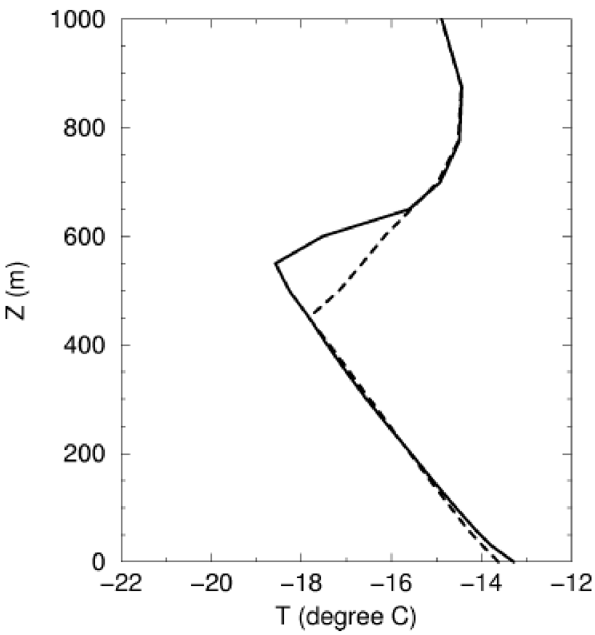

Fig. 2 Vertical profile of temperature (°C) at 2230 UTC 25 April 1998 from model simulation with standard (dashed) and new (solid) schemes.

Satellite and aircraft observations indicate that a cloud layer was present over most of the polynya. The structure of the cloudy boundary layer south of the polynya is illustrated in Figure 1 obtained from the aircraft vertical sounding at about 2245 UTC. The boundary layer is characterized by a well-mixed layer, extending from the surface up to about 600 m, topped with a convective cloud layer from 300 to 600 m. The near-surface air temperature is -14° C and the cloud top temperature is almost -19° C. The total water content (Figure 1b) indicates a nearly-adiabatic profile typical of a cloudy boundary layer, with a value of 1.1 g kg^{-1}. Vertical profiles of liquid and ice water content show that the cloud is of mixed phases, but is largely dominated by the presence of cloud liquid droplets despite the low temperatures. Cloud liquid water content reaches 0.10-0.15 g kg^{-1} (Figure 1b) and ice water content is less than 0.01 g kg^{-1} near the cloud base (not shown).

Figure 2 shows the corresponding structure of the simulated PBL at the same location as the aircraft sounding at 2230 UTC close to the time of the aircraft sounding. The new scheme results in a temperature profile that is quite similar to the observations. A well-mixed PBL extends from the surface up to about 550 m, with near-surface temperature slightly in excess of -14° C and top temperature of about -18.5° C. In contrast, the standard simulation produces a mixed PBL that barely extends to 450 m.

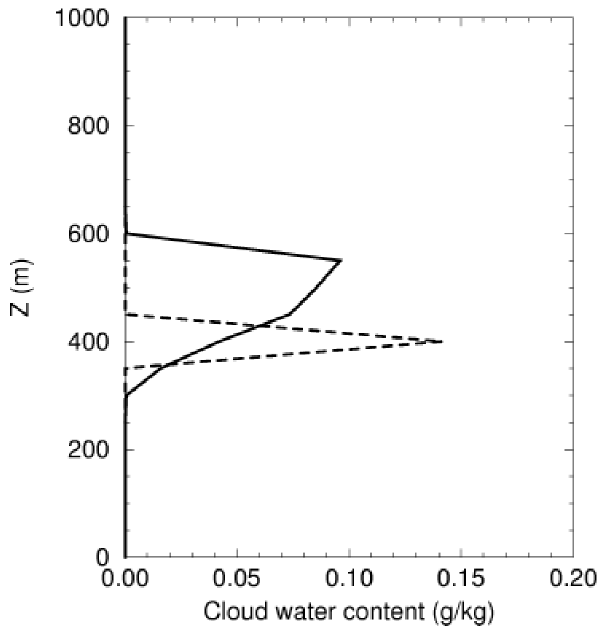

Fig. 3 Vertical profile of cloud water content (g kg^{-1}) at 2230 UTC 25 April 1998 from model simulation with standard (dashed) and new (solid) schemes.

Figure 3 indicates that the simulation with the new scheme generates a cloud layer about 250-300 m thick. The cloud base is near 300 m, and cloud top reaches 550-600 m. The cloud water content is almost 0.10 g kg^{-1}, a little less than observations. Most of the simulated cloud is generated in the form of non-precipitating supercooled liquid water; ice crystals are present in the simulated cloud but account for less than one third of the total cloud water content (ice content values do not exceed 0.03 g kg^{-1}). The values of cloud water content generated by the standard simulation are quite similar to the observed values, but the cloud vertical structure differs considerably. The simulated cloud layer in this case is only 100 m thick and located at an altitude of about 400 m. The most likely explanation for this important discrepancy with respect to the observations in this case appears to lie in the formulation of vertical diffusion based on non-conservative variables (dry potential temperature and specific humidity) coupled somewhat artificially with the cloud microphysical scheme to describe the cloud-topped boundary layer. The new scheme results in a significantly deeper extension of the well-mixed layer into the Arctic inversion capping the PBL and a more realistic cloud layer.

Clearly, as shown in Figure 4 (to be compared to Figure 1b), the simulation using the unified cloudiness-turbulence approach produces a more physically realistic profile of the cloudy boundary layer. A number of weaknesses are still noticeable, in particular the slightly smaller values of specific humidity in the mixed layer and the significantly larger values of specific humidity above the PBL, possibly due to deficiencies in our initial conditions over the relatively data-sparse Beaufort Sea region.

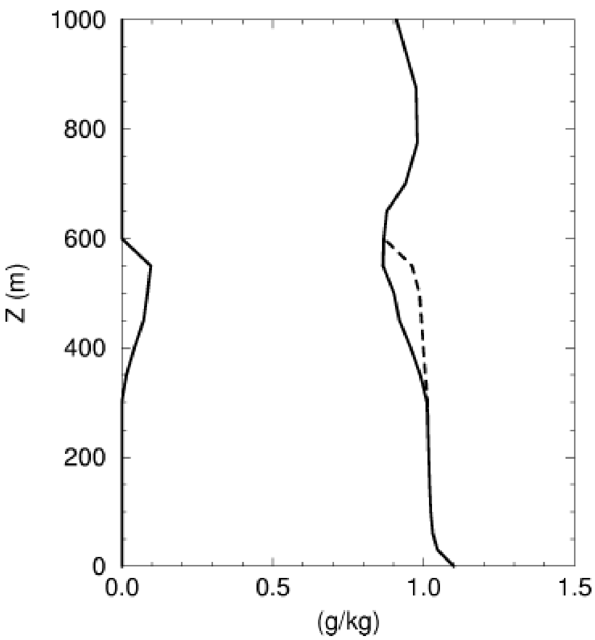

Fig. 4 Vertical profile of the cloudy boundary layer at 2230 UTC 25 April 1998 from model simulation with the new scheme. Cloud water content (solid, g kg^{-1}), specific humidity (solid, g kg^{-1}), and total water content (vapor and cloud, dashed line).

4. MODEL EVALUATION USING MERMOZ-II DATA

MERMOZ-II sampled interesting clear and cloud-topped convective BL cases, with an emphasis put on the entrainment zone and the convective BL evolution, together with detailed measurements of surface forcings (surface energy fluxes and soil moisture evolution). Very good observations were obtained in particular for two days: one with evolving scattered shallow Cu (19 August), and one mostly clear day with a short period of thin dissipating Cu (20 August).

A preliminary examination of the case of 19 August 1997 has just begun starting with our standard current TKE-based turbulence scheme coupled with the shallow convection scheme (15 km resolution in the horizontal, 50 m in vertical, and timestep of 300 sec). The aircraft observations of TKE and turbulent flux profiles (sensible heat H and latent heat LE) exhibit the usual features of a well-developed convective BL, with typical peaks in the cloud layer near the convective BL top due to enhanced turbulence (not shown). The standard simulation reproduces relatively well the turbulence profiles in the lower part of the convective BL, with some underestimates of the H and LE fluxes. However, the effects of the clouds are clearly lacking in the standard simulation, despite the use of the shallow convection scheme.

Work is currently underway to simulate these two cases with the unified cloudiness-turbulence approach. More results will be presented at the Symposium.

5. REFERENCES

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