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SHEAR-DRIVEN CLOUDY BOUNDARY LAYER IN THE ARCTIC

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1. INTRODUCTION

Arctic stratus clouds (ASC) have a significant effect on the surface energy budget and the growth of sea ice in the Arctic. The atmospheric radiation from the ASC strongly influences global climate (Curry et al. 1993). To understand and predict the physical processes which determine the surface energy budget and the sea ice mass balance in the Arctic, the SHEBA (Surface HEat Budget in the Arctic) was carried out from October 1997 to October 1998. The FIRE (First ISCCP [International Satellite Cloud Climatology Project] Regional Experiment) ACE (Arctic Clouds Experiment) was also conducted during April-July 1998 to study Arctic cloud systems under spring and summer conditions.

One of the aspects of ASC is the complicated structure with multiple cloud layers. A number of numerical and observational studies point out that a key role during the developing stage of cloud formation is radiative cooling at the cloud top (Herman and Goody 1976; Curry and Herman 1985). However, this kind of clouds are also formed after a passage of a synoptic low characterized by a strong wind shear, which strongly influences the structure of the boundary layer. In this study, we investigate multiple cloud layers in a stably stratified Arctic boundary layer using observation from FIRE ACE/SHEBA (29 July 1998) and large-eddy simulations.

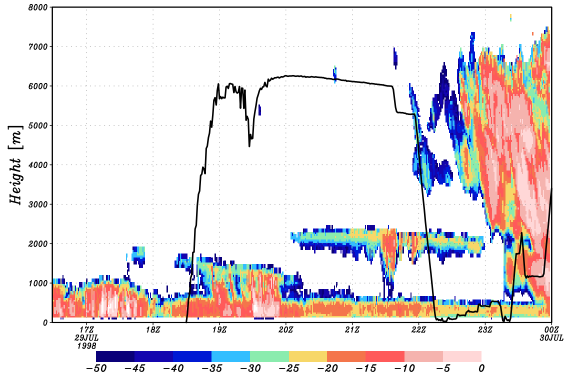

Figure 1: Time-height cross sections of radar reflectivity at SHEBA observation site and flight coordinate of C-130 on 29 July 1998.

2. OBSERVAIONS

The National Center for Atmospheric Research (NCAR) C-130 flew on 29 July 1998 after a passage of a synoptic low. The main objective of this flight was to obtain meteorological data within a cloudy boundary layer. Measurements of cloud microphysics, radiative fluxes, turbulence, atmospheric temperature, humidity and winds were obtained during this flight.

Figure 1 shows the time-height cross section of radar reflectivity of SHEBA site and coordinates of the boundary layer flight pattern. The boundary layer gradually developed during six hours and decayed when the upper clouds were advected in. Vertical profiles of air temperature, potential temperature, water mixing ratio and u and v winds at 22:15 UTC 29 July are shown in Fig. 2. The boundary layer is characterized by two inversion layers which come form upper clouds at 2200m level and lower clouds below 400m level. Water vapor increases with height through the lower cloud layer reaching a peak value near 400m level. The wind is westerly, categorized as a cold advection regime behind a synoptic low. Both wind components are generally uniform below the cloud layer. However, it is noted that there is a strong shear layer below 250m level in the westerly (u) wind component.

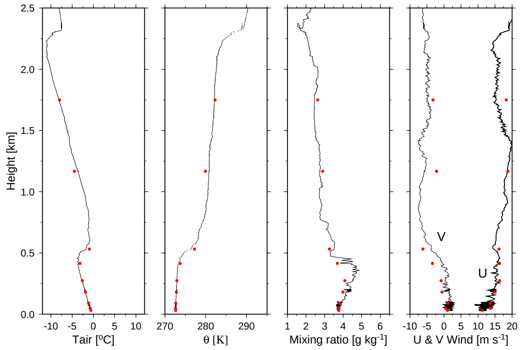

Figure 2: Profiles of air temperature, potential temperature, water vapor mixing ratio, and u and v wind components obtained from an aircraft decent at 22:15 UTC 29 July 1998. The points depicted by closed circles represent leg-average values.

3. TURBULENCE

Spectra and cospectra are calculated from the high-frequency temperature and velocity data collected during each leg. The time series of each variable is partitioned into 60-s segments. By integrating over the spectrum and cospectrum, variance and covariance are calculated at each level. These calculations are performed using data that have been filtered to omit the high-frequency noise generated by the aircraft.

The buoyancy and shear production terms in the TKE budget are calculated to provide insight into the turbulent processes that determine the boundary layer structure. The turbulent transport, viscous dissipation, and pressure correlation terms are not calculated explicitly but may be inferred from the imbalance term assuming the TKE is in steady state following

$$I = -\overline{w'u'}\frac{\partial U}{\partial z} - \overline{w'v'}\frac{\partial V}{\partial z} + \frac{g}{T_0}\overline{w'\theta_v'} \qquad (1)$$

where I is the imbalance term, the first two terms on the right represent shear production, and the third term on

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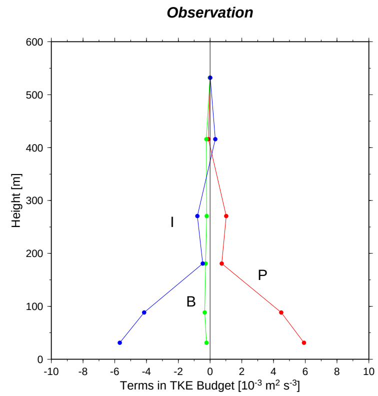

Figure 3: Turbulent kinetic energy budget terms determined from aircraft measurements. The terms are P, shear production; B, buoyancy production; and I, imbalance term.

the right buoyancy production. The constant of gravity is denoted by g. The reference temperature T_0 is chosen to be the ice surface temperature. Using mean wind, turbulent stress, and heat flux at the lowest along-wind legs, the production of TKE from buoyancy and shear are obtained (Fig. 3). After the upper cloud layer was advected over the existing cloud layer (see Fig. 1), the TKE budget indicates that the cloud layer below 250m is maintained predominantly by large shear production. In this case the cloud top cooling at the lower cloud top may have been suppressed by radiative effects of the upper cloud layer.

4. LARGE EDDY SIMULATION

In order to investigate the role of shear production in the maintenance of the boundary layer, we conducted Large Eddy Simulation (LES). The basic dynamic framework of the LES model follows that of Kosović and Curry (2000). Periodic boundary conditions are adopted to the LES model in both the x and y directions. The resolution for each direction is 25m (60^3 grid points). The initial conditions, surface cooling rate, and inversion strength for these simulations were based on the measurements made during FIRE ACE/SHEBA on 29 July 1998. In addition to the control simulation (CTR), we varied the basic parameters: without wind shear (NOSHEAR), without radiation after 12 hours in CTR (NORAD).

Figure 4 shows the time-height cross section of each TKE budget term for CTR (P shear production, B buoyancy production, T transport, D dissipation). The TKE structure can be divided into two stages; one is a developing stage with cloud-filled boundary layer which has strong buoyancy production at the cloud top and shear production near the surface, and turbulent transport at the middle of the layer; and the other is a mature stage which has weak buoyancy production at the cloud top and turbulent transport. In case of NOSHEAR (figure not shown), the boundary-layer clouds also developed, but a subcloud layer formed below them. These results suggest that wind shear is important for the maintenance of the low level cloud near the surface.

Once the cloud reaches a certain height depending on the amount of cloud-top cooling, the two sources of production begin to separate in space. TKE budget profile in CTR after 24 hours (left panel in Fig. 5) is quite similar to that in NORAD (right panel in Fig. 5) and observation (Fig. 3). The separation of the lower layer below 250m from the upper mixed layer is indicated by the small values of the production terms, which means that the structure of TKE is essentially decoupled between the layers. This causes a more strongly stratified surface layer and another cloud layer to form near the surface due to the strong shear mixing. This may be one of the mechanisms of the multiple-layer ASC formation.

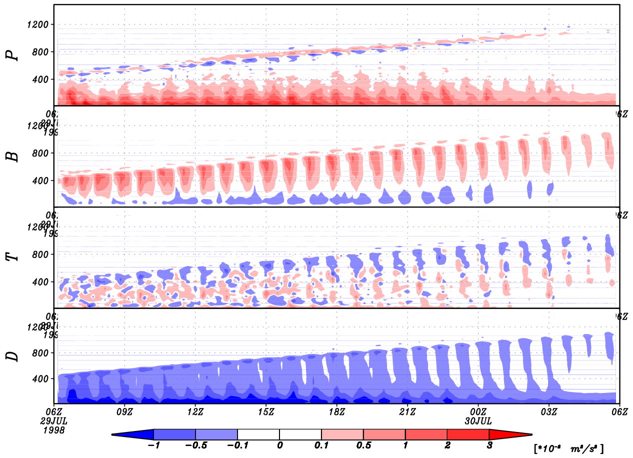

Figure 4: Time-height cross section of each TKE budget term (P, shear production; B, buoyancy production; T, turbulent transport; D, dissipation) for CTR.

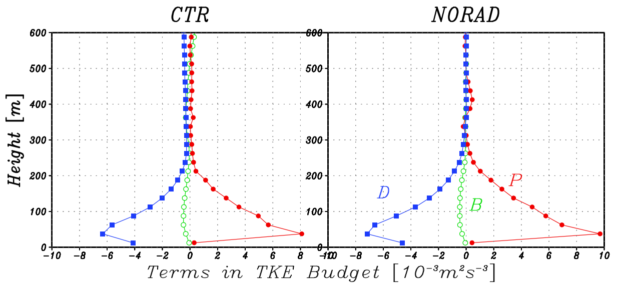

Figure 5: TKE budget terms for CTR and NORAD after 24 hours LES model. The terms are P, shear production; B, buoyancy production; and D, dissipation term.

5. CONCLUSIONS

We study multiple cloud layers in stably stratified Arctic boundary layers using observation from FIRE ACE / SHEBA and large-eddy simulation. The results of the aircraft observations and the LES model show the importance of the wind shear near the surface for the maintenance of the low level clouds. This layer tends to be decoupled with the upper cloud layer, which is one of possible mechanisms of formation of multiple ASC.

6. ACKNOWLEDGEMENTS

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