2.2 THE DIURNAL CYCLE OF THE SUMMER CLOUD-CAPPED ARCTIC BOUNDARY LAYER

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1. INTRODUCTION

One of the most fundamental features of the conventional picture of boundary-layer development is the diurnal cycle. Driven by the diurnal variation in solar radiation, it governs the variation not only of the surface, and therefore the near-surface, temperature but also impacts the boundary layer vertical structure. Diurnal changes in surface stress causes the well-known inertial wind-speed oscillation, often referred to as the low-level, jet appearing on top of the nocturnal boundary layer (Thorpe and Guymer 1977). Higher in the nocturnal low-level troposphere, one often finds the remnants of the previous days convective boundary layer; the so-called residual layer (Stull 1988). The fact that this layer is often nearly neutrally stratified means that it insulates the surface layer from the influence of free troposphere buoyancy waves (Zilitinkevich 2002). Thus, the entire lower troposphere column is affected by the diurnal cycle; neither of these properties would be present without the diurnal cycle.

Convection is influenced by the diurnal variability in the surface turbulent fluxes of heat and moisture. Even over the ocean, slight diurnal variations in SST are important for the precipitation (Li et al. 2001). Other mesoscale phenomena obviously driven or affected by the diurnal cycle are the sea breeze (Tijm and van Delden, 1999), coastal flows (Söderberg and Tjernström, 2002) and mountain induced flows (Gohm and Mayr 2005). The boundary-layer diurnal cycle over the Great Plains of the US, together with effects of gently sloping terrain, gives rise to a regional-scale low-level jet (Stull 1988; Higgins et al. 1997) with major effects on the moisture convergence over northern mid-west US (Mo et al. 2005). The timing of this moisture transport from the Gulf of Mexico, correlated with the local diurnal cycle of surface turbulent fluxes determines the convective-precipitation climate for the interior US (Liang et al. 2001). A review of the climatic importance of low-level jets is found in Stensrud (1996). In the stratocumulus-capped marine boundary layer, the diurnal cycle in cloud thickness, or cloud-water path, ensures that the cloud layer is the thinnest when solar insolation is the strongest (Duynkerke et al. 2004).

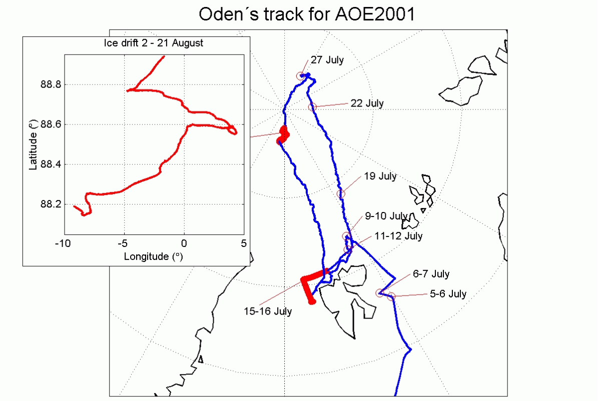

Figure 1. Cruise track (blue) of the AOE-2001 expedition with research stations with dates marked in red. The ice drift is shown in the insert.

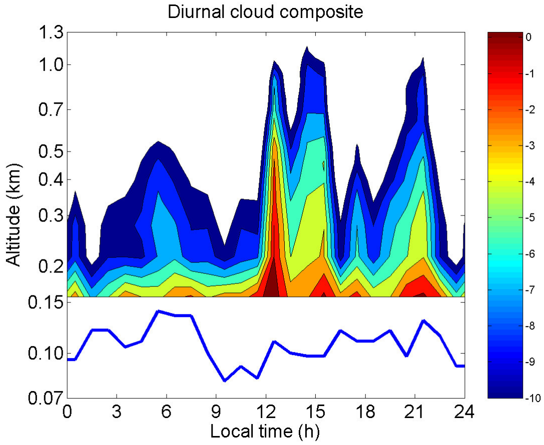

Figure 2. The diurnal cycle of Arctic summer clouds. The lower (blue) line is the median cloud-base height, from a cloud celiometer, while the color shading shows the median cloud-radar reflectivity, from an S-Band cloud radar. The data is from the AOE-2001, from the roughly 1.5 months that the expedition was north of 85 °N, mid-July thorugh most of August 2001.

From a modeling point-of-view, many models have problems simulating the ABL diurnal cycle. In Zhang and Zheng (2004) the diurnal temperature range differed several °C, while the maximum temperature differed by as much as 6 - 8 °C, for a given day in a particular model, by just interchanging the ABL parameterization. Preliminary results from the GABLS (Holtslag 2003) second experiment reveals equally discouraging results (Svensson 2006). It is entirely possible to “calibrate” models to have the correct, for example, diurnal mean temperature or mean stratocumulus thickness, without having a correct diurnal cycle; modelers often refer to this as “tuning” (Randall and Wielicki 1997). However, without the correct diurnal cycle in the surface temperature the average long-wave radiation emitted from the surface will be in error. Likewise, without a correct diurnal cycle of stratocumulus thickness the diurnally averaged solar radiation reaching the surface will be in error.

Far less is known about the Arctic ABL and its diurnal cycle at least partly is due to a paucity of observational data (Tjernström et al. 2004a, Tjernström 2005; Uttal et al. 2002). Much of our understanding of Arctic ABL pro-

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cesses derive from field experiments near the coasts adjacent the Arctic Ocean, except for a few more extensive programs on the Arctic pack ice: e.g. the Surface Heat Budget of the Arctic Ocean (SHEBA, Uttal et al. 2002) and the Arctic Ocean Experiment 2001 (AOE-2001, Leck et al. 2004, Tjernström et al 2004a).

Arctic ABL conditions are special due to the lower boundary consisting of perennial pack ice and to the large and pronounced annual cycle, with a long winter night and continuous daytime conditions during much of summer. In winter, the diurnal cycle is absent, since there is no diurnal radiative solar forcing. During much of summer, the sun is constantly above the horizon but the solar zenith angle does vary with the time of the day. Clouds, in the Arctic dominated by low-level stratocumulus, play an important role, usually contributing to surface warming (Intrieri et al. 2002, Tjernström 2005). Very little is known about their diurnal variation.

2. THE EXPERIMENT

The data in this study comes from the Arctic Ocean Experiment 2001 (AOE-2001, Tjernström et al 2004a), based on the Swedish icebreaker *Oden*. The AOE-2001 consisted of two parts: a three week ice-drift experiment with the ship moored to, and drifting passively with, the ice from 2 to 21 August, embedded in a longer cruise lasting 26 June to 26 of August. Figure 1 shows the cruise track; the insert shows the track for the ice drift. In this paper, the period from mid-July through most of August is used, to ensure that only data from within the pack ice is used.

3. THE DATA

The analysis in this paper relies on on-board surface-based remote sensing (a 60 MHz scanning microwave radiometer and an S-Band cloud radar) and data from the weather station located onboard; these instruments were operated continuously during the entire cruise. For the shorter ice drift period, observation on the ice were used; the boundary-layer temperature and wind speed profiles, turbulence observations and surface radiation instruments. A complete description of the instrumentation during AOE-2001 can be found in Tjernström et al (2004a) and its electronic supplement (Tjernström et al 2004b).

To analyze the diurnal cycle, all data was hig-pass filtered to remove all variability at lower frequency than one day. The remaining signal was composited according the local time of the day; the location of the ship was used to determine the local time of the day since all data

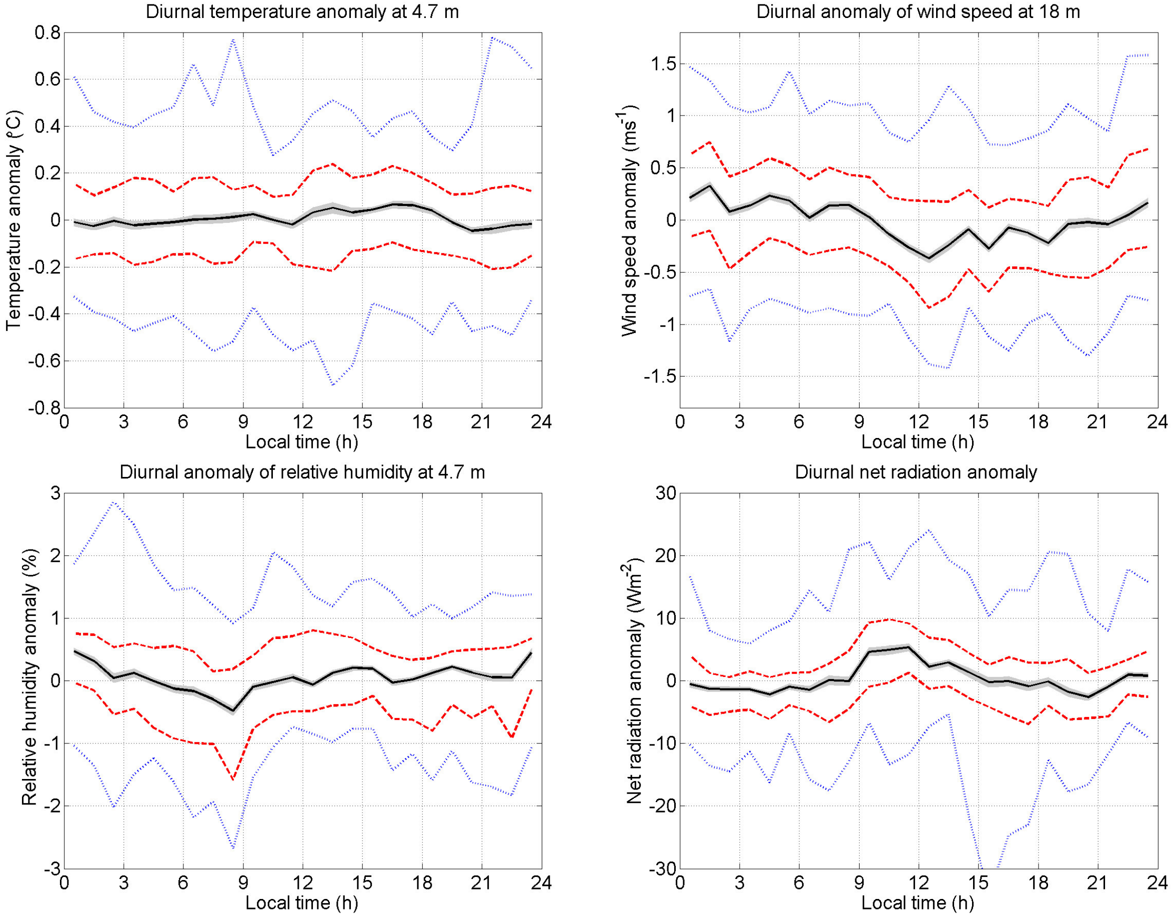

Figure 3. The surface-layer diurnal cycle from the ice drift, 2 – 21 August 2001. Each panel shows (black solid) the median diurnal anomaly, (red dashed) the 25- & 75-, and (blue dotted) 5- & 95 anomaly percentiles. The gray band around the median is the 95% confidence interval of the median anomaly, from a double-sided Student's t-test.

was logged using UTC. The diurnal cycle is defined as the median of the diurnal anomaly. Note that while the mean of the anomaly over one day is always zero this need not be the case for the median. To illustrate the actual values, some variables are also shown here using the data composited directly according to time, without filtering away the sub-diurnal frequencies.

4. THE NEAR-SURFACE DIURNAL CYCLE

The most striking, and initially somewhat puzzling, diurnal feature found from this data is the variation of the cloud field illustrated in Figure 2. This figure shows the diurnal variation of the (median) cloud-base height and cloud-radar reflectivity. The cloud-base height was consistently low though the whole AOE-2001 (Tjernström 2005), commonly lower than 100 m, but the lowest cloud-base height seems to consistently appear in the middle of the day, from 9 to 15 local time (LT); with the very lowest clouds appearing between 9 LT and local noon. The cloud radar had both higher echo intensity, indicating more drizzle, and temporarily higher cloud-top heights in the afternoon. The mid-latitude marine counterpart to these clouds also has a diurnal cycle, but different from what is found here. They are typically the thinnest during noon into afternoon, with a drizzle maximum during early morning. Thus, the diurnal cycle in the Arctic stratocumulus is out of phase with the traditional view of marine stratocumulus.

Figure 3 shows the cycle of the median diurnal anomaly of some surface-layer variables. The near-surface temperature shows a very small diurnal variation. This was expected and is likely due to the strong control from surface freeze/melt processes; Added energy goes into melting and an infrequent negative surface energy balance leads to freezing of open water surfaces before the temperature drops appreciably. This constrains the near-surface temperature to most often between ~ -1.8 and 0.0 ℃ (the melting points of the salty ocean and fresh water, respectively). There is, however, a statistically significant, although, small increase in the temperature between ~ 12 – 19 LT. The diurnal variation of the relative humidity is also small, only ~ 1% peak-to-peak. This should, however, be considered in the context of the very moist Arctic boundary layer. During the two months of the AOE-2001, boundary-layer relative humidity never sank below 94% and most of the time stayed above 95%. Thus the systematic variation of ~ 1% is, although small, still significant. Wind speed also shows a systematic variation of ± 0.5 m s^{-1}, with the lowest values during the middle of the day. The diurnal variation in net radiation is mostly due to changes in solar radiation. Although the sun never sets during this time of the year, there is a diurnal variation in solar zenith angle. The peak-to-peak variation of slightly less than 10 W m^{-2}; recall, however, that this was measured over a relatively high-albedo surface under a more or less constant cloud cover. More interestingly, however, the peak in the net radiation does not appear at local noon, when the solar insolation is at its maximum. Instead, it occurs before noon, indicating an interplay with the cloud thickness. This implies less energy reaching the surface than if the cloud layer had been diurnally homogeneous.

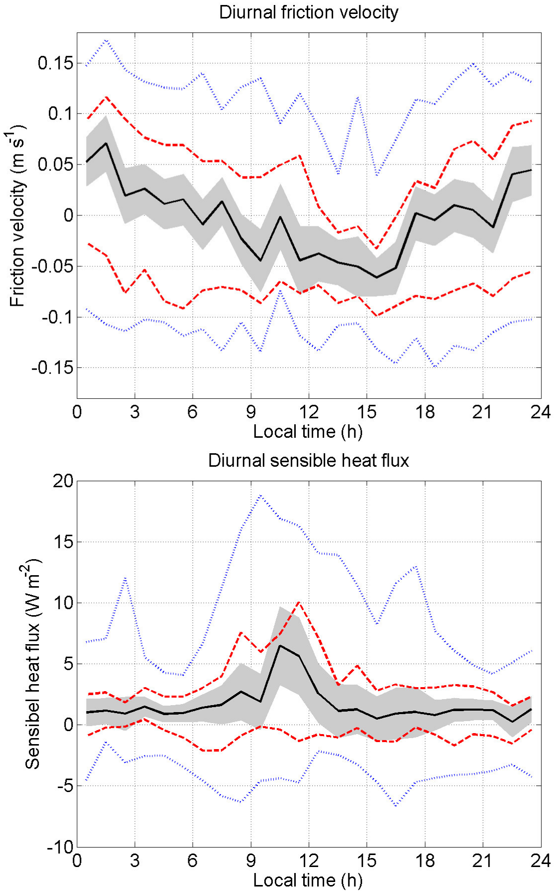

Figure 4. Same as Figure 3, but for (top) the surface friction velocity and (bottom) turbulent sensible heat flux. Note that the plots show the median anomaly; although the mean of the anomaly for the sensible heat flux is by definition zero, this does not necessarily hold for the median of the anomaly, due to a positively skewed probability.

The diurnal variation of the surface momentum flux (Figure 4) has a mid-day minimum consistent with the corresponding wind-speed minimum. The turbulent kinetic energy, however, has no diurnal variation (not shown). Figure 4 also shows the diurnal anomaly of the sensible heat flux. Note that the median anomaly is slightly positive, reflecting the skewed distribution to a few very large values; the mean anomaly off course has a zero mean. The turbulent sensible heat flux has a significant, although not large, positive peak coinciding with the lowest cloud-base heights in Figure 2. This also coincides with the lowest occurrence of low visibility (fog), but is preceded by a several-hours long period with enhanced probability for fog.

5. THE BOUNDARY LAYER AND CLOUD DIURNAL CYCLE

The diurnal anomaly of the cloud base is shown again in Figure 5; note that this is now the median *anomaly* and this is different from the median itself as shown in Figure 2. This result is based on the 1-hourly mean of the cloud base and there is a substantial variability, thus

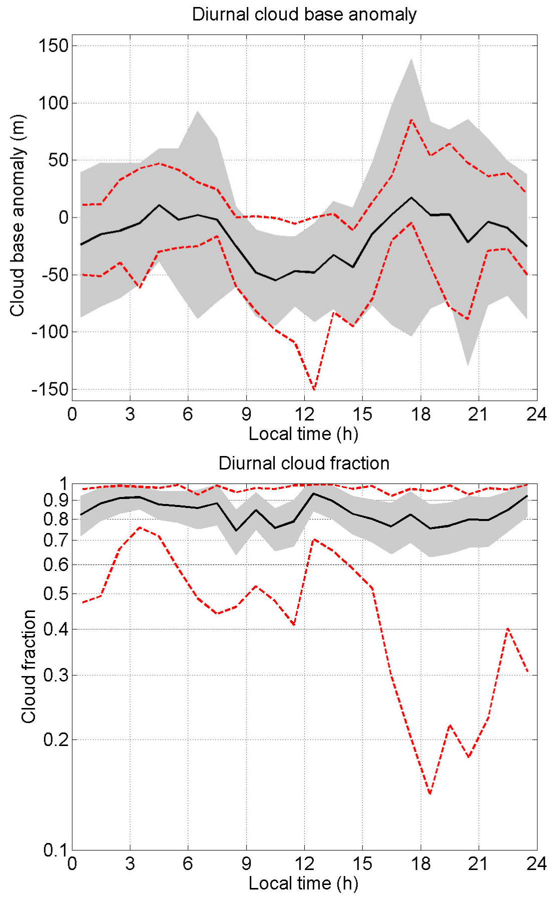

Figure 5. Variation of the (top) median diurnal cloud-base height anomaly and (bottom) median cloud fraction (Note, median, not median anomaly). The red dashed lines shows the 25- and 75-percentiles.

the confidence interval is larger. Still, as it is not possible to assign one single value for the whole day within the confidence interval, we can reject the zero-hypothesis at the 95% confidence level. Figure 5 also shows the median variation of the cloud fraction (Note the median, not the median anomaly). This shows a significant drop just as the lowest cloud-base heights appear the infrequent (as indicated by the 75-percentile) very low values in the afternoon and evening, when the cloud radar indicated higher than average cloud tops.

The high resolution, in time and space, temperature profiles from the scanning microwave radiometer allows a detailed analysis of the thermal structure of the boundary layer (Figure 6). On average, the boundary layer has a two layer structure where the upper ~ 75% of the boundary layer (essentially the cloud layer) was well mixed, with a near moist-adiabatic lapse rate, overlying a more stable layer below the clouds. This figure shows that these two layers also have a diurnal development that is out of phase. The cloud layer is the coldest in the early morning around ~ 03 LT but remains cool through the day and is the warmest in the evening, around 19 – 21 LT. The lower layer is instead warmest around local noon. Thus there is the least static stability between the layers between ~ 09 LT and 12 LT, when the cloud-base height drops and the relative humidity has its low anomaly. This is also when the cloud-layer vertical temperature gradient is the most near neutral. Later, when the higher cloud tops appear in the cloud-radar, the cloud layer is the warmest but also the most statically stable, while the stability in the inversion layer is the weakest.

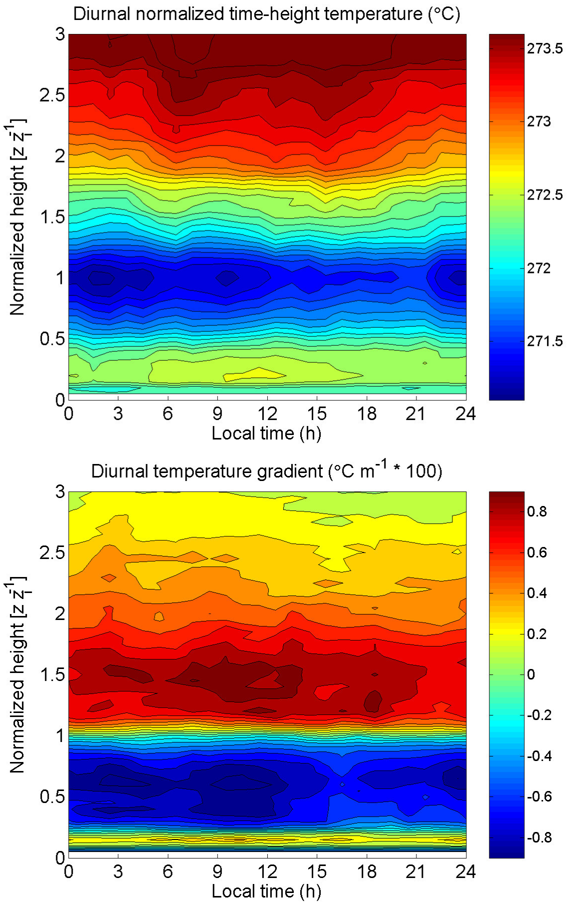

Figure 6. The diurnal variation of the boundary-layer thermodynamic structure showing (top) the median temperature (anomaly plus diurnal mean) and (bottom) the median vertical temperature gradient. The height is scaled with the height to the base of the capping inversion.

5. DISCUSSION

There is a significant diurnal cycle in most variables through the entire Arctic summer cloud-capped boundary layer. One of the most significant diurnal variations appears in the cloud layer, with a lower than average cloud-base height around noon, and more drizzle and more often a substantially broken cloud field later in the afternoon and into the evening.

We hypothesize that this cycle is related to the cloud microphysics. In the Arctic summer, with little anthropogenic influence and a near-solid ice cover, the aerosol number concentrations are often low, leading to low concentrations of cloud-condensation nuclei (e.g. Heintzenberg et al. 2006), and thus to promotion of drizzle-formation processes. It has been speculated that heavy drizzle alters the structure of marine stratocumulus from the typical stratiform to a more convective-cumulus-like structure (Stevens et al. 1998); this is consistent with observed the structure here. But, the diurnal cycle in these clouds also appear to be out of phase with the traditional cycle of marine cloud-capped boundary layers.

It seems unlikely that the diurnal variation in solar radiation is sufficient to be the driving force behind this variation. Instead, we further hypothesize that it is the differential diurnal cycle in the boundary-layer thermal structure that is the key. The mean boundary-layer structure is two-layered, with turbulence in the upper cloudy layer presumably driven by cloud-top cooling, while the lower layer is more constrained by low-level surface processes. This promotes larger stability during night and an accumulation of water vapor near the surface from evaporation; this is when fog is most frequent. As the lower layer heats in the morning, while the cloud-layer remains relatively cool, a point in time is eventually reached when the two layers connect and the water vapor is mixed through the whole boundary layer. This first leads to a lowering of the cloud-base height, then to an increase in the cloud water. This increase subsequently leads to a more rapid warming of the cloud layer through absorption of solar radiation and release of latent heat, and then to the enhanced drizzle in the afternoon and evening. In the afternoon, the cooling of the lower and warming of the upper layers again limits the supply of water vapor, and the cycle restarts the following day, with a build-up of water vapor close to the surface.

This all relies on the ability of the cloud layer to promote the heavy drizzle, which is dependent on the low cloud-condensation nuclei number concentration. Without the drizzle, the cloud layer would remain more stratocumulus-like stratified through the whole day, the diurnal temperature cycles in the two layers would be more synchronized and the boundary layer would eventually become similar to the nighttime marine cloud-capped boundary layer at lower latitudes.

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