Evaluation of Boundary Layer Depth Estimates at Summit Station, Greenland

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ABSTRACT

Boundary layer conditions in polar regions have been shown to have a significant impact on the levels of trace gases in the lower atmosphere. The ability to properly describe boundary layer characteristics (e.g., stability, depth, and variations on diurnal and seasonal scales) is essential to understanding the processes that control chemical budgets and surface fluxes in these regions. Surface turbulence data measured from 3D sonic anemometers on an 8-m tower at Summit Station, Greenland, were used for estimating boundary layer depths (BLD) in stable to weakly stable conditions. The turbulence-derived BLD estimates were evaluated for June 2010 using direct BLD measurements from an acoustic sounder located approximately 50 m away from the tower. BLDs during this period varied diurnally; minimum values were less than 10 m, and maximum values were greater than 150 m. BLD estimates provided a better comparison with sodar observations during stable conditions. Ozone and nitrogen oxides were also measured at the meteorological tower and investigated for their dependency on boundary layer structure. These analyses, in contrast to observations from South Pole, Antarctica, did not show a clear relation between surface-layer atmospheric trace-gas levels and the stable boundary layer.

1. Introduction

Recent studies on photochemistry occurring within polar snowpacks and the influence reflected in the overlying atmosphere have revealed that reactions occurring in the snowpack can be both sources and sinks of reactive trace gases to the atmosphere (Grannas et al. 2007). Understanding this dynamic chemistry, as well as physical processes in the snowpack, is critical in evaluating how chemical constituents are preserved in ice cores and in assessing the influence of snowpack on polar tropospheric chemistry. One important factor influencing surface trace gas levels is the atmospheric boundary layer. Studies at the South Pole (SP) have shown that a combination of conditions—including low snow accumulation rates allowing for efficient recycling of nitrogen, emissions of nitrogen oxides (NO_x: NO + NO_2) from the snowpack, a long fetch allowing NO_x accumulation in the surface layer, and sustained shallow stable boundary layers—promote elevated levels of nitric oxide (NO) and ozone (O_3) production near the surface (Davis et al. 2001, 2008; Neff et al. 2008; Helmig et al. 2008a). Understanding the cycling and budgets of tropospheric O_3 and NO_x is essential for characterizing the oxidation capacity of the lower atmosphere.

Cohen et al. (2007) investigated the behavior of the boundary layer and its influence on atmospheric trace gas chemistry at Summit Station, Greenland. Their study estimated boundary layer depths (BLD) using a diagnostic model previously applied in Neff et al. (2008).
Without access to frequent BLD observations, an evaluation of the efficacy of implementing the model at Summit was not viable. In this study we address two main objectives: 1) to assess the accuracy of BLD estimates derived from two diagnostic models that rely on sonic-anemometer turbulence quantities using BLD measurements from a minisodar at Summit and 2) to evaluate ambient NO\textsubscript{x} levels alongside minisodar-derived BLDs to test for a relationship such as that seen in locations on the Antarctic Plateau.

2. Methods

a. Site and instrumentation

Measurements were conducted at Summit Station (72°34′N, 38°29′W, 3210 m MSL). Instrumentation was installed during May of 2008, and measurements were conducted continuously through July of 2010. This study focuses on data from June of 2010. Turbulence measurements were taken on a meteorological tower that was located ~660 m southwest of the main camp structures within the Summit clean-air sector. Surface turbulence quantities were derived from a 3D sonic anemometer (USA-1 model; Metek GmbH) that was mounted at 5.6 m above the snow surface. Turbulence data were processed and filtered as described in Cohen et al. (2007), with several modifications. Sonic-anemometer data were collected at a sampling rate of 10 Hz, and turbulent covariance values were calculated in ½-h blocks. Data for north-wind periods were removed because of tower contamination. The sonic anemometer used in this study was equipped with a self-heating feature programmed to turn on automatically when rimeing of the sensor head was detected.

A high-resolution acoustic sounder (minisodar) was deployed approximately 50 m to the northeast of the meteorological tower. A description of the minisodar implemented in this study and an explanation of the BLD extraction method can be found in Neff et al. (2008). The minisodar measured up to a height of ~165 m with a lower detection limit of 4 m to focus on high-resolution detection of the near-surface layer at Summit. BLD estimates from the minisodar were averaged to ½ h, allowing for equivalent comparisons between the turbulence and minisodar data. Figure 1 shows a photograph of the sodar and meteorological tower.

Air was sampled from an inlet at 6.3 m for determination of NO. Nitric oxide was detected by chemiluminescence after reaction with O\textsubscript{3} (Ridley and Grahek 1990); nitrogen dioxide (NO\textsubscript{2}) was determined as NO via UV photodissociation (Kley and McFarland 1980) with a photolytic NO\textsubscript{2} converter. Ambient levels of O\textsubscript{3} in the surface layer were measured at 1.6 m using...
a UV photometric O₃ analyzer (Model 49C; Thermo Environmental Instruments, Inc., Franklin, Massachusetts).

b. Theoretical background

A variety of diagnostic equations have been proposed to estimate BLD that are based on simple scaling approaches (Zilitinkevich and Baklanov 2002; Zilitinkevich et al. 2002; Vickers and Mahrt 2004). A primary motivation for developing these diagnostic equations is the desire to use surface turbulence measurements to estimate BLD; it is worth mentioning that BLD estimates that are based on observations will depend somewhat on the observational method, however. Two such diagnostic equations were investigated previously using surface turbulence data from SP (Neff 1980; Neff et al. 2008). Conditions at SP are unique because of the lack of a diurnal solar cycle, which allows the boundary layer to approach an equilibrium depth. The first of these equations for the BLD (also called $H_i$) is an expression that was originally devised by Pollard et al. (1973) for an oceanic mixing layer, driven primarily by surface stress and assuming equilibrium at inertial time scales:

$$H = 1.2 u_* (f N_b)^{-1/2}.$$  \hspace{1cm} (1)

In this equation, $u_*$ is the friction velocity [defined as $(\overline{uw})^{1/2}$, where $u$ and $w$ are the horizontal and vertical wind components, respectively], $f$ is the Coriolis parameter, and $N_b$ is the Brunt–Väisälä frequency given by

$$N_b = \sqrt{\frac{g}{T} \frac{\partial \theta}{\partial z}}.$$ \hspace{1cm} (2)

Here, $g$ is the gravitational acceleration, $T$ is the absolute temperature recorded by the sonic anemometer, and $\partial \theta / \partial z$ is the potential temperature gradient with height. Neff (1980) found that this diagnostic model gave a good estimation of BLD during weak-to-moderate stability conditions at SP when compared with sodar measurements. This model was tested against sodar measurements more recently at SP using vertical temperature gradients from a 22-m tower and rawinsonde temperature profiles. It was found that model results were representative of the BLD during very stable conditions but were overestimates in other cases. In this expression, $H_i$ is only weakly dependent on vertical static stability. The Pollard et al. (1973) model assumes a sensible heat flux $H_s = (\rho c_p w T_v)$ of zero (a reasonable approximation at SP) and is dominated by the value of $u_*$ as a measurement of turbulence-induced mixing (here, $\rho$ is air density, $c_p$ is the specific heat of air at constant pressure, and $T_v$ is the virtual temperature). We included another diagnostic model that is sensitive to the value of $H_s$. This scaling expression, which is derived by Zilitinkevich and Baklanov (2002), is described by

$$H = C_s \left( u_* L / f \right)^{1/2},$$ \hspace{1cm} (3)

where $C_s = 0.7$, $u_*$ and $f$ are the same as above, and $L$ is the Monin–Obukhov length, defined as

$$L = \frac{-u_*^3 T_v}{(kgH_s)},$$ \hspace{1cm} (4)

where $k$ is the von Kármán constant. In the SP experiments, Eq. (3) proved to be problematic when compared with sodar data. This was a result of transient changes in $H_s$, for example, as a result of the passage of clouds, that changed the surface radiative balance but did not affect the more slowly evolving BLD. It was determined that $u_*$ was the surface parameter with the most influence on boundary layer mixing at this location (Neff et al. 2008).

Aside from SP, these diagnostic equations were also tested at Summit and Barrow, Alaska. As mentioned in the introduction, the Cohen et al. (2007) study used Eq. (1) to estimate BLD at Summit. In lieu of frequent direct observations, BLD that were inferred from four radiosonde profiles were used for a limited assessment. A comparison of the four available observations indicated that Eq. (1) estimated the BLD to within ±55 m. At Barrow, in comparison with a minimum of twice-daily radiosonde data, Eq. (1) estimated BLD within ±50 m for 76% of the data comparisons, whereas Eq. (2)
estimated BLD within ±50 m for 61% of the comparisons (Boylan et al. 2013, manuscript submitted to J. Geophys. Res.). Both models primarily underestimated the inferred BLDs.

3. Results

a. Boundary layer characteristics

A frequency distribution of June 2010 stability conditions (estimated by the Monin–Obukhov stability parameter $z/L$) is shown in Fig. 2. Unstable conditions ($z/L < 0$) were common during June of 2010, occurring for 47% of the period. In a similar way, Cohen et al. (2007) reported unstable conditions for 51% of the time during July–August of 2004. Cullen and Steffen (2001) reported that unstable conditions were present during 11%–43% of their observations from June to October during 1998–2000 at Summit. The average diurnal cycle (median measurement for each hour of the day over the entire month) of $H_s$ and $z/L$ is shown in Fig. 3. Positive $H_s$ and negative $z/L$ values (indicating unstable conditions) existed between the hours of 0700 and 1700 western Greenland summer time (WGST). This diurnal variation in stability is a noteworthy contrast to conditions observed at SP and early-spring observations at Barrow, where extended multiday periods of very stable conditions have been observed (Neff et al. 2008; Boylan et al. 2013, manuscript submitted to J. Geophys. Res.). Detailed discussion of the surface energy balance at Summit can be found in, for example, Albert and Hawley (2000) and Cullen and Steffen (2001). Helmig et al. (2002) described boundary layer conditions at Summit in June of 2000 on the basis of vertical profiling with a tethered balloon, documenting stable nighttime conditions and a well-mixed boundary layer during daytime.

Parameters contributing to changes in the depth of the stable to weakly stable boundary layer at Summit are investigated in Fig. 4. Sodar observations of BLD are binned by 15-m depth intervals, and the median BLD within each bin is compared with the median $u_*$ and $H_s$ values. A linear regression analysis was conducted for each dataset, with the data weighted by the fraction of the total number of observations available in each bin indicated by the gray bars in (a), using the same y-axis scale but with the units being decimal fraction (i.e., ranging from 0 to 0.3, or from 0% to 30% of total observations; the same weighting was used in (b)]. The linear regression $R^2$ value is 0.83 in (a) and is 0.29 for (b).

FIG. 3. Median hourly values (asterisks) of (a) $z/L$ and (b) $H_s$ for the entire month of June 2010. The gray lines indicate the 25th and 75th percentile ranges of the hourly data.

FIG. 4. Data for late evening through early morning (1900–0300 WGST) were binned by sodar observations of the BLD. Median values of the (a) $u_*$ and (b) $H_s$ are shown as a function of binned BLD. A linear regression analysis was conducted for each dataset, with the data weighted by the fraction of the total number of observations available in each bin indicated by the gray bars in (a), using the same y-axis scale but with the units being decimal fraction (i.e., ranging from 0 to 0.3, or from 0% to 30% of total observations; the same weighting was used in (b)]. The linear regression $R^2$ value is 0.83 in (a) and is 0.29 for (b).
There is no significant relationship between the two, and the large variance in \( H_s \) that is experienced for each BLD bin indicates that observed rapid changes in \( H_s \) are not reflected in the development of the BLD. These results point to \( u_* \) as the more important scaling parameter in estimating BLD at Summit; this conclusion is investigated further in the following section.

**b. BLD estimation**

Equations (1) and (3) were used to estimate the BLD from the sonic-anemometer surface turbulence data. Figure 5a shows a linear regression analysis of Eq. (1) calculations versus the sodar measurements; the linear regression line slope of 1.16 with an \( R^2 \) value of 0.7 indicates that this model slightly overestimates BLD.
Figure 5b shows a similar plot using estimates from Eq. (3). Here, the linear regression line has a slope of 1.6, demonstrating that this model also overestimates the BLD, to a larger degree than does the model derived from Pollard et al. (1973). Color contouring the data in these figures according to $z/L$ shows that there is less variability in the model estimates when conditions are highly stable, as compared with weakly stable or neutral. To improve estimations of BLD at Summit, diagnostic models such as the two described here could be implemented for stable conditions and a separate method could be used when conditions become neutral to unstable. One example is the method of calculating BLD on the basis of the integral length scales of turbulence data (Oncley et al. 2004). In that study, an empirical result from Liu and Ohtaki (1997) was applied by using similarity relationships to calculate estimates of BLD during unstable conditions. It is shown here that, despite the fact that a prominent diurnal cycle in heat exchange and atmospheric stability is present during the summer months at Summit, an estimation that uses $u_*$ as the primary scaling parameter still provides a better estimate of BLD than does one that utilizes $H_s$. Very different boundary layer conditions have been reported at Barrow (Boylan et al. 2013, manuscript submitted to J. Geophys. Res.) and SP (Neff et al. 2008), where sustained periods of strong stability and low BLD were observed. Yet both of these studies also determined that $u_*$ was the primary scaling parameter and that Eq. (1) provided the closest estimate of BLD during stable conditions.

Figure 6a illustrates a time series of the sodar measurements and the estimated BLD using the two diagnostic equations implemented in this study. Both equations capture the general day-to-day variations observed in the BLD; it is apparent, however, that both models overestimate the boundary layer, with Eq. (3) more substantially doing so. Figure 6b shows $H_s$ and $u_*$, the primary scaling parameters for Eqs. (1) and (3). It demonstrates the faster fluctuations in $H_s$ that are not reflected in the growth or variation in the BL. Figure 6c shows surface-layer $O_3$, NO, and $NO_x$ time series data during the same period. The [NO] was examined to test whether a linear relationship existed with BLD. This relationship was documented at SP, where high [NO] was observed to be associated with sustained highly stable conditions that were characterized by low BLD (Davis et al. 2001; Helmig et al. 2008a; Neff et al. 2008). BLD was also shown to exhibit strong control on diurnal cycles of [NO$_x$] at Dome C, Antarctica (Frey et al. 2013). To determine whether a relationship between [NO] and the stable BLD was evident at Summit, binned [NO] and binned [NO$_x$] were both compared with BLD [using a method similar to that of Davis et al. (2004)]. Linear regression analysis gave $R^2$ values of less than 0.3 for both comparisons. This result implies that the BLD during stable to weakly stable conditions did not play a critical role in determining [NO$_x$] at Summit during the investigated period. This is likely because of diurnal changes in turbulence, the lack of sustained shallow BLDs, and differences in chemical fluxes between the snowpack and atmosphere. During June, mean $\pm$ 1 standard deviation [NO] was 10 $\pm$ 5 pptv. A one-way analysis of variance (ANOVA) demonstrated a statistically significant difference between the nighttime (defined here as
2200–0200 WGST) and daytime (defined as 1200–1600 WGST) [NO] at the $\alpha = 0.05$ significance level, illustrating a diurnal cycle in [NO] with a median nighttime value of 5 pptv and daytime value of 11 pptv. These levels are $\sim 1/10$ or less of observed summertime [NO] at SP and at Dome C (Davis et al. 2001; Helmig et al. 2008b; Frey et al. 2013). Sustained shallow BLD is not the only contributor to the high levels of [NO] on the Antarctic Plateau; additional factors that cause differences between Summit and the Antarctic sites include the longer fetch and lower snow accumulation rates (Davis et al. 2001, 2004, 2008).

4. Summary

Two diagnostic equations developed for estimating the BLD from surface-layer turbulence data were applied for conditions encountered at Summit, and results were evaluated using data from an acoustic sounder. These models scaled well with sodar BLD for stable to weakly stable conditions. Both overestimated the BLD, with the model that was sensitive to $H_b$ overestimating to a larger degree. The error in both estimates increased when stability conditions shifted toward neutral. Our study focused on the boundary layer during stable to weakly stable conditions. This focus follows prior results at SP that have shown the important influence of shallow BLDs and stable conditions on near-surface trace gas levels over snow (Davis et al. 2004; Helmig et al. 2008b; Neff et al. 2008).

Using concurrent measurements of BLD and ambient trace gases, we showed that BLD in June 2010 at Summit was not as important of a factor in determining summertime trace gas levels when compared with SP, where a positive correlation between [NO] and BLD was evident. Future directions of this work should include investigating how the diagnostic models for the stable BL examined here perform seasonally at Summit (since variations in BLD are expected to change drastically during the dark winters and in transitional seasons), implementing turbulence data for BLD estimation in the unstable regime at Summit, and examining whether the BLD–NO$_x$ relationship varies during other time periods.

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