Boundary Layer Depth Estimation for Chemical Box Model Applications at the South Pole using Short-Tower Meteorological Measurements

W. Neff [1], D. Gottas[1], and D. Davis[2]
[1]NOAA Earth System Research Laboratory, Physical Sciences Division, Boulder, United States (william.neff@noaa.gov, 303 497 6020),
[2]Earth & Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA

1. Background

As part of the ANTCI (ANtarctic Tropospheric Chemistry Investigation) 2003 program (Eisele et al. 2008) we operated a sodar to determine boundary layer (BL) depth routinely and establish a quantitative relationship between nitric oxide concentrations and BL depth. This worked well as shown Figure 1 (Neff et al. 2008).

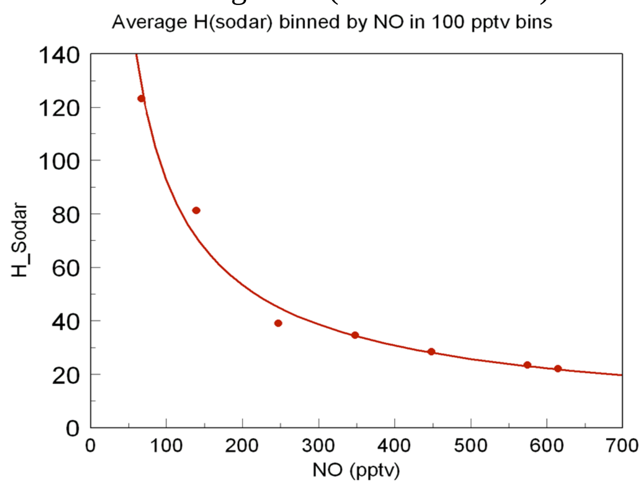

Figure 1. Average BL depth for 100 pptv bins of NO concentrations from ANTCI 2003.

In a follow-on ANTCI effort during 2006-2007, chemical measurements were made during the sunrise to summer period (e.g., Sept 21, 2006 –Jan 15, 2007). However, sodar data were not available to provide a direct estimate of BL depth. Past work has indicated a significant dependence of surface NO_X concentrations (and, indirectly, BL depth) on wind speed, direction and surface static stability (Davis et al. 2004). In addition, others have examined the use of surface turbulence measurements to estimate the BL depth (Neff et al. 2008; Oncley et al. 2004). The 2006-2007 experiment and the absence of direct turbulence measurements or sodar-derived BVL depth measurements raised the question of whether the BL depth at the South Pole could be deduced from routine meteorological measurements including those from the adjacent 22-m tower. This effort is intended to support chemical modeling calculations which along with other supporting data are to be used to infer surface fluxes and concentration levels of NOx (i.e., $NO_X = NO + NO_2$) for comparison with observational data. The goal here being that of determining whether new photochemical mechanisms may be needed to explain the exceptionally high levels of NOx observed on the plateau. Past work with chemical modeling at the South Pole used model estimates of BL depth estimated from a numerical model (Wang et al. 2007) after tuning from direct observations obtained during a portion of the period modeled. Here we use multiple linear regression analyses using data sets from late November 2003 – December 2003 (the most complete and high resolution data) and a second test data set from October through November 1993 (coarse resolution sodar data under more statically stable conditions). The following example in Figure 2 shows one case where changes in wind speed and direction and Delta T (2-22 m) were coincident with a major increase in nitric acid (2006 data set) suggesting that these three variables should play a role in any estimation technique. It should be noted that this particular case appears to be one of advection of high-NO boundary layer air from the east (i.e., downslope flow). Other cases have been observed where high NO concentrations occur with higher sustained winds from northeast directions suggesting longer range transport and still other cases with prolonged light wind regimes where significant local accumulation of NO may occur. Separating these cases will be the subject of future work.

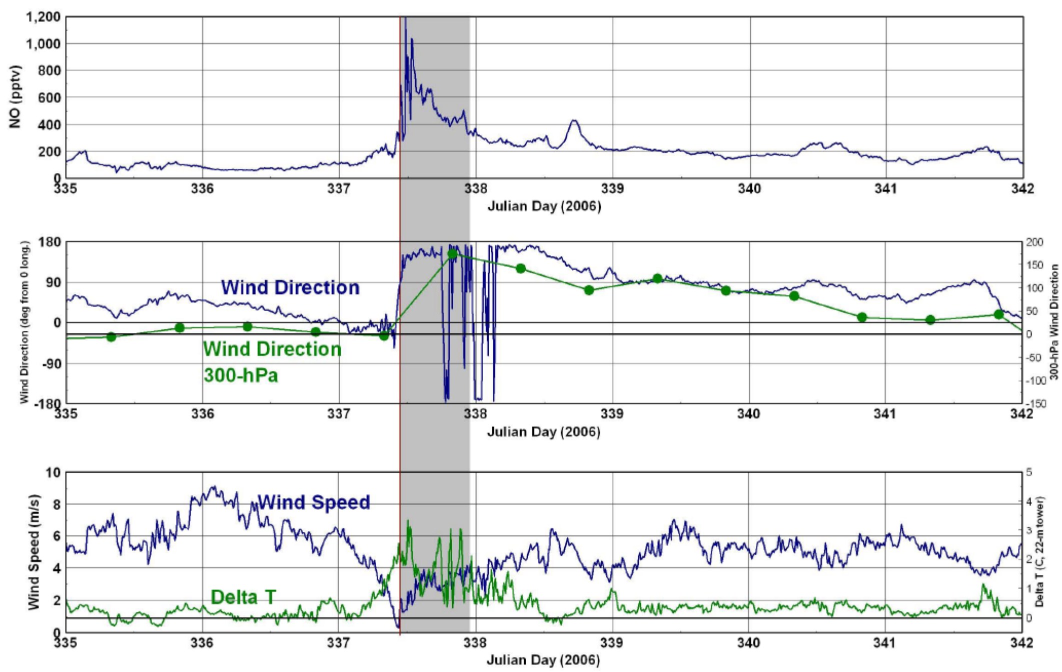

Figure 2. Example of a rapid increase in NO associated with a rapid shift of the surface wind to the downslope direction, lowering wind speed and increasing static stability (Delta T). The 300-hPa wind direction is also plotted to show that this event was generated by larger-scale synoptic activity.

2. ***Why should a multiple linear regression (MLR) approach work?***

The South Pole provides one of the most unique locations on the Earth to study the behavior of stable boundary layers due to the lack of a diurnal insolation cycle and the presence of very gentle sloping ice fields that produce a systematic katabatic component to the surface winds. This wind field is only somewhat perturbed by passing synoptic weather systems (Neff, 1999, JGR) so that there can be some expectation that the boundary layer can approach an equilibrium state within an inertial period (12 hr). Figure 2 shows, however, that these synoptic events can trigger changes in wind speed, direction and temperature that are directly related to changes in BL depth and, consequently, surface chemistry behavior.

2.1 Initial results for 2003

With this caveat we used routine observations of wind speed, direction, temperature, delta temperature (22 m), and sodar-derived BL depth measurements over the time period of late November through December 2003 to carry out a series of multiple regression analyses to determine key variables from which to infer BL depth. BL depths were those described in (Neff et al. 2008). As part of this effort we also examined relationships involving daily cloud cover as well as the depth and strength of the surface inversion based on rawinsonde data taken twice a day. Figure 3 shows results for the multiple linear regression results together with a table that lists r^2 between BL depth (BLD) and each variable independently. In this case the regression equation is

BLD=-27.2+21.2*WS+0.31*WD-16.2*Delta T (tower)-4.2*(Delta T (bulk rawinsonde)) (1)

	r^2
Wind Speed	0.56
Wind Direction	0.10
Delta T (22m)	0.32
Cloud Fraction	0.03
Bulk Delta T	0.14

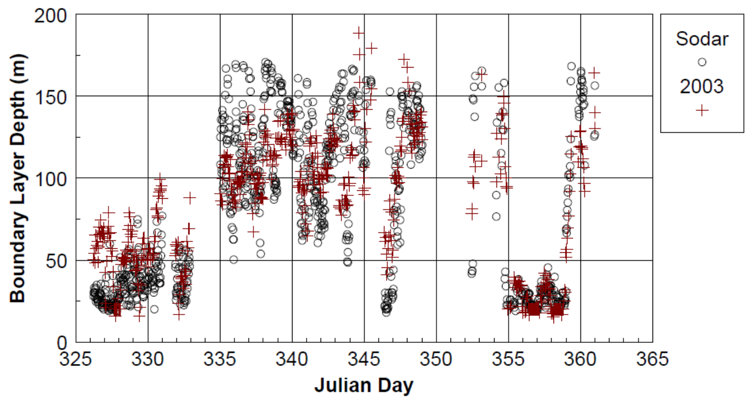

Figure 3. Multiple linear regression fit for ANTCI 2003 (r^2=0.67). Table to left shows individual r^2 for each variable with sodar-derived BL depth. Cloud fraction was neglected in final results because of the low correlation. (Predicted values <15m set to 15 m).

2.3 Results from Spring 1993 at the South Pole

Sodar measurements made in 1993 at South Pole over the time period of October to the end of November provided an additional data set from which such algorithms could be tested. This data set was obtained from a sodar operating in its Doppler mode which requires a longer transmitted pulse: the effect was to create the appearance of a deeper boundary layer by about 15 m. This earlier sodar instrument did not record digital data of sufficient resolution to apply automatic detection routines: this then required manual estimates of the BL depth from the recorded facsimile images. These were obtained to the nearest 10 m on an hourly basis: 15 m was then subtracted to compensate for the long transmitted pulse. We examined individual correlations as for 2003 which are shown in the table in Figure 4: for this data set the bulk Delta T and cloud fraction showed small r^2. Overall, the remaining correlations were also smaller. Figure 4 shows MLR fit for 1993. Cloud fraction was neglected in final results yielding for the 1993 MLR:

BL=+20.7+9.6*WS-0.07*WD-4.8*Delta T (tower)-0.58*(Delta T: bulk rawinsonde) (2)

As before, predicted values <15m were set to 15 m. In this case the multiple linear regression was less effective at capturing the variability in the observed data than in the

2003 exercise with an $r^2 = 0.37$ compared to 0.67 in 2003. When we applied the 2003 algorithm to the 1993 data, $r^2 = 0.32$. Reversing this procedure, we applied the 1993 best-fit equation to the 2003 data with the results shown in Figure 5. In this figure, it is clear that the 1993 algorithm appears to work well for shallow BL depths but does not capture the deeper mixing episodes. This presumably is due to higher stability through the October-November 1993 period compared to December 2003

	r^2
Wind Speed	0.30
Wind Direction	0.10
Delta T (22m)	0.16
Cloud Fraction	0.03
Bulk Delta T	0.02

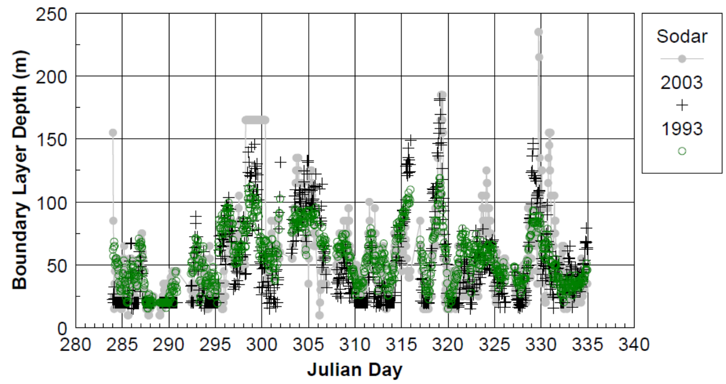

Figure 4. Comparison of observed BL depth (gray circles) with the 2003 MLR algorithm (black crosses) as well as best-fit 1993 MLR (open green circles).

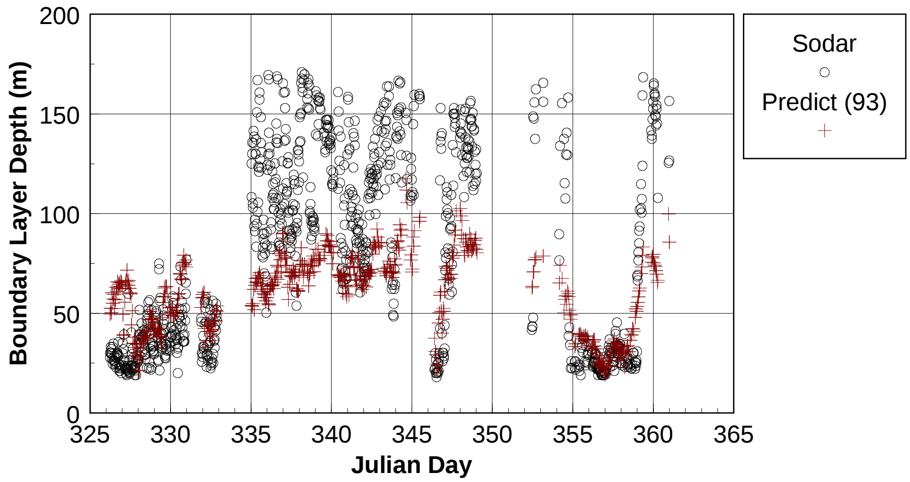

Figure 5. Results of Eq. 2 from the 1993 MLR to data from 2003 compared with observations.

2.4 Summary and a Reduced Algorithm

The 2003 analysis showed the best linear regression fit (r^2=0.67). The linear regression fit for 1993 (r^2=0.37) and the 2003 best-fit applied to 1993 (r^2=0.32) both account for only about a third of the variance. Analyses from 1993 do not extend well to 2003 for deeper BL depths: in part, this is due to improved quality of data during 2003 and the range of BL characteristics observed. We carried out a further reduction in the analysis using only wind speed, direction and near-surface temperature difference (over 22 m) as shown in Figure 6 ("Reduced fit") and then compared the results that also included the daily inversion strength from rawinsonde data ("Full fit").

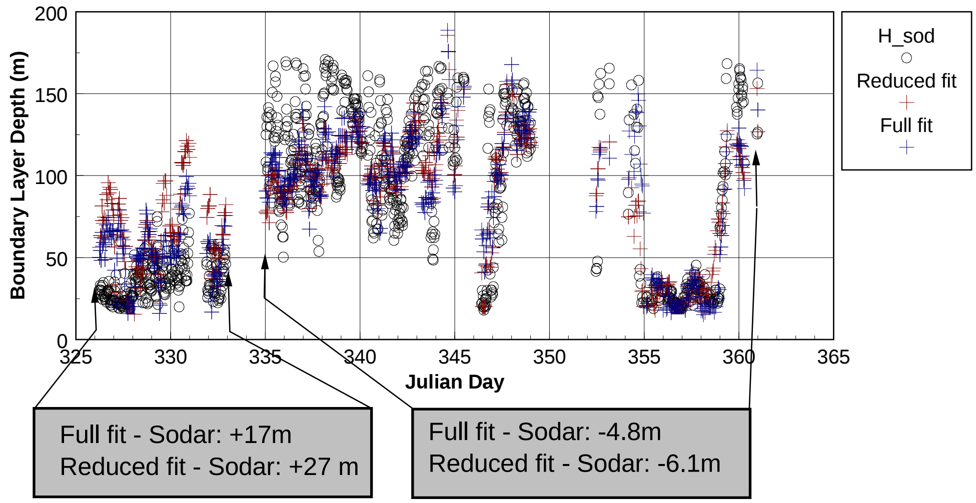

Figure 6. Effects of eliminating the bulk inversion strength obtained twice a day from the rawinsonde sounding from the MLR analysis. The bulk inversion value is typically found over several hundred meters in depth and reflects larger synoptic weather influences. The major influence of this change appears in the MLR prior to JD335 (1 December 2003) and results in an increase of 10 m in predicted BL depth.

3. Application to the interpretation of NO concentrations

Time series of predicted BL depth (black) and observed NO (red) are shown (below) for October, November and December using 1-hr average data. Note the effect of increasing sunlight on the production of NO and the effect of shallower BL depths even in October. (Note the difference in vertical scales.) Figure 8 shows power law fits to data from JD 326 through JD 14 2006 (Red line, blue markers) and JD 326 –JD 361, 2003 (Green line).

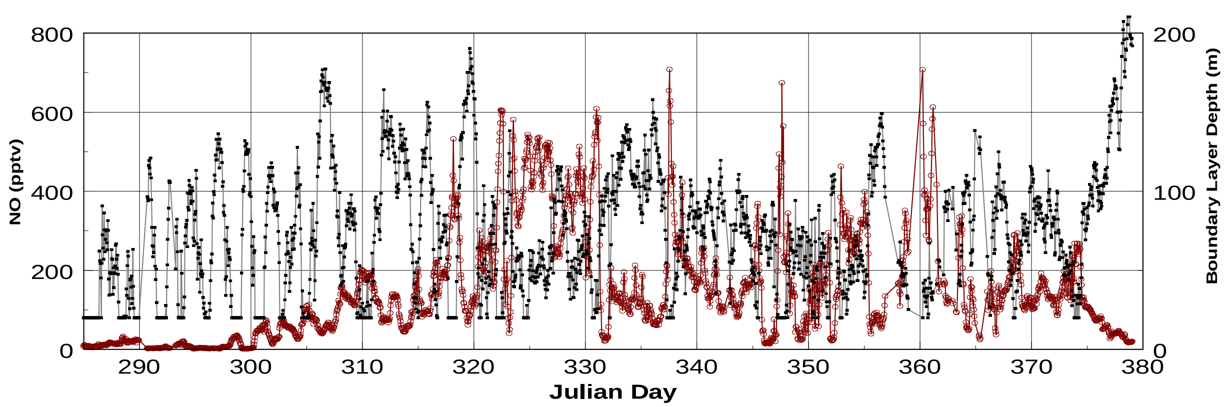

Figure 7. Time series from 2006-2007 of observed NO and predicted BL depth. Note the anti-correlation between BL depth and NO concentrations.

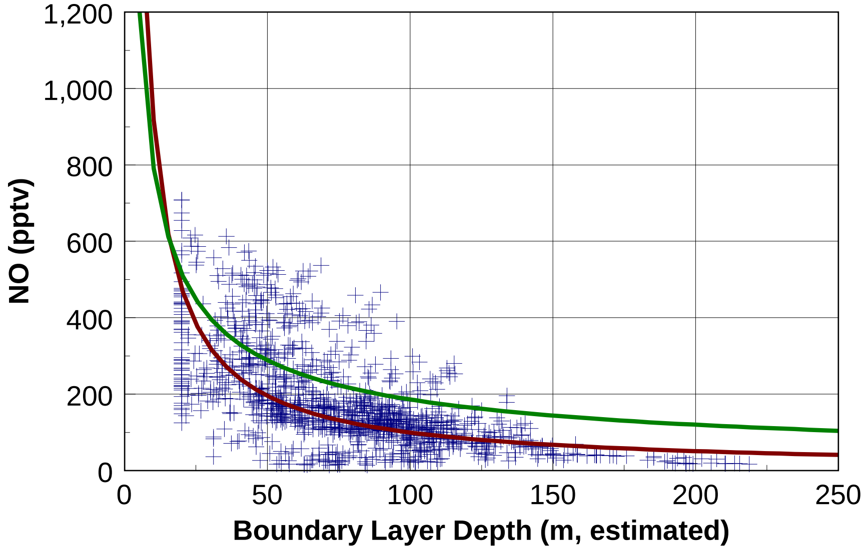

Figure 8. Power law fit to 2006 data (Red line, blue markers) compared with results from 2003 (Red line).

References

Davis, D., and Coauthors, 2004: South Pole NOx chemistry: an assessment of factors controlling variability and absolute levels. *Atmospheric Environment*, **38,** 5375-5388.

Eisele, F., and Coauthors, 2008: Antarctic Tropospheric Chemistry Investigation (ANTCI) 2003 overview. *Atmospheric Environment*, **42,** 2749-2761.

Neff, W., D. Helmig, A. Grachev, and D. Davis, 2008: A study of boundary layer behavior associated with high NO concentrations at the South Pole using a minisodar, tethered balloons and sonic anemometer. *Atmospheric Environment*, **42,** 2762-2779.

Oncley, S. P., M. Buhr, D. H. Lenschow, D. Davis, and S. R. Semmer, 2004: Observations of summertime NO fluxes and boundary-layer height at the South Pole during ISCAT 2000 using scalar similarity. *Atmospheric Environment*, **38,** 5389-5398.

Wang, Y. H., Y. Choi, T. Zeng, D. Davis, M. Buhr, L. G. Huey, and W. Neff, 2007: Assessing the photochemical impact of snow NOx emissions over Antarctica during ANTCI 2003. *Atmospheric Environment*, **41,** 3944-3958.