Estimating climatological planetary boundary layer heights from radiosonde observations: Comparison of methods and uncertainty analysis

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[1] Planetary boundary layer (PBL) processes control energy, water, and pollutant exchanges between the surface and free atmosphere. However, there is no observation-based global PBL climatology for evaluation of climate, weather, and air quality models or for characterizing PBL variability on large space and time scales. As groundwork for such a climatology, we compute PBL height by seven methods, using temperature, potential temperature, virtual potential temperature, relative humidity, specific humidity, and refractivity profiles from a 10 year, 505-station radiosonde data set. Six methods are directly compared; they generally yield PBL height estimates that differ by several hundred meters. Relative humidity and potential temperature gradient methods consistently give higher PBL heights, whereas the parcel (or mixing height) method yields significantly lower heights that show larger and more consistent diurnal and seasonal variations (with lower nighttime and wintertime PBLs). Seasonal and diurnal patterns are sometimes associated with local climatological phenomena, such as nighttime radiation inversions, the trade inversion, and tropical convection and associated cloudiness. Surface-based temperature inversions are a distinct type of PBL that is more common at night and in the morning than during midday and afternoon, in polar regions than in the tropics, and in winter than other seasons. PBL height estimates are sensitive to the vertical resolution of radiosonde data; standard sounding data yield higher PBL heights than high-resolution data. Several sources of both parametric and structural uncertainty in climatological PBL height values are estimated statistically; each can introduce uncertainties of a few 100 m.

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1. Introduction

[2] The planetary boundary layer (PBL), the lowest portion of atmosphere, is of prime importance to climate, weather, and air quality. Processes within the PBL control exchanges of momentum, water, and trace substances between the Earth's surface and the free troposphere, and these processes are represented, often in parameterized form, in atmospheric models. The structure of the PBL can be complex and variable [*Stull*, 1988; *Oke*, 1988; *Sorbjan*, 1989; *Garratt*, 1992], and the height (or depth) of the PBL is commonly used to characterize the vertical extent of mixing within the boundary layer and the level at which exchange with the free troposphere occurs [*Bhumralkar*, 1976; *Seibert et al.*, 2000; *Medeiros et al.*, 2005].

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[3] Traditionally, studies of the PBL have been highly localized and of relatively short duration. Although climatological analyses of PBL height have been undertaken for some areas (e.g., for the United States by *Holzworth* [1964, 1967]), a global climatology of PBL height has not been compiled. In this study we explore some issues pertinent to the development of such a climatology, which would have applications in (1) evaluation of the representation of the PBL in climate and air quality models; (2) interpreting PBL heights obtained in nontraditional ways, such as from ground-based and space-based lidar measurements of aerosols, from boundary-layer profiler observations, from cloud base estimates from ceilometers, and from Global Navigational Satellite System (GNSS) radio occultation measurements; and (3) understanding the variability and long-term changes in PBL structure and related features, such as precipitable water, cloudiness, temperature and humidity profiles, and atmospheric stability.

[4] A global PBL height climatology will, perforce, be based on automated algorithms applied to a very large data set. Such an approach is distinctly different from the careful and detailed examination of atmospheric profile data that

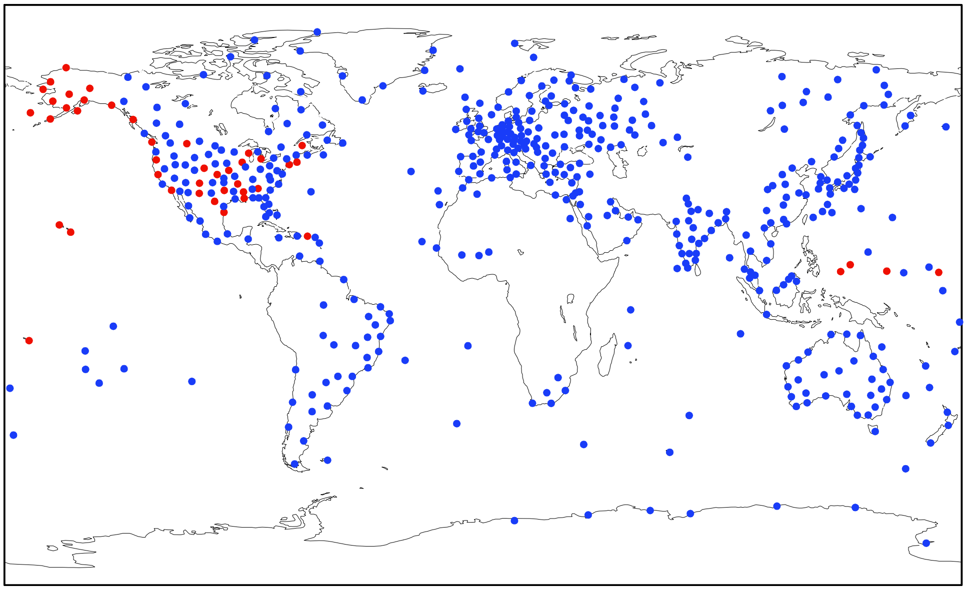

Figure 1. Map of 505 radiosonde stations used in this study. The 44 U.S.-operated stations shown in red have high-vertical-resolution observations and were used to analyze the effect of vertical resolution on estimated PBL height.

can be made for local, micrometeorological PBL studies of short duration. The latter approach allows the investigator to identify different types of boundary layers and complex features, such as surface layers (also called inner layers or inertial sublayers), residual layers, and entrainment zones [e.g., *Stull*, 1988; *Garratt*, 1992]. The main goals of this investigation are to evaluate automated algorithms by applying several different PBL height definitions to a relatively large radiosonde data set, to compare the results, to quantify the uncertainty of climatological PBL height estimates, and to use these findings to suggest optimal methods for developing useful global climatologies of PBL height. Section 2 describes the radiosonde data, the PBL height definitions, and the statistical tests used in the comparison. Section 3 presents results in an objective fashion and compares them with previous studies. Section 4 discusses the results in the context of the overall goal of developing global climatologies, and section 5 presents the summary.

2. Data and Methods

[5] This paper applies seven methods for estimating PBL height to radiosonde data and compares the results using statistical tests, as described in this section.

2.1. Radiosonde Observations

[6] Daily observations from the global, land-based radiosonde station network for the 10 year period 1999–2008 were obtained from the Integrated Global Radiosonde Archive (IGRA) [*Durre et al.*, 2006] (available at www.ncdc.noaa.gov). We used a special version of IGRA with enhanced information for studies of vertical structure [*Durre and Yin*, 2008] that includes the observed temperature, geopotential height, and humidity data at pressure levels, as well as additional derived moisture variables and calculated vertical gradients of several variables.

[7] Beginning with the full network of more than 1100 stations, we restricted our analysis to 505 stations, shown in Figure 1, that met the following criteria:

[8] 1. Soundings were accepted only if there were at least 10 upper air data levels at or below 500 hPa.

[9] 2. At least 50% of the expected number of such soundings were available for a given observation time and for all four seasons (except in polar regions, where only one season was required).

[10] On average, about 3030 soundings (83% of an expected 3653) were available for each station and time of observation selected for inclusion, and a total of more than 2.2 million soundings were analyzed.

[11] Most of the results presented here are based on radiosonde data from the IGRA, which include data at the surface, at standard (or mandatory) pressure levels (1000, 925, 850, 700, 500 hPa, etc.), and at so-called significant levels at which the sounding deviates from linearity (in logarithm of pressure) between two standard levels. In section 3.4, we examine the effect of vertical resolution on PBL height estimates, using high-resolution sounding data for 1999–2007 (2008 was not available) from 44 U.S.-operated stations (available from the Stratospheric Processes and their Role in Climate data center, www.sparc.sunysb.edu) [*Wang and Geller*, 2003].

2.2. Planetary Boundary Layer Height Estimates

[12] Seven different methods were used to estimate PBL height in each sounding, as summarized in Table 1. Four methods are traditional approaches often encountered in the PBL literature. They include

[13] 1. The "parcel method" [*Holzworth*, 1964; *Seibert et al.*, 2000], in which a mixing height is evaluated by comparing the surface value of virtual potential temperature (Θ_v) to values aloft and identifying the height at which Θ_v is the same as the surface value, and a hypothetical parcel of air, lifted from the surface, would be in equilibrium with its

Table 1. Methods for Estimating PBL Height and Percentage of Cases With Significant Seasonal Changes and Significant Diurnal Differences in Climatological Mean PBL Height[a]

Abbreviation	Method	Significant Seasonal Changes (%)	Winter PBL Lowest (%)	Significant Diurnal Differences (%)	Nighttime PBL Lowest (%)
Parcel	Mixing height based on hypothetical vertical displacement of a parcel of air from the surface and identification of the height at which virtual potential temperature (Θ_v) is equal to the surface value.	83	50	87	76
Θ	Location of the maximum vertical gradient of potential temperature (Θ)	92	51	72	42
q	Location of the minimum vertical gradient of specific humidity (q)	87	49	67	23
RH	Location of the minimum vertical gradient of relative humidity (RH)	88	60	62	28
N	Location of the minimum vertical gradient of refractivity (N)	87	55	67	31
Elevated inversion	Height of the base of an elevated temperature inversion	94	50	72	43
Surface-based inversion or SBI	Height of the top of a surface-based temperature inversion	n/a	n/a	n/a	n/a

[a]Only stations poleward of 30° latitude are included in the seasonal difference statistics, and only stations with nighttime data are included in the diurnal difference statistics. Also shown are the percentages of those cases with significant seasonal and diurnal signals for which the lowest median PBL heights are found in winter and at nighttime, respectively. Percentages are not shown for surface-based inversions because the substantial seasonal and diurnal variation in their frequency of occurrence makes comparison of their mean heights problematic.

environment. The resulting PBL height is often called the "mixing height" and is commonly used in air pollution and dispersion studies to estimate the dilution of a pollutant released within the boundary layer. We evaluate the mixing height at the time of the sounding and make no attempt to estimate the daily maximum value, which is sometimes done using forecasts or observations of surface temperature and humidity for application to air quality forecasts [e.g., *Holzworth*, 1964], or the daily minimum value, which provides a worst-case scenario for estimating surface concentrations of pollutants released into the PBL.

[14] 2. The level of the maximum vertical gradient of potential temperature (Θ) [*Oke*, 1988; *Stull*, 1988; *Sorbjan*, 1989; *Garratt*, 1992], indicative of a transition from a convectively less stable region below to a more stable region above.

[15] 3. The base of an elevated temperature (T) inversion. Not all soundings have elevated inversions, but when present, the base serves as a cap to mixing below and so can be considered the PBL height.

[16] 4. The top of a surface-based inversion (SBI) [*Bradley et al.*, 1993]. While the three methods above allow for the possibility of an unstable or neutral PBL, a surface-based T inversion is a clear indicator of a stable boundary layer, whose top can define a PBL height. If an SBI is found in a sounding, the other six methods are not evaluated, as they assume a different PBL structure.

[17] Three additional methods have recently been proposed for identifying PBL height using GNSS radio occultation (RO) data, which can be used to derive vertical profiles of atmospheric refractivity, temperature, and specific humidity [*Kursinski et al.*, 1997]. These methods assume the PBL is a moister, denser, more refractive region than the overlying troposphere, and the PBL height is estimated as

[18] 1. The level of the minimum vertical gradient of specific humidity (q) [*Ao et al.*, 2008].

[19] 2. The level of the minimum vertical gradient of relative humidity (RH).

[20] 3. The level of the minimum vertical gradient of refractivity (N) [*Sokolovskiy et al.*, 2006; *Basha and Ratnam*, 2009].

[21] For the last of these, a refractivity profile is computed from the temperature, pressure, and vapor pressure data [*Smith and Weintraub*, 1953]. Thus, we simulate GNSS RO profiles with radiosonde data. (In a companion study, we will directly compare PBL heights derived from GNSS RO data and from radiosonde data, using identical algorithms.)

[22] The reported surface level was not used in these calculations; instead, we use the first reported upper air level as a near-surface observation. This was to avoid spurious estimates of large vertical gradients resulting from horizontal (or vertical) separation of the surface instrument shelter from the radiosonde launch site. In section 3.5 we quantify the effect of this decision by comparing climatological PBL height estimates obtained with and without the surface level for a sample of stations.

[23] For all methods, to avoid mistaking free tropospheric features for the top of the PBL, if the PBL height was not found in the lowest 4000 m, then it was considered missing. Thus, cases of deep convection, which may reach or even penetrate the tropopause, were not captured. To facilitate comparison of climatological PBL heights from stations at different elevations, all PBL heights are given in meters above ground level (not above mean sea level).

[24] We also attempted to evaluate PBL height using the Richardson number (the dimensionless ratio of suppression of turbulence by buoyancy to production of turbulence by wind shear). Although this method is frequently applied to model simulations, data limitations make it more difficult to apply to observations. The lack of wind data at the same levels as the temperature and humidity data and the lack of information with which to parameterize local surface roughness led to erratic and unreliable results, not included

here. Other methods for estimating PBL height exist (see *Seibert et al.* [2000] for a comprehensive review), but they also involve information not available from radiosondes, such as cloud base height, micrometeorological covariance statistics, or turbulence flux profiles.

2.3. Statistical Tests and Uncertainty Estimates

[25] One important goal of this study is to quantify the parametric and structural uncertainty of climatological PBL height estimates. Parametric, or value, uncertainty is associated with the necessity of using a finite sample of data to estimate population statistics. (See *Thorne et al.* [2005] for a discussion of uncertainties in climate data sets.) We evaluate an aspect of parametric uncertainty in climatological median PBL height values using interquartile ranges, as described below. Structural uncertainty is associated with the methodology chosen in developing a data set from a set of observations and is often ignored in climatological data set development. Here we evaluate the structural uncertainty in climatological PBL height values associated with the choice of PBL height estimation method and with radiosonde data choices, using several statistical tests.

[26] To evaluate the parametric uncertainty of climatological values for a given method of estimating PBL height, computed PBL heights are binned according to station, 3 month season (summer = December, January, and February in the Southern Hemisphere; June, July, and August in the Northern Hemisphere), and time of day. For each bin, we calculate quartile values of PBL height as well as averages and variances. Binning is a simple way to separate expected atmospheric variability associated with the diurnal and seasonal cycles from sampling uncertainty (although weather-related, within-season variability will remain in the binned data).

[27] The diurnal variability of the PBL can be complex, but discerning this variability with radiosonde data is a challenge, because soundings are generally made only once or twice daily at fixed times (0000 and 1200 UTC). However, they may be at any time of day or night depending on station longitude and time of year. We binned the data into four periods to capture the expected development of the PBL from stable nighttime conditions to convective conditions in afternoon, as follows: night (sunset to sunrise), morning (sunrise to solar noon), midday (noon to 3 h past noon), and afternoon (end of midday to sunset). Local time of day relative to solar noon, sunrise, and sunset was computed for every sounding based on station latitude and longitude. Thus, for the purposes of this paper, we define climatological PBL heights as the mean, or median, seasonal (or annual) value for a given station, portion of the day, and method, based on the 10 year period 1999–2008.

[28] Structural uncertainty in climatological PBL heights based on different methods is evaluated using five statistical tests. We compare mean PBL heights with the Student's t test and PBL height variances with the F test. The Student's t test evaluates the null hypotheses that two samples (in this case, two sets of PBL height estimates based on two different definitions) have consistent (not significantly different) means, based on the two sample means, variances, and sizes. Similarly, the F test uses these same parameters to test the null hypothesis that the sample variances are consistent. In both cases, the P value (ranging from 0 to 1) indicates the probability that differences as large as observed could occur by chance in samples with consistent means or variances, so that a small P value can be interpreted as a statistically significant difference in means (or variances): We take $P \leq 0.05$ to indicate statistically significant differences.

[29] Pearson's linear correlation coefficient and the non-parametric Spearman rank-order correlation coefficient are used to measure the association of PBL heights based on different methods and to test the null hypothesis that two samples are uncorrelated. Both correlations can range from −1 to 1 (−100%–100%), and small P values indicate that the two samples are statistically significantly correlated. We also use the Komolgorov-Smirnov test for differences in cumulative distribution function, a nonparametric test based on rank ordering of the data. The Kolmogorov-Smirnov test evaluates the null hypothesis that two samples are drawn from the same distribution, using the test statistic D, the absolute difference between two cumulative distribution functions. In this case small P values indicate statistically significant differences between the samples.

3. Results

[30] Because surface-based inversions (SBI) represent a separate category of stable PBL for which the other six methods of estimating PBL height are not applicable, this section first presents results related to the frequency and variability of SBI. Next, we examine systematic differences among the remaining six methods and then discuss patterns of seasonal and diurnal variability of PBL height. We then examine the sensitivity of PBL height estimates to the vertical resolution of the soundings and to the choice regarding use (or not) of the surface observations in radiosonde reports. Finally, we compare our findings with previous studies.

3.1. Surface-Based Inversions

[31] Figure 2 shows the frequency of occurrence of SBIs for each station, as a function of station latitude. Nighttime and morning (Figure 2, right) are clearly the times of day at which SBIs are likely to occur, and nighttime SBI frequency ranges from less than 50% at tropical stations up to about 80% in polar regions. Typical frequencies during nighttime and morning are about 40%. During midday and afternoon (i.e., from noontime until sunset, Figure 2, left), SBIs are rarer, with frequencies of less than 15% in the tropics and midlatitudes, with higher values up to 50% in the polar zones.

[32] The median height of the SBI is typically within 200–500 m of the surface, with 25th and 75th percentile values of about 200 and 700 m, respectively (not shown). Thus, the SBI is a shallow layer, whose detection in radiosonde observations often depends on the existence of "significant" level data and which may be difficult to observe using satellite methods that do not penetrate the atmosphere to within a few hundred meters of the surface, such as GNSS RO. (See section 3.4 for more on the issue of vertical resolution.) The tops of SBIs are generally lower than the bases of elevated inversions. The 25th and 75th percentile heights of the bases of elevated inversions are typically about 750 and 2500 m, respectively.

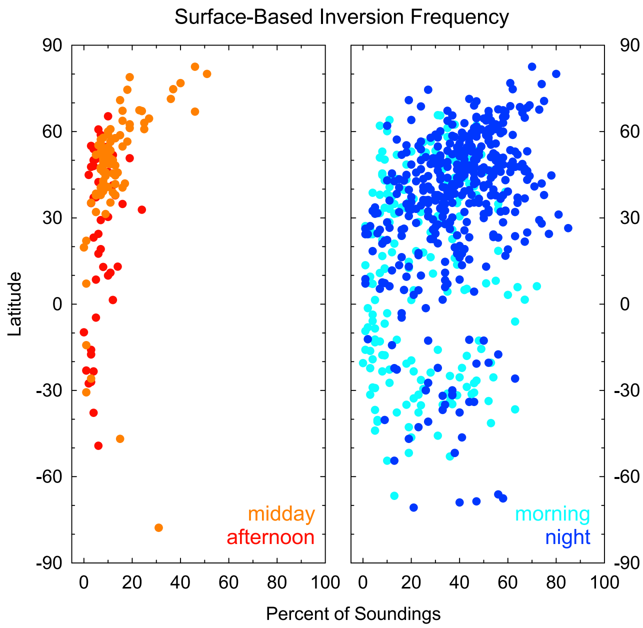

Figure 2. Frequency of occurrence of surface-based inversions (left) during midday and afternoon and (right) during nighttime and morning as a function of station latitude.

[33] The SBI exhibits marked seasonal and diurnal variability. For 53% of the 727 cases (505 stations, some with observations at two different times of day), the highest frequency of SBI occurrences is during winter, more than twice the percentage expected by chance (25%, one season of four). Of the 505 stations in our analysis, 253 had SBI observations available during both nighttime and one other time of day, and 71% of that set exhibit a higher frequency of SBI at night. These results are not surprising, as SBIs tend to form in association with radiative cooling of the surface, and it is encouraging to see this expected pattern borne out in a 10 year radiosonde-based climatology with limited sampling of the diurnal cycle.

3.2. Systematic Differences Among Methods

[34] A fundamental purpose of this analysis is to determine the robustness of estimates of climatological PBL height and their sensitivity to the method chosen. Each of the six remaining methods (excluding SBI) is based on vertical profiles of different variables. Sometimes they yield identical estimates of PBL height, as in the case of the 1100 UTC 17 February 2007 sounding from Lerwick, UK (Figure 3, left). In this case four gradient-based methods indicate identical PBL heights of 2419 m, and an elevated inversion was located just 31 m lower. The parcel method yields a mixing height of 266 m, substantially lower than the other estimates.

[35] In contrast, we estimate five different values of PBL height using the sounding of 2300 UTC 23 December 2006 from the same station (Figure 3, right). They range from 219 m for the parcel method to 2560 m for the specific humidity and relative humidity gradient methods. The high values obtained with the humidity methods in this case highlight a distinctive tendency of those methods in the presence of clouds. Total cloud amount at the time of the sounding was reported as 8 oktas with stratocumulus having base height of 200 m (D. Hollis, UK Met Office, personal communication, 2009). The mixing height of 219 m agrees well with the

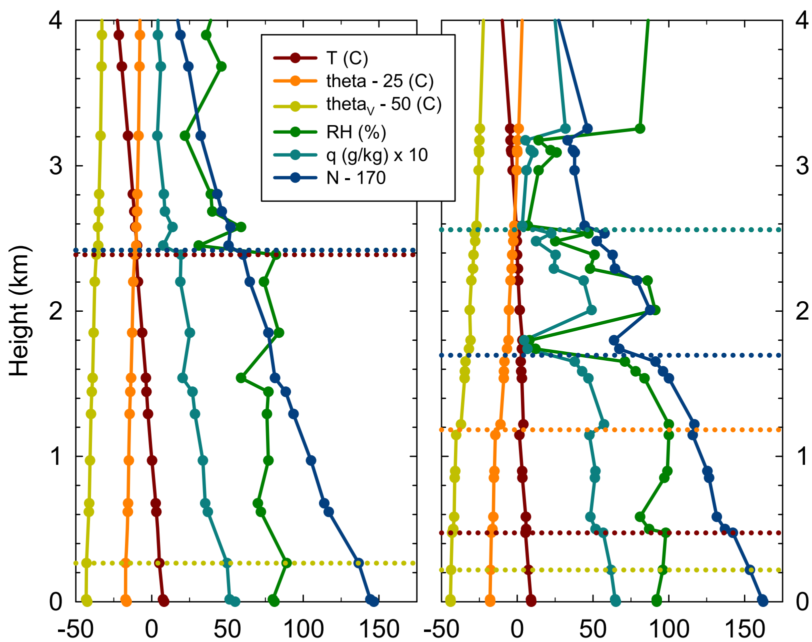

Figure 3. Planetary boundary layer height estimates using six methods for Lerwick, United Kingdom, for (left) 1100 UTC 17 February 2007 and (right) 2300 UTC 23 December 2006. Profiles include temperature, potential temperature (Θ), virtual potential temperature (Θ_v), relative humidity, specific humidity, and refractivity (N), some shifted for clarity. Estimated PBL heights are shown by dashed horizontal lines. These soundings do not indicate the presence of surface-based inversions.

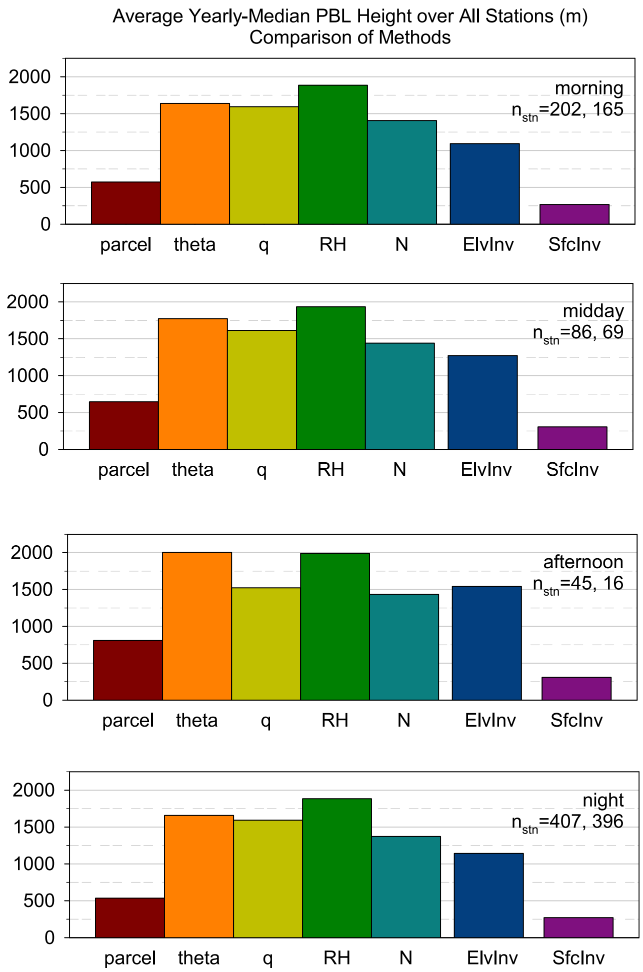

Figure 4. Average values (over all stations) of yearly median planetary boundary layer heights estimated using seven different methods. (top to bottom) Results for morning, midday, afternoon, and nighttime (see text for details). The number of stations used to compute each average (n_{stn}) is shown; the first value applies to six methods and the second applies to surface-based inversions.

depth of the layer below the cloud base, and the much higher PBL heights from the humidity methods might coincide with the top of the cloud deck. In contrast, the 1100 UTC 17 February 2007 observation indicates cloud cover of 3 oktas, which the sonde might well have missed during its ascent, so there is good agreement among the estimates from different methods.

[36] As an aside, we note that radiosonde humidity sensor uncertainties may introduce systematic errors in PBL height estimates in presence of cloud. If the humidity sensor properly registers high humidity within the cloud and lower values above, both humidity methods will likely identify the cloud top as the PBL height. However, if there is a lag in the humidity observations, a higher PBL height will be found. In either case, the resulting height is likely to be above the heights based on temperature or potential temperature, which may show sharper gradients at lower altitude, possibly at cloud base. Quantification of this source of uncertainty in PBL height estimates is beyond the scope of this study.

[37] Figure 4 shows a gross comparison of PBL height estimates from all seven methods. The data are separated by local time of day (as described in section 2.3), and each bar represents the average over all stations of the annual climatological PBL height (the median over all observations during 1999–2008). Note that the SBI heights are based on a different set of soundings than all the other heights, and because some stations do not exhibit SBIs, data from fewer stations were used to compute SBI height average. Furthermore, elevated inversion base heights were not always present; on average, 13% of soundings had neither an elevated nor a surface-based inversion. The parcel method could not be applied in about 0.1% of soundings in which the sounding had no value of Θ_v matching the near-surface value. Thus, the sample sizes for those two methods are somewhat smaller than for the other four, which are based on identical samples.

[38] Typical average values of PBL height are between 200 and 2000 m, with SBI showing lowest values, as expected. Among the other methods, PBL heights based on the RH gradient are consistently high, and those based on the parcel method are consistently low, differing by about a factor of 3 or 4, or more than 1 km. Disaggregated median values reveal patterns consistent with the averages shown in Figure 4. Comparing climatological seasonal means for individual stations and for specific parts of the day (2925 cases in all), and not including the SBI heights, we find statistically significant differences between methods yielding the lowest and highest values of PBL height in 99.8% of the cases. Heights based on the parcel method were overwhelmingly (96% of cases) the lowest, and heights based on RH and Θ gradients were the highest (72% and 22% of cases, respectively).

[39] The possible effect of cloud cover, as illustrated in the examples from Lerwick (Figure 3), may explain the high values obtained from RH profiles, which are sensitive to cloud top heights. The low values associated with the parcel method can be understood both in terms of the computational algorithm and the underlying physical processes. The parcel method algorithm seeks the first level at which Θ_v matches the near-surface value, whereas the other methods search the entire sounding for extrema in gradients, and the former is more likely to be found at lower altitude than the latter [see, e.g., *Stull*, 1988, Figure 1.12]. Moreover, the effective depth of atmospheric mixing within the boundary layer, which depends on the buoyancy of parcels displaced from the surface, might well be below the level at which the profile shows steepest gradients (for example, due to mid- or high-level clouds), irrespective of surface conditions.

[40] The impact of the near-surface Θ_v on PBL heights from the parcel method is also a plausible explanation for the stronger diurnal variation in those heights than from other methods. (Note, however, that the four ensembles in Figure 4 are not based on the same stations, so they should not be construed as a true representation of local diurnal variation.) If PBL Θ_v profiles vary less than near-surface values and if near-surface values diminish at night, the mixing height estimate will perforce be lower at night, as seen in Figure 4, where average values increase from nighttime to morning to midday to afternoon, when they are highest. The average decrease in parcel method PBL height from afternoon maximum to nighttime minimum is about

Table 2. Results of Five Statistical Tests Comparing Six Methods for Estimating PBL Height[a]

(a) Difference in means (m)

	Parcel	Θ	*q*	RH	*N*	Elevated Inversion
Parcel	-	1197	1104	1354	952	751
Θ	100	-	−92	156	−244	−440
q	100	76	-	249	−152	−343
RH	100	80	96	-	−401	−594
N	100	87	88	99	-	−191
Elevated inversion	100	99	93	98	88	-

(b) Ratio of variances

	Parcel	Θ	*q*	RH	*N*	Elevated Inversion
Parcel	-	10.9	11.0	11.5	10.3	8.8
Θ	100	-	1.1	1.1	1.1	1.3
q	100	49	-	1.1	1.1	1.4
RH	100	40	43	-	1.2	1.4
N	100	45	32	66	-	1.3
Elevated inversion	100	76	78	81	71	-

(c) Pearson linear correlation coefficient (%)

	Parcel	Θ	*q*	RH	*N*	Elevated Inversion
Parcel	-	18	10	12	14	1
Θ	100	-	37	49	41	4
q	99	100	-	67	60	0
RH	100	100	100	-	52	0
N	100	100	100	100	-	0
Elevated inversion	96	97	96	96	96	-

(d) Spearman correlation coefficient (%)

	Parcel	Θ	*q*	RH	*N*	Elevated Inversion
Parcel	-	19	12	12	17	2
Θ	99	-	37	50	42	1
q	99	100	-	66	60	0
RH	100	100	100	-	51	1
N	99	100	100	100	-	1
Elevated inversion	97	96	97	96	96	-

(e) Kolmogorov-Smirnov *D* statistic

	Parcel	Θ	*q*	RH	*N*	Elevated Inversion
Parcel	-	0.64	0.61	0.63	0.56	0.48
Θ	100	-	0.11	0.9	0.12	0.21
q	100	88	-	0.10	0.80	0.21
RH	100	84	83	-	0.17	0.27
N	100	92	87	99	-	0.16
Elevated inversion	100	100	98	100	96	-

[a]Each section of the table shows average values of the relevant test statistic in the upper right corner, and the percentages of cases for which the test yielded statistically significant results ($P = 0.05$) in the lower left corner. Each table entry represents 740 comparison cases, with one case being all the PBL height values for 1999–2008 from a single station and part of the day. The statistics are the (a) difference in mean PBL height evaluated with Student's *t* test, (b) ratio of PBL height variances evaluated with the *F* test, (c) Pearson linear correlation coefficient, (d) Spearman rank-order correlation coefficient, and (e) *D* statistic from the Kolmogorov-Smirnov test of differences in distribution functions of PBL heights (representing the maximum value of the absolute difference between two cumulative probability distribution functions). Note that high percentages of statistically significant results (values near 100% in the lower left corners) indicate statistically significant differences in most of the test cases for the Student's *t* test, the *F* test, and the Kolmogorov-Smirnov test, whereas they indicate significant correlations in most cases for the two correlation tests.

170 m. The other methods do not show such pronounced differences.

[41] Are these differences among methods statistically significant? Table 2 shows results from each of the five statistical tests used to compare methods. For each part of the table, the percentage of cases for which the statistical test yielded a statistically significant result ($P \leq 0.05$) is shown in the lower left corner, and the mean value of the test statistic is shown in the upper right corner. The SBI results are not compared because of the different population of soundings used.

[42] Overall, we find statistically significant correlations among the methods in practically all comparisons (Table 2, c and d), with similar results for the Pearson and Spearman correlations. However, the correlation coefficients are low. Mean values (shown in the table) are ~0.5 for comparisons of the RH, Θ, *N*, and *q* methods; ~0.15 for comparisons between those four methods and the parcel method; and ~0 for comparisons involving elevated *T* inversions. In the latter case, mean correlation values close to zero, with an overwhelming majority of statistically significant values, are the consequence of averaging positive and negative significant correlations.

[43] The high percentages of statistically significant *t*, *F*, and Kolmogorov-Smirnov test results (Table 2, a, b, and e) reinforces the notion of significant differences among methods. The large *t* and *F* test values for comparisons involving the parcel method are consistent with the much lower PBL heights obtained with that method and the consequently lower means and variances. The high fraction of statistically significant test results is due to the large sample sizes used: The 10 year climatological values are based on average sample sizes of 3030 soundings (section 2.1).

[44] The entries in Table 2 can be used to estimate the structural uncertainty in climatological PBL heights associated with choice of method. The average differences in mean PBL height are several hundred meters for most of the methods compared and close to 1 km for comparisons involving the parcel method. Thus, climatological averages can have a structural uncertainty (Table 2) that is of order 10%–100% of climatological mean values (e.g., Figure 4).

3.3. Seasonal and Diurnal Patterns

[45] Seasonal variations in PBL height should be easy to detect in radiosonde data because of excellent daily sampling throughout the year. Table 1 shows the percentage of cases (a case being a station and a time of day) in which there are statistically significant differences in seasonal mean PBL heights (based on *t* tests), considering only stations outside the tropical belt (i.e., poleward of 30° latitude). All of the methods are very sensitive to the seasonal cycle, with 83%–92% of cases showing a significant variation. However, the nature of the seasonal variation is not consistent, either from station to station or from method to method. The fraction of cases with significant seasonal changes that also have lowest seasonal median PBL heights in winter is about 50%. (We have already seen, in section 3.1, that SBI frequencies are also greatest in winter.)

[46] While spatial differences in seasonal PBL height changes can be explained (and will be illustrated below), that different methods sometimes show different seasonal variations for a given station and time of day suggests again

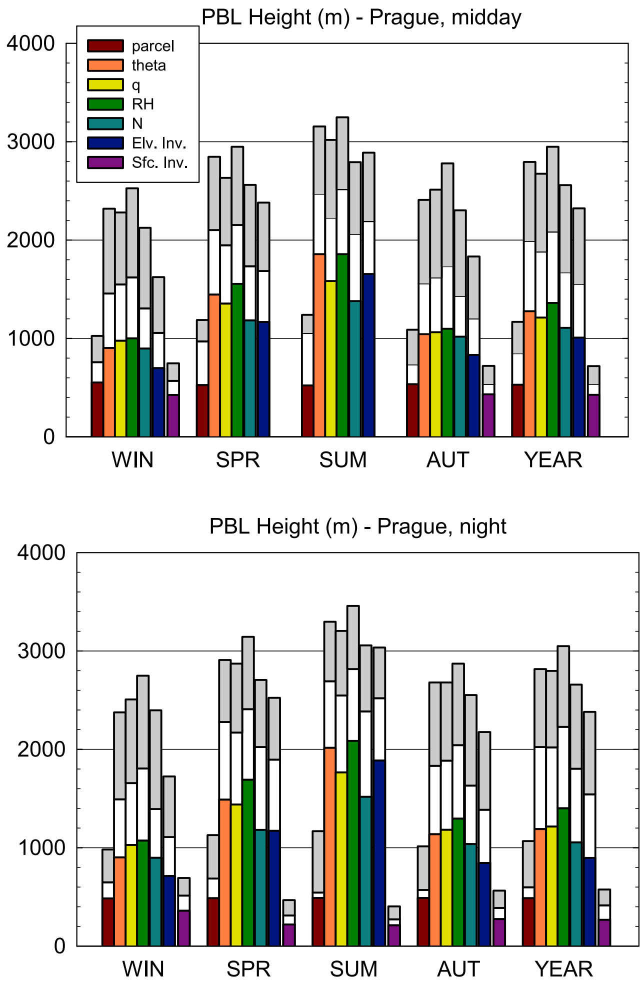

Figure 5. Seasonal and annual quartile values of planetary boundary layer height (m above ground level) at Prague, Czech Republic (50°N, 14°E), based on data for 1999–2008. For each method, the 25th, 50th, and 75th percentile values are shown (in colored, white, and gray bars, respectively), for (top) midday and (bottom) nighttime. Heights based on surface-based inversions are from a different set of soundings than heights based on the other methods. They are not shown for daytime for some seasons at Prague because they occur rarely (1% of soundings).

that they cannot be viewed as surrogates for one another. Seasonal variations, when significant, tend to be several hundred meters, with a median value of 440 m and interquartile range of 210–750 m. This is comparable to the magnitude of the structural uncertainty in mean PBL height estimates discussed above, which complicates efforts to distinguish true seasonal variations from effects associated with choice of PBL height method.

[47] Radiosonde data are not well suited to analysis of diurnal variations because observations are made only 1 or 2 (or at a few stations four) times daily. However, we have attempted an analysis of day/night differences for those 275 of the 505 stations at which the comparison is possible. Table 1 indicates the percentage of cases with significant differences in PBL height between nighttime and one of the three other parts of the diurnal cycle (see section 2.3 on partitioning of the day), with most cases showing a significant difference. The parcel method shows a significant difference for 87% of the stations, and the overwhelming tendency (76% of the significant cases) is for lower PBL heights at nighttime. The other six methods show somewhat smaller percentages of stations (62%–72% of cases) with significant differences and a much weaker tendency for lower nighttime PBL heights. Considering all methods, median day/night differences are about 210 m, with an interquartile range of 100–420 m. Although slightly smaller than typical seasonal variations, these diurnal changes are also comparable in magnitude to the structural uncertainty of PBL height estimates. Recall that SBI frequency of occurrence is much greater at night (Figure 2).

[48] Examples of the seasonal and diurnal variations in PBL height at four sample stations are shown in Figures 5, 6, 7, and 8, which also illustrate differences among the seven methods. The observations at Prague, Czech Republic (Figure 5), show the presence of SBIs in 24% of soundings at night (Figure 5, bottom) but only in 12% of midday soundings (Figure 5, top). The top of the SBI is low (median height 539 m in the afternoon and 413 m at night) and varies relatively little (interquartile ranges are 292 and 308 m, respectively). When SBIs are not found, the PBL height

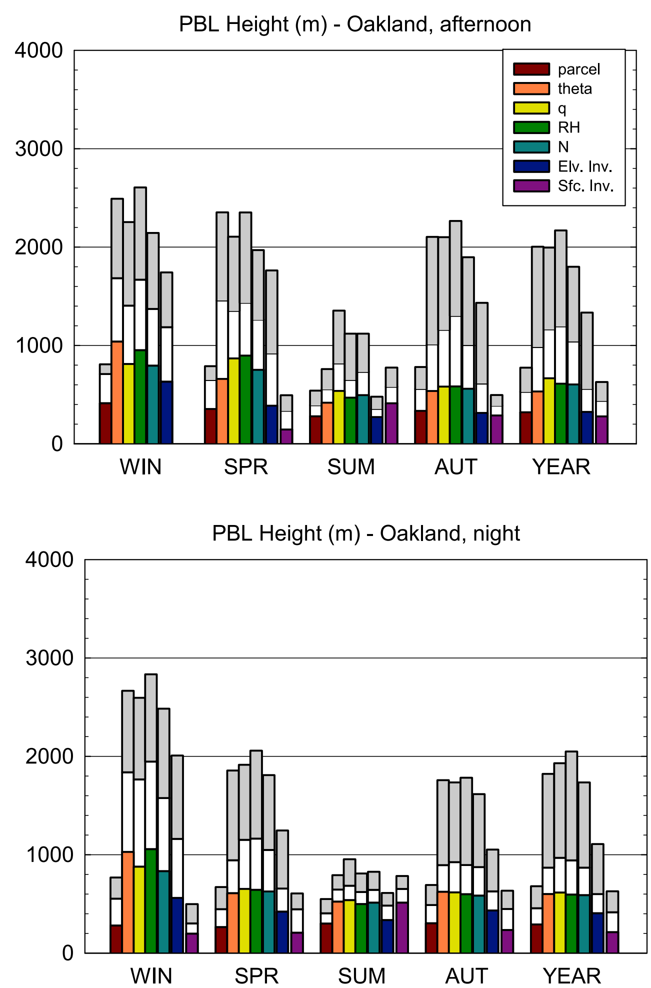

Figure 6. Same as Figure 5 but for Oakland, California (38°N, 122°W), for afternoon and nighttime.

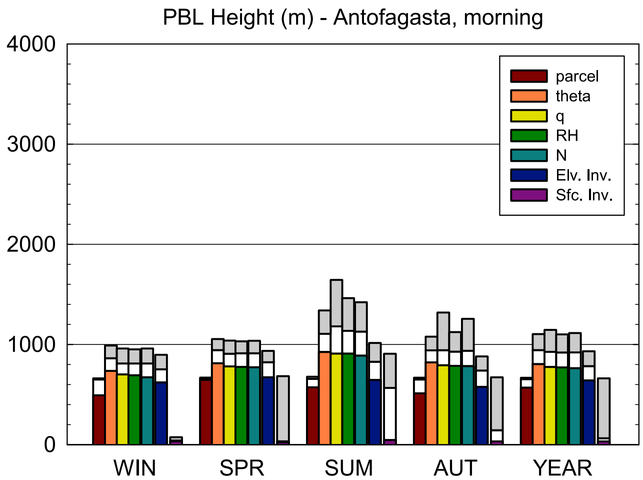

Figure 7. Same as Figure 5 but for Antofagasta, Chile (22°S, 137°W), for morning only.

estimates are generally much higher, with median heights for all but the parcel method of about 1500–2200 m, and much more variable. They show seasonal variation, with statistically significantly higher values in summer and lower values in winter for all methods except the parcel and SBI. The most salient diurnal patterns are the much lower mixing heights (from the parcel method) at night than at midday (with median heights of 597 and 851 m, respectively). Other methods show the opposite diurnal pattern (higher PBL at night) but not consistently for all methods or seasons. This different behavior of day/night patterns is a clear indication that the gradient methods are not sensitive to the same diurnal variations as the parcel method and therefore are indicators of different PBL processes.

[49] Much lower PBL heights and a much different seasonal cycle are seen at Oakland, California (Figure 6), where median PBL heights are over 1000 m in winter and about 500 m in summer, when subsidence inversions associated with the Pacific high-pressure system dominate the region. All six non-SBI methods show lowest heights in summer, highest in winter, and statistically significant differences between them. As at Prague, SBIs are rarer in the daytime (afternoon in this case) than at night (13% versus 30% frequency of occurrence).

[50] Morning PBL heights at Antofagasta, Chile (where nighttime data are not available), are about 900 m, are generally higher in summer than winter, and show little variability within a given season (Figure 7). The area is influenced by the trade inversion [*Hastenrath*, 1991], which appears to cause a well-defined PBL. About 21% of soundings show SBIs. The q, RH, and N methods give PBL height distribution and mean values that are in better agreement than at other stations, probably because of the dominating effect of the trade inversion on the vertical profile of these moisture/density parameters. The parcel method gives lower values and a distribution that is significantly different from these others.

[51] As a final example, Majuro Atoll in the Marshall Islands (Figure 8) shows the high (typically above 2000 m) PBL heights and flat seasonal structure expected in the deep tropics. Both midday and at night, SBIs were found in only 1% of cases. Parcel method mixing heights are much lower than the PBL heights estimated using the other methods (about 800 versus 2000 m, respectively), both midday and nighttime. While parcel method heights are significantly lower at night than midday for all seasons, the opposite pattern prevails for the q, RH, and N methods, although less consistently from season to season.

[52] As these examples demonstrate, there is considerable diversity among stations in seasonal and diurnal patterns of PBL height variations. These can sometimes be explained in terms of prevailing climatic conditions associated with the global general circulation of the atmosphere. Nevertheless, the main systematic features discussed in the preceding section are fairly robust.

3.4. Sensitivity to Vertical Resolution of Sounding Data

[53] The analysis presented above is based on standard-resolution radiosonde data, as transmitted from stations for use in numerical weather prediction, which may include as few as three or four mandatory data points within the PBL (surface and 1000, 925, 850, 700, 500 hPa). Additional significant level reports should be included if the structure of the atmosphere is such that interpolation between the

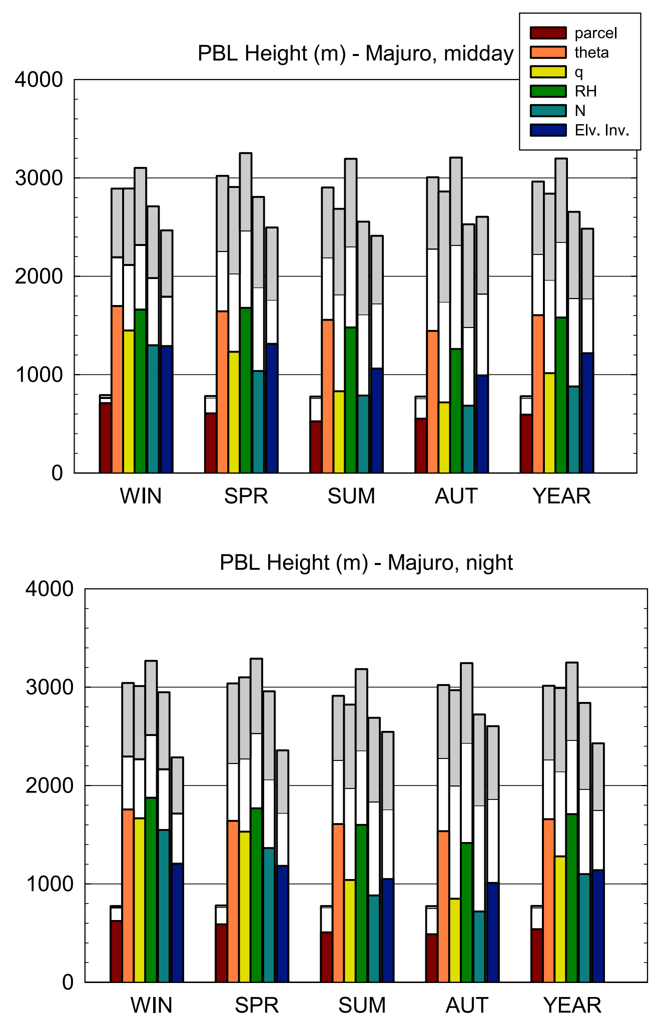

Figure 8. Same as Figure 5 but for Majuro Atoll, Marshall Islands (7°N, 171°E), at midday and nighttime.

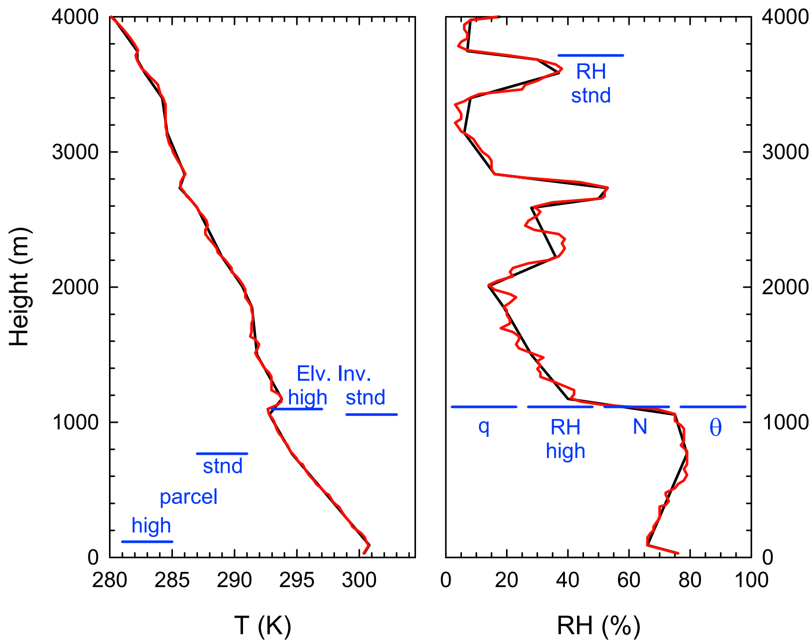

Figure 9. Effect of sounding vertical resolution on estimated PBL heights (m) at Koror Island, Republic of Palau (7°N, 134°E), for the 1200 UTC sounding of 21 February 2007. Standard-resolution and high-resolution (black and red curves, respectively) (left) temperature (K) and (right) relative humidity (%) soundings are shown, along with the PBL heights identified by six methods. For the parcel, elevated inversion, and RH gradient methods, estimated heights differ for the high-resolution and standard-resolution cases. For the q, N, and Θ gradient methods, estimated PBL heights are the same.

mandatory levels would not reproduce the sounding. As mentioned in section 2.1, we required at least 10 data levels at or below 500 hPa for the IGRA data used in this study; the average number (over all soundings during 1999–2008) ranged (over all stations) from 11 to 34 levels, with a network average of 16 levels. In contrast, high-resolution data are reported at regular time intervals during the sounding, and their vertical resolution is about an order of magnitude greater than in the standard-resolution IGRA.

[54] Figure 9 compares the high-resolution and standard-resolution sounding reports for 1200 UTC on 21 February 2007 from Koror, Republic of Palau, to illustrate the potential impact of vertical resolution on estimated PBL height. Between the surface and 4 km, the standard report includes 19 levels, whereas the high-resolution report has 127, with the latter showing more fine structure in the relative humidity profile (Figure 9, right) than the former. The q, N, and Θ gradient methods yield identical PBL heights (1114 m) from both reports. However, the minimum RH gradient occurs at 3715 m in the standard-resolution IGRA sounding and at 1114 m in the high-resolution sounding. The parcel and elevated inversion methods also give different results: 1098 and 116 m, respectively, in the high-resolution data versus 1057 and 767 m, respectively, in the standard-resolution data.

[55] To test the overall sensitivity of climatological PBL height results to the vertical resolution of the sounding, we applied the same methods for estimating PBL height and for computing climatological statistics to paired sounding reports from 44 stations (in the United States and a small number of Caribbean and Pacific islands) for which both standard and high-resolution data were available (Figure 1) for 1999–2007. Figures 10 and 11 illustrate the level of agreement between the standard and high-resolution results for each of the PBL height estimation methods.

[56] Although it may not be visually apparent in the figures, there are statistically significant differences between standard and high-resolution results for most cases. The best agreement is for the RH and Θ methods, for which sounding resolution has no statistically significant effect on mean PBL height at about half the stations tested. For all of the other methods, and at almost all the stations, the choice of sounding resolution results in statistically significant differences in mean values, with differences up to several 100 m. In general, we obtain lower PBL heights from the high-resolution data. This result is expected for the parcel and temperature inversion (both elevated T inversion and SBI) methods, which involve a search for the first instance (working upward from the surface) of Θ_v matching the near surface value, or of a change in the sign of the temperature lapse rate, respectively. These conditions are more likely to be found lower in the atmosphere when more data levels are available, as in the Koror example discussed above (Figure 9). The frequency of finding SBIs is not very sensitive to sounding resolution (Figure 11, middle and bottom). The frequency estimates from both sets of soundings are typically within 5%.

[57] Thus, it appears that, although standard-resolution sounding data contain sufficient information to allow identification of PBL height, the estimated height is sensitive to the number of data levels available. Use of standard-resolution sounding data yields higher PBL heights than

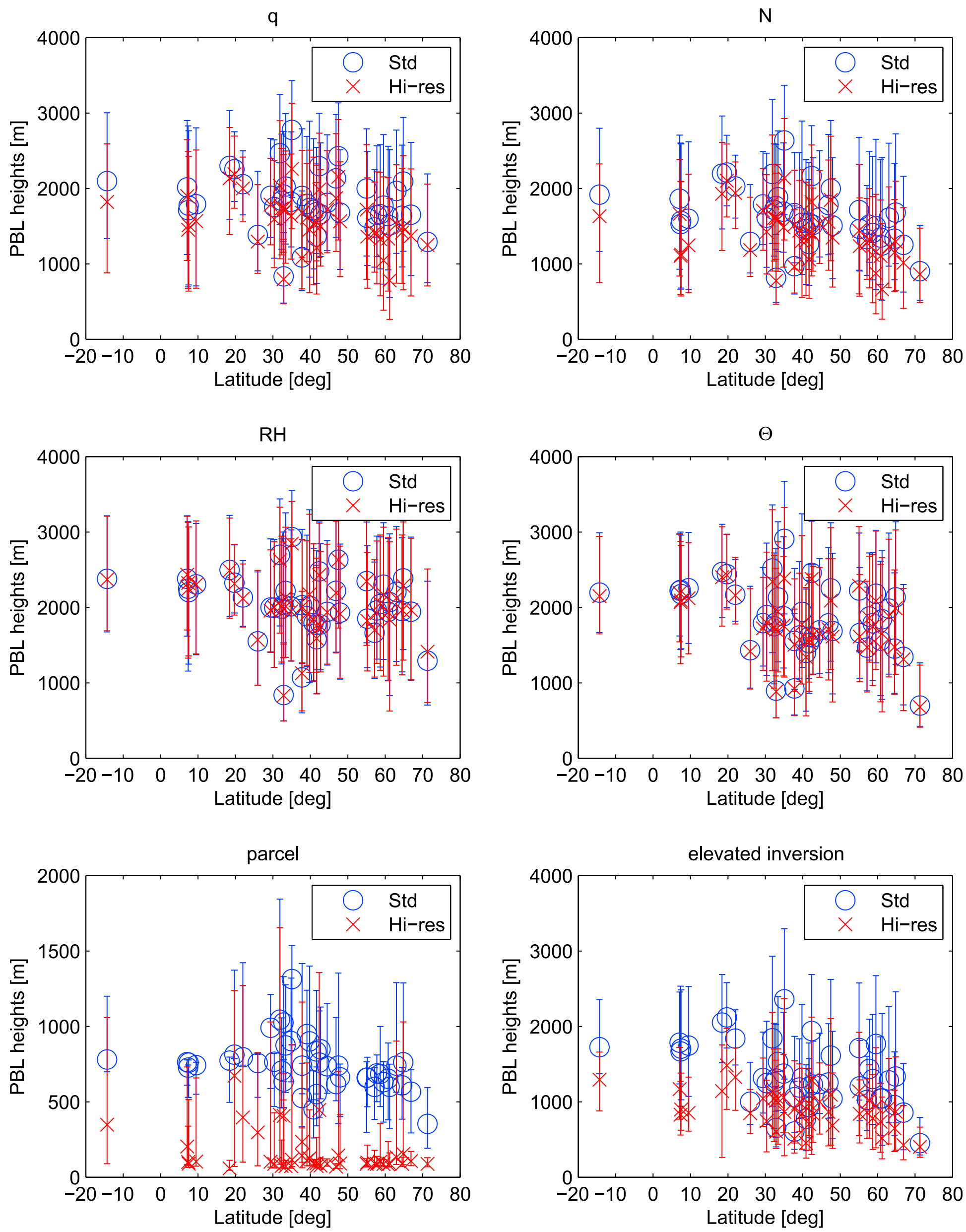

Figure 10. Comparison of 25th, 50th and 75th percentile values of PBL heights (m) from 44 stations based on standard (blue) and high (red) vertical resolution sounding data, as a function of station latitude. Each frame shows results for a different method of estimating PBL height using observations for 1999–2007. Note the different vertical axis scale for the parcel method (lower left frame).

high-resolution data and can introduce structural uncertainties of a few 100 m in climatological means.

3.5. Sensitivity to Surface-Level Observations

[58] A related source of structural uncertainty is our decision to ignore the surface-level data in estimating PBL height, as discussed in section 2.2. Figure 12 compares estimated annual climatological PBL heights from Prague, Czech Republic, both including and excluding the surface observations. (The results excluding the surface are the same as those shown in Figure 5, top, for the year.) While all seven methods are sensitive to the inclusion of surface data (and the *t* test confirms statistically significant differences in 10 year mean values), the most striking differences are for the parcel and surface-based inversion methods, as would be expected, since both of these methods are strongly dependent on the surface (or assumed-surface) data.

[59] Table 3 shows a summary of the results of this comparison applied to the 505-station network. For each method, the median and interquartile range of the difference in climatological PBL height estimated with and without surface-level data measure this source of structural uncertainty. The most striking feature of the results is that the differences are generally positive, i.e., PBL heights obtained without including the surface observation are higher. This is expected for the parcel and SBI methods because they

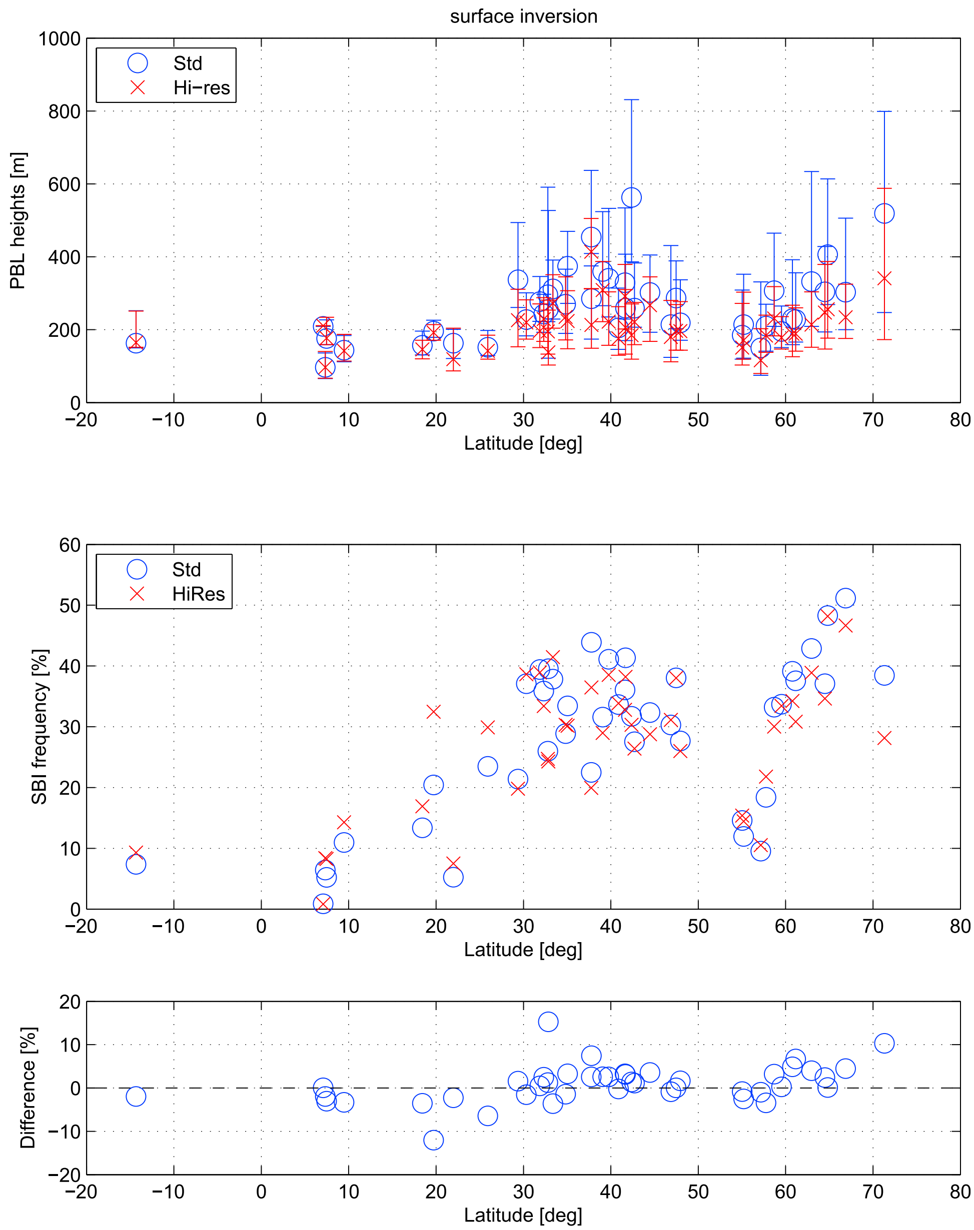

Figure 11. (top) Same as Figure 10, but showing results for the height of the top of surface-based inversions (SBI). (middle) Frequency (%) of SBI occurrence based on standard (blue) and high vertical resolution (red) data. (bottom) Difference (standard minus high resolution) in SBI frequency.

depend directly on the lowest data level. That the gradient methods also yield this result suggests that the strongest gradients are frequently found between the surface and the first level above the surface. This finding could be interpreted as a confirmation of the potential for unrepresentative gradients because of noncollocation of the surface and upper air observations, which was our reason for omitting the surface observations in most of our analyses.

[60] The magnitude of the differences in climatological means is several hundred meters (Table 3), with the humidity and refractivity methods showing the most sensitivity, due to strong near-surface humidity gradients. Expressed as a fraction of climatological mean PBL height, this source of structural uncertainty is typically about 10%–30% for the six non-SBI methods (Table 3). Thus, the effect of surface observations introduces uncertainty that is comparable in magnitude to the effect of vertical resolution of sounding data (section 3.4).

3.6. Comparison With Prior Studies

[61] To our knowledge, there are few prior studies of climatological PBL heights on global or even regional scales. We have attempted to compare our SBI and mixing height (parcel method) results for U.S. stations with those of *Hosler* [1961] and of *Holzworth* [1964, 1967], respectively, who analyzed radiosonde data from continental U.S. stations. However, differences in the location of stations in the radiosonde network, standard observing times, analysis method, period of record, and assumptions, as well as the lack of digital data records from these early studies, posed

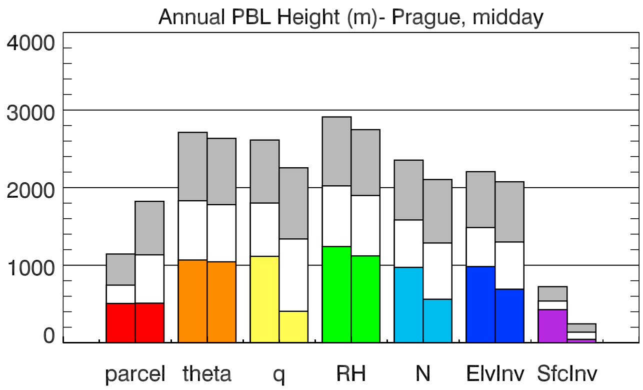

Figure 12. Effect of surface-level observations on climatological annual PBL height estimates at Prague, Czech Republic (50°N, 14°E), based on data for 1999–2008. For each PBL height estimation method, 25th, 50th, and 75th percentile values of PBL height (m) are shown based on calculations excluding (bars on left) and including (bars on right) surface data. The results excluding surface data are as in Figure 5, top.

serious challenges to direct quantitative comparison. Qualitatively, the spatial pattern of low-level inversion frequency obtained by *Hosler* [1961, Figures 1 and 2], showing higher frequencies in the western United States than over much of the eastern United States, agrees with the pattern in SBI frequency from this analysis (not shown).

[62] Mixing depth estimates (mixing height from the parcel method) by Holzworth are also difficult to compare because, rather than use surface values at the same time and place as the upper air observation, he estimated daily maximum surface temperature [*Holzworth*, 1964] and urban temperatures [*Holzworth*, 1967] for comparison with the observed (nonurban) T (not Θ_v) profile. Nevertheless, we compared our mixing height values at three of the seven stations studied by *Holzworth* [1967]. (The other four are no longer in operation.) Nighttime values at Salt Lake City, UT, appear to be in reasonably good agreement; Holzworth obtained monthly mean values ranging from 130 to 400 m, and our seasonal values range from 216 to 284 m. Our nighttime mixing heights from Pittsburgh, PA, and from Nashville, TN, show an annual variation similar to *Holzworth*'s [1967] estimated afternoon values but with heights about 200–700 m lower, which may be due to his use of estimated daily maximum surface T, leading to a deeper mixing layer.

[63] In a study more similar in concept to ours, *Basha and Ratnam* [2009] compared PBL height estimates based on N, Θ, Θ_v, and water vapor mixing ratio (r) using high-resolution radiosonde data from tropical Gadanki, India (13.5°N, 79.2°E), for April 2006 to August 2008. They concluded that "(v)ery good correlations in all weather conditions indicate that N can also be used … for detecting ABL height," (where ABL is atmospheric boundary layer), but note that the result may not be applicable in other climatic regimes. Gadanki data do not appear in the IGRA (probably because it is a research station); the nearest available station for comparison is at Chennai (Madras, India, 13.0°N, 80.2°E), closer to the Bay of Bengal.

[64] On the basis of our 10 year record at Chennai, we can compare PBL heights based on N and Θ, the two methods common to both studies. We obtain statistically significant differences in mean values, with Θ yielding PBL heights 836 m higher in afternoon soundings and 608 m higher in nighttime soundings than N. The F test and Kolmogorov-Smirnov test also showed statistically significant differences, and Pearson and Spearman correlation coefficients, while statistically significant, were ~0.15–0.20. These results suggest that the two methods are not in particularly good agreement at Chennai, and this conclusion does not change when we reduce the period of analysis to 2006–2008 to better correspond with the work of *Basha and Ratnam* [2009].

[65] They also report large (2–3 km) diurnal variations in PBL height in their 4 times daily data set. The Chennai data are only available at approximately 0000 and 1200 UTC, but those times appear to correspond to daily minimum and maximum PBL heights [see *Basha and Ratnam*, 2009, Figure 9]. Our annual median values show significant but much smaller (a few hundred meters) differences, with the most striking difference being the much lower values, particularly for the N gradient method, than obtained by Basha and Ratnam. The explanation for these disparities could be real climatological differences between the two stations (one coastal, one inland), methodological differences in estimating PBL height, or data quality differences between the Gadanki research site and the India Meteorological Department station at Chennai. Whatever is the underlying cause, they lead to very different conclusions about the comparability of different methods for obtaining PBL height.

4. Considerations for Developing Global Climatologies of the PBL

[66] On the basis of our findings in section 3 of significant differences among methods for estimating PBL height, it seems reasonable to consider development of multiple, different global climatologies of the PBL, for different applications. This section discusses three specific issues with particular bearing on that endeavor: the special case of stable boundary layers with SBIs, the distinctive features of the

Table 3. Effect of Surface-Level Observations on Climatological PBL Height Estimates[a]

Method	Height Difference (m)			Fractional Height Difference (%)		
	25th	50th	75th	25th	50th	75th
Parcel	−39	146	322	−2	15	37
Θ	138	266	452	8	21	41
q	267	405	612	28	41	61
RH	233	347	532	13	21	34
N	268	411	666	20	33	54
Elevated inversion	77	128	194	5	9	15
Surface inversion	75	122	210	34	55	96

[a]For each PBL height estimation method, the difference (without-surface minus with-surface) in annual climatological (1999–2008) PBL height (m) was computed for each of 505 stations, for each portion of the day. These are summarized using the medians and interquartile ranges (25th, 50th, and 75th percentile values) of the distributions of PBL height differences and of percentage differences (height difference divided by average of heights estimated with and without surface-level observations).

mixing height, and issues relevant to combining radiosonde data with Global Navigation Satellite System Radio Occultation observations.

4.1. Special Case of Surface-Based Inversions

[67] Although the analysis presented above does not specifically address measures of PBL stability (such as lapse rates), surface-based temperature inversions are a clear indication of a stable layer. The prevalence of SBIs, particularly at night and in the polar regions, and the incompatibility of SBI with the other six methods of determining PBL height explored here, suggest that separate consideration of the climatology of SBIs may be warranted. *Bradley et al.* [1993], focusing on Arctic SBIs, and *Bourne et al.* [2010], focusing on Alaska, outline compelling reasons for in-depth analysis of this type of especially stable PBL in which mixing is confined to a shallow layer and the PBL is effectively decoupled from the free troposphere. The large diurnal signal in SBI occurrence frequency provides a strong rationale for directly addressing diurnal variations in any PBL climatology. One potential area of concern is the dependence of SBI frequency and height both on the surface-level data (section 3.5) and on the vertical resolution of the archived sounding data (section 3.4), which suggests that high-resolution data may be more suitable than standard resolution for SBI analysis.

4.2. Distinctive Features of the Mixing Height

[68] If detailed PBL turbulence and surface roughness information is not available (as is likely the case for any global data set from which PBL climatologies might be developed), air quality studies might tend to favor the mixing height, based on the parcel method, as an indication of the potential atmospheric ventilation and dilution of pollutants emitted from the surface. As we have seen, mixing height statistics have unique features in comparison with the other methods we have examined. Mixing heights are lower than, and poorly correlated with, the other PBL height estimates, exhibit greater diurnal changes with more consistent low values at night, and can show different seasonal changes. For these reasons, climatologies of parcel method mixing heights appear warranted, specifically for air quality applications. Given the spatial sampling of the radiosonde network (Figure 1), mixing height climatologies for Europe, Australia, and the United States might be attempted. As with SBIs, the dependence of mixing height on sounding vertical resolution (and the tendency to obtain lower heights from higher resolution data) will complicate the analysis.

4.3. Issues Relevant to Global Navigation Satellite System Radio Occultation Observations

[69] To evaluate newly proposed methods of evaluating PBL height from GNSS RO observations, we included those based on vertical gradients of specific humidity, relative humidity, and refractivity in our study. Using radiosonde data to obtain refractivity profiles, we find that these three methods tend to yield more similar results than the other four, more traditional, methods we examined. Nevertheless, the agreement among them remains poor. They yield higher PBL heights than the others; are only moderately well correlated ($r \sim 0.5$); and more often than not show statistically significantly different means, variances, and distribution functions.

[70] Nevertheless, because GNSS RO data are (and will be) available in regions and for times of day that radiosonde observations are lacking, it seems worthwhile to further evaluate their potential, either independently or in combination with other data sources, to provide a global PBL climatology. Therefore, we intend to make direct comparisons of PBL heights based on actual GNSS RO data with those derived from radiosonde profiles. However, it is important to recognize that some features of the PBL will be very difficult, if not impossible, to delineate with GNSS RO observations. These include surface-based inversions and shallow boundary layers because of the degradation of GNSS RO profiles at low altitudes above the surface.

5. Summary

[71] This paper lays the groundwork for development of a global climatology of the planetary boundary, which, to our knowledge, has not previously been attempted with radiosonde or other observations. Using a 10 year, 505-station global radiosonde data set, we have compared seven methods of computing PBL height and have attempted to quantify aspects of the structural and parametric uncertainty in climatological values. The main findings are

[72] a. Surface-based inversions are a distinct type of PBL; when they are present, the other six methods were not applied. They are more common at night and in the morning (i.e., sunset to noon) than during midday and afternoon, more common in polar regions than in the tropics, and more common in winter than other seasons. The top of the SBI is typically between 200 and 700 m (typical 25th and 75th percentile values).

[73] b. The other six methods (based on vertical gradients of T, RH, q, N, and Θ, and based on the parcel method involving Θ_v) generally yield different estimates of climatological PBL height.

[74] (i) The parcel (or mixing height) method consistently yields significantly lower heights than the other methods and exhibits larger and more consistent diurnal and seasonal variations, with lower values at night and in winter.

[75] (ii) The RH and Θ gradient methods consistently yield higher PBL height estimates than the others.

[76] (iii) Methods based on finding maximum or minimum vertical gradients (of RH, q, N, or Θ) are in better agreement than those based on locating elevated T inversions or on the mixing height. However, in the majority of cases, there are statistically significant differences (in climatological mean values, variances, and cumulative distribution functions) among all the methods. Correlations among methods are statistically significant but small (generally less than 0.5, with some significant negative correlations).

[77] (iv) Specifically, PBL height based on refractivity (N) gradients, such as those that may be obtained from GNSS radio occultation observations, are not equivalent to those based on gradients in other meteorological parameters.

[78] c. Seasonal and diurnal patterns of PBL height variability differ from station to station and can sometimes be

interpreted in terms of climatological phenomena, such as nighttime radiation inversions, the trade inversion, and tropical convection and associated cloudiness.

[79] d. Climatological PBL heights are subject to both parametric, or sampling, uncertainty and structural uncertainty associated with methodological choices. Typical magnitudes of these uncertainties are several hundred meters.

[80] (i) The parametric uncertainty of 10 year climatological PBL heights for a given station, season, time of day, and method can be characterized by the interquartile range about the median, which range from a few hundred meters to more than 1 km. This sampling uncertainty encompasses PBL changes associated with day-to-day weather variability.

[81] (ii) Three sources of structural uncertainty are choice of PBL height estimation method, vertical resolution of sounding data, and inclusion or exclusion of surface-level observations in estimating climatological PBL heights. Each of these introduce uncertainties of order several hundred meters. The effects of these choices tend to be systematic rather than random. Lower PBL heights are associated with the parcel method than the gradient methods, with high-resolution rather than standard-resolution sounding data, and with including rather than excluding the surface observation.

[82] (iii) These uncertainties are important to consider in comparing radiosonde-based climatological estimates with those from models and from other observing systems.

[83] e. Because of the substantial sensitivity of PBL heights to estimation method, there is merit in separate climatological analyses for specific purposes. Because of its importance in air quality modeling, mixing height based on the parcel method is an obvious choice for PBL climatologies, particularly over the relatively well-sampled and densely populated continents. In the polar regions, climatologies of surface-based inversion characteristics and frequencies of occurrence would aid in evaluating the role of this common PBL type in high-latitude climate processes. Other methods may be better suited to climatologies designed for comparisons with climate models or with other observing systems.

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