# **Trends in Planetary Boundary Layer Height over Europe**

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#### ABSTRACT

Estimates of trends in planetary boundary layer height over Europe are presented, based on daily radiosonde observations at 25 stations during 1973–2010 and using a bulk Richardson number approach to determine heights. Most stations show statistically significant increases in daytime heights in all four seasons, but fewer show statistically significant trends in nighttime heights. Daytime height variations show an expected strong negative correlation with surface relative humidity and strong positive correlation with surface temperature at most stations studied, on both year-to-year and day-to-day time scales. Similar relations hold for long-term trends: increasing daytime boundary layer height is associated with decreasing surface relative humidity and increasing surface temperature at most stations. The extent to which these changes are regionally representative or local reflections of environmental changes near the observing stations is difficult to ascertain.

#### 1. Introduction

The planetary boundary layer (PBL) is the bottom layer of the troposphere in contact with the surface of the earth. As a critical component of the earth's climate system, the PBL controls exchanges of heat, momentum, moisture, and chemical constituents between the surface and free atmosphere. The structure of the PBL can be complex, influenced by local terrain and land surface features and varying strongly from day to night and with synoptic and mesoscale weather situations.

Recent studies (Liu and Liang 2010; Seidel et al. 2010) have investigated aspects of the global climatology of PBL height using radiosonde data. A recent climatological study of the PBL over the continental United States and Europe (Seidel et al. 2012) estimated PBL height using a method based on the bulk Richardson number (Ri) (Vogelezang and Holtslag 1996), quantified

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observed diurnal and seasonal variations in PBL height (above ground level), and compared radiosonde observations of PBL height climatology to a reanalysis dataset and two climate models. The present study extends that work by examining long-term trends over Europe, where the time of radiosonde (launched at 0000 and 1200 UTC) sample interesting parts of the diurnal cycle of PBL height evolution (near midnight and midday).

The height of the PBL is often used in climate and air quality studies to characterize convective and turbulent processes, cloud entrainment, and air pollutant dispersion and deposition (e.g., Stull 1988; Seibert et al. 2000; Liu and Liang 2010). In general, a deeper PBL means greater vertical mixing and lower surface pollution concentrations; PBL height is greater when surface temperature is high and humidity is low, which result in surface sensible heat fluxes dominating latent heat fluxes and leading to increased buoyancy. Given that surface temperature has increased over most of the globe in recent decades because of increased atmospheric greenhouse gas concentrations (Solomon et al. 2007), it is reasonable to ask whether PBL height also changed during those decades.

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TABLE 1. Seasonal trends in 1200 UTC planetary boundary layer height  $[z(Ri_{0.25})]$ , surface relative humidity, surface temperature  $(z, RH, and T \text{ with units of m decade}^{-1}, \% \text{ decade}^{-1}, and K \text{ decade}^{-1}, respectively})$ , and the number of years used to calculate trends at stations with homogeneous time series. Trends in boldface are significant at the 95% confidence level or greater. Missing values indicate that there were insufficient radiosonde data for a particular station and season with the required vertical resolution to compute PBL height.

		Dece	ember (D.	–Febru JF)	ıary	Mar	ch–Ma	ıy (MA	June–August (JJA)				September– November (SON)				
Country	Station (°N, °E)	Years	z	RH	Т	Years	z	RH	Т	Years	z	RH	Т	Years	z	RH	Т
Norway	Stavanger (59, 6)	_	_	_	_	25	-15	2.0	-0.3	33	42	0.4	0.1	_	_	_	_
Ireland	Valentia (52, -10)	29	110	-1.5	0.2	33	104	-0.9	0.2	36	105	-0.7	0.2	32	104	-0.5	0.3
Denmark	Kobenhavn (56, 13)	28	26	0.0	0.8	30	-21	2.8	-0.1	32	$^{-4}$	3.1	0.0	31	20	1.0	0.3
Netherlands	De Bilt (52, 5)	27	17	0.6	0.4	29	136	0.1	0.5	28	127	-1.2	0.8	28	91	0.4	0.1
France	Brest (48, -4)	_		_	_	_	_	_	_	27	61	0.7	0.3	26	83	-0.1	0.5
France	Bordeaux $(45, -1)$	33	79	-2.0	0.1	37	98	-2.5	0.6	36	94	-2.8	0.6	37	99	-2.7	0.4
France	Nimes (44, 4)	27	39	0.5	-0.2	31	69	-0.1	0.4	34	90	-1.3	0.6	32	44	0.7	0.1
France	Ajaccio (42, 9)	29	73	-0.3	0.0	35	42	-1.4	0.5	37	48	-2.1	0.5	35	114	-2.4	0.4
Spain	La Coruna (43, -8)	29	167	-1.3	0.4	29	84	-2.3	0.8	30	120	-2.0	0.8	26	94	-1.8	0.4
Spain	Murcia (38, -1)	26	85	0.3	0.5	26	104	-0.3	0.7	27	157	-2.7	0.9	25	68	-0.5	0.3
Gibraltar	Gibraltar (36, -5)	27	72	1.1	0.0	_	_	_	_	_	_	_	_	_		_	_
Portugal	Lisboa (39, -9)	26	80	0.3	0.3	25	77	-0.9	0.8	26	88	-1.1	0.9	27	109	-0.6	0.4
Germany	Schleswig (55, 10)	31	41	0.9	0.5	33	29	0.5	0.2	36	58	0.9	0.4	34	38	1.0	0.1
Germany	Greifswald (54, 13)	35	75	0.6	0.7	37	74	1.0	0.3	36	97	0.2	0.4	35	55	0.9	0.1
Germany	Lindenberg (52, 14)	_	_	_	_	_	_	_	_	25	8	0.3	0.1	27	59	0.1	0.2
Slovakia	Poprade (49, 20)	34	48	-1.0	0.0	34	154	-1.1	0.9	—	_	_	_	30	102	-1.3	1.4
Poland	Leba (55, 18)	28	44	-0.6	0.5	29	42	-0.8	0.1	30	54	-1.0	0.7	31	55	-0.4	0.2
Poland	Legionowo (52, 21)	27	37	-0.4	0.1	25	122	-2.2	0.5	27	105	-0.6	0.5	28	63	0.0	0.3
Hungary	Szeged (46, 20)	_	_	_	_	_	_	_	_	_	—	_	—	_		_	_
Hungary	Budapest (47, 19)	25	16	1.5	-0.1	_	_	_	_	_	—	_	—	25	73	1.0	0.9
Italy	Brindisi (41, 18)	36	11	-2.6	0.2	36	45	-3.2	0.5	37	34	-2.7	0.7	34	38	-2.1	0.1
Italy	Trapani (38, 13)	30	42	0.6	0.1	32	-11	-0.2	0.4	29	77	1.0	0.4	32	57	0.6	0.2
Italy	Cagliari (39, 9)	26	77	-2.1	0.2	27	53	-3.6	0.7	25	147	-6.5	0.7	27	90	-3.9	0.2
Greece	Athens (38, 24)	31	50	-0.6	0.3	30	187	-2.0	0.3	29	381	-2.6	1.1	28	121	0.3	0.4
Turkey	Istanbul (41, 29)	25	68	-1.8	0.8	25	111	-2.2	0.9	_	_	_	_	_	_	_	_
Turkey	Izmir (38, 27)	—	—	—	—	26	90	-2.9	1.0	—	—	—	—	—	—	—	—

To our knowledge, no study to date has reported longterm changes in PBL height. Here we estimate linear trends in PBL height over Europe. The following section describes the data and methods, section 3 presents longterm changes in the PBL height over Europe and associations with other variables, and conclusions are given in section 4.

### 2. Data and method

The PBL height data used in this study are based on radiosonde observations from the Integrated Global Radiosonde Archive (Durre et al. 2006), using methods developed by Seidel et al. (2012), who give details of data processing, quality control, the algorithm for estimating climatological boundary layer heights, and methodological uncertainties. Seidel et al. (2012) evaluated 10 different methods for estimating PBL mixing height and identified a bulk Ri method (Vogelezang and Holtslag 1996) as best for climatological analysis of large datasets. The method is suitable for both stable and convective boundary layers; can identify a height in all cases; and is not strongly dependent on sounding vertical resolution, which is an important factor for long-term trend studies, because sounding resolution has increased as automated data processing capabilities have improved (Zhang et al. 2011).

In brief, the bulk Ri is defined as

$$\operatorname{Ri}(z) = \frac{(g/\theta_{vs})(\theta_{vz} - \theta_{vs})(z - z_s)}{(u_z - u_s)^2 + (v_z - v_s)^2 + (bu_*^2)},$$
 (1)

where z is altitude, g is the acceleration of gravity,  $\theta_v$  is virtual potential temperature, u and v are zonal and meridional wind speeds, b is a constant,  $u_*$  is the surface friction velocity, and the subscript s denotes the surface. The friction velocity term is much smaller than the wind shear terms in the denominator (Vogelezang and Holtslag 1996) and so is ignored in this study. As no surface wind components are reported in radiosonde observations, we set the surface wind to zero (Seidel et al. 2012). After deriving the Ri profile from a radiosonde



FIG. 1. Time series of summer (JJA) daytime (1200 UTC) planetary boundary layer height [ $z(Ri_{0.25})$ ] (black dot curves), surface temperature (blue x curves), and surface relative humidity (red x curves) at 20 European stations. Error bars represent ±1 standard deviation of daily values about the seasonal means. Linear trend lines are plotted for series with trends significant at 95% confidence level or greater.

observation, we scan it from the surface upward; identify the first level with Ri  $\ge$  0.25; and interpolate linearly between that level and the next lowest level to estimate the height at which Ri = 0.25,  $z(Ri_{0.25})$ . We use the terms "PBL height" and "mixing height" as shorthand for  $z(Ri_{0.25})$ .

Trends were computed for each of the four seasons [December–February (DJF), etc.] using data during the period 1973–2010. Trends were computed using the nonparametric median of pairwise slopes method (Lanzante 1996), with statistical significance levels based on Spearman rank-order tests. Because of the large differences in PBL between day and night (Seidel et al. 2012), 0000 and 1200 UTC profiles are analyzed separately.

For PBL height detection in a given radiosonde observation, we required at least 7 levels of reported temperature and humidity data and at least 4 levels of reported wind component data between the surface and 5 km above ground level. Station data were considered sufficient if at least 50 soundings per season met these criteria for identifying mixing height in a given year, and at least 25 yr of data met this requirement during the 38-yr period. Sensitivity tests indicated that varying these requirements slightly does not much influence either the data retention rate or the estimated trends.

In a related analysis of PBL trends in the Arctic, Zhang and Seidel (2011) identified spurious changes in surface-based inversion characteristics because of the changes in vertical resolution of radiosonde observations and stressed the need to ensure such changes do not bias trend estimates. Here we used similar nonparametric statistical methods to identify possible



FIG. 2. Maps of seasonal trends in daytime (1200 UTC) planetary boundary layer height  $[z(Ri_{0.25})]$  during 1973–2010. Symbols outlined in thick black lines indicate values that are statistically significant at 95% confidence level or greater. Data periods differ among stations; see Table 1 for details.

change points in time series of  $z(Ri_{0.25})$  associated with detected change points in vertical resolution at each station. By using 1973 as a start date and perhaps because mixing height is less affected by sounding resolution changes than surface-based inversion height, we found only a few stations whose records were affected by these data inhomogeneities. Those records were truncated to eliminate the lower-resolution data period. Even though the fraction of soundings with vertical resolution meeting our requirements increases over time, sometimes abruptly, at some stations, there are no sharp changes in PBL height.

These considerations resulted in 22 stations at 0000 UTC (near midnight) and 25 stations at 1200 UTC (near noon) for trend analysis, although not all stations had sufficient valid data in all four seasons. Table 1 gives station location information, along with seasonal trends. Because the nighttime trends are mainly not statistically significant, we focus on the daytime  $z(Ri_{0.25})$  changes here.

### 3. Results

Figure 1 shows time series of average ( $\pm 1$  standard deviation) summer [June–August (JJA)] daytime PBL height  $z(\text{Ri}_{0.25})$  (black dot curves) at 20 European stations. Typical heights are  $\sim 1$  km, but most stations (16 of 20) show statistically significant increases during the past few decades. Table 1 gives numerical values of trends at

each station in all seasons, and Fig. 2 shows  $z(Ri_{0.25})$  daytime trends for all four seasons. Daytime trends are overwhelmingly positive, with all statistically significant trends and most of those that are not statistically significant indicating increasing PBL heights. Daytime significant trends range from 38 to 381 m decade<sup>-1</sup>, with an average value of 76 m decade<sup>-1</sup>, and there is little indication of seasonal structure to the trends. Nighttime trends are smaller, less frequently statistically significant, and more likely to be negative than daytime trends (not shown here). The bulk Ri method used in this study has relatively larger uncertainties in low  $z(Ri_{0.25})$  cases as are found at night (Seidel et al. 2012), which contributes to uncertainties in trend estimates.

Changes in near-surface atmosphere conditions could be expected to cause changes in PBL height. Indeed, Ri(z) depends on vertical gradients including near-surface observations. We analyzed associations between  $z(Ri_{0.25})$ and near-surface (2 m) relative humidity, temperature, and wind components, as reported in the radiosoundings. The numerical values of near-surface relative humidity and temperature trends are included in Table 1. Surface temperature (blue x curves) at most stations (5 of 6) in Fig. 1 exhibits statistically significant increases (Solomon et al. 2007). In Fig. 1, summertime surface relative humidity (red x curves) at most stations shows statistically significant decreases, which is consistent with Dai (2006) and Simmons et al. (2010), who found



FIG. 3. Correlations of seasonal mean daytime (1200 UTC) boundary layer height  $[z(Ri_{0.25})]$  and surface relative humidity during 1973–2010. Symbols outlined in thick black lines indicate values that are statistically significant at 95% confidence level or greater. Data periods differ among stations; see Table 1 for details.

decreases in relative humidity over Europe during 1976–2004 and 1973–2008, respectively.

Figure 3 shows correlations between daytime seasonal mean  $z(Ri_{0.25})$  and surface relative humidity. Correlations are overwhelmingly negative in all seasons and are

strongest and more often statistically significant in summer. The strongest anticorrelation (-0.85) is found at Lindenberg, Germany  $(52^{\circ}N, 14^{\circ}E)$ , in summer. These correlations indicate that seasons with lower than average surface relative humidity also have higher than



FIG. 4. As in Fig. 3, but for correlations between seasonal mean daytime boundary layer height and surface temperature.

average PBL height. In addition, the long-term trends toward higher PBL heights are associated with longterm relative humidity decreases. Similar correlation maps for surface temperature (Fig. 4) show strong positive correlations in winter, spring and summer. Thus, warmer than average seasons are associated with higher than average PBL heights, and previously documented surface temperature increases (e.g., Hansen et al. 2010) are associated with rising PBL height. These tendencies are consistent with the notion that higher surface temperature and lower relative humidity results in greater sensible heat flux and lower latent heat flux, leading to deeper convection and larger  $z(Ri_{0.25})$ . Similar correlation analyses using near-surface wind speeds showed no significant association between wind speed and  $z(Ri_{0.25})$ . These correlation analyses for each season were also performed by using the daily  $z(Ri_{0.25})$  instead of the seasonal means. In general (but not shown here), day-to-day changes reveal similar associations as year-to-year changes.

## 4. Conclusions

Analysis of trends in planetary boundary layer height over Europe during the period 1973–2010 has revealed significant changes in the daytime PBL and close associations with some surface climate variables. Most of the European stations analyzed show statistically significant increases in daytime PBL height  $z(Ri_{0.25})$  in all seasons. Nighttime trends are much smaller, less consistent, and less statistically significant. Daytime  $z(Ri_{0.25})$  shows strong negative correlation with surface relative humidity and positive correlation with surface temperature. The increases in PBL height are associated with decreases in surface relative humidity and increases in surface temperature.

Interpretation of these results is subject to a caveat related to the spatial representativeness of the radiosonde station data. Whether the trends presented here are indicative of changes over larger regions in Europe is difficult to ascertain.

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