Met Office

Comparison of planetary boundary layer heights from Jenoptik ceilometers and the Unified Model

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1 Introduction

The planetary boundary layer (PBL) is the lowest part of the atmosphere and its behavior is directly influenced by its contact with the earth's surface. This is the layer of the atmosphere with the strongest vertical mixing and it plays a crucial role in influencing air quality and the weather. Typically, the boundary layer is a few hundred meters to a couple of kilometers thick and has a diurnal cycle where it is greatest during the day and decreases at night (Stull, 1988). This is because the heating of the earth's surface during the day leads to thermal instability and results in vertical mixing. During the day, the PBL is characterized by atmospheric pollutants being well mixed up to the top of the layer (also known as the mixing height) because of both thermal and mechanical turbulence. As such, it plays a vital role in air quality. The diurnal cycle can lead to what is called the residual layer at night which exists because of the mixed pollutants from the day having not settled towards the ground before the PBL depth decreases. PBL depth is also integral to processes like cloud formation and so is important for weather forecasting and climate models.

There are various methods for determining the boundary layer height both from observations (e.g. in-situ measurements such as radiosondes, tethered balloons or aircraft; remote soundings such as radar or lidar) and from model simulations. A review of some of those methods can be found in Seibert et al. (2000). Two methods commonly applied to calculate the PBL height are the parcel method and the bulk Richardson number method (see Seibert et al., 2000, and references therein):

- The parcel method assumes that an air parcel with an excess temperature at the surface is lifted adiabatically until it reaches its level of equilibrium (same temperature as surroundings). This level is taken as the height of the PBL.
- The bulk Richardson number methods define the top of the PBL as the height h where

$$Ri_b(h) = \frac{gh}{\Theta_{v1}} \frac{\Theta_v(h) - \Theta_{v1}}{U(h)^2 + V(h)^2}$$

  exceeds a critical value Ri_c. Here, Θ_{v1} is the virtual potential temperature at the lowest vertical level and $\Theta_v(h)$ is the same at a height h. U and V are the mean flow components at height h and g is the gravity of the earth.

This work will present a comparison of modelled PBL heights, which are diagnosed based on parcel and Richardson number methods, against PBL heights derived from remotely sensed observations of the UK ceilometer network.

2 Observed data and model diagnostics

2.1 Ceilometers

The CHM 15k (Jenoptik A.G., Germany) ceilometer is a low-power lidar designed to observe the vertical structure of the atmosphere (JENOPTIK, 2011). These lidars are active remote sensing instruments which emit a finite pulse of light and detect the back-scatter signal from clouds, aerosols and air molecules. The manufacturer's software includes algorithms to automatically derive the cloud base height (CBH) and PBL height (JENOPTIK, 2011; Cox and Adam, 2013). To calculate the PBL height, the instrument takes the three maximum gradients of the back-scatter signal and the three heights are output as PBL1, PBL2 and PBL3. The lowest two of these heights (PBL1 and PBL2) are the main considerations in this comparison. The Laser Cloud Based Recorder (LCBR) network in the UK includes this type of instrument. Figure 1 shows the location of the 11 sites considered here for summer 2013. It was concluded that data from Lerwick should not be included as this site did not have good coverage during the period of analysis, therefore 10 sites were used. For this work we have used the Jenoptik "instrument" data files, which consist of raw (i.e. not processed) data (Horseman, 2013).

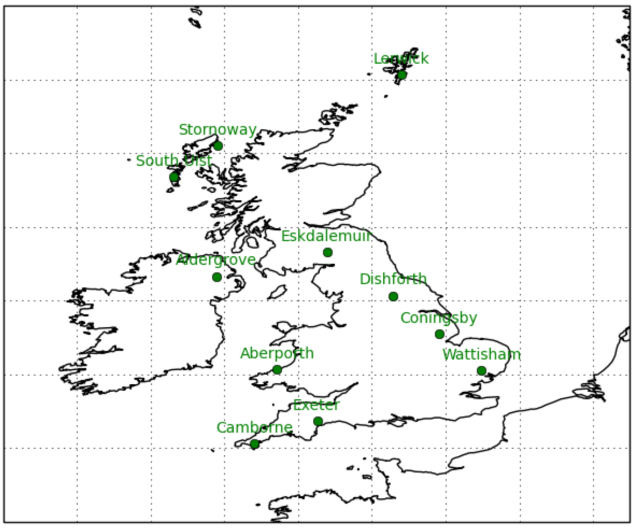


Figure 1: Locations of CHM 15k Jenoptik ceilometer sites across the UK.

2.2 AQUM and boundary layer model diagnostics

In this work PBL heights from the UK ceilometer network have been compared with boundary layer diagnostics from AQUM (Air Quality in the Unified Model). AQUM is a limited area configuration of the Met Office's Unified Model (UM) which is used operationally to provide a 5-day air quality forecast for the UK. The representation of chemistry in AQUM is given by the Regional Air Quality (RAQ) chemistry scheme of the United Kingdom Chemistry and Aerosols (UKCA) sub-model of the UM. At the present time all aerosol processes are parameterised within the Coupled Large-scale Aerosol Simulator for Studies In Climate (CLASSIC) sub-model. The model is operated with a 12 km horizontal resolution grid covering much of Western Europe, and 38 vertical levels spanning from the ground up to around 40 km altitude. For further details on AQUM see Savage et al. (2013).

The UM includes several boundary layer height diagnostics (Lock et al., 2015), three of which are used in this comparison. The 'height of surface mixed layer top', z_h (STASH 3,357) is based on a parcel ascent method. The 'boundary layer depth diagnosed from RiCrit', z_{loc} (STASH 3,358) uses a critical Richardson number. The 'boundary layer after timestep' (STASH 0-25) is calculated by taking the maximum of the previous two and so represents the depth of the boundary layer. This is the diagnostic used operationally in AQUM as well as in NAME (Numerical Atmospheric-dispersion Modelling Environment).

3 Data analysis and results

3.1 Data filtering

The boundary layer structure, especially on an island with very changeable weather like the UK, can often be quite complex making it difficult to measure and diagnose. Visual inspection of the range corrected signal (RCS) of the ceilometer sites during summer 2013 allowed exclusion of those days with very complex structure in the boundary layer or with low level clouds which might yield a strong backscatter signal. The months of June and July in 2013 were identified as having a number of days with clear boundary layers that would be good for consideration. Good days were selected separately for each site and only these days were considered for our analysis. As there were more of these days in July than in June, for this comparison only the results for July are discussed. Figure 2 highlights the days in July finally selected for each site.

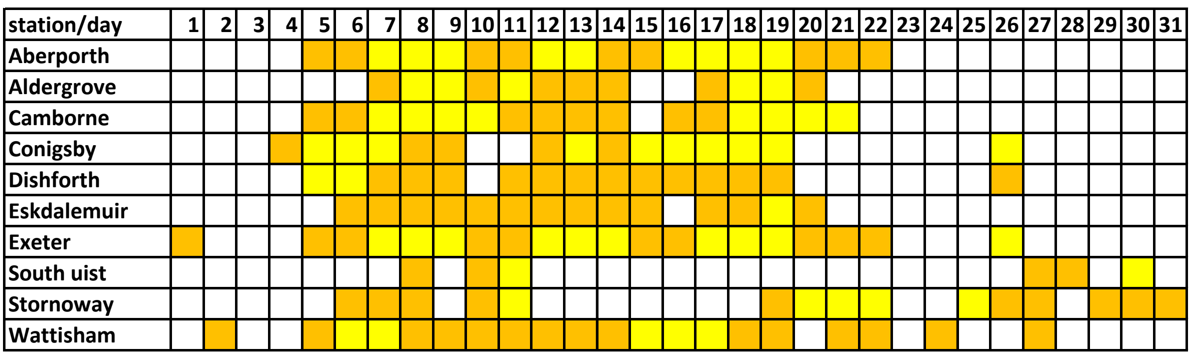


Figure 2: Days of good data in July from the Jenoptik ceilometer at each station are coloured orange (for a day of reasonable data) and yellow (for a day of particularly good data).

Output from the ceilometer is available every 30 seconds. For the purposes of making scatter plots of the range corrected signal, these are averaged over 5 minutes. UM diagnostics were output every hour for 1-day AQUM forecasts, so the 5 minute averages from the ceilometers are further averaged to give a single value for each hour. Before these averages are calculated, a filter is used to try to reduce the noise in the data. An initial mean and standard deviation is calculated for the hour using the 5 minute averages. Then any points outside of the mean plus or minus one standard deviation are removed before the hourly average is recalculated. This filtered data is used for all the plots other than the initial scatter plots of the ceilometer RCS.

3.2 Results

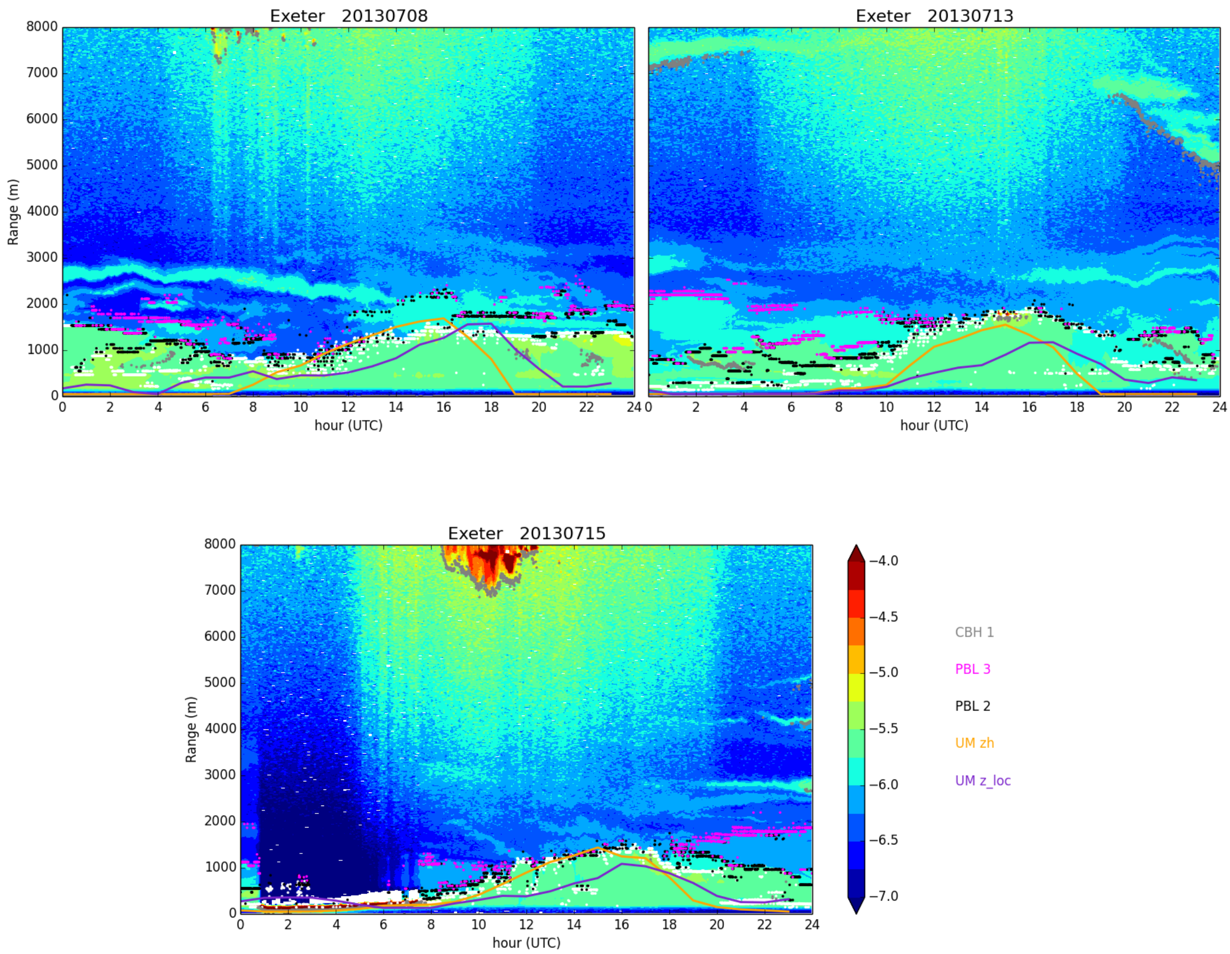


Figure 3: Scatter plots of the ceilometer range corrected signal averaged over 5 minutes for 8th, 13th and 15th July 2013 in Exeter. Boundary layer heights (PBL1, white; PBL2, black; PBL3, pink) and the first cloud base height (CBL1, grey) retrieved from the ceilometer as well as two boundary layer diagnostics from the UM (z_h, orange ; z_{loc}, purple) are overplotted. See text for further details.

Figure 3 shows the ceilometer RCS as well as boundary layer heights from both the ceilometer and the UM overplotted for Exeter on 8th, 13th and 15th of July, some typical good days of data. The boundary layer heights derived by the ceilometer are here averaged for every 5 minutes rather than using the filter and hourly averaging described above, which is used for the remainder of the comparison. The two boundary layer heights given by the ceilometer that are used for this comparison are PBL1 and PBL2 (plotted in white and black respectively). After a careful visual inspection of similar plots for all Jenoptik ceilometer sites during summer 2013, these two heights seem to give the most reasonable representation of what one would expect the boundary layer to look like. A third height PBL3 (pink) is also given by the ceilometer, but this generally appears to give less feasible heights that are very sporadic and so is not considered here. The plots also show the first cloud base height (CBH1, grey) as given by the ceilometer. Overplotted are two of the UM diagnostics in orange and purple where the third to be considered is the maximum of the two. z_{loc} (purple) generally tends to reach the maximum later in the day than z_h (orange). The diagnostic z_h is too low at night but we can deduce that this is due to the fact it does not take into account any mechanical turbulence, so once there is no thermal mixing (when the sun has set) the estimate would be expected to be too low. The maximum of these two diagnostics (the BL depth often used in AQUM, not shown in the Figure) agrees fairly well with the ceilometer readings during the daytime for these particular days and location, but at night, as is often the case, the ceilometer continues to give high readings once the UM diagnostics decrease. A possible reason for this is that the ceilometer is detecting the residual layer.

Figure 4 shows the time series of boundary layer heights for July 2013 in Exeter, with the good days in bold and the bad days shaded (see also Figure 2). Here, the hourly data are plotted and averages for the ceilometer were found using the filter described in the previous section to try to reduce the noise. There is a clear diurnal cycle and we again see the ceilometer readings remaining higher than expected during the night; this is particularly the case for PBL2 (red) which is most likely detecting the residual layer. We also note the tendency for the second UM diagnostic (z_{loc}, blue) to peak after the first one (z_h, green) and for the first to be particularly low during the night. Interestingly, the data filtering does not necessarily make the graphs look less noisy as in some cases this increases the variability from one hour to the next (not shown). This is probably due to the reduction of data points considered for averaging under the 1-sigma criterion imposed, although a more detailed investigation of this feature might be needed in the future.

Now looking at an average taken of all the good days during July in Exeter and Eskdalemuir, Figures 5 and 6 show what we would expect a typical good day to look like for each site. From this we see that the best match is found for PBL1 from the ceilometer (blue) and BL depth after timestep from the UM (red), with a clear diurnal cycle present in both of them.

Using the hourly data from all the good days in July, Figure 7 shows scatter plots of the three UM boundary layer height diagnostics against PBL1 and PBL2 from the ceilometers at the same sites: Exeter and Eskdalemuir. As we know that the ceilometer tends to overestimate the boundary layer depth during the night, the daytime hours are plotted in blue (hourly averages ending 1000 - 1900UTC) while the night-time hours are plotted in red to help distinguish the two. Two correlation coefficients are also given, one using just the daytime data (blue) and one with all the data (black).

Overall, the best correlations are found for PBL1 from the ceilometer and the BL depth after timestep from the UM (upper left panels). As this is the UM diagnostic commonly used in AQUM, it is reassuring that this appears to be the best approximation to the observations. The middle panels also illustrate the very low boundary layer heights given by the UM diagnostic z_h at night-time (red). Finally, all UM boundary layer diagnostics tend to correlate better with PBL1 than with PBL2.

Reasonably good correlations between the boundary layer heights from the ceilometers and the model have been found for the two mentioned sites (Exeter and Eskdalemuir) as well as for Aldergrove and Dishforth (not shown). There are also some sites where the results appear to show no correlation between the two. In particular Coningsby, Aberporth and Camborne. Figures 8-11 show some plots from Coningsby and Aberporth to illustrate this.

In the monthly average plots (Figures 8 and 9), the ceilometers seem to give boundary layer heights that do not vary much during the day and have no clear diurnal cycle. In Consingsby, the model shows a clear increase of the boundary layer height during the day which goes far above the relatively constant height given by the ceilometer. It has been observed that several Jenoptik ceilometers show an artificial band around 300-400m, therefore the PBL algorithm picks an artificial PBL height. The issue is under investigation with the manufacturer. This artificial estimation can clearly be seen in the plots for Coningsby (Figures 8 and 10). Work to try to recalibrate the instrument at the Coningsby site has revealed that this specific ceilometer has problems with these low heights. In comparison, the heights given by the ceilometer in Aberporth are consistently above the model diagnostics and in fact appear to be slightly lower during the day than at night - the opposite of what one would expect. We do note however that the boundary layer according to the model gets very shallow at night reaching heights as low as about 200m. It is known that these ceilometers tend not to perform well at such a low level so this might explain the overestimation here. We also note that the high PBL during the night estimated by the ceilometer in Figure 9 is a particular PBL behaviour which can be specific to locations close to the sea. Although most of the sites are quite close to the coast, Aberporth is particularly so. This could explain the relatively constant PBL height given by the ceilometer and it could be that the model is not capturing this atypical behaviour.

The lack of correlation between the ceilometer output and the model diagnostics is particularly stark looking at the correlation plots for Coningsby in Figure 10, which clearly illustrates the lack of variation and low values in the heights given by the ceilometer compared to those from the model. The same scatter plots for Aberporth shown in Figure 11 also display little correlation between the boundary layer heights given by the ceilometer and the model.

For completeness, average diurnal cycles for the sites not shown here can be found in Appendix II.

4 Summary and conclusions

The first and second boundary layer heights (PBL1 and PBL2) automatically derived from Jenoptik CHM 15k ceilometers at various locations across the UK were compared with three boundary layer height diagnostics (z_h, STASH 3-357, based on a parcel ascent method; z_{loc}, STASH 3-358, based on the critical Richardson number method; 'boundary layer after timestep', STASH 0-25) from 12-km UM simulations for July 2013. After careful visual inspection of the ceilometer signals at all sites, the days when the ceilometer range corrected signal did not show complex structure or clouds within the boundary layer were selected for the comparison with the UM diagnostics.

We found that for some sites such as Exeter and Eskdalemuir, PBL1 seems to correspond fairly well with the most commonly used diagnostic from the model ('boundary layer after timestep'). This is the case for most inland sites (including Aldergrove and Dishforth) excepting the discrepancy for the night-time period. However, there are also sites where the two seem to bear no resemblance to each other and the way in which they differ (e.g. overestimation or underestimation) is dependent on the site. Although the origin of such discrepancies is not completely clear, it is possible that some of the mismatches found are due to the boundary layer being too shallow for the ceilometer to give reliable results. We have also found that there are some problems with the ceilometers (the instrument at the Coningsby site has a known problem) resulting in an artificially low estimation of PBL height.

It was also noted that the UM forecasts low PBL heights during the night (stable or nocturnal boundary layer). This is especially seen in UM output z_h for which the values are closer to a typical surface layer than a nocturnal boundary layer. However, the values predicted by UM output z_{loc} during the night-time follow a nocturnal boundary layer pattern. The ceilometer estimations (PBL1) for nocturnal boundary layer do not seem reliable for some sites, where the PBL is almost constant over a 24 hour period (Consingsby) while sometimes even increases during the night (Aberporth). Thus, it is very probable that ceilometer estimates during the night-time pick the residual layer. The new firmware version for the ceilometers includes high resolution measurements over the first 150 meters. It has not yet been investigated whether these data are more suitable for shallow boundary layer depth estimations.

Looking at the site locations in Figure 1, we note that most of them are close to the coast where the boundary layer structure is likely to be more complicated than over land. Locations on the coast are expected to have a higher boundary layer at night than inland sites. This constant height throughout the day (or sometimes even increasing slightly at night) can be seen in the ceilometer output for coastal locations such as Aberporth, Camborne and Stornoway but the model appears to underestimate the PBL height at these locations. It is also worth noting that the proximity of the coastline could affect the diagnostics given by the model if the grid cell covering this location includes a large portion over sea rather than land. A detailed analysis of the model sensitivity to this is out of the scope of this report.

In a relatively small country surrounded by sea like the UK, the boundary layer structure can often be quite complex and difficult to measure by ceilometers. This is accentuated by the extremely changeable weather experienced in the UK leading to even more complex boundary layer structures. It is difficult to discern how accurate these may be as neither the model diagnostics nor observations are fully reliable.

Promising studies have however been carried out in regions that tend to have less complex boundary layer structures like continental Europe. As an example, Stachlewska et al. (2012) reported reasonably good comparisons between boundary layer heights derived from the same type of ceilometer instrument used here and from radiosoundings over Warsaw, Poland. However we note that radiosoundings are not always a reliable way to diagnose the depth of the turbulent layer, with the profiles having features related to the history of the turbulence as well as the current turbulence (with there not always being an easily observable transition at the top of the currently turbulent layer). That study also proved that in-house developed algorithms to retrieve boundary layer heights from Jenoptik ceilometers may perform better than the automated algorithm provided by the manufacturer. This may suggest that with the development of improved retrieval algorithms in the future, such instruments could become appropriate for the detection of boundary layer heights over the UK. However it is unclear that such good results can be expected for the UK given its complex boundary layer structure, often with low level clouds and strong variability throughout much of the year. Due to the dynamics (quick variation) and complex processes within the PBL over the UK, PBL height estimation using ceilometers and lidars still remains a challenge. Note that even when the evaluation presented here was focused on a summer period when the structure of the boundary layer is expected to be less complex than in winter due to more stable weather, we had to visually inspect the signal from all ceilometer instruments in order to select the most appropriate days. This clearly precludes the use of these data for operational verification of boundary layer height diagnostics in AQUM or any other configuration of the UM.

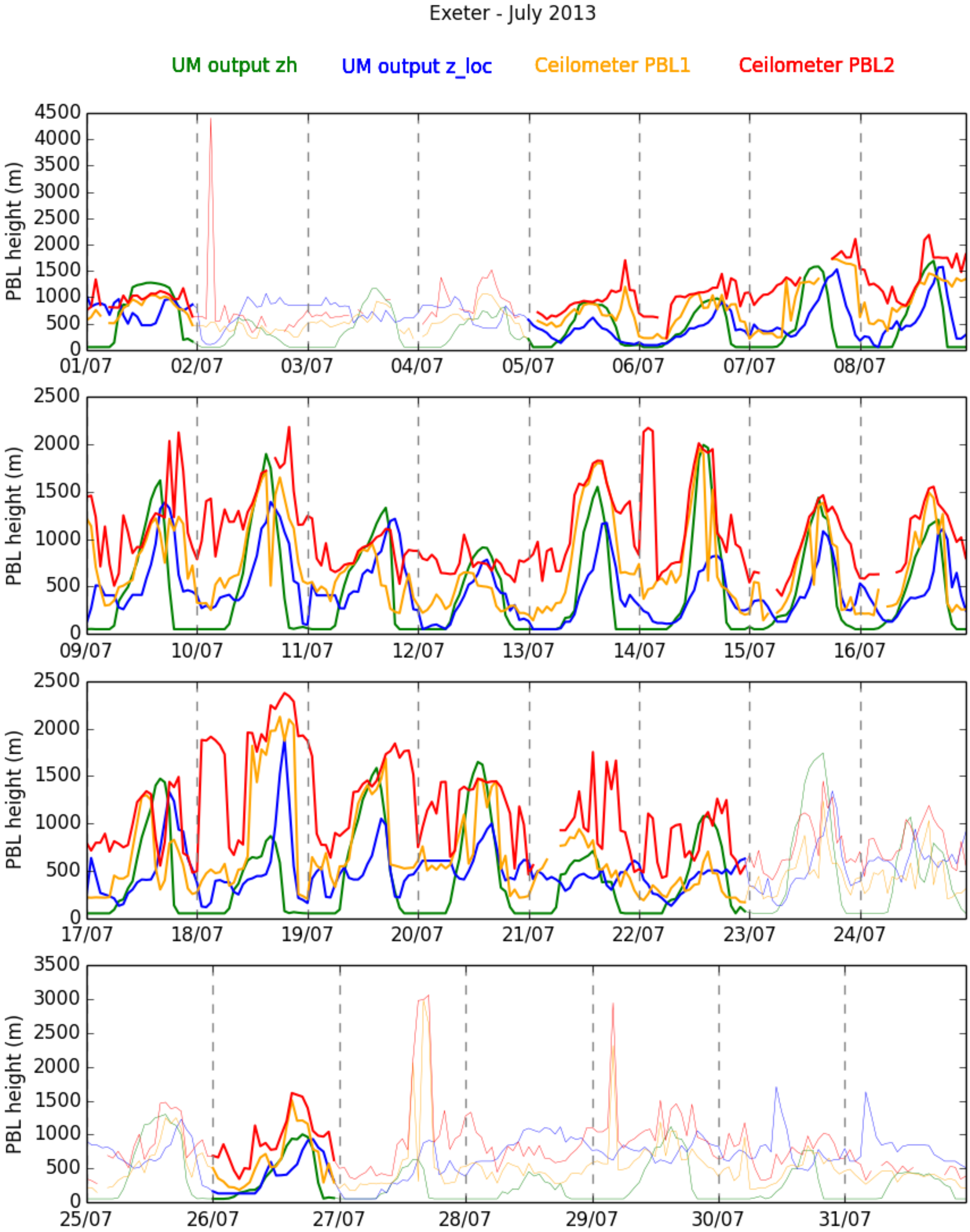


Figure 4: Time series of boundary layer heights from the ceilometer and model output for July 2013 in Exeter. Good days of ceilometer data are represented by bold lines while bad days are shaded.

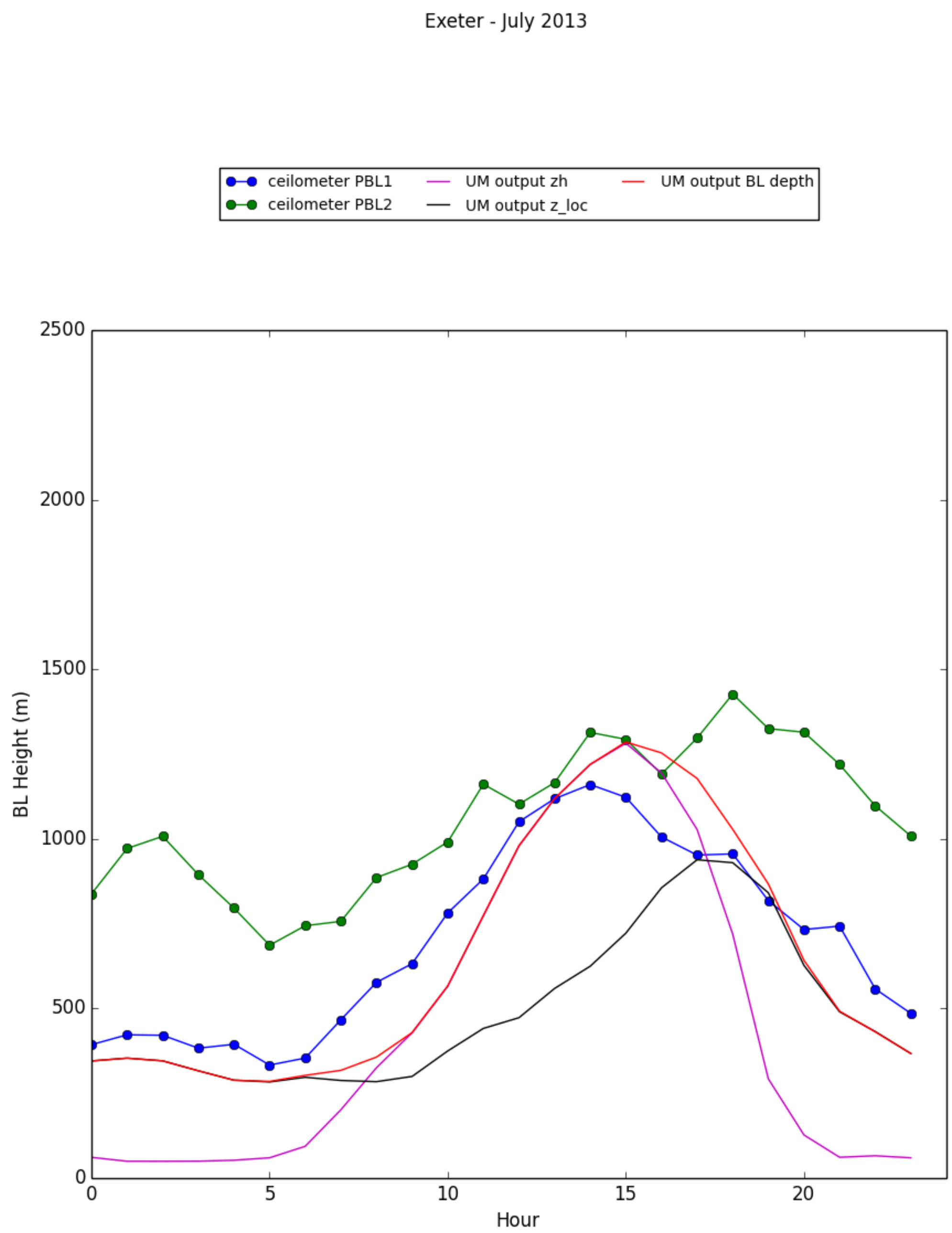


Figure 5: Average diurnal cycle of the boundary layer heights from the ceilometer and model considering only good days during July 2013 in Exeter.

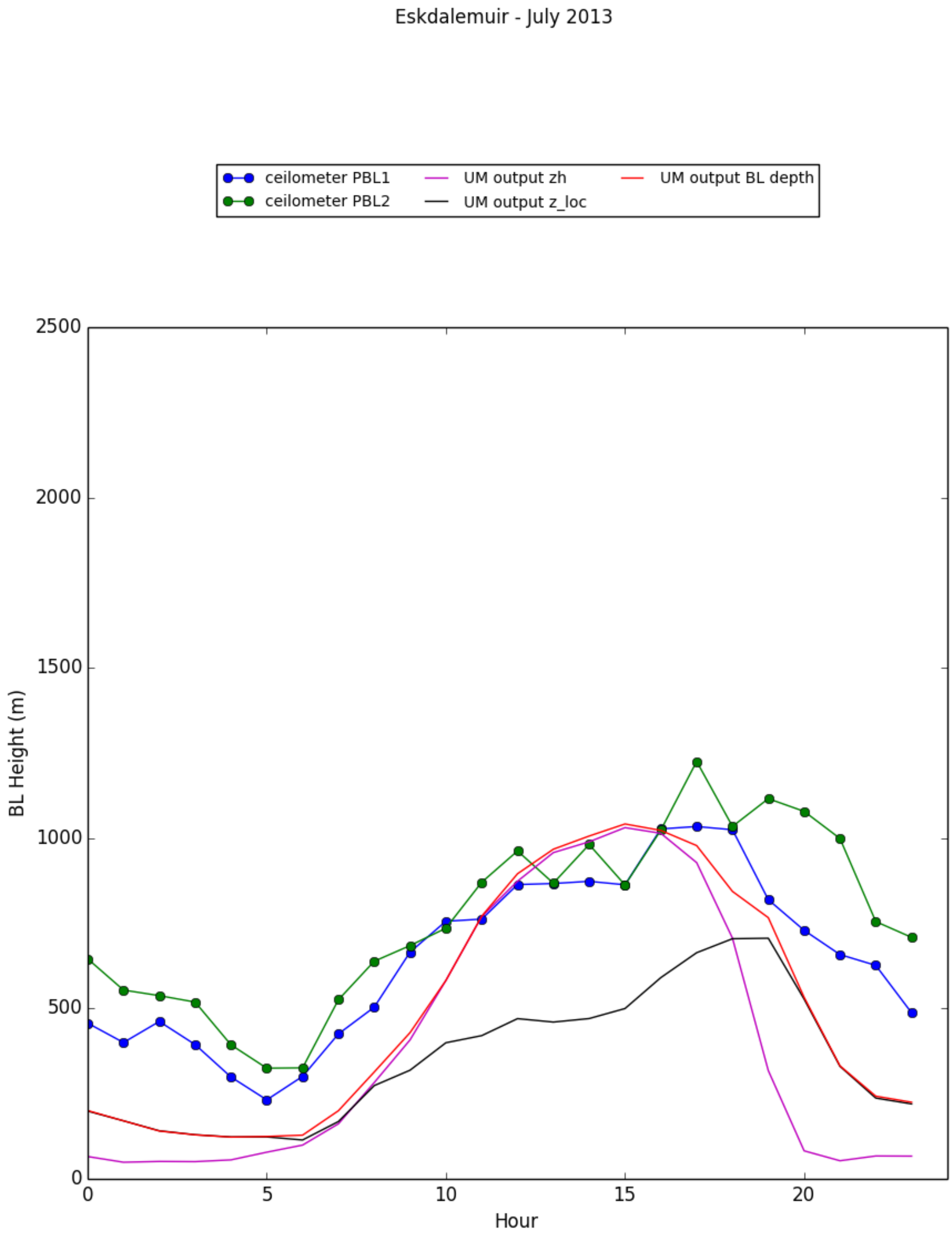
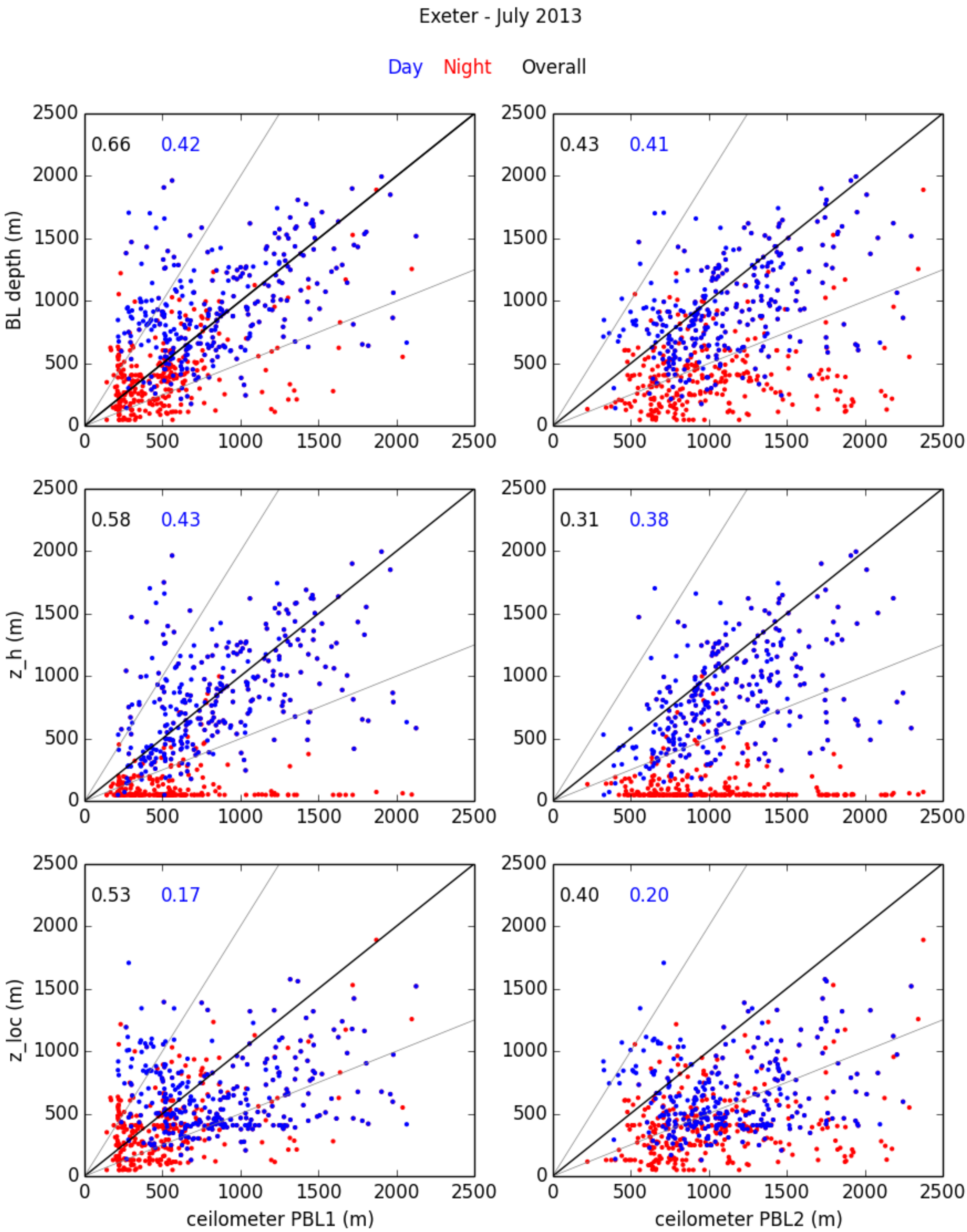


Figure 6: Average diurnal cycle of the boundary layer heights from the ceilometer and model considering only good days during July 2013 in Eskdalemuir.


Exeter - July 2013
Day Night Overall
0.66 0.42
0.43 0.41
0.58 0.43
0.31 0.38
0.53 0.17
0.40 0.20
BL depth (m)
z_h (m)
z_loc (m)
ceilometer PBL1 (m)
ceilometer PBL2 (m)
0
500
1000
1500
2000
2500

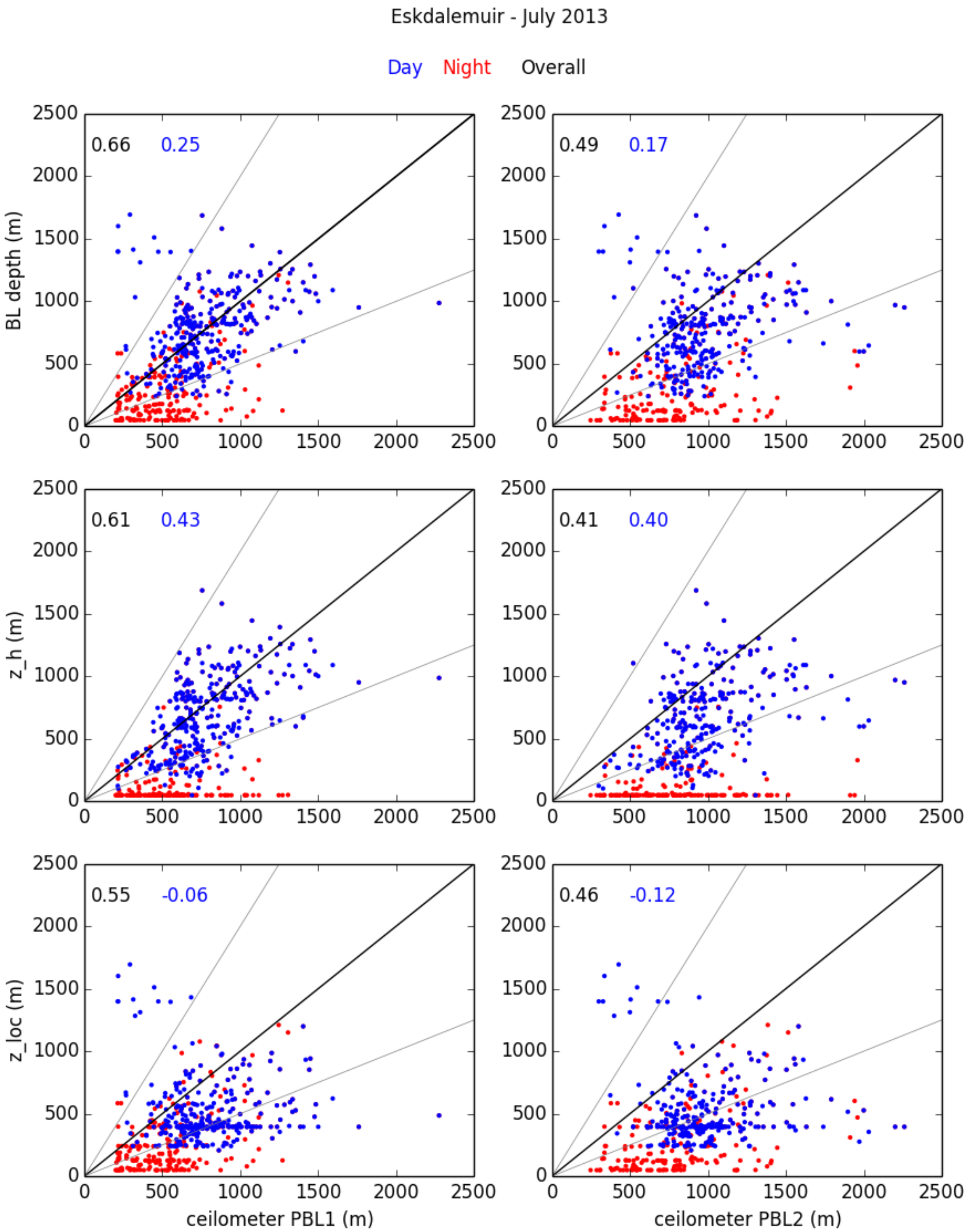


Figure 7: Scatter plots of boundary layer heights diagnosed by the UM (from top to bottom: BL depth, z_h and z_{loc}) against PBL1 (left) and PBL2 (right) from the ceilometers at Exeter and Eskdalemuir in July 2013. Daytime hours are shown in blue and night-time in red, with the correlation coefficient in blue for daytime data and black for all data.

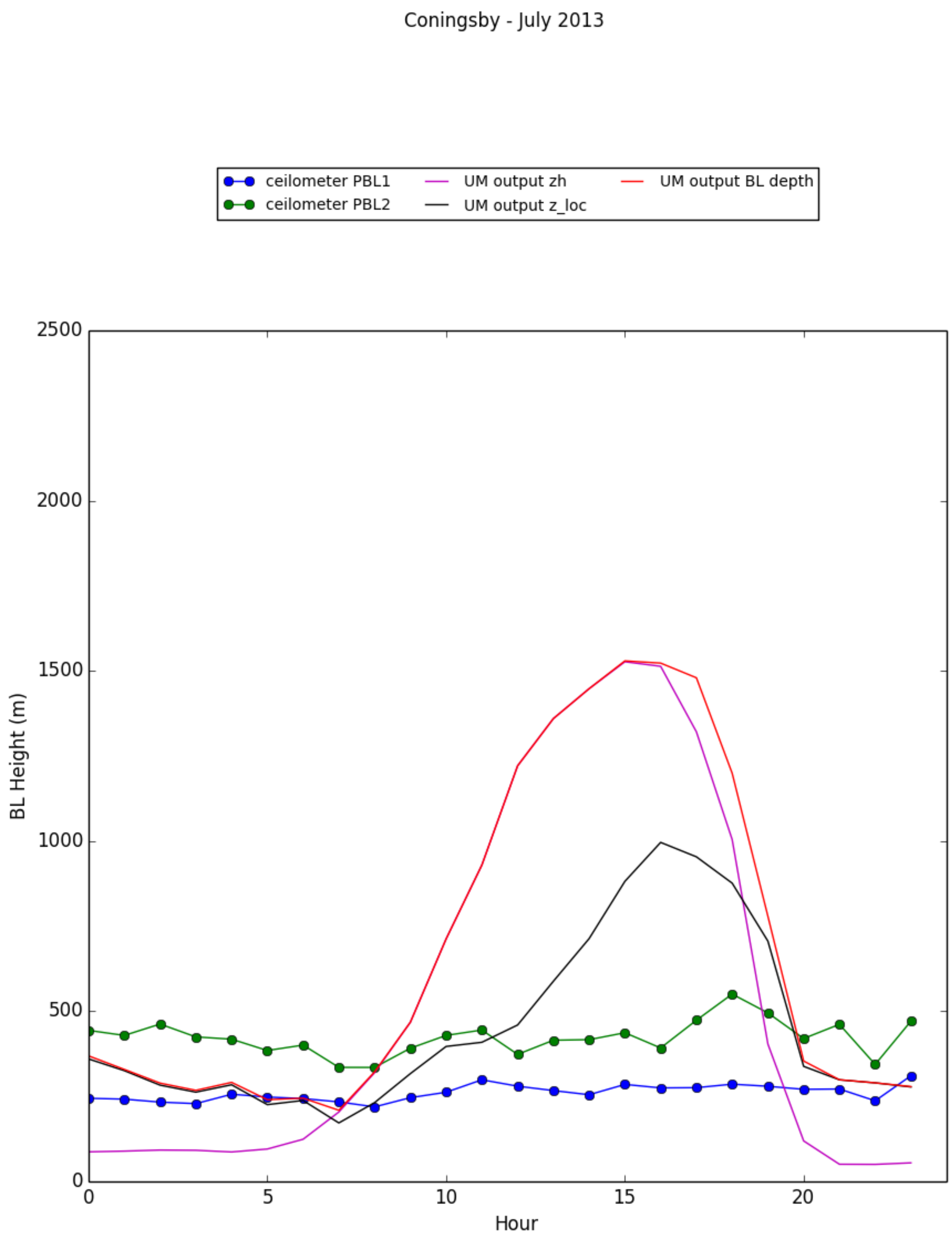


Figure 8: Monthly average plot for Coningsby in July 2013.

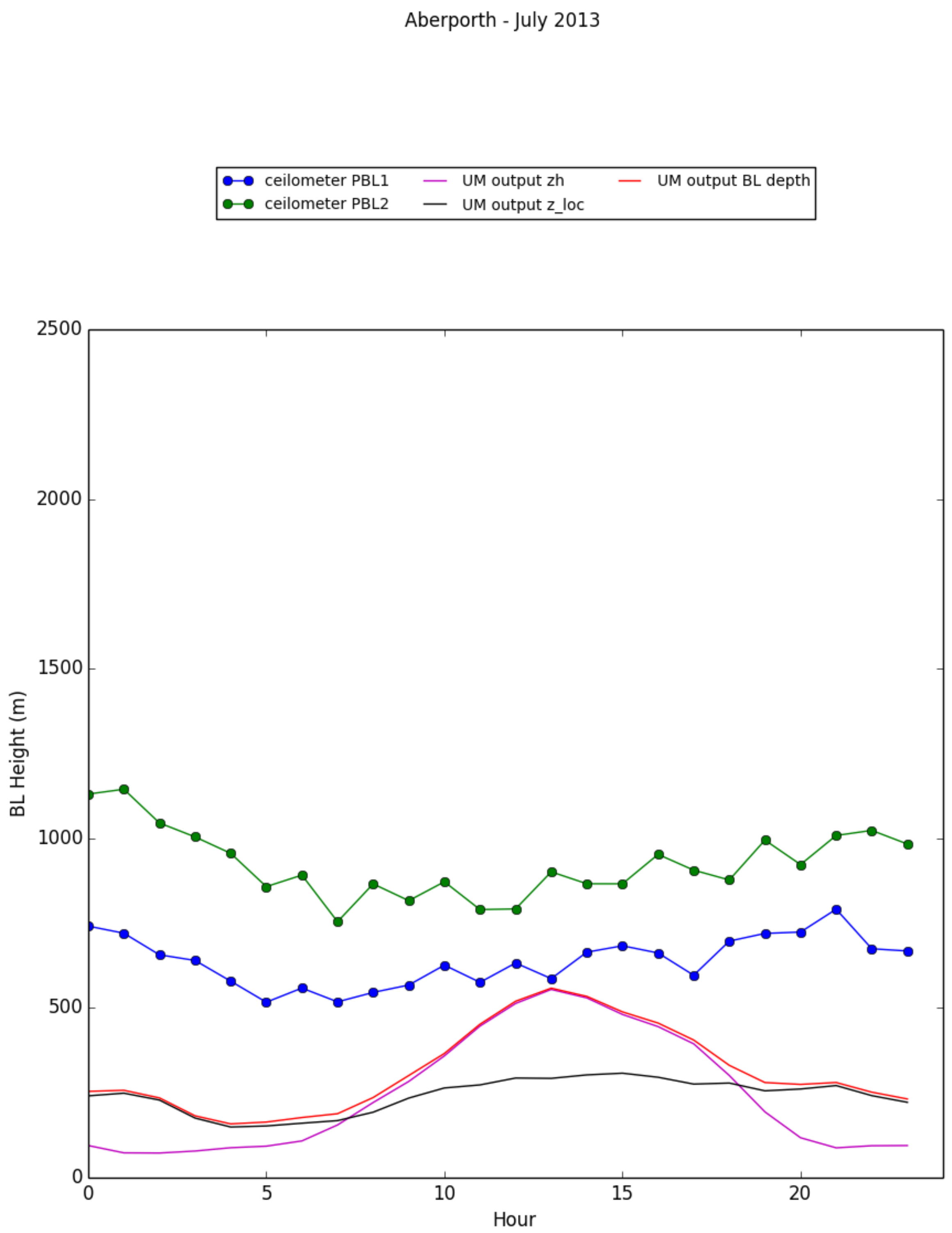


Figure 9: Monthly average plot for Aberporth in July 2013.

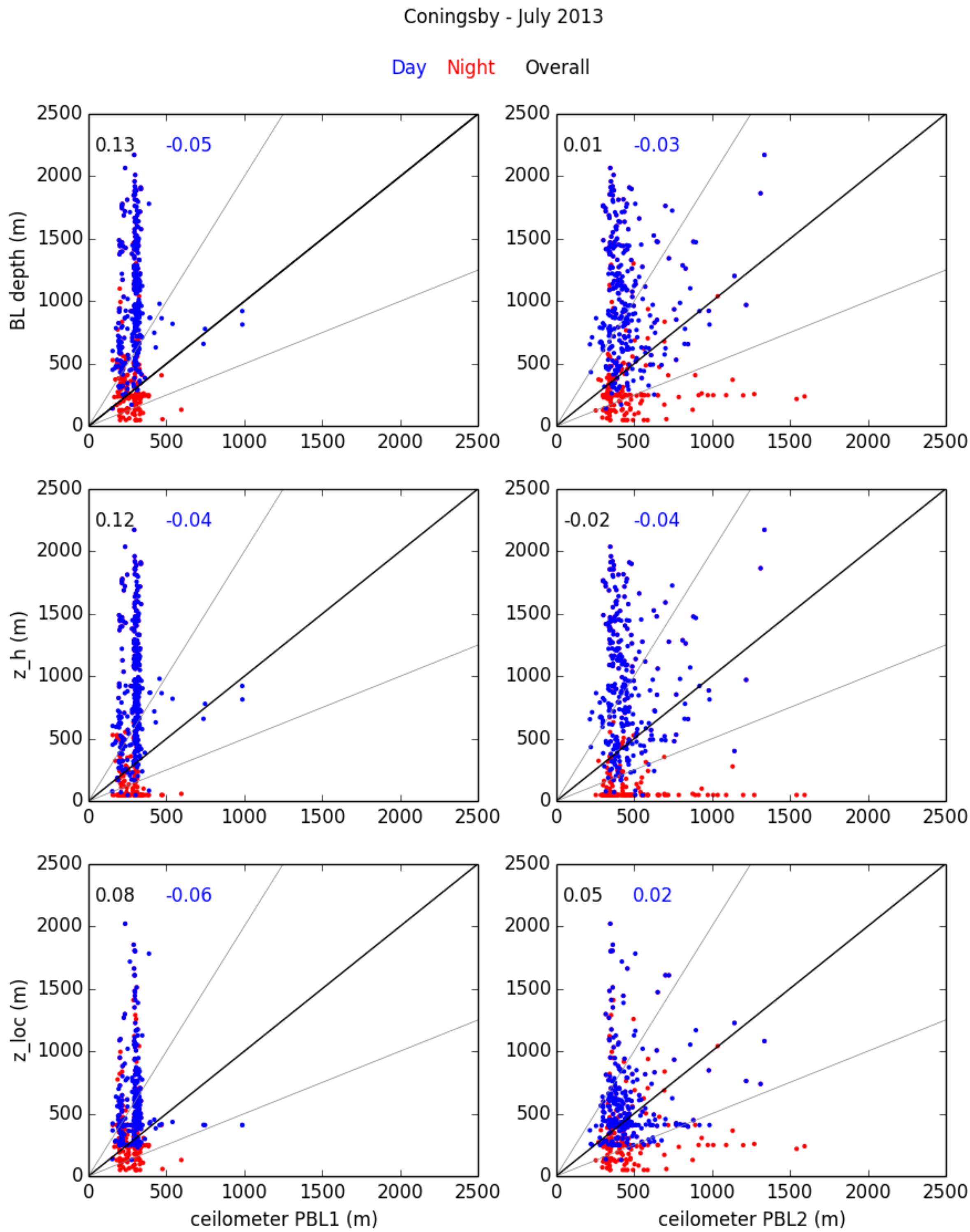


Figure 10: Correlation plots for Coningsby in July 2013.

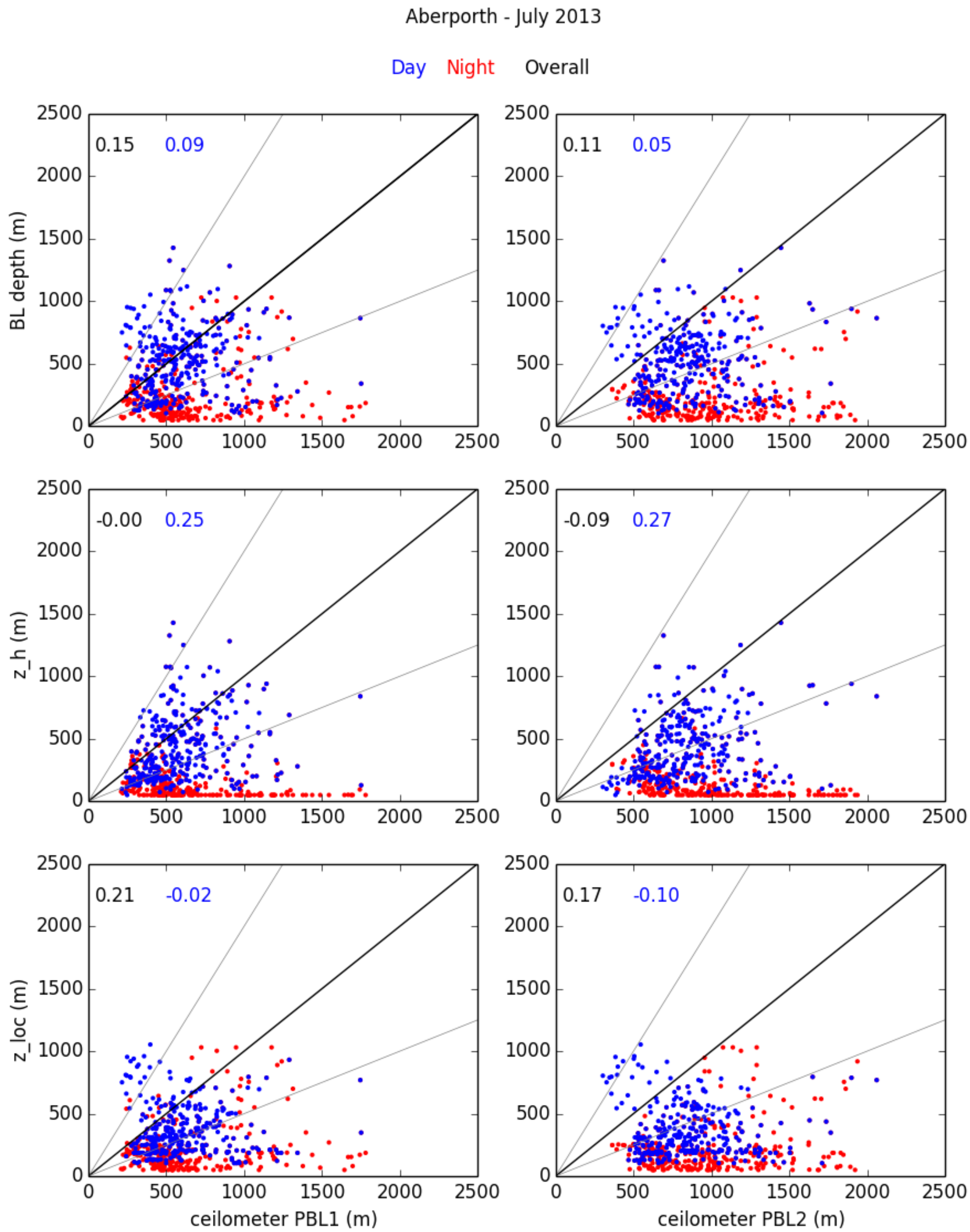


Figure 11: Correlation plots for Aberporth in July 2013.

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Appendix I: Python code

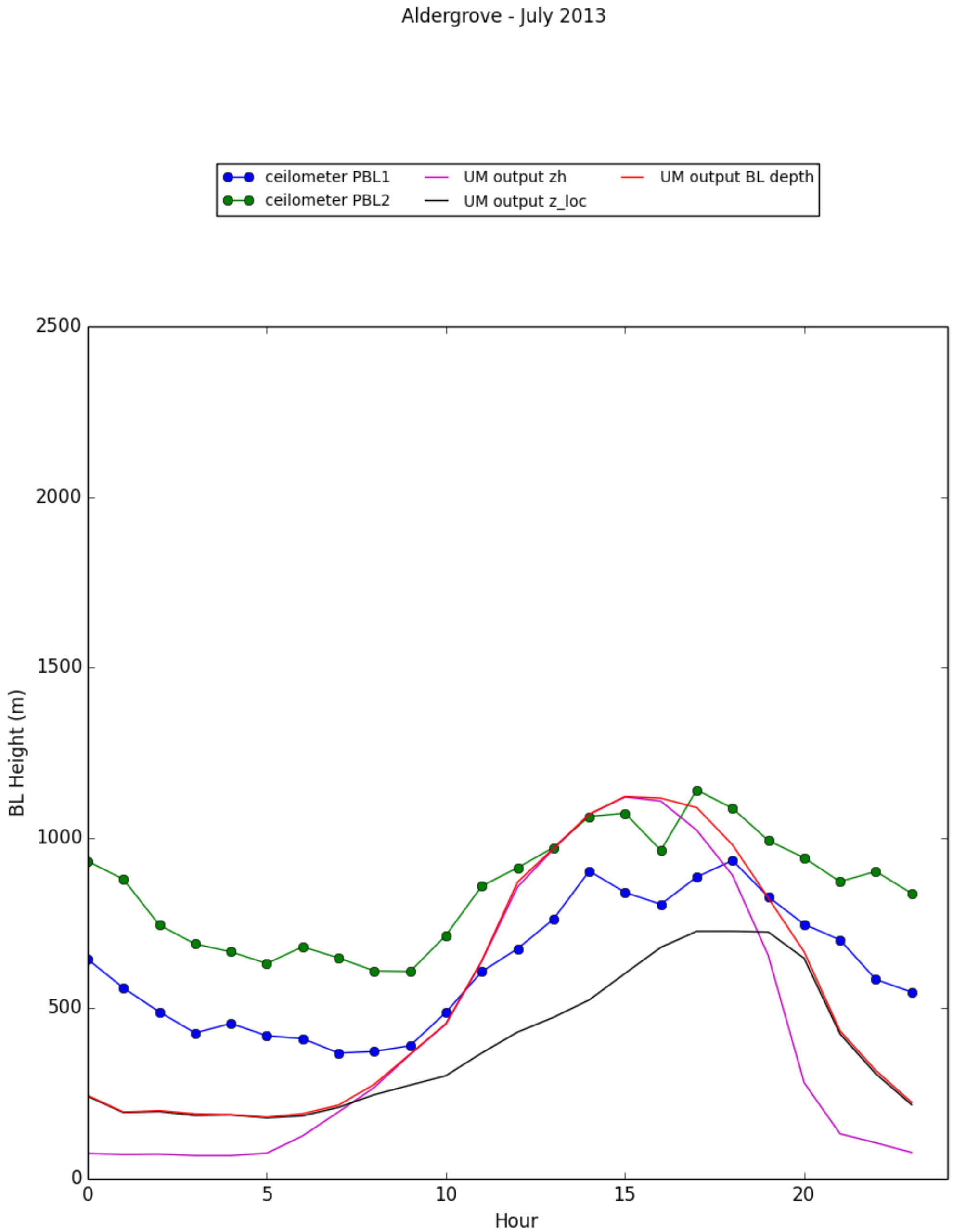
All the plots shown have been created with a branch from the ADAQ_PythonCode repository (vselvara/blh_jenoptik_aqum/adaqcode/boundary_layer_height). The revision of the branch used is [381] with a corresponding ticket #96.

Details of the programs are briefly documented here:

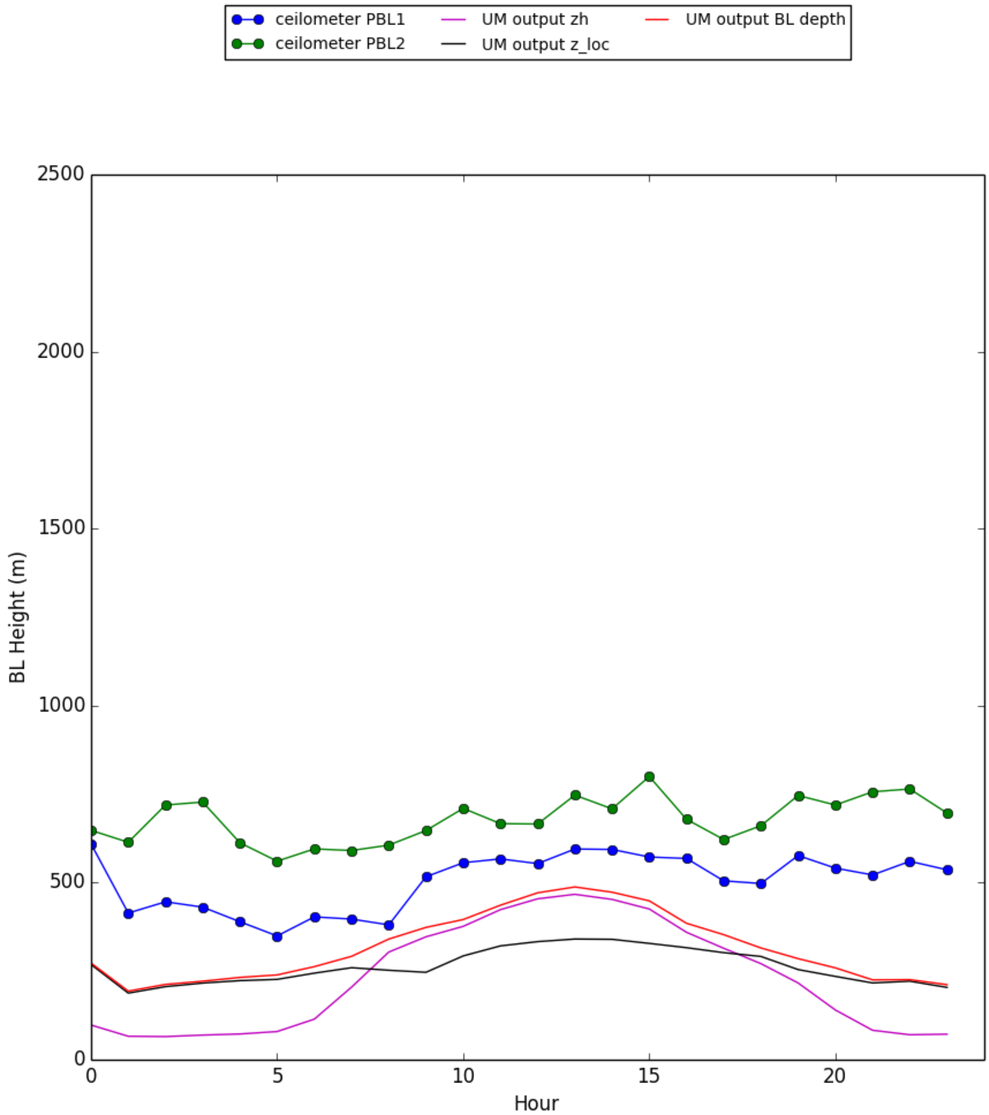
get_blh_diags_from_mass.py - extracts some BLH diagnostics from AQUM output stored on mass
extract_blh_diags_sites.py - gets BLH diagnostics at specific sites (into netCDF files)
blh_diags_sites_output.py - puts these BLH diagnostics at the sites into text files
get_rcs_blh_jenoptik.py - makes scatter plots of ceilometer output
get_rcs_blh_jenoptik2.py - makes scatter plots of ceilometer output with AQUM diagnostics over-plotted
rcs_hourly_average.py - hourly averaged ceilometer data
rcs_noise.py - filtered ceilometer hourly averaged data to reduce noise
plot_tseries_selection.py - plots time series of ceilometer and UM data for whole month for each site with good days in bold
plot_tseries_selection2.py - same plots using filtered ceilometer data
plot_monthly_avg.py - plots average diurnal cycles of ceilometer and UM data considering all good days in a month for each site
plot_monthly_filt.py - same using filtered ceilometer data
plot_corr.py - ceilometer vs. UM data scatter plots with correlation coefficients
plot_corr_filtered.py - same plots using filtered ceilometer data

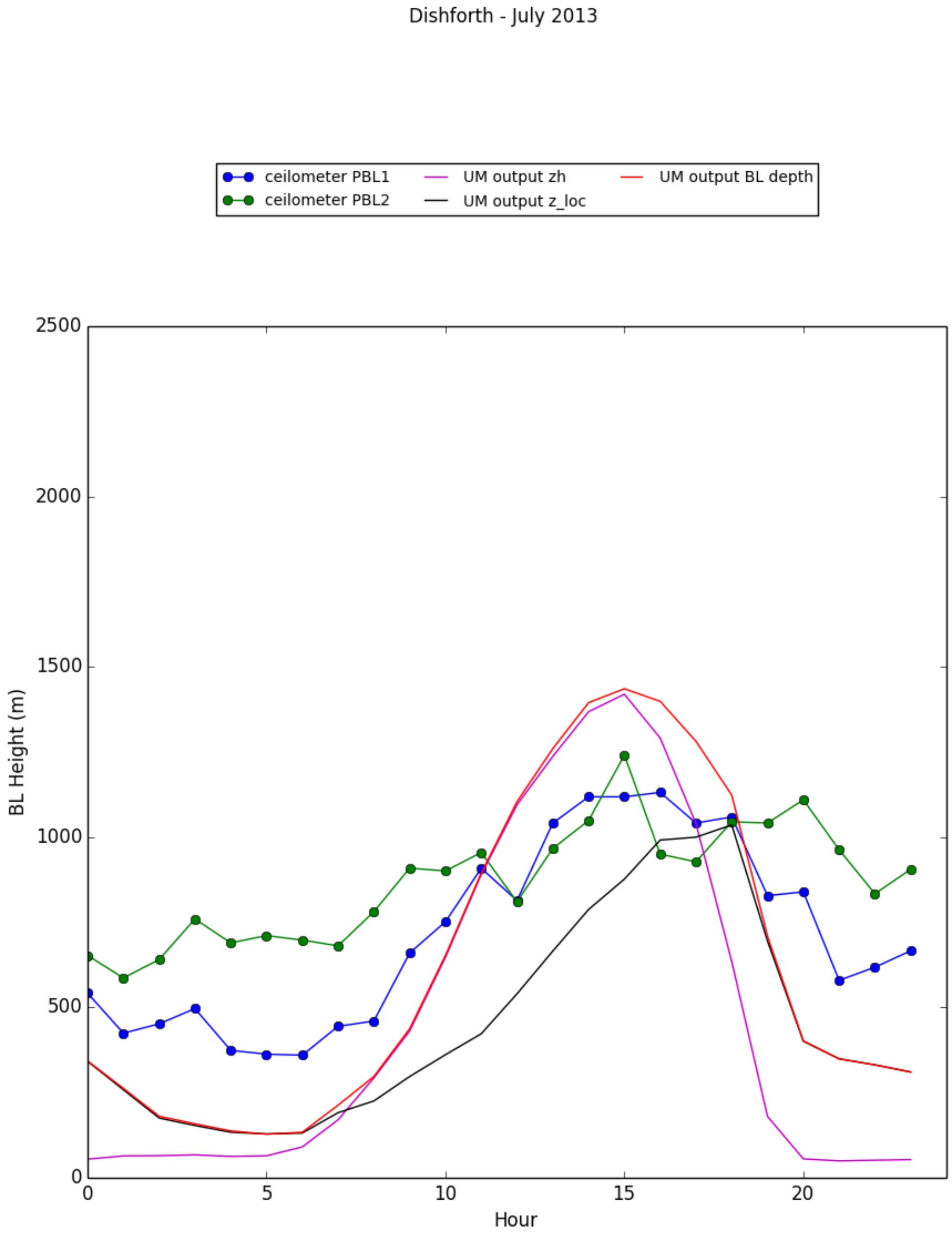
Appendix II: Additional plots

Below are the monthly average plots of boundary layer heights from the ceilometer and model for the good days at the sites not yet shown. South Uist has been omitted due to a limited number of good days to average over.


Aldergrove - July 2013
ceilometer PBL1
ceilometer PBL2
UM output zh
UM output z_loc
UM output BL depth
BL Height (m)
2500
2000
1500
1000
500
0
Hour
0
5
10
15
20

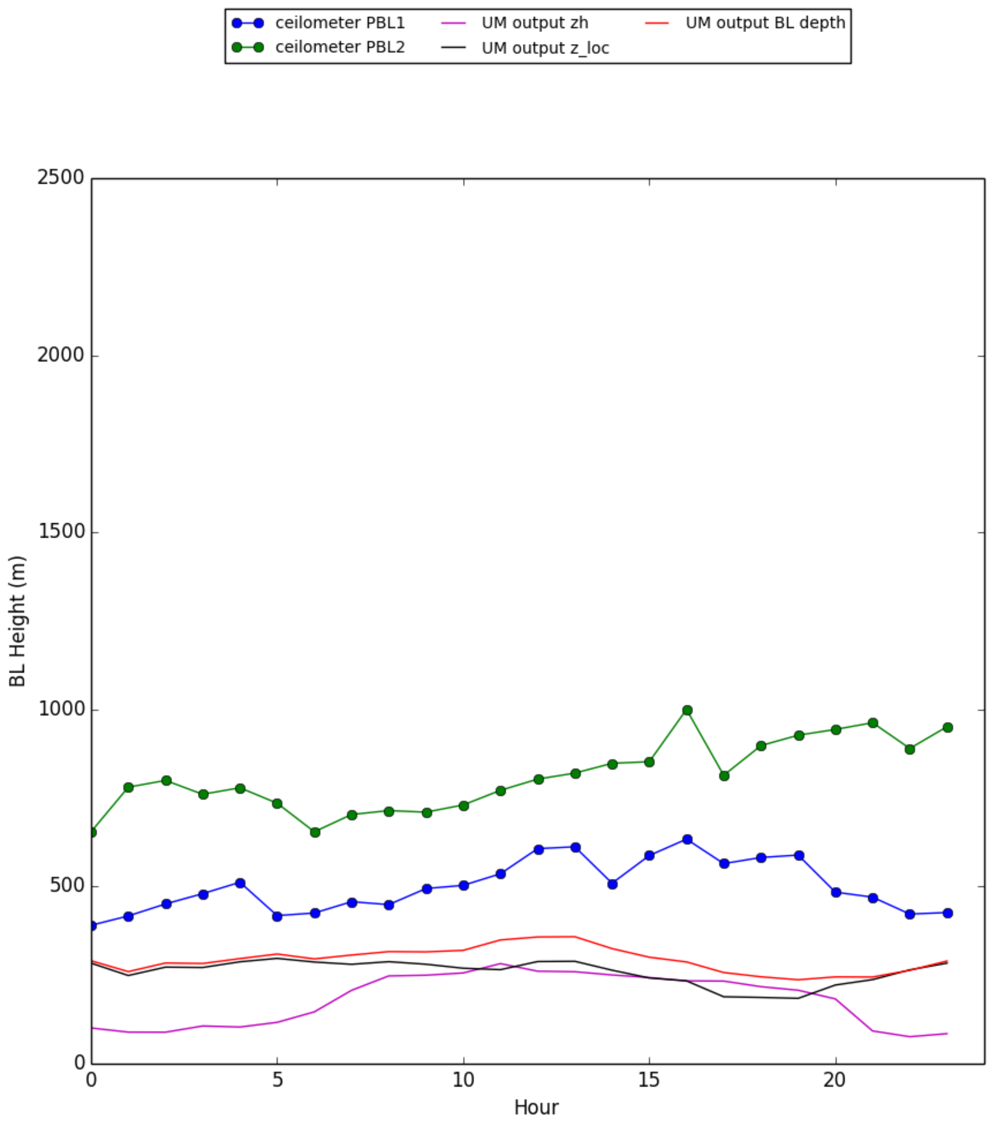
Camborne - July 2013

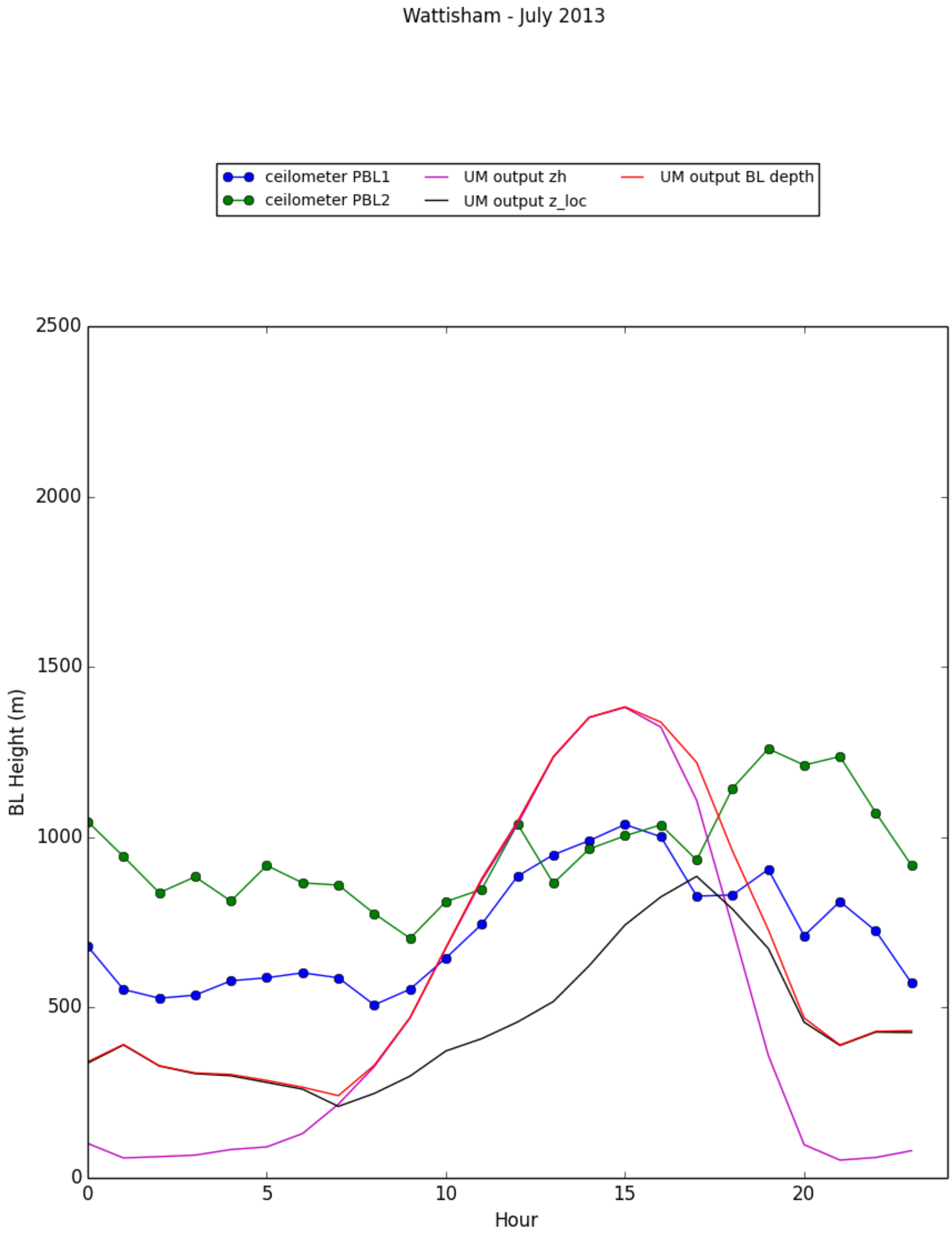




Dishforth - July 2013
ceilometer PBL1
ceilometer PBL2
UM output zh
UM output z_loc
UM output BL depth
BL Height (m)
Hour
0
500
1000
1500
2000
2500
0
5
10
15
20

Stornoway - July 2013




Wattisham - July 2013
ceilometer PBL1
ceilometer PBL2
UM output zh
UM output z_loc
UM output BL depth
BL Height (m)
Hour
0
500
1000
1500
2000
2500
0
5
10
15
20

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