



UNIVERSITY OF LEEDS

This is a repository copy of *Verification of Mountain Weather Information Service forecasts for three upland areas in the UK.*

White Rose Research Online URL for this paper:  
<http://eprints.whiterose.ac.uk/85894/>

Version: Accepted Version

---

**Article:**

Procter, N, Birch, CE, Monk, G et al. (1 more author) (2014) Verification of Mountain Weather Information Service forecasts for three upland areas in the UK. *Weather*, 69 (12). 342 - 349. ISSN 0043-1656

<https://doi.org/10.1002/wea.2314>

---

**Reuse**

Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.



[eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk)  
<https://eprints.whiterose.ac.uk/>

**Verification of Mountain Weather Information Service  
forecasts for three upland areas in the UK**

Journal:	<i>Weather</i>
Manuscript ID:	WEA-13-0098.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Procter, Nathan; University of Leeds, School of Earth and Environment Birch, Cathryn; University of Leeds, School of Earth and Environment Monk, Geoffrey; The Weather Centre, Mountain Weather Information Service Marsham, John; University of Leeds, National Centre for Atmospheric Science
Keywords:	Mountain weather, Weather forecasting, Forecast verification

SCHOLARONE™  
Manuscripts

Review

## Verification of Mountain Weather Information Service forecasts for three upland areas in the UK

N. Procter<sup>1</sup>, C. E. Birch<sup>1</sup>, G. Monk<sup>2</sup>, J. H. Marsham<sup>1</sup>

<sup>1</sup>School of Earth and Environment, University of Leeds, UK

<sup>2</sup>Mountain Weather Information Service, Dumfries and Galloway, UK

Correspondence to: Dr Cathryn Birch, School of Earth and Environment, University of Leeds, Leeds,

LS2 9JT, UK, [C.E.Birch@leeds.ac.uk](mailto:C.E.Birch@leeds.ac.uk)

### 1 Introduction

UK mountains pose a particular forecast challenge; the proximity of all the upland regions to a coastline produces localised and complex weather, which is difficult to forecast. Conditions in the mountains can be vastly different from neighbouring low-lying regions and the severity of the weather often surprises people, given the fairly low altitude of the hills and the relatively mild British weather. The location of the UK in the mid-latitude storm track means the weather can change quickly, from calm and beautiful (e.g. Figure 1) to severe conditions, sometimes within only a few hours.

The Mountain Weather Information Service (MWIS) provides daily weather forecasts for eight upland regions of the UK: Northwest Highlands, West Highlands, Cairngorms National Park and Monadhliath, Southeastern Highlands, Southern Uplands, Lake District, Snowdonia National Park, and Peak District and Yorkshire Dales (<http://www.mwis.org.uk>). MWIS is run by a small team, headed by Geoffrey Monk, who combine freely available model products from the UK, US and Canadian national weather services and the European Centre for Medium-Range Weather Forecasts with their knowledge and experience of complex mountain weather conditions to create the mountain forecasts. Until now MWIS have had little opportunity to verify their forecasts against

1  
2  
3 observations. Through collaboration between MWIS and the University of Leeds this study uses  
4  
5 publically available observations from automatic weather stations (AWS) located in upland areas to  
6  
7 evaluate forecasts from three of the regions.  
8  
9

10 MWIS was established between 2002 and 2005 from a small office in Dumfries and Galloway. Prior  
11  
12 to this mountain forecasts were only accessible from the UK Met Office via premium rate fax and  
13  
14 telephone lines. Having an interest in mountain forecasting, Geoff surveyed the requirements of the  
15  
16 mountain user community and MWIS was then established after a long trial of forecasts for a limited  
17  
18 area of the West Highlands. The forecasts are specifically tailored to the users' needs and are set out  
19  
20 in a way that effectively communicates the potential dangers by, for example, placing wind speed at  
21  
22 the top of the forecast and giving the likely effect of that particular speed on a hill-walker. Since  
23  
24 October 2007 Sportscotland, the national agency for sport in Scotland, have fully funded the  
25  
26 provision of the Scottish forecasts, however the English and Welsh forecasts remain without funding  
27  
28 and the additional operational costs of the website are covered by commercial sponsorship. The  
29  
30 forecasts may now be viewed by as many as two million people every year.  
31  
32

33  
34 In this paper, the relative accuracy and consistency of the 1, 2 and 3-day MWIS forecasts are  
35  
36 analysed, and an assessment of improvements in the forecast performance between 2006 and 2012  
37  
38 is made. The forecasting of high-wind speed and low-temperature events is investigated further, and  
39  
40 finally two case studies are presented, which highlight reasons for some of the larger forecast errors.  
41  
42  
43

## 44 **2 Forecasts and observations**

45

46  
47 Each MWIS forecast consists of two A4 pages. The first page presents a summary of the general  
48  
49 conditions followed by a more detailed forecast, which includes sections describing how windy, wet,  
50  
51 cloudy, hazy and cold the day is expected to be. Numeric values for temperature and wind speed are  
52  
53 given, as well as qualitative descriptions of temporal and spatial variations and, when appropriate,  
54  
55 the possibility of more severe conditions is highlighted (see example in Table 1). The second page  
56  
57  
58  
59  
60

1  
2  
3 looks ahead to the following two days, with brief entries for the same sections. The forecasts for  
4  
5 Scottish regions specify wind and temperature values at an altitude of 900m, and for the Lake  
6  
7 District at an altitude of 750m.  
8  
9

10 Observations from AWSs located on or close to the top of hills, were used to verify the forecasts  
11  
12 from three of the eight regions. Data are recorded hourly by the stations and include wind direction,  
13  
14 wind speed, temperature, dew point temperature and highest gust speed in the last hour. The Lake  
15  
16 District (LD) was chosen as a region to be verified due to the large number of walkers it attracts. An  
17  
18 AWS at Great Dun Fell (Figure 2) provided the observational data against which to verify the  
19  
20 forecasts. The Northwest Highlands (NW) was chosen due to its frequency of severe weather, with  
21  
22 an AWS at Bealach-na-ba providing the observational data. Neither Great Dun Fell AWS (847m) nor  
23  
24 Bealach-na-ba AWS (773m) match the 750 and 900m forecasting altitudes closely. The region of  
25  
26 Southeastern Highlands (SE), with data from an AWS at Cairnwell (933m), was therefore selected as  
27  
28 the third region for verification specifically because the AWS-forecast height difference is small  
29  
30 (33m).  
31  
32  
33  
34

### 35 **3 Method**

36  
37 Verification was only possible for aspects of the forecasts that provide a numerical value and thus  
38  
39 the study focuses on wind and temperature, which are also two of the key variables for mountain  
40  
41 safety. Attempts to verify the 'chance of summits in cloud' forecasts by comparison with  
42  
43 temperature and dew point temperature proved unsuccessful, perhaps due to unreliable dew point  
44  
45 measurements and are thus not presented here. The forecasts describe the expected conditions 'for  
46  
47 the day'; with the emphasis on the middle of the day because this is the time users tend to be out on  
48  
49 the hills. The observation recorded at midday is used to verify the forecast but if conditions are  
50  
51 predicted to change considerably over the day a range of values is given in the forecast description  
52  
53 and for the analysis a midday estimate is determined by interpreting the wording of the forecast.  
54  
55 Day one (d+1) values are verified for both 2006 and 2012 and additionally, day two (d+2) and day  
56  
57  
58  
59  
60

1  
2  
3 three (d+3) are verified for 2006. It is necessary to be aware of the limitations of using a point  
4  
5 measurement to verify daily forecasts for a large region of complex terrain during the analysis.  
6  
7

8 Three statistical measures were used to compare the relationship between forecast and  
9  
10 observation. Root mean square error (RMSE) is a measure of dispersion from the one-to-one  
11  
12 (perfect forecast) line – a low value indicates generally accurate forecasts. Another measure used is  
13  
14 the least squares regression, or best-fit line; a gradient of close to 1 and an intercept close to 0 is  
15  
16 desirable. Pearson's correlation coefficient (PCC) is a measure of linear correlation; an absolute value  
17  
18 close to one indicates highly consistent, but not necessarily accurate, forecasts. For example, the  
19  
20 data in Figure 4a could be well correlated along the regression line (red) but the regression line may  
21  
22 not be equal to the one-to-one line (black).  
23  
24

25  
26 Correct forecasting of very cold or very windy conditions is especially important as these are  
27  
28 particularly dangerous conditions. These events were defined as freezing temperatures ( $\leq 0$  °C) or  
29  
30 wind speeds equal to or greater than 40 mph since these values represented thresholds beyond  
31  
32 which weather becomes significantly more hazardous. The performance of forecasting these events  
33  
34 was examined through contingency tables.  
35  
36

#### 37 38 **4 Statistical assessment of forecast error**

39  
40 Data from the three sites are combined in Figure 3 to present the study results for forecasting  
41  
42 accuracy of d+1 wind direction. The plots show the difference between forecast and observation as a  
43  
44 proportion of total days for each year. Both years' forecasts are generally accurate with the majority  
45  
46 of forecast wind directions close to the observed value: the percentage of forecasts that are within  
47  
48 45° of the true wind direction improves between the two years, increasing from 69% for 2006 to 82%  
49  
50 for 2012. Neither year shows significant asymmetry about 0°, demonstrating that the forecast is  
51  
52 equally likely to be anticlockwise or clockwise of the true direction. Separate plots for each region  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 indicate that all three regions improved, with the level of improvement greatest for SE and least for  
4  
5 NW (not shown).  
6

7  
8 As an example, Figure 4 shows the d+1 observation-forecast scatterplots for temperature and wind  
9  
10 speed against the 'perfect forecast' one-to-one line for the SE region. The d+1 observation-forecast  
11  
12 scatterplots for wind speed indicate similar results for NW and LD (not shown). Statistics for all three  
13  
14 regions are shown in Table 2. The scatterplots indicate a good degree of overall consistency with  
15  
16 most winds speeds being accurately forecast (e.g. PCC=0.8 for 2012) and improvement between  
17  
18 2006 and 2012 is evident for all three regions. For LD and SE the gradient of the line of best-fit  
19  
20 increases toward 1, the intercept decreases toward zero, and both the RMSE and PCC improve. For  
21  
22 NW the gradient, intercept and PCC improve but the RMSE is almost unchanged – in fact it increases  
23  
24 by 0.016mph. The improved PCC (which is unaffected by bias) for each region indicates more  
25  
26 consistent forecasts, but there is some evidence of systematic bias. LD data displays a general trend  
27  
28 of under-forecasting wind speed, consistent with the forecast being for a lower altitude than the  
29  
30 observation, although this bias was reduced between 2006 and 2012. NW data shows little bias in  
31  
32 the 2006 forecasts, but in 2012 a tendency to over-forecast was evident (consistent with the  
33  
34 forecast being for a higher altitude than the observation). SE forecasts, where the observation-  
35  
36 forecast height difference was only 33 m, displayed no obvious bias in either year.  
37  
38  
39

40  
41 Temperature d+1 scatterplots for all three regions and both years demonstrated accurate forecasts  
42  
43 although again differences are to be expected due to the differences between the altitudes of AWS  
44  
45 observations and the altitude of the forecast. Points on the NW plot tend to lie to the right of the  
46  
47 one-to-one line because the observation altitude is lower than the forecast altitude and to the left  
48  
49 on the LD plot because the observations altitude is higher than the forecast altitude. There was no  
50  
51 clear bias for the SE where the AWS is only 33m above the forecast altitude of 900m. All three  
52  
53 regions produced very high PCCs in both years (around 0.95) and showed reductions in the RMSE of  
54  
55 5.4% (LD), 8.8% (NW) and 8.5% (SE) from 2006 to 2012 respectively. All six lines of best-fit are also  
56  
57  
58  
59  
60

1  
2  
3 close to the one-to-one line, although the gradient for each of the three regions decreases away  
4  
5 from 1 between 2006 and 2012 by 0.11 (LD), 0.10 (NW) and 0.07 (SE) respectively. The shallower  
6  
7 2012 gradients are partly explained by under-predictions of high temperatures during the heat wave  
8  
9 at the end of May in that year (see case study below). If the last 11 days of May are removed from  
10  
11 the data, the three best-fit line gradients increase by 0.031 (LD), 0.029 (NW) and 0.027 (SE)  
12  
13 respectively.  
14  
15

16  
17 Hill-walkers and mountaineers often make the decision to travel to an upland region two or three  
18  
19 days in advance, hence the quality of the two and three-day forecasts is important. Table 2 also  
20  
21 shows the 2006 statistics for the two (d+2) and three (d+3) day forecasts. As is to be expected for all  
22  
23 three regions the PCC, RMSE and gradient worsen for the longer range forecasts of both wind speed  
24  
25 and temperature. However the deterioration is by no means severe (e.g. PCC decreases by less than  
26  
27 0.1 between d1 and 3 for all three regions for both wind speed and temperature).  
28  
29

30  
31 The contingency tables shown in Table 3 combine the results for all three regions and examine the  
32  
33 forecast accuracy of high wind speed ( $\geq 40$  mph) and low temperature ( $\leq 0$  °C) events Each day is  
34  
35 assigned to one of four categories: hits (correct predictions of events), false alarms (predictions of  
36  
37 events which are incorrect), misses (observed events which are not forecast), or correct predictions  
38  
39 of the non-occurrence of events. a, b, c and d are the percentages of days which fall into each  
40  
41 respective category. Furthermore a+b is the total percentage of days that are forecast as high wind  
42  
43 speeds/low temperature events, so  $a/(a+b)$  is the 'Proportion of Forecasts of Events that are Correct'  
44  
45 (denoted PFEC), which can be interpreted as the probability that an event will occur given that it is  
46  
47 forecast. Similarly a+c is the total percentage of days that are observed as events, so  $a/(a+c)$  is the  
48  
49 'Proportion of Events that are Correctly Forecast' (denoted PECF), which can be interpreted as the  
50  
51 probability an event will be forecast given that an event will occur.  
52  
53

54  
55 The temperature contingency tables show very little change between the two years. Both had high  
56  
57 numbers of hits (17.6% and 18.6%), with comparatively few misses (3.6% and 4.2%) or false alarms  
58  
59  
60

1  
2  
3 (6.8% for both). Both years show a bias toward over-forecasting, with a greater number of forecasts  
4 of sub-zero days ( $17.6\%+6.8\%=24.4\%$  and  $18.6\%+6.8\%=25.4\%$ ) than observations  
5 ( $17.6\%+3.6\%=21.2\%$  and  $18.6\%+4.2\%=22.6\%$ ). This is influenced by the AWS-forecast altitude  
6 difference; the LD and NW AWS observations are above and below the forecast height so under and  
7 over-forecasting are evident in these regions respectively. Conversely, the SE AWS is at a slightly  
8 higher altitude than the forecast and yet significant over forecasting is apparent. This indicates that  
9 the over forecasting displayed in the contingency table is indeed genuine. For the two years the  
10 PECFs were high (0.83 and 0.81) as were the PFECs – (0.72 and 0.73).

11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21 The wind speed contingency tables show a slight decrease in the number of high wind speed events  
22 observed; from  $5.5\%+7.2\%=12.7\%$  to  $7.2\%+4.9\%=12.1\%$  between 2006 and 2012. Given this  
23 decrease it may be expected that the number of hits and false alarms would decrease because there  
24 are fewer opportunities for them to occur. However both percentages increase; the hits from 5.5%  
25 to 7.2% and the false alarms from 4.7% to 7.5%. This is to most likely due to the apparent increase in  
26 the readiness to forecast high winds; the percentage of days forecast as high wind speed events  
27 increases from 10.2% to 14.7%. Both the increase in the forecasting and the decrease in the  
28 observation of high wind speed events lead to a decrease in misses (from 7.2% to 4.9%). The large  
29 increase in the forecasting of high winds would also lead to the expectation that the PECF would rise  
30 – indeed it rose from 0.43 to 0.60 - and that the PFEC would fall – it did, from 0.54 to 0.49. This is  
31 again because the forecast is more likely to catch the high wind speed days, but at the cost of  
32 increased risk of causing false alarms. Given that the increase is much greater than the decrease, and  
33 that misses are a greater concern than false alarms, this could well be interpreted as an overall  
34 improvement in the forecasting of high winds.

### 52 **5 Conditions associated with large forecast errors**

53  
54  
55 Whilst the verification statistics suggest that the forecasts are in general reasonably accurate, there  
56 are outliers apparent on the scatterplots (e.g. Figure 4, marked in black for temperature in 2012)

1  
2  
3 represent days with larger forecast errors. The days with the 10 largest errors in temperature and  
4  
5 wind speed in each year and region are considered in more detail. For several of these days the  
6  
7 textual summary of the forecasts conveyed the forecaster's uncertainty of weather conditions or  
8  
9 their timing, or presented more than one possible outcome. This qualitative information cannot be  
10  
11 reflected in the statistics but sometimes did in fact correspond well with the hourly observations.  
12  
13 Any days in the top ten errors for which it was felt the forecast adequately described the  
14  
15 observations of the day were discounted, and the conditions of the remaining days analysed.  
16  
17 Conditions which were prone to large errors are discussed below.  
18  
19

20  
21 The majority of the largest errors in wind speed were under high-wind conditions, associated with  
22  
23 the passage of low-pressure systems. Comparisons of forecast and analysis charts indicated that in  
24  
25 most cases the timing of the passage of the front was incorrectly predicted by the NWP models,  
26  
27 leading to errors in the forecast wind speed (not shown).  
28  
29

### 30 **5.1 Winter inversions**

31  
32  
33 Three of the largest temperature errors in 2006 occurred during the winter months, when the UK  
34  
35 weather was dominated by high-pressure conditions. A region of high pressure moved over the UK  
36  
37 on 23<sup>rd</sup> January, became well-established on 26<sup>th</sup> January and persisted until 7<sup>th</sup> February (see  
38  
39 example charts, Figure 5c and d). During this period the error in forecast temperature was up to 7 °C.  
40  
41 On some days the textual summary for temperature in the forecast suggests a large  
42  
43 uncertainty/range, although some large errors do remain. Figure 5 illustrates two examples during  
44  
45 this period. The plots show the hourly observations over each day, the observation at midday and  
46  
47 the forecast value. On 30 January 2006 in LD the forecast midday temperature was 3.5°C and the  
48  
49 observed midday temperature was 10.8°C. In fact, the observed temperature remained at least 4°C  
50  
51 warmer than the forecast throughout the daylight hours (Figure 5a). The opposite occurred on 1  
52  
53 February 2006 in NW; the forecast value was 4°C but the observed value was -3.3°C, more than 7°C  
54  
55 cooler than predicted (Figure 5b).  
56  
57  
58  
59  
60

1  
2  
3 Radiosonde observations from Castor Bay in Northern Ireland at 1200 UTC on 30 January and 1  
4  
5 February are illustrated by the tephigram plots in Figures 6 and 7, which should be indicative of  
6  
7 conditions in NW and LD. The temperature (red line) and dew point temperature (blue line) are  
8  
9 plotted in this format so that the stability of the atmosphere can be easily assessed. An explanation  
10  
11 of the axes is given in the figure caption. A temperature inversion exists when the temperature  
12  
13 increases with height. Figure 6 shows two inversions close to the surface. The first exists from very  
14  
15 near the surface up to 1010 hPa (200 m) with a temperature difference of  $\sim 5^{\circ}\text{C}$  and the second  
16  
17 spans 990 to 970 hPa (360-500 m) with a temperature difference of  $\sim 6^{\circ}\text{C}$ . On 1 February there is a  
18  
19 single inversion that is elevated from the surface, spanning 930 to 875 hPa (775-1300 m), with a  
20  
21 temperature difference of  $\sim 6^{\circ}\text{C}$ . The elevated inversions in Figure 6 and 7 are likely caused by the  
22  
23 anticyclone, which is associated with large-scale subsidence and low-winds (Iijima and Shinoda,  
24  
25 2000) that cause air to warm as it descends. The surface-based inversions are likely due to the  
26  
27 radiative cooling of the surface. Sharp temperature changes in the vertical and their variation on  
28  
29 sub-daily scales are extremely challenging to represent in NWP models (Sheridan *et al.*, 2010). When  
30  
31 the altitude of the inversion is close to the forecast height, it is extremely difficult to produce an  
32  
33 accurate forecast because slight variations in the height of the inversion will lead to large errors in  
34  
35 the temperature profile.  
36  
37  
38

39  
40 A spectacular example of a temperature inversion from this period was photographed near  
41  
42 Aviemore in the North-East Highlands at 1200 UTC, 29 January 2006 (Figure 1). On this day the  
43  
44 tephigram is very similar to those in Figure 7, the inversion base at approximately 900 m above sea  
45  
46 level. The top of the cloud layer in the photograph resides at approximately 900 m, in agreement  
47  
48 with the radiosonde observations.  
49

50  
51  
52 Predicting any cloud layers associated with the inversion can also be challenging (Fernando and Weil,  
53  
54 2010) and is another reason for NWP forecast uncertainty or the uncertainty in forecast-observation  
55  
56 comparisons. The forecast for the LD on 30 January 2006 suggested cloud may be present in the east  
57  
58  
59  
60

1  
2  
3 of the region for at least part of the day. The satellite image in Figure 8a shows cloud is only present  
4  
5 in the northern-most part of the region at 1200 UTC, which may help explain the under-prediction of  
6  
7 temperature. On 1 February 2006 cloud was forecast only in the western part of the NW highlands,  
8  
9 which is in agreement with the satellite image in Figure 8b. The cloud layer was predicted to reside  
10  
11 between 400 and 700 m (i.e. below the inversion). The AWS at Bealach-na-ba is at 773 m and thus  
12  
13 could have been in cloud on this day, possibly adding to the forecast-observation difference.  
14  
15

## 16 17 **5.2 Heat wave conditions**

18  
19  
20 7 of the 10 largest temperature errors in 2012 occurred during a period of 'heat-wave' weather  
21  
22 during May. The temperatures increased between the 19 and 23 May during dominant high pressure  
23  
24 (Figure 9b). The hot weather continued through to the 28 May with Scotland breaking its May  
25  
26 temperature record on the 25<sup>th</sup> when 30.9 °C was recorded at Inverailort, Highland, and the  
27  
28 temperatures then cooled toward the end of the month. On all of these occasions the forecast  
29  
30 temperature was up to 6 °C cooler than that observed.  
31  
32

33  
34 23 May 2012 in the Lake District is taken as an example for this period. The temperature was  
35  
36 forecast to be 12-15 °C but the observed temperature was above 15 °C between 0600 and 2000 UTC  
37  
38 and peaked at midday with a recording of 19.5 °C (Figure 9a). The LD was generally cloud-free during  
39  
40 this period and the forecast was consistent with this (not shown). The radiosonde observations from  
41  
42 Nottingham at 1200 UTC (Figure 10) show cloud-free conditions (for cloud to be present  
43  
44 temperature must equal the dew point temperature) with a temperature inversion spanning  
45  
46 approximately 4 °C, from 930 to 910 hPa (800-1000 m). The height of the inversion is close to the  
47  
48 forecast height of 750 m. As with the winter case, it is possible that the forecast temperature was  
49  
50 too low because the height and strength of the temperature inversion were not predicted accurately  
51  
52 by the NWP models.  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 Experience from MWIS suggests that the NWP models they use tend to underestimate maximum  
4  
5 temperatures in mountainous regions during hot weather. NWP models struggle to represent soil  
6  
7 moisture and the coupling between the land and atmosphere (Koster *et al.*, 2004). If errors exist in  
8  
9 this field, they will cause biases in the partition between sensible and latent heat, which could  
10  
11 explain the near-surface temperature biases highlighted by this study. Another reason could be that  
12  
13 heatwaves occur relatively infrequently in the UK and thus forecaster experience in describing them  
14  
15 is more limited compared to other weather conditions.  
16  
17

## 18 19 **6 Conclusions**

20  
21 This study uses observations from upland weather stations to verify mountain weather forecasts  
22  
23 provided by the Mountain Weather Information Service for three different regions in the UK. MWIS  
24  
25 forecasts made one day in advance generally exhibit good levels of accuracy and consistency and  
26  
27 this is largely, and perhaps surprisingly, maintained in day two and three forecasts. The forecasters  
28  
29 at MWIS were pleasantly surprised at the degree to which forecasting performance is maintained. A  
30  
31 possible explanation for this is that the errors associated with the d+2 and d+3 numerical weather  
32  
33 prediction forecasts from the operational centres are small compared to both the errors associated  
34  
35 interpolation of forecast products to the heights and locations required and the issues associated  
36  
37 with representing a relatively large, complex region with a single forecast value.  
38  
39

40  
41 The general accuracy of the wind speed forecasts was good (PCC=0.8 and Gradient>0.7 for all three  
42  
43 regions in 2012), with the largest errors mostly due to incorrect model forecasts of the timing of  
44  
45 incoming fronts. There were very few large errors (>45°) in the forecasting of wind direction, and the  
46  
47 large errors that did occur mainly occurred during periods of very low wind speeds. There is strong  
48  
49 evidence for improvement of the forecasts of the wind, both speed and direction between 2006 and  
50  
51 2012. Improvements to the forecasts of temperature are also apparent but these are less marked,  
52  
53 perhaps due to high quality of the 2006 forecasts. Reasons for these improvements may include  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 increases in forecaster experience and the increased on-line availability of model products since  
4  
5 2006.  
6  
7

8 The analysis of high wind speed or sub-zero temperature days through contingency tables gave  
9  
10 additional insight into the quality of the forecasting of the more severe weather conditions. The  
11  
12 contingency tables for wind speed and temperature differed. The wind-speed tables showed a clear  
13  
14 shift towards more readily forecasting high winds, leading to a large increase (from 0.43 to 0.60) in  
15  
16 the PECF, and a small decrease (from 0.54 to 0.49) in PFEC. In contrast the temperature tables  
17  
18 showed little change between the two years with both tables having PECFs and PFECs just over 0.80  
19  
20 and 0.70 respectively.  
21  
22

23  
24 The largest forecast errors in temperature tend to occur during certain types of weather conditions.  
25  
26 The difficulty in forecasting the exact height and strength of temperature inversions and their  
27  
28 variation over the day was the most common cause of large errors during the winter months. The  
29  
30 hot spell of weather at the end of May 2012 was persistently under-forecast which may also have  
31  
32 been due to similar problems with temperature inversions, due to forecaster inexperience or due to  
33  
34 the inability of models to represent land-surface processes adequately. The precise reasons are  
35  
36 unclear and thus the obvious follow-up study would assess the accuracy of MWIS forecasts during all  
37  
38 heatwaves between 2006 and 2012 and evaluate the near-surface temperature, soil moisture and  
39  
40 surface heat fluxes over the three UK upland regions in NWP models.  
41  
42  
43

#### 44 **Acknowledgements**

45  
46  
47 Our thanks go to NERC for providing the funding for the student placement. We would also like to  
48  
49 thank Hazel Bremner, Duncan Malone and Zoe Dupuy for their help with the collection of the  
50  
51 forecast data. We are grateful to the University of Granada whose archives provided the  
52  
53 observational data, the University of Wyoming for providing the tephigram data, the UK Met Office  
54  
55 (via wetter3 and wetterzentrale) for the synoptic charts and the Dundee Satellite Receiving Station  
56  
57  
58  
59  
60

1  
2  
3 for providing the satellite imagery. We are grateful to two anonymous reviewers for their helpful  
4  
5 comments and suggestions.  
6  
7

#### 8 **References**

9  
10 **Fernando HJS, Weil JC.** 2010. Whither the stable boundary layer?: A shift in the research agenda.  
11  
12 *Bull. Am. Meteorol. Soc.* **91**:1475-1484.  
13

14  
15 **Iijima Y, Shinoda M.** 2000. Seasonal changes in the cold-air pool formation in a subalpine hollow,  
16  
17 Central Japan. *Int. J. Clim.* **20**: 1471-1483.  
18

19  
20 **Koster RD and coauthors.** 2004. Regions of strong coupling between soil moisture and precipitation.  
21  
22 *Science.* **305**: 1138-1140.  
23

24  
25 **Sheridan P, Smith S, Brown A, Vosper S.** 2010 A simple height-based correction for temperature  
26  
27 downscaling in complex terrain. *Meteorol. App.* **17**: 329-339.  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

	<b>Headline for the Lake District</b> Fairly light wind; a few snow showers. May deteriorate later afternoon.
<b>How windy? (On the summits)</b>	Southwesterly 25mph. Will back southerly and into afternoon strengthen toward 35 or perhaps 40mph from west.
<b>Effect of wind on you?</b>	<b>Fairly small, although in afternoon buffeting may become significant.</b>
<b>How wet?</b>	<b>Showers: later merging to give frequent precipitation</b> A few showers, snow above 550m. In early afternoon, from west, showers merging to give almost constant precipitation for around 3 hours.
<b>Cloud on the hills?</b>	<b>Extensively on higher areas</b> Generally cloud rarely clearing above 800m and occasional patches below 600m – most breaks to higher areas northern and eastern fells. Into afternoon cloud may lower toward 350 to 550m
<b>Chance of cloud free summits?</b>	30%
<b>Sunshine and air clarity?</b>	Bursts of sunshine morning eastern and northern fells. Fog on higher areas, and in some valleys at first.
<b>How Cold? (at 750m)</b>	0°C
<b>Freezing level</b>	800m

**Table 1** Example forecast text for the Lake District, 13 January 2014.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49

Correlation Data		LD				NW				SE			
		2012 d 1	2006 d 1	2006 d 2	2006 d 3	2012 d 1	2006 d 1	2006 d 2	2006 d 3	2012 d 1	2006 d 1	2006 d 2	2006 d 3
Wind Speed (mph)	PCC	0.80	0.71	0.69	0.61	0.79	0.61	0.57	0.52	0.80	0.68	0.66	0.59
	RMSE	8.63	10.70	11.04	11.52	11.21	11.19	11.94	12.52	9.06	9.51	9.98	10.91
	Gradient	0.71	0.58	0.55	0.47	0.85	0.56	0.53	0.47	0.85	0.65	0.62	0.55
	Intercept	5.24	6.47	7.19	10.15	9.41	12.48	13.90	15.77	5.58	9.74	10.70	13.06
Temp. (°C)	PCC	0.95	0.96	0.94	0.92	0.95	0.95	0.94	0.92	0.94	0.96	0.94	0.93
	RMSE	1.67	1.76	2.03	2.35	1.80	1.96	2.05	2.11	1.70	1.84	2.10	2.16
	Gradient	0.86	0.98	0.97	0.92	0.90	1.00	1.00	0.97	0.82	0.89	0.89	0.87
	Intercept	1.40	0.65	0.76	1.26	-0.73	-1.15	-1.10	-0.59	0.33	-0.20	-0.19	0.12

**Table 2** Forecast statistics for wind speed and temperature during 2006 and 2012 for each of the three forecast regions.

Wind Speed 2012 (%)		Observed	
All Regions		$\geq 40\text{mph}$	$< 40\text{mph}$
Forecast	$\geq 40\text{mph}$	7.2 (a)	7.5 (b)
	$< 40\text{mph}$	4.9 (c)	80.2 (d)

PECF=0.60, PFEC=0.49

Wind Speed 2006 (%)		Observed	
All Regions		$\geq 40\text{mph}$	$< 40\text{mph}$
Forecast	$\geq 40\text{mph}$	5.5 (a)	4.7 (b)
	$< 40\text{mph}$	7.2 (c)	82.6 (d)

PECF=0.43, PFEC=0.54

Temperature 2012 (%)		Observed	
All Regions		$\leq 0^\circ\text{C}$	$> 0^\circ\text{C}$
Forecast	$\leq 0^\circ\text{C}$	18.2 (a)	6.8 (b)
	$> 0^\circ\text{C}$	4.2 (c)	70.8 (d)

PECF=0.81, PFEC=0.73

Temperature 2006 (%)		Observed	
All Regions		$\leq 0^\circ\text{C}$	$> 0^\circ\text{C}$
Forecast	$\leq 0^\circ\text{C}$	17.6 (a)	6.8 (b)
	$> 0^\circ\text{C}$	3.6 (c)	72.0 (d)

PECF=0.83, PFEC=0.72

**Table 3** Contingency tables for temperature and wind speed during 2006 and 2012 for all three of the forecast regions.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

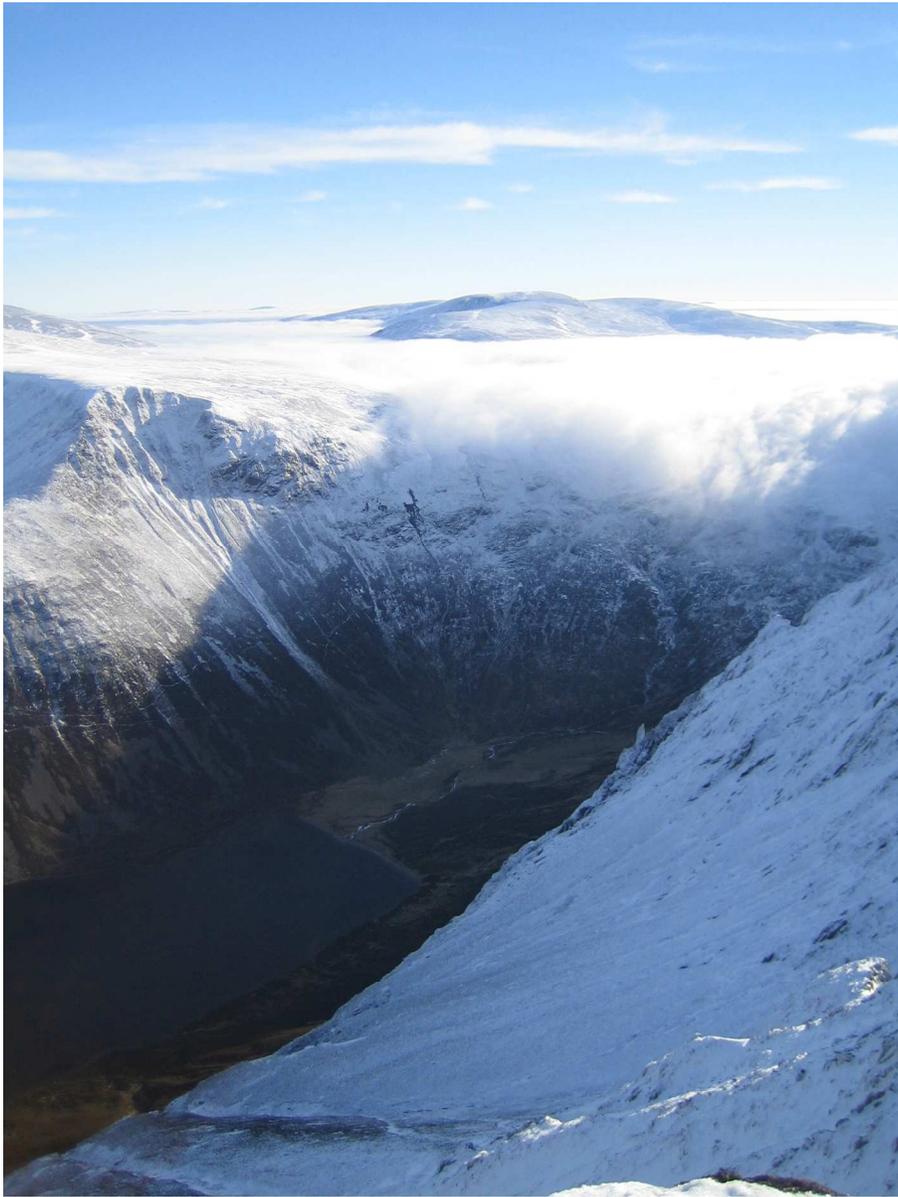


Figure 1 Photo of cloud trapped beneath a temperature inversion, taken at 1200 UTC, 29 January 2006, near Aviemore, North-East Highlands (Photographer Cathryn Birch).  
240x320mm (180 x 180 DPI)

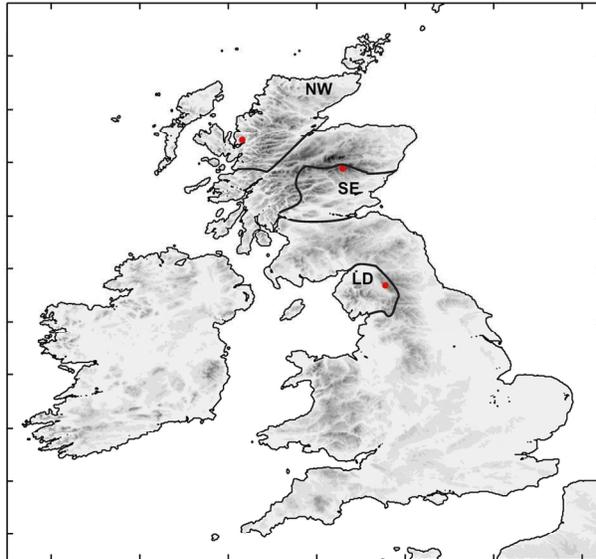


Figure 2 Map illustrating the three forecast regions verified in this study. The AWS locations are marked by the red dots.  
138x97mm (300 x 300 DPI)

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

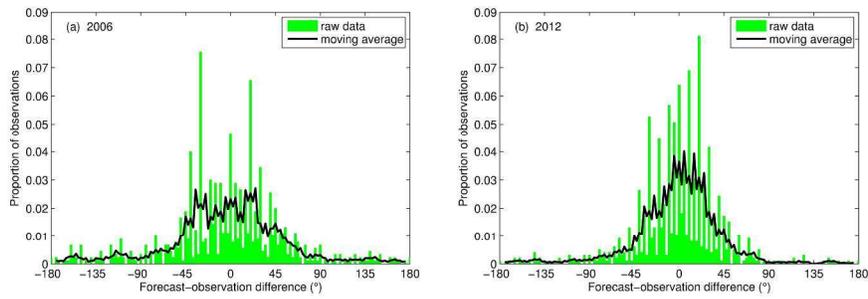


Figure 3 Wind direction errors for all three forecast regions. A positive error denotes a forecast clockwise of the observation. The green bars show the proportion of observations in each bin and the black line is a moving average.

254x179mm (300 x 300 DPI)

review

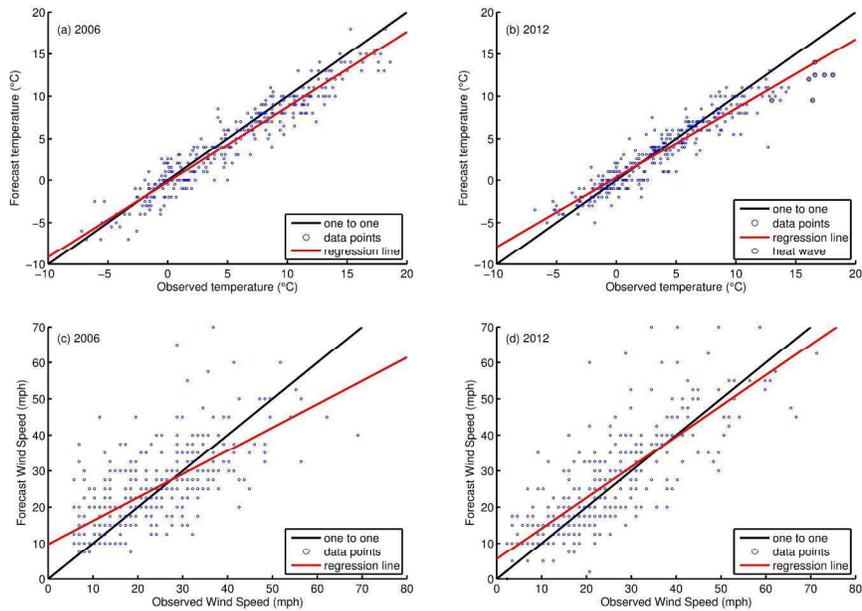


Figure 4 Observation versus forecast scatterplots for SE for (a) 2006 temperature, (b) 2012 temperature, (c) 2006 wind speed and (d) 2012 wind speed. Black points show outliers discussed in relation to heat waves in section 5.2.  
254x179mm (300 x 300 DPI)

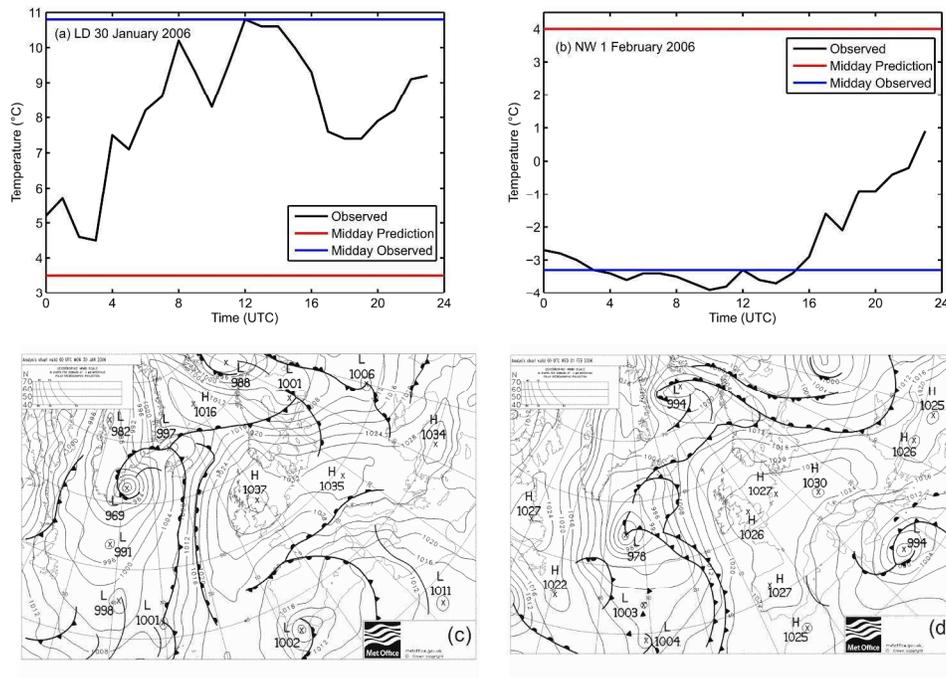


Figure 5 Hourly temperature observations and the midday forecast and observed value from two 1-day periods (a) Lake District/Great Dun Fell, 30 January 2006 and (b) North-West Highlands/Bealach na Ba, 1 February 2006 during the winter inversion period and the corresponding 0000 UTC pressure charts (c and d).

289x200mm (300 x 300 DPI)

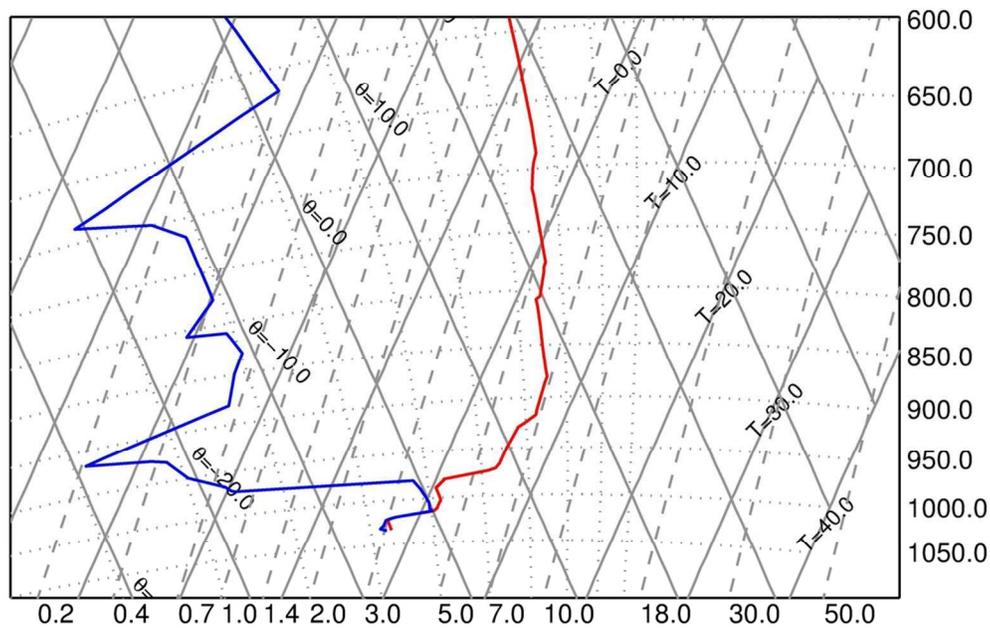


Figure 6 Tephigrams for Castor Bay, Northern Ireland at 1200 UTC, 30 January 2006. The temperature and dew point temperature are shown by the red and blue lines respectively. The numbers on the y-axis represent lines of constant pressure (hPa, curved grey dotted lines running left to right) and the numbers on the y-axis correspond to the straight dashed grey lines, which are lines of constant saturation mixing ratio ( $\text{g kg}^{-1}$ ). The solid grey lines running from bottom-left to top-right are lines of constant temperature and the solid grey lines running from bottom-right to top-left are lines of constant potential temperature (both marked by the black text within the figure).

102x66mm (300 x 300 DPI)

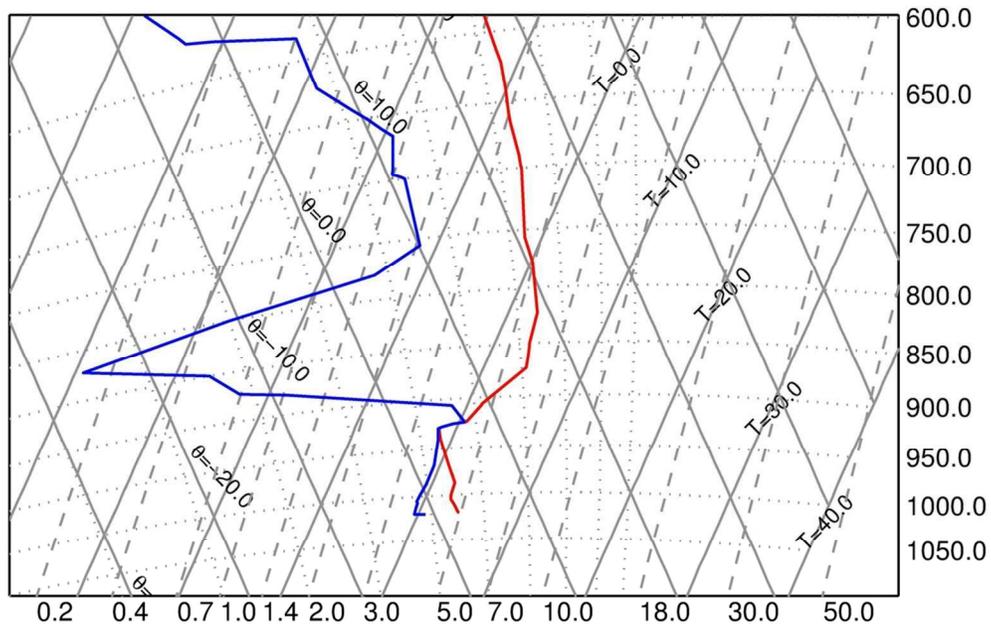


Figure 7 Same as Figure 6 but for Castor Bay at 1200 UTC, 1 February 2006.  
102x66mm (300 x 300 DPI)

Review

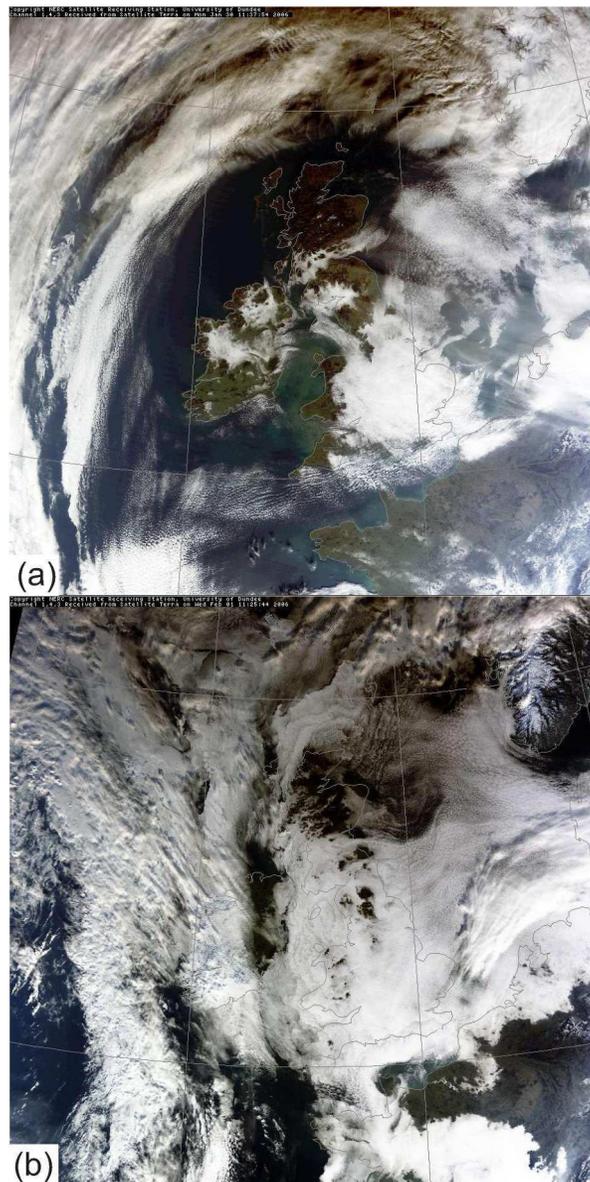


Figure 8 RGB composite MODIS satellite images for (a) 1137 UTC, 30 January 2006 and (b) 1135 UTC, 1 February 2006.  
154x311mm (300 x 300 DPI)

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

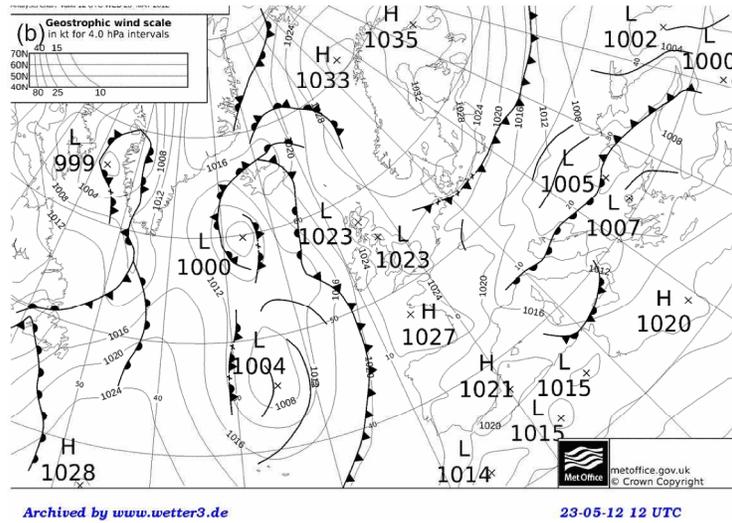
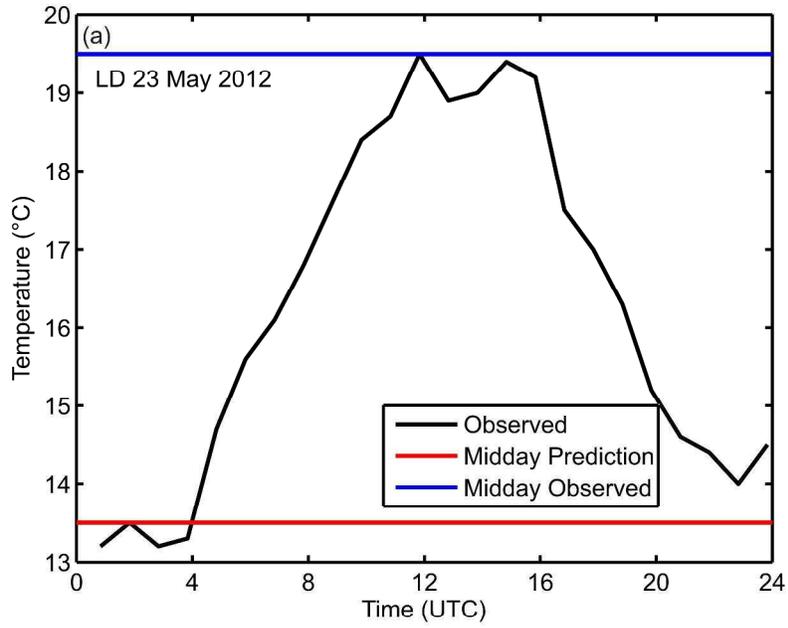


Figure 9 Same as Figure 5 but for the Lake District, 23 May 2012.  
428x569mm (300 x 300 DPI)

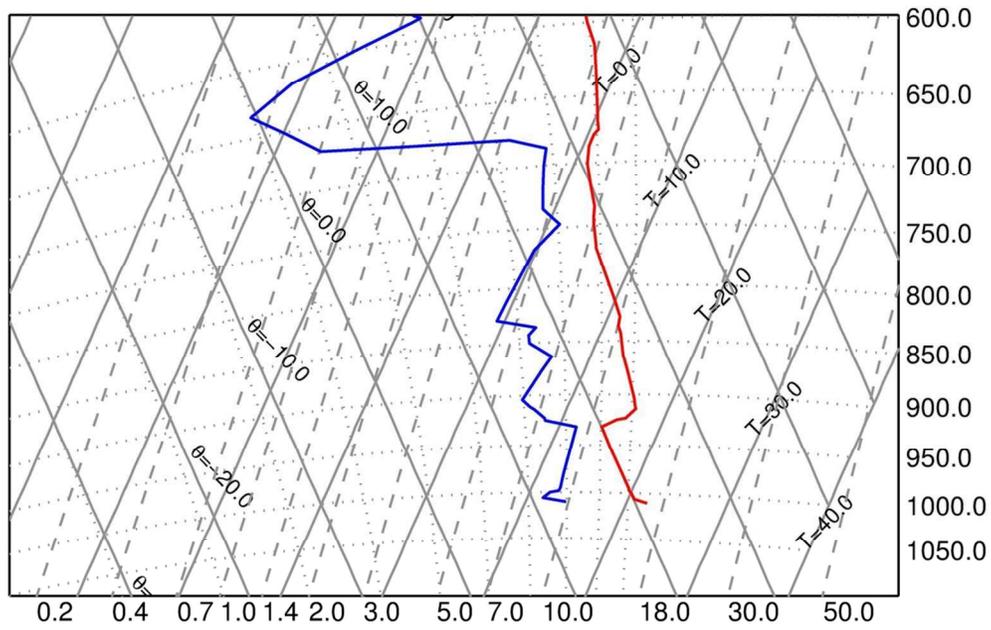


Figure 10 Same as Figure 6 but for Nottingham at 1200 UTC, 23 May 2012.  
102x66mm (300 x 300 DPI)

Review

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60