The usefulness of model-comparison statistics for wind-profiling radar operators

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1 Introduction

Wind-profiler radar data are commonly assimilated by meteorological organisations for the purposes of numerical weather prediction (NWP). Within Europe, radars of different types are operated by a variety of organisations. Nevertheless, they effectively form a single network through the co-ordination of the EUMETNET Composite Observing System (EUCOS) E-WINPROF programme. This grew out of the CWINDE demonstration network, which was set up under COST-76 [*Dibbern et al.*, 2003b]. The data are submitted to a central hub before being distributed to the various meteorological organisations across Europe. The quality of the data is evaluated through statistical comparisons against NWP model wind fields [e.g. *Dibbern et al.*, 2003a]. The (UK) Met Office carry out comparisons against their Unified Model (UM), Météo France against their ARPEGE model, and Deutscher Wetterdienst against their COSMO model. These statistics are fed back to the radar operators on a monthly basis in graphical form.

The aim of this extended abstract is to demonstrate how the model-comparison statistics can be of use to the radar operators. It is focused entirely on the Natural Environment Research Council's (NERC's) MST Radar at Aberystwyth. Although this has always been operated primarily on behalf of the UK's research community, the Met Office took an early interest in its potential to contribute to their upper air measurement network. This long association has benefitted both parties. The involvement of the research community has ensured that the characteristics of the radar observations have been studied in great detail. The involvement of the Met Office has provided a mechanism for quantifying data quality. Consequently, this abstract will focus on the model-comparison statistics provided by the Met Office rather than those provided by Météo France or Deutscher Wetterdienst. An introduction to these statistics is given in Section 2. Section 3 gives a case study of how the statistics were used to validate a new signal processing scheme. Section 4 looks at how they were use to identify a range gating error. Section 5 looks at the effects of renovating the Aberystwyth radar and demonstrates the limits of what can be inferred from these monthly statistics. Finally, Section 6 looks at how daily statistics, derived from comparisons against the Deutscher Wetterdienst model, are starting to be used to identify highly-localised problems.

2 Met Office monthly statistics

Figure 1 shows three different Met Office (global) model-comparison statistics for February 2012. The root mean square (RMS) differences between radar and model wind components give a combined indication of

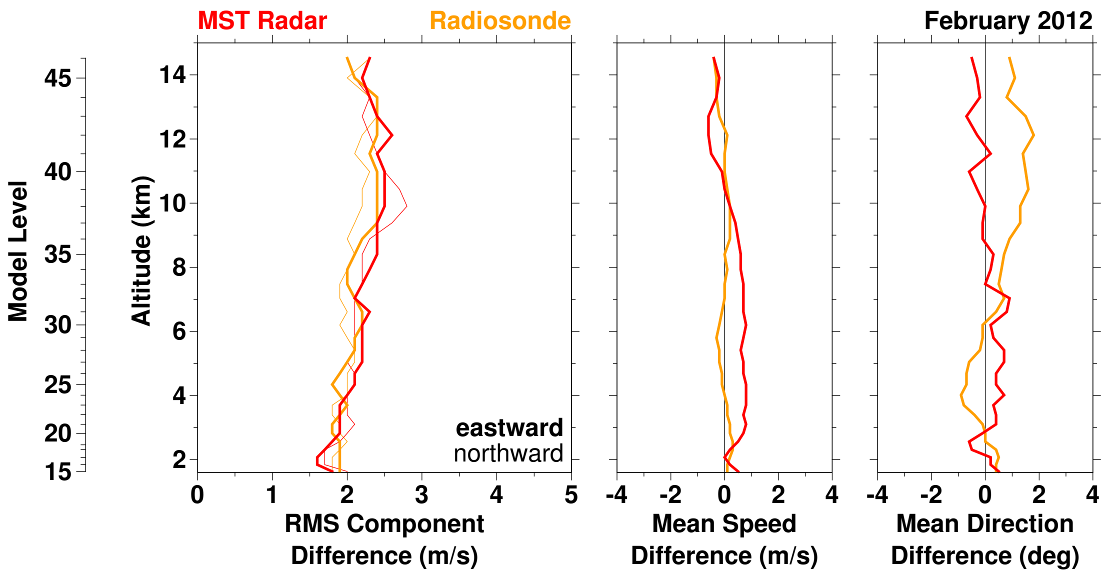

Figure 1: Met Office model-comparison statistics for February 2012. The orange lines relate to the composite data from all radiosonde sites in the British Isles. The red lines relate to the NERC MST Radar at Aberystwyth. In the left hand panel, eastward wind component data are represented by thick lines and northward wind component data by thin lines.

the systematic, random, and representativeness errors [*Dibbern et al.*, 2003a]. It is emphasised that NWP models are not perfect and so these differences should not be attributed solely to errors in the radar data. In particular the models have a limited (albeit increasing) ability to accurately represent smaller-scale features. For example, they parameterise gravity waves rather than modelling their effects explicitly. Nevertheless, inertia-gravity waves are commonly observed in the lower-stratosphere above Aberystwyth [e.g. *Vaughan and Worthington*, 2007]. They give rise to wind perturbations with magnitudes of a few m s^{-1}. This is an example of a representativeness error. Therefore, in order to distinguish between the model and wind-profiler contributions to such statistics, the Met Office do not consider each wind-profiler in isolation.

The ideal source of data for evaluating wind-profiler data quality would be radiosondes launched from a nearby location. Temporal and spatial separations will both be expected to give rise to natural variations. Radiosondes are still regarded as the standard instrument for measuring winds. However, as can be seen in Figure 2, the nearest primary radiosonde sites (large orange dots) are 200 km away from the Aberystwyth radar (52.42°N, -4.01°E). Indeed, the fact that the radar conveniently fills a gap in the pre-existing upper-air observation network is one of the reasons that the data are of interest to the Met Office. Similarly, three out of the Met Office's five Boundary-Layer Wind-Profilers (small blue dots) are located within gaps in the network (the other two are located at test sites). Consequently, for routine evaluation of UK-based wind-profiler data quality, the Met Office also calculate model-comparison statistics for the composite data from all radiosonde sites across the British Isles. This reduces the impact of natural variations associated with any one radiosonde site. Similar analyses are carried out for wind-profilers in other countries, albeit using different groups of radiosondes.

As an aside, atmospheric measurements made by commercial aircraft also contribute to the upper air network through the Aircraft Meteorological Data Relay (AMDAR) programme. The locations of the airports used by contributing aircraft are indicated by the black crosses in Figure 2. During extreme wind events at near-surface levels, radiosondes cannot be launched and aircraft cannot take-off or land for safety reasons. However, wind-profiling radars can continue to operate as long as there is no disruption to their electricity supplies. *Parton et al.* [2010] has shown that that this leads to a systematic absence of such (admittedly-rare) events from the radiosonde record.

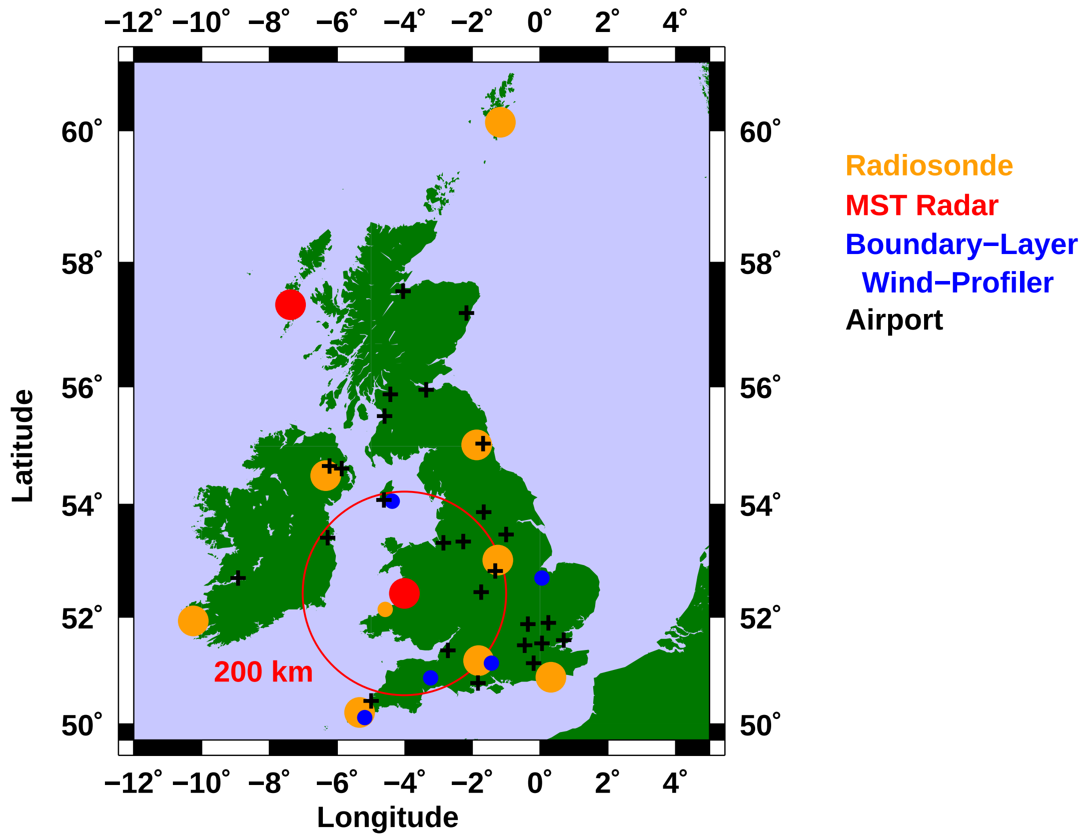

Figure 2: Map of measurement sites within the Met Office's upper-air network for the British Isles. The large orange dots show the locations of the primary radiosonde launch sites. The small orange dot represents the Aberporth launch site. The red dots show the locations of the South Uist and Aberystwyth MST radars. The red circle has a radius of 200 km and is centred on the Aberystwyth MST radar. The small blue dots show the locations of the boundary-layer wind-profilers. The black crosses show the locations of airports associated with the AMDAR programme.

If two sources of measurements have similar model-comparison statistics, it can be inferred that their measurement errors are comparable [*Dibbern et al.*, 2003a]. Therefore the differences between the wind-profiler and radiosonde values are more-significant than the absolute values for either instrument in isolation. The pattern seen in Figure 1, of similar RMS component differences for both the radar and radiosonde data, is typical for the Aberystwyth radar. Similar conclusions regarding the data quality [e.g. *Thomas et al.*, 1997; *Hooper et al.*, 2008] have been reached from directly comparing winds measured by the radar and those measured by radiosondes launched from Aberporth (small orange dot on Figure 2). The latter is just 45 km to the south-west of the Aberystwyth radar. However, it is not part of the Met Office's primary observation network and so radiosondes are not launched from there as frequently as from the other sites.

The typical cycle time for the Aberystwyth radar is approximately 5 minutes. Consequently, each half-hourly wind-profile sent to the E-WINPROF hub represents an average of up to 6 individual wind profiles. Although such averaging reduces the magnitude of the random measurement error, it has no effect on systematic errors. These show up in the mean differences between the measured and model winds (i.e. measured - model) - or rather, in the separations between the radar and radiosonde model-comparison values. As can be seen in Figure 1, the biases are small. It is typical for the radar wind speed to show a slight positive bias (with respect to the radiosonde data) at tropospheric altitudes and a slight negative bias at lower-stratospheric altitudes. The altitude of the tropopause above Aberystwyth is most-commonly between 10 and 12 km [*Hooper et al.*, 2008]. The difference between the biases is thought to be related to the aspect sensitivity of the radar returns. This causes the effective zenith angle, for off-vertical radar beams, to be slightly smaller than the nominal angle. The effect, which leads to an underestimate of the wind speed, tends to be largest at lower-stratospheric altitudes. The signal processing scheme applies a compensation for this [*Thomas et al.*, 1997; *Hooper et al.*, 2008]. The mean direction differences suggests a bias in the radar-derived wind direction of no more than 1°.

3 Evaluating a new signal processing scheme

The original Aberystwyth radar signal processing scheme, which is referred to as version-0 or v0, was gradually developed over the period 1990 - 2000. The development benefitted from the Met Office's early efforts to evaluate the usefulness of the wind-profile data. Nevertheless, the scheme relied on a number of not-entirely-accurate simplifying assumptions. Although these were of use in the early years of radar operation, when computing power was relatively limited, they were no longer necessary a decade later. This prompted the development of a new scheme [*Hooper et al.*, 2008]. It had reached version-3, or v3, before it began real-time operations in January 2006. It was run in parallel with the v0 scheme for a full year. During this time, wind-profiles from both schemes were sent to the E-WINPROF hub. However, data from only one scheme (initially v0) were operationally assimilated.

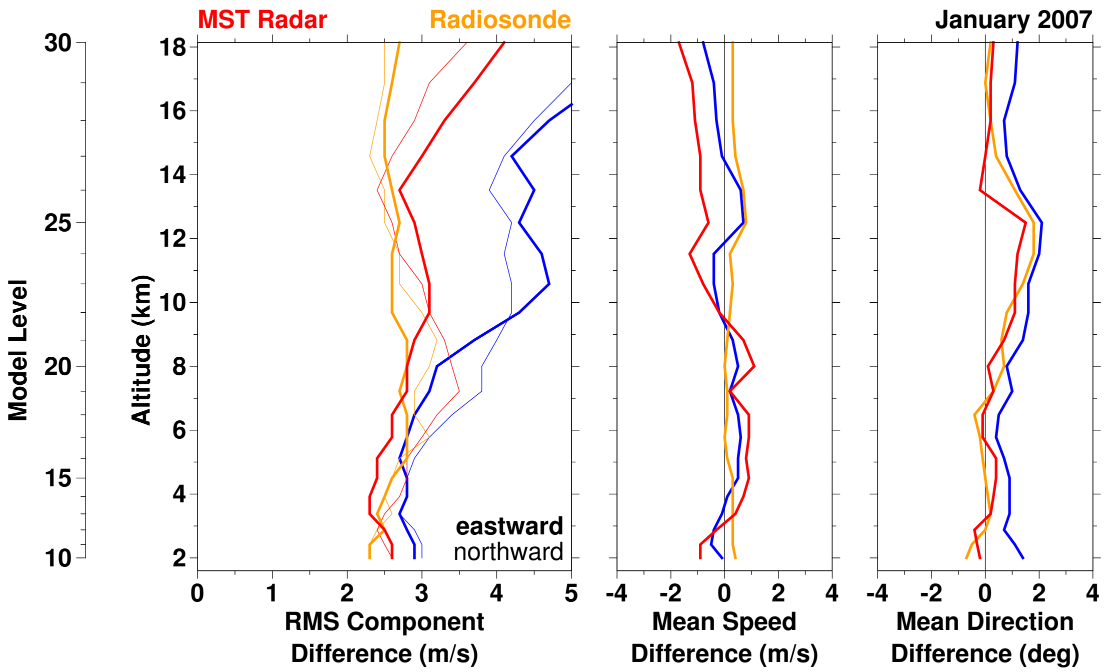

Figure 3: As for Figure 1, but for January 2007. Also shown in blue are model-comparison statistics for winds derived from the version-0 MST radar signal processing scheme.

Figure 3 shows the model-comparison statistics for January 2007. The v0 mean direction difference had always shown a small positive bias. This was reduced slightly by the v3 scheme. However, the magnitude of its mean speed difference shows a slightly larger bias than the v0 scheme. Ultimately, it is the RMS component differences which differentiate the two schemes. For the duration of the evaluation period, the v3 scheme consistently outperformed the v0 scheme. This is particularly noticeable at altitudes above 8 km. This led to the Met Office switching over to the v3 data stream for operational purposes in August 2006. Use of the v0 scheme was discontinued in February 2007.

Attention is drawn to the fact that Figure 3 shows data up to an altitude of slightly greater than 18 km, whereas all other examples of Met Office monthly model-comparison statistics only extend to 15 km. It should be noted that the even the v3 data quality, in this example, decreases noticeably at the highest altitudes. This is a consequence of the decreasing radar return signal power with increasing altitude, which results in fewer signals passing quality control tests. During March 2011, the radar underwent its first major renovation in a 22 year lifetime - see *"Renovation of the Aberystwyth MST radar: Evaluation"* in these proceedings for more details. This led to a significant increase in altitude cover. However, the performance was slowly decreasing before then, which led the Met Office to discontinue their consideration of data above 15 km in late January 2009. Also note that the number of NWP model levels increased in late 2009.

4 Diagnosis of a range gating error

A new radar control and data acquisition PC was installed in February 2007. Although the software for the new Linux-based PC was a modified version of that used for the old WindowsNT-based PC, it introduced a range gating error [*Hooper et al.*, 2010]. Winds were reported 4 gates lower, corresponding to an altitude difference of 597 m, than they should have been.

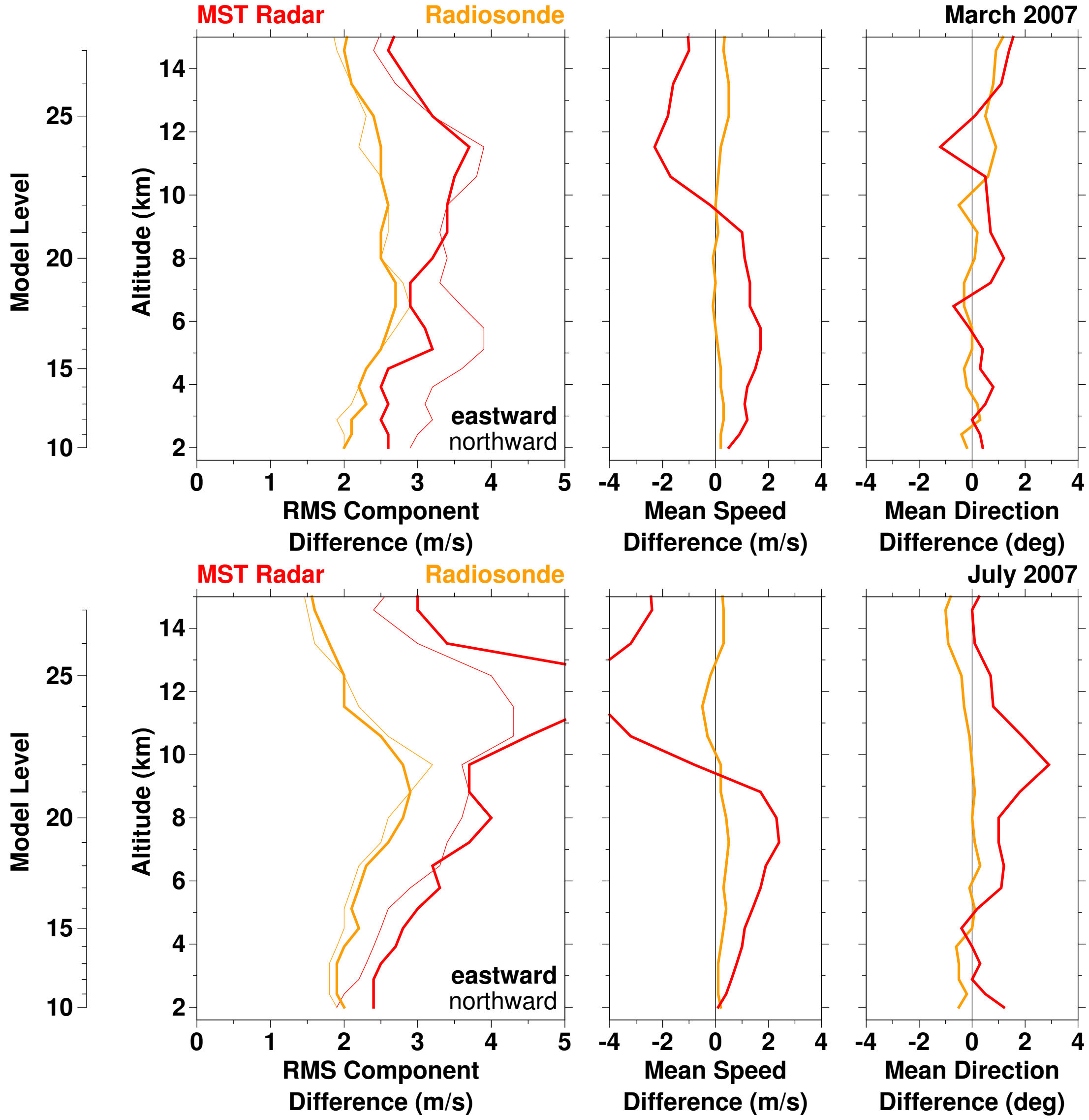

Figure 4: As for Figure 1, but for (upper panels) March 2007 and (lower panels) and July 2007.

The Met Office model-comparison statistics for March 2007, i.e. the first full month following the change, gave an immediate indication that there was a problem - see upper panels of Figure 4. This was surprising since the radar wind data showed no change in self-consistency, i.e. in terms of changes with time and altitude. Although the statistics did not reveal the cause of the problem, it is easy to see its signature in the mean speed difference profiles. This is particularly true for months such as July 2007 (lower panels of Figure 4), when jet stream activity predominated. Wind speeds can be as large as 90 m s^{-1} within the peak of the jet, which typically occurs in the altitude range 10 - 12 km above Aberystwyth, but are seldom more than a few tens of m s^{-1} elsewhere. Moreover, the speed reduces more-rapidly as a function of altitude above the peak than below it. The MST radar wind speed difference values show a large negative bias at altitudes of between 10 and 12 km, i.e. where the jet peak should be located but where much-lower wind speeds are reported. A smaller positive bias is found at altitudes of between 8 and 10 km , i.e. below the peak of the jet but where it is reported to be.

5 Evaluating the effects of renovating the Aberystwyth radar

As mentioned above in Section 3, the Aberystwyth radar underwent its first major renovation in a 22 year lifetime during March 2011. This principally consisted of a replacement of the beam steering components. It is clear that the poor condition of the original components led to a reduction in the useful altitude coverage for wind-profiling purposes. It also appears that other aspects of the radar's performance were affected. These would be expected to have had a negative impact on the wind data quality. An analysis of limited periods of pre and post renovation data suggests that the random measurement errors, for single cycle data, were reduced as a result of the renovation. Nevertheless, the Met Office's RMS component differences for a pre-renovation month and a post-renovation month - upper and lower panels, respectively, in Figure 5 - do not suggest a significant change in the 30 minute averaged data quality. This was surprising.

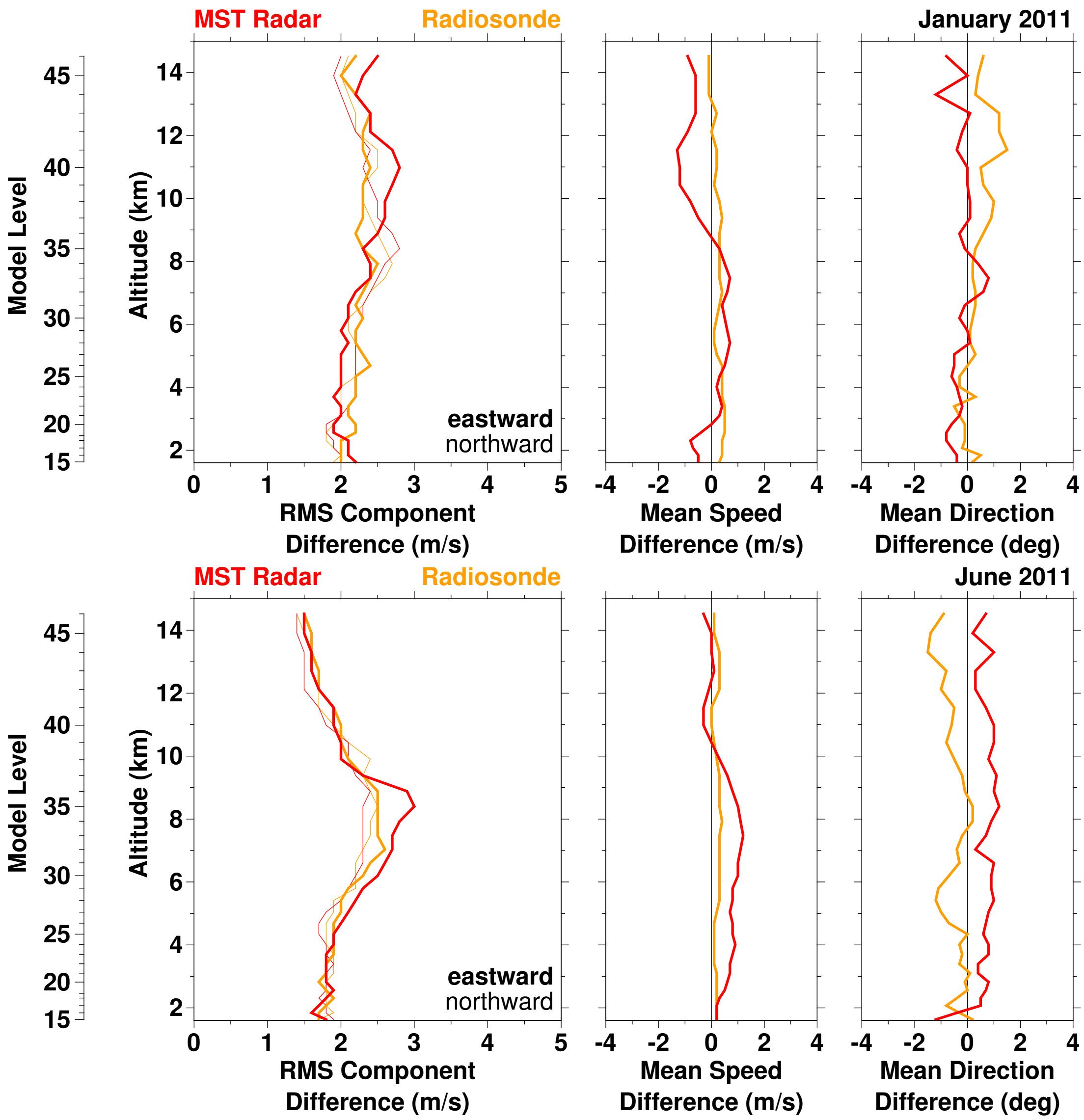

Figure 5: As for Figure 1, but for (upper panels) January 2011 and (lower panels) June 2011.

Between February and May 2011, inclusive, a special observation format was used for the specific purpose of evaluating the effects of the renovation. The approximately 10 minute duration of the cycles was double that for standard observations. This meant that the 30 minute average wind-profiles sent to the E-WINPROF hub were based on, at most, 3 individual measurements rather than the usual 6. For this reason, data from January and June 2011, when standard observations were being made, have been used to represent the pre- and post-renovation conditions. The characteristics seen in Figure 5 are typical of the months to either side.

An analysis of the special observation format data suggests that the radar's beam shape and/or its zenith angle, for off-vertical beams, would have been affected by the state of the pre-renovation beam steering components. If the zenith angles were affected, they would be expected to be slightly smaller than their nominal angles. This would lead to the horizontal wind speeds being underestimated. This is separate to the effects of radar return aspect sensitivity, described in Section 2, which also tend to cause an underestimate of the horizontal wind speeds. Nevertheless, the analysis of the special observation format data suggests that the aspect sensitivity compensation factor was actually over-correcting the horizontal wind speeds. The mean speed differences shown in Figure 5 suggest that the net result of these influences was to actually slightly underestimate the wind speed. The values for the post-renovation period consistently (i.e. for the months to either side) show a positive bias relative to those of the pre-renovation period. However, the differences are only of the order to 1 m s^{-1}. There is also a slight positive bias in wind direction, but again this is small - approximately 1°.

6 EUCOS statistics

The changes in Met Office monthly model-comparison statistics as a result of the renovation are considerably smaller than those resulting from the improved signal processing scheme or from the range gating error. Although the small shifts in speed and direction biases appear to be genuine, the changes in the RMS component differences, relative to the radiosonde values for January and June 2011, are comparable to the variability seen from month to month. This is despite the fact that the analysis of the special observation format radar data (in isolation) suggests a reduction in random measurement error (for single cycle data). This suggests a limit to the magnitude of changes which can be inferred from the Met Office's monthly model-comparison statistics.

Since January 2011, the Met Office have been distributing an additional measure of monthly data quality. These are provided by EUCOS from comparisons against the Deutscher Wetterdienst model, but in the form of just 3 parameter values which cover all altitudes. These values are expected to fall within target limits, which have been defined by EUCOS.

The "Quality" parameter is similar to the Met Office's RMS component difference. It represents the RMS difference between the measured and model wind vectors. The target is that this value should not exceed 5.0 m s^{-1}. As can be seen from Figure 6, winds from the Aberystwyth MST Radar mostly fall below this threshold, indicating that the data are typically of an acceptable quality. Owing to the fact that these new model-comparison statistics only started to be distributed 2 months prior to the March 2011 renovation, it is not possible to say with confidence whether the data quality has improved. However, it is noted the value of the "quality" parameter slightly exceeded the threshold for both of the pre-renovation months.

The "Timeliness" parameter refers to the number of wind-profile messages within 30 minutes of the end of the averaging period. The target is for a minimum of 90%. This is virtually-always achieved for the Aberystwyth radar. The exception was during March and April 2011, i.e. when the special, 10 minute long cycle format was being used as part in order to evaluate the effects of the radar renovation. The signal processing chain has been optimised for the standard 5 minute long cycle format. Consequently, it is not surprise that this was less effective, in terms of timeliness, when the cycle time was doubled.

The "Availability" parameter refers to the percentage of wind-profile messages received relative to the max-

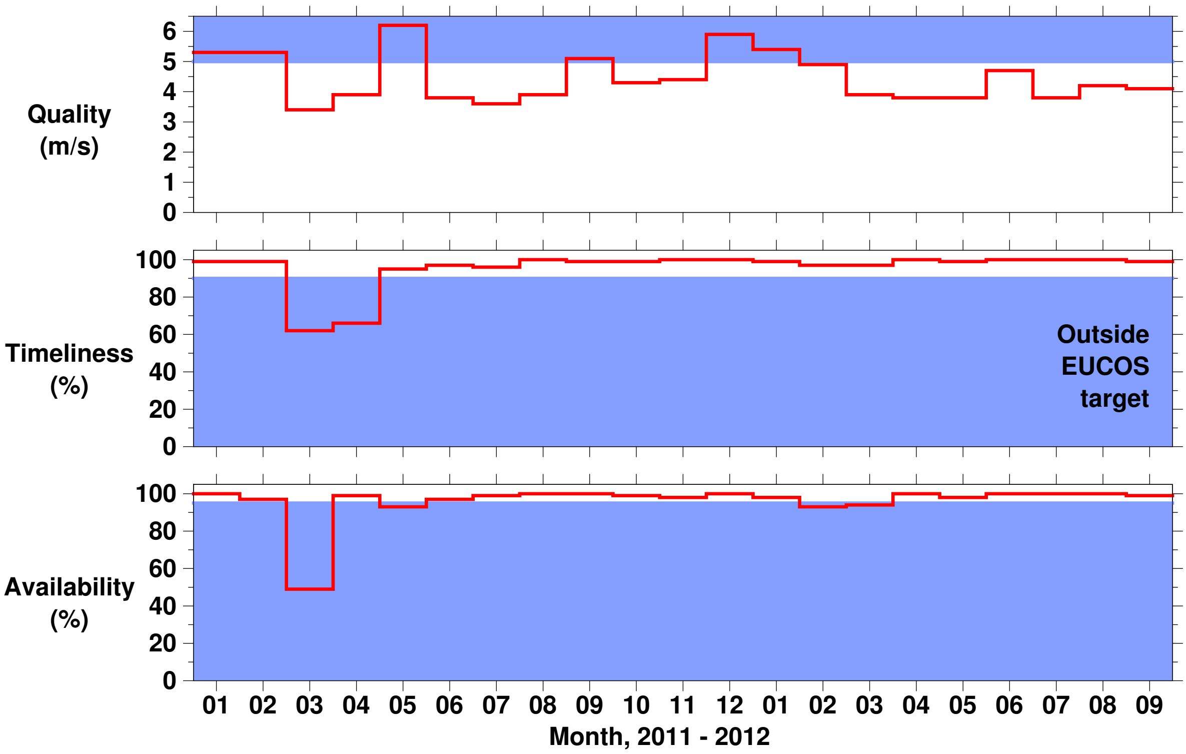

Figure 6: Monthly EUCOS model-comparison statistics for the Aberystwyth MST Radar for January 2011 - March 2012. Values in the blue regions are outside of the EUCOS targets.

imum number possible. The target is for a minimum of 95%. The only month for which this was missed by a significant margin was March 2011, i.e. when the radar was out of action for half the month as a result of the renovation.

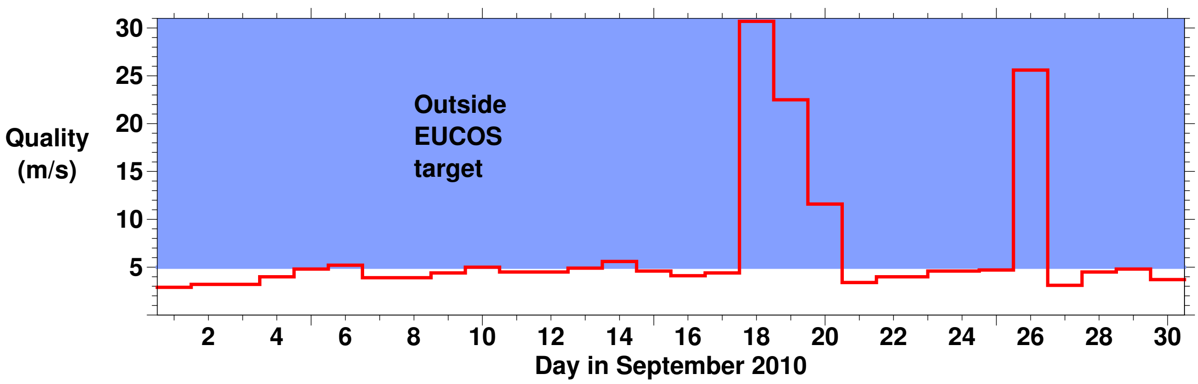

Figure 7: Daily EUCOS "Quality" parameter for the Aberystwyth MST Radar during September 2010.

EUCOS model-comparison statistics can be generated for any time interval and the Met Office have access to the daily data. Although these are not distributed on a routine basis, the Met Office are starting to make use of them in order to identify transitory but significant problems with the data quality. The Aberystwyth radar beam steering unit became stuck in an off-vertical direction at 16:00 UT on 18th September 2010, a Saturday, and was not fixed until the following Monday morning (20th) at 11:00 UT. During this period, the winds were still passing self-consistency checks, since their variations as functions of time and altitude were within realistic limits. Consequently they were flagged as being reliable. As can be seen in Figure 7, this malfunction leads to the daily values of the "Quality" parameter of between 10 and 30 m s^{-1}, which are considerably in excess of the 5.0 m s^{-1} target.

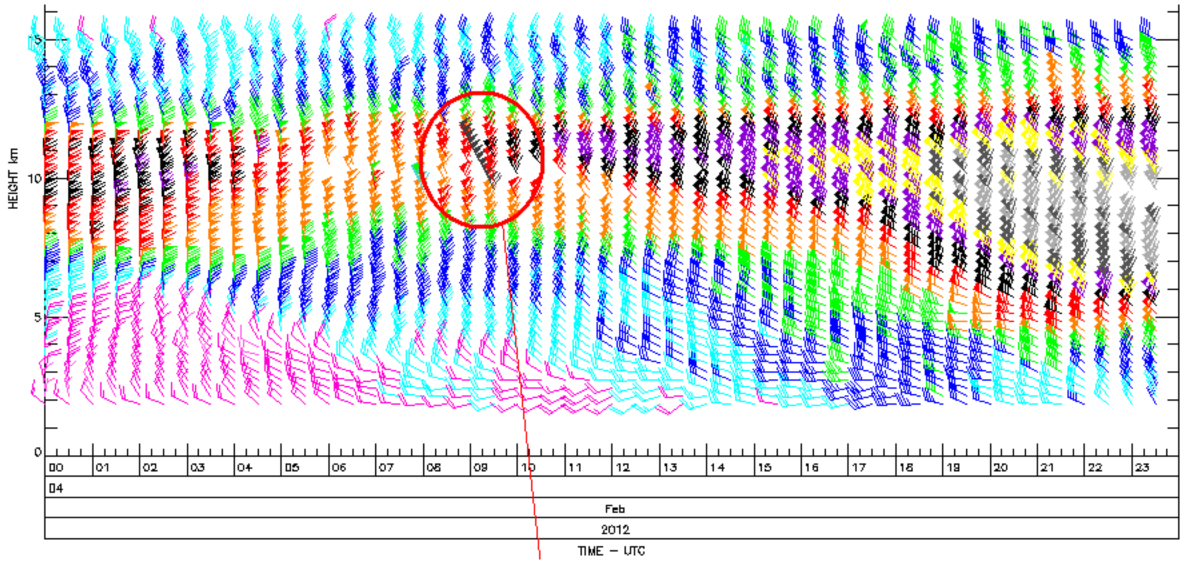

Figure 8: Horizontal winds measured by the Aberystwyth MST radar on 4th February 2012. The red circle highlights the outlying data point.

It is not clear what caused the large value on 26th September 2010 in the above example. Nevertheless, in other cases, similarly-large daily values have been traced to erroneous wind vectors that are confined to just one or two range gates and to only a single 30 minute averaging period. Figure 8 shows one such example, from 4th February 2012. The v3 signal processing scheme is typically highly-effective at removing outlying data points, so it is not yet clear how this wind vector managed to be flagged as reliable. The point of showing this is to demonstrate how the daily EUCOS statistics can be used to identify highly-localised problems with the signal processing scheme.

7 Conclusions

This abstract has demonstrated the usefulness of monthly model-comparison statistics for identifying significant changes in data quality. The two examples shown relate to a change in signal processing scheme and a long-term instrument problem. However, the statistics cannot be used for identifying more-subtle changes. Nevertheless, daily model-comparison statistics appear to have the potential for identifying highly-localised problems with signal processing.

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