TECHNICAL MEMORANDUM

807

An assessment of different radiosonde types 2015/2016

Bruce Ingleby

Research Department

August 2017

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/en/research/publications

Contact: library@ecmwf.int

European Centre for Medium Range Weather Forecasts
Shinfield Park, Reading, Berkshire RG2 9AX, England

Abstract

Observation minus background radiosonde statistics have been examined for a two year period, split by latitude band and radiosonde type (or groups of types). As a result some dependence of observation uncertainty on radiosonde type is being introduced for temperature and humidity. The background information helps to detect some gross errors in the radiosonde data and the radiosonde data helps to document some weaknesses of the background – due to model biases or inability to represent small scale features. There are also implications for quality control and verification. Available information on currently used radiosonde types and their processing has been summarised.

1 Introduction

The traditional way of assessing radiosonde types is an intercomparison, such as that by Nash et al (2011). These compare different radiosondes flown together (sometimes with extra reference instruments) and are very good at documenting and sometimes correcting some weaknesses. However intercomparisons are expensive, difficult to organise and cannot look at all radiosonde types. They are also generally free of problems that afflict a small proportion of operational radiosonde reports: incorrect metadata including station height errors, sensor failure due to rough handling, temperature/humidity 'ascents' starting inside a ship's cabin, apparent pressure drift at upper levels and other issues.

This study compares operational radiosonde data to ECMWF background (12 hour forecast) values giving mean and root-mean-square (rms) Observation-minus-Background (O-B) statistics. Many features seen in these statistics appear to relate to observation error but some relate to forecast error. Until recently ECMWF used the same assumed observation error profiles for all radiosonde types but new error profiles - smaller for some types than others - were derived and are being implemented operationally in 2017. Some 'gross errors' are excluded from the rms statistics, the proportion of such 'bad' data is also examined. Some of the features in background errors and hence in the O-B statistics are linked to tropopause or jet stream level – the results are presented by latitude band so as to compare 'like with like' as much as possible. There are also some variations with the seasonal and diurnal cycles – these effects are only touched on.

Section 2 presents the data, including maps of the radiosonde type distribution and relevant aspects of the ECMWF system, and methodology. Section 3 provides the main results firstly for temperature, humidity and wind (assimilated) and then for geopotential height (not assimilated but still important for forecast verification). Section 4 shows examples of individual profiles to illustrate some of the issues. Section 5 discusses other ways of categorising radiosonde data and section 6 provides a summary. Appendix 1 provides more details of the different radiosonde types. Results from the ECMWF assimilation/forecasting system changing aspects of radiosonde processing will be reported separately.

2 Data and methodology

2.1 Radiosonde data

For simplicity and comparability the study is restricted to TEMP observations from land stations (SHIP TEMP, DROP TEMP and PILOT are excluded) and standard levels. There is a transition underway from alphanumeric TEMP format to the binary BUFR format (Ingleby et al, 2016a) but for the period considered (January 2015 to December 2016) the TEMP coverage is almost complete whereas the BUFR coverage is patchy and presents various quality problems and duplicate checking issues. There are approximately 800 land stations reporting regularly, most report either once or twice a day. Most are maintained by National Meteorological Services (NMSs), some, particularly in Antarctica, by research agencies and some by the military (some of the military reports are not distributed on the World Meteorological Organisation Global Telecommunications System, WMO GTS). Some NMSs are under severe budgetary pressures and in some cases the radiosonde program has been cut back (sometimes from two ascents a day to one), see Ingleby et al (2016b). Globally the numbers of reports per month are approximately constant, but it appears that a few island stations have closed.

Although not covered by this report (apart from one example and brief discussion in section 4) it is worth noting that there is some radiosonde coverage over the oceans. A few research vessels make radiosonde ascents, but the main coverage comes from the European Automated Shipborne Aerological Program (http://eumetnet.eu/activities/observations-programme/current-activities/e-asap/). There are about 20 ASAP vessels operating in the North Atlantic, of which an average of about seven are reporting on any given day. They currently use a mixture of Vaisala, Modem and Graw radiosondes and their performance is broadly similar to that of the same radiosondes at land stations. Dropsondes (dropped from an aircraft) can be used in field programs but are mainly dropped around tropical cyclones, especially those heading towards the USA. Comparison of statistics from dropsondes would be complicated by their very selective sampling. The new Vaisala RS41 radiosonde has an option to generate separate reports from the radiosonde as it falls (with or without a parachute) after balloon burst. These descent reports may be somewhat lower quality than the ascent data (standard radiosondes are optimised for ascent!), but at little additional cost they should provide useful additional data. Several European countries are producing such descent reports and in early 2017 such reports from two German stations were put on the GTS.

Dirksen et al (2014) provide a very useful insight into the processing of radiosonde data before the reports are compiled, and to the measurement uncertainties. Their GRUAN processing of RS92 data gives similar results to the operational Vaisala processing of RS92 data for temperature but more differences for humidity. The “CIMO guide” (WMO, 2014) also provides detailed information on radiosonde operations.

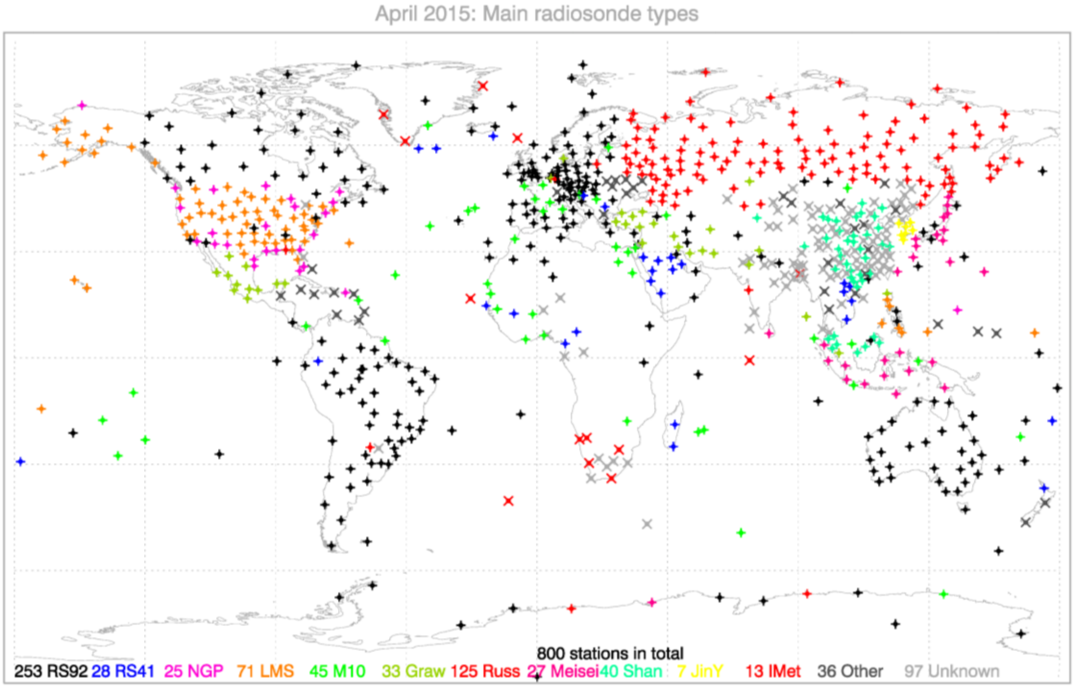
2.2 Global distribution of radiosonde types

Table 1 and figure 2.1 summarise the main radiosonde types worldwide in 2015/2016. They are identified by the ‘Radiosonde/sounding system used’, see WMO (2015, common code table C-2), referred to simply as type from now on. The type numbers given are those used in TEMP code, some of them have 100 added in BUFR (17 becomes 117, 41 becomes 141 etc; note that where table C-2 has two entries for alphanumeric types the first has generally been discontinued and the second is the currently used type). The most used type is currently the Vaisala RS92, following preliminary results and discussion (with Aki Lilja, Vaisala) it was decided to group together the four code numbers that use Vaisala processing, but to keep separate types 52 and 83 that use Vaisala instruments but non-Vaisala processing. Vaisala will cease to supply RS92-SGP radiosondes at the end of 2017 and various NMSs have changed to the newer RS41 radiosonde. Further details about radiosonde types are provided in the appendix. Russian and also Japanese (Meisei) types are combined in the main plots but disaggregated in the regional results (section 3.5). Unfortunately some radiosondes report the type as missing (denoted **).

Make, Manufacturer	Type number(s)	Area used	Label
RS92, Vaisala, Finland	14, 79, 80, 81	Worldwide	RS92
RS92-NGP, Vaisala	52	USA	NGP
RS41, Vaisala, Finland	23, 24, 41, 42	Worldwide	RS41
DFM-09, Graw, Germany	17	Various	Graw
M10, Modem, France	77	Worldwide	M10
LMS6, Lockheed, USA	82	USA+Pacific	LMS6
Russian, various	27-29,53,58-62,69,88-90	Russia, Kazakhstan	Russ
Meisei, Japan	22, 30, 35, 55	Japan, Indonesia	Meisei
GTS1-1, Shanghai, China	32	China	Shan
JinYang, South Korea	21	Korea, India	JinY
iMet-2 InterMet, S Africa	99	South Africa	IMet

Table 1. Summary of major radiosonde types, July 2015. The ‘area used’ is intended as a general guide only – and changes over time. The label is that used in Figure 3.1 and elsewhere. Other less used radiosonde types are from other Chinese manufacturers, Ukraine (Paza) and Switzerland (Meteolabor), see Appendix 1 for more details.

Most radiosonde types occur predominantly in mid-latitudes, Russian types are mainly at high latitudes, and many of the Meisei (Japanese) radiosondes are in low latitudes. In 2015 most RS41 reports were from low latitudes although this is changing over time.



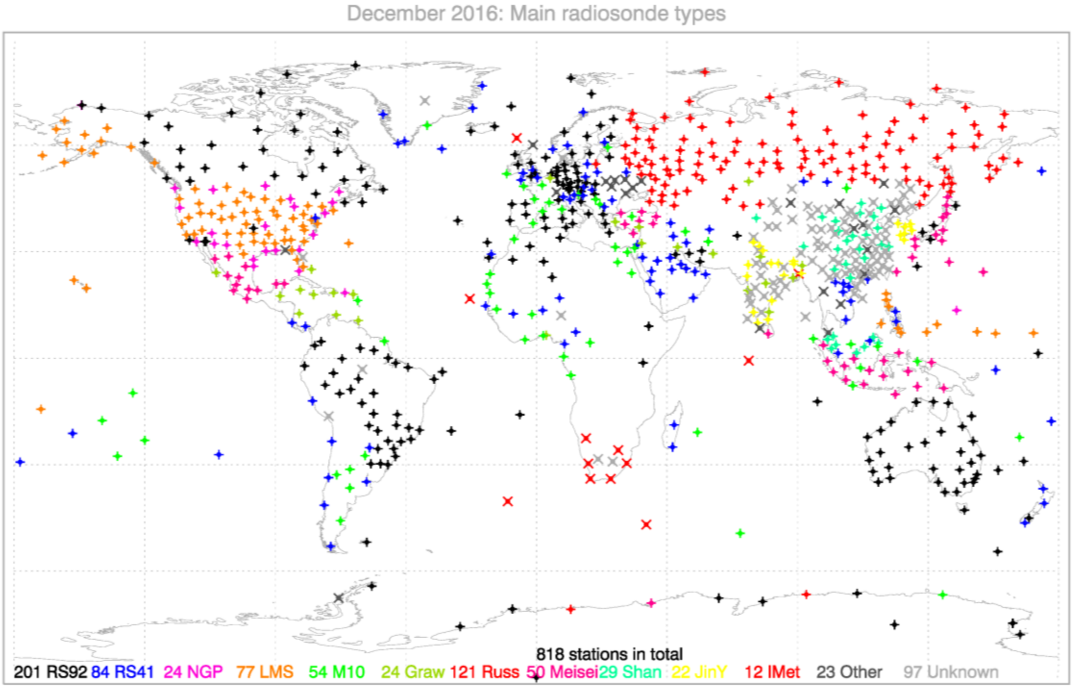


Figure 2.1. Main radiosonde types, April 2015 and December 2016 (TEMP only), see colour key at bottom which gives the number of stations reporting predominantly in each type (first 9 categories are marked with a + on the map, the last 3 with x). In parts of south and south-east Asia there are significant numbers of stations reporting wind-only (PILOT), these are not shown.

Figure 2.2 shows the numbers of reports per standard level for the four latitude zones used in section 3. For temperature the numbers are approximately constant from 925 hPa to 100 hPa but fall off above (due to balloon burst) and below (due to high ground). The numbers for height and wind (not shown) are rather similar. Those for humidity reduce in the upper troposphere (UT) due to reporting practices in some countries. As is well known the numbers are dominated by reports in the northern extratropics.

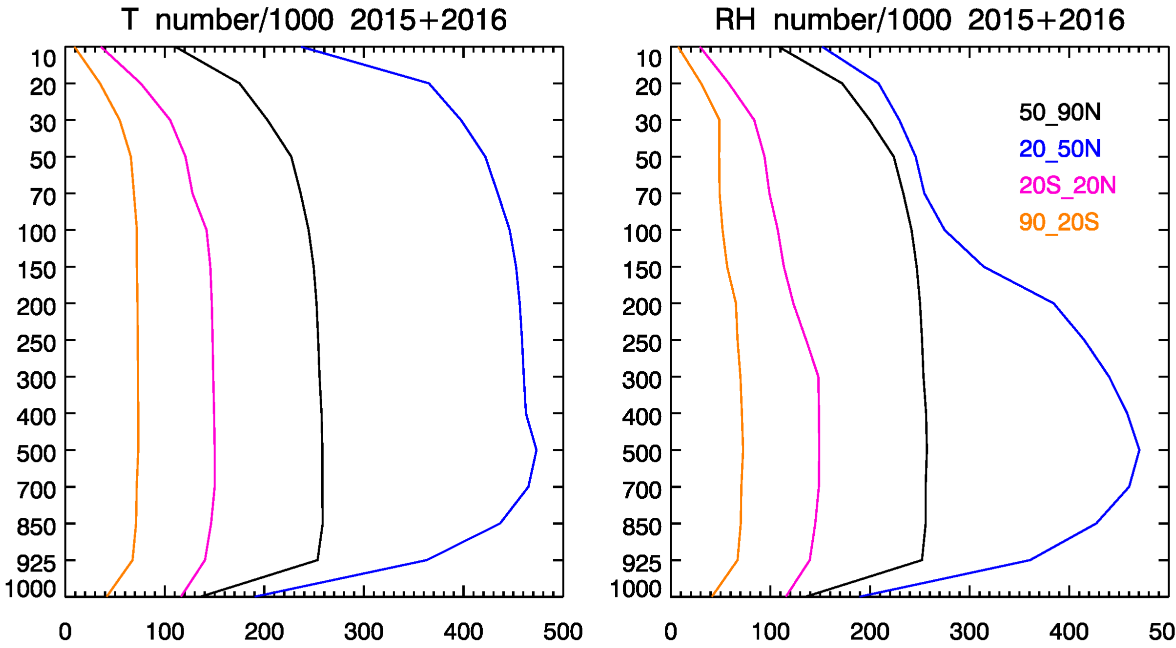


Figure 2.2. Numbers of TEMP reports for 2015-2016 on standard pressure levels for temperature and humidity by latitude band (see key for colour code).

2.3 ECMWF forecast system

The background (nominally a twelve hour forecast) comes from the operational ECMWF forecast system with 137 levels in the vertical. Until 8 March 2016 the forecast horizontal grid spacing was about 16 km it then improved to about 9 km. Until then the 4D-Var analysis used TL255 (~60 km) in its three inner loops, this improved to TL399 (~38 km) in the last inner loop. (For further details of ECMWF upgrades see cycles 40r1, 41r1, 41r2 and 43r1 at http://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model.) In November 2014 ECMWF started assimilating 1 or 2% of radiosonde ascents from high resolution BUFR reports (the TEMP reports are still processed), this proportion is gradually increasing. By December 2016 BUFR reports from about 12% of TEMP stations (mainly in Europe and Australia) were being assimilated. On 22 November 2016 there was a change to the humidity processing – see section 3.2. In 2017 there will be an upgrade to the specification of radiosonde temperature and humidity uncertainties.

Ingleby and Edwards (2015, including supplemental information) present details of the Met Office radiosonde processing. The ECMWF radiosonde processing includes many of the same elements but does not perform vertical averaging over model levels, each radiosonde level (standard and significant) is presented to the assimilation essentially as a point value (for significant levels this is sub-optimal as discussed by Ingleby et al, 2016a). Currently ECMWF treats radiosonde ascents as instantaneous and vertical (i.e. ignoring the two hours or so that an ascent takes and the horizontal drift with the wind). For BUFR reports treatment of radiosonde drift will be introduced operationally in early 2018 – this will improve O-B statistics at upper levels (see Ingleby and Edwards, 2015, and references). For TEMP reports the ECMWF system uses the station position as given in the WMO list (now OSCAR/Surface legacy files, see http://www.wmo.int/pages/prog/www/ois/volume-a/vola-home.htm). The four parts of the TEMP report are combined into a single report to aid quality control and processing, this also enables the 'radiosonde type' (often reported in only one Part of the TEMP) to be applied to the whole ascent. (Unfortunately there is an error in the ECMWF system and a small proportion of TEMP radiosonde types are set incorrectly.) Radiosonde type is used in the temperature/humidity bias correction (see below) and it is also used to decide whether to use upper-tropospheric humidity or not. More details of humidity processing can be found in section 3.2.

In any Numerical Weather Prediction (NWP) system and in a study of this type it is necessary to exclude (or downweight) observations with 'gross' errors (eg Ingleby and Lorenc, 1993). The background quality control is described in section 3.3.3 of ECMWF (2015). The square of the background departure O-B is divided by the sum of observation and background-error variances $V = \sigma_o^2 + \sigma_b^2$ and put into four categories (making the usual assumption that observation and background errors are uncorrelated). For most variables the category boundaries are 9/16/25, for surface pressure and height they are 12.25/25/36 (for the wind observations, the background quality control is performed simultaneously for both wind components). The use of the "Huber norm" (Tavolato and Isaksen, 2015) relaxes the upper categories. Preliminary statistics for the first category only suggested that this was too restrictive, the statistics presented use the first two categories, see section 3.6. ECMWF also has a reject list, updated most months along with the production of monitoring statistics, which excludes data from particularly poor stations. However these data are included in the figures below provided that they pass the background check.

The role of radiosonde data in providing reference information was examined by Radnóti et al (2012, section 5.1). They found that GPS radio occultation (GPS-RO) data had a stronger influence than radiosondes on the mean state of the analyses in 2011. Recent results from ERA-5, the new ECMWF reanalysis, highlight stratospheric temperature biases as an area of concern, particularly for the period before GPS-RO availability. Ingleby et al (2016b) found that reducing Russian radiosonde ascents from two to one per day (mirroring a real reduction that took place in January 2015, reversed in April 2015) did worsen forecast scores over Russia at short range and downstream at two or three days range. The impact was mainly in winter (when tropospheric satellite radiances were not used over snow) and comes despite Russian radiosondes being less accurate than average (see later).

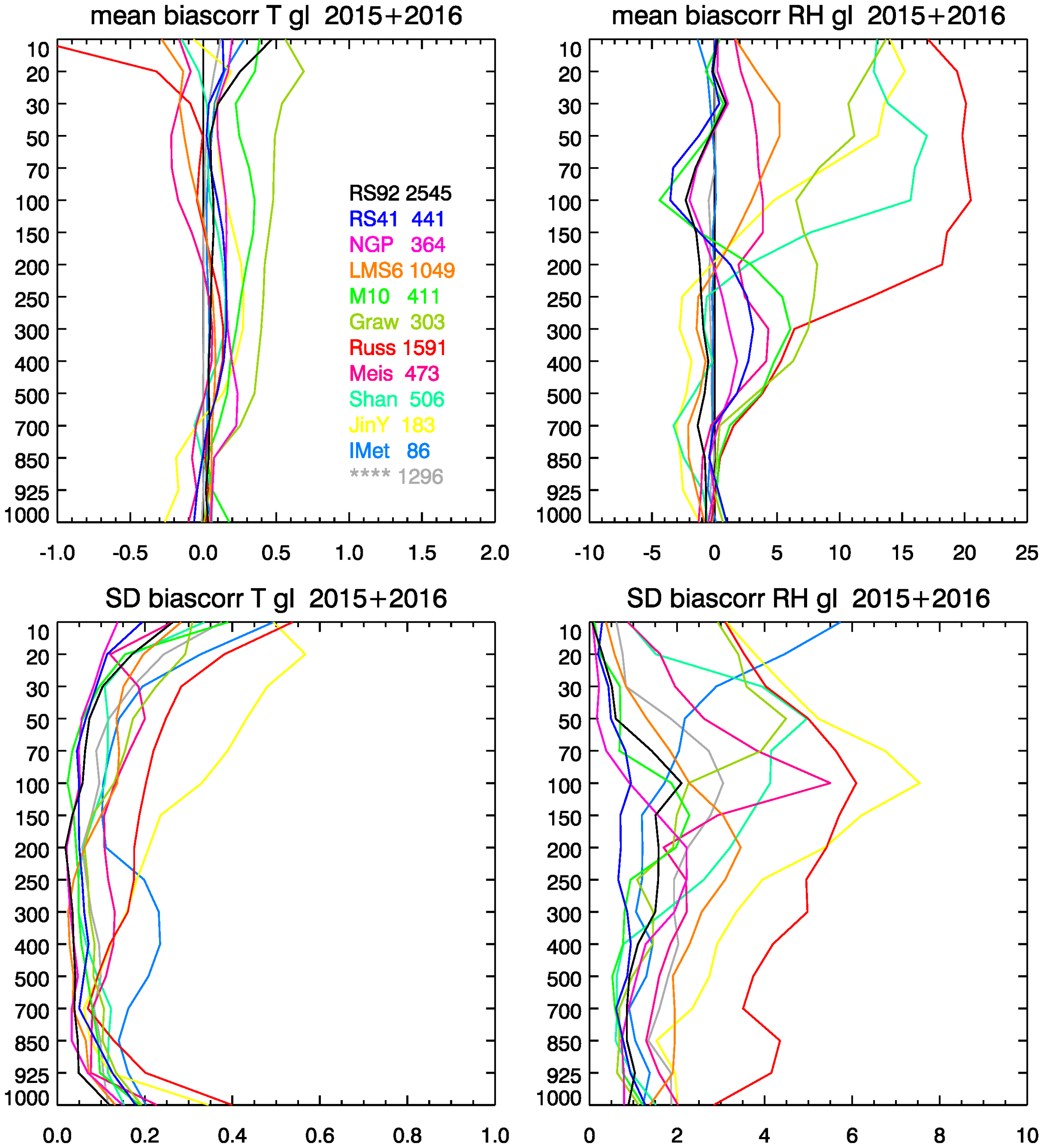


Figure 2.3. Mean and standard deviation (SD) of the bias correction applied (subtracted from reported values) at ECMWF for common types, January 2015 to December 2016, temperature and relative humidity. See key for colours, this also gives (/100) the number of reports for each category (taken as the maximum of the number of reports per standard level).

2.4 ECMWF radiosonde bias corrections

The operational ECMWF bias correction system for radiosonde temperature and humidity is described by Agusti-Panareda et al (2009), further information has been supplied by D Vasiljevic (2016, pers. comm.). Briefly it uses the last 12 months of O-B statistics (updated once a month) to calculate bias corrections as a function of radiosonde type, pressure and solar elevation angle. Nighttime RS92 (actually type 81 the Autosondes) are used as a reference – this assumes that any biases in the background fields are relatively constant. In general the temperature bias corrections are quite small, especially in the troposphere (figure 2.3). Of the most common radiosonde types Graw has the largest temperature correction applied. Upper troposphere Russian humidities (not assimilated) have rather large bias corrections applied. In one sense the stratospheric humidity bias corrections don't matter (the data are not assimilated), but they do give some indication of humidity sensor contamination – discussed further in section 3.2. The results presented in later sections are after the application of the ECMWF bias correction. Possible future changes to the bias correction are discussed in section 3.2.

The standard deviations shown in figure 2.3 were calculated for individual types and then averaged when types were combined. They should only be taken as an approximate guide to the variation of the correction, they will partly depend on the numbers of day/night reports from each type. JinYang, InterMet and Russian types have relatively large standard deviations for temperature.

2.5 Previous work

The work by Hollingsworth and Lonnberg (1986) represented a milestone in the study of observation and background (or first guess) errors. They looked at the correlations of O-B between pairs of stations as a function of distance in order to separate out observation and background errors. This requires relatively homogeneous observation and background errors over a region (they used North America) and would not be suitable for the more scattered radiosonde types. We present single station mean and rms O-B statistics accumulated for various samples – simpler but still containing a contribution from the background errors. In 1987 ECMWF hosted a workshop on radiosonde data quality and monitoring (ECMWF, 1987).

A different approach was taken by Sun et al (2010) who compared radiosonde stations by type with temperature and humidity retrievals from GPS-RO observations. Note however that their temperature and humidity retrievals contain some information from the NCEP background so the distinction between their study and ours is less marked than might appear at first sight. By selecting only radiosonde ascents with a collocated GPS-RO observation they reduce the sample size. Moradi et al (2013) compared upper tropospheric humidity by radiosonde type against microwave satellite data, using radiative transfer to simulate brightness temperatures from the radiosonde profiles. Ho et al (2017) used reprocessed GPS-RO temperature retrievals for 2006-2014 to characterize radiosonde temperature biases and the variability of these biases in the upper troposphere and lower stratosphere for different radiosonde types. They found that

Vaisala RS92 radiosondes showed better quality and stability than other commonly available radiosondes over that period. Tradowsky et al (2017) present a new method (not currently operational) to derive radiosonde temperature bias corrections using GPS-RO data. They also discuss a "null space" that makes GPS-RO almost blind to certain upper level error structures.

3 Results of O-B comparison

3.1 Temperature results

Dirksen et al (2014) concluded that the time lag of RS92 temperature sensors was sufficiently small that any biases arising from the lag would be less than 0.1 K, it might however be larger for other radiosonde types. They also found that the largest temperature uncertainties are at upper levels in daytime, because of solar radiation effects which cannot be fully removed (and correction algorithms have their own uncertainties). For the temperature sensors tested by Tschudin and Schroeder (2013, their table 5) under standard conditions the time constant ranged between about 2 and 8 seconds. The MMT-1 sensor used in most Russian radiosondes had the largest values (i.e. is slower to react). For the statistics presented here the overall effect of time lag is likely to be small, but one possible exception is discussed.

Figure 3.1 shows O-B results in four latitude bands for the main radiosonde categories. Results for a few others can be found in the regional results later. For 50°–90°N the low level temperatures (especially in winter, not shown) have rather large rms(O-B) values – this is partly due to surface inversions that are poorly resolved or absent in the model. These near-surface differences are largest for the Russian reports, possibly exacerbated by time-lag issues - Mahesh et al (1997) discussed the effect of thermal lag in strong Antarctic inversions. (Some low level background values are extrapolated below the model surface adding extra uncertainty.) Above the boundary layer it is thought that the results reflect somewhat poorer quality of the Russian radiosondes (possibly including vertical coordinate error in some cases). In the southern extratropics the large 1000 hPa difference for InterMet radiosondes comes essentially from one station: Walvis Bay Airport in Namibia (68098). This is not far inland from the cold Benguela current and often has a marked low level inversion which is typically not fully represented in the model. In the tropics Graw performs poorly. (For 50°–90°N Modem M10 is colder relative to the background at 200 hPa, but this is a relatively small sample.) The stratospheric rms is lowest in the summer extratropics (seasonal variation not shown). Generally good performance is seen for RS92 (including NGP), RS41, LMS6, M10, Meisei and Shanghai.

There are certain general features in figure 3.1: a near-surface maximum in rms O-B, a minimum in the mid- or upper troposphere (~0.6° in the best cases, at ~400 hPa in the extratropics and ~250 hPa in the tropics) and then an increase to the tropopause level. The "tropopause maximum" is clearly a function of latitude (and is lowest in altitude for the Russian radiosondes). In the stratosphere the rms is larger in the tropics than in the extratropics. This is thought to be due to higher levels of gravity wave (and perhaps Kelvin wave) activity in the tropics. This is consistent with Alexander et al (2002) who found a pronounced peak in wave activity (with short vertical scales) at tropical latitudes. Gravity waves can sometimes be seen in individual temperature profiles – they may be represented to some extent in the background fields, but vertical resolution and other issues generally prevent a good match, so that gravity waves are, in effect, 'representativeness noise'. The lower stratospheric radiosonde temperatures are mostly higher than the background values, by up to about 0.4° for 50°–90°N. In the tropics from

1000 to 700 hPa the reported temperatures are higher by 0.2-05°. These mean differences are thought to be mainly due to model biases, in the latter case due to too much cloud in the tropics (P Bechtold, 2016, pers. comm.). At 200 hPa the O-B difference is more negative than at adjacent levels – this is due largely to a warm bias in flight level aircraft temperatures feeding through to the background fields. Figure 3.2 shows that at 200 hPa the background values at radiosonde locations are about 0.2° higher without aircraft assimilation, this should improve when the aircraft bias correction is upgraded in late 2017 or early 2018.

3.1.1 TEMP rounding and minor temperature offsets

In BUFR temperatures are reported in Kelvin to two decimal places, in TEMP code they are reported in Celsius to a precision of 0.2 degrees, with one bit being used to indicate the sign of the temperature (Code Table 3931 in WMO 2015). For raw data available to one decimal place the ECMWF decoding should give unbiased results. For example the temperatures +13.4°C and +13.5°C are both coded as 134, ECMWF decodes this as +13.45°C or 286.6K; temperatures -13.4°C and -13.5°C are both coded as 135 and decoded as -13.45°C or 259.7K; both positive and negative values are correct on average. Comparing TEMP and BUFR reports Ingleby and Edwards (2015) found that RS92 DigiCORA III TEMP reports are offset by -0.05K on average using ECMWF decoding. More recently TEMP vs BUFR standard level comparisons have been performed for a few other radiosonde types and it was found that Vaisala MW41 processing (used for some RS92 radiosondes and almost all RS41 radiosondes) gives TEMP temperature reports that are slightly warmer than BUFR on average. This is now understood using information from M Lehmuskero (Vaisala, pers. comm. 2017) summarised in the next paragraph.

DigiCORA III TEMP software (and some earlier versions) stores temperature multiplied by 10 as an integer and effectively uses 273.2 to convert between Kelvin and Celsius, which is where the -0.05K offset arises. Most Vaisala BUFR processing (DigiCORA III and MW41) stores temperature as floating point values – the rounding when stored in BUFR to two decimal places is negligible for most purposes. MW41 stores temperature as floating point values, when producing TEMP reports the values in Celsius are truncated to one decimal place and then coded using the WMO rules. The truncation is towards zero so that for positive temperatures there is a mean offset of -0.05K, whereas for negative temperatures the mean offset is +0.05K.

For Graw DFM-09 TEMP temperature reports are 0.05K higher on average than the BUFR values. For Modem M10 the TEMP/BUFR offset appears to be zero (this also seems to be true of the InterMet iMet-2, although the sample of high-resolution BUFR is very small). In such comparisons one should only use native BUFR, other approximations/roundings may have been made when TEMP has been reformatted to BUFR (and most reformatted reports are unusable, Ingleby et al, 2016a). Other TEMP decoders may vary (the Met Office decoder treats ‘134’ as +13.4°C and then adds 273.1 to convert to Kelvin – giving values 0.1K lower than the ECMWF decoder) but the relative difference between different radiosondes should be the same. These offsets are too small to make much difference in NWP, but should be noted by climate users.

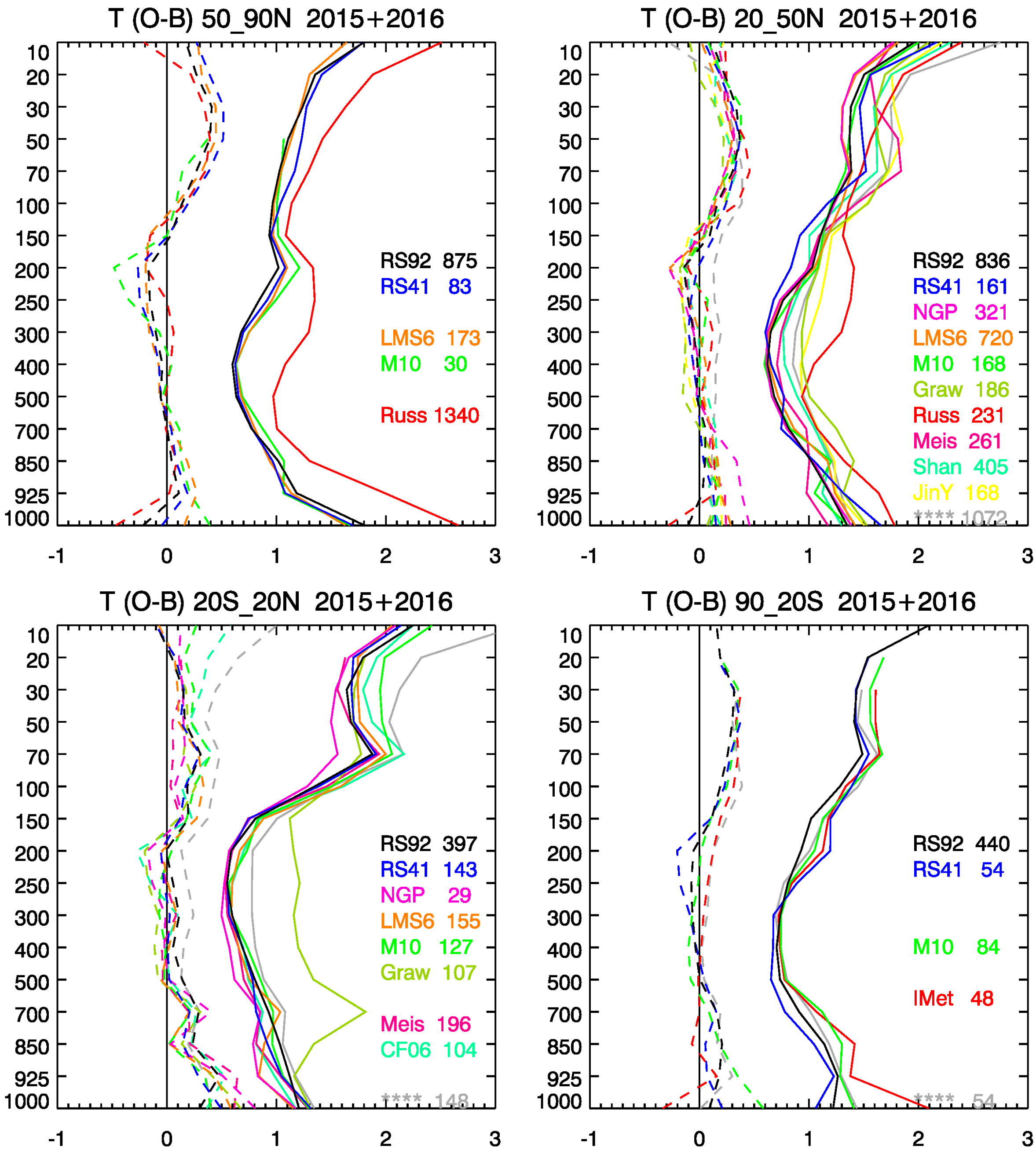


Figure 3.1. ECMWF temperature (K) O-B statistics for 2015 and 2016 combined, mean (dashed) and rms (solid): versus pressure (hPa, standard levels) for main radiosonde categories. The different panels show 50°N – 90°N, 20°N – 50°N, 20°S – 20°N and 90°S – 20°S. The colour key shows the radiosonde type (labels as in table 1) and the number of reports in hundreds (for standard level with the most values), only categories with at least 2000 reports shown.

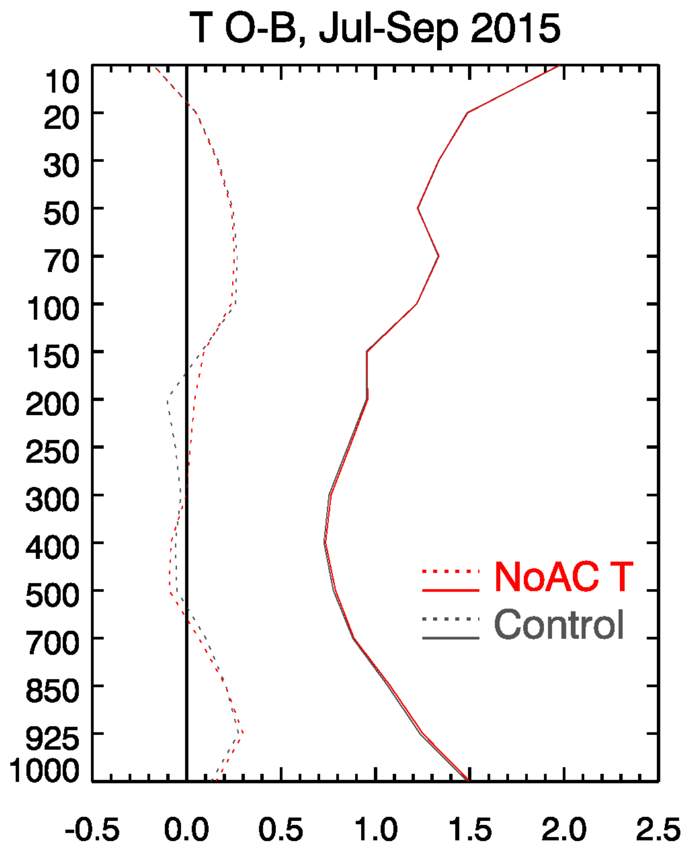


Figure 3.2. Global mean (dashed) and rms (solid) radiosonde temperature O-B statistics for a three month trial not assimilating aircraft temperatures (red) and a control that does assimilate them (grey).

3.2 Relative humidity results

Figure 3.3 shows results for relative humidity (RH). In the lower troposphere the different radiosonde types have relatively similar O-B statistics (with rms at 1000 hPa generally around 10%). The mean O-B is near zero or positive in the lower troposphere but negative in the upper troposphere (UT). Background humidity values are subject to their own errors and biases, but the comparison is still useful. The UT rms values are wildly divergent with the Vaisala radiosondes generally showing closest agreement to the background. At ECMWF only limited radiosonde humidity data is assimilated in the UT and humidity is not assimilated in the stratosphere, however large mean or rms differences in the stratosphere indicate contamination problems – that may well affect the troposphere as well. Thus stratospheric humidity can be useful for detecting humidity sensor contamination (the values should only be a few %RH). Despite guidance to the contrary a few types appear to set stratospheric humidity to climatological values. Older Meisei types stop reporting humidity at 300 hPa, but some iMS-100 reports include upper level humidity. The tropical UT (with temperatures down to -90°C at times) is particularly challenging for humidity measurement, but the best radiosonde types now give usable humidity there (Nash et al, 2011). It is also where the humidity conversions have the largest effect on the biases (see below). At 100 hPa in the tropics figure 3.3 suggests that the RS41 performs better than other radiosondes including the RS92.

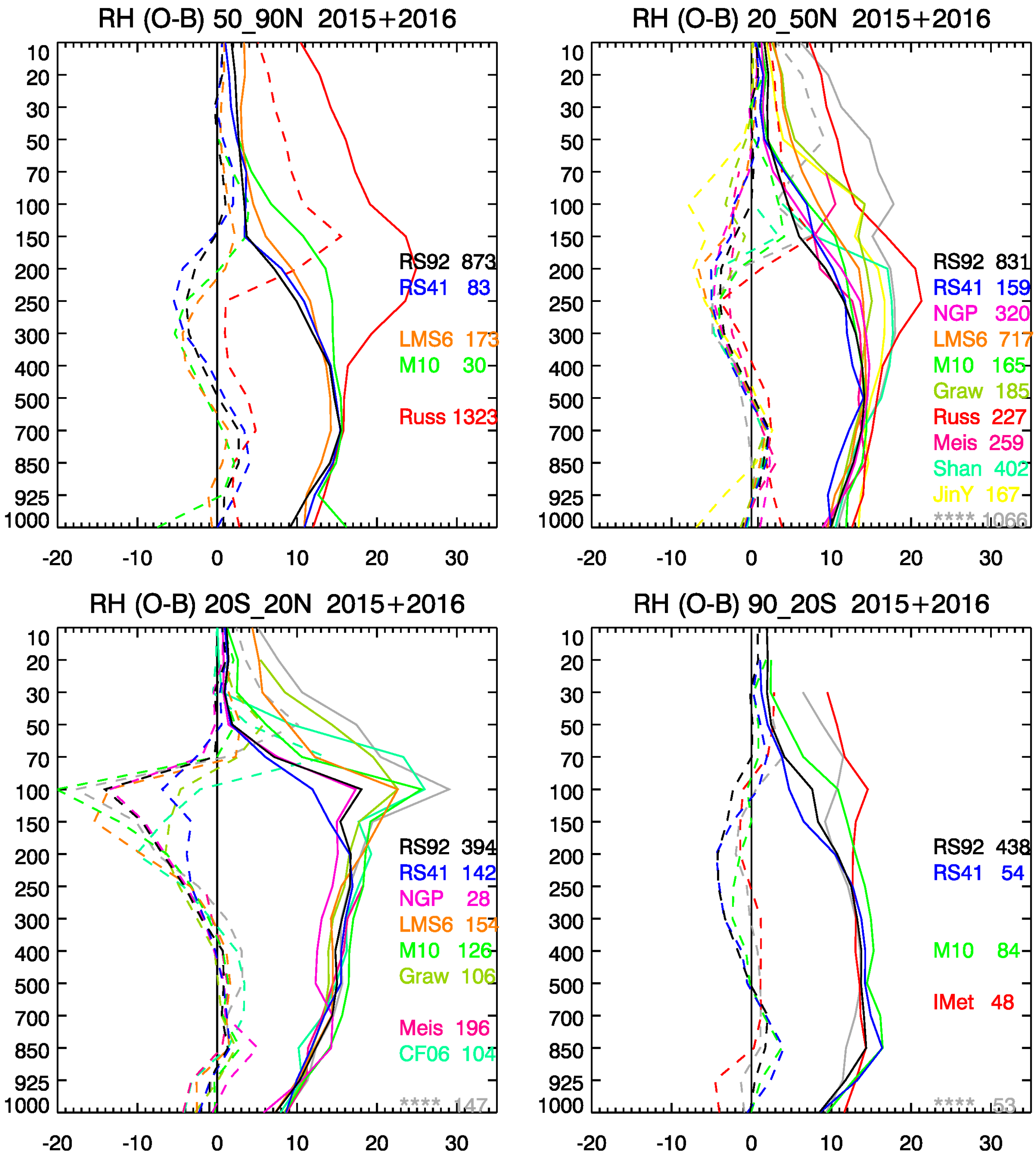


Figure 3.3. As figure 3.1 but for relative humidity (%).

The main instrumental problems for UT humidity are a) the sensors react more slowly in cold air (the effect of density is less clear), b) solar radiation effects in daytime and c) sometimes after passing through cloud the sensor can be contaminated (perhaps ice-coated) either temporarily or for the rest of the flight. There can also be issues of the formulae used to calibrate the measurements and then to process them (discussed below). It seems that most radiosonde types occasionally suffer from cloud contamination, but the Russian radiosondes are particularly susceptible, e.g. after exiting from a mid-level cloud the radiosonde continues to indicate near saturation (often even into the stratosphere). The ECMWF bias correction scheme applies a large 'correction' to the Russian radiosondes in the mid- and upper-troposphere (figure 2.3), without this their statistics in figure 3.3 would look even worse – however this issue should be considered a quality control rather than a bias correction matter. In practice many, but not all, of the contaminated humidities are excluded by the prior rejections. At ECMWF the default is to reject radiosonde humidity where the temperature is less than -40°C or the pressure less than 300 hPa, for RS92 and RS41 the limits are set as -80°C and 100 hPa (the limits for a few other types could be reassessed/relaxed). Ingleby and Edwards (2015, supplemental information) introduced a quality check into the Met Office system that starts at the top of the profile and moves downwards comparing RH with the background value – if the stratospheric RH seems too high then values are rejected until a clearly cloud-free layer is found. The previous generation of US radiosondes also suffered badly from cloud contamination, current US radiosondes whilst not immune (see example plot at figure 4.6) are rather better. The heating of humidity sensors in Vaisala radiosondes give significant protection against contamination (RS92 has two humidity sensors heated alternately down to a temperature of -60°C, RS41 has a single sensor heated at all levels and a built-in thermistor). Jensen et al (2016) and other studies suggest that RS41 humidity is at least as good as that from RS92 and probably better, the results here are consistent with that.

3.2.1 Humidity conversions and processing at ECMWF

Radiosondes report humidity as dew point temperature (Td). ECMWF converts this to RH (with respect to liquid water at all temperatures), applies a bias correction and then converts to specific humidity (q) which is assimilated. (The temperature bias correction is applied before the humidity conversions, it would be slightly better to use the reported temperature in the conversions.) Dew point temperature is a curious concept at very low temperatures (ice point temperature would be more physical) and both Td and RH implicitly depend on the saturation vapour pressure (SVP) equation used. Below about -40°C noticeable differences between the different liquid water SVP equations arise (there is a useful website comparing them at http://cires1.colorado.edu/~voemel/vp.html). WMO (2014) recommends the use of Wexler, Hyland and Wexler or Sonntag SVP equations (which all give similar results) for radiosonde calibration and processing (Vaisala uses Hyland and Wexler). Until recently ECMWF used the Buck SVP equation but in November 2016 (cycle 43r1) changed to use the Sonntag SVP equation for radiosonde processing (including the matching background RH values). (Arguably the SVP equation should vary to match that used by the manufacturer, but most of the older formulae are not technically valid below -40 or -50°C and ECMWF would not assimilate them at those temperatures, so we prefer to use a single formula for simplicity.) Figure 3.4 shows results for three months from the pre-operational trial of the 43r1 with the operational system at the time (41r2). (43r1 included many other changes https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model/ but for radiosonde humidity the conversion change is dominant.) The largest biases, and changes, are in the tropical UT where RS41 fits the background better than RS92 and the ‘Sonntag change’ significantly reduces the biases relative to the background. Part of the RS92 bias is because some stations were still using pre-2010 versions of the Vaisala software – without humidity corrections. The corrections bring Vaisala processed humidities closer to GRUAN processed humidities (Yu et al, 2015).

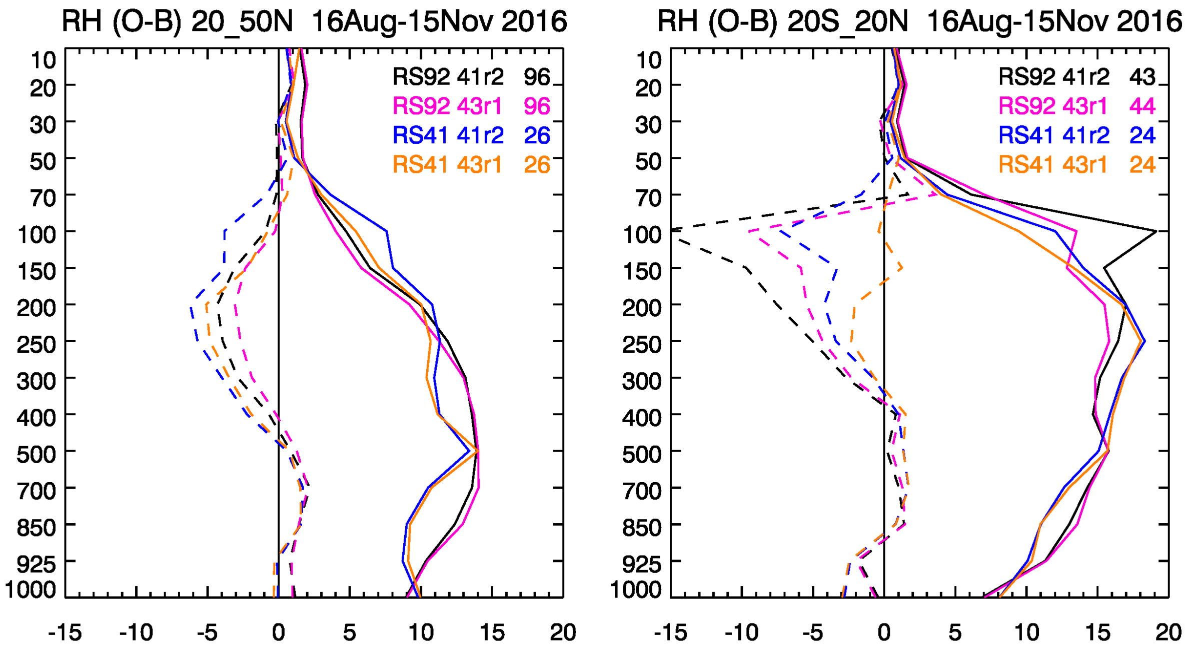


Figure 3.4. RH statistics for Northern mid-latitudes (left) and tropics (right) for RS92 and RS41 from 16 August to 15 November 2016 in both the ECMWF operational system at the time (41r2) and pre-operational tests of version 43r1.

A forecast trial was performed at ECMWF switching off the RH bias correction (some centres, including the Met Office, do not bias correct radiosonde humidity), the forecast results were slightly worse perhaps in part because some measurements contaminated by lower level cloud are being assimilated. The bias correction method at ECMWF currently uses nighttime type 81 (RS92 autosonde) as the reference – this will have to change as the RS92 is gradually phased out. Current plans are to use an average of nighttime RS92 and RS41 as the reference, to switch off the bias correction for selected radiosonde types and (later) to tighten the humidity quality control in some respects. Looking at the overall picture it is somewhat disconcerting that most radiosondes have radiation corrections applied before the reports are transmitted and further bias corrections applied at ECMWF. However with the present system the ECMWF radiosonde bias corrections improve forecast skill on average. For RS92 humidity it would be useful to know the processing applied at source (more recent Vaisala DigiCORA III and MW41 software versions include radiation and time-lag corrections) – this information is appended to BUFR reports (Ingleby et al, 2016a) but is not available in TEMP reports. For example Germany and the UK changed to use newer software versions, with humidity corrections, during 2015.

3.3 Wind results

One feature of the wind O-B statistics in figure 3.5 is that (except near the surface) the reported winds are slightly stronger than the background winds, about 0.1 m/s at high northern latitudes, but about 0.2 m/s up to 250 hPa in the Tropics and 0.5 m/s above. The bias may be partly that the forecast model does not resolve the full wind spectrum, but in the tropical stratosphere the model climate may well be biased.

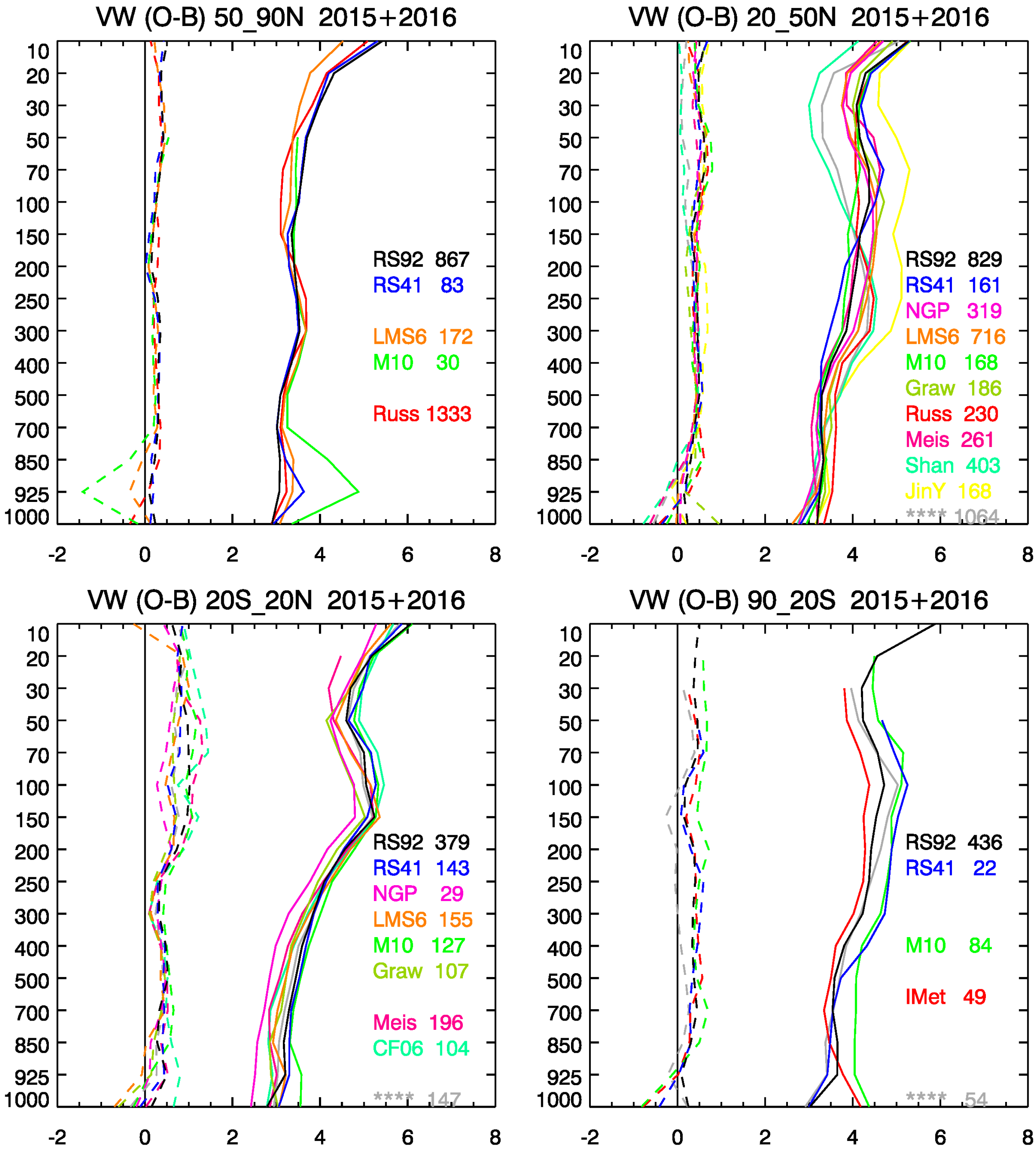


Figure 3.5. As figure 3.1 but for wind differences (m/s). The dashed lines give the speed bias, the solid lines the rms vector wind difference.

For 50-90°N the various radiosonde types generally give rather similar O-B statistics, the exception being Modem at low levels (due to station 04360 on the Greenland coast – subject to an intermittent low level barrier jet not always well forecast, see section 4.3). For 20-50°N JinYang radiosondes have the largest wind rms at 300 hPa and above. All radiosonde winds need some smoothing in the vertical, this is partly because of the pendulum motion of the instruments below the balloon (the magnitude of the pendulum motion varies from ascent to ascent and also within a particular ascent). Occasionally winds are insufficiently smoothed, however it seems that some can be over-smoothed – giving smaller rms(O-B) statistics. Smaller rms is generally a good sign but not in this case. This is discussed further in section 3.5. There is a maximum in vector wind rms difference at the top (10 hPa) and also some sign of a maximum of wind rms (O-B) at jet level but this is much less marked than 20 or 30 years ago (discussed below). In the extratropics the stratospheric rms is larger in winter (not shown). From about 500 to 50 hPa the wind rms values are lower north of 50°N than for the other latitude bands shown.

It is of interest to compare the northern mid-latitude results with Figure 3 of Hollingsworth and Lonnberg (1986), they looked at North American radiosonde data from 30° to 60°N for January to March 1983 compared to the ECMWF system at the time. Their vector wind rms was over 4 m/s at 925 hPa, peaked at over 8 m/s at 300 hPa and was ~5 m/s at 100 hPa. Since then there has probably been a minor improvement in radiosonde wind quality, but there have been major improvements in the skill of short range forecasts. (Their choice of a winter period would give larger differences than an annual average, but the seasonal cycle is also less marked now.) The improvement is most marked at the tropopause level, the rms is now ~4 m/s compared to ~8 m/s in 1983.

3.4 Geopotential height results

Radiosonde heights are not assimilated at ECMWF (and most other NWP centres) but they are used for forecast verification and it was found during this study that their accuracy can and should be improved in various ways. For some radiosonde types/groups the biases, as seen in figure 3.6, can be very significant. Meisei shows less bias relative to the ECMWF background than other types (between 8 and 20 km Nash et al, 2011 found that daytime Meisei results were cooler than the other radiosondes tested). Between 1000 and 700 hPa tropical background temperatures are biased (section 3.1) giving height biases at 500 hPa and above. Some of the biases come from station height errors or processing errors as discussed below. For the rms there is also a significant contribution from reporting precision.

3.4.1 Improved height precision from BUFR

In TEMP code each standard level height measurement has to be represented in three digits (with the leading digit often being inferred). Between 1000 and 700 hPa the reporting is to the nearest metre, but at 500 hPa and higher standard levels the reporting is to the nearest 10 m. This is unfortunate because the uncertainty of reference radiosondes at 500 hPa is about 3 or 4 m (Dirksen et al, 2014; figure 20).

Figure 3.7 shows observation minus background (O-B) statistics for German radiosonde stations. From 1000 to 700 hPa the TEMP and BUFR root-mean-square (rms) O-B statistics are very close, at 500 hPa the TEMP rms is somewhat degraded, evidently due to rounding error. However looking at global rms statistics for Vaisala RS92 or all radiosondes (red and black lines in figure 3.7a) these degrade more around 500 hPa – mainly due to model biases in the tropics as discussed above. At upper levels radiosondes are subject to radiation errors in daylight, these are corrected as far as possible by the

Vaisala software but the uncertainties are still large (the GRUAN and Vaisala temperature corrections are fairly similar, see Dirksen et al, 2014, which also shows day/night estimated uncertainties). Figure 3.7b shows day/night differences for German radiosonde height statistics, at 50 hPa the nighttime statistics are slightly better, the gap increases markedly at higher altitudes. (The day/night differences are present but less marked in global statistics, they are also less marked in temperature O-B statistics, not shown.) At these upper levels, especially 20 hPa or 10 hPa it is difficult to know whether the background or the (nighttime) radiosonde values are nearer the truth.

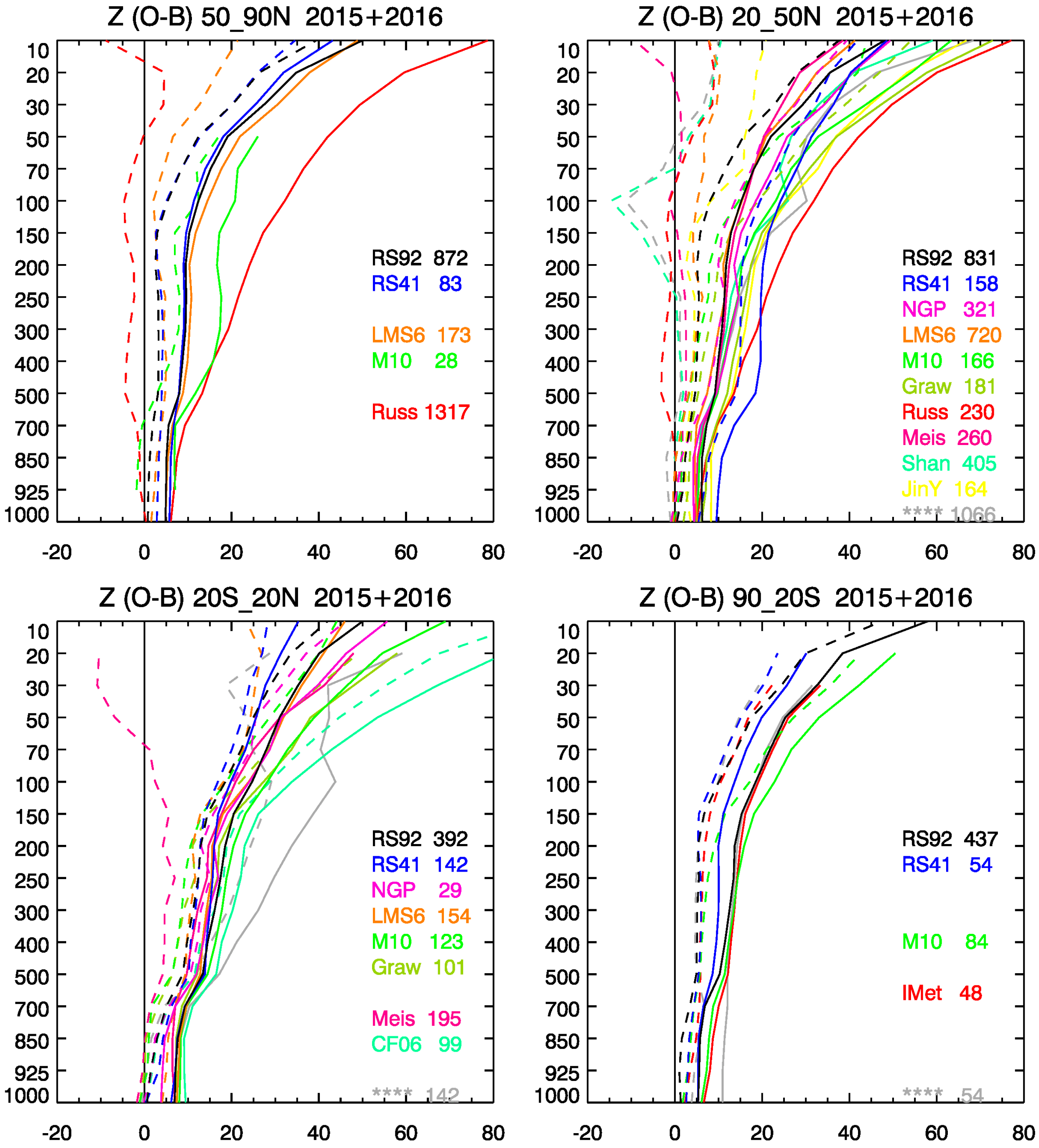


Figure 3.6. As figure 3.1 but for geopotential height (gpm).

At tropospheric levels some stations show a constant height offset from the ECMWF background – this most likely indicates station height errors. Two German stations have offsets of 8 or 9 m (not shown) but globally there are more and worse outliers.

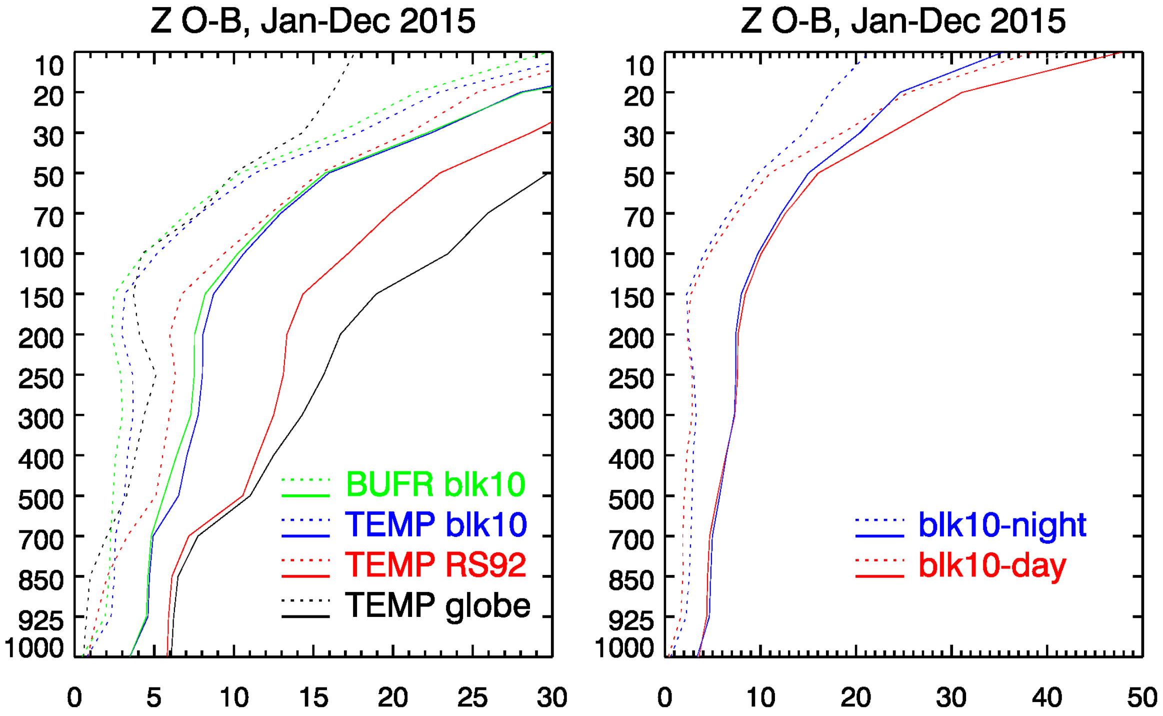


Figure 3.7. Radiosonde height O-B statistics for 2015, mean (dotted) and rms (solid). Left: global TEMP reports (black), global TEMP RS92 reports (red), German (block 10) TEMP reports (blue), German BUFR reports (green), x axis chosen to emphasise tropospheric details. Right: German BUFR reports for daytime (red) and nighttime (blue).

3.4.2 Station height errors (GPS reference and other issues)

Figure 3.8 shows monthly mean O-B height differences for four selected stations. The ideal is for each station to have a vertical line close to zero (within say ±5 m), an offset vertical line is consistent with a station height error. Globally there were about 80 stations with mean height O-B differences of 15 m or more at one or more levels between 1000 and 500 hPa. O-B differences are due to both observation and background errors, but in general near-surface background height fields are very good (partly because many surface pressure observations are assimilated) – mean height differences over 15 m indicate likely systematic observation errors (in the stratosphere it is more difficult to separate background and observation error).

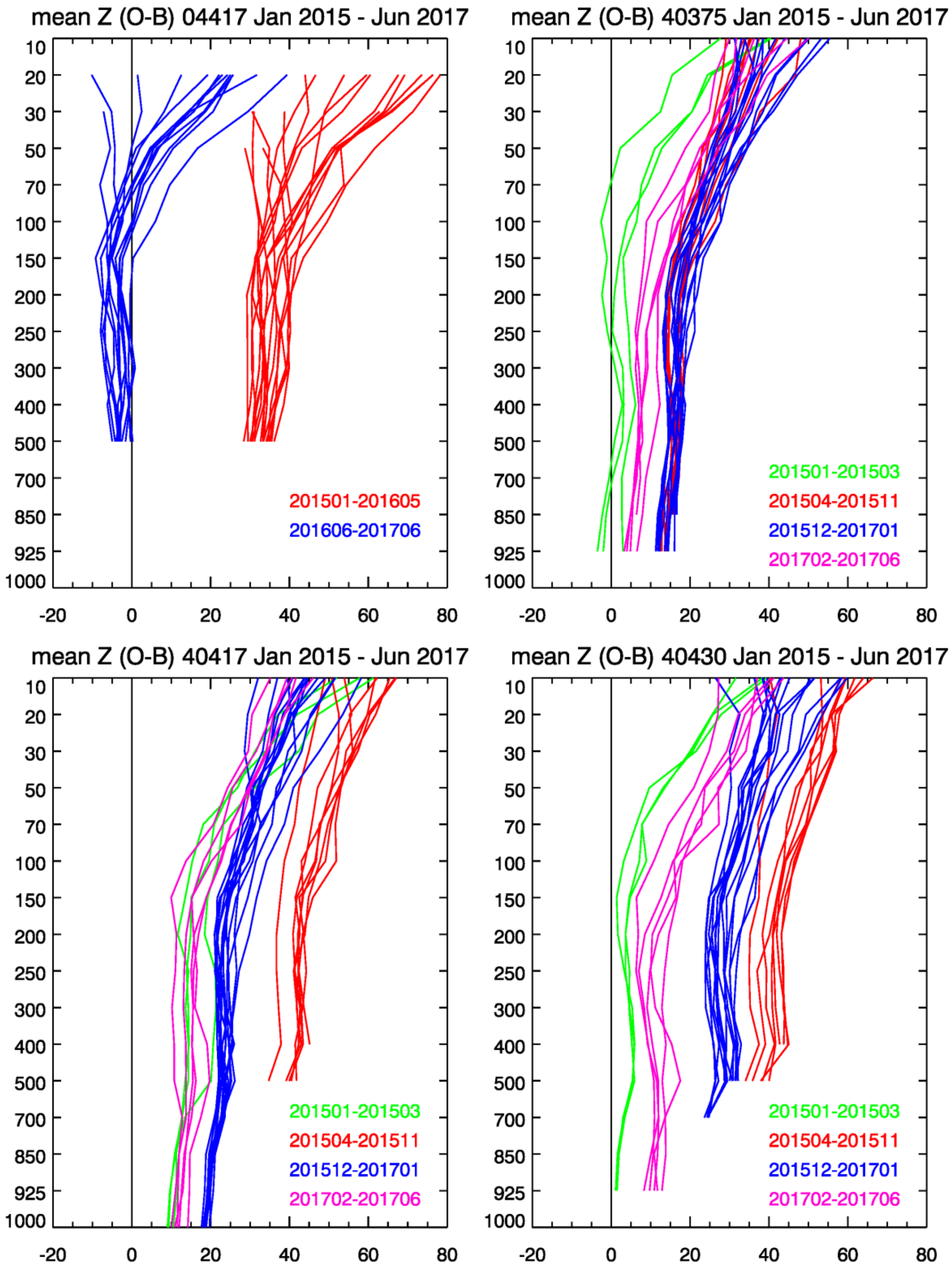


Figure 3.8. Height biases by month (colour coded as in key) for one station from Greenland (top left) and three from Saudi Arabia. Ideally the height difference (particularly in the troposphere) should be near zero. All these stations show jumps in bias over time, for 04417 (top left) this is due to the height being corrected. For the Saudi stations the earlier months (coloured green) correspond to RS92 data.

Early in 2016 an O-B height bias of about 35 m for levels between 700 and 150 hPa for the Greenland Summit station (04417) was noted at ECMWF (Figure 3.8a, red lines). This station is run by the US National Science Foundation in association with the Danish Meteorological Institute. The bias was suspected to be due to a station height error, possibly because GPS systems (by default) give height above a reference ellipsoid, whereas for meteorological purposes height above the geoid (~mean sea level) is required. For the position of this station the difference between the two (the 'undulation of the geoid') is about 44 m. Email exchanges confirmed that station 04417 was using an unadjusted GPS height, it also seemed too high by comparison with the adjacent surface station 04416; the surface pressure values from 04416 were in very good mean agreement with the ECMWF background. In early June 2016 Matthew Shupe (University of Colorado/NOAA) modified the height as used in the PC at station 04417 and as can be seen (Figure 3.8a, blue lines) this results in a much better mean fit to the ECMWF background. (Being on ice the position and height of this station will vary slowly over time)

Until relatively recently station heights were derived from ground-based surveys (referenced to mean sea level) but now GPS offers a very attractive alternative, especially for remote stations. The GPS system uses the World Geodetic System 1984 (WGS-84) ellipsoid as reference and meteorologists need to take account of differences between the ellipsoid and the geoid given by Earth Geodetic Model 1996 (EGM96). The difference between the two references can be up to 100 m worldwide – potentially causing a very large error in meteorological measurements. WMO guidance (such as the CIMO guide) does state that elevation should be relative to mean sea level but (in the author’s opinion) should clearly point out the possible pitfall of using GPS “reference ellipsoid” heights without adjustment. Unless the people checking existing stations or setting up new stations are clear about this then related errors (at both surface and radiosonde stations) will increase in the coming years.

For 500 hPa the uncertainty of good height measurements is 5 m or less – it only takes a small proportion of stations with offsets of 15 m or more to seriously degrade verification and other statistics. Station heights can be wrong for various reasons: a) typing errors, b) failure to update metadata (eg if the barometer is moved) c) reference errors (as above) or d) confusion between different heights. When setting up a modern radiosonde system the software may require: general station (or runway) height, barometer height, height of radiosonde launch and GPS antenna height.

Until March 2015 stations in Saudi Arabia used Vaisala RS92 radiosondes, they then changed to Vaisala RS41. Unfortunately at some stations the change introduced larger height biases (some of the low level statistics disappear from the plots in figure 3.8 because all the values failed the background check). Near the end of 2015 there was an attempt to correct the problem – only partially successful (three stations are shown in figure 3.8 others were also affected). This is not a problem with the RS41 raw data or software. Unlike the RS92 the standard version of the RS41 does not include a pressure sensor but pressure is calculated from height and temperature profiles (this gives reasonable pressure accuracy, see Jensen et al, 2016, and also recent WMO radiosonde intercomparisons). To start the pressure calculation a surface pressure reading is needed, from communications it appeared that the Arabian stations had assigned general station altitude (HHa, instead of barometer altitude, HP) to the pressure measurement. The pressure altitude within the RS41 software was corrected in early 2017 for these three stations, so the latest results (purple) show smaller biases, although for two of the stations the bias is still a bit larger than expected.

Errors in station height are nothing new, Ingleby (1995) described their detrimental effect on assimilation of station pressure. For high level surface stations computing pressure at mean sea level (Pmsl) is very similar to sub-surface extrapolation of height values and should be avoided. For nearly all stations direct use of station level pressure (Pstn) should be better for assimilation than assimilation of Pmsl. Although reporting of station level pressure has been mandatory for many years some countries/stations still only report Pmsl. Although the details vary, both ECMWF and Met Office tend to use Pstn in preference to Pmsl and both apply pressure bias corrections to a small proportion of stations, for some of these stations this effectively compensates for an error in the reported station (barometer) height. Arguably NWP centres should also apply bias corrections to radiosonde heights, for verification even if the heights are not assimilated, where there is a consistent tropospheric bias (as shown in some of the examples above). However it is always more satisfactory to fix the problem at source (as has been done for the Greenland Summit station).

3.4.3 Extrapolation below the surface!

Another issue can be illustrated by data from 04417 (similar examples could be found for other high level stations). The station is at 3211 m (revised elevation) with a mean pressure of about 675 hPa. Figure 3.9 shows temperature and height statistics: temperature for 500 hPa and upwards but height for lower levels as well. The height statistics at 1000, 925 and 850 hPa are quite different from those at higher levels, height has been extrapolated downwards using a hypothetical temperature profile (for both the observation and the model, there is no 'correct' way to do such extrapolation over a large height difference; extrapolated values can be useful just below the station location). If used in verification such extrapolated values will just add noise and possibly swamp any signal. The earlier plots have explicitly excluded such sub-surface values – without this some of the low level statistics would have been worse. Arguably there should be guidance from WMO discouraging such ‘sub-surface’ reporting.

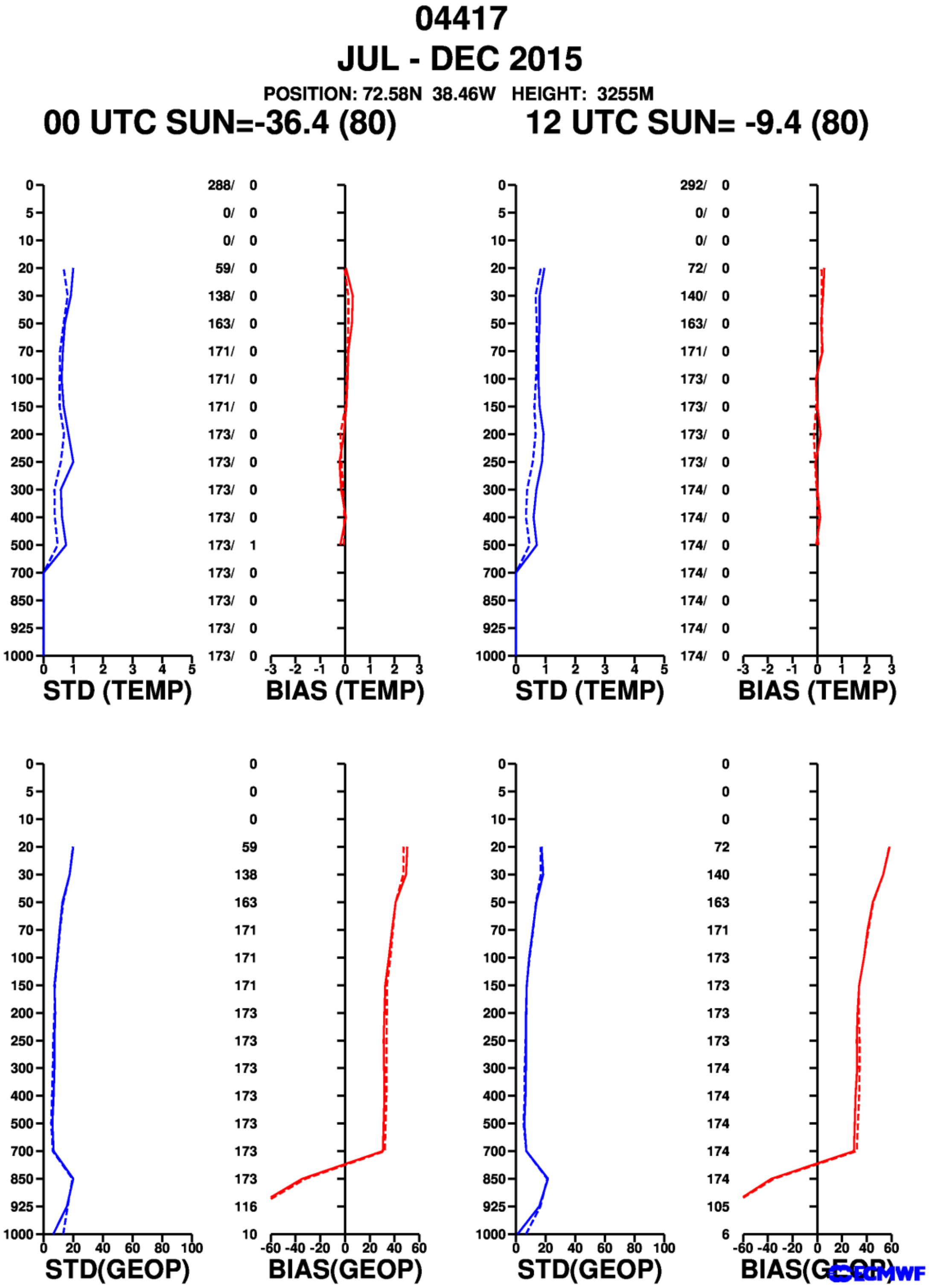


Figure 3.9. Extract from operational ECMWF monitoring statistics for 04417 (standard deviation and bias of O-B) for second half of 2015. Top: temperature, bottom: geopotential height; left: 00 UTC data, right: 12 UTC data. ECMWF monitoring statistics and reports are available from http://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system

3.5 Regional results

3.5.1 Russia, Kazakhstan and Ukraine

For practical reasons all Russian radiosonde types (which are used in both Russia and Kazakhstan) were combined in sections 3.1 to 3.4. Broadly speaking this is supported by the results in figure 3.10 which have a lot in common. Type 60 (MARL-A or Vektor-M – I-2012) has the largest low level temperature differences and type 90 (actually an amalgam of types) has particularly large humidity biases. The overall impression is that Russian radiosonde types are quite “old fashioned” with relatively slow temperature and humidity sensors, the upper tropospheric humidity also suffers from frequent sensor contamination after passing through cloud (see example in figure 4.7). However the Russian reports are still valuable for NWP (Ingleby et al, 2016b). More details of Russian types can be found in the appendix.

From Ukraine PAZA-12M (type 15) looks particularly poor for temperature and wind – perhaps because of vertical coordinate errors (see example in Figure 4.9). All four stations using this type have similar extraordinary speed biases relative to the background fields. The information available suggests that the Ukrainian radiosondes (like the Russian ones) are direct descendants of the Soviet-era radiosondes (Zaitseva, 1993) and use radar position-finding. The results for PAZA-22/AVK-1 (type 16, three stations) are more respectable, but the individual stations have rather large temperature biases at some levels.

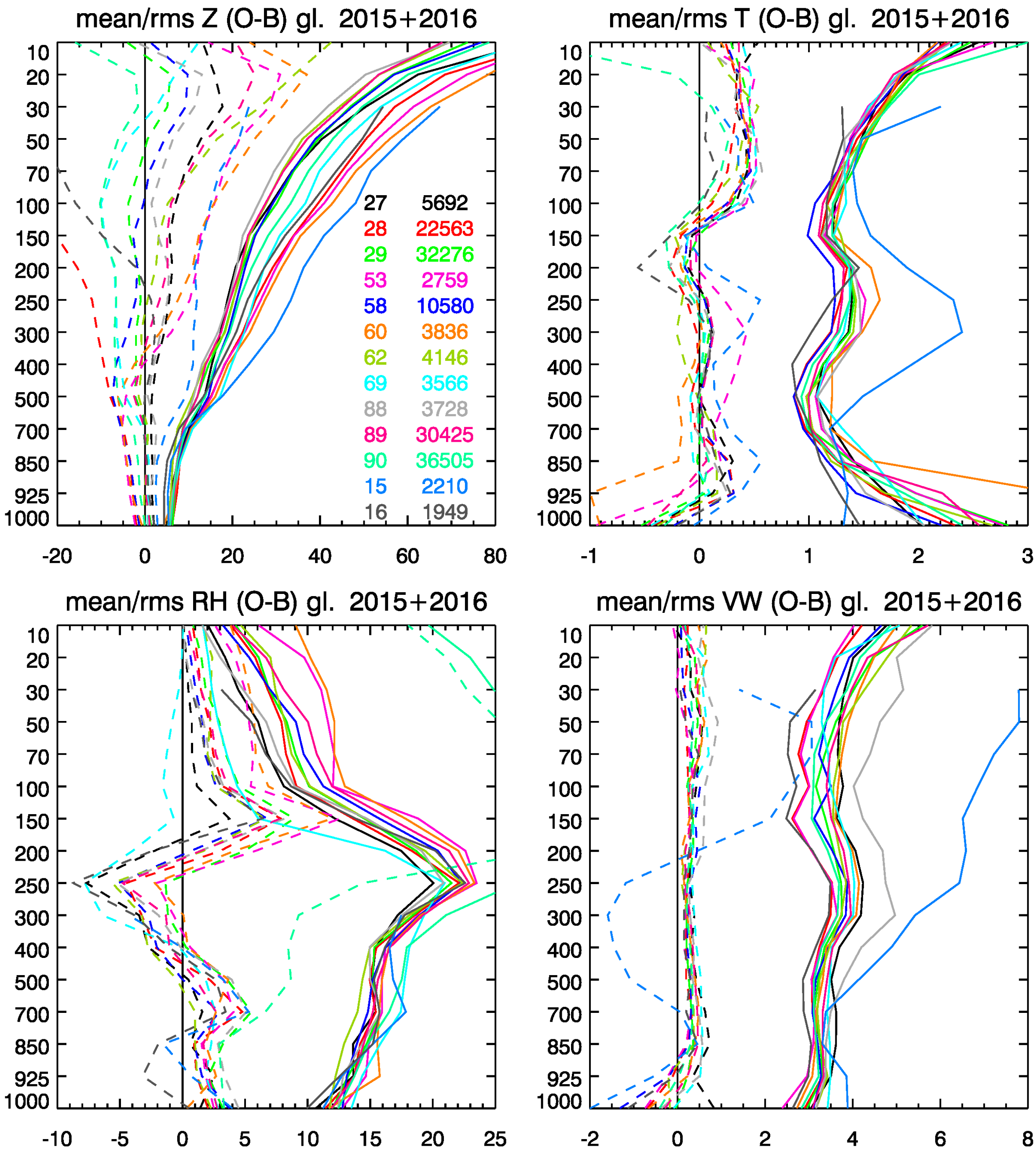


Figure 3.10. O-B statistics for selected types but different variables (similar to figures 3.1, 3.3, 3.5 and 3.6). The key gives the type and number of reports (maximum over the standard levels).

3.5.2 China and Malaysia

The current generation of Chinese radiosondes generally became operational around 2004/2005 and represented a distinct improvement on the previous generation. Unfortunately many Chinese stations report missing radiosonde type (** in figure 3.11), these have similar behaviour to the other Chinese stations except that upper level humidities are worse. The most common labelled type is 32 (Shanghai) and this is arguably the best – type 31 (made to the same design as 32) is broadly similar but somewhat worse for upper level heights and humidities. (The peak in RH rms(O-B) at 200 hPa but much lower values at 100 hPa may indicate that upper level humidity values are reset to climatology.) Type 33 has somewhat worse O-B statistics. Type 32 in Malaysia is actually Beijing Changfeng CF-06 and should be type 45. It has large height biases at upper levels apparently due to confusion between geometric and geopotential height. Apart from this (and stratospheric humidities that should not be taken seriously) the CF-06 results are broadly acceptable – the differences in wind statistics are due to the lower latitude of Malaysia (see figure 3.5).

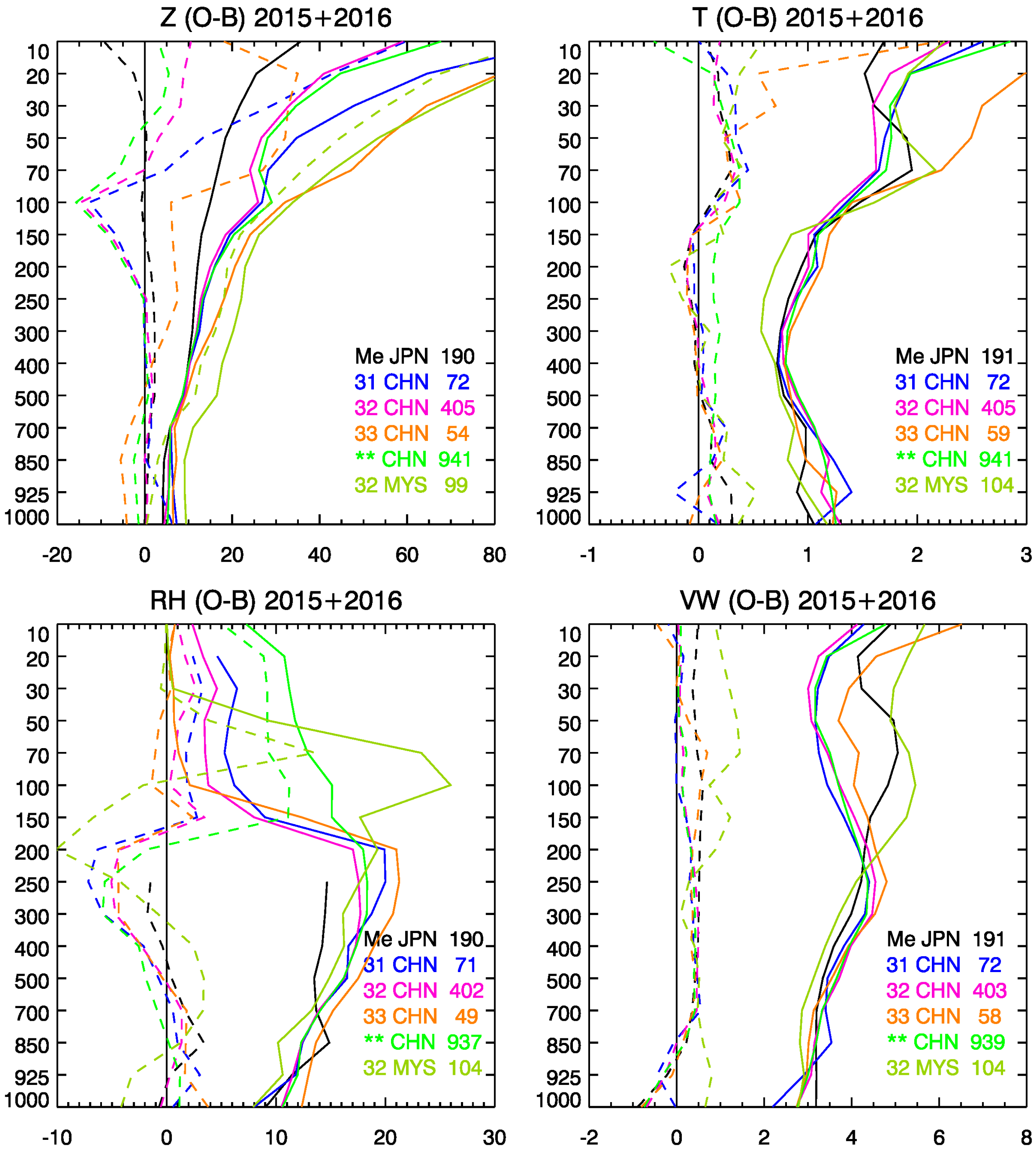


Figure 3.11 Similar to Figure 3.10 (but numbers in 100s). (Meisei/Japan included for comparison.)

3.5.3 Japan, Korea and India

Figure 3.12 shows results for Japanese, Korean and Indian radiosondes. JinYang radiosondes (type 21) are used in both South Korea and India, but the results from Indian stations are markedly worse for temperature and humidity. Meisei iMS-100 (type 35) is used in Turkey – the winds from this subset have a particularly low vector wind rms apparently due to extra vertical smoothing being applied at the customer's request. (Meisei radiosondes are also used in Indonesia and recently in Mexico, but these data do not show the same feature and were not included for clarity.)

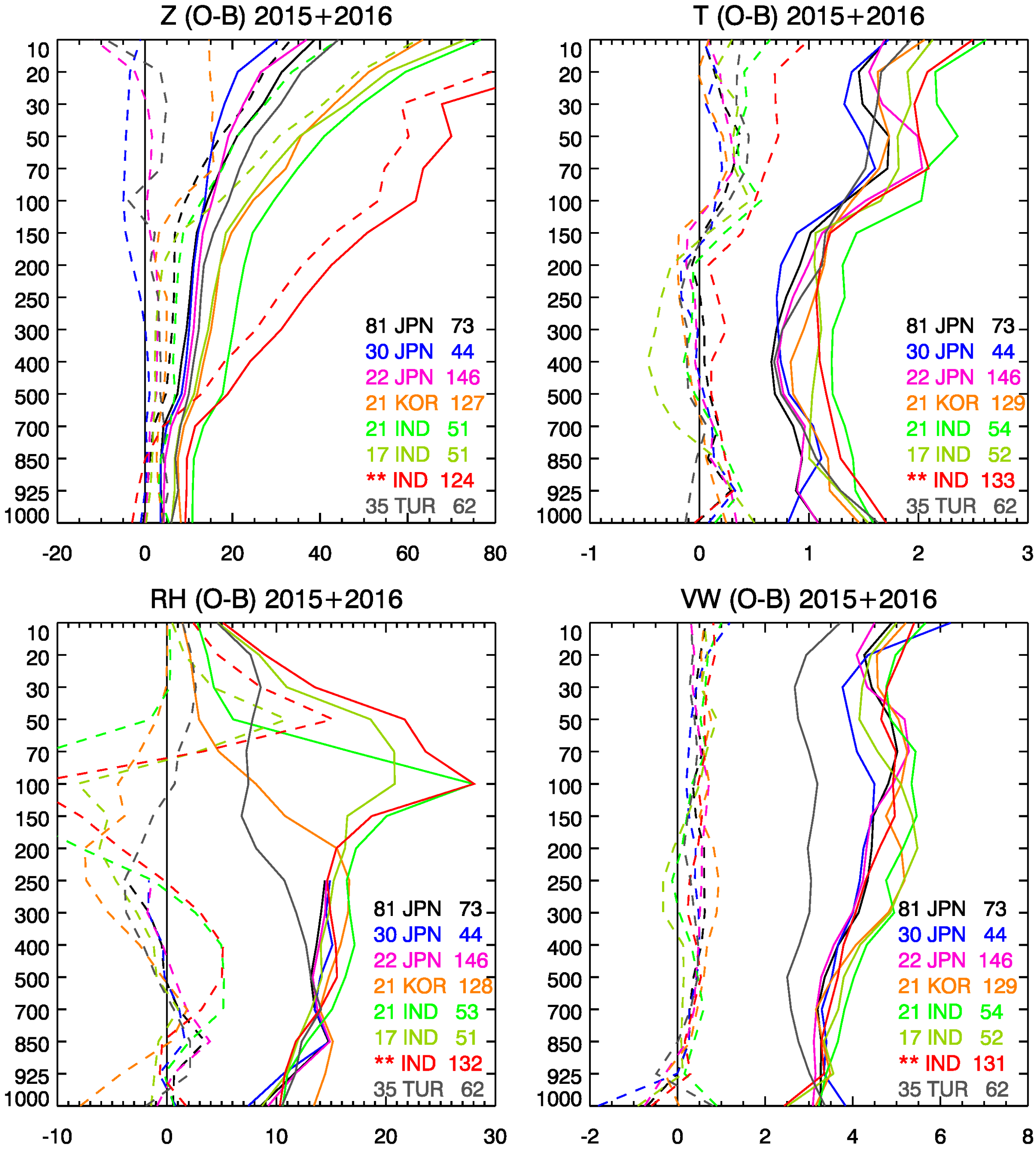


Figure 3.12. Similar to figure 3.11 but for for Japanese, Korean and Indian radiosondes.

Often geopotential height is calculated from the temperature profile using the hydrostatic equation. It is also possible to calculate geopotential height from geometric height as given by GPS or a radar (see WMO 2014, chapter 12, section 12.3.6). Some Beijing Changfeng CF-06 radiosondes reporting in India with missing type (** IND in figure 3.12) and in Malaysia with the wrong type 32 (32 MYS in Figure 3.11) are reporting geometric height rather than geopotential height. This gives a height bias increasing with altitude from 700 to 200 hPa despite moderately unbiased temperature O-B statistics. Since September 2015 India has not been using Indian-made radiosondes (Das Gupta, pers. comm. 2016).

3.6 Percentage rejected

Tables 2 and 3 show the percentages of standard level temperature and wind values rejected by the background check by radiosonde type and for several groups of levels. (For significant levels the rejection rates would almost certainly be larger because, in some sense, the significant levels are chosen to be unrepresentative.) The percentages are rather small and generally give an underestimate of the proportion of "gross errors" (except that some stratospheric temperature rejections are due to the presence of gravity waves rather than to observation error). Within the ECMWF system further adjustments to the weight given to outliers are performed by 'Variational quality control' and the 'Huber norm' – Tavolato and Isaksen, (2015) and references. Some statistics were performed using a tighter version of the background check (not shown) – this reduced the rms(O-B) differences between different types whilst increasing the spread of rejection rates and generally giving similar rankings to the different radiosonde types.

Values in tables 2 and 3 over 0.1% appear to indicate problems. Graw, JinYang and InterMet all have high rejection rates for some variables/pressures. Paza and Nanjing have large stratospheric wind rejections. RS92-D (used in the Caribbean with InterMet radiotheodolites, largely phased out now) had high wind rejection rates. Indian stations (60% in WMO block 42, the rest in block43) had rather high rejection rates in 2015: between 700 and 100 hPa inclusive over 0.6% of block 42 standard level temperatures failed the background check in 2015 whereas in 2016 the rate was about 0.15% (still higher than average, but much improved). Although the results are presented in very different ways there is some consistency between the O-B and rejection results here and the summary table 12.1 of Nash et al (2011). In their results RS92 scored very highly closely followed by LMS-6. Of course there were several radiosonde types operational in 2015/2016 which were not available for their intercomparison in 2010.

Type	**NumRep**	**1000-850**	**700-300**	**250-100**	**70-10**
14+ FIN Vaisala RS92	254601	0.02	0.01	0.00	0.01
15+ UKR PAZA-12M/22	4171	0.02	0.04	0.01	0.00
17 DEU Graw DFM-09	30446	0.08	**0.29**	**0.14**	**0.28**
21 KOR JinYang	18399	0.06	**0.16**	**0.21**	0.01
22 JPN Meisei RS-11G	15796	0.00	0.01	0.01	0.00
26 CHE Meteolabor	1538	0.00	0.02	0.03	0.06
27+ RUS Various	159177	0.04	0.07	0.03	0.01
30 JPN Meisei RS-06G	5375	0.01	0.00	0.01	0.01
31 CHN Taiyuan	7267	0.00	0.00	0.00	0.00
32 CHN Shanghai	50690	0.02	0.01	0.02	0.01
33 CHN Nanjing	7132	0.03	0.05	0.04	0.03
35 JPN Meisei iMS100	15064	0.03	0.03	0.02	0.05
41+ FIN Vaisala RS41	44207	0.02	0.02	0.02	0.08
52 USA RS92-NGP	36477	0.00	0.00	0.00	0.00
55 JPN Meisei RS-01G	11166	0.02	0.02	0.02	0.01
57 FRA Modem M2K2-DC	2286	0.05	0.02	0.07	0.04
71 FIN Vaisala RS90	2362	0.00	0.00	0.00	0.00
77 FRA Modem GPS M10	41108	0.02	0.02	0.04	0.07
82+ USA Lockheed LMS-6	104958	0.00	0.00	0.00	0.00
83 FIN Vaisala RS92D	2708	0.01	0.02	0.05	0.01
99 ZAF InterMet	8615	**0.14**	0.09	**0.18**	**0.26**
**** Unknown type**	129736	0.07	0.06	0.05	0.02

Table 2. Global percentages of temperature reports 2015/2016 rejected by the ECMWF background check for four groups of standard levels, values of 0.1% or more are in bold. For type the code number is given (followed by + if several codes are combined) the country of manufacture, the maker and model.

Type	**NumRep**	**1000-850**	**700-300**	**250-100**	**70-10**
14+ FIN Vaisala RS92	250960	0.00	0.00	0.01	0.01
15+ UKR PAZA-12M/22	4155	0.03	0.02	0.05	**0.36**
17 DEU Graw DFM-09	30306	0.06	0.01	0.02	0.03
21 KOR JinYang	18397	0.03	0.04	**0.10**	0.02
22 JPN Meisei RS-11G	15798	0.00	0.00	0.00	0.00
26 CHE Meteolabor	1537	0.00	0.02	0.02	0.01
27+ RUS Various	158317	0.04	0.04	0.04	0.07
30 JPN Meisei RS-06G	5375	0.00	0.00	0.01	0.01
31 CHN Taiyuan	7252	0.00	0.00	0.00	0.01
32 CHN Shanghai	50625	0.01	0.01	0.02	0.01
33 CHN Nanjing	7065	0.00	0.04	0.08	**0.43**
35 JPN Meisei iMS100	15064	0.00	0.00	0.04	0.01
41+ FIN Vaisala RS41	40942	0.01	0.01	0.00	0.01
52 USA RS92-NGP	36304	0.00	0.00	0.00	0.00
55 JPN Meisei RS-01G	11169	0.01	0.00	0.00	0.00
57 FRA Modem M2K2-DC	2278	0.00	0.01	0.05	0.01
77 FRA Modem GPS M10	41063	0.01	0.01	0.02	0.01
82+ USA Lockheed LMS-6	104449	0.01	0.00	0.00	0.00
83 Vaisala/IMet RS92D	2706	**0.16**	**0.25**	**0.70**	**0.43**
99 ZAF InterMet	8610	0.01	0.00	0.01	**0.14**
**** Unknown type**	128632	0.02	0.02	0.04	0.02

Table 3. As table 2 but for wind.

4 Case studies: different types of errors

The cases presented here are mostly for 1 November 2015 (or to be more precise 2100 UTC on 30 October to 2100 UTC on 1 November) a date chosen at random. On this date there were 1342 radiosonde temperature profiles (or fragments of profiles) in the ECMWF operational archive.

4.1 Model and representativeness errors for temperature

Figure 4.1 shows a 'good' radiosonde profile with an inversion at the boundary top (about 900 hPa), but in this case the background inversion is too low. The reported inversion is clear-cut with temperature increasing and dew point decreasing above the same level (indicating warm, dry descending air). Taken at face value there is cloud from about 650 to 525 hPa but no cloud at the top of the boundary layer, however note that many radiosonde types do not reach 100%RH even in cloud and whilst there are empirical algorithms for detecting (presumed) cloud layers they are not infallible. Note also that in this case the background slightly underestimates the sharpness of the tropopause.

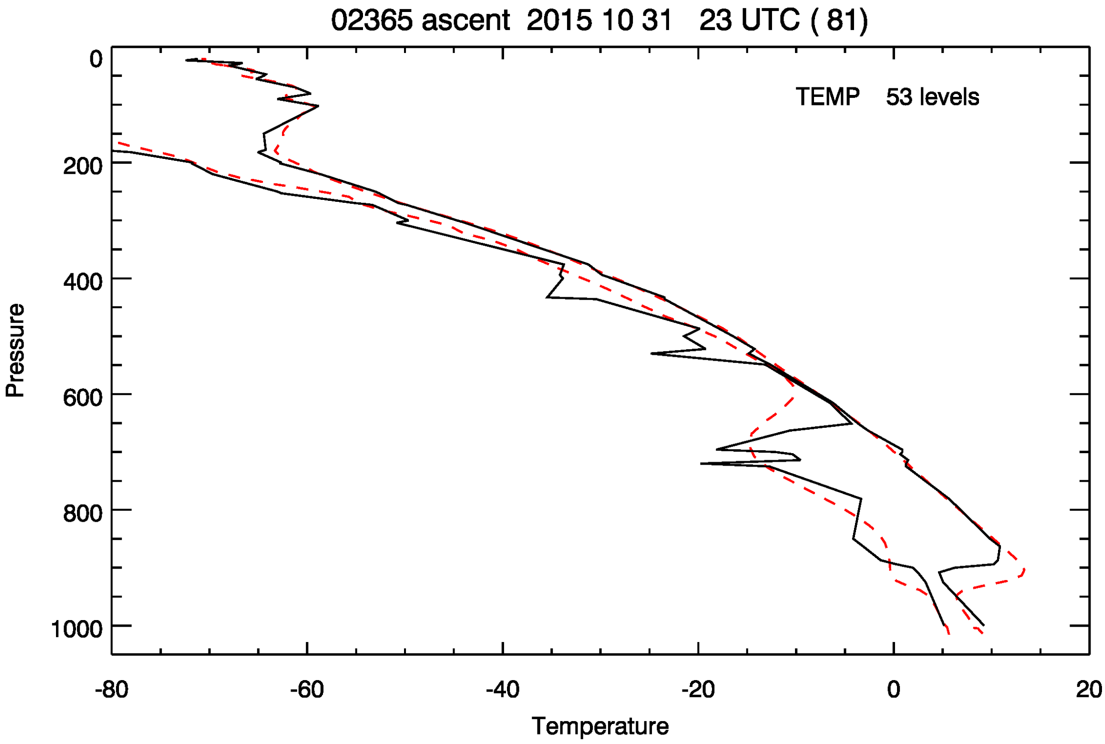


Figure 4.1. Observed (black line) and background (red dashes) temperature and dew point temperature. The title gives the station identifier (02365, Sundsvall Harnosand, Sweden), date/time and then type (81, RS92) in brackets.

Figure 4.2 shows an example with a marked surface inversion in the report which is much weaker in the background. Especially in high latitude winter conditions poor short range forecasts of surface inversions are relatively common (sometimes the background has no inversion), very large O-B temperature differences can occur and the observed values may be rejected by the quality control. For Russian radiosondes the sensor time-lag (discussed in section 3.1) can make the temperatures in an inversion appear colder than they are, and radar-derived pressures may also play a role. Although in most cases the observed temperatures appear correct it is unclear whether trying to ‘force them in’ via the assimilation would be beneficial (in the longer term model improvements should help). In some cases, especially where the model and station height differ markedly, it could be argued that this is a representativeness error rather than a background error. Although the observed temperature appears correct the observed dew point is almost certainly in error over of the profile – the way that Td shadows T is typical of cases where the humidity sensor has been contaminated passing through cloud, a well-known problem for Russian radiosondes.

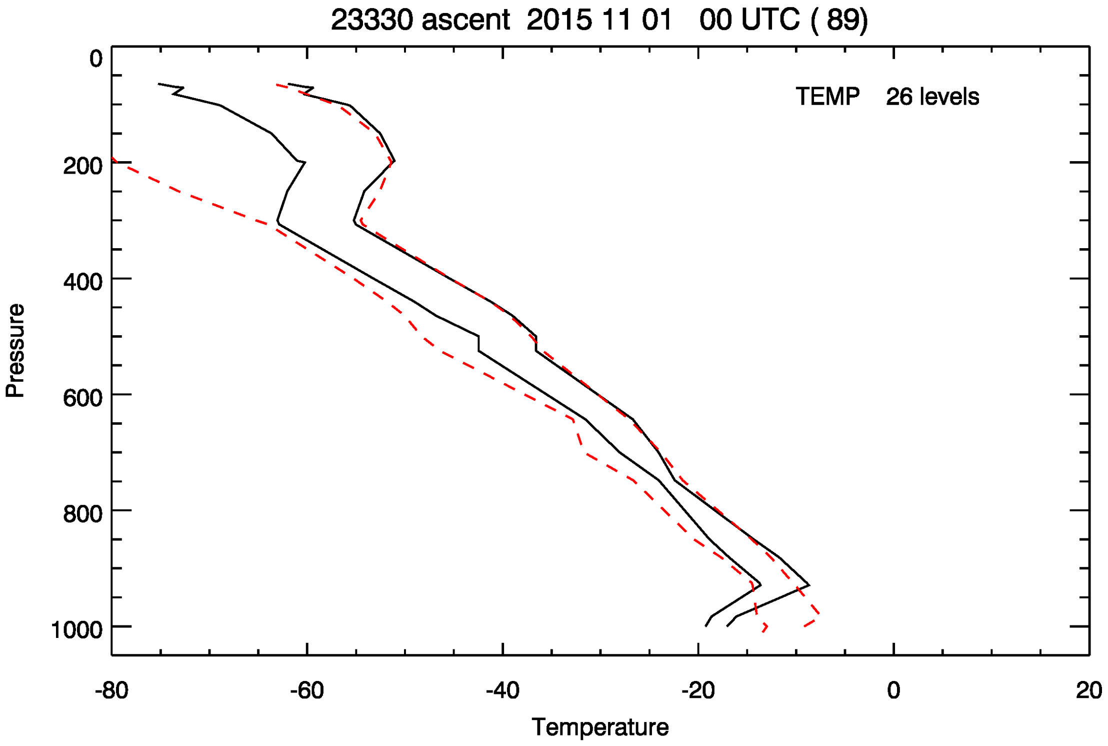


Figure 4.2. As figure 4.1 but for station 23330, Salehard, Russian Federation.

In the stratosphere gravity waves can cause marked temperature (and wind) fluctuations, for 1 November 2015 these were clearest over northern North America and Figure 4.3 shows an example. Because of the relatively short vertical wavelength and timescale it is unrealistic to expect the forecast model to get the details right (if the model has gravity waves with the wrong phase then O-B differences will be even larger). ECMWF assimilates radiosonde data as a set of point measurements. The large O-B differences can result in the observations being rejected (or downweighted by the variational quality control), whereas it might be better to assimilate a smoothed version of the observed temperature profile (the Met Office assimilates radiosonde data averaged over model layers). ECMWF has a multi-level quality control check: if four or more values within certain pressure bands have category 1 flags (typically differences larger than $3\sigma_o$, see section 2.3) then all the values within those pressure bands are rejected. This multi-level rejection can be triggered by gravity wave cases. A change to relax category 1 (to $5\sigma_o$) for radiosondes and hence the multi-level check became operational in July 2017.

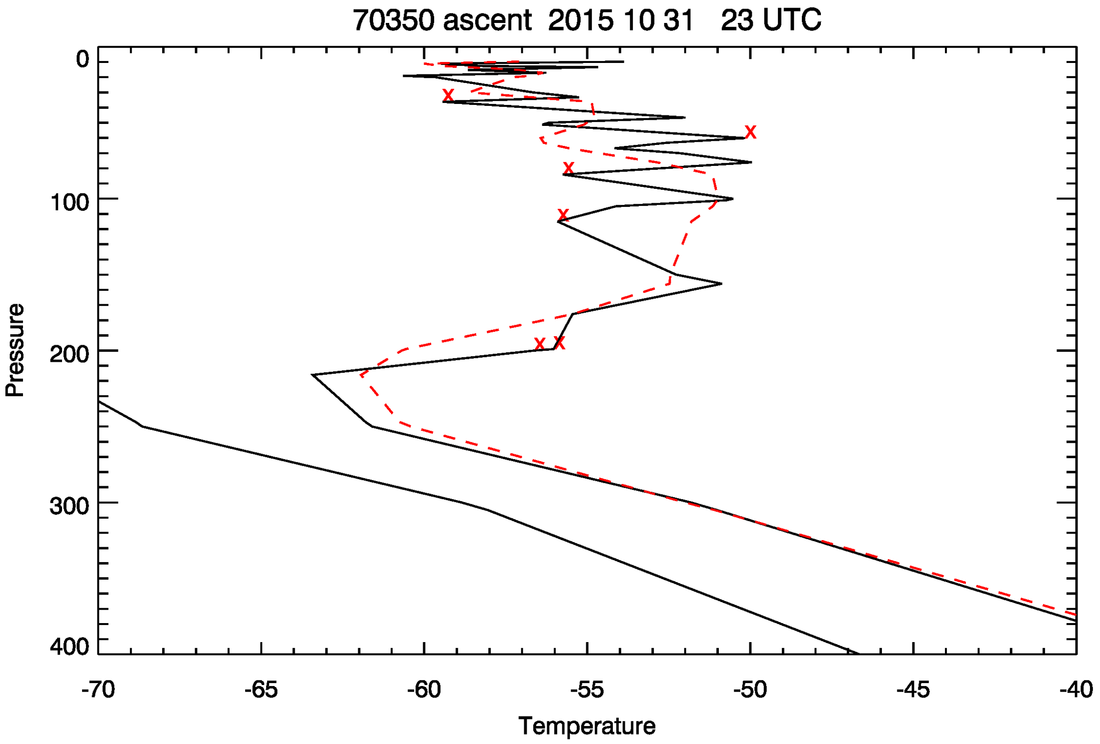


Figure 4.3. Similar to figure 4.1 but only showing the upper part of a profile for station 70350, Kodiak, Alaska, USA, type 11. The red Xs indicate points that are category 1 or higher from the background check.

4.2 Issues with temperature and humidity reports

Figure 4.4 shows what may be a case of ‘wet-bulbing’ where the temperature sensor has a coating of water or ice on emerging from a cloud and the evaporation or sublimation depresses the reported temperature until the coating has dissipated. This problem is difficult to diagnose with certainty (unless there are duplicate in situ measurements as in Nash et al, 2011) but the dip in temperature above 800 hPa is suspicious and it seems likely that the background temperature profile (red dashed line) is approximately correct. The surface temperature and dew point in this report seem unrealistically high and may reflect conditions in a cabin before the radiosonde was taken outdoors. The abrupt drop of dew point temperature at ~300 hPa is curious and is most likely an artifact. Six hours earlier there was another possible example (not shown) of wet-bulbing from ASEU06 with even larger |O-B| difference and a slightly less marked example from ASDE03 (not shown, another ASAP using Graw radiosondes, type 17). Similar features have not been seen from the ASAPs using RS92 and M10 radiosondes.

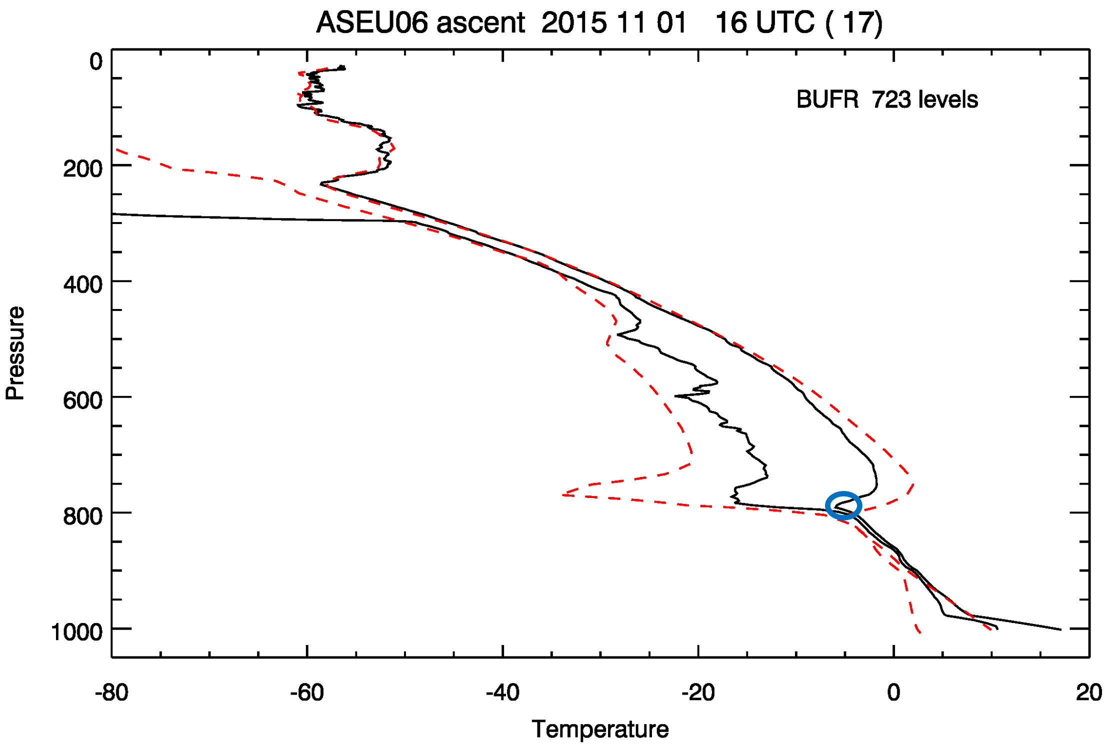


Figure 4.4. As figure 4.1 but for ASAP ship ASEU06, type 17, Graw – BUFR report. The temperature dip (ringed) is suspicious and the temperatures above this (up to 600 hPa) may or may not be too cold.

Humidity sensors react more slowly than temperature sensors and this can result in excessive Td values just above an inversion – example in figure 4.5 just above 700 hPa, sometimes, as here, the problem is fleeting and the sensor then recovers to give realistic looking dry values. There is a small inversion at about 950 hPa, the reported humidity just above this point may or may not be realistic – near-surface inversions may not follow the classical ‘dry above’ pattern. The background has apparently smoothed out the inversion near 700 hPa, but this could be partly because the background is only sampled at the reported levels. The stratosphere shows some evidence of gravity waves in the temperature profile (smaller amplitude than in figure 4.3). It was something of a surprise to see the wet ‘nose’ just above 700 hPa because RS92 is less prone to humidity problems than most other radiosonde types. On 1 November similar features were seen for some other Canadian ascents (also RS92), some slightly less transitory.

.

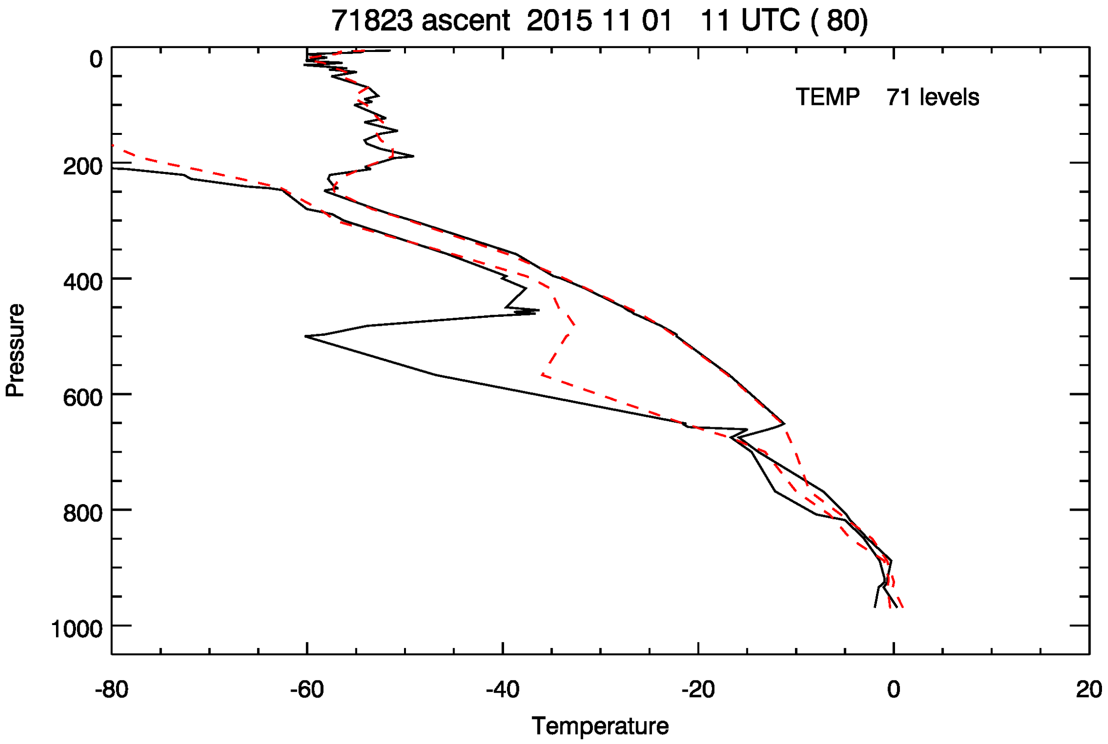


Figure 4.5. As figure 4.1 but for station 71823, La Grande Iv, Quebec, Canada, RS92.

Figure 4.6 shows a case (for type 82, LMS-6) where the humidity sensor seems contaminated after the inversion at about 600 hPa. In some cases the sensor gradually dries out and recovers somewhat. On this date seven cases where US ascents had apparently contaminated upper tropospheric humidity were identified, all but one were type 82. Such contamination is even more prevalent for Russian radiosondes, see figure 4.7 for an example – in this case the lower tropospheric humidities up to about 600 hPa are probably OK (the 00 UTC report from 20046 was wet at all levels, including just above an inversion at 900 hPa). In both figures 4.6 and 4.7 the dew point remains high in the stratosphere – indicating contamination, and the humidities down to about 600 hPa are suspect. Ingleby and Edwards (2015, supplementary material) introduced a check for this type of error in the Met Office system, starting at the top of the profile and if suspect moving downwards rejecting humidity until it was within 20% RH of the background humidity. This seemed to work reasonably well, but there was significant overlap with the permanent rejections. They also introduced a check for the more transient wet values just above an inversion. Similar checks could be considered for the ECMWF system.

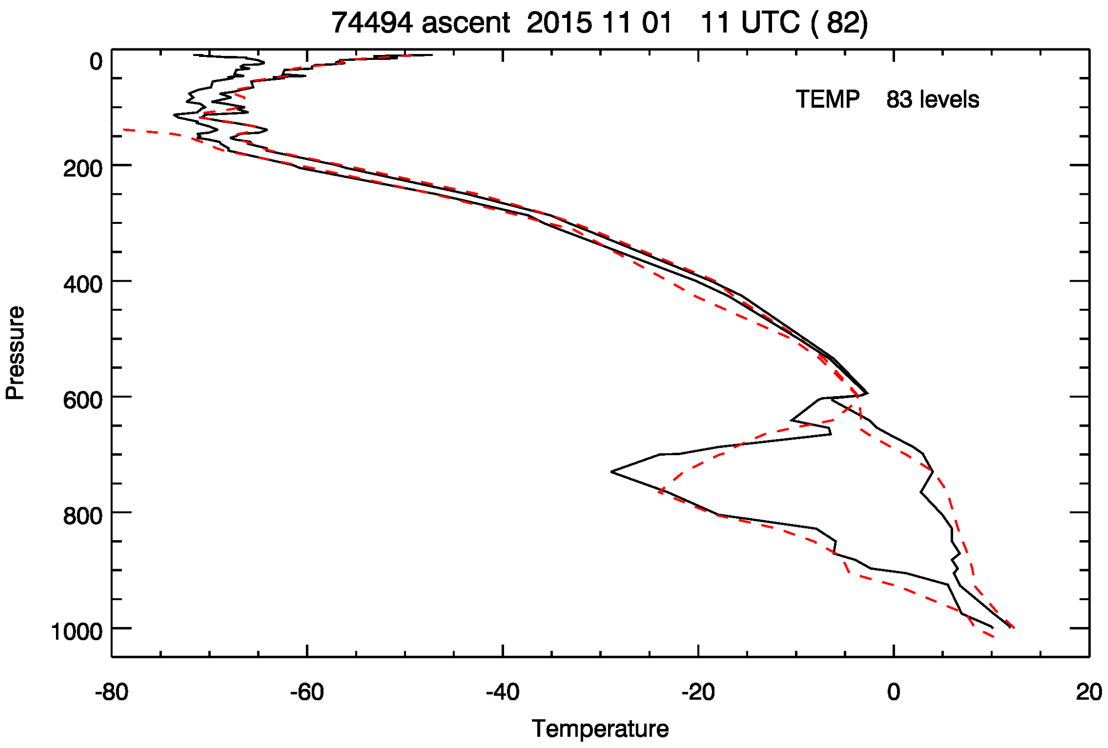


Figure 4.6. As figure 4.1 but for station 74494, Chatham, Massachusetts, USA, type 82, LMS6.

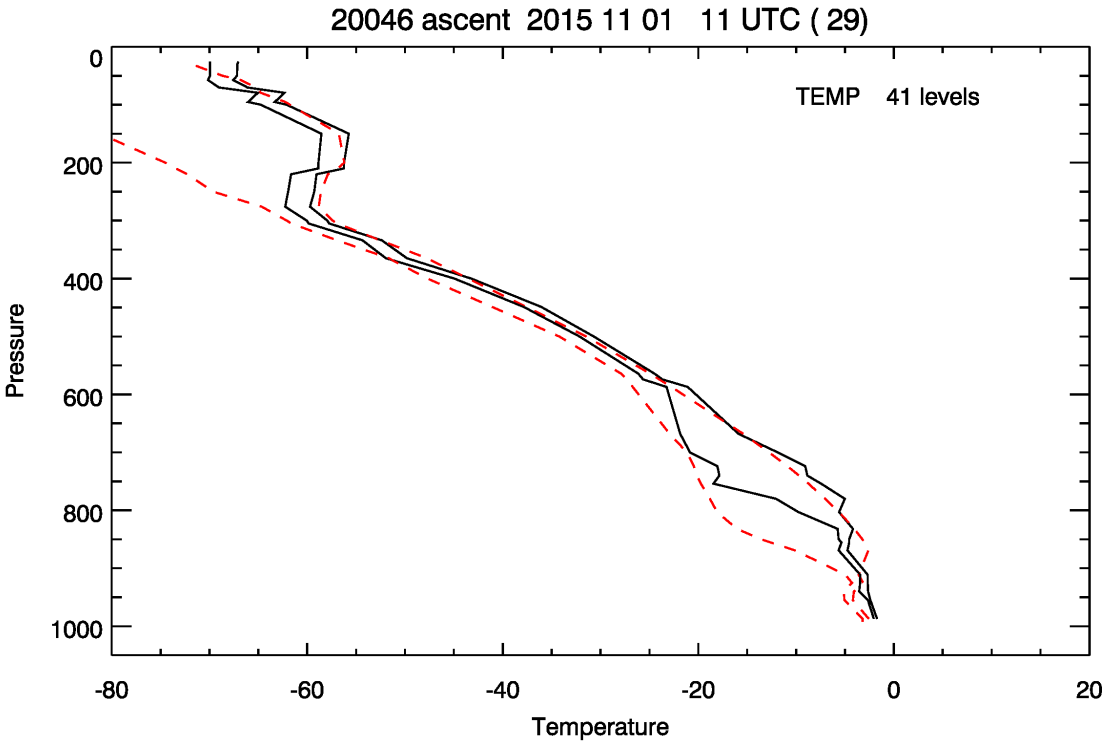


Figure 4.7. As figure 4.1 but for station 20046, Polargmo IM. E.T. Krenkelja, Russian Federation (in Asia).

Figure 4.8 shows a very marked "dry slot" close to the surface, missing from the forecast background, also seen 12 hours later from the same station. The station is in western Sicily, close to North Africa, and this is almost certainly a layer of desert (Saharan) air (as suggested by L. Haimberger, pers. comm.). On 1 November similar near-surface dry slots were seen for stations 40848 (Iran, type 80), 80035 (Columbia, type 14) and 83779 (Brazil, type 80, two cases), all RS92.

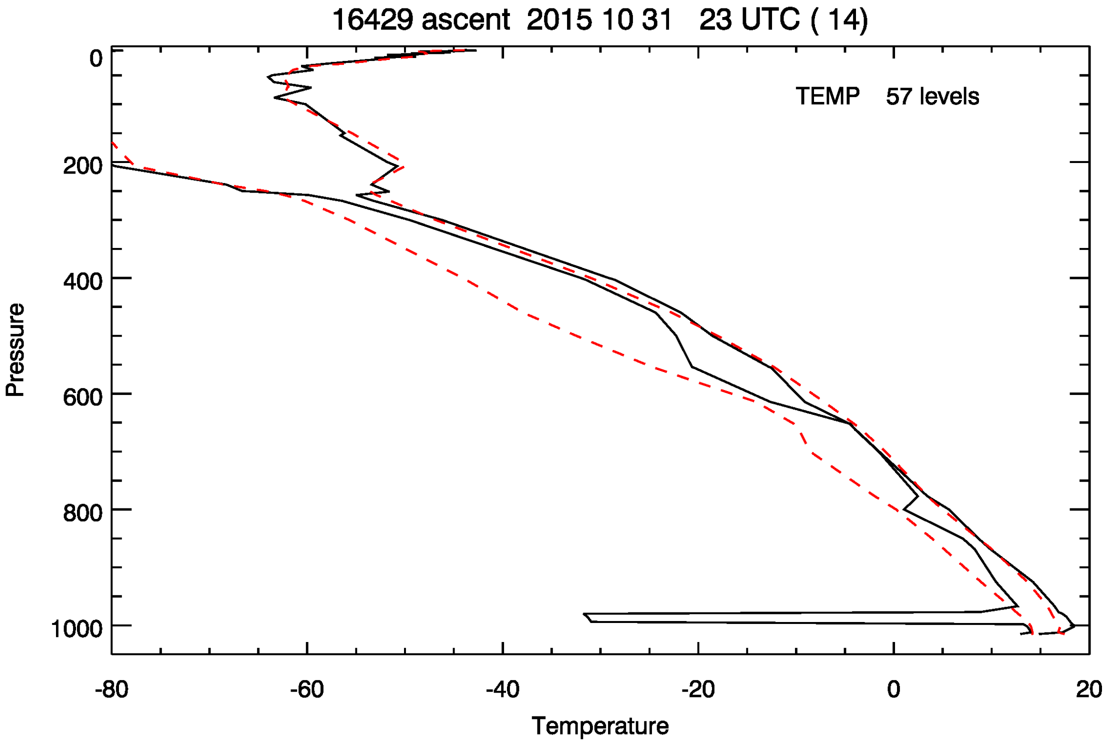


Figure 4.8. As figure 4.1 but for station 16429, Trapani Birgi, Italy, type 14, RS92.

In July 2015 station 03953 (Valentia, Ireland) had just changed radiosonde type (to M10, type 77 with an automatic launcher) and MetEirann asked ECMWF to check the reports. On 27 and 28 July there were rather dry reports immediately above the surface (of order of 10°C dew point depression and with less vertical extent than in figure 4.8). These were queried and the following answer received (R McGrath, pers. comm.): "For technical reasons the launcher has to be kept warm and dry internally, which means that the humidity sensor is initially reading quite low and a bubble of warm/dry air escapes with the balloon at launch - the net effect is that the first few decametres the dewpoint reading is too low. We are awaiting a fix from the manufacturer of the system so that it can tolerate a more acceptable environment."

Figure 4.9 shows a profile with moderately good O-B fit in the lower troposphere but a significant difference in tropopause height - we do not believe that the background could be this much in error over such a range in the vertical. For this case the wind maximum (not shown) has a similar vertical offset. Soviet/Russian (and presumably Ukrainian) radiosondes have not used pressure sensors for decades (Zaitseva, 1993) and rely on radar heights, measured temperatures and the hydrostatic equation to calculate the pressures. At low radar elevation angles the accuracy of radar heights is relatively poor, affecting the calculated pressures (see Kats et al, 2005). This would appear to be the problem in this case. On 1 November there were somewhat similar but smaller magnitude problems from stations 23415 (Russia, type 29) and 47122 (South Korea, type 21).

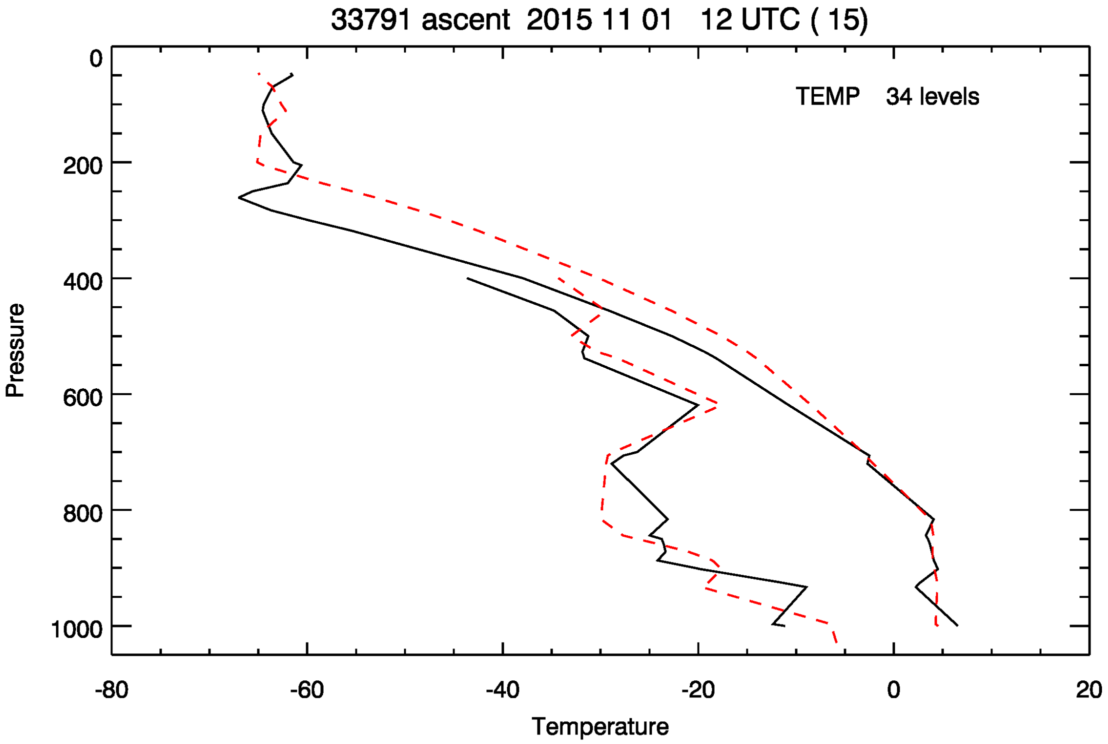


Figure 4.9. As figure 4.1 but for station 3379, Kryvyi Rih, Ukraine, type 15, PAZA.

Figure 4.10 shows a case with somewhat noisy temperatures, too warm (relative to background) near the surface, becoming even warmer with height – apparently a failure of the temperature sensor. The ascent 12 hours earlier was fine. Throughout 2015 there were about two similar poor ascents a month from 06011 and “a large part of the problem seems to be related to poor ground check and/or pre-launch handling of the radiosonde” (B Amstrup, DMI, pers. comm.). The subcontractor responsible for launching the radiosondes was replaced. Even if the problem is not directly related to the (InterMet) radiosondes it does highlight the value of radiosondes being robust and simple to operate. Just looking at the reported values (sometimes smoother than in this case) it is not necessarily easy to spot such a problem – comparing to the background values help a lot.

On 1 November there were a few cases where there seemed to be a temperature offset: 17064 (Turkey, type 35), 29231 (Russia, type 90), 38064 (Kazakhstan, type 9). For 76679 (Mexico, type 17) the lowest 200 hPa of the temperatures appeared wrong and for ASEU06 (type 17) the top 100 hPa of the temperatures appeared wrong. Figure 4.11 shows an example from India where lower tropospheric values are wrong, but it isn’t a simple offset, above about 700 hPa there is good agreement with background.

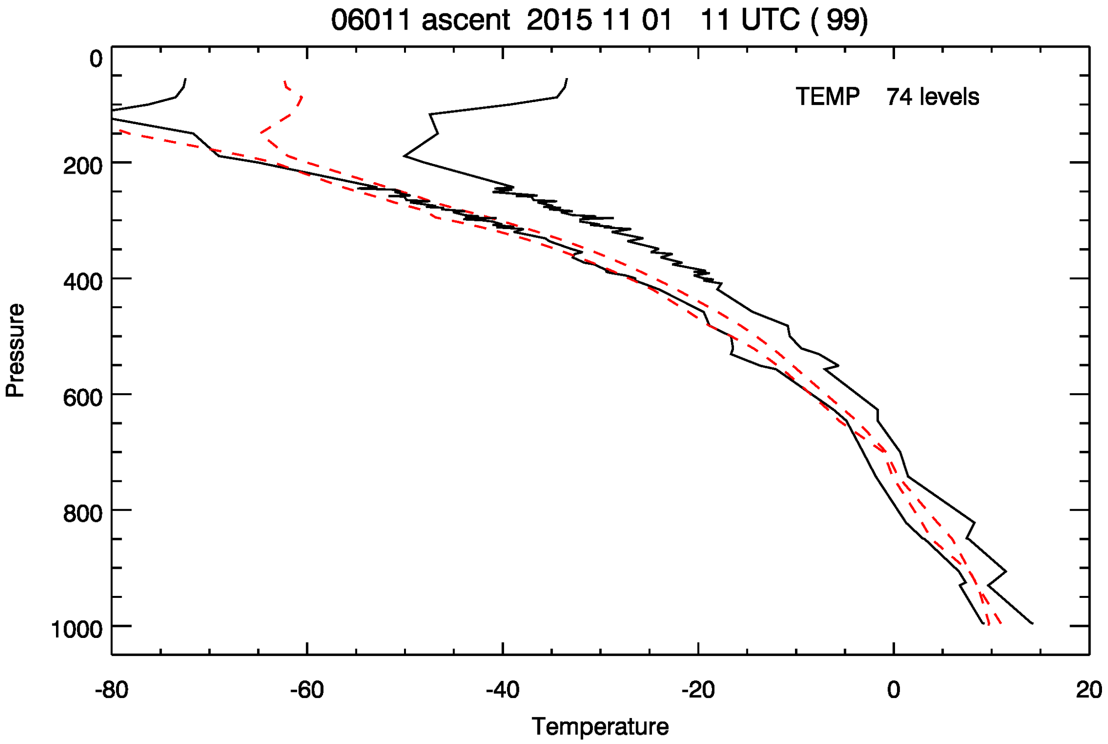


Figure 4.10. As figure 4.1 but for station 06011, Thorshavn, Faroe Islands, type 99, InterMet.

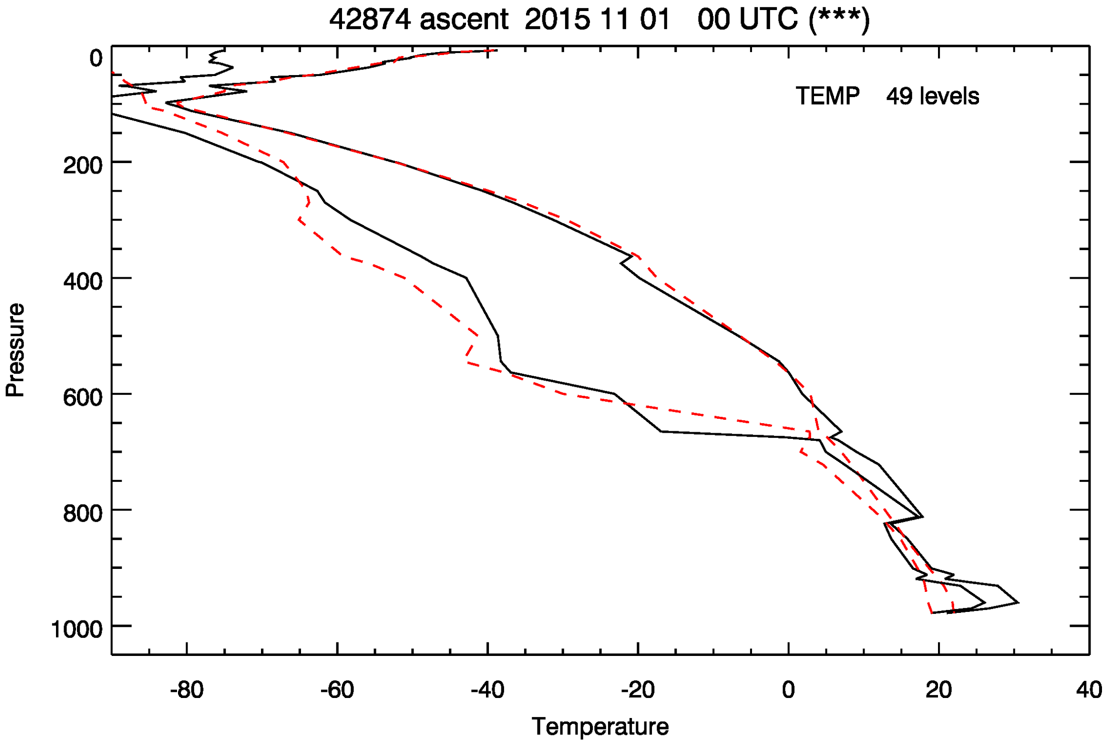


Figure 4.11. As figure 4.1 but for station 42874 PBO Raipru, India, unknown type.

Figure 4.12 shows an ascent without obvious errors, but only giving a minimum of detail (standard levels only). Many ascents from China are similar (and humidities stop at about 250 hPa), others have

30-40 levels, but very few have more than that. Elsewhere there are cases where only values above 100 hPa are available – parts A and B are missing.

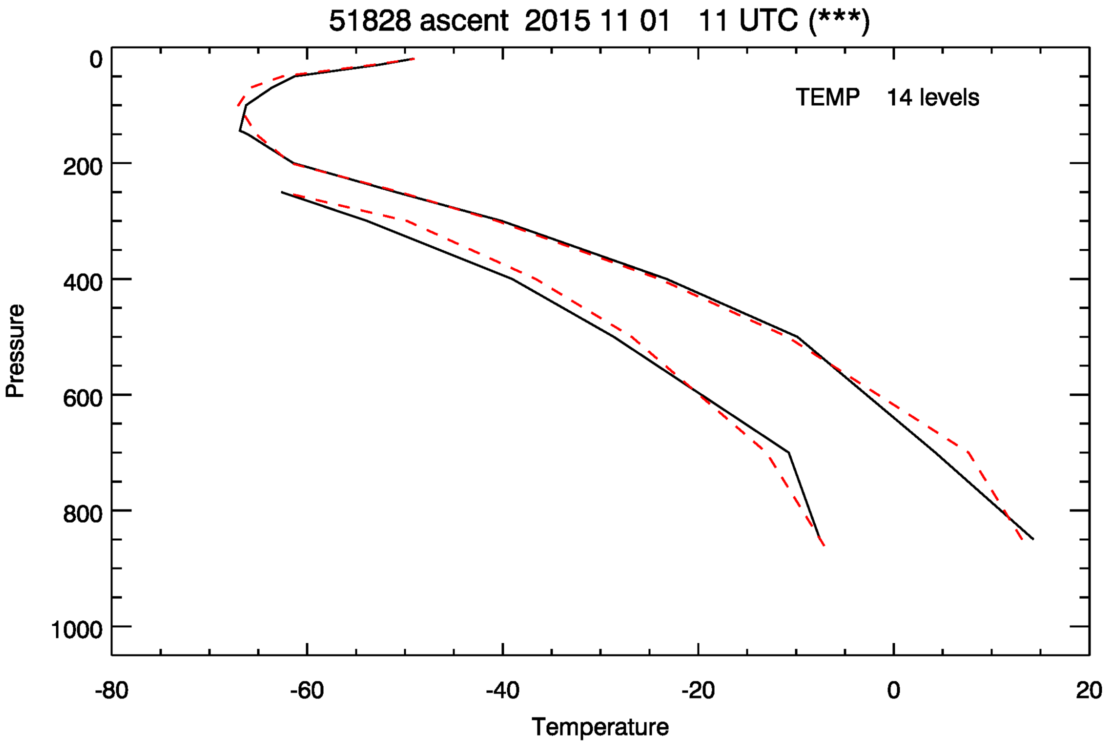


Figure 4.12. As figure 4.1 but for station 51828, Hotan, China (BUFR indicates type 32).

Not seen on 1 November 2015 but later were large temperature and wind spikes at 600 and 775 hPa from several African stations using Modem M10 radiosondes (and an old version of the Modem processing according to C Raux, Modem, pers. comm. 2017). These are extra African 'regional levels'.

4.3 Wind examples

Figure 4.13 shows reported TEMP (black) winds from a Spanish station, the high resolution BUFR winds have also been included (in blue). In the troposphere there is good overall agreement between the observations and the background; there are some low amplitude oscillations in the high-resolution winds and it is difficult to be sure if these are "real" or not. In the stratosphere there is some gravity wave activity that is largely absent from the background winds. The report times differ by about an hour between the TEMP and BUFR reports (reflected in the figure title), this results in slightly different background winds for TEMP (red, dashed) and BUFR (blue, dashed).

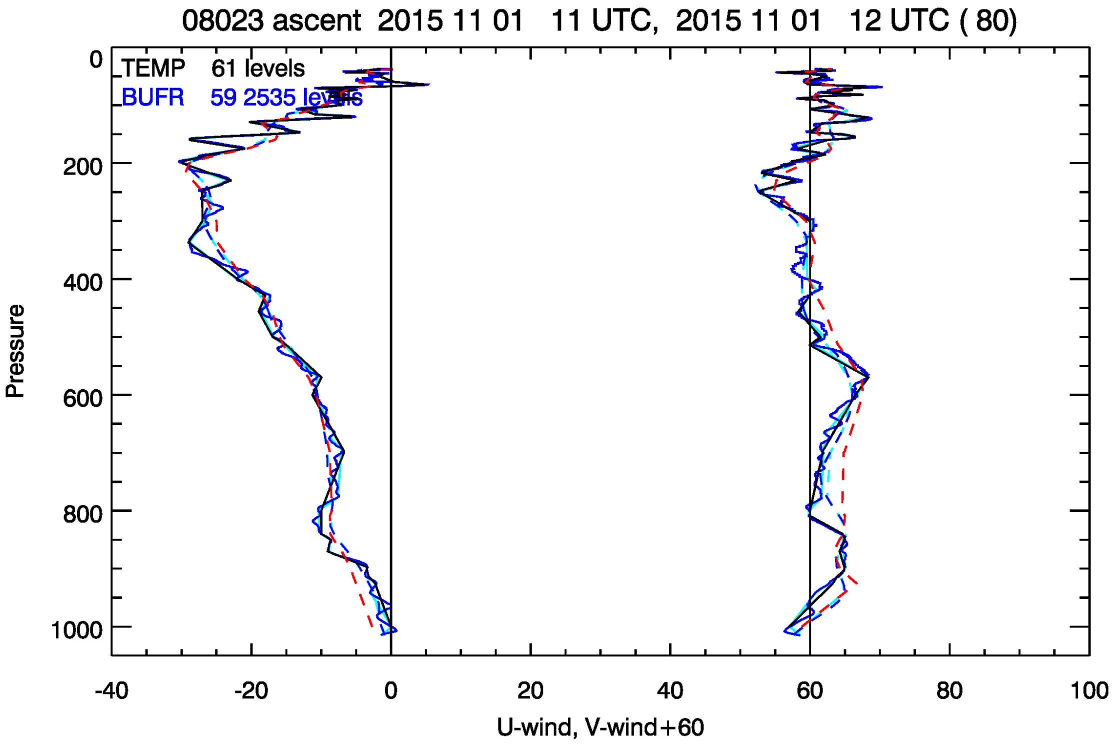


Figure 4.13. Wind components in m/s (60 has been added to the v component to separate them): black: TEMP; blue: BUFR (light blue low resolution BUFR); dashed red line: background for the TEMP; dashed blue line: background for the BUFR. Station 08023, Santander, Spain. The radiosonde type is given in brackets at the end of the title.

Figure 4.14 shows an example from station 04360 on the East coast of Greenland. Some reports from this station show a low level jet (between about 900 and 800 hPa), as here. The representation of this jet by the background varies, it is not particularly good in this case. As already mentioned this station is largely responsible for the relatively large M10 low level wind differences in figure 3.5. The radiosonde station at the southern tip of Greenland sometimes observes very large tropospheric wind “features” (not shown) because of the orography nearby.

Early in 2017 it was discovered that the MétéoFrance processing of M10 wind data had a bug (introduced during 2016?). Sometimes when v=0 the reported wind direction has a 180° error – giving the spike shown in figure 4.15. A corrected version of the software is now being tested.

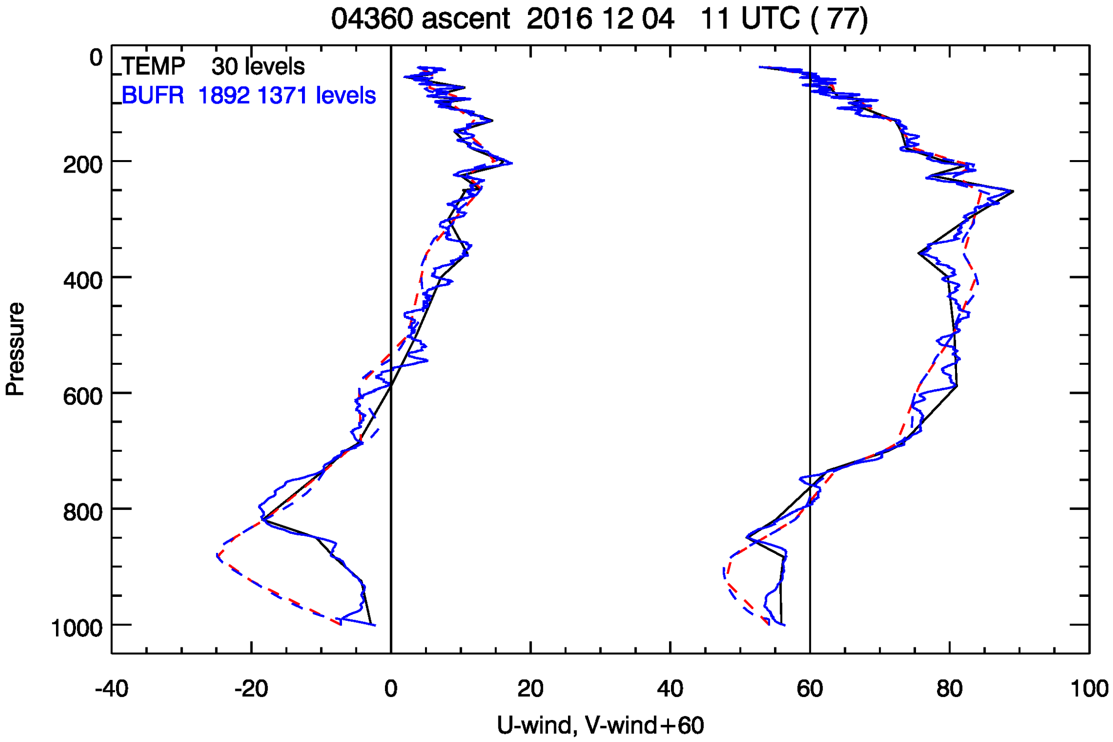


Figure 4.14. As figure 4.13 but an example from station 04360, Tasiilaq, Greenland.

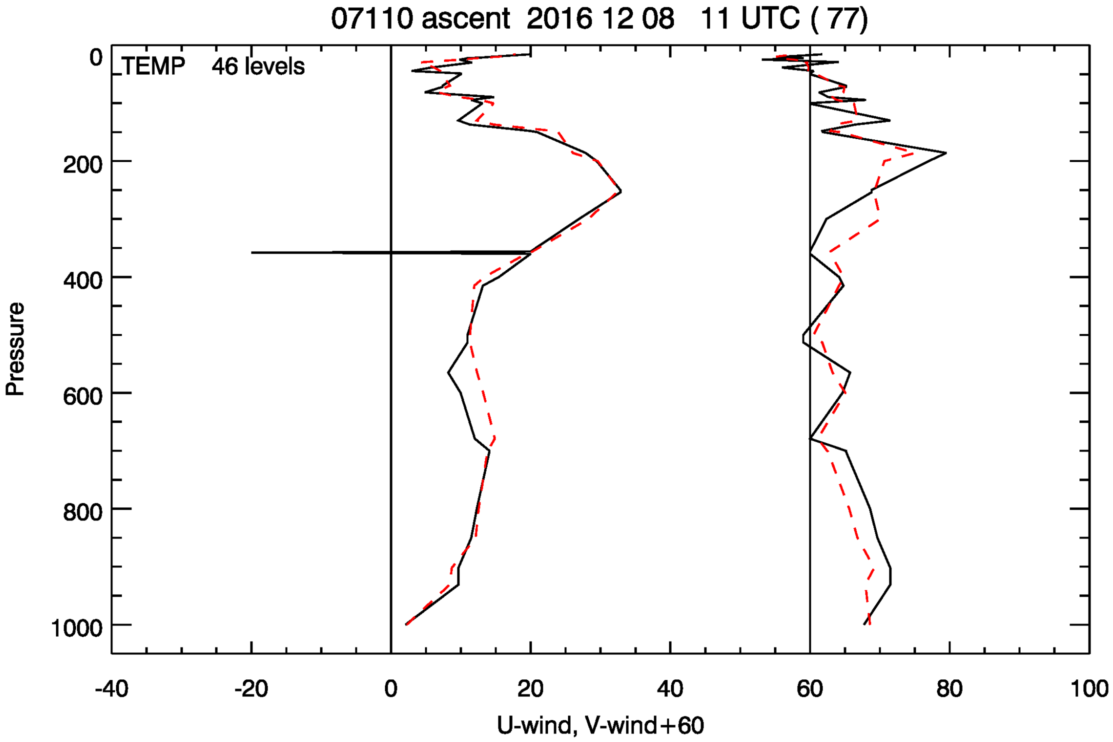


Figure 4.15. As figure 4.13 but an example from station 07110 (BUFR not shown), Brest-Guipavas, France.

On 1 November 2015 a number of Indian stations (and a few from elsewhere) showed somewhat ‘spiky’ winds, see Figure 4.16. In this case some of the winds have also been reported in PILOT code (grey line). US stations tend to report their ‘non-standard level’ winds in PILOT code, which is a minor complication for NWP centres.

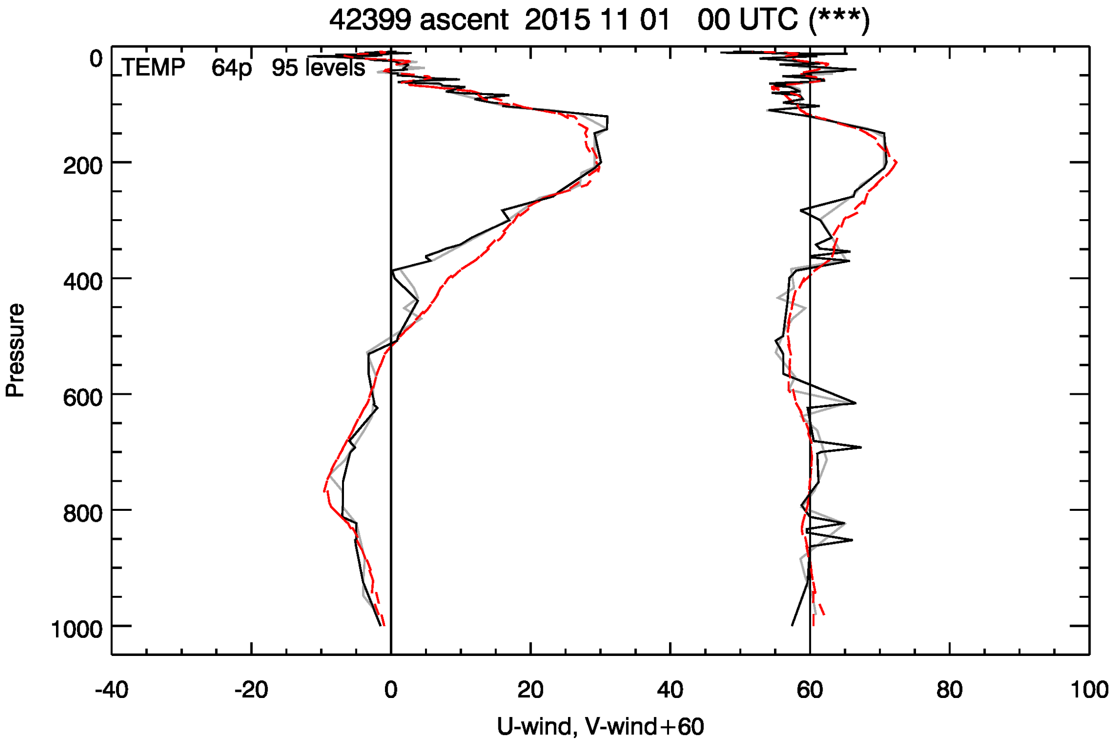


Figure 4.16. As figure 4.13 but an example from station 42399, Jalpaiguri, India. As well as the TEMP (black), this also shows PILOT winds (grey, 64 levels).

Figure 4.17 shows an example of stratospheric wave activity (at about 1°S), in this case the background has done a creditable job of reproducing the v-component, but is less good for the u-component. At ECMWF the tropical upper tropospheric and stratospheric winds are arguably the least well analysed part of the general circulation – in the extratropics satellite observations of the mass field help to constrain the wind field, but any such constraint in the tropics is weaker.

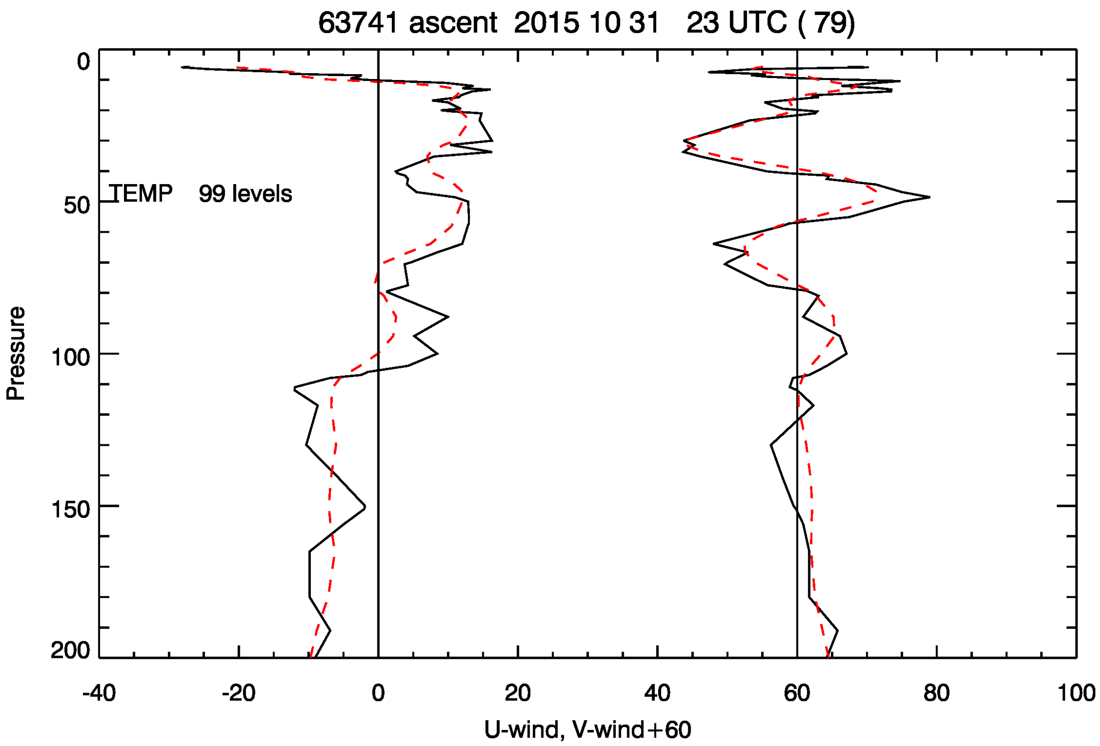


Figure 4.17. As figure 4.13 but an example from station 63741, Dagoretti Corner in Kenya. Note that the y-axis only starts at 200 hPa for this plot.

4.4 Notes on case studies

It should be remembered that the vast majority of radiosonde wind and temperature measurements are ‘good’ and some of the problems shown in this section are fairly rare. However it is important to understand and detect gross errors as far as possible. For a NWP system it is relatively easy to detect large magnitude spikes, it is more difficult to detect, say, a 1K temperature error throughout the troposphere (a check on the integrated O-B differences could be considered). Humidity measurement, especially in the upper troposphere, is more problematic but the best radiosonde types provide generally good humidities in the upper troposphere.

5 Other ways of categorizing radiosondes

5.1 Position and wind finding; measured or calculated pressure

The position-finding method is perhaps the most fundamental difference between different radiosonde systems. The main systems in use are:

- **Radiotheodolite** (or optical theodolite can be used over short distances), this measures the azimuth and elevation angles to the target radiosonde. A separate measurement (or estimate) of radiosonde height is needed.
- **Radar** measures the azimuth and elevation angles and also the distance to the radiosonde (from the elevation angle and distance the radiosonde height can be calculated). For both radiotheodolite and

radar the horizontal difference between two positions divided by the time difference is used to calculate the horizontal wind.

- **GNSS** (global navigation satellite system, in practice GPS is the main system used operationally at present; some earlier radiosondes used earlier navigation systems such as Loran C). Winds can be derived using a difference technique as above, or high-resolution instantaneous winds can be calculated from the Doppler shift.

WMO (2014, chapter 13) gives much more details about position and wind-finding. Broadly speaking there is improved position accuracy in going from radiotheodolite to radar to GPS. Radiotheodolite and radar systems become less accurate at low elevation angles (below about 10 or 15°) and larger distances, some also have problems if the balloon flies directly overhead. These systems require significant capital investment (plus maintenance and calibration) but once this is made the marginal cost of an extra ascent is lower. It is also possible to perform wind-only PILOT ascents (generally to lower altitude). Persistently poor wind results from certain radiosonde stations may be due to radar misalignment (Hollingsworth and Lonnberg, 1986, presented an example). GPS radiosondes can suffer from interference or reception problems – sometimes resulting in missing winds - (and there may be risks from solar storms) but in general they have good or very good accuracy. The GNSS receiver adds to the cost of a radiosonde, but the ground station is smaller and more suitable for use on ships or temporary deployments.

Looking at the metadata available in the reports at least two thirds of radiosonde stations use GNSS wind finding (figure 5.1). The main users of radar are Russia (plus Kazakhstan and Ukraine) and China. For about 100 stations (mainly from China, India and central Asia) the information is missing. Very few stations now appear to use radiotheodolite for TEMP reports (perhaps for PILOTs). India, Indonesia and some other countries in that region produce large numbers of PILOT reports, presumably using radar or radiotheodolite. Australia has a few radars used for PILOT reports, but these will be retired in the next year or two (K Monnik, pers. comm. 2017). Some PILOT reports (notably from USA) actually contain winds from TEMP reports.

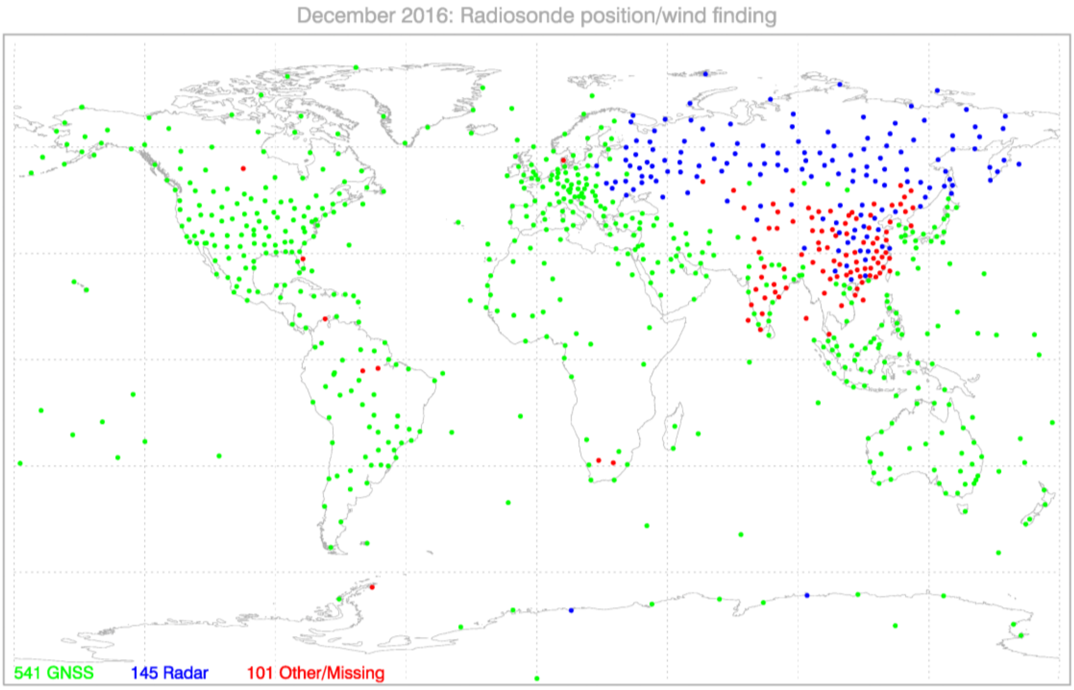


Figure 5.1. ‘Tracking technique/status of system used' taken from TEMP reports December 2016, with thanks to Larry Morgan (Met Office) for assistance.

There is some interaction with another issue: whether the radiosonde has a pressure sensor or not. Nash et al (2011) and others have found that pressure can be calculated sufficiently accurately for NWP from the other variables measured by a modern GPS radiosonde. For radar or theodolite systems, especially at low elevation, the accuracy of the height and hence the pressure may be more problematic. Of course, uncertainty in the vertical coordinate will affect the apparent error and usefulness of all the variables. The Russian network uses radiosondes without a pressure sensor with radar (Kats et al, 2005) whereas the Chinese network uses radiosondes with a pressure sensor with radar.

5.2 Other factors

Prior to widespread **automation,** processing and coding errors were not uncommon (such as the wrong sign of temperature in °C partly due to complicated coding rules).

Carrier or telemetry frequency: this is often in the band around 403 MHz but 1680 MHz or other bands can also be used. In one sense this should not affect the data quality, but it can become tied up with particular sounding systems (see notes on US radiosondes in the appendix).

The balloon and gas used mainly affect the height reached by the sounding. Special (expensive) balloons are available for extra accuracy of the derived winds (WMO, 2014, chapter 13).

In general it is best to use a radiosonde within a year or so of manufacture (but some seem to be stored for much longer). The humidity sensor is the component that suffers most from aging. For Vaisala radiosondes the age can be determined from the serial number amongst the extra metadata appended to BUFR reports. Occasionally details of sensor design may change, again the serial number could be used to provide more information.

5.3 GUAN and GRUAN stations

There are two initiatives by GCOS (Global Climate Observing System) to try to ensure the availability and quality of radiosonde data suitable for climate studies. Some stations are nominated by NMSs as GUAN (GCOS Upper Air Network) sites with a commitment to long-term operation, a guideline that at least 25 reports per month should reach 30 hPa, and compliance with best practice for GUAN stations (see links from http://www.wmo.int/pages/prog/gcos/index.php?name=ObservingSystemsandData; GUAN stations are not distinguished in ECMWF or other NWP systems, but ECMWF does monitor availability, http://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system.) Figure 5.2 shows the GUAN network (March 2014 list, 171 stations) along with the full radiosonde network (land stations, as available over the GTS). It is notable that 15 GUAN stations (from Africa, Asia and island stations) did not report in December 2016. Some of these stations have not reported for months or years, for others there may be a temporary outage due to failure of a hydrogen generator or lack of consumables – slower to remedy at a remote station. Despite these gaps the global radiosonde network would almost certainly be in worse condition without the GUAN initiative (T Oakley, pers.comm.). In some cases GUAN stations provide ascents to higher levels than neighbouring ones or two ascents a day rather than one. In countries where different radiosonde types are in use the more established or ‘better’ radiosonde type may be used at GUAN stations (this appears to be the case in China and the USA).

The GUAN network is chosen partly to provide relatively uniform geographical coverage – as far as possible. As might be expected from earlier results it is not homogenous in terms of data quality. Figure 5.3 shows O-B results for GUAN stations against three distinct subsets of the total global observing system: a) RS92, including NGP, b) other selected radiosondes (RS41, LMS6, Modem, Meisei and Shanghai) and c) the rest. Broadly speaking RS92 and Select subsets show similar, good results and GUAN is not that different south of 50°N. North of 50°N the GUAN rms (O-B) results are adversely affected by the inclusion of Russian radiosondes (this would also apply to humidity, not shown), although the mean differences are fairly similar (excluding 1000 and 10 hPa). The choice of which subset to use would depend on the application: climate studies might use GUAN whereas providing reference information for comparison with satellites might use RS92+Select (possibly plus some reports from ships) which has a larger sample and generally good quality.

The role of radiosondes as reference instruments is promoted by the GRUAN (GCOS Reference Upper Air Network) project, already mentioned, envisaged to be a network of 30 to 40 sites across the globe. Figure 5.2 shows past and current GRUAN stations by orange squares – these use RS92 radiosondes (GRUAN products for other radiosondes are under development). Unfortunately the two West Pacific sites closed in 2013/2014 and the New Zealand site (Lauder) changed to MW41 processing and does not currently produce GRUAN reports, so in 2016 GRUAN reports are only available from about 10 stations in the northern extratropics. Several stations in Australia are expected to start contributing GRUAN reports soon. The stations involved pass relatively raw data files to the GRUAN lead centre at Lindenberg, the lead centre runs the GRUAN processing and makes high-resolution data together with uncertainty estimates available in NetCDF. Most, but not all, of the GRUAN stations also send real-time reports from the same raw data, but using Vaisala software, on the GTS. Within the EU Horizon 2020 GAIA-CLIM project the Met Office and ECMWF are working to compare their background fields to GRUAN reports. Also ECMWF is starting to compare GRUAN reports to real-time reports and one RS92 station to another, to try to judge if average GRUAN uncertainties are more widely applicable.

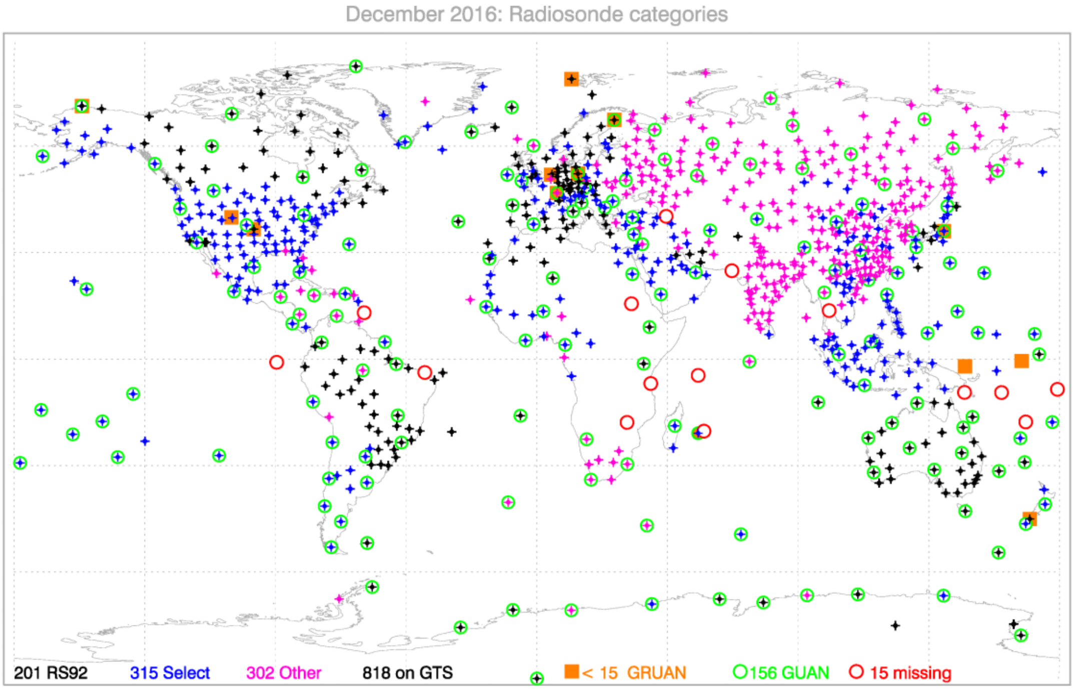


Figure 5.2. Radiosonde network, December 2016. Crosses mark stations with data available over the GTS (see text regarding colours), circles mark GUAN stations (empty red circles have no data for this month) and orange squares mark GRUAN stations.

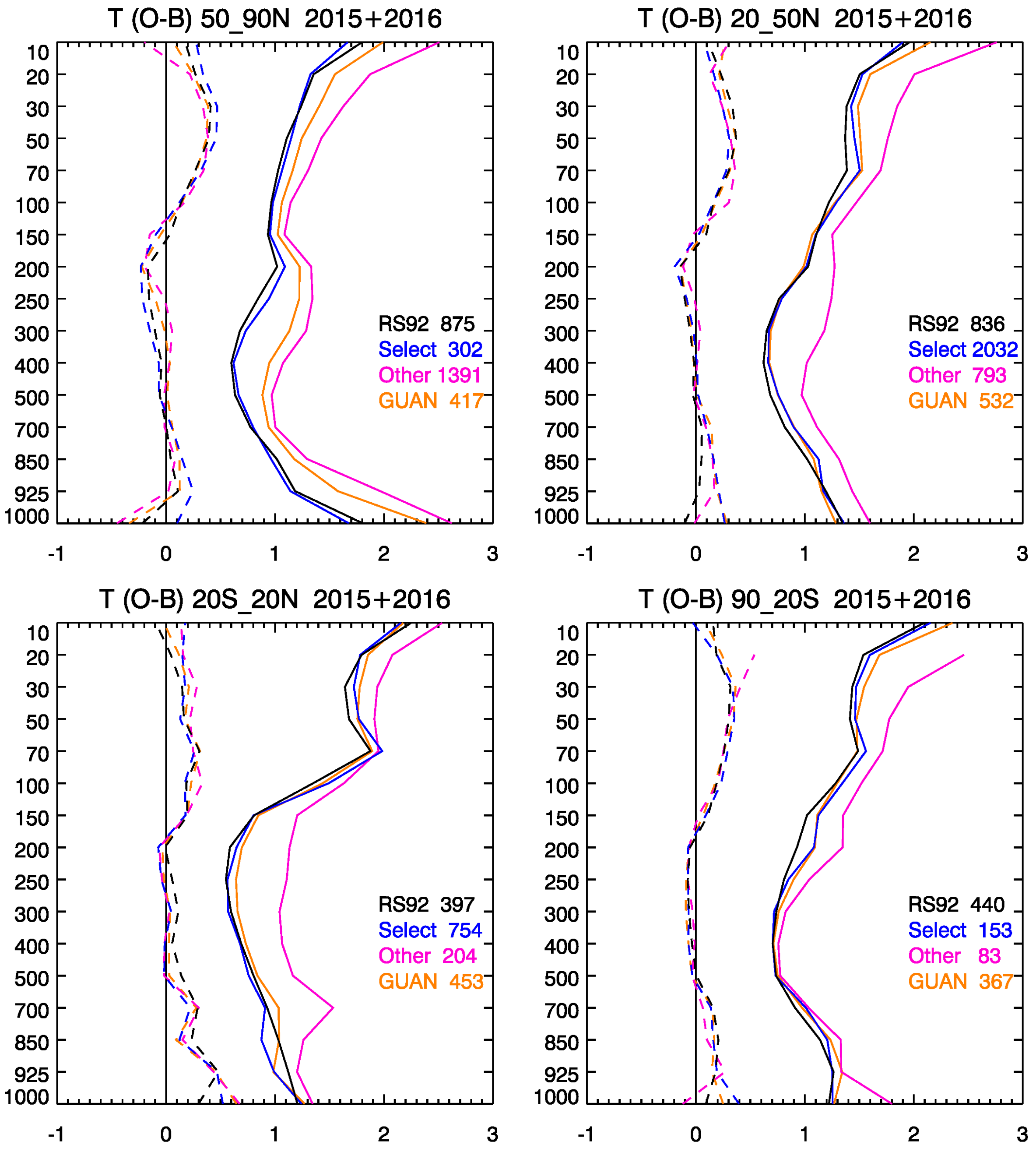


Figure 5.3. As figure 3.1 but for different subsets, see text for details. (Note that in the tropics the ‘Select’ group includes some CF06 data reported with type 32 – reserved for Shanghai GTS1 sondes.)

6 Summary and future work

6.1 Temperature, humidity, wind and height performance

The quality of different radiosonde types has been assessed, primarily by examining observation minus background statistics for the two year period 2015-2016. Particular aspects or problems have been investigated by more detailed statistics, or examination of individual cases. Of the radiosonde types available in 2015/2016 those with good sample size and good comparison with the ECMWF temperature fields are Vaisala RS92 (including NGP) and RS41, LMS6, Modem M10, Meisei RS-06G, RS-11G and iMS-100 and Shanghai GTS1-1. Bigger differences are seen for upper tropospheric humidity, particularly in the tropics, where the Vaisala types are in best agreement with the ECMWF fields, with some indication that RS41 is better than RS92. Some of the other types perform well most of the time, but are compromised by occasional (say >0.5% of ascents) temperature sensor problems, perhaps due to a lack of robustness. In some cases poor pre-launch handling or checks may play a part. Some of the issues identified by this study are:

- The JinYang radiosondes used at Korean stations appear rather better than the same radiosondes used at Indian stations.

- Graw radiosondes have a relatively large temperature bias correction applied in the ECMWF system.

- There are smaller differences between wind statistics, but Paza type 15 winds look particularly poor.

- Some of the Meisei iMS-100 winds appear to be over-smoothed, and this may apply to some other types as well. (Some smoothing is needed in order to remove pendulum motion, but further studies/guidance on the appropriate degree of smoothing/filtering would be useful.)

- Very close to the surface (over the first minute or less) there can be temperature/humidity adjustment or windfinding problems – these are more apparent in high resolution BUFR reports.

- Just after emerging from a cloud there can be transient problems in humidity or temperature, these have little effect on O-B statistics but are significant to forecasters (trials at the Met Office some years ago found RS92 better than an alternative radiosonde in this respect), the effect on NWP isn't clear.

For about 10% of stations tropospheric height values are biased due to station height (or barometer height) errors. Radiosonde heights are typically not assimilated at NWP centres, but errors will adversely affect verification statistics. One cause can be that GPS heights may be used without adjustment from the reference ellipsoid to the geoid (mean sea level). This is probably relatively rare at present but will become a bigger problem over time, affecting surface stations as well, unless the need for such adjustment is clearly communicated (by WMO and others) to those who survey station positions. Some CF-06 reports provide geometric height rather than geopotential height – this shows up as a bias increasing with altitude.

Newer radiosonde types, such as the Vaisala RS41 and Modem M10, tend to be smaller, lighter and easier to use (fewer or no ground checks). Smaller sensors react quicker which is an advantage. There is a continuing move away from inclusion of a pressure sensor as standard. In principle this is not a problem (low level pressures calculated using the hydrostatic assumption may be marginally worse but still quite acceptable for NWP). In practice, for GPS radiosondes, there may be height/pressure offsets at some stations if the wrong height is specified for the station pressure value that is supplied from a separate instrument. There can be larger problems, particularly at upper levels, for non-GPS (i.e. radar or radiotheodolite) radiosondes that do not have a pressure sensor – these problems tend to be worse for low radar elevation angles (large radiosonde drift). Some radars may be better maintained/aligned than others. There is a trend towards increased use of automated radiosonde launchers. Radiosonde prices are not generally published but, as expected, there seems to be a positive correlation between price and quality.

6.2 Radiosonde types

One problem in a study of this type is that about 15% of ascents have missing radiosonde type – many of these ascents are from Chinese or Indian stations. Several subsets of data were discovered with the wrong radiosonde type. (Beijing Changfeng CF-06 started being used operationally before it a type was asked for and allocated by WMO: in India CF-06 reports were/are sent with missing type, in Malaysia CF-06 reports were/are sent with the wrong type – 32. Indonesian stations using Meisei RS11-G report as type 55 instead of 22. Also various Russian types use the non-specific code 90 and InterMet use of several types is 'unofficial'.)

Over the long term (affecting climate studies and reanalyses) reuse of the same code numbers for different radiosonde types causes some confusion. Perhaps more than 255 slots should have been allocated in the BUFR table. Some radiosonde models have design or software changes during their lifetime that have a material impact on the performance or bias (the RS92 has had both hardware and software changes affecting upper tropospheric humidity biases). In TEMP code there is no ability to convey such information. In BUFR it is possible to add extra metadata (such as radiosonde serial number and the software version) which will allow identification of such changes in the future.

6.3 Uses: NWP and climate

As a result of this study some type dependent observation error estimates are being introduced into the ECMWF NWP system for temperature and humidity. ECMWF bias corrections (particularly for humidity but perhaps also for temperature) may be switched off for some radiosonde types and the reference will change from nighttime RS92 to an average of nighttime RS92 and RS41 in view of the phasing out of RS92.

Feedback to data producers is important but works better in some cases than others. Within Europe there is regular monitoring of the observing system and communication via EUMETNET, a grouping of 31 national meteorological services. As WMO CBS lead centre for monitoring radiosondes ECMWF also provides global data reports (see http://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system). These could be used by NMSs to identify problems but this relies on the reports being read and information getting to the right people (which doesn't always happen). WMO is setting up the WIGOS Data Quality Monitoring System (WDQMS) to try to improve the effectiveness of feedback. Currently there is the added complication of the migration to BUFR (see https://software.ecmwf.int/wiki/display/TCBUF/) – done well this potentially improves radiosonde data quality and usefulness, but done badly could worsen data quality or increase gaps. Native BUFR data includes radiosonde drift information which enables better use of the data, especially at upper levels. Tests at ECMWF allowing for radiosonde drift are encouraging and this is expected to become operational early in 2018.

One aspect which is particularly relevant for climate users is documentation of the different radiosondes, which varies markedly. This includes manufacturer's description and uncertainty estimates, details of any changes within a particular model and independent studies – preferably peer-reviewed. The Vaisala RS92 is particularly well documented in the literature whilst many other radiosonde types are only mentioned in passing. Vaisala provides radiosonde data sheets and data continuity pages but not all details of the instruments and processing. Some other manufacturers provide data sheets or similar but others provide little or no public information. As GRUAN (GCOS Reference Upper Air Network) processing for other radiosonde types is developed this should help to fill in some of the documentation gaps (Meisei RS-11G is close to certification, Meteolabor SRS-C34, Modem M10, Vaisala RS41 are in progress; M Sommer, 2017, pers. comm.).

During a radiosonde upgrade some NMSs conduct trials to assist in the decision of which new radiosonde type to choose, but these are commercial in confidence. Ideally they carry out further comparisons during the implementation of the new radiosondes (eg Edwards, 2016), but these are rarely if ever published in the detail that climate scientists would like. In the case of the RS41 there is a comprehensive report (Edwards et al, 2014; commissioned by Vaisala).

7 Acknowledgements

Lars Isaksen supervised the work and provided suggestions and information. Aki Lilja and Matti Lehmuskero of Vaisala provided information and useful discussion points. Information from various other manufacturers and NMSs is noted within the text, but Alexander “Sasha” Kats (Roshydromet, and WMO CIMO Theme Leader on Radiosonde Performance Monitoring) was particularly helpful and provided introductions to others. Sadly, Sasha Kats died suddenly in May 2017. Some examples/information came out of the work of Cristina Prates, Mohamed Dahoiu and Ersagun Kuscu, of the ECMWF observation monitoring team. This study was mainly funded by Vaisala, the section on GUAN/GRUAN data was supported by the EU-funded GAIA-CLIM project (grant number 640276).

8 Appendix 1. Notes on radiosonde types, 2015/2016

This appendix is organised partly by radiosonde manufacturer and partly by country – reflecting the complexity of the global radiosonde network. Brief details of the radiosondes in use in 2015/2016 are provided using information from various sources. This information is not guaranteed to be complete/correct/up-to-date although where possible details have been checked with the manufacturer and/or NMS concerned. The type numbers are mainly taken from the WMO Common Codes table C-2 (Radiosonde/sounding system see http://www.wmo.int/pages/prog/www/WMOCodes/WMO306_vI2/LatestVERSION/LatestVERSION.html .) although a few ‘unofficial’ numbers are also mentioned. TEMP uses numbers from 1 to 99, and some of these have been reused for newer radiosonde types, in which case a number over 100 is used in BUFR. For example the French radiosonde ‘Modem GPSonde M10’ is reported as type 77 in TEMP and type 177 in BUFR (denoted 77/177 below), originally type 77 was used for a now obsolete French radiosonde.

Eleven operational radiosondes were included in the 2010 WMO Intercomparison held in China (Nash et al, 2011, see their table 4.1.1 for an overview), these are noted below. Table A1, taken from the intercomparison report, gives some details of the calibration range of the radiosondes used. It also notes the saturation vapour pressure formula used. The ‘Western’ manufacturers mostly use one of the more recent formulae as recommended by WMO (2014) – the Wexler, Hyland and Wexler and Sonntag formulae are very similar; the others mostly use the older Goff Gratch formula or variants of it (it is possible there have been some changes since 2010, especially where new radiosonde models have been produced). The choice of formula only really makes a difference at temperatures below -40°C (see http://cires1.colorado.edu/~voemel/vp.html).

Manufacturer	Model	RH formula	Lowest Temp for RH Calibration	Lowest Temp for Temp Calibration
Vaisala	RS92-SGP	Wexler	-90	-90
Graw	DFM-09	Hyland Wexler	-80	-85
Modem	M2K2DC	Goff Gratch [1]	-60	-90
LMS (Sippican)	LMS 6	Wexler	-55	-70
Meteolabor	SRS C34	Sonntag	-40	-100
Meteolabor	Snow-White	Sonntag	-100	-100
Meisei	RS-06G	Buck (1981)	Room temp	-85
InterMet	InterMet 2-AA	Bolton [2] (Goff Gratch)	Room temp	-70
JinYang	RSG-20A	Goff Gratch	Room temp	-80
Nanjing Daqiao	GTS 1-2	Goff (1957)	-40	-90
Huayun	GTS(U)1-1	Goff Gratch	-30	-90
Changfeng	CF-06-A	Goff Gratch	-60	-90

Table A1. Taken from table 4.1.2 of Nash et al (2011): Formula used for water vapour of ice at low temperatures and the ranges of calibration of temperature and relative humidity sensors. Note that Snow-White is a research/reference instrument not used operationally. Notes. 1 The Modem M10 processing uses the Goff Gratch formula (Adrien Ferreira, pers. comm., 2017). 2 InterMet changed to use "Wexler (modified to ITS-90 by Hardy) saturation vapour pressure formula in August 2013" (Andrew Spenser, pers. comm., 2017).

Tables A2 and A3 summarise the availability of radiosonde reports in TEMP code at ECMWF for 2015/2016, A2 by radiosonde type and A3 by maker. A small fraction (less than 1%) of reports have the wrong type set at ECMWF during the merge of the different TEMP parts. Almost all land stations were still reporting in TEMP code at the end of 2016 (most ship stations, not considered here, were reporting in BUFR only).

			2015			2016		
Type	**Maker**	**Radiosonde**	**Nstn**	**Nrep**	**%rep**	**Nstn**	**Nrep**	**%rep**
0	Unknown	Unknown	247	63906	13.5	256	74098	14.7
7	InterMet	iMet-1-AB	2	94	0.0	2	190	0.0
9	Unknown	Unknown	1	712	0.2	1	718	0.1
11 b	LMS	LMS6	11	5536	1.2	19	8096	1.6
14 b	Vaisala	RS92 MW41	32	7978	1.7	39	9269	1.8
15 b	Techprylad (UKR)	PAZA-12M/Rtheodolite-UL	4	949	0.2	4	1252	0.2
16 b	Techprylad (UKR)	PAZA-22/AVK-1	3	827	0.2	3	1117	0.2
17 b	Graw	Graw DFM-09	59	14970	3.2	56	15519	3.1
18	Graw	Graw DFM-06	3	418	0.1	2	410	0.1
21 b	JinYang	1524LA	19	7137	1.5	23	11494	2.3
22 b	Meisei	RS-11G	10	7288	1.5	26	8466	1.7
23 b	Vaisala	RS41 MW41	4	144	0.0	5	703	0.1
24 b	Vaisala	RS41 Auto	1	14	0.0	5	744	0.1
26 b	Meteolabor	SRS-C34	2	742	0.2	3	749	0.1
27	Meteo (RUS)	AVK-MRZ	14	3311	0.7	10	2254	0.4
28 b	Aeropribor (RUS)	AVK-AK2-02	38	10585	2.2	32	12417	2.5
29 b	Aeropribor (RUS)	MARL-A/Vektor-M AK2-02	48	17217	3.6	48	15893	3.1
30 b	Meisei	RS-06G	6	2387	0.5	5	3004	0.6
31 b	Chinese	Taiyuan GTS1	5	3722	0.8	6	3560	0.7
32 b	Chinese	Shanghai GTS	40	28130	5.9	37	24866	4.9
33 b	Chinese	Nanjing GTS1	6	4254	0.9	5	3434	0.7
35 b	Meisei	iMS-100	8	1031	0.2	39	14080	2.8
41 b	Vaisala	RS41p MW41	42	12651	2.7	76	28670	5.7
42 b	Vaisala	RS41p Auto	1	662	0.1	1	791	0.2
51	VIZ (US)	B2	4	387	0.1	0	0	0.0

52 b	Vaisala	RS92-NGP	25	18204	3.8	25	18279	3.6
53 b	Multiobrabotka	AVK I-2012	8	1696	0.4	13	1101	0.2
55	Meisei	RS01G	14	9261	2.0	12	1951	0.4
57	Modem	M2K2-DC	13	1730	0.4	4	724	0.1
58	Radiy (RUS)	AVK-BAR	23	5133	1.1	29	5496	1.1
60 b	Multiobrabotka	MARL-A/Vektor-M I-2012	10	1834	0.4	11	2099	0.4
62 b	Radiy (RUS)	MARL-A/Vektor-M MRZ-3	15	1031	0.2	16	3115	0.6
68	Vektor (RUS)	AVK-RZM-2	2	42	0.0	3	437	0.1
69	Vektor (RUS)	MARL-A/Vektor-M RZM-2	6	619	0.1	10	2933	0.6
71	Vaisala	RS90	3	1626	0.3	2	722	0.1
75	Meteo (RUS)	AVK-MRZ-ARMA	1	191	0.0	0	0	0.0
77 b	Modem	GPSonde M10	55	19042	4.0	54	23770	4.7
78	Vaisala	RS90/DC3	3	550	0.1	1	28	0.0
79	Vaisala	RS92/DC	31	9130	1.9	22	6902	1.4
80	Vaisala	RS92/DC3	199	96159	20.3	160	80696	16.0
81	Vaisala	RS92 Auto	49	23635	5.0	49	23164	4.6
82 b	LMS	LMS6p	64	45647	9.6	65	45928	9.1
83 b	Vaisala	RS92-D	9	2664	0.6	1	62	0.0
87	Unknown	? Block 91	5	959	0.2	0	0	0.0
88	Meteo (RUS)	MARL-A/Vektor-M MRZ	11	2093	0.4	8	1610	0.3
89	Radiy (RUS)	MARL-A/Vektor-M BAR	50	15520	3.3	57	15377	3.0
90	Russian	Unspecified	49	15423	3.2	70	21787	4.3
97	InterMet	iMet-2-BI	0	0	0.0	3	235	0.0
99	InterMet	iMet-2-A	13	4910	1.0	15	3758	0.7

Table A2. Radiosonde reports in TEMP code for 2015/2016; Nstn – number of stations reporting that type at least 10 times, Nrep – number of reports, %rep – percentage of the total number of reports. A ‘b’ by the type number indicates that 100 is added to give the type reported in BUFR. (Types with fewer than 100 reports have been omitted.)

	2015		**2016**	
Maker	**Nrep**	**%rep**	**Nrep**	**%rep**

Vaisala	173641	36.6	170205	33.7
Modem	20776	4.4	24544	4.9
LMS	51233	10.8	54047	10.7
Graw	15447	3.3	15975	3.2
InterMet	5036	1.1	4205	0.8
Meisei	20016	4.2	27561	5.5
Chinese	36151	7.6	31901	6.3
JinYang	7172	1.5	11517	2.3
Russian	75078	15.8	84941	16.8
Other	70061	14.8	79647	15.8
Total	474611	100.0	504543	100.0

Table A3. As table A2 but summarised by maker (those with over 1% of total).

8.1 Vaisala (made in Finland)

Currently the Vaisala RS92(-SGP) is the most widely used radiosonde in the world although the numbers are declining as it will be withdrawn in favour of the RS41, which was introduced operationally in late 2013. In 2015 there were a few stations still apparently using the older RS90 (types 71 and 78); these were either quite old radiosondes (RS90 was last manufactured in 2003) or a coding error. The RS92 has a pressure sensor and (apart from the RS92-D) uses GPS windfinding, see section 8.14 of Appendix 1 for more details. The various versions of the RS92 are:

- 79 uses older versions of Vaisala software (Digicora I, II or Marwin)
- 80 uses Vaisala Digicora III software
- 81 RS92 Autosonde (launched automatically/remotely)
- 13/113 MARWIN MW32 software (hardly used in practice)
- 14/114 Digicora MW41 software
- 52/152 RS92-NGP, RS92 radiosonde but US National Weather Service software (used in USA)
- 83/183 RS92-D, RS92 radiosonde but radar winds using InterMet IMS 1500 software (used in the Caribbean until 2015)

The RS41 uses GPS windfinding, most operational RS41s do not include a pressure sensor:

- 41/141 RS41, no pressure sensor, uses Digicora MW41 software
- 42/142 RS41, no pressure sensor, Autosonde (launched automatically/remotely)
- 23/123 RS41, with pressure sensor, uses Digicora MW41 software
- 24/124 RS41, with pressure sensor, Autosonde
- 25/125 RS41 (with or without pressure sensor) uses MARWIN MW32 software (not used at present?)

The RS92 was included in the 2010 Intercomparison and has been extensively documented in various papers. It is used by GRUAN as a reference radiosonde, with processing as described by Dirksen et al (2014). Jensen et al (2016) provide a comparison of RS41 and RS92 radiosondes. All versions of RS41 and most versions of RS92 are capable of producing good, high-resolution BUFR data (with extra metadata appended). Product information and data continuity pages are available via http://www.vaisala.com/en/meteorology/products/soundingsystemsandradiosondes/Pages/default.aspx

8.2 Modem (made in France)

The Modem (or MeteoModem) M10 is a GPS radiosonde without a pressure sensor. It is used in France and various other countries and on some of the North Atlantic ASAP ships. Worldwide there are 17 Modem Robotsonde systems automatically launching M10 radiosondes (these use the same radiosonde type: 77 or 177). An earlier Modem radiosonde (the M2K2-DC) took part in the 2010 Intercomparison. A few M2K2-DC systems are still used in Africa.

- 57 Modem M2K2-DC
- 77/177 Modem GPSonde M10

Relative to the M2K2-DC, the M10 is lighter, more compact, white, easier to use (a LED indicates when ready for launch), has better ventilation of the humidity sensor, the sensors are less exposed to solar radiation and it has improved corrections for humidity (Gaëlle Clain, Modem, pers. comm. 2017). The M10 is capable of producing good, high-resolution BUFR data. MétéoFrance use their own processing software which currently provides low-resolution BUFR (similar resolution to TEMPs), but they are rolling out a version that provides high-resolution BUFR and announced that their alphanumeric TEMP reports will cease in early July 2017 – this appears to have been deferred. (The stations using MétéoFrance software are 07110, 07145, 07510, 07761, 61998, 61980, 78897, 81405, 89642, 91592, 91925, 91938, 91948 and 91958.)

8.3 USA (LMS and NGP radiosondes) plus Caribbean

OFCM (1997) gives some general background and instructions for radiosonde operators including quality issues that may arise. Some parts of the document are outdated now but much is still relevant. Most radiosondes in the USA are operated by the National Weather Service (NWS, part of NOAA). The NWS did not use LMS-5 radiosondes but one or two military sites did, the NWS now uses Lockheed-Martin LMS-6 and Vaisala RS92-NGP radiosondes. To give two quotes (from http://www.ua.nws.noaa.gov/rrs_overview.htm): "The National Weather Service (NWS) developed the Radiosonde Replacement System (RRS) to replace its antiquated Microcomputer Automatic Radio-theodolite (Micro-ART) system, which was in operation since the late 1980s. The RRS is comprised of a new Global Positioning System (GPS) tracking antenna referred to as the telemetry receiving system or TRS, 1680 MHz GPS radiosondes, and a new PC workstation." "The RRS was deployed in a phased approach starting in 2005 and was completed in late 2013." Brown and Fitzgibbon (2016) presented preliminary results of the NWS data continuity study associated with the RRS transition, they compared RS92-NGP with the previous radiosonde. The emphasis was on RS92-NGP as that is used at US GUAN sites. The dual flight data is archived at NCEI. No recent LMS-6 comparisons or documentation appear to be available. RRS software (called RWS) is utilized in collecting and processing data from both the LMS-6 and RS92-NGP 1680 MHz NWS radiosondes (at other sites Lockheed or Vaisala software is used). About 20% of LMS-6 radiosondes are recovered, reconditioned and reused – the quality is similar to new radiosondes. Both radiosondes used with RRS have a pressure sensor and GPS for measuring winds. “A radiation correction is applied to the temperature data. We do not apply any corrections to the RH data. The sonde vendors may be applying corrections to the raw sonde data before it is sent to the NWS software, but that is proprietary information.” (W Blackmore, US NWS, pers. comm, 2017; further details in this section from A Poyer and H Escabi NWS, R Brown, CyberData Technologies and P Pauley, NRL).

The NWS supports 10 Caribbean Hurricane Upper Air Stations (CHUAS), these used to use Vaisala RS92-D radiosondes (type 83, non-GPS, radar winds) but in 2015 changed to use Graw DFM-09. In 2015 a few Caribbean stations were apparently using VIZ-B2 radiosondes (type 51), still manufactured until about 2012.

For some years high resolution NWS ascents in NetCDF format have been openly available (see http://www.sparc-climate.org/data-center/data-access/us-radiosonde/). Recently (early 2017) test real-time high resolution BUFR reports (produced by a prototype version of the RRS software) became available from a few stations and widespread availability is expected later this year. A switch of CHUAS and NWS stations to use the ~403 MHz frequency has started (Brown et al, 2017) and has to be complete by February 2021. There will be a major procurement exercise, but about 10 NWS stations changed frequency in 2016 due to the launch of the GOES-R satellite to avoid downlink frequency interference. This involves a significant change to the ground stations. NWS stations using 403 MHz are not using the RRS software and will not provide high resolution BUFR data for the time being.

Lockheed Martin Sippican produce the LMS-6 GPS radiosonde used in the USA and on some Pacific islands. The LMS-6 (with Lockheed processing) took part in the 2010 Intercomparison.

- 10/110 LMS-5 without pressure sensor (duct mounted humidity sensor)
- 11/111 LMS-6 without pressure sensor (boom mounted humidity sensor)
- 82/182 LMS-6 with capacitive pressure sensor (boom mounted humidity sensor)

LMS radiosonde software does not currently produce native BUFR reports.

8.4 Graw (made in Germany)

The main Graw radiosonde is currently the DFM-09 (code 17/117) which uses GPS windfinding. It is usually used without a pressure sensor, but there is an option to add one. During 2015/16 it was used in Mexico (replaced by Meisei in 2016), the Caribbean and at some Indian and ASAP stations. The DFM-09 took part in the 2010 Intercomparison. The DFM-09 software is capable of producing high-resolution BUFR data.

8.5 InterMet (South Africa)

InterMet is based in both South Africa and USA, the radiosondes are used in South Africa and at a few other stations worldwide. The iMet-2-AA radiosondes report as type 99 (allocated to BAT-4G a non-production predecessor of the iMet-2 radiosondes). iMet-2 is available in a 403MHz version (type 99; iMet-2-AA/iMet-2-AB without/with a pressure sensor, also iMet-2-AR for research) as well as 1680MHz versions (type 97 is iMet-2-BI with RDF windfinding – all the others use GPS windfinding and 98 iMet-2-BA/iMet-2-BB without/with a pressure sensor). InterMet in United States manufactures the iMet-1 range of radiosondes which have types 01 (1680MHz; iMet-1-BA/iMet-1-BB without/with pressure sensor) and 07 (403MHz; iMet-1-AA/iMet-1-AB without/with pressure sensor, also iMet-1-RSB for research). The ‘research’ versions can carry external research instruments (e.g. ozone sonde).

In practice few of types 1, 7, 97 and 98 are seen on the GTS. In general, the 1680MHz radiosondes are supplied to non-synoptic (military) users, which is why they might not contribute much onto the GTS.

The iMet-2 took part in the 2010 Intercomparison. Radiation correction is applied to all day time temperatures, but not to night-time temperatures. Reported humidity values are compensated for their time response, based on data supplied by the sensor manufacturers. No bias correction is applied. The software is capable of producing high-resolution BUFR data.

InterMet Africa intend to release a completely new radiosonde within the next few months, initially targeting the 403MHz band. In this band it will have GPS windfinding. It will have different temperature and humidity sensors (and a different P sensor in the appropriate models) to the iMet-2, which it is intended to replace. Since there are numerous important changes, it should receive a new code figure. (Most of the InterMet details from Andrew Spencer, InterMet Africa, 2017.)

Some URLS:

iMet-1 Radiosonde http://intermetsystems.com/index.php/products/imet-1/

iMet-2 Radiosonde https://www.intermetafrica.co.za/radiosondes/imet-2/

8.6 Meteolabor (Switzerland)

Meteolabor SRS-C34 radiosondes took part in the 2010 Intercomparison, see also Philipona et al (2013). The Meteolabor radiosondes (type 26/126) are only used at one station – which is now reporting high resolution BUFR.

The SRS-C34 has a GPS for position finding and wind. There is no separate pressure sensor included. Radiation correction is only applied for daytime soundings. Nighttime infrared influences are very small and not corrected. Time-lag correction is applied on humidity.

8.7 Meisei (made in Japan)

Meisei currently provide three or four different types of operational radiosonde (all using GPS, and without a pressure sensor):

- 22/122 RS-11G
- 30/130 RS-06G
- 35/135 iMS-100
- 55 RS-01G

The RS2-91 radiosonde (type 47, but no longer used) had a pressure sensor, with wind measurement by radio-theodolite. This was succeeded by the RS-01G and then the RS-06G: neither had a pressure sensor and both used GPS with a Ground Based Augmentation System (GBAS) for altitude and wind. RS-01G and RS-06G differ in the radiosonde housing and the thermistor. The hygrometer used for these 3 types has a wet bias at temperatures below 0°C, so a temperature-dependent correction was applied (no other correction was applied to the humidity. The Japan Meteorological Agency does not consider differences between the three types in climate statistics (Jitsuko Hasegawa, pers. comm., 2016).

All of the Meisei radiosondes, use a solar radiation correction for temperature during the day time, but no infrared radiation correction. The RS-06G took part in the 2010 Intercomparison. The RS-11G uses a different, fast-response hygrometer and time-lag and radiation corrections for the humidity (also applied to the iMS-100). The newest and smallest Meisei radiosonde is the iMS-100, first used in Turkey in 2015 and in 2016 rolled out to Mexico and Indonesia. In 2009 Indonesia changed from RS-01G or RS89A radiosondes to RS-06G, in 2014 Indonesia upgraded to RS-11G (but some were still reporting as type 55, RS-01G!) and in 2016 to iMS-100. Types RS-06G and RS11-G are used in Japan. Most Meisei radiosondes do not report upper tropospheric humidity below -40°C (the iMS-100 does), even if not used for assimilation it can be useful for NWP centres to be able to see the upper level humidities. (Some details from Kizu, JMA, pers. comm., 2016.)

Kobayashi et al (2012) and Sugidachi and Fujiwara (2013) give some details and comparisons of Meisei radiosondes. Meisei radiosondes do not currently generate native BUFR.

8.8 Chinese-made radiosondes

The types allocated (in 2011 for the first three, 2014 for the other four) are:

- 31/131 Taiyuan GTS1-1/GFE(L)
- 32/132 Shanghai GTS1/GFE(L)
- 33/133 Nanjing GTS1-2/GFE(L)
- 43/143 NanJing Daqiao XGP-3G (not currently operational?)
- 44/144 TianJin HuaYunTianYi GTS(U)1 (not currently operational?)
- 45/145 Beijing Changfeng CF-06 (operational but not using this number, see below)
- 46/146 Shanghai Changwang GTS3 (not currently operational?)

The situation is somewhat confused because many Chinese radiosonde reports do not give the radiosonde type, the majority that do give a type are Shanghai GTS1 radiosondes. All Chinese stations currently use radar windfinding. GTS1-1 from Taiyuan Radio factory (type 31) and GTS1 from Shanghai Changwang Weather Technology Co., Ltd. (type 32) use the same design (resistance humidity sensor, silicon pressure sensor, operate at 1675MHz and compatible with GFE(L) secondary wind-finding radar) but are produced by different manufacturers. GTS1-2 from the Nanjing Daqiao Machine Co., Ltd. has a capacitive humidity sensor, a diaphragm capsule capacitor as a pressure sensor, operates at 1675MHz and is compatible with GFE(L) secondary wind-finding radar. (Some details from Fang Zhao, CMA.)

The Nanjing Daqiao GTS1-2, Beijing Changfeng CF-06, TianJan HuaYunTianYi GTS(U)1-1 took part in the 2010 Intercomparison. It isn’t known if the Huayun GTS(U)1-1 is used operationally (in 2014 it was allocated type 44/144). Changfeng radiosondes are not currently used in China but started to operate in India in 2012, and the radiosonde type was set missing (code 45/145 was only allocated in 2014) – still the case. At the end of 2014, CF-06 radiosonde began to operate in all 8 Malaysian stations but due to a mistake TEMPs are sent with type=32 instead of 45.

Chinese radiosondes do not currently generate native BUFR.

8.9 JinYang (made in Republic of Korea)

According to the WMO table type 21/121 is the 1524LA LOLAN-C/GL5000 it is used in Korea and at some Indian stations. The JinYang RSG-20A took part in the 2010 intercomparison. Some of the

Korean stations using JinYang radiosondes started generating high-resolution BUFR in November 2016.

8.10 Indian radiosondes

For years many Indian stations used radiosondes made by the India Department of Meteorology (IMD) along with some imported radiosondes (currently Graw and JinYang). The use of IMD radiosondes has been phased out, finishing in September 2015, replaced (at some stations at least) by Beijing Changfeng CF-06 radiosondes. This is not obvious from the reports on the GTS as the radiosonde type was missing both before and after the change. Many Indian stations use radar windfinding and some perform wind-only PILOT ascents (generally shorter). Indian radiosondes do not currently generate native BUFR.

8.11 Russian-made radiosondes

Russian radiosondes are descended from Soviet-era systems (see Zaitseva, 1993), they are used in Russia and Kazakhstan (in May 2016 Kazakhstan requested code figures for a new radiosonde ASPAN, similar to the AK2 family). There are three active manufacturers: AVK, MARL and VEKTOR (the fourth, Meteorit, seems to have ceased). The systems used at Russian stations in early 2015 can be seen in Figure 1 of Ingleby et al (2016b). All the stations use radar windfinding (a demonstration GLONASS/GPS radiosonde seems not to be operational yet). Combined with the lack of a pressure sensor this can result in relatively inaccurate stratospheric pressures when the radar elevation angle is low (Kats et al, 2005). Occasional radar alignment issues can also result in wrong heights/pressures. Extra details are provided in section 8.14 of Appendix 1.

The Russian-made radiosonde types are:

- 27 AVK-MRZ
- 28/128 AVK – AK2-02
- 29/129 MARL-A or Vektor-M - AK2-02
- 58 AVK-BAR
- 53/153 AVK – I-2012
- 60/160 MARL-A or Vektor-M - I-2012
- 62/162 MARL-A or Vektor-M – MRZ-3MK
- 69 MARL-A or Vektor-M-RZM-2 (hardly used)
- 75 AVK-MRZ-ARMA (hardly used)
- 88 MARL-A or Vektor-M-MRZ
- 89 MARL-A or Vektor-M-BAR
- 90 officially unspecified, used for a mixture of Russian types mostly made by Aeropribor: AK2m, AK2s and AK2-02m with all types of radar (AVK, MARL-A or Vektor-M)

Only two Russian stations currently provide high-resolution BUFR reports.

8.12 PAZA (Ukraine)

The PAZA radiosondes appear to share some characteristics with Soviet/Russian radiosondes, they are used in Ukraine and at some stations in Kazakhstan.

- 15/115 PAZA-12M/Radiotheodolite-UL[1]

- 16/116 PAZA-22/AVK-1

[1] despite the name this appears to use a radar (i.e. the distance is measured as well as the angles)

The Ukrainian PAZA sonde (http://techprulad.lviv.ua/index.php/ua/vyhotovliaiem/aerolog-pril/meteozond_1) looks rather similar to the AK2 (http://zondr.ru/development-product/10-ak-2.html - Russian manufacturer).

PAZA radiosondes do not currently generate native BUFR.

8.13 More details on RS92 and RS41 types (from Aki Lilja, Vaisala)

RS92-NGP is a RS92-SGP with specific changes required by the U.S. National Weather Service. The sensors themselves are identical to the standard RS92-SGP sondes, but the ground processing is a combination of Vaisala processing and NWS processing practices. The telemetry is based on 1680 MHz band instead of the 400 MHz band used in many other countries. RS92-NGP uses GPS windfinding.

RS92-D is a radiosonde without windfinding. It is used together with radiotheodolites. Height is taken from pressure (and not by triangulating GPS height and radiotheodolite direction). In Caribbean, they used InterMet radiotheodolite (instead of Vaisala one) to receive the data.

Regarding types 79, 80 and 81:

79: DigiCora I and II refer to older MW11 and MW15 systems, and Marwin to MW12 systems. These are quite old software systems, from the 1980's and 1990's (but still operational). These systems can't necessarily use all the algorithm improvements done in the DigiCORA III era.

80 and 81: DigiCORA III refers to the SW used in MW21 and MW31 systems (identical processing, just hardware differences). AUTOSONDEs have exactly the same processing.

All the types mentioned above run with identical pTU sensors, and all except types 52 and 83 run 100% Vaisala processing. There may be minor differences in the processing of Vaisala code 79 compared to 80 and 81.

RS92 and RS41 have completely different temperature sensors, but they produce very consistent and similar data. RS41 uses a platinum resistor, whereas RS92 used a capacitive wire sensor (both made in Vaisala cleanroom). RS92's temperature sensor was one-point corrected prior to flight by comparing to ground check device GC25, which incorporated a reference temperature sensor (platinum resistor). With RS41 no corrections to the temperature sensor are done, due to very good linearity and stability of the platinum resistor. The measurement principle and technology in RS41 radiosonde is the same as the reference level measurement in the ground check device of the RS92. RS41's ground check procedure consists of checking that the sensor is not broken, by comparing its reading to the temperature sensor inside the humidity sensor - the humidity sensor is not warmed at that point yet.

Solar radiation corrections are done in both radiosondes for the temperature measurement, and time lag correction is also applied in RS41. Solar radiation correction tables are available for RS92 and RS41.

According to Vaisala's tests in the R&D phase (including both laboratory tests and >1000 soundings in various climates), they specified RS41 to have smaller T uncertainty than RS92. RS41 has combined uncertainty in sounding (k=2 level) 0.3 C below 16 km and 0.4 C above 16 km, whereas RS92's number is 0.5 C (irrespective of height).

8.14 More details on Russian types (from A Kats, Roshydromet)

1. Russian radiosondes do not use goldbeater’s skin humidity sensors any more. Instead most of them use HIH-5030 or HIH-5031 Honeywell integrated polymer humidity sensors. These are two versions of the same sensor, but HIH-5030 has no protection against condensation (and can generate a reading of 0% humidity if liquid water forms on the sensor). As well as goldbeaters skin sensors, HIH-503* are not certified for humidity measurements below -40°C both due to long response time and temperature induced errors. The only exception is RZM radiosondes (types 68 and 69). Till recently they used Sencera capacitance humidity sensor which was of similar or worse performance than HIH-503*. Since at least 2015 the manufacturer introduced a new humidity sensor which is certified for temperatures down to -70°C.

2. Almost all Russian radiosondes have two versions which differ only by carrier frequency: 1782 and 1680 MHz and absolutely similar in all other respects. 1782 MHz radiosondes are used with old AVK radars, installed around 1987-1994; 1680 MHz radiosondes work with new radars. Nominally, all the radars have the same performance specifications but there are some differences in practice.

3. I requested code figures for new radars in 2007 and because of limited capacity of C-2 code tables I had to share the same code figures between MARL-A and VEKTOR-M. You can find information about actual ground systems at http://cao-ntcr.mipt.ru/monitor/locatore.htm and in the list of upper-air stations http://cao-ntcr.mipt.ru/all_doc/c4/catalogue.htm I compiled on behalf of WMO CIMO. In many circumstances MARL-A and VEKTOR-M perform similar but VEKTOR-M performance may become worse at low ambient temperatures, strong surface winds or high tangential velocity of the radiosonde. MARL-A may become worse when radiosondes traverse through the zenith. (The MARL antenna has no rotation in vertical, vertical beam position is controlled electronically. Therefore, antenna has to be moved around by 180° and in some cases tracking may suffer.)

Both new radars (MARL-A and VEKTOR-M) may be worse than AVK at very long distance when elevation becomes lower than 12 deg. AVK has a dish antenna, while MARL has active phased array antenna and Vektor has passive phased array antenna, therefore AVK antenna is more effective at low elevations.

4. In addition to those radiosondes/systems listed in C-2 we have three more types of radiosondes we have to refer to with code figures 90: they are I-2012, digital radiosonde MRZ-3MK and a new modification of AK2-02 (AK2m, AK2s and AK2-02m, all called AK2m in the next paragraph for brevity). I-2012 and AK2m/AK2-02m have 1782 and 1680 MHz versions while MRZ-3MK has only a 1680 MHz version. I-2012 and MRZ-3MK used type 90 for a short time in autumn 2014 – spring 2015.

Since06/05/2015 new code types were introduced in C-2 for I-2012 and MRZ-3MK (see Table A.2). In 2015 Roshydromet ordered some 6600 MRZ-3MK for use at different stations.

Except MRZ-3MK and AK2m all radiosondes have the same temperature sensor MMT-1 described in the literature (Luers and Eskridge, 1998; Zaitseva, 1993; Fridzon et al 1988; Tschudin and Schroeder, 2013; WMO, 1989). MRZ-3MK has modern miniature bead thermistor. Thus, each type ground station can operate with radiosonde of different types, often - within short time period. AK2m has a smaller sensor than MMT-1 but still rather a big thermistor.

All Russian radiosondes (except MRZ-3MK) use coefficients R01, R02 (radio transducer coefficients), A, B, C (for temperature), K, N, M (for humidity). A ground system has no idea which sensors a radiosonde has - it just converts frequencies to temperature and humidity. On the next step, temperature is corrected for solar radiation using radiation correction scheme derived for RKZ5-MMT-1, again - regardless of the sensor used in a radiosonde. IE. The same data processing including radiation correction derived for RKZ5 - MMT-1 is applied to all types of radiosonde in use now.

Temperature sensor resistance from temperature Rt=A*Exp(B/(C+t+273.15)

Humidity from humidity sensor resistance U = K + N*Ru + M*R*R

Sensor resistance from telemetry frequency yt,u=R01/(Rt,u+R02) where dimensionless parameter yt,u is derived from frequency in temperature (Ft) or humidity (Fu) channel and frequency (Fref) in reference channel yt,u=Fref/Ft,u

The SVP equation used in Russian radiosondes is still the “USSR algorithm” as given by Gaffen (1993), a Magnus-like approximation.

5. You may find pictures (small thumbnails are clickable, 76 RF95 is not in use anymore) of various radiosondes with MMT-1 at http://cao-ntcr.mipt.ru/monitor/consum/gosreestr.htm (in Russian). One can see that design of radiosondes is rather different that may influence temperature measurement performance. Except 27/88 MRZ (which production was discontinued in 2010 and remains are about to be spent soon) with gold-beater skin humidity sensor and RZM with Sensera capacitive sensor all other radiosonde have Honeywell HIH-5030, but again design of sensor arrangement is very different. At last, none of our radiosondes has pressure sensors and pressure is calculated by integrating hydrostatic equation. Thus, radar height performance (and, subsequently, ground system in use do matters).

So, we do observe rather noticeable variations in our upper-air stations performance (see e.g. http://cao-ntcr.mipt.ru/monitor/2015/03/qual2015_03e.htm#hobfg) but it is rather difficult to attribute them to particular type of radiosonde or ground system. Comparison of average figures yields rather similar figures: see e.g. http://cao-ntcr.mipt.ru/monitor/awb/main_awb.htm#hobfg where (in Russian) geopotential OB-FG RMS is shown for old radars with yellow diamonds, MARL-A with red circles and Vektor-M with blue triangles.

8.14.1 Corrections applied

Since the introduction of AVK-1 radars in 1980-s for all Soviet and, then, Russian radiosondes (except RF95) data processing basically remained the same (except increased resolution and some windfinding details). In fact, data processing of raw temperature, humidity and radar tracking data is independent from a radiosonde in use. Except the latest MRZ-3MK digital sonde raw telemetry processing is completely independent from a radiosonde in use.

Subject to corrections are:

- Temperature - for solar radiation. The used radiation correction scheme was derived in 1970-s for RKZ-5 with MMT-1 thermistor from statistical analysis of day-night differences at various sun elevations. It's quoted in WMO reported cited below. Later estimates of Dr. Fridzon based on models of radiation equilibrium of a temperature sensor were never used in practice.

- Radar height - for Earth curvature and radio-refraction. Now most of ground systems use effective radius equals to 8/7 of Earth's one while early AVK ground processing systems used coefficient 4/3.

- Conversion of radar height to geopotential (not in all AVK) - for variation of gravity acceleration constant with latitude and height.

No corrections are made:

- for temperature errors caused by radiation heat exchange in infrared

- for differences between radar antenna phase center height and barometer height

- for humidity errors caused by temperature deviation from normal conditions

- for deviations found at ground check (comparison between radiosonde and psychrometer placed into ventilated shield - similar to weather screen but artificially ventilated http://meteoweb.ru/img/meteoserv/meteoserv009-3.jpg)

9 References

Agustí-Panareda, A., and Coauthors, 2009: Radiosonde humidity bias correction over the West African region for the special AMMA reanalysis at ECMWF. Quart. J. Roy. Meteor. Soc., 135, 595–617.

Alexander, M., T. Tsuda, and R. Vincent, 2002: Latitudinal Variations Observed in Gravity Waves with Short Vertical Wavelengths. J. Atmos. Sci., 59, 1394-1404, doi: 10.1175/1520-0469(2002)059<1394:LVOIGW>2.0.CO;2.

Anderson, E. and Järvinen, H. 1999: Variational quality control. Q.J.R. Meteorol. Soc., 125: 697–722. doi:10.1002/qj.49712555416

Brown R and J Fitzgibbon, 2016: A Preliminary Discussion on the National Weather Service's Upper Air Data Continuity Study. AMS 18th Symposium on Meteorological Observation and Instrumentation, New Orleans, 11-14 January 2016 (video available from https://ams.confex.com/ams/96Annual/webprogram/18SMOI.html)

Brown R, D. Brewer and H. Escabi, 2017: Recent and Upcoming Changes to the National Weather Service's Upper Air Network. AMS Annual Meeting, January 2017, https://ams.confex.com/ams/97Annual/webprogram/Paper315692.html

Desroziers G, Berre L, Chapnik B, Poli P. 2005. Diagnosis of observation, background, and analysis error statistics in observation space. Q. J. R. Meteorol. Soc. 131: 3385–3396.

Dirksen, R. J., M. Sommer, F. J. Immler, D. F. Hurst, R. Kivi, and H. Vömel, 2014: Reference quality upper-air measurements: GRUAN data processing for the Vaisala RS92 radiosonde. Atmos. Meas. Tech., 7, 4463-4490, doi:10.5194/amt-7-4463-2014

ECMWF, 1987: ECMWF/WMO Workshop on Radiosonde Data Quality and Monitoring, 14-16 December 1987, ECMWF. Papers available via http://www.ecmwf.int/search/elibrary?page=1&title=radiosonde&year=1987

ECMWF, 2015: CY41R1 Official IFS Documentation, Part I Observations, available from http://www.ecmwf.int/en/elibrary/9208-part-i-observation-processing

Edwards D, 2016: Retiring the RS92: Met Office Radiosonde Trials, Assessment and Operation (4 pp), CIMO TECO conference, Madrid, September 2016, https://www.wmocimo.net/eventpapers/session3/O3(7)_Edwards_RS92.pdf

Edwards D, G Anderson, T Oakley, Peter G, 2014: Met Office Intercomparison of Vaisala RS92 and RS41 Radiosondes, http://www.vaisala.com/Vaisala%20Documents/Scientific%20papers/Met_Office_Intercomparison_of_Vaisala_RS41_and_RS92_Radiosondes.pdf

Fridzon M.B. et al. 1988. Radiation Corrections in Radiosonde Measurement of Temperature. Meteorologia i Gydrologia [Soviet Meteorology and Hydrology], No. 6

Gaffen D J, 1993: Historical changes in radiosonde instruments and practices: final report. 123 pp. WMO/TD- No. 541; IOM Report- No. 50, http://library.wmo.int/pmb_ged/wmo-td_541_en.pdf

Ho, S.-P., Peng, L., and Vömel, H. 2017: Characterization of the long-term radiosonde temperature biases in the upper troposphere and lower stratosphere using COSMIC and Metop-A/GRAS data from 2006 to 2014, Atmos. Chem. Phys., 17, 4493-4511, https://doi.org/10.5194/acp-17-4493-2017

Hollingworth A, Lonnberg P. 1986. The statistical structure of short-term forecast errors as determined from radiosonde data. Part I: The wind field. Tellus 38A: 111–136.

Ingleby N.B., 1995: Assimilation of station level pressure and errors in station height. Weather and Forecasting, 10, 172-182.

Ingleby B. and D. Edwards, 2015: Changes to radiosonde reports and their processing for numerical weather prediction, Atmosph. Sci. Lett., 16: 44-49. doi: 10.1002/asl2.518

Ingleby, N. B. and Lorenc, A. C. 1993 Bayesian quality control using multivariate normal distributions. Q. J. R. Meteorol. Soc., 119, 1195–1225

Ingleby B., P. Pauley, A. Kats, J. Ator, D. Keyser, A. Doerenbecher, E. Fucile, J. Hasegawa, E. Toyoda, T. Kleinert, W. Qu, J. St James, W. Tennant, R. Weedon, 2016a: Progress towards high-resolution, real-time radiosonde reports. Bull. Amer. Meteor. Soc., 97, 2149–2161, doi: 10.1175/BAMS-D-15-00169.1.

Ingleby B., M. Rodwell and L. Isaksen, 2016b: Global radiosonde network under pressure. ECMWF newsletter 149, 25-30 available from http://www.ecmwf.int/en/about/media-centre/media-resources

Kobayashi, E., Y. Noto, S. Wakino, H. Yoshii, T. Ohyoshi, S. Saito and Y Baba, 2012: Comparison of Meisei RS2-91 Rawinsondes and Vaisala RS92-SGP Radiosondes at Tateno for the Data Continuity for Climatic Data Analysis. Journal of the Meteorological Society of Japan. Ser. II. 90, 923-945

Luers, J. and R. Eskridge, 1998: Use of Radiosonde Temperature Data in Climate Studies. J. Climate, 11, 1002–1019, http://dx.doi.org/10.1175/1520-0442(1998)011%3C1002:UORTDI%3E2.0.CO;2

Jensen, M. P., Holdridge, D. J., Survo, P., Lehtinen, R., Baxter, S., Toto, T., and Johnson, K. L.: Comparison of Vaisala radiosondes RS41 and RS92 at the ARM Southern Great Plains site, Atmos. Meas. Tech., 9, 3115-3129, doi:10.5194/amt-9-3115-2016, 2016.

Kats A., A. Balagourov, and V. Grinchenko, 2005: The impact of new RF95 radiosonde, introduction on upper-air data quality in the North-West region of Russia, TECO conference, available from http://ftp.wmo.int/pages/prog/www/IMOP/publications/IOM-82-TECO_2005/Posters/P2(07)_Russia_Kats.pdf

Milan M., and L. Haimberger, 2015: Predictors and grouping for bias correction of radiosonde temperature observations, J. Geophys. Res. Atmos., 120, 10,736–10,766, doi:10.1002/2015JD023635.

Moradi, I., S. Buehler, V. John, A. Reale, and R. Ferraro, 2013: Evaluating instrumental inhomogeneities in global radiosonde upper tropospheric humidity data using microwave satellite data, IEEE T. Geosci. Remote, 51, 3615-3624, doi:10.1109/TGRS.2012.2220551.

Miloshevich L.M., A. Paukkunen, H. Vömel, and S. J. Oltmans, 2004: Development and Validation of a Time-Lag Correction for Vaisala Radiosonde Humidity Measurements. J. Atmos. Oceanic Technol., 21, 1305–1327. doi: http://dx.doi.org/10.1175/1520-0426(2004)021<1305:DAVOAT>2.0.CO;2

Miloshevich L.M., H. Vömel, D.N. Whiteman, and T. Leblanc. 2009: Accuracy assessment and correction of Vaisala RS92 radiosonde water vapor measurements. J. Geophys. Res., 114, D11305, doi:10.1029/2008JD011565.

Nash J., T. Oakley, H. Vömel, and Wei LI. 2011: WMO Intercomparison of High Quality Radiosonde Systems Yangjiang, China, 12 July - 3 August 2010, WMO Instruments and Observing Methods Report No. 107, available from http://www.wmo.int/pages/prog/www/IMOP/publications-IOM-series.html

OFCM, 1997 Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) Federal Meteorological Handbook No. 3 - Rawinsonde and Pibal Observations. http://www.ofcm.gov/publications/fmh/FMH3/00-entire-FMH3.pdf

Philipona R., A. Kräuchi, G. Romanens, G. Levrat, P. Ruppert, E. Brocard, P. Jeannet, D. Ruffieux, B. Calpini, 2013: Solar and Thermal Radiation Errors on Upper-Air Radiosonde Temperature Measurements. Journal of Atmospheric and Oceanic Technology, 30, 2382-2393. doi: http://dx.doi.org/10.1175/JTECH-D-13-00047.1

Radnóti G, P. Bauer, A. McNally, A. Horanii, 2012: ECMWF study to quantify the interaction between terrestrial and space-based observing systems on Numerical Weather Prediction skill, ECMWF Technical Memorandum 679.

Simmons A.J. and A. Hollingsworth, 2002: Some aspects of the improvement in skill of Numerical weather Prediction. Q.J.R.Meteorol.Soc. 128, 647–677

Sugidachi, T., and M. Fujiwara (2013), Correction of the stepwise change observed at 0C in Meisei RS2-91, RS-01G, and RS-06G radiosonde relative humidity profiles, Journal of the Meteorological Society of Japan, 91(3), 323-336, doi:10.2151/jmsj.2013-306.

Sun, B., A. Reale, D. J. Seidel, and D. C. Hunt, 2010: Comparing radiosonde and COSMIC atmospheric profile data to quantify differences among radiosonde types and the effects of imperfect collocation on comparison statistics, J. Geophys. Res., 115, no. D23 104.

Tavolato C. and L. Isaksen, 2015: On the use of a Huber norm for observation quality control in the ECMWF 4D-Var. Quart. J. Roy. Meteor. Soc., 141, 1514-1527, DOI: 10.1002/qj.2440

Tradowsky J S, C P Burrows, S B Healy and J Eyre, 2017: A new method to correct radiosonde temperature biases using radio occultation data. J. Appl. Meteor. Climatol., 56, 1643–1661, https://doi.org/10.1175/JAMC-D-16-0136.1J Appl Meteorol and Clim. (accepted)

Tschudin, M. and S. Schroeder, 2013: Time Constant Estimates for Radiosonde Temperature Sensors. J. Atmos. Oceanic Technol., 30, 40–56 http://dx.doi.org/10.1175/JTECH-D-11-00181.1

Wang J., L. Zhang, A. Dai, F. Immler, M. Sommer, and H. Vömel, 2013: Radiation Dry Bias Correction of Vaisala RS92 Humidity Data and Its Impacts on Historical Radiosonde Data. J. Atmos. Oceanic Technol., 30, 197–214. doi: http://dx.doi.org/10.1175/JTECH-D-12-00113.1

WMO International Radiosonde Comparison, Phase III, Dzhambul, USSR, 1989: final report. WMO/TD- No. 451; IOM Report- No. 40. Available online at: http://library.wmo.int/pmb_ged/wmo-td_451_en.pdf

WMO, 2014: Guide to Meteorological Instruments and Methods of Observation (WMO No. 8) available from https://www.wmo.int/pages/prog/www/IMOP/IMOP-home.html

WMO, 2015: *WMO Publication No. 306 - Manual on codes. Volume I.1 and Volume I.2* Available at http://www.wmo.int/pages/prog/www/WMOCodes.html

Yu H., P.E. Ciesielski, J. Wang, H-C. Kuo, H. Vömel, and R. Dirksen, 2015: Evaluation of Humidity Correction Methods for Vaisala RS92 Tropical Sounding Data. J. Atmos. Oceanic Technol., 32, 397-411. doi: http://dx.doi.org/10.1175/JTECH-D-14-00166.1

Zaitseva, N.A., 1993: Historical Developments in Radiosonde Systems in the Former Soviet Union. Bull. Amer. Meteor. Soc., 74, 1893-1900. http://dx.doi.org/10.1175/1520-0477(1993)074%3C1893:HDIRSI%3E2.0.CO;2