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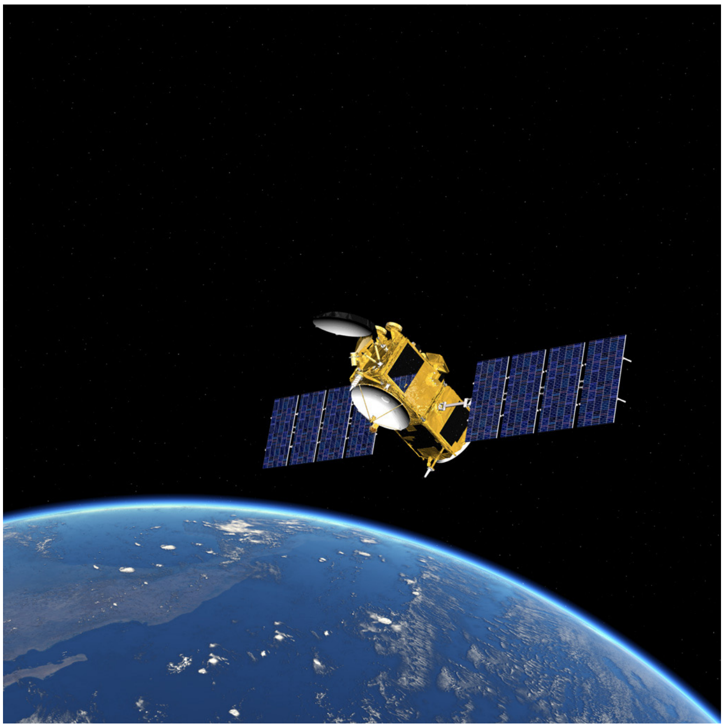

Artist's impression of Jason-3 satellite (© EUMWTSAT)

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Global radiosonde network under pressure

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In early January 2015, ECMWF's automated monitoring system started warning of reductions in the number of Russian radiosonde reports. As a result of budget constraints, Russia had cut its radiosonde programme from two ascents per day to one. There were representations from ECMWF and WMO to the Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Roshydromet) that this was a serious reduction in the global observing system. In its representations to Roshydromet, ECMWF was able to present results from experiments which showed that reductions in Russian radiosonde reports as seen in 2015 have a significant impact on forecast performance. At short range the increased errors are mainly over Russia, moving downstream over the Pacific at longer range and then affecting forecast scores for the whole of the northern hemisphere. In April 2015, Roshydromet reversed its decision and resumed making two ascents per day.

More recently there were similar reductions to one ascent per day in Mexico and Brazil, where the number of stations affected is smaller but regionally significant. Over the last few years a number of remote island stations have also stopped making radiosonde reports or are planning to do so.

The effects of smaller-scale reductions in the number of reports in other parts of the world are more difficult to assess. In some cases radiosonde reports are particularly important because they come from data-sparse areas. Beyond numerical weather prediction (NWP), radiosonde reports are also useful for general forecasting, climate studies and the calibration of satellite data.

Russian radiosondes

There are about 800 active radiosonde stations worldwide and many report twice per day at 00 and 12 UTC (nominal times – the ascent can take about two hours). A few stations report four times per day but some report just once. Russia provides data from 111 radiosonde stations. This is more than any other country, so the Russian cutback in early 2015 constituted a major change. ECMWF's automated warning system (Dahoui et al., 2014) alerted us to the Russian change in January 2015. Very quickly ECMWF performed impact studies to compare the quality of control forecasts (CONTROL) using full Russian radiosonde data with that of test forecasts using reduced data in line with the cutbacks made in early 2015 (TEST). The experiments covered the period December 2013–February 2014 (forecast resolution T511, equivalent to a grid spacing of about 40 km) and April–June 2014 (forecast resolution T639, equivalent to about 31 km). Both tests used the operational IFS configuration of 137 vertical levels and 12-hour 4DVar, with successive analysis inner-loop resolutions of TL95/TL159/TL255 and an outer-loop resolution of TL639. During the cutback, some of the Russian stations ceased their 00 UTC ascent (for the most part those east of 110°E, see Figures 1 and 2a) and others ceased their 12 UTC ascent. The ECMWF experiments mirrored this as closely as possible.

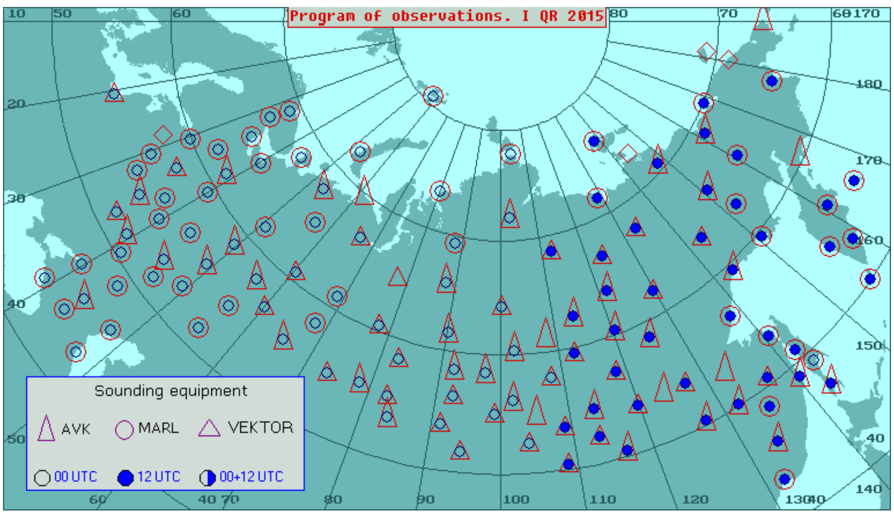

Figure 1 Russian radiosonde network in early 2015, showing which stations reported at 00 UTC and which at 12 UTC (courtesy of A. Kats, Roshydromet). AVK, MARL and VEKTOR are different radiosonde manufacturers, as is Meteorite, represented by diamond symbols.

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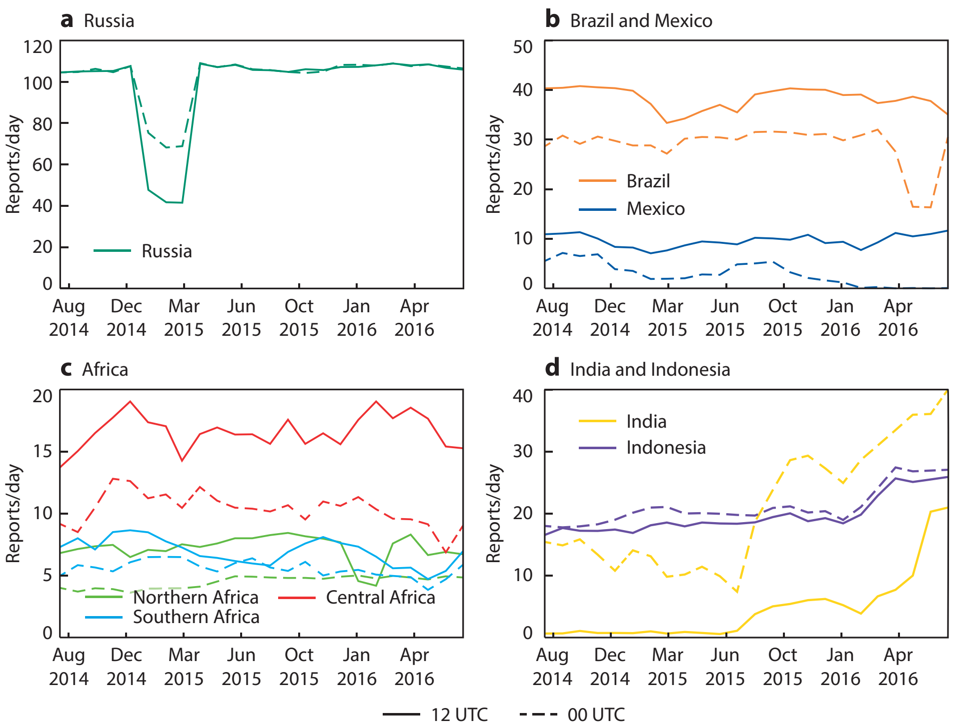

Figure 2 Monthly average number of radiosonde reports per day at 00 UTC (dashed lines) and 12 UTC (solid lines) for August 2014 to July 2016 inclusive, for (a) Russia, (b) Brazil and Mexico, (c) Africa and (d) India and Indonesia. Only reports that include temperature are included. India and Indonesia both make significant numbers of wind-only (PILOT) reports, generally to lower altitude, which are not included in the count. For technical reasons, one Mexican station from which data was received in BUFR format only in May and June 2016 is not included.

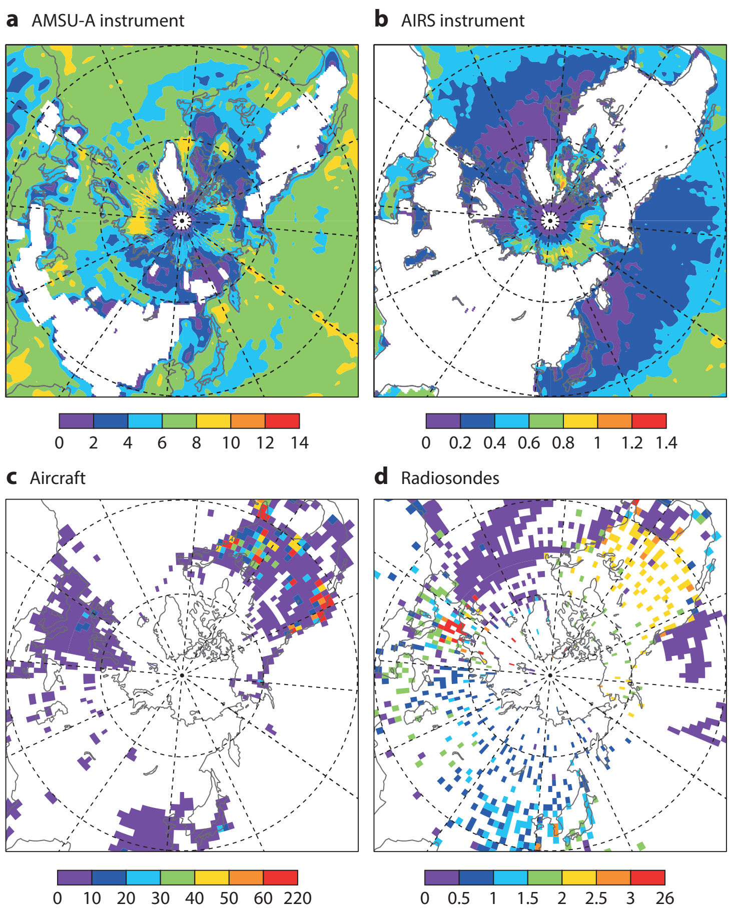

Figure 3 Average observation counts for temperature at about 500 hPa per 12-hour cycle per 2° grid box for (a) AMSU-A microwave radiometer, channel 5, (b) AIRS infrared sounder, channel 215, (c) aircraft reports, and (d) radiosonde reports, based on actively assimilated data from December 2014 to February 2015. Note the satellite observation gaps over Russia (bottom-left quadrant) and the lack of aircraft data, except near a few airports.

Over Russia, radiosondes provide the main information source for the lower/mid-troposphere. There are few reports from aircraft ascents/descents and no wind profilers, and the uncertainty of land surface emissivity and skin temperature makes it difficult to use lower/mid-tropospheric satellite sounding channels. For infrared satellite instruments, the skin temperature issue makes cloud screening very difficult and limits the use of tropospheric channels both in snow and snow-free conditions. Microwave instruments are easier to use when the land is snow free. When snow or ice is present, high uncertainty in emission, scattering and skin temperature, frequently in combination with significant heterogeneity, limits the use of tropospheric microwave channels over large parts of the boreal winter hemisphere, as well as Antarctica. Figure 3 shows representative mid-tropospheric temperature data usage in wintertime for infrared and microwave satellite data as well as aircraft and radiosonde in situ data.

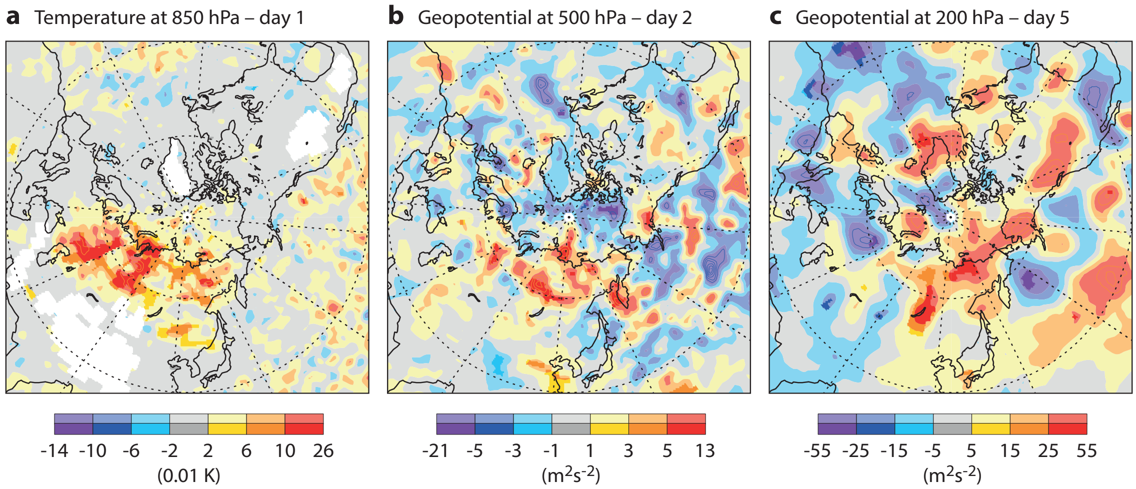

Figure 4 Difference in RMS error between CONTROL and TEST forecasts shown for (a) temperature at 850 hPa at day 1, (b) geopotential at 500 hPa at day 2, and (c) geopotential at 200 hPa at day 5. Positive (yellow/red) values imply larger errors in the TEST forecasts. Increased temperature errors in day 1 forecasts are concentrated over Russia. Larger errors in day 2 forecasts of geopotential at 500 hPa are clustered over the North Pacific as well as Russia. Increased errors in day 5 forecasts of geopotential at 200 hPa show the impact on the jet stream, which will communicate the differences across the hemisphere. The experiment covers the period December 2013–February 2014. Saturated colours denote statistical significance at the 5% level.

Consistent with the reduced use of satellite data over land in boreal winter, the impact on forecasts of reducing the radiosonde data was greatest during the cooler months tested (December–February). Results for these months show that 48-hour forecasts of 500 hPa geopotential height fields over Russia were degraded by 4–10%, as measured by root-mean-squared (RMS) differences from analyses (Figure 4). Similar results were also obtained for forecasts of temperature, wind and relative humidity. At longer lead times, these degradations propagate eastwards and eventually affect the entire northern hemisphere. While the largest effects are centred on Russia and the Pacific stormtrack, the detrimental impact on northern hemispheric scores as a whole (Figure 5) amount to about half a year of progress in NWP development (based on progress over the last ten years).

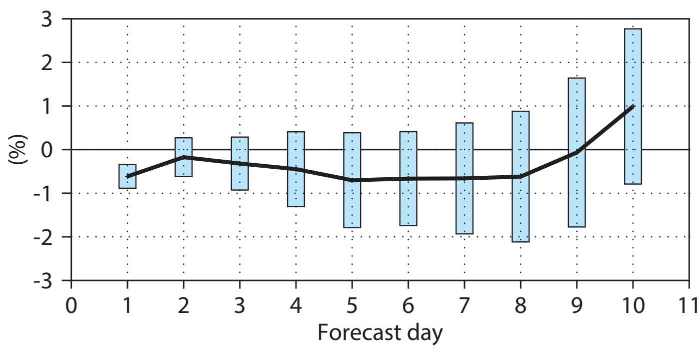

Figure 5 Relative difference in RMS error between CONTROL and TEST forecasts of geopotential height at 500 hPa in the northern hemisphere extratropics (20–90°N). The bars indicate 95% confidence intervals. Negative values indicate that the forecasts with fewer radiosonde reports were worse than those with full radiosonde reports. The experiment covers the period December 2013–February 2014.

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Figure 6 shows that Russian radiosonde temperature and humidity observations are somewhat lower quality than those from other radiosondes north of 50°N, but the winds have similar RMS statistics. One factor specific to Russian radiosondes is that pressure is derived from radar heights and, at low radar elevation angles, it has large uncertainty. However, from our results it is clear that Russian radiosondes provide a very valuable contribution to the global observing system and the accuracy of NWP forecasts.

Other regions

Between October 2015 and February 2016, Mexico, which has 13 stations, cut back from mainly two reports per day to one. In March/April 2016, about half of the 40 Brazilian radiosonde stations went from two to one report per day, although this was largely reversed in July 2016 (Figure 2b). It should be noted that various other Latin American stations only report once per day, generally at 12 UTC (Table 1). Numbers of reports from Africa are relatively low and quite variable (Figure 2c). The variability may partly arise from telecommunications issues rather than from ascents not being made at all. Some countries in the world do not make reports at all.

Remote island stations may be more expensive to maintain, and equipment failures may take longer to rectify. In the Atlantic, Ascension Island stopped reporting in September 2010 and Gough Island is being considered for closure. The numbers from Gough have been somewhat erratic recently. The most recent report from Cape Verde was in June 2016. In the Tropical Western Pacific, Nauru stopped reporting at the end of August 2013 after 15 years of operation, and Manus Island stopped in July 2014 after 18 years. Vanuatu last reported in April 2016 and, much further East, Galapagos last reported in January 2016. In the Indian Ocean, Gan in the Maldives is still reporting but has some gaps in the record due to technical problems, including the breakdown of the hydrogen generator (Box A). On a more positive note, the numbers of reports from India and Indonesia have increased recently (Figure 2d). The Indian reports are of somewhat mixed quality (temperatures from some stations are excluded from the ECMWF assimilation due to poor monitoring statistics) although they have improved in recent years.

Region	Number of stations	0000 UTC		1200 UTC	
		Total number	At least 25 T30 reports	Total number	At least 25 T30 reports
Africa	43	25	1	37	10
Asia	301	294	192	265	159
S America	55	37	7	54	19
N America & Caribbean	156	138	119	156	128
SW Pacific	97	95	52	70	14
Europe	151	143	97	134	98
Antarctica	15	9	2	11	3

Table 1 Number of radiosonde stations from which reports are received at ECMWF (in TEMP format) for July 2016 by WMO region. For 0000 UTC (2100–0859 UTC window) and 1200 UTC (0900–2059 UTC window) the 'total number' column gives the number of stations which reported at that time and the second column the number of stations which reported 30 hPa temperature at least 25 times.

Inflating radiosonde balloons A

All radiosonde stations need either hydrogen or helium to inflate the balloons. Hydrogen generators are expensive to purchase and require ongoing maintenance and technical understanding. They also need a good power supply and clean water. Despite this, and the unfortunate frequency of generator failures, most remote locations have to rely on hydrogen generators. Using helium is not a viable alternative for these stations because of its high price and the logistics of supply. Except for accidents (premature burst), the height which a particular radiosonde reaches is determined primarily by the size of the balloon and the amount of gas used.

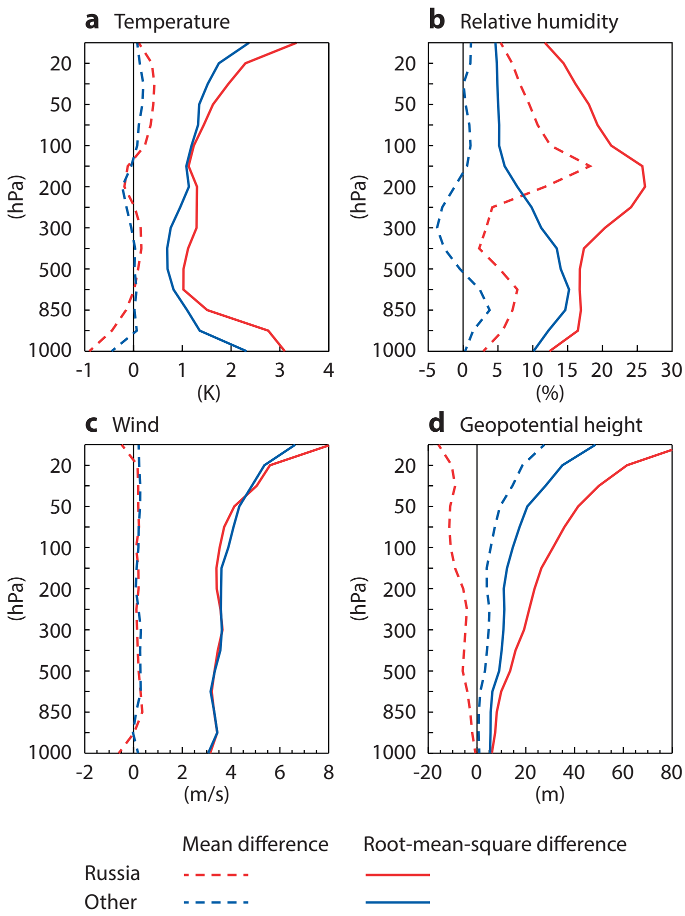

Figure 6 Observation minus background (12-hour forecast) statistics for Russian radiosondes and other radiosondes north of 50°N. Results are shown for standard-level data that passed the operational first guess check, October 2014–March 2015. For wind, the mean speed difference and the RMS vector difference are shown. Note that upper-tropospheric humidity from Russian radiosondes is not assimilated in the ECMWF system. The very large near-surface temperature differences partly stem from the fact that the forecast model has difficulty representing the very sharp low-level inversions that occur in winter over Russia and to a lesser extent over other land areas.

A challenge all regions face is the migration from alphanumeric TEMP/PILOT code to binary BUFR code for radiosonde reports. The BUFR code allows reporting of high vertical resolution data, including the position of each level, and also enables higher-precision reporting (*Ingleby et al.*, 2016). So far the adoption of high-resolution reporting is mostly confined to Europe and Australia, and unfortunately many of the other BUFR reports do not meet the regulations and are unusable. Updated information on the migration to BUFR is available at *https://software.ecmwf.int/wiki/display/TCBUF/*.

Importance for NWP

Within Europe there are regular discussions about the observing system and its importance in NWP through EUMETNET, a grouping of 31 national meteorological services. There is also some pooling of resources to support radiosonde launches from 18 ships in the North Atlantic, of which on average seven are active on any particular day, and from a number of land stations. EUMETNET also funds aircraft (AMDAR) reports from European aircraft, and ECMWF helps to provide monitoring to ensure that the various observing systems are providing good-quality data.

Besides the direct impact of radiosondes on weather forecasts, they also have an indirect effect as a result of being used as reference data – helping to bias-correct satellite sounding and aircraft temperature data, especially in the troposphere. In the stratosphere, a EUMETNET-funded ECMWF study by *Radnoti et al*. (2012) found that satellite radio occultation measurements were a valuable source of reference data. From an NWP perspective, radiosondes, aircraft (on ascent and descent) and wind profilers complement each other in terms of the variables provided: radiosondes are less frequent but ascend higher and also measure humidity, while only a small proportion of aircraft have humidity sensors. Radiosondes are also used extensively for forecast verification.

The large number of Russian radiosonde stations involved in the cutback makes it relatively easy to get a clear view of their importance. It is much more difficult to assess the impact of a few radiosonde stations when smaller changes to the observing system are contemplated. However, for global analysis and forecasting, radiosonde reports from remote island stations are especially valuable because they come from data-sparse areas. Being surrounded by ocean, they are also particularly useful for the bias correction and validation of satellite data. An OSSE (Observing System Simulation Experiment) performed

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by *Privé et al*. (2014) suggested that doubling the number of radiosonde reports per day would be beneficial for weather forecasts.

Drive for availability and quality

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. About 170 stations worldwide are designated 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. The role of radiosondes as reference instruments is promoted by the GRUAN (GCOS Reference Upper Air Network) project, envisaged to be a network of 30 to 40 sites across the globe. Currently GRUAN reports are available from about ten stations using the Vaisala RS92 radiosonde. Most of these stations also send real-time observations using the manufacturer's algorithms. GRUAN provides estimates of the measurement uncertainty. One notable feature is that upper level temperature uncertainty is much lower at night than in sunlight (*Dirksen et al.*, 2014).

At present, for operational NWP the designation of a station as GRUAN or GUAN makes no difference to its processing. GRUAN is useful for minimising and quantifying errors in radiosonde data, and as a standard against which to compare the worldwide radiosonde network and satellites. The best operational radiosondes outside GRUAN (launched from about 450 stations using RS92 and other good-quality radiosonde types) also provide accurate data, and with better coverage. As noted by *Eyre* (2016), NWP satellite bias correction methods need good proportions of reference observations in order to work well. The Met Office and ECMWF are looking at the role of radiosondes in calibrating satellite sounding data as part of the EU-funded GAIA-CLIM project.

Further reading

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