Developments in 4D-Var assimilation of in situ observations at ECMWF

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ECMWF

ECMWF Annual Seminar
September 2026, Reading

Overview

In May 2025 ECMWF started assimilating global Mode-S aircraft winds, the data volumes are HUGE and they give MAJOR benefits especially at low latitudes at short range, spreading out at medium range.

We have been looking at the use of GNSS height data from aircraft and radiosondes plus studying the impact of radiosonde data as a function of variable, pressure and season.

Mode-S aircraft data

The Mode-S meteorological reports are produced from Air Traffic Control messages at EMADDC in the Netherlands as described by de Haan et al (2025). For EMADDC Met Office Global Mode-S data see https://www.emaddc.com/participate/data+users/emaddc-met-office-global/default.aspx. ECMWF started assimilating European Mode-S winds during the Covid lockdowns (summer 2020), changed aircraft thinning in November 2023 (Ingleby, 2026) and started using global Mode-S winds in May 2025. The data density can be very high and the thinning is important.

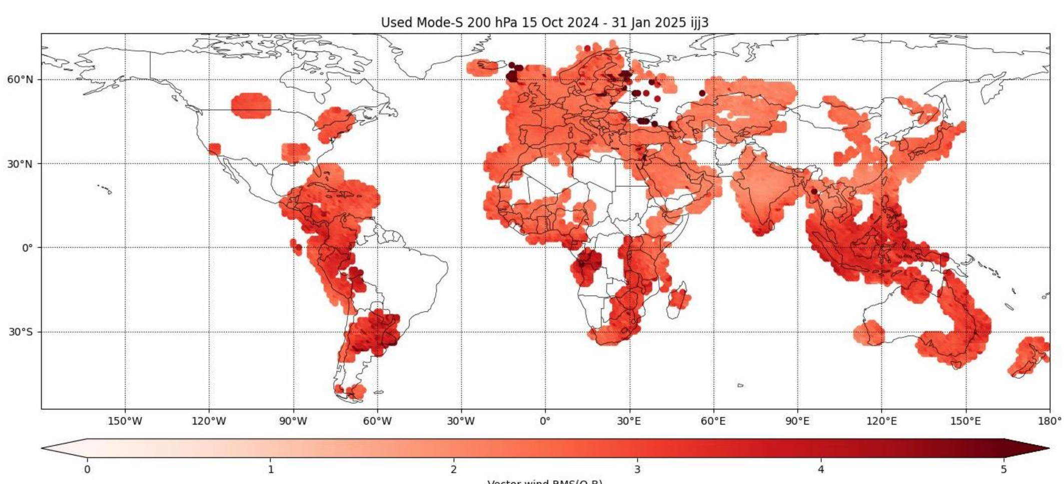

Figure 1. RMS vector wind O-B (m/s) at 200 hPa in 1 degree boxes, 15 Oct 2024 to 31 Jan 2025. Coverage at low levels is restricted to the vicinity of airports.

Figure 1 shows vector wind RMS observation-minus-background (O-B) at 200 hPa for European+Global Mode-S data in 1x1 degree boxes. There are relatively large RMS values in parts of the tropics due to deep convection and also the sparsity of other wind observations. Wind quality is similar to that of AMDARs although there are some subtle features due to a need for a heading correction in the processing (Ingleby, 2026).

Figure 2 shows the T+12 improvement in vector wind RMS fit to AMDAR aircraft winds: largest (up to 8%) in the tropics, but also up to 4% at 30°S. Figure 3 shows an estimate of operational forecast impact – the aircraft timeseries shows a large increase in May 2025.

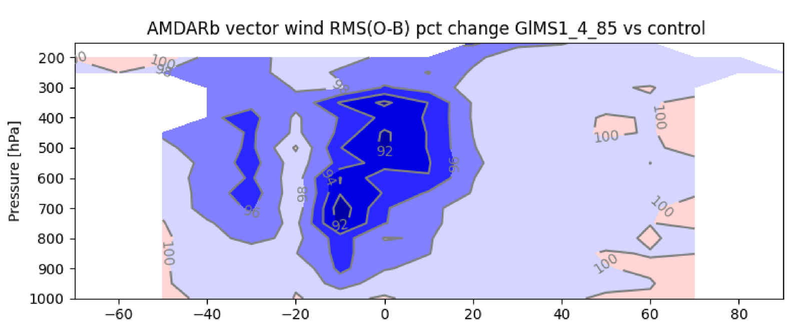

Figure 2. Percentage change in 12-hour forecast fit to AMDAR winds: use of global Mode-S winds relative to control.

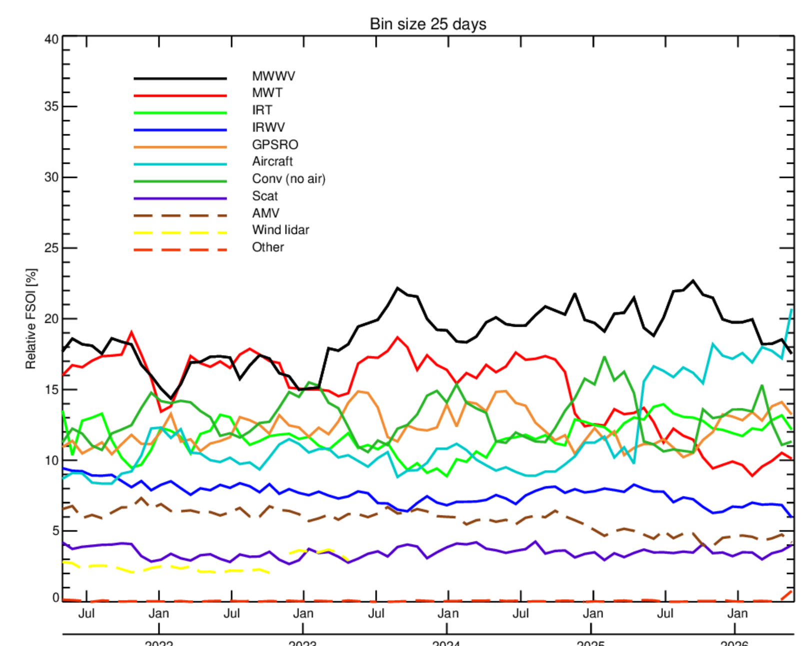

Figure 3. Operational FSOI timeseries (courtesy A Geer). This provides an estimate of the impact of different observation types on 24 h forecasts. In May 2025 the aircraft FSOI jumped by 5 or 6% and aircraft are now ranked second.

It is well known that winds in the tropics are important but undersampled. Although the global Mode-S coverage is patchy it clearly provides important extra data there. Mode-S temperature must be rederived from Mach number and airspeed and so have errors 10-20% larger than AMDAR temperatures. Their use has been trialled several times at ECMWF and shows both benefits and detriments, work is ongoing and a possible cause of problems in certain areas has been identified. For aircraft the impact of temperatures is less than that of the winds, eg Warren et al (2026).

GNSS height vs pressure

For historical reasons aircraft and radiosonde data are assimilated using pressure as the vertical coordinate. Aircraft pressure measurements are subject to a complex set of adjustments, and their accuracy is not well documented (Christmann, 2025, is an exception). AMDAR reports can contain the GNSS altitude, but unfortunately only two subsets report this: British Airways (BAW) A319/A320/A321 and KLM B777 aircraft. For comparison WindBorne balloons measure pressure (to an accuracy of about 0.1 hPa) and GNSS altitude. Figure 4 shows one year's O-B statistics. Through most of the troposphere the WindBorne heights have little bias and SD(O-B) of about 7m, suggesting that both O and B are accurate to about 5m or better. For KLM and BAW SD(O-B) are about 11m and 17m respectively and the biases can be larger (they vary from one aircraft to another). It is thought that the errors come mainly from the pressures. Height could be used either as an additional variable or as an alternative coordinate. Using it as a coordinate for aircraft data has not shown clear benefits so far, but using it as a coordinate for radiosonde descent data does improve the temperature O-B statistics (Figure 5).

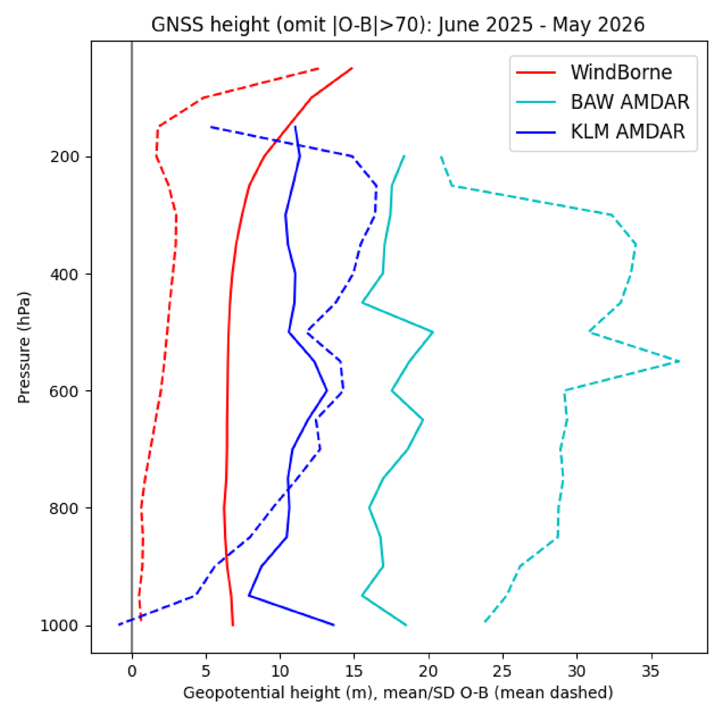

Figure 4. Height O-B statistics for WindBorne and AMDAR (KLM and BAW).

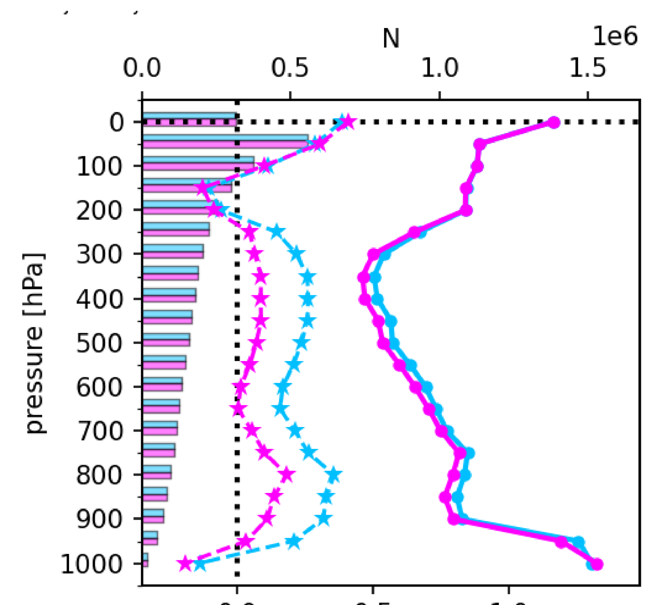

Figure 5. RS41 temperature descent data, June-July 2025. O-B as fn(P) and as fn(Z). The warm bias often seen on descent (Ingleby et al, 2022, AMT) is reduced using the GNSS heights.

Upper-level Radiosonde impact in Winter

In the stratosphere north of 45°N there is huge variability in the extended winter period, whereas there is much less variability in the summer (Fig 6). This prompted the hypothesis that high-level radiosonde and satellite data in the area have more impact in winter. Radiosonde FSOI (Fig 7) supports this with much larger FSOI above 100 hPa (Fig 7a) in winter/spring months. Most of this upper-level radiosonde impact comes from the winds, partly because satellites provide a wealth of temperature data in the stratosphere but little direct wind data. Note that the number of radiosonde data points (green bars) are lower in the winter because the balloons burst at lower altitude then ☹. More details including OSE results can be found in Ingleby and Policthchouk (2026).

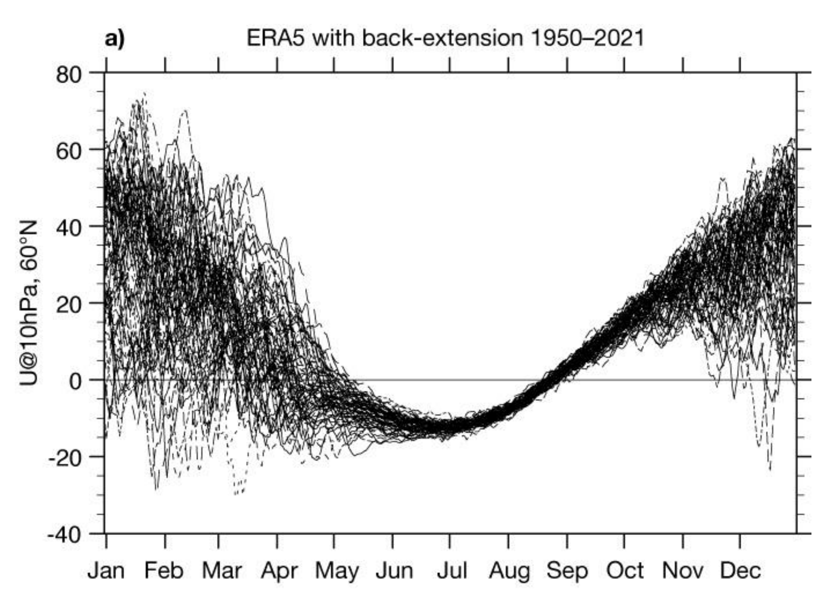

Figure 6. Daily timeseries of zonal-mean zonal wind (m/s) at 10 hPa, 60°N, ERA5

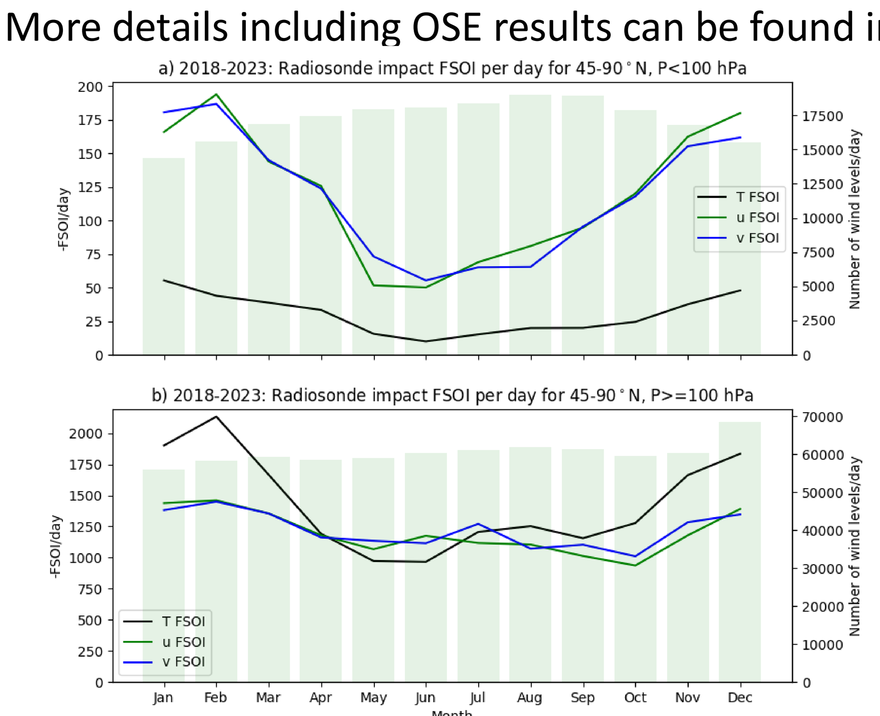

Figure 7. radiosonde FSOI by variable 2018-23, 45-90°N, number of winds per day as bars.

Summary

Whilst not fully global **the Global Mode-S data represent a huge opportunity**, particularly the winds in the tropics, to improve global weather forecasts. Thanks are due to the Met Office and EMADDC (KNMI) for making them available. With such dense data care is needed to thin the observations appropriately. This is the largest change in the use of in situ data over the last decade.

Ongoing longer-term work is looking at the possibility of using GNSS altitude data from aircraft (hardly reported at present in AMDAR) to improve the forecasts. Evidence suggests that GNSS altitude is more accurate than aircraft pressure altitude, so in principle it would be better to assimilate variables like wind and temperature as a function of height rather than pressure. For radiosonde descent data we see improved O-B fit from using height as the coordinate.

Partly in response to discussion about WMO GBON requirements a close look was taken at radiosonde impact. Upper-level winds are particularly important N of 45°N in Winter/Spring. It is desirable to use larger balloons at some stations in Winter to improve burst heights then.

References

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