Impact of assimilating Mode-S EHS winds in the Met Office’s high-resolution NWP model

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Abstract
Aircraft play an important role in providing in-situ upper air observations for use in numerical weather prediction (NWP) models. Aircraft observations of wind, temperature and humidity have been routinely assimilated into NWP models for decades. More recently, the Met Office has installed a network of six receivers to collect Mode-Select Enhanced Surveillance (Mode-S EHS) broadcasts and derive wind and temperature information. The paper focuses on the assimilation of high-frequency (sub-hourly) Mode-S winds into the Met Office’s hourly cycling high-resolution NWP model, which employs four-dimensional-variational data assimilation (4D-Var). An observing system experiment (OSE) experiment was carried out to assess the impact of additionally assimilating Mode-S wind data on the model forecasts in both summer and winter. It is shown that assimilating Mode-S winds has a positive benefit on the forecast skill in the first 6 hr wind profiles, with an improvement of the mean bias and root mean square (RMS) errors of up to 0.5 m·s⁻¹ in the first hour and 0.3 m·s⁻¹ in the sixth hour. The assimilation of Mode-S winds is also seen to be beneficial to the near-surface-focused UK NWP composite index, and to the hourly precipitation accumulations in fractions skill score (FSS) for forecasts up to 9 hr ahead.

KEYWORDS
aircraft data, AMDAR, data assimilation, high-resolution NWP, Mode-S EHS winds, OSE, verification

1 | INTRODUCTION
Aircraft represent an important data source in providing in-situ upper air observations for use in numerical weather prediction (NWP) models. Earlier aircraft observations came from pilot aircraft reports (AIREPs), which contain wind and temperature information at cruise levels. Observations of wind, temperature and occasionally humidity from aircraft under the World Meteorological Organization’s (WMO) Aircraft Meteorological Data Relay (AMDAR) programme have been assimilated into NWP models since the 1980s. More recently, higher resolution wind and temperature observations inferred from Mode-Select Enhanced Surveillance (Mode-S EHS) broadcasts have become available (de Haan, 2011; Stone and Pearce, 2016).

Several studies have assimilated Mode-S EHS data into limited area NWP models in recent years. de Haan...
and Stoffelen (2012) assimilated Mode-S wind and temperature data into 1 and 3 hourly cycling versions of the three-dimensional-variational data-assimilation (3D-Var) HIRLAM model. Results from assimilation experiments for winter 2008, using Mode-S observations available at that time from one receiver at Schiphol Airport in the Netherlands, showed a generally positive impact on wind and temperature forecasts. When verified against radiosonde observations, smaller biases and root mean square (RMS) wind errors were seen for the first few hours of forecasts when Mode-S and AMDAR data were both included in the assimilation. In their experiments, the Mode-S wind error profile was assumed to be the same as AMDAR. Mode-S observations were thinned spatially at a grid spacing of 6 km × 50 hPa such that only about 5% of the raw data were used in the assimilation. A preprocessing, time-smoothing scheme, developed at the Royal Netherlands Meteorological Institute (KNMI) (de Haan, 2011), was applied to Mach number and airspeed so that the quality of the derived Mode-S temperature was improved (but it was still poorer than the AMDAR temperatures).

An impact study of assimilating Mode-S EHS observations was also documented by Lange and Janjić (2016) in the COSMO-KENDA modelling system, in which an ensemble Kilometre Scale Ensemble Data Assimilation (KENDA) Kalman filter was coupled to an ensemble COSMO forecast model. They showed that, over a period of 5 days, the assimilation of Mode-S winds and temperatures led to a reduction in the RMS errors in forecasts of 1–3 hr lead time. Similar to de Haan and Stoffelen (2012), theMode-S wind error profile was assumed to be the same as the AMDAR and Mode-S temperature data were pre-processed at the KNMI to reduce the observation errors. Fifteen times more Mode-S data than the AMDAR were used in the assimilation. A test of random thinning applied to Mode-S data suggested a saturation of the forecast error reduction when more than 50% observations were assimilated.

In addition to Mode-S EHS observations, Mode-S Meteorological Routine Aircraft Report (MRAR) is another type of Mode-S message that contains wind and temperature observations. The effect of Mode-S MRAR wind and temperature on forecasts was investigated by Strajnar et al. (2015) in which data-assimilation experiments using the 3 hourly cycling, 3D-Var ALADIN model were undertaken. An improvement in wind and temperature forecasts was found in the 1–3 hr lead time forecasts in both summer and winter, though the benefit to forecasts 24 hr ahead was less clear.

Compared with Mode-S EHS observations, both wind and temperature in Mode-S MRAR are directly computed by the aircraft’s flight management system. Mode-S MRAR temperatures are therefore of higher quality than derived Mode-S EHS temperatures as they do not suffer from the limiting precision of airspeed and Mach number as Mode-S temperatures. However, Mode-S MRAR data are not as widely available as Mode-S EHS data, as most aircraft cannot transmit MRAR messages and they are rarely interrogated.

With high temporal and spatial resolution, Mode-S EHS data provide a rich data source which is well suited to be assimilated in high-resolution NWP models such as the 4D-variational data-assimilation (4D-Var) UKV. The paper presents an observing system experiment (OSE) study of high-frequency Mode-S EHS wind assimilation using the Met Office’s hourly cycling 4D-Var UKV model. The impact of Mode-S winds on the model forecasts over 30 day winter and summer periods is discussed. The focus is on Mode-S winds only, with Mode-S temperatures not assimilated due to their large observation errors (though an improved method for deriving Mode-S temperatures has recently been reported by Sondij 2020).

The remainder of the paper is structured as follows. The remainder of this section overviews the UKV and aircraft-based observations (including derivation of Mode-S wind and temperature, and their error characteristics). The main results of Mode-S wind assimilation are presented in Section 2. Section 2.1 describes the experimental set-up, which includes data-thinning options for the high-density Mode-S winds. Sections 2.2 and 2.3 discuss the spatial and vertical distributions of assimilated Mode-S winds with reference to other existing upper air observations. Vertical profiles of mean and RMS errors of Mode-S and AMDAR winds, compared with the UKV model background, are shown in Section 2.4. Section 2.5 discusses the verification of wind forecasts at T + 1 and T + 6 hr lead times against radiosonde observations. The impact on a composite UK NWP index, which is a measure of accuracy in the UKV model forecasts of near-surface fields (e.g. 10 m winds), is examined in Section 2.6 in order to qualify changes in the model forecast skill on UK weather elements. Model forecast skill for precipitation forecasts is presented in Section 2.7 using the fraction skill score (FSS) method of Roberts and Lean (2008). Conclusions are presented in Section 3.

1.1 Overview of the high-resolution 4D-Var UKV model

With continuing enhancements to computer power and improvements to model formulation and data-assimilation techniques, convection-resolving resolution NWP models have been introduced in many operational centres. Météo France operates the 1.3 km horizontal
resolution AROME model with hourly cycling 3D-Var assimilation and Deutscher Wetterdienst (DWD) runs 2.2 km-resolution ICON-DE2 model with analysis calculated hourly with the ensemble data-assimilation system KENDA. The higher resolution models require denser and more frequent observational data. To achieve this aim, a variety of observations ranging from Meteosat Second Generation cloud-tracked winds to high-resolution radar data have been exploited and used in many of regional NWP systems.

The Met Office runs a high-resolution limited-area NWP model (UKV) operationally, primarily for UK weather forecasts at convection-resolving resolution on an enlarged UK-wide domain (Figure 1). The UKV forecast system uses the Met Office’s Unified Model (UM) (Davies et al., 2005) and variational data-assimilation scheme (Lorenc et al., 2000; Rawlins et al., 2007). The hourly cycling UKV uses a 4.5 km-resolution version of the 4D-Var and a 1.5 km-resolution version of the UM to provide forecasts every hour for up to 120 hr ahead (Milan et al., 2020). The UKV model domain consists of 950 × 1,025 horizontal grid points and 70 vertical levels, with the model top located at 40 km above the surface. In the hourly cycling assimilation scheme there are 24 assimilation cycles each day, and at each cycle sub-hourly observations distributed within the assimilation time window $T - 30$ to $T + 30$ min are assimilated, where $T$ is the nominal analysis time in hours UTC, that is, 0000, 0100, ..., 2300 (Ballard et al., 2016; Li et al., 2018). The incremental 4D-Var assimilation enables the time history of the observations to be used fully by incorporating a linear Perturbation Forecast (PF) model which generates time-varying increments over the assimilation window. An adjoint (backward) integration of the increments is performed from the observation time using the adjoint of the PF model so that the penalty gradients or analysis increments, hence analysis, are found at the (correct) initial time, $T - 30$ min (Lorenc and Rawlins, 2006).

In contrast to the previous 3D-Var UKV (which was operational from the beginning of May 2013 to July 2017) where assimilation had 3 hourly cycles and used mainly conventional hourly observations, a shorter 1 hr cycle length is used in the 4D-Var UKV to exploit higher time-frequency (i.e. sub-hourly) observations data (Figure 2). Doppler radial winds from the Met Office’s weather radars are available every 10 min (Simonin et al., 2014), in precipitation only, and winds from wind profilers every 15 min, for example, are included in the assimilation in the current 4D-Var UKV model. Li et al. (2018) described hourly cycling 3D- and 4D-Var assimilation systems and showed that the 4D-Var assimilation produced forecasts with greater spatial accuracy and longer lead times compared with 3D-Var in their study of NWP-based precipitation nowcasting. In the context of a global NWP model, Lorenc and Rawlins (2006) showed that

**FIGURE 1** UKV model domain and horizontal grid-spacing: 1.5 km fixed-grid-resolution inner area (red) and 1.5 to 4 km variable stretched-grid-resolution outer area (lighter reds)
forecasts using the 4D-Var improved over the 3D-Var as the 4D-Var benefited from allowing for the correct observation times, and implicit time-evolved co-variances.

1.2 | Aircraft-based observations

Conventional upper air winds assimilated into the operational UKV are those from radiosondes and commercial aircraft data. Until October 2018, there were seven radar wind profilers (RWP) in the UK providing wind profiles up to 12 km altitude routinely every 15 min. Their horizontal coverage, however, remains low in the high-resolution NWP context as RWP are often separated hundreds of kilometres apart (e.g. Figure 3). Similarly, radiosonde observations are very limited in space and time (e.g. a total six stations launch radiosondes twice a day in UK at 0000 and 1200 UTC). With a short 45 min
observation cut-off time, radiosonde data can arrive too late to be assimilated into the hourly cycling 4D-Var UKV.

Traditionally, aircraft-based wind observations used in the Met Office's NWP come mainly from AMDAR as part of the E-AMDAR programme in Europe and the UK's AMDAR programme. Profiles of horizontal wind, temperature and occasionally humidity measured by aircraft are reported every 1 or 3 hr. Under the UK AMDAR programme, the number of AMDAR reports received by the Met Office is essentially a choice the Met Office makes as to how many reports it buys. The E-AMDAR programme uses a “grid box” structure for a fair distribution of European National Meteorological Services (EUMETNET)-funded observations across the EUMETNET Composite Observing System (EUCOS) area, which extends from 10 to 90° N and from 70° W to 40° E (EUMETNET, 2015), and a single 3 hourly profile is received in each of the 11 grid boxes over the UK. Further hourly profiles at UK airports, funded by the Met Office’s Observation Programme, are additionally received under the UK AMDAR programme. There are about 20,000 AMDAR wind and temperature observations received by the Met Office every 24 hr, but only approximately 2,000 humidity observations. The AMDAR humidity reports over the UK are very few in number as only nine Lufthansa aircraft are equipped with a humidity sensor, and these give mainly profiles over Germany (Hoff, 2008).

AIREPs are another source of aircraft observations. These are pilot reports of cruise level wind and temperature. AIREPs, under the regulations of the International Civil Aviation Organization (ICAO), are released routinely and are typically generated from an automated system to be received by a service provider that forwards this information on the Global Telecommunication System (GTS) to national meteorological services. In the UKV domain, the daily number of AIREP winds received by the Met Office is about 4,000, with observations mostly over the Atlantic at cruise levels.

Mode-S EHS is a further (newer) source of aircraft-based observations. Compared with AMDAR, where measurement and processing are carried out on board the aircraft before sending observations directly to the ground-receiving stations, Mode-S observations come from freely available transponder messages from aircraft to air traffic control and the position of the aircraft as tracked by the tracking and ranging radar. Information such as airspeed, heading, Mach number and ground track is then used by end users to obtain wind and temperature. Essentially, the wind vector is calculated from the difference between the ground and air movement vectors, whilst temperature is derived from the airspeed and the Mach number using the ideal gas law (de Haan, 2011). Large errors in Mode-S temperatures exist due to significant truncation errors of Mach number and true airspeed as a result of limited reporting resolution for these parameters (de Haan, 2011; Mirza et al., 2016).

A pre-processing method was developed at KNMI for the derivation of wind and temperature observations (de Haan, 2011). Specifically, a time-averaging (60 s for level flight and 12 s for ascending/descending) was applied to the reported Mach number and the true airspeed to reduce the effect of their reporting inaccuracy so that smoother temperature profiles were obtained. In calculating wind, an aircraft-type-dependent heading correction (with respect to true north) was made against the runway angle shortly after aircraft landing. Heading correction is necessary as the magnetic rather than true heading is transmitted by aircraft. It was shown that processed Mode-S winds had comparable quality to AMDAR winds, whilst the quality of smoothed Mode-S temperatures improved when compared with unsmoothed equivalents, but was still lower than AMDAR temperatures.

The Met Office collects Mode-S EHS-encoded data messages from several receivers at sites in the UK and derives wind and temperature observations (Stone and Pearce, 2016). Currently Mode-S data come from a network of six receivers, five co-located with weather radar sites (Figure 3) to make use of pre-existing communication bandwidth. These Mode-S sites, mostly in the southern UK where busier airports are located, provide good spatial coverage of aircraft measurements over most of the UK airspace in the free troposphere, though observations are restricted to areas near airports in the boundary layer during aircraft descent/ascent phases (Figure 4). The raw data, collected typically every 5–8 s, are first quality controlled and pre-processed on site before being ingested into the Met Office’s observation database (MetDB). Analysis from November 2019 showed 99.4% of the data arrive in the MetDB within 20 min. Quality control is carried out so that the manoeuvring aircraft and incorrectly identified or partially corrupted messages can be removed during the pre-processing. In the derivation of the wind and temperature from the reported data, a heading correction, using the UKV model background for the wind, is made to the reported aircraft state vector, but no smoothing is applied to the Mach number and airspeed when the temperature is derived (Stone and Pearce, 2016). As described above, de Haan (2011) by comparison used a runway method when calculating heading corrections in derivations of Mode-S wind. de Haan (2013) showed that the NWP-based heading correction is as effective as the runway-based approach (with
the difference $<1^\circ$). Compared with runway correction, more aircraft headings can be corrected in the NWP-based method as it is not restricted to those aircraft landing at airports, though its effectiveness is determined by the accuracy of the underlying NWP model.

The Mode-S observations from Met Office receivers have been routinely monitored against the operational UKV model since July 2014. Typically, there are about 5 million Mode-S observations every 24 hr over the UKV model domain (Figure 4). Observation minus model background (O – B) root mean square (RMS) errors of 2–3 m·s$^{-1}$ for Mode-S winds are similar in magnitude to those for AMDAR, but Mode-S temperature errors are much larger than AMDAR (Mirza et al., 2016; Stone, 2018). This is illustrated in Figure 5, which shows O – B temperature error profiles for Mode-S and AMDAR for a 30 day period. The Mode-S temperature error increases with decreasing height, from 2 K at 500 hPa to 3.5 K at 700 hPa, 5 K at 850 hPa, with a sharp increase to 8.5 K at 1,000 hPa. By comparison, the AMDAR error varies from 0.9 to 1.3 K on these corresponding pressure levels.

2 | ASSIMILATION OF MODE-S WINDS IN AN HOURLY CYCLING 4D-VAR UKV MODEL

2.1 | Experimental set-up

The Met Office aims to improve the accuracy of weather forecasts continually through improvements to the formulation of its NWP model (UM), the improved use of existing and new observations and the data-assimilation techniques. Improvements are implemented into the next operational model suite (OS) through Parallel Suite (PS) trials which use the current OS as the baseline (or control). The OS40 of the UKV model, which was operational from February 6 to September 24, 2018, used UM v.10.8 and hourly cycling 4D-Var assimilation (science version 40).

At the time of the assimilation experiment, science version 40 was used in the operational UKV model and therefore OS40 of the UKV model was used as a control run, which included the assimilation of all existing operational observations at OS40 (Table 1), but not Mode-S, in the 4D-Var. Mode-S EHS winds from the Met Office’s network of six receivers were added to the existing types of observations at OS40 in the assimilation in a separate experiment run. The impact of the Mode-S winds was then assessed by comparing results between the control and Mode-S experiment runs.
At the Met Office, the Observation Processing System (OPS) is used to extract and process observations from the MetDB for use by data assimilation and monitoring. Processing in OPS includes quality control (e.g. removing observations that are blacklisted) and selection of the data (e.g. thinning, removing data duplication) whilst O – B can be used, for example, to monitor the availability and quality of the existing or newly available observations such as Mode-S. Observations are grouped into types/subtypes in the OPS. For “conventional” upper air (i.e. non-satellite) observations, these types are aircraft, radiosonde, wind-profile and doppler radial winds. In the hourly cycling 4D-Var UKV model, in each 1 hr assimilation time window [from $T - 30$ to $T + 30$ min], the subtypes of “conventional” upper air observations assimilated into the control and experiment runs are listed in Table 1. These include aircraft AMDAR and AIREP wind, temperature and humidity; wind from RWPs and velocity–azimuth display (VAD) winds from weather radars; as well as wind, temperature and humidity from radiosondes. A full list of all observations, including surface and satellite data, assimilated at 4D-Var UKV model is given by Ballard et al. (2016).

As in the operational UKV model, all AMDAR and AIREP observations were used in the control and Mode-S experiment runs (i.e. AMDAR and AIREP data were not thinned in space and time). Because of active data management (to limit costs) the AMDAR reports are only available to the Met Office from a subset of flights by AMDAR-equipped aircraft. The AMDAR data the Met

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**TABLE 1** Existing upper air observation usage in the 4D-variational data assimilation (4D-Var) in the control and assimilation experiment runs

| Observation type (and subtype) | Assimilated quantities | Frequency | Thinning |
|-------------------------------|------------------------|-----------|----------|
| Aircraft (AMDAR, AIREP)       | Wind, Temperature, Humidity | Hourly    | None     |
| Radiosonde (SONDE: high spatial-resolution radiosonde; Temp: traditional lower spatial resolution radiosonde) | Wind, Temperature, Humidity | Every 12 or 24 hr | Average for each model layer |
| WINPRO (radar wind profiler, weather radar) | Wind | Every 15 min, VAD in precipitation | None |
| RADIAL (Doppler radar)       | Wind                   | Every 10 min in precipitation | 10 km |

*Note: AIREP: aircraft report; AMDAR: Aircraft Meteorological Data Relay; VAD: velocity–azimuth display.*
Office receives are therefore essentially thinned and no further thinning was carried out in the assimilation. For high-density observations data such as Mode-S, thinning reduces the impact of spatial and temporal error correlations in the assimilation, as the observations are currently assumed to have uncorrelated errors. Reducing the high volumes of the Mode-S data before assimilation also decreases the computational cost associated with the 4D-Var while retaining the improved fit of the background to other existing observation types. Thinning of Mode-S winds was achieved using a simple time–space box method. Specifically, if more than one observation was present in the thinning box, that closest to the centre of the box was retained and used in the subsequent assimilation.

Thinning of the Mode-S winds in an hourly assimilation window \([T - 30, T + 30\text{ min}]\) was carried out horizontally, vertically and temporally on a box of 3, 4.5 or 9 km × 40 hPa × 10 min (Table 2). Horizontal thinning options of 3, 4.5 or 9 km, which corresponds to Mode-S data being assimilated at 1/2, 1/3 or 1/6 the resolution of the UKV forecast model (i.e. 1.5 km), were tested so that model forecast sensitivity could be studied and a preferred thinning option determined.

In Table 2, 40 hPa in the thinning corresponds approximately to the minimum vertical separation distance between aircraft flight levels at low altitudes. A time of 10 min was chosen following an earlier similar OSE study (Li, 2018) that showed the temporal thinning option of 10 min gave a better impact on the NWP forecasts than 15 min. In Li (2018), involving also the assimilation of Mode-S and AMDAR winds, the use of 10 and 15 min thinning yielded an improvement in the UK NWP index over the control (i.e. assimilation of AMDAR data only) by 0.25%.

As the Mode-S data have not previously been assimilated in the UKV, observation errors needed to be defined. It was assumed that observation errors (standard deviation) in Mode-S winds were the same as in AMDAR winds due to the similarity in O – B RMS errors between the Mode-S and AMDAR winds, as in de Haan and Stoffelen (2012). The vertical profiles of the observation errors are shown in Figure 6 for the types of aircraft winds used in the assimilation. It can be seen that the errors in the AMDAR winds are lower than AIREP since the AMDAR measurements are of higher quality than the traditional AIREP measurements.

As in de Haan and Stoffelen (2012), the observation errors were assumed to be uncorrelated for the thinned Mode-S winds. Thinning of Mode-S winds before the assimilation had a desired effect in reducing the correlation of errors (though it did not eliminate them completely).

The experiments, which covered two seasons, were performed for winter 2016 (November 16–December 15, 2016) and summer 2017 (June 21–July 20, 2017), each 30 days in duration. These periods, which covered different types of weather regimes, were chosen to allow for reasonable turnaround from available computing resources for the experiments. The experiments followed the recommended procedure for PS trials which also use summer and winter (but each typically 45–60 days in duration).

For a limited-area model, lateral boundary conditions (LBCs) are required. The LBCs for the UKV model are provided by the Met Office’s global model. The

| OSE  | OSE description                      | Mode-S thinning option               |
|------|--------------------------------------|--------------------------------------|
| Control | Control run with all observations assimilated operationally at OS40 (see Table 1) | 3 km × 40 hPa × 10 min |
| S3   | As per control, plus Mode-S wind data assimilation | 3 km × 40 hPa × 10 min |
| S4.5 | As per control, plus Mode-S wind data assimilation | 4.5 km × 40 hPa × 10 min |
| S9   | As per control, plus Mode-S wind data assimilation | 9 km × 40 hPa × 10 min |

FIGURE 6 Vertical profiles of observation wind errors for aircraft report (AIREP) (green), Aircraft Meteorological Data Relay (AMDar) and Mode-Select (Mode-S) (black) used in the assimilation experiments. AIREP and AMDAR errors were those from the operational UKV model at OS40
operational version of the global model OS40, which had a horizontal grid length of approximately 10 km at mid-latitudes and used a 6 hr cycling hybrid 4D-Var assimilation scheme (Clayton et al., 2013), were rerun for the winter 2016 and summer 2017 experiment periods. All the experiments in Table 2 used the same LBCs, which were time interpolated from the global model forecast output at 60 min intervals, for consistency with the control. There was a time lag in LBCs between the global model forecast and the UKV model run. The LBCs were updated four times a day at UKV cycles 0300, 0900, 1500 and 2100 UTC from the global model run 3 hr earlier at 0000, 0600, 1200 and 1800 UTC. Thus, LBCs had a minimum of 3 hr and maximum 8 hr data time latency at the UKV analysis time.

In the following sections, the assimilated observations refer to those observations that have been quality controlled and thinned (if required) in the OPS. In the case of aircraft, these "assimilated" observations are used directly in the subsequent 4D-Var as they are treated as single-point observations, whilst for radiosonde the 4D-Var uses their profilers that have been averaged over the model layers.

2.2 | Vertical profiles of the numbers of assimilated upper air wind observations

Figure 7 shows the vertical distribution of the cycle mean number of "conventional" upper air (i.e. non-satellite) wind observations, assimilated in the S4.5 experiment, for winter 2016. The observations are binned by pressure altitude between 1,000 and 100 hPa, with a bin width of 100 hPa. It is apparent that Mode-S winds had the largest number of assimilated observations, accounting for 77% of all upper air observations. Compared with AMDAR and AIREP aircraft reports, there were more Mode-S observations in each pressure band from 1,000 to 100 hPa, with the total number being about 45 and 170 times more, respectively.

Figure 7 reveals that the number of Mode-S observations increased steadily with height, but then with a marked peak at 300–200 hPa (which corresponds with the flight cruising altitudes at 10–12 km), before decreasing above. Comparing the number of reports (Figure 7a) with number of aircraft/sites reporting (Figure 7b), it can be seen that for Mode-S winds there was a large increase in the number of reports per aircraft at cruising height level (300–200 hPa). For Mode-S and AMDAR each identifier signifies a different aircraft. However, AIREPs report the "flight number". One aircraft can use many different flight numbers (AIREP identifiers) over time. This explains the much greater number of identifiers reporting for AIREP in the band 300–200 hPa than for Mode-S or AMDAR (Figure 7b). The number of AIREP reports (i.e. observations) was very small (Figure 7a), due to its low temporal frequency of reporting.

At low altitudes (>800 hPa), the largest numbers of assimilated observations were those from WINPRO observation type, which included six boundary layer wind profilers in the UK and VAD winds from weather radars (which provide wind information in...
precipitation only). Mode-S winds were the second largest in terms of the number of assimilated observations at low altitudes. However, even at these low altitudes, there were far more aircraft reporting in Mode-S and AMDAR winds than WINPRO sites (Figure 7b). This is consistent with the spatial distribution shown in Figure 4 where aircraft reporting covers much wider areas when compared with the WINPRO in the boundary layer (1,000–700 hPa) and in the free troposphere (700–300 and 300–100 hPa).

In comparison with winter, summer had about 19% more Mode-S wind observations assimilated due to an increase in the number of flights. On average per cycle, including both winter and summer, thinning of Mode-S winds in the S3, S4.5 and S9 experiments resulted in about 15%, 11% and 7% of the total available observations being used in the assimilation respectively (Table 3).

### 2.3 Hourly variations in assimilated wind observations

As the 4D-Var UKV model is run every hour throughout the day, it is useful to look at the diurnal variation in the number of observations. The cycle mean number of upper air wind observations assimilated per hourly time window for winter 2016 in the S4.5 experiment is plotted in Figure 8.

Compared with fixed site upper air observations (e.g. WINPRO), Figure 8 shows that there are distinct diurnal variations in both Mode-S and AMDAR winds due to the operation hours of airports and the flight frequency when airports are open. The number of observations was relatively steady between around 0700 and 2100 UTC, but then decreased rapidly from 2100 to 0000 UTC. It remained at a minimum until 0300 UTC, before beginning to increase again. Summer showed a similar pattern, but with more observations assimilated than winter (Table 3). Compared with Mode-S and AMDAR where the majority of reports are made near airports, AIREPs report over the North Atlantic, mostly flight routes to North America, at cruise levels (e.g. Figure 7b), resulting in a peak in observation numbers between 1100 and 1500 UTC. On average, per hourly cycle, the numbers of assimilated winds from Mode-S, AMDAR, AIREP, WINPRO, SONDE and Temp (Table 1) are 23,805, 546, 132, 3,569, 2,177 and 34, respectively. By comparison, the numbers of assimilated winds from Mode-S, AMDAR, AIREP, WINPRO, SONDE and Temp per cycle were 30,523, 678, 173, 4,832, 1,634 and 39, respectively, in summer 2017. The ratios between assimilated Mode-S winds and those in AMDAR, AIREP, WINPRO and SONDE + Temp are given in Table 4. Among the existing upper air observations, radiosonde (i.e. SONDE + Temp) had a large variation in the number of observations between winter 2016 and summer 2017, whilst the differences were much smaller in other observation types. There were noticeably fewer sonde observations in summer 2017 than in winter 2016. The biggest reduction in observations in SONDE occurred at 1200 UTC with the average number of observations being 8,815 in summer 2017 as compared with 12,574 in winter 2016 (Figure 8), a reduction of 30%. (At 0000 UTC there was a much smaller 4.6% reduction.) These features are indicated in Table 4 in the ratio between assimilated Mode-S winds and their respective observation types. Compared with AMDAR/AIREP winds, it may seem surprising that the ratios for Mode-S/radiosonde and wind profiler are not higher, given the relatively small number of sites that provide these observations. For wind profiler, the large number of observations was primarily due to the very high vertical and temporal resolutions in the boundary layer (e.g. 1,000–700 hPa) (Figure 7), whilst in the case of radiosonde, the reported data are every 2 s, typically 3,000–4,000 levels per ascent, but with the averaging over-model layers a maximum of 70 levels are used in the 4D-Var.

### TABLE 3 Impact of thinning options employed in the S3, S4.5 and S9 experiments on the average number of assimilated Mode-Select (Mode-S) winds per cycle for winter 2016 and summer 2017

|               | Number of Mode-S winds | Number and % of assimilated Mode-S winds in S3 | Number and % of assimilated Mode-S winds in S4.5 | Number and % of assimilated Mode-S winds in S9 |
|---------------|------------------------|-----------------------------------------------|--------------------------------------------------|-----------------------------------------------|
| Winter 2016   | 216,874                | 31,989 (14.8%)                                | 23,805 (11.0%)                                   | 14,194 (6.5%)                                |
| Summer 2017   | 257,994                | 40,571 (15.7%)                                | 30,523 (11.8%)                                   | 18,427 (7.1%)                                |
| Average       | 237,434                | 36,280 (15.2%)                                | 27,164 (11.4%)                                   | 16,310 (6.8%)                                |
2.4 | Observation minus background (O – B) statistics

Figure 9 shows vertical profiles of O – B statistics for AMDAR and Mode-S wind speeds for the S4.5 experiment for winter 2016. Also shown is the total number of assimilated observations and the number of aircraft reporting (note the different scale used for the number of AMDAR and Mode-S observations). The mean bias was small (<0.5 m·s⁻¹) for both AMDAR
and Mode-S winds from 2 to 10 km altitude. At low levels <1 km, the bias increased with deceasing altitude for both AMDAR and Mode-S winds. AMDAR winds were worse than those for Mode-S with a bias of 1.5 m·s⁻¹ compared with 0.5 m·s⁻¹ close to the ground. Mode-S winds had RMS errors of around 2 m·s⁻¹ up to 8 km altitude, increasing to approximately 3 m·s⁻¹ at 12 km. By comparison, AMDAR winds had similar RMS errors (2.0 m·s⁻¹) from 2 to 8 km, increasing to around 3 m·s⁻¹ at 12 km. Compared with high altitudes, there were relatively more AMDAR reports at lower levels (e.g. approximately 40% at 4 to 10 km) compared with Mode-S (about 6%). This is due to the additional hourly profiles at UK airports that the Met Office acquires under the UK AMDAR programme, though the total number of reports from Mode-S was still greater due to more aircraft reporting together with greater reporting frequencies in Mode-S. Nearly identical results were obtained in O – B statistics for summer 2017.
2.5 Wind forecast verification versus radiosonde

Wind profile forecasts from the control and S3, S4.5 and S9 experiments are verified for winter and summer against radiosonde observations at pressure levels of 1,000, 850, 700, 500, 400, 300, 250, 200, 100 and 70 hPa. Verification was carried out using eight radiosonde stations in the UKV inner 1.5 km-resolution domain (Figure 3 shows their locations) at verifying times of 0000, 0600, 1200 and 1800 UTC (but only one or two stations routinely report at 0600/1800 UTC). Figures 10 and 11 clearly show a significant positive impact at T + 1 hr from assimilating Mode-S winds, with smaller mean differences and RMS errors, in both winter and summer. In winter, at T + 1 hr (Figure 10a, b), the magnitude of the mean difference from the S3, S4.5 and S9 experiments was very similar, with the difference <0.1 m s\(^{-1}\). The reduction in the mean difference compared with the control was most noticeable above 700 hPa, with the biggest reduction from 1.0 to about 0.3 m s\(^{-1}\) at around cruising level 250 hPa where a relatively large number of Mode-S winds are present. Compared with the control, a reduction in RMS error of 0.6 m s\(^{-1}\) from close to 4.5 m s\(^{-1}\) (i.e. 15\%) was seen between 500 and 200 hPa in the Mode-S assimilations. In comparison with winter, Figure 11a, b shows that the reduction in mean error in summer at T + 1 hr was smaller (e.g. about 0.2 m s\(^{-1}\) at 400 and 200 hPa), but similar in magnitude in RMS errors (e.g. about 0.6 m s\(^{-1}\), or 15\% at 300 hPa in S4.5). The significant reduction in error between 500 and 200 hPa is consistent with the assimilation of very large numbers of Mode-S reports at cruising level heights (Figure 7a).

As model forecast errors grow with time, the positive impact diminishes with forecast lead time (but bearing in mind that the largest impact will be advected downstream). Figure 10c,d shows that the impact on winds at T + 6 hr was less pronounced than T + 1 hr compared with the control in the mean and RMS errors in winter, where the errors improved by 0.2 m s\(^{-1}\) at 250 hPa and by 0.3 m s\(^{-1}\) at 400 hPa. In summer (Figure 11c,d) there was a noticeable reduction in the RMS error of 0.3 m s\(^{-1}\) (about 10\%) up to 300 hPa as more winds were assimilated. The impact was slightly more mixed in the mean error, being positive (about 0.2 m s\(^{-1}\)) from 700 to 200 hPa and a very slight degradation (<0.1 m s\(^{-1}\)) from 850 to 700 hPa. As with at T + 1 hr, mean differences and RMS errors were again very similar at T + 6 hr among the different thinning options. At low levels (1,000–850 hPa) all experiments were in a really good agreement in terms of mean differences and RMS errors.

2.6 Impact on the UK NWP index

At the Met Office, a UK NWP index is designed to give a single overall measure of UKV forecast skill on the UK weather elements. The index is a weighted average of the scores based on several weather-related surface fields from model forecasts against observations over the UK. The selected fields are chosen to reflect the importance of the fields to users and customers of the UKV forecasts.

The fields currently used in the index are near-surface visibility (≤200, 1,000 and 4,000 m), 6 hr precipitation accumulation (≥0.5, 1.0 and 4.0 mm over the preceding 6 hr), total cloud amount (≥2.5, 4.5 and 6.5 oktas), cloud-based height given at least 2.5 oktas (≤100, 500 and 1,000 m), near-surface (1.5 m) temperature, and near-surface (10 m) wind speed and direction (vector wind). Verifying observations are those from the SYNOP reports in WMO block 03 UK stations at 0000, 0600, 1200 and 1800 UTC. The UKV “long” runs at 0000, 0600, 1200 and 1800 UTC covering a 36 hr forecasts are used for verification. For each run six forecast lead times are verified, namely T + 6, 12, 18, 24, 30 and 36 hr.

A score is first calculated for each above field (for details including equations, see Met Office, 2010). For continuous variables (temperature and wind), the skill score is obtained in terms of a reduction in variances relative to persistence forecasts, while equitable threat score (ETS) is obtained for the categorical variables (precipitation, total cloud amount, cloud base height and visibility). The ETS is defined as the ratio of the number of observed events that were correctly forecast to the total number of events that were either observed or forecast, after removing the “chance” from the numerator and denominator. The individual scores are then combined in a weighted average to form a single value (index). The weighting factors are chosen to give equal overall weighting to each of the five components in wind, temperature, precipitation, cloud and visibility.

The impact of the Mode-S winds on the UKV forecasts is assessed by the changes in the UK NWP index over the control. Tables 5 and 6 show the weighted ETS and skill score difference in the NWP index components and total weighted score (i.e. NWP index) due to the assimilation of Mode-S winds for winter 2016 and summer 2017 in the S4.5 experiment.

In winter 2016 (Table 5), whilst there was a slight degradation in the 6 hr precipitation accumulations, five remaining components were improved with an overall positive index score of 0.43\%. In summer 2017 (Table 6), the improvement occurred in each of the NWP index components, leading to positive impact of 0.68\% in the NWP index.
FIGURE 10  (a, c) Vertical profile of mean wind speed differences and (b, d) root mean square (RMS) vector wind errors for (a, b) $T + 1$ and (c, d) $T + 6$ hr lead time versus radiosonde for the winter period November 15–16, 2016. The red line is the control run and the other three lines are Mode-Select (Mode-S) wind assimilations with different thinning options: S3 (blue), S4.5 (green) and S9 (purple). Statistics were generated from 120 verification times (30 day × 4 times per day) on eight radiosonde sites.
FIGURE 11  As for Figure 10, but for the summer period June 20–21, 2017
The sensitivity of thinning options on the NWP index in winter 2016 and summer 2017 is shown in Table 7. The assimilation of Mode-S had a positive impact on the NWP index in each of the experiments S3, S4.5 and S9 and in both winter and summer. The largest improvement of +0.55%, averaged from winter and summer, was seen in experiment S4.5 using the thinning option 4.5 km × 40 hPa × 10 min.

It is useful to compare the 0.5% improvement in the UK index in the S4.5 assimilation with the impact from other observing networks in the context of the Met Office’s NWP system. The OSEs carried out recently using the 4D-Var UKV model showed an improvement of 0.48% in the UK index for the AMDAR/AIREP network (G. Dow, personal communication).

2.7 Precipitation forecast impact using fractions skill score (FSS)

Traditionally verification of model forecast performance was carried out on a point-by-point basis (e.g. UK NWP
index). For the high-resolution, convection-resolving UKV model, parameters can also be verified by alternative techniques that take account of the uncertainty in the exact timing and spatial location of the forecast since model predictability at the new resolved scales decreases as convection is partly resolved. The FSS is such a method of verification in which model skill is determined from a comparison of forecasts with observations using fractional coverage over different sized areas (Roberts and Lean, 2008). The FSS is preferred for precipitation verification in high-resolution NWP because it rewards model skill in forecasting, for example, small-scale convective showers, even if their exact location and timing are not accurate. For a given accumulation threshold, the FSS measures how the skill of a precipitation forecast varies with changing sampling size (neighbourhood) of verification grid length and accumulation period. At the Met Office, the high-resolution (1 km) radar rainfall composite, produced every 5 min, is used as the ground truth when evaluating precipitation forecasts using the FSS (Li et al., 2018).

Calculation of the FSS involves several steps. For a verification point, a surrounding verification (sampling) square is first defined. The model precipitation forecast at each grid box in this verification square is converted into a binary field: those exceeding a given accumulation threshold are given a value of 1, or 0 otherwise. Fractions with model forecast exceeding the given accumulation threshold are computed (e.g. 7/9). Fractions from radar observations in the same verification square are also computed in the same manner. The FSS is then calculated in terms of normalized mean square error (MSE) between the model forecasts and the observations in the fractions.

For a given accumulation threshold, the FSS at a sampling square of width \( l \) is given by:

\[
\text{FSS}(l) = 1 - \frac{\text{MSE}(l)}{\text{MSE}_{\text{worst}}} = 1 - \frac{\sum_{j=1}^{N} \left( O_j^l - M_j^l \right)^2}{\sum_{j=1}^{N} \left[ \left( O_j^l \right)^2 + \left( M_j^l \right)^2 \right]},
\]

where \( N \) is the total number of 1.5 km grid boxes in the verification area; \( O_j^l \) and \( M_j^l \) are the observed and model forecast fractions (at each 1.5 km verification grid point \( j \)) exceeding the given accumulation threshold within the sampling square of width \( l \) (as described above); and \( \text{MSE}_{\text{worst}} \) is the largest possible MSE that represents the worst forecast when no overlap occurs between the observed and model forecast fractions.

For a given accumulation threshold, the FSS can therefore be computed for different spatial scales by changing the neighbourhood size surrounding each 1.5 km grid point, \( j \). Starting from the smallest 1.5 km verification grid-length mesh, the neighbourhood size increases progressively with the width of the neighbourhood size being \( l = 1.5(2i - 1) \), \( i = 1, 2, 3, \ldots \), or \( l = 1.5, 4.5, 7.5 \) km, \( \ldots \), and the sampling squares corresponding to \( l \times l \).

In a model forecast, the FSS ranges between 0 (zero skill) and 1 (perfect skill). Typically, the FSS increases with increasing spatial scale \( l \) as progressively larger spatial errors in the model prediction are allowed for.

It is informative to look at verification for different rain accumulation thresholds. These can be specified as either an absolute precipitation amount (e.g. 1 mm in 1 hr) or a percentile of grid points of precipitation. The percentile threshold gives a better idea of model forecast skill in predicting locations of the precipitation if the model has a large bias in the rainfall intensities. The 90th percentile threshold, for example, selects the 10% grid points with the highest accumulation over 1 hr in both the model and observed rainfall, respectively.

To assess the impact of the Mode-S wind assimilation on the FSS, Hinton diagrams (Hinton et al., 1986) are used to visualize values of a two-dimensional (2D) (lead time and threshold) array, \( \Delta \text{FSS} \), in which:

\[
\Delta \text{FSS} = \text{FSS}_{\text{Mode-S}} - \text{FSS}_{\text{Control}}
\]

(i.e. FSS differences between the Mode-S assimilation experiment and the control run). The positive and negative values in \( \Delta \text{FSS} \) are represented by upward-pointing green and downward-pointing red triangles, and the size of each triangle represents the magnitude of each value.

Figure 12 are Hinton diagrams showing the differences in the FSS of 1 hr precipitation accumulation against forecast lead time for winter and summer between the 4.5 km thinning experiment (S4.5) and the control run on a neighbourhood size of five grid boxes. The upwards (green) triangles indicate an improvement in the FSS and downward (red) triangles shows a degradation to the FSS. The size of the triangle is proportional to the magnitude of the difference, and a bold outline indicates statistical significance. Figure 12 shows that Mode-S wind assimilation had an overall positive impact on precipitation forecasts for both absolute and relative rainfall thresholds, with the biggest benefits occurring for the first 9 hr forecast lead time (i.e. from \( T + 1 \) to \( T + 9 \) hr ahead) in winter (Figure 12a) and for the first 12 hr in summer (Figure 12b). For forecast lead times beyond \( T + 12 \) hr, the impact was more mixed with no statistical significance apparent. Similar improvements in the FSS were also seen for the first 9 hr forecast in experiments S3 and S9. It is noted in Figure 12 that high scores were obtained for higher thresholds (e.g. 4 mm and 95th percentile), demonstrating the benefit of assimilating Mode-S winds in significant rainfall events.
3 | SUMMARY AND CONCLUSIONS

High-resolution numerical weather prediction (NWP) models have been introduced and run routinely in many operational centres to improve the forecasts of high-impact weather. The higher model resolution ideally requires observations that sample the model resolved...
scale. Mode-Select Enhanced Surveillance (Mode-S EHS) data provide such a potential source of wind and temperature observations due to their high temporal and spatial resolution. Compared with Aircraft Meteorological Data Relay (AMDAR), the cost of acquiring Mode-S EHS data is significantly lower with the cost ratio per observation estimated to be 1:1000 at the Met Office (E. Stone, personal communication).

Derived Mode-S EHS winds obtained from the Met Office's network have similar quality to the AMDAR. Root mean square (RMS) errors of wind speed from observation minus model background (O – B) statistics are shown to be 2–3 m s\(^{-1}\), whilst the speed bias of Mode-S and AMDAR winds are both very small.

By contrast, the Mode-S EHS temperatures available were of much lower quality in comparison with the AMDAR as a result of limited precision in the reported Mach number and airspeed. Lack of precision causes even greater errors near the surface as the truncation impact of Mach number and airspeed become more significant. The O – B RMS errors in Mode-S temperatures are about 2 K at upper levels (e.g. 500 hPa), roughly twice of those in AMDAR temperatures, and increase to 5–8 K when the surface is approached.

Assimilation experiments including Mode-S wind observations has been performed in the hourly cycling four-dimensional-variational data assimilation (4D-Var) model. The impact of additionally assimilating Mode-S winds, over existing observations on UKV model forecasts were studied for a 30 day summer and 30 day winter. Thinning options for Mode-S winds were tested in the assimilation experiments S3, S4.5 and S9 using a data-selection method based on a spatial and temporal box 10 min × 40 hPa × 3 km, 10 min × 40 hPa × 4.5 km and 10 min × 40 hPa × 9 km.

Compared with existing upper air observations, Mode-S data have a much higher density both spatially and temporally, with the biggest increase occurring at the flight levels. The application of the above thinning options for Mode-S has led to Mode-S winds assimilated in the experiments S3, S4.5 and S9 being 15%, 11% and 7% of the 5.5 million Mode-S observations per day. These thinned Mode-S winds, which are about 60, 45 and 25 times the number of AMDAR reports, have been additionally assimilated in experiments S3, S4.5 and S9.

By assimilating Mode-S winds, the results indicate that there is an encouraging improvement in forecast skill in T + 1 and T + 6 hr wind profiles compared with the baseline control run, when verified against radiosondes. Mean and RMS errors are both reduced, with the biggest reduction around flight cruising levels. Reductions in RMS errors of 15% and 10% have been seen at T + 1 and T + 6 hr forecast lead time, respectively.

Assimilating Mode-S winds has also been beneficial to near-surface forecasts measured by the UK NWP index. Each of the S3, S4.5 and S9 experiments has shown a positive impact on the index in winter 2016 and summer 2017, with the improvement ranging from 0.27% to 0.71%. When verified against radar-based precipitation, the assimilation of Mode-S winds shows a benefit for the hourly precipitation in the first 9 hr in terms of the fractions skill score (FSS).

Among the three thinning options for the Mode-S winds examined, the setting of 4.5 km × 40 hPa × 10 min in experiment S4.5 gave the best overall UK NWP index score, while retaining the benefits of improved forecast skill in the T + 6 hr wind profile and improvement in the FSS for hourly precipitation accumulations in the first 9 hr of the forecast. This preferred thinning option has been subsequently included in the Met Office's PS42 trials, covering the period from November 20, 2018, to March 11, 2019, leading to operational implementation of the Mode-S wind assimilation in the UKV model (OS42) on March 12, 2019.

In the present paper, only the benefit of assimilating Mode-S EHS wind data on the model forecasts have been evaluated. To maximize the benefit from the Mode-S data, further work is needed to optimize the use of the Mode-S temperatures. An improved method for deriving temperatures using the Mach number based on the indicated speed and static pressure instead of reported Mach number has been devised at the Royal Netherlands Meteorological Institute (KNMI) recently. Standard deviations of the derived temperatures from this new method have been shown to reduce to 1 K, close to those in AMDAR (Sondij, 2020).

The Met Office is in the process of extending its network of Mode-S receivers to give more observations over Scotland and the North Sea. Holehead and Hill of Dudwick radar sites in Scotland were fitted with Mode-S receivers in 2020. An additional receiver at radar site Crug-Y-Gorllwyn in Wales was installed into the Mode-S network to improve the coverage to the west of the UK and over Ireland. Making fuller use of Mode-S data including temperatures is likely to lead to further improvements in model forecast accuracy.

**ACKNOWLEDGEMENTS**

The author thanks Dawn Harrison and three anonymous reviewers for their useful comments, which improved the article; and Gareth Dow, whose work on the development of the 4D-Var UKV trialling system allowed the study to be extended for Mode-S wind assimilation.

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How to cite this article: Li Z. Impact of assimilating Mode-S EHS winds in the Met Office’s high-resolution NWP model. Meteorol Appl. 2021; 28:e1989. https://doi.org/10.1002/met.1989