Operational Assimilation of GPS Zenith Total Delay Observations into the Met Office Numerical Weather Prediction Models

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ABSTRACT
Zenith total delay (ZTD) observations derived from ground-based GPS receivers have been assimilated operationally into the Met Office North Atlantic and European (NAE) numerical weather prediction (NWP) model since 2007. Assimilation trials were performed using the Met Office NAE NWP model at both 12- and 24-km resolution to assess the impact of ZTDs on forecasts. ZTDs were found generally to increase relative humidity in the analysis, increasing the humidity bias compared to radiosonde observations, which persisted through the forecasts at some vertical levels. Improvements to cloud forecasts were also identified. Assimilation of ZTDs using both three-dimensional and four-dimensional variational data assimilation (3D-Var/4D-Var) was investigated, and it is found that assimilation at 4D-Var does not deliver any clear benefit over 3D-Var in the periods studied with the NAE model. This paper summarizes the methods used to assimilate ZTDs at the Met Office and presents the results of impact trials performed prior to operational assimilation. Future improvements to the assimilation methods are discussed.

1. Introduction
The EUMETNET GPS Water Vapor Programme (E-GVAP; http://egvap.dmi.dk) is a collaboration between several European national meteorological institutes and the European geodetic community. The purpose of E-GVAP is to provide atmospheric water vapor observations for use in operational meteorology. Several regional networks of global positioning system (GPS) stations are processed by the geodetic members, and some by meteorological institutes, supplying observations of zenith total delay (ZTD) to the meteorological institutes in near–real time. The ZTD is a measure of the delay in receipt of a signal from a GPS satellite directly overhead, caused by the presence of the neutral atmosphere, expressed as excess path length (Bevis et al. 1992). The slant path signal delays from the satellites are mapped to the zenith using a mapping function (Niell 1996). The ZTD can be considered as having two components: the delay due to hydrostatic pressure and the delay due to the amount of water vapor along the ray path (Bengtsson et al. 2003). Generally, slow variations in the ZTD are due to the hydrostatic component, whereas more rapid changes are due to water vapor variations (Poli et al. 2007).

The impact of assimilating ZTD observations in numerical weather prediction (NWP) models has previously been described by authors such as Yan et al. (2009), Boniface et al. (2009), Macpherson et al. (2008), Poli et al. (2007), Faccani et al. (2005), and Vedel and Huang (2004). Using a four-dimensional variational (4D-Var) assimilation system, Poli et al. (2007) found assimilation of ZTD observations into the Méteo-France global Action de Recherche Petite Echelle Grande Echelle (ARPEGE) model (Courtier et al. 1991) to have a positive impact on synoptic-scale circulation over a forecast range of one to four days. In spring and summer, Poli et al. (2007) saw an improvement in the prediction of precipitation patterns in cases where ZTDs were assimilated. Later experiments performed by Boniface et al. (2009) and Yan et al. (2009) using the Méteo-France Applications of Research to Operations at Mesoscale (AROME) regional nonhydrostatic model and the Aire Limitée Adaptation Dynamique Développement International (ALADIN) hydrostatic model made use of the ZTD assimilation scheme described by Poli et al. (2007), but focused on heavy rainfall forecasts in the Mediterranean region. Yan et al. (2009) use the analyses of the ALADIN model to initialize forecasts using the nonhydrostatic Méso-NH model. Both Yan et al. (2009) and Boniface et al. (2009) saw some positive
impact on precipitation forecasts when assimilating ZTDs. Faccani et al. (2005) conducted a smaller-scale assimilation study using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; Grell et al. 1995) with a domain centered on Italy, running with a three-dimensional variational (3D-Var) assimilation system. This study showed improvement of the precipitation forecast during the transition from winter to spring over their case study area in southern Italy. Vedel and Huang (2004) assimilated ZTD observations into the High Resolution Limited Area Model (HIRLAM; http://hirlam.org) using 3D-Var and found no improvement in temperature, wind, and humidity forecasts, some improvement in geopotential height forecasts, and an improvement in the prediction of strong precipitation. Macpherson et al. (2008) saw a mostly positive impact on forecasts of precipitation amounts when assimilating ZTD observations from North America into the Environment Canada regional NWP model.

Higgins (2001) reported on very early progress on assimilation of ZTD at the Met Office, using 3D-Var analyses to initialize forecasts from the now obsolete Mesoscale NWP model. Using observations from 14 GPS sites within the model domain, Higgins (2001) showed results from one assimilation cycle with a precipitation forecast out to 6 h. The study highlighted many areas requiring further research in order to establish how to optimize any potential benefits from assimilating ZTD observations in NWP models. The scope of the study in Higgins (2001) was very limited, and therefore the Met Office has since conducted further trials to enhance their ZTD assimilation capability. To assess any benefit of introducing a new observation type to the assimilation system, it is desirable to assess the impact in more than one season as done in the more recent trials presented here.

After the demonstration study by Higgins (2001), assimilation trials began at the Met Office under the framework of the Targeting Optimal Use of GPS Humidity Measurements in Meteorology (TOUGH; http://web.dmi.dk/pub/tough/) project. The earliest trials used the now obsolete Met Office Mesoscale model. The Mesoscale model was a regional NWP model centered on the United Kingdom with a horizontal grid resolution of approximately 11 km, and 38 vertical layers with a model lid at approximately 42 km. The model employed a 3D-Var assimilation scheme. The results of these trials were presented in TOUGH Deliverable Item D48 (Jupp 2006).

The Met Office operates a global NWP model, together with three local area models: the North Atlantic and European (NAE) model and two UK area models (UK4 and UKV). The models use a latitude–longitude gridpoint model known as the Unified Model (UM) (Davies et al. 2005). In their current operational configuration, these four models have horizontal resolutions approximating to 25, 12, 4, and 1.5 km, respectively. In their operational configurations, each model has 70 vertical levels, which extend to 80-km altitude for the global and NAE and 40-km altitude for both UK models. The global and NAE models employ a 4D-Var assimilation system (e.g., Rawlins et al. 2007) whereas the UK4 and UKV models currently use a 3D-Var assimilation system (e.g., Lorenc et al. 2000). The Met Office began assimilating ZTD observations operationally into its NAE and UK4 NWP models in March 2007. This paper presents results of ZTD assimilation trials with 12- and 24-km versions of the NAE model. A description of the observation operator is given in section 2, the monitoring and selection of the observations in section 3, a description of assimilation experiments performed in section 4, and their results in section 5, with a discussion of the results in section 6 and conclusions in section 7.

2. ZTD observation operator

Variational data assimilation involves the minimization of a cost function, $J(x)$,

$$J(x) = \frac{1}{2}(x - x_b)^T B^{-1}(x - x_b) + \frac{1}{2}[H(x) - y_0]^T R^{-1}[H(x) - y_0],$$

(1)

where $x$ is a vector representing the model state variables, $x_b$ represents the background values obtained from a short-range forecast with error covariance $B$. $y_0$ is a vector of observed values, $H$ is the observation operator, and $R$ represents the combined observation and forward operator error covariances (Lorenc et al. 2000). ZTD can be converted to integrated water vapor (IWV) estimates or similar (e.g., Duan et al. 1996; Emardson and Derks 2000), using additional meteorological information that can be more useful for visualization and nowcasting (e.g., de Haan et al. 2009). Gutman et al. (2004) found improvements to short-range lower troposphere humidity forecasts when assimilating total precipitable water derived from ZTD observations. The preferred practice at the Met Office is to assimilate observations that have undergone the least processing and conversions for which an observation operator may be derived from standard meteorological variables. For example, satellite data are assimilated as radiance measurements rather than retrieved temperature and humidity profiles. Assimilating raw observational data makes the observation
errors less complex and easier to characterize by reducing the errors associated with assumptions made in performing a conventional retrieval. For the reasons stated above, the Met Office has chosen to assimilate ZTDs directly into their NWP models.

The ZTD observation operator calculates the ZTD using model variables from a previous short-range forecast (model background) at each observation location. This is required in both the observations processing system, to provide a comparison for quality control, and in the assimilation scheme. ZTD in meters can be expressed as

\[ ZTD = 10^{-6} \int_{z=0}^{z=\infty} N \, dz, \quad (2) \]

where \( z \) is the height above the surface in meters, and \( N \) is the scaled-up refractivity [see Smith and Weintraub (1953); the refractivity of air is scaled by a factor of 10\(^6\)], which can be expressed as

\[ N = \frac{k_1 p_d}{T} + \frac{k_2 p_v}{T} + \frac{k_3 p_u}{T^2}, \quad (3) \]

where \( p_d \) is partial pressure of dry air, \( p_v \) is partial pressure of water vapor, \( T \) is temperature, and \( k_1, k_2, \) and \( k_3 \) are refractivity constants (Bevis et al. 1994). Smith and Weintraub (1953) empirically derived the constant values, and later, Bevis et al. (1994) and then Rueger (2002) conducted evaluations of the constants reported by Smith and Weintraub (1953) and others, but a consensus on which values are the best to use is not evident within the scientific community. Substituting \( p_d = p - p_v \) into Eq. (3) gives

\[ N = \frac{k_1 p}{T} + \frac{(k_2 - k_1) p_v}{T} + \frac{k_3 p_u}{T^2}, \quad (4) \]

where \( p \) is the total pressure. Smith and Weintraub (1953) combined the second and third terms in Eq. (4) by assuming a limited temperature range within the atmosphere, reducing Eq. (4) to

\[ N = \frac{a p}{T} + \frac{b p_v}{T^2}, \quad (5) \]

where the constant values \( a \) and \( b \) are 77.6 K hPa\(^{-1}\) and 3.73 \times 10^5 K^2 hPa\(^{-1}\), respectively, which have been adopted for use at the Met Office.

In the current operational observation operator, it is assumed that \( N \) is constant between the model levels, which appears reasonable since the model levels are closely spaced near the surface where the water vapor contributes most to the ZTD. As the refractivity decreases exponentially with height, this may cause some systematic underestimation of ZTD. The assumption that \( N \) is constant between model levels is in contrast to the observation operator used to assimilate ZTD at Météo-France, where refractivity is assumed to decay exponentially with height (Poli et al. 2007). The Met Office chose this approach as it simplifies the algorithm, assuming any underestimation could be accounted for through application of a bias correction.

As described by Davies et al. (2005), the Met Office UM uses Charney–Phillips vertical grid staggering for prognostic variables. In the Charney–Phillips grid, potential temperature, humidity variables (water vapor, cloud water, cloud ice, and hydrometeors) and vertical wind velocity are calculated on levels known as \( \theta \) levels, and horizontal wind velocity, Exner pressure, and density are calculated on the primary levels known as \( \rho \) levels. Similar to the observation operator for GPS radio occultation, in the ZTD operator, the Exner pressure on the primary \( (\rho) \) levels is linearly interpolated to the \( \theta \) levels (Rennie 2010), which lie at the midpoint between the primary model levels (illustrated in Fig. 1). Using the interpolated Exner pressure on \( \theta \) levels, pressure \( p \) is calculated on \( \theta \) levels. By assuming that potential temperature \( \theta \) is constant across the model layer, and solving the hydrostatic equation, the layer mean virtual temperature is calculated on \( \theta \) levels, which is combined with the humidity information to find the layer mean temperature \( T \). Equation (3) can be used to calculate \( N_i \) for each \( \theta \) model level \( i \), using

\[ N_{i+1} \]
\[ N_i \]
\[ N_{i-1} \]
\[ N_{i-2} \]

FIG. 1. Schematic of Unified Model levels showing GPS receiver heights (unfilled circles) and illustrating calculation of zenith delays when GPS receiver is (left) above model surface and (right) below model surface. Prognostic model variables of potential temperature \( \theta \), specific humidity \( q \), and Exner pressure \( P \) used in the derivation of model refractivity are shown on their native levels. The thickest black line shows the model surface.
\[ N_i = \frac{ap_{\theta_i}}{T_i} + \frac{bp_{\theta_i}q_{\theta_i}}{T_i^2[1 - (1 - \varepsilon)q_{\theta_i}]} \]  

(6)

where \( q \) is the specific humidity, \( T_i \) is the mean temperature in layer \( i \) centered on the \( i \)th \( \theta \) model level, and \( \varepsilon \) is the ratio of molecular mass of water and dry air. By assuming \( N \) is constant in each model layer, and integrating Eq. (2), the partial zenith delay for each model layer \( i \) bounded by the \( \rho \) model levels at height \( z \) is given by

\[ \Delta ZTD_i = 10^{-6}N_i(z_{\rho_{i+1}} - z_{\rho_i}). \]  

(7)

The ZTD observation operator starts at the highest model level and iterates downward, adding the delay calculated for each layer to the column total. Assuming the top of the model is high enough that the water vapor contribution to the delay is negligible, we can drop the second term in Eq. (6) at the top model level. Assuming hydrostatic equilibrium at the top of the model, Eq. (7) becomes

\[ ZTD_{\text{top}} = 10^{-6} \frac{ap_{\theta_i}}{T_i} \left( \frac{\rho_{\infty} - \rho_{\text{top}}}{\rho_{\infty}} \right). \]  

(8)

where \( \rho_d \) is the density of dry air, \( g \) is the acceleration due to gravity, \( \rho_{\text{top}} \) is the pressure at the model top, and \( \rho_{\infty} \) can be considered to be zero. Applying the ideal gas law for dry air therefore yields

\[ ZTD_{\text{top}} = 10^{-6} \frac{aR_d \rho_{\text{top}}}{g}. \]  

(9)

where \( R_d \) is the gas constant for dry air and \( g \) is the acceleration due to gravity. In the Met Office ZTD observation operator, Eq. (9) is used to calculate the delay above the model top, using the mean acceleration due to gravity at the surface, \( g_0 \) (9.806 65 m s\(^{-2}\)), and the delay is added to the total delay from the other model layers. This is in contrast to the approach of Poli et al. (2007), where the delay above the model top is not calculated but is compensated for by a bias correction. A similar formula is used by Yan et al. (2009) in their 3D-Var ZTD assimilation experiments using the ALADIN model, although they use a more accurate formula to calculate \( g \) at the model top for specific latitudes. A slight underestimation of \( ZTD_{\text{top}} \) will occur in the method we use here. Because of discrepancies between the model orography and the real orography [see section 3b(3)], the GPS station height is unlikely to lie on the model surface. The final iteration in the operator will calculate either a partial layer delay, if the GPS station lies above the model surface, or an extrapolated delay if the GPS station lies below the model surface (Fig. 1).

3. ZTD observations

a. Observation monitoring

The ZTD observation operator described in section 2 can be used to make comparisons between ZTD observations from the near-real-time network and estimates derived from NWP models. Using forecast variables from a previous short-range forecast, referred to as the background, a value of ZTD can be calculated for the model’s atmosphere. The model ZTD values are calculated at the site and time of the received ZTD observations and are routinely used for monitoring the observation quality. Comparisons between model and observed ZTDs have been made at the Met Office since 2002. The comparison of ZTDs assists in determining the quality of observations received from the numerous analysis centers contributing to the near-real-time network; it should be noted that data processing configurations and strategies differ among the analysis centers and therefore both the quality of the observations and timeliness of delivery may differ, even for observations calculated from signals at the same fixed site at a given time.

Observations received from the different analysis centers have varying time resolution, from 5 to 60 min. The time resolution largely depends on the processing strategy used and the available computing resources. The typical range of ZTD at sites across the E-GVAP networks is between 1.6 and 2.6 m. The ZTD range is due mainly to the variation of receiver heights present throughout the networks. At an individual site the range of ZTD values observed might typically have a maximum range of 0.2 m throughout the year. Figure 2 (top) shows a typical time series of ZTD observations for a site in the United Kingdom (Lichfield) over 28 days. The ZTD observations supplied by the Met Office analysis center generally correlates well with the NWP background values and shows how ZTD can change rapidly. Figure 2 (bottom) plots the difference between the ZTD supplied by the analysis center and the NWP background ZTD for the same site and time period. Differences up to 14 mm can be seen, and deviations are seen both as short sharp spikes and lower-frequency fluctuations. The higher-frequency fluctuations may be more indicative of higher-resolution meteorological fluctuations, which cannot be represented by the NWP models because of the constraints on temporal and spatial resolution. Figure 3 shows the good correlation (correlation coefficient 0.984) between the background
ZTD and ZTD observations for the same site as in Fig. 2. Monitoring the bias statistics in this way can assist in determining whether a bias correction needs to be performed (see section 2). The standard deviation and root-mean-square error (RMSE) of the differences, as seen in Fig. 3, can be used as an upper limit for the magnitude of the observation errors, which are required in order to give the observations the correct weighting in the data assimilation system. Statistical monitoring of the observation quality provides the information that is used in preprocessing prior to assimilation.

b. Observation preprocessing

The Met Office uses a “white list” approach in its Observation Processing System (OPS) whereby all available observations are initially rejected, and then observations that are ordinarily deemed to be of sufficient quality are automatically accepted. These observations are then subject to further quality control in order to retain only the best observations for assimilation. The quality control procedures are described in the following four sections.

1) WHITE LIST SELECTION

Routine observation monitoring is used to decide which analysis centers are providing observations of a consistently suitable quality. Analysis centers that regularly show large and probably unphysical isolated spikes in ZTD are not selected. These spikes may arise from faults in the parameters used in the processing by the analysis center and are therefore transient, generally affecting one hour’s worth of observations. Because of the nature of the processing techniques used by the analysis centers, spikes are seen concurrently across many GPS sites. While most analysis centers process GPS sites predominantly from their own national networks, there are many sites that are processed by multiple analysis centers. This enables further comparison of the observation quality (e.g., Pacione et al. 2011). The spikes can be identified as deviations from other analysis centers ZTD observations for a site. Based on the observation monitoring, a subset of analysis centers has been chosen, reflecting the good quality of their observations and geographical coverage and taking into account preprocessing time constraints. The primary indicator of quality of the analysis center from the monitoring is the mean standard deviation of the ZTD difference from the model background, across all of the sites processed, which for those analysis centers chosen is generally less than 5 mm. The poorer quality analysis centers tend to have standard deviations greater than 10 mm. The analysis centers chosen for assimilation are the Helmholtz Centre Potsdam (GFZ German Research Centre for Geosciences, Germany), the Geodetic Observatory Pecny (Czech Republic), Institut Geographique National (France), and the Met Office (United Kingdom).

2) BIAS CORRECTION

In data assimilation systems, observations are assumed to be unbiased (Lorenc 1986), and therefore a correction should be made for any bias arising from measurement or forward model errors. As described in section 3a, the
difference of ZTD observations from the model background ZTD is monitored routinely. Comparisons are made for every GPS site where ZTD observations are received at the Met Office, and for every analysis center. The differences at each site are averaged over a 28-day period to give an idea of any biases. This time period was chosen in order to capture any systematic bias between the model background and ZTD observations, and to minimize the possibility that any bias correction applied is correcting a transient bias due to a particular synoptic situation. While there is high-frequency noise in the ZTD differences, when averaged over 28 days, the biases for the selected analysis centers are relatively stable, and any significant change in bias is generally attributable to changes to the forecast model. Some seasonal variation occurs in the 28-day bias, with the magnitude and tendency depending on individual location.

As a starting point, the Met Office chose to implement a static bias correction, calculated as the mean of 28 days of ZTD differences. These bias corrections are currently updated manually, when major changes are made to the NWP models. Updating of biases is required three times a year on average, which generally captures some of the seasonal bias shifts. During the observation preprocessing, the individual bias corrections are added to the ZTD observations from each site. Observations will be rejected if there is no bias correction value for that site and analysis center combination, ensuring that new sites will only be assimilated once the quality has been assured and a bias correction has been calculated.

3) QUALITY CONTROL

The bias-corrected ZTD observations are subjected to various quality control measures. Because of the limited resolution of the orography used in NWP models, the model surface varies from reality, so it is unlikely that the height of the GPS receiver lies at the model surface. In regions of highly variable topography, there may be large discrepancies between the true surface and the model orography. If the model surface is significantly higher than the receiver height, then large extrapolations of model variables will be required in the observation operator, which may be unrealistic. If the model surface lies significantly below the receiver height, the observation operator will not allow accurate representation of boundary layer gradients of humidity or temperature. Therefore, observations are rejected if the height difference between the model surface and the receiver height is greater than 300 m.

The difference between the model background ZTD and the bias-corrected ZTD observation is checked for large departures, which may arise due to unexpected data quality degradation. Monitoring of the differences for each analysis center revealed a typical annual maximum standard deviation of 11 mm occurring during the summer, for those analysis centers chosen for assimilation. Assuming the differences follow a normal distribution, then a value of greater than 5 times the standard deviation would not be expected in normal circumstances. Therefore, if the difference in the ZTDs is greater than 55 mm, the observation is rejected.

4) TEMPORAL THINNING

Because of the high time resolution of the ZTD observations, temporal thinning for both 3D- and 4D-Var is performed. Observations are only thinned once they have passed all of the previous preprocessing checks described above. The Met Office 4D-Var assimilation system uses observations in a time window of 6 h, centered on the analysis time of the forecast (Rawlins et al. 2007). Therefore observations closest to each whole hour within the time window are selected at each site. In the 3D-Var assimilation system, the observations closest to the analysis time are selected at each site. After temporal thinning has been performed, in the instance of a GPS site having more than one analysis center’s observations selected, one set is eliminated according to a predefined ranking. Currently the order of preference for assimilation is the Geodetic Observatory Pecny (Czech Republic), the Met Office, Institut Geographique National (France), and then the Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences (Germany). The ranking of analysis centers is decided on the ranking of the mean standard deviations of the ZTD difference from the model background across all sites for each analysis center, deduced from the monitoring. The Met Office chose not to implement any spatial thinning of ZTD observations, as the resolution of the models and the distribution of sites used in the assimilation trials in this study (Fig. 4) was
assumed to be sufficient to minimize any spatial error correlation.

4. Assimilation trials

This section will focus on assimilation trials performed using the Met Office NAE model, using both 3D-Var and 4D-Var assimilation schemes. The Met Office NAE model was upgraded from a 3D-Var to 4D-Var assimilation system in March 2006 (Rawlins et al. 2007). The larger domain of the NAE model compared to the mesoscale model enabled a larger area of ZTD observations to be assimilated, enabling the Met Office to better judge the benefits of the observations prior to operational assimilation. The upgrade from 3D- to 4D-Var presented the opportunity to assess the effect of exploiting the high time resolution of the ZTD observations.

Four trials were successfully conducted using the Met Office NAE model, with each trial validated against a control. The trials were conducted for different periods during the year in order to gauge whether ZTD assimilation could be more or less beneficial at different times of the year. A summary of the trials can be seen in Table 1.

<table>
<thead>
<tr>
<th>Control experiment</th>
<th>Trial experiment</th>
<th>Dates</th>
<th>Description</th>
<th>Horizontal resolution (km)</th>
<th>Maximum GPS sites selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoGPS1C</td>
<td>3DGPS1T</td>
<td>8–20 Mar 2005</td>
<td>3D-Var assimilation of ZTD validated against No GPS assimilation</td>
<td>12</td>
<td>330</td>
</tr>
<tr>
<td>NoGPS2C</td>
<td>4DGPS1T</td>
<td>27 Jun–20 Jul 2006</td>
<td>4D-Var assimilation of ZTD validated against No GPS assimilation</td>
<td>12</td>
<td>408</td>
</tr>
<tr>
<td>3DGPS1C</td>
<td>4DGPS2T</td>
<td>23–31 Jul 2006</td>
<td>4D-Var assimilation of ZTD validated against 3D-Var assimilation</td>
<td>24</td>
<td>407</td>
</tr>
<tr>
<td>3DGPS2C</td>
<td>4DGPS3T</td>
<td>18 Oct–10 Nov 2006</td>
<td>4D-Var assimilation of ZTD validated against 3D-Var assimilation</td>
<td>24</td>
<td>390</td>
</tr>
</tbody>
</table>

The forecasts are validated using conventional surface and radiosonde observations. Validation is performed for a reduced area within the NAE model domain, to minimize any effects from the model boundaries. In addition to validation over the model domain, validation is performed for a reduced set of observations, which are classified as the World Meteorological Organization (WMO) Block 03 observations. The WMO Block 03 observations are from sites located in the British Isles and are commonly used by the Met Office for validation as improvement of forecasting over the British Isles is a primary focus for the organization’s research. Standard validation procedures at the Met Office involve computation of the mean error and root-mean-square error for model variables compared to conventional surface and radiosonde observations of temperature and relative humidity. In addition to relative humidity and temperature validation, we look for improvements in the forecasts of precipitation accumulation over six hours, cloud amount, and visibility. To validate forecasts of precipitation, cloud, and visibility against observations, the equitable threat score (ETS) (Rogers et al. 1996) is calculated for three thresholds within each category.

5. Assimilation results

a. March 2005 trial: GPS versus no GPS (3D-Var)

Assimilation of ZTDs during this trial period produces a small overall decrease in the magnitude of the negative
surface temperature forecast bias across the model domain (Fig. 5, left). There is a reduction in the surface temperature mean error at all forecast ranges apart from 6 h and 18 h. The change in the surface temperature RMS error across the model domain is negligible (Fig. 5, right).

There is a noticeable change in the relative humidity mean error when ZTDs are assimilated (Fig. 6). At 1000, 850, 700, and 500 hPa, the relative humidity absolute mean error has generally increased in the 3DGPS1T trials compared to the NoGPS1C trial, resulting from a small increase to relative humidity when ZTDs are assimilated. At 850 hPa, this has brought about a reduction in the relative humidity bias after the analysis time. At 850 hPa a 1.5% average decrease in the RMSE for relative humidity was also found when assimilating ZTDs across the forecast ranges (not shown).

Forecasts of cloud amount over the United Kingdom show some minor improvement in the 3DGPS1T trial compared to the NoGPS1C trial. The ETS for total cloud amount is improved for the 0.6 and 0.8 total cloud amount thresholds for all forecast ranges up to 48 h (Fig. 7). For smaller amounts of cloud (0.3 total cloud amount threshold), assimilation of ZTDs has an overall neutral effect over all the forecast ranges. There was no clear impact on the forecasts of precipitation and visibility when ZTDs were assimilated in this trial (not shown).


Assimilation of ZTDs using 4D-Var in this trial shows a small improvement in the mean error of the surface temperature forecasts (Fig. 8). At analysis time, the mean error is increased when assimilating ZTDs but this produces a better surface temperature forecast out to 48 h. The surface temperature RMSE has not been significantly changed when assimilating ZTDs.

The relative humidity mean error at all levels is generally positively shifted in the 4DGPS1T trial compared to the NoGPS2C trial (Fig. 9). This positive shift persists in the forecast to 48 h at 700 and 500 hPa (Fig. 9c), which reduces the absolute bias from 6 h onward at 700 hPa and from 30 h onward at 500 hPa, but at other levels the shift is reversed at different times in the forecast. At 500 and 1000 hPa the relative humidity RMSE is decreased by approximately 1.0% but the RMSE is increased at 850 hPa by 0.6% (not shown) as an average across the forecast ranges.

There is generally a beneficial increase in the ETS over the United Kingdom for total cloud amount when assimilating ZTDs in this trial period (Fig. 10). For the higher categories of cloud amount (0.6 and 0.8 thresholds) an improvement to ETS is seen at almost every forecast range. At the lower cloud amount threshold (0.3) the ETS is improved for forecast ranges between 12 and 30 h.

c. July 2006 trial: GPS (3D-Var) versus GPS (4D-Var)

Forecasts of cloud amount and visibility in the 4DGPS2T trial show minor improvements in ETS compared to the 3DGPS1C trial at some forecast times, but minor degradation at other forecast times, resulting in a
largely neutral impact on cloud amount and visibility overall (Figs. 11a,b). There is some improvement in forecasts of light precipitation accumulation in the 4DGPS2T trial (Fig. 11c). Examination of the surface temperature and humidity validation for the 3DGPS1C and 4DGPS2T trials shows no notable change induced by assimilation of ZTDs with 4D-Var compared to 3D-Var.

**d. October–November 2006 trial: GPS (3D-Var) versus GPS (4D-Var)**

Overall, the assimilation of ZTDs at 4D-Var compared to 3D-Var in these trials has had a small effect on forecasts. The impacts on surface temperature and humidity forecasts were not consistent, with minor improvement at some forecast ranges offset by minor degradation at other ranges. The effect on cloud forecasts when assimilating ZTDs at 4D-Var compared to 3D-Var was varied (Fig. 12), with improvements at some forecast ranges countered by degradation at other forecast ranges.

**6. Discussion**

The trials presented here have shown that the assimilation of ZTDs into the Met Office NAE model generally results in an increase in the mean relative humidity at analysis time. The increase in relative humidity when assimilating ZTDs compared to trials without ZTDs assimilated generally persists throughout the forecast ranges used in this study. Although these results may appear to suggest that ZTDs introduce a wet bias to the analysis, it is important to consider the observations with which the model relative humidity is compared. During the trial periods, the Vaisala RS80 radiosonde was in use, which has been widely shown to have a dry bias (e.g., Turner et al. 2003). Radiosondes are often used as a validation tool as they are generally considered to be “truth” (Cady-Pereira et al. 2008) but since biases are known to exist in radiosonde humidity sensors, we do not suggest that the increase in relative humidity introduced here by assimilation of ZTDs is necessarily unfavorable. Radiosonde humidity observations are also assimilated into the NAE model, without any bias correction performed.

The radiosonde humidity observations may therefore
consistently make the analysis too dry, making the model backgrounds too dry. Therefore the assimilation of the bias corrected ZTD observations could produce the shift in humidity bias seen in the trials presented here. Thornton et al. (2009) presented evidence for a significant dry bias in the Met Office assimilation system for the stratosphere. Similar problems are seen in the troposphere in the Met Office models. Thornton et al. (2009) suggest that the problems in the humidity analysis are due to unrealistic vertical correlations in the background error covariances. The effective assimilation of humidity observations remains a focus of research at the Met Office. The introduction of the Vaisala RS92 radiosonde during 2006, which is shown by Wang and Zhang (2008) to have less of a dry bias than the Vaisala RS80, could have alleviated some of the dry bias. This could be tested by performing further assimilation impact studies, and verifying results against the RS92 radiosonde.

It may appear paradoxical that the assimilation of new observations, which have been corrected to have zero mean bias relative to the background, can lead to any change in the mean value of the analysis. This occurs because the inclusion of new observations, even when bias corrected, changes the relative weights given by the analysis process to the background and to the other observations. This will tend to change the analysis bias if there are biases either in the other observations or in the assimilating forecast model (Dee 2005).

A complication with the assessment of the biases results from the assumption of constant refractivity between model levels in the observation operator. This assumption will result in the underestimation of the refractivity when calculating the model ZTD. Consequently, the bias correction that is calculated from the model ZTD is more likely to shift the observation toward a ZTD that is too low when it is applied. An assessment of the magnitude of this underestimate is required to determine how this could affect the biases and is a subject for further work.

Despite the shifts in the bias, there are some encouraging reductions in relative humidity RMS error, and improvements in the surface temperature forecasts. The mixed impact on the humidity in the vertical can be attributed to the ZTD representing an integrated total column measurement. ZTDs do not have the ability to distinguish the vertical structure of the humidity, relying on the background error covariances of the assimilation system to distribute the moisture, and so complementary humidity observations are desirable over land. Yan et al. (2009) observed a shift in specific humidity bias when assimilating ZTD observations using 3D-Var in the ALADIN model at 9.5-km horizontal resolution. In this study we look at relative humidity, rather than specific humidity, and so a direct comparison cannot be made, but the similarity suggests that the increase in relative humidity found in this study is a result of addition of moisture.

The increase in relative humidity at some pressure levels that the ZTDs give appears to benefit forecasts of moisture-related variables, for example total cloud amount. In particular, the ETS for cloud forecasts over the United Kingdom show improvement by up to 15% at some forecast times for higher cloud amounts. The Met Office aims to make improvements to its forecasts over the
United Kingdom in particular, so this is a promising result. Forecasts of larger amounts of cloud are particularly improved. Dry biases in the model at some levels may cause problems in the forecast of cloud, and these deficiencies appear to have been improved by the assimilation of ZTD observations in the periods studied. The improvements in forecast cloud may lead indirectly to the improvement of the surface temperature forecasts.

The relative humidity mean error in both the March 2005 and June–July 2006 trial periods tends to decrease after analysis time, apart from at 1000 hPa in the March 2005 case. The decreasing trend may suggest that the model becomes too dry compared to observations after the analysis. Since the ZTDs are generally seen to increase relative humidity during these trials, the increased relative humidity could increase the formation of cloud within the model and therefore prevent the loss of cloud as the forecast progresses. This could explain the improvement in the forecasts of cloud and precipitation seen during these trials.

The 4D-Var assimilation system is able to take advantage of the temporal evolution of ZTD observations. In the trials reported in this study, the impact of assimilating ZTDs with 4D-Var compared to 3D-Var was very slight. Although the changes to the humidity field were very small, using 4D-Var may be useful in rapidly developing weather events and nowcasting. The decision was taken to assimilate ZTDs using 4D-Var, in the expectation that in specific cases the high time resolution of the observations could be of use in improving forecasts. A study of the impact of assimilating ZTD observations in specific high-impact weather cases is in progress. The low impact seen in this study of assimilating ZTDs using 4D-Var versus 3D-Var may also be attributable to the lower horizontal resolution of the model used. As seen in Fig. 2, the ZTD can change very rapidly,
and so the lower-resolution model used may not have been able to represent the finer-scale meteorological features captured by the ZTD observations. In this study, we have not made any account for temporal error correlations, such as discussed by Macpherson et al. (2008), which may have limited the impact we see when assimilating ZTDs in 4D-Var. Further studies of the temporal error correlations may be beneficial.

The results of this study facilitated the decision to assimilate ZTDs operationally in the Met Office NAE model from March 2007. Initially, the ZTDs were assimilated using 3D-Var, and then upgraded to 4D-Var a couple of months later. The decision was also made to assimilate ZTDs into the Met Office UK4 model, which uses 3D-Var. It is recognized that ongoing research is required to improve and maintain the assimilation of ZTDs. The assumption made in the calculation of ZTD in the observation operator, namely that refractivity can be approximated to be constant in a model layer, could be tested for robustness: a future enhancement will be to integrate refractivity exponentially between model layers and assess the impact of such a change. A second enhancement could be to assimilate ZTDs with a tangent linear and adjoint operator for pressure and temperature, in addition to humidity, to make better use of the information represented in the ZTD. The Met Office also plans to assimilate ZTDs into its global NWP model. Assimilation into the global model may require some spatial thinning of the observations over Europe because of the lower horizontal resolution of the global model, and a review of the estimate of the observation error. In addition to assimilating the ZTD observations available through E-GVAP in Europe, it is expected that more near-real-time observations may be available from other regional GPS receiver networks on other continents. Since performing the assimilation trials in this study, the number of sites for which ZTD observations are available has increased to over 1500 in Europe, with new regional networks becoming available and new analysis centers producing observations. With planned increases in resolution of NWP models, further work is required at the Met Office on the assignment of observation errors, and to address any temporal and spatial correlations.

7. Conclusions

Assimilation of ZTD observations into the Met Office NAE model has been shown to give some modest improvements to numerical weather prediction forecasts.
In the trials presented in this study, ZTDs tend to increase relative humidity in the model at the pressure levels that were analyzed. The increase in relative humidity in the model has some benefits in the forecasting of cloud. Compared to assimilation at 3D-Var, assimilation of ZTDs at 4D-Var has had a largely neutral impact on forecasts. The Met Office plans to further develop its capability to assimilate ZTDs and make improvements to the processing of the observations. A more statistical approach to quality control such as that used by Poli et al. (2007) could be beneficial and is a focus for future work.

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