Assimilation of OLCI total column water vapour in the Met Office global numerical weather prediction system

Roger Saunders

Met Office, UK

Correspondence
Roger Saunders, Met Office, UK.
Email: roger@saunders-home.co.uk

Funding information
Met Office

Abstract
The representation of water vapour in numerical weather prediction models is still subject to significant uncertainties, which are partly due to the lack of observations of water vapour in the lower troposphere over land and sea-ice areas. There are now several satellite datasets of total column water vapour available, which make use of the reflected radiances from the surface in the near-infrared spectral region where there are water vapour absorption bands. The ocean and land cover imager (OLCI) on the Sentinel-3A and 3B satellites measures the top of atmosphere radiances in the near infrared, and a total column water vapour product is retrieved and made available in near real time. Comparisons of the total column water vapour from OLCI with NWP model 6-h forecasts, collocated ground-based GNSS measurements and radiosonde profiles have been undertaken to determine the accuracy of the product. Following the monitoring, some experiments were made to assimilate the OLCI total column water vapour over land using the Met Office 4D-Var assimilation system. A 5-month trial assimilating the OLCI data has shown consistently positive impacts on the forecast scores with some changes to the water vapour distribution in the model.

KEYWORDS
data assimilation, numerical weather prediction, satellite observation, specific humidity, total column water vapour

1 INTRODUCTION

The accurate 4D representation of water vapour in numerical weather prediction (NWP) models is crucial to our understanding of the hydrological cycle and its feedbacks and as a greenhouse gas influencing global warming but it is still subject to significant uncertainties (Schröder et al., 2019). The water cycle strongly influences the cloud, rainfall and radiative balance in the atmosphere, which must be accurately represented in NWP models. It also plays an important role in atmospheric chemistry.

Despite its important role, the measurements of water vapour over land areas at low levels in the boundary layer are still very limited. This is despite the availability of more and better observations from hyperspectral
infrared sounders in recent years and the increased coverage of microwave humidity sounders. It is true the upper tropospheric humidity (UTH) in models has improved over the past decade as seen by the model comparisons with several microwave and infrared sounders (Saunders et al., 2021), but the total column water vapour (TCWV) over land and sea-ice areas has to date not been routinely monitored accurately by satellites. The GEWEX water vapour assessment (Schröder et al., 2019) has highlighted the differences between various reanalyses and observational datasets, showing a wide range of trends among the different datasets.

There are a limited number of observations of the water vapour profile over land other than from radiosondes, for which the coverage is sparse in most parts of the globe. Aircraft humidity profiles are only just starting to become available over the United States and Europe in the vicinity of airports. Zenith total delay measurements from ground-based global navigation satellite system (GB-GNSS) stations are another source of TCWV data, but the data currently available to numerical weather prediction (NWP) centres are limited in their coverage outside of Europe and the United States. Although satellite infrared and microwave radiances in water vapour absorption bands can be used to provide information on the UTH in the model inferring the water vapour at lower levels is challenging due to uncertainties in the variable radiative properties of the land surface. The lower peaking water vapour channels on the geostationary imagers centred at 7.35 μm wavelength do provide some information on the mid-level water vapour over land areas. Over the ice-free oceans, satellite measurements of TCWV from the passive microwave imagers (e.g. SSMI (S), AMSR-2, GMI) provide excellent coverage (Fennig et al., 2020; Schröder et al., 2013) with an uncertainty of typically 2 kg/m2 (Schröder et al., 2012) and have been assimilated in NWP models for many years.

The ocean and land colour imager (OLCI) on the polar orbiting satellites Sentinels 3A and 3B is a new source of water vapour information over land areas, which has become available since 2017 and could potentially fill the gap. The Sentinel-3 satellite series is planned to be operational for several decades, and the data are available to NWP centres in near real time using the EUMETCAST service provided by EUMETSAT. There was a precursor instrument to OLCI, the medium resolution imaging spectrometer (MERIS) (Rast et al., 1999) on ENVISAT but the satellite failed in April 2012. An ESA project GlobVapour (Schneider et al., 2013) made use of the MERIS data to demonstrate a useful accuracy of the TCWV measurements when comparing monthly means with other TCWV datasets and climate models. The moderate resolution imaging spectroradiometer (MODIS) has similar channels to OLCI, and a TCWV product has also been derived with errors between 5% and 10% (Gao & Kaufman, 2003), but to the author’s knowledge, it has not been used for NWP assimilation experiments.

The aim of this study is to first assess the differences between the TCWV measured by OLCI and the Met Office global Unified Model 6-h forecasts of TCWV over different regions in winter and summer seasons. Comparisons between the OLCI measurements and other independent observations (i.e. GB-GNSS TCWV and radiosondes) are also made. Having assessed the characteristics of the OLCI data, some experiments are performed assimilating the TCWV values in the Met Office hybrid 4D-Var assimilation system (Rawlins et al., 2007) along with all the other observations assimilated operationally to assess the impact the data have on the model water vapour analyses and weather forecasts. It is believed that this is the first attempt of assimilating the OLCI TCWV in a global NWP model and reporting its impact.

Section 2 gives a description of the observational datasets of water vapour used in this analysis. Section 3 presents some of the passive monitoring results of the OLCI water vapour product. Section 4 describes the results of the assimilation experiments carried out, and Section 5 summarizes the results and suggests future prospects.

## 2 Satellite and Surface-Based Observations of Water Vapour Over Land

The water vapour observations used in this study are described briefly in this section. The satellite data are from the European Copernicus Sentinel-3 satellites, which all have an equator crossing time of around 10:30Z, with the 3A and 3B platforms being 180 degrees apart in the orbit to maximize the coverage. OLCI is an instrument on the Sentinel-3 satellites and is a visible and near-infrared radiometer primarily for measuring ocean colour and land surface vegetation. However, it can also measure the TCWV in cloud-free areas during daylight hours, using reflected solar radiation in water vapour absorption bands in the near infrared. It has 21 channels that span the ultra-violet through visible to near-infrared wavelengths with a spatial resolution at the surface of 300 m. The channels used for the water vapour measurements are at 885 and 900 nm utilizing the absorption band centred at 940 nm to retrieve a total column using the different water vapour transmittances in each channel. The retrieval of the OLCI TCWV is described in the OLCI Land Products ATBD (Fischer et al., 2010; Preusker et al., 2015) and is based on an optimal estimation approach (Lindstrot et al., 2012) using ECMWF forecast surface temperatures and pressures. For a typical atmosphere, the radiances from this band
are sensitive to water vapour from the surface up to 400 hPa, from which a TCWV product can be inferred. Although the retrievals are optimized for clear skies over land, values are also provided over ocean, but no use was made of them in this study as their uncertainties are larger due to the dark background. At the Met Office, the OLCI data are received in near real time from the EUMETCAST system and stored locally in BUFR format prior to extraction for monitoring and/or assimilation. The TCWV product used for this study was the original retrieval described in Fischer et al. (2010) and Preusker et al. (2015), available on EUMETCAST in 2019–2020. Other products also retrieved from the OLCI radiances with TCWV are mean sea level pressure, cloud optical thickness and cloud top pressure, but these are not assessed here. An example of the coverage of the product for 1 day is shown in Figure 1 for Sentinels 3A and 3B, which is almost global with just narrow strips over tropical latitudes not covered. The quoted uncertainty value for the TCWV values from OLCI is in the range of 1–3 kg/m² (Diedrich et al., 2012).

To assess the OLCI TCWV measurements, the regional networks of ground-based GNSS stations were used. The observations can be made frequently, and so good matchups with the satellite data are possible. The GB-GNSS stations measure the zenith total delay of the signal from the satellites, and this can be used to infer a TCWV, which is one of the factors that cause a delay in the signal (Bengtsson et al., 2003; Bennitt & Jupp, 2012). The European E-GVAP network (Guerova et al., 2016) gives good real-time coverage over Europe, and the Suominet¹ (Ware et al., 2000) provides good coverage over the continental United States. The coverage of real-time data for NWP centres is very sparse over the rest of the globe, although efforts are underway to expand the network. The zenith total delay observations have been assimilated in global NWP models for many years (Bennitt & Jupp, 2012). The matchup criteria between the OLCI measurement and the GNSS station were 10 km in distance and 60 min in time in order to obtain sufficient matchups.

The European radiosonde network provides another estimate of TCWV through the water vapour profile measurements. This is a rather sparse network and only has measurements around 0Z and 12Z, which makes matchups with the OLCI data difficult. Given the OLCI overpass times, the only matchups that were remotely close were within 3 h and 10 km and only over Europe. In addition, there were a significant number of radiosondes rejected because of incomplete profiles from the surface to 400 hPa. For the profiles that were accepted, the layer mean water vapour concentrations from the radiosonde temperatures and dew points were computed from the surface to the top of the profile or 100 hPa, if that is reached, and then the TCWV was obtained by integrating the profile values.

3 | MONITORING

3.1 | Comparisons with Met Office NWP model forecasts

The OLCI TCWV values are compared with the Met Office background 6-h forecasts of TCWV. The model background TCWV (kg/m²) is computed by integrating the mean specific humidity fields at each model level from the surface to the top of the atmosphere:

$$TCWV_{\text{model}} = \frac{1}{g} \int_{\text{Surf}}^{P=0} q(P) \, dP$$  \hspace{1cm} (1)

where $g$ is the value of the Earth’s standard gravity (m/s²) and $q(P)$ is the layer mean specific humidity (kg/kg) defined by the model pressure levels $P$ (Pa). This observation operator defined in Equation (1) is also used for the TCWV assimilation experiments described in Section 4.

The comparisons were made for a summer JJA (2020) and winter DJF (2020) period when data from both Sentinel-3A and 3B are available, ensuring almost complete global coverage in 1 day. Only the observations over the land surface during daylight are included in the monitoring. The model background values at the four grid points that surround the observation point are selected (with a bi-linear interpolation) to compare with the OLCI observations. For temporal colocation, the hourly background model fields before and after the observation are used, with linear interpolation to the observation time. Both time series and histograms of the observation minus background values, hereafter O-B, are generated, and the mean and SD of the O-B values over several different

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¹https://www.suominet.ucar.edu/data/
regions listed in Table 1 are computed. Table 2 lists the TCWV means and O-B means and SDs for each region for a winter (DJF) and summer (JJA) period in 2020.

Figure 2 shows the annual time series for 2020 for Europe, South-east (SE) Asia, United States, and the Arctic regions as defined in Table 1. All regions, except SE Asia, have a definite annual cycle in the TCWV values increasing from 9 kg/m² in winter to around 23 kg/m² in mid-summer. There is a smaller increase over SE Asia from approximately 32–42 kg/m². The mean O-B values are all close to zero (<0.5 kg/m²) for all regions in the Northern Hemisphere (NH) winter, although variable over SE Asia. In the NH summer, the mean O-B values become more positive following the annual cycle in the absolute TCWV amounts to approximately 1.5 kg/m² in all regions except the poles. This implies the model fields are too dry or the observations too wet in the summer months. The SD of the O-B values for the extratropical regions also increases in the summer from approximately 2–3 kg/m² in the winter to 4 kg/m² in the summer, reflecting the larger TCWV values that are present. The SDs over the tropical areas only increase by 10% during the summer months but are typically over twice the values seen at mid-latitudes.

Another way to look at the O-B values is to look at histograms as shown in Figure 3 for the different regions for January and July 2020, which show the peak (mode) and spread of the distribution. The peaks of the histograms are all just the negative side of zero in contrast to the positive values for the means in Table 2. The biases are much smaller than the SDs, which is an important factor for assimilation of these data. The much larger spread in the tropical regions compared with Europe and the United States is clear, which is related to the higher TCWV amounts. The other thing to note is that the distributions are skewed so that there are more positive O-B values seen in Figure 3. This suggests the model is underestimating the TCWV in the tropics more than overestimating it, and the same is true for mid-latitudes in the summer months or the OLCI observations are skewed.

| Area         | Lower latitude | Upper latitude | Westerly longitude | Easterly longitude |
|--------------|----------------|----------------|-------------------|-------------------|
| Global       | 80 S           | 80 N           | 180 W             | 180 E             |
| Europe       | 35 N           | 60 N           | 10 W              | 40 E              |
| SE Asia      | 18 S           | 30 N           | 90 E              | 154 E             |
| Tropics      | 20 S           | 20 N           | 180 W             | 180 E             |
| Arctic       | 55 N           | 85 N           | 180 W             | 180 E             |
| United States| 10 N           | 48 N           | 132 W             | 100 W             |

### 3.2 Comparisons with ground-based GNSS total zenith delay observations

The best independent validation of the OLCI TCWV observations is to compare with the collocated GB-GNSS zenith total delay measurements, which can be converted to TCWV. The Suominet array of measured TCWV over the United States is used here as it covered a wider range of TCWV values for each season. It was also more consistent with the NWP model having less anomalous values than seen in the European E-GVAP data. All datasets were collected in near real time from the data providers. A map of the location of the Suominet sites is plotted in Figure 4, and the comparisons of the TCWV values for winter 2019/20 and summer 2020 are plotted in Figure 5a,b. The summer has a much wider range of values to compare and higher correlation of 0.95 with a bias of +1.8 kg/m² and an SD of 4.1 kg/m² but the winter data show similar biases and spread over a more limited range of TCWV values. When compared with the NWP model at the same locations (Figure 5c), a similar correlation of 0.95 is seen but a smaller bias of +1.2 kg/m² though a similar spread. The NWP model will be influenced by the GB-GNSS observations that are assimilated but will also take into account radiosonde humidity profiles. Similar comparisons were made over the European area and SE Asia, though with much less GB-GNSS matchups for the latter, with similar bias and correlation statistics.

In order to reduce the bias of the OLCI measurements shown by comparing with the GB-GNSS data, a simple bias correction factor of 0.93, which is multiplied by the observed TCWV value, was determined by a best fit analysis for all seasons and the plot of the bias-corrected data is shown in Figure 6d. Note this only applies to the OLCI TCWV product on EUMETCAST in 2019–2020. A newer version of the TCWV product with lower biases is being developed, referred to as ‘COWa’ (Preusker et al., 2021), to replace the current TCWV product on EUMETCAST.

### 3.3 Comparisons with radiosonde profiles

The European radiosonde network was used to monitor the OLCI TCWV observations during the summer of 2020. As the time differences are significant (up to 3 h), the differences have to be treated with caution, but it was thought at least worth analysing the differences qualitatively. Figure 6a shows a map of the sites where profiles were used in the seasonal statistics, and Figure 6b shows the comparison between OLCI TCWV observations and integrated radiosonde profiles of water vapour. There is a bias of +2.63 kg/m² and SD of 5.47 kg/m² between both sets of measurements with a correlation of 0.79. This at least gives some independent support...
to the GB-GNSS comparisons reported in Section 3.2, although the large time differences in the colocations will inevitably lead to a larger spread.

### 4 | ASSIMILATION EXPERIMENTS

#### 4.1 | Experimental set-up

Based on the comparisons of the OLCI TCWV observations with independent observations described in Section 3, it was decided to embark on assimilation trials of the TCWV product from OLCI on Sentinel-3A and 3B using the OS43 operational configuration of the Met Office global NWP suite run at N320 (40 km) resolution. It used hybrid 4D-Var to produce atmospheric analyses at 0, 6, 12 and 18 UTC. Details of the data assimilation set-up can be found in Rawlins et al. (2007) and Clayton et al. (2013). The hybrid aspect of the scheme is the use of an ensemble of short-range forecasts to estimate the flow-dependent part of the background error covariance (B) matrix. Twice daily at 0 and 12 UTC, the analyses are used to initialize forecasts out to 6 days. A comprehensive set of satellite and conventional observations are assimilated (Saunders, 2021), which included the GB-GNSS zenith total delay measurements and lower peaking water vapour channel radiances from the geostationary imagers that directly influence the water vapour fields over land.

The observation operator used for TCWV is given in Equation (1) together with its adjoint. The OLCI observations were only assimilated over land and thinned to a spacing of 120 km to avoid horizontal error correlations. The observation errors were initially assumed to be 1.5 kg/m² in the extra-tropics and 2.5 kg/m² in the tropics based on the monitoring and values recommended by the data producers (Lindstrot et al., 2012). The methodology outlined by Desroziers et al. (2005) was also used to determine the observations errors and horizontal error correlations by examining the statistics of observation minus analysis and innovations (analysis minus background). The horizontal error correlations were confirmed to be approximately 100 km by this technique, but the observation errors were estimated to be somewhat higher (2 kg/m² in the extra-tropics and 3.3 kg/m² in the extra-tropics and 2.5 kg/m² in the tropics).
tropics) than originally assumed. Experiments were run with both sets of observation errors over several months and the forecast impacts were assessed, and it was clear the lower observation errors initially used were giving the best impacts on the forecasts, so they were used for the subsequent trials. It is suspected the reason for the overestimate in observation errors by the Desroziers method is due to the background errors in humidity being suboptimal. Although a bias correction was derived as described in Section 3.2, it was not applied in the assimilation experiments as it was small relative to the observation error and a new product (Preusker et al., 2021) with lower biases is planned for implementation.

4.2 Impact on analyses

A trial using the OS43 configuration was run from 7 February to 31 July 2020 to assess the impact of assimilating the TCWV product measured by OLCI in both winter and summer periods. All other observations were assimilated as in the operational system. Figure 7 shows the mean differences between the experiment and control as maps for relative humidity at 850 hPa for February/March and June/July. This pressure level was chosen as it should encompass the boundary layer water vapour concentration in the tropics, an important factor for driving convection in the model.
FIGURE 5  Comparison between OLCI and ground-based GNSS TCWV for winter (a) and summer (b) over the United States. A comparison with the Met Office NWP model is shown in (c) for the summer. A simple bias correction factor of 0.93 is applied to the OLCI values in (d).

FIGURE 6  Radiosonde stations collocated with OLCI measurements (left panel) and comparison of OLCI TCWV measurements with integrated radiosonde humidity profiles for JJA 2020
There were no big changes over Europe and North America, where the GB-GNSS ZTD observations have already constrained the humidity analyses. Much bigger changes are seen over Africa, Australia and South America in both summer and winter months. These changes persist into the short-range 24-h forecast (not shown). Over tropical Africa, the OLCI data dry the boundary layer in the winter months but moisten it in the summer. Both Australia and South America are moistened in the boundary layer for both winter and summer seasons. The boundary layer over China is also moistened in the summer months.

Figure 8 shows the equivalent zonal plots, which show there is an overall moistening below 600 hPa at all latitudes in the North Hemisphere summer but only small changes in the North Hemisphere in February/March. The differences reduce into the forecast period. There is an increase in relative humidity close to the North Pole for both seasons, although this represents only small increases in specific humidity there. The spurious drying at 100 hPa over the tropics is probably caused by the background error covariances and again will only be small decreases in specific humidity at these levels.

A comparison of the GB-GNSS TCWV observational network over SE Asia, Europe and the United States with the NWP model background (6 h forecast) for the control and for the experiment where the OLCI data were
assimilated was made and is shown in Figure 9 for SE Asia. For Europe and the United States, the bias between the GB-GNSS TCWV and the model increases from 0.8 to 1.5 kg/m² when the OLCI observations are assimilated and the correlations are unchanged. This is likely caused by the moist bias seen in the OLCI data compared with the GB-GNSS measurements (Section 3.2). In contrast, for SE Asia, the GB-GNSS TCWV shows a reduced bias with the model from 1.1 to 0.5 kg/m² and a closer correlation to the model analyses for the experiment, which is encouraging as this is an independent assessment of the impact the OLCI data are having on the model tropical moisture fields. The tropical band is where the OLCI data are having the most impact, as seen in Figures 7 and 8.

The fit of all the observations assimilated to the new analysis fields (O-A) after assimilation of the OLCI TCWV observations was compared with the analysis fields of the control, and the SDs of O-A are shown in Figure 10. The values are averaged over the globe and the entire experiment period from 20 February to 31 July 2020. For the in situ observations, there is a significant improvement in the fit of the radiosonde temperatures

**FIGURE 8** Zonal mean plots of the changes in the analysis of relative humidity between the experiment assimilating OLCI TCWV and the control. The top panel is for February/March 2020 and the bottom panel is for June/July 2020.
FIGURE 9  Plots of TCWV from the GB-GNSS network over SE Asia compared with the NWP model background (from a 6 h forecast) for May–July 2020. The left panel is for the control where OLCI TCWV is not assimilated and the right panel is for the experiment where the OLCI TCWV is assimilated.

FIGURE 10  The difference from 100% of the ratio of the SD of the observations-analysis (O-A) of the experiment where TCWV is assimilated and O-A for the control for in situ observations (upper panel) and satellite observations assimilated (lower panel). Negative values indicate a closer fit of the observations to the analysis.
and meridional winds when the OLCI TCWV data are assimilated. For the satellite observations, the main difference is, for those instruments that have spectral channels sensitive to low-level water vapour, the fit to these channels is degraded. This applies to the geostationary imagers (Meteosat, GOES and Himawari) and polar orbiter microwave and hyperspectral infrared sounders (IASI, CrIS, ATMS, Saphir). The explanation for this is that with the addition of a new source of low-level humidity information, the analysis has to fit both the radiance data and the new TCWV data, which cause the fit to the radiances to be less than for the control. The Met Office radiance bias correction using VarBC (Eyre, 2016) intentionally does not include any predictors based on water vapour due to the known model biases, and so changes to the model water vapour will not necessarily modify the radiances to reduce any biases. The fit to the temperature sounding channels was unaffected by the assimilation of OLCI TCWV. The ground-based GNSS zenith total delay observations also have a degraded fit to the analyses due to the addition of the OLCI TCWV observations in the extra-tropics.

4.3 Impact on forecasts

The changes made in the analyses to the boundary layer humidity by the OLCI TCWV assimilation gradually reduce into the forecast, and by T + 48, they are essentially the same as the control (not shown). The changes at 250 hPa appear to last longer into the forecast, and this is consistent with the unified model forecasts in general where the forecasts depart from the verifying analyses at this level.

Figure 11 gives a summary of the mean forecast scores averaged over the entire experiment period from 20 February to 31 July 2020. The forecasts are verified both by observations, though these are sparse in the tropics and South Hemisphere and ECMWF analyses, which
give good global coverage. Encouragingly the forecast improvements are broadly consistent between both proxies for measures of truth. At longer forecast ranges (beyond T + 24), the verification against the own analyses (not shown) are also consistent with the other verifications, but at short range, the changes in the analyses make verification with own analyses hard to interpret.

It should be borne in mind that large changes in forecast impacts using the traditional forecast verification metrics are not generally seen when changes in the model moisture fields are made as forecasts of water vapour fields are not a standard metric in the assessment of forecast skill at the Met Office. The impacts seen are in the changes to the temperature and wind fields, and overall, the changes are small. Despite this, the impact of the OLCI TCWV observations was consistently positive using the standard forecast metrics. The largest positive impacts on the forecasts are for the 250 hPa geopotential in the North Hemisphere and South Hemisphere and the tropical 250 hPa temperature throughout the forecast range. The largest consistent negative impact is on the tropical 500 hPa temperature, and the reason for this is unclear.

In addition to the experiment described above, two more trials were run for December 2019 to February 2020 and March to June 2020 with a newer version of the Unified Model as part of the assessment for operational implementation of OLCI TCWV assimilation. The winter trial gave a neutral forecast impact overall, but the spring trial gave similar impacts to those shown in Figure 11. This suggests that over the North Hemisphere land areas in winter, the impact of the OLCI TCWV is small but becomes significant in the summer months when the TCWV amounts are higher. The negative tropical 500 hPa temperature scores were much smaller for both these latter experiments.

5 | CONCLUSIONS

The lack of observations of low-level water vapour concentration over most land areas has prompted an investigation into the use of new satellite measurements of total column water vapour (TCWV) to improve analyses of water vapour for numerical weather prediction (NWP). The ocean and land cover imager (OLCI) instruments on Sentinels 3A and 3B measure near-infrared reflected radiances, which allows a retrieval of TCWV to be made using a water vapour absorption band at 940 nm wavelength. There is only one overpass a day as the retrieval is only possible in daylight hours. An assessment was made of the quality of the OLCI data over land areas by comparing with NWP fields, ground-based global navigation satellite system (GB-GNSS) TCWV measurements and radiosonde profiles over Europe. It was noted that there was a small positive bias in the current OLCI data at higher TCWV values, which could be corrected. However, EUMETSAT plans to correct this with an improved version of the product in 2022 with much smaller biases, and so no bias correction was implemented.

Overall, given the quality and coverage of the OLCI TCWV observations, it was judged they were worth investigating for assimilation and assessing their impact in the Met Office global NWP model. Several experiments have been run assimilating the OLCI TCWV values at a spatial sampling of 120 km and increasing the observation error from 1.5 to 2.5 kg/m² in the tropics. Over South-east (SE) Asia, the GB-GNSS values were more closely correlated to the model analyses when the OLCI data were used, indicating the water vapour fields were improved. There were no big changes over Europe and North America where the GB-GNSS ZTD observations have already constrained the humidity analyses. Over SE Asia, the GB-GNSS observations show a reduced bias of the TCWV in the model from 1.1 to 0.5 kg/m² and a closer correlation to the model analyses, which is encouraging as this is an independent assessment of the impact the OLCI data are having on the model tropical moisture fields. Based on the results presented here and other pre-operational experiments, it was decided to make the assimilation of OLCI TCWV operational in the Met Office global model data assimilation set-up planned for 2022.

In the future, as the spatial resolution of the TCWV product is typically a few kilometres, the OLCI measurements could also be used in high-resolution convection resolving NWP models with a different thinning strategy. The new generation of geostationary imagers have similar spectral channels to OLCI and allow retrievals of TCWV every 10 min in clear areas during daylight hours if required, and this would make it a valuable source of data for both high-resolution and global NWP models. In the longer term, direct assimilation of the near-infrared radiances would be a more optimal way to exploit the water vapour information, but there are significant challenges in describing the surface reflectance correctly for the forward model to enable this.

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AUTHOR CONTRIBUTIONS
Roger Saunders: Formal analysis; methodology; software; validation; visualization; writing – original draft.

ORCID
Roger Saunders https://orcid.org/0000-0002-4128-0366

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