Impact of the latest reanalysis model from ECMWF (ERA5) in the computation of radar altimeter wet path delays

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Abstract: Accurate measurements of sea surface heights derived from satellite altimetry depend on the accuracy of all terms involved in their computation, namely the Wet Tropospheric Correction (WTC). The WTC is best determined from on-board Microwave Radiometers (MWR) measurements, however these become invalid close to land surfaces and some satellites do not possess an on-board MWR (e.g. CryoSat-2). Alternative WTC sources are Numerical Weather Models (NWM), e.g. from European Centre for Medium-Range Weather Forecasts (ECMWF).

NWM commonly provide parameters to estimate the WTC at 6-hour intervals, however the latest reanalysis model from ECMWF, ERA5, provides hourly atmospheric parameters at 0.3°x0.3° spatial sampling. The best spatial resolution is provided by the ECMWF Operational model at 0.125°x0.125°.

The focus of this study is the global assessment of the impact of using different temporal and spatial resolutions of ERA5 and ECMWF operational models in the computation of WTC (or its symmetric value, the Wet Path Delay, WPD). Aiming to identify the best compromise between spatial/temporal resolutions and computation time, WPD computed using various combinations of these resolutions were inter-compared and compared with WPD derived from MWR. This provides a quantification of the WPD errors and their spatial distribution.

This analysis provides relevant information to derive accurate WPD from NWM, important to obtain accurate absolute water levels, when MWR measurements do not exist, as over inland waters.

1. Introduction

Satellite radar altimetry is a remote sensing technique, whose principal objective is to measure the range from the satellite to the water surface, which can then be converted into the height of the water surface relative to the reference ellipsoid (Chelton *et al.*, 2001). This allows the determination of the water level and its monitoring, at regional and global scales. This measurement involves the determination of several parameters, namely the effect of the troposphere in the altimetric signals. Due to the presence of water vapour and liquid water in the atmosphere, when the signal travels from the satellite to the Earth's surface it suffers a delay, the Wet Path Delay (WPD). The corresponding correction that needs to be accounted for in the altimeter observations is its symmetric value, the Wet Tropospheric Correction (WTC). Otherwise, any water surface height measurement derived from satellite altimetry would be affected by this undesirable error.

With a value up to 50 cm, WPD is highly variable, both in space and time. Over the open-ocean, the best and most accurate way to measure this effect is from Microwave Radiometer (MWR) measurements, a passive instrument on board the altimetric missions. However, MWR-derived WPD measurements become invalid over some regions (e.g. coastal, inland water and polar zones) and, on the other hand, some satellites (e.g. CryoSat-2) do not possess an on-board MWR. For these reasons, alternative sources for the wet correction are required, such as those computed using Numerical Weather Models (NWM) parameters. Although the overall accuracy of the WPD from NWM is worse than the corresponding values from MWR, in the absence of any other data source, the WPD from NWM must be used (Fernandes *et al.*, 2014). WPD may be computed from global grids of single-level atmospheric parameters, at the corresponding NWM orography height, as described in Section 2, or from 3D model fields, the latter approach being much more computationally intensive.

Concerning the available NWM for the WPD computation, the quality of the models has been increasing (Miller *et al.*, 2010), particularly for the reanalysis model from European Centre for Medium-Range Weather Forecasts (ECMWF), ERA Interim (Dee *et al.*, 2011). The latest reanalysis model produced by ECMWF, ERA5, is the fifth major global reanalysis, after ERA Interim. At present, only a first batch covering the period 2010 to 2016 was released. Compared to ERA Interim, ERA5 has a much higher spatial (0.3ºx0.3º) and temporal (1-h) resolutions and an improved troposphere modelling, being the first ECMWF atmospheric model at 1-hour intervals. Another ECMWF product of interest is the operational model, which has the finest spatial sampling (0.125ºx0.125º).

Motivated by the high temporal resolution of ERA5, the focus of this study is the assessment of the impact of having atmospheric parameters at 1-hour intervals in the WPD computation for application in satellite altimetry. For this, WPD computed from ERA5 at different temporal resolutions are inter-compared in Section 3. Similar comparisons are performed concerning different spatial resolutions, also presented in the same section.

All analyses mentioned above are inter-comparisons that allow the assessment of using different spatial and temporal resolutions of the same atmospheric model. To perform an independent assessment of the WPD derived from ERA5 at different resolutions, Section 4 presents the comparison between ERA5-derived WPD and those retrieved from on-board MWR measurements. This independent comparison is performed for MWR on board Jason-2 and EnviSat satellites. Finally, Section 5 summarizes the main achievements of this research.

2. WPD computation from NWM single-level parameters

In the analysis performed in this study, two ECMWF atmospheric models have been used: ERA5 with the best temporal resolution (1-h) and ECMWF Operational model with the best spatial resolution (0.125ºx0.125º). The latter is only used in the inter-comparison using different spatial resolutions, while ERA5 is used both in the inter-comparisons and in the independent comparisons with MWR measurements.

For use in satellite altimetry, NWM-derived WPD is calculated from global grids of two single-level parameters provided by the corresponding model: Total Column Water Vapor (TCWV) and the near-surface air temperature (two-meter temperature, T_0). This computation is performed using Eq. (1), where TCWV is expressed in kg/m^2 (or mm), and WPD results in meters (Bevis *et al.*, 1992, 1994).

$$WPD = \left(0.101995 + \frac{1725.55}{T_m}\right)\frac{TCWV}{1000} \tag{1}$$

In Eq. (1), T_m is the mean temperature, in Kelvin, of the troposphere, which is modelled from T_0, as given by Eq. (2), according to Mendes (1999).

$$T_m = 50.440 + 0.789\, T_0 \tag{2}$$

Single-level parameters (e.g. TCWV and T_0) provided by an atmospheric model are relative to the height of the corresponding orography (usually a smoothed representation of a digital elevation model). Thus, WPD provided by Equations (1) and (2) are computed at the level of the same orography. Apart from the comparisons with MWR, all analyses made in this study were performed at the level of the corresponding atmospheric model orography, in order to avoid introduction of undesirable biases.

As an example of the wet delay derived from NWM, Figure 1 shows the global distribution of the WPD mean values in cm, computed from Equations (1) and (2), using TCWV and T_0 provided by ERA5. This was computed using the period 2010.0 to 2014.0, with grids every 6 hours at 3ºx3º spatial sampling. Overall, the magnitude of the WPD is small over the polar regions and increases towards the equator.

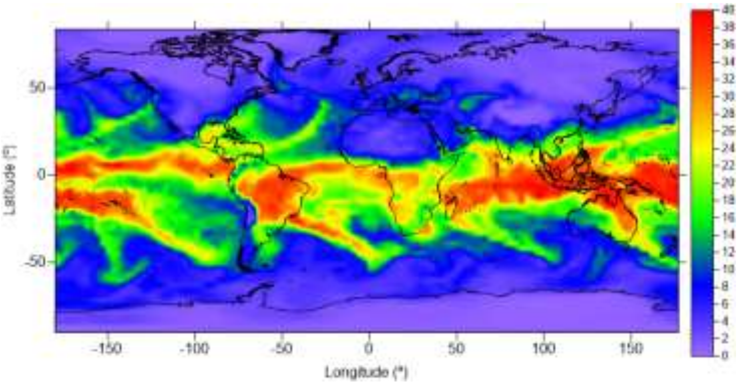

Figure 1 – WPD mean (cm) computed from ERA5 for the period 2010.0-2014.0 at 3ºx3º spatial sampling

3. Inter-comparisons of NWM-derived WPD

Using a time span of 4 years (2010.0 to 2014.0), several WPD from ERA5 and ECMWF Operational models have been inter-compared. For the ERA5 model, WPD computed from atmospheric parameters at 2-h, 4-h and 6-h intervals and at 0.6ºx0.6º and 1.2ºx1.2º spatial samplings have been considered (Figures 2-4). For the ECMWF Operational model, WPD derived from atmospheric parameters at 0.25ºx0.25º, 0.50ºx0.50º and 0.75ºx0.75º spatial samplings have been compared (Figures 3-4). Other WPD values have been computed for the instants and grid points of each model, without any temporal or spatial interpolation, to be used as reference.

3.1 Temporal resolution

For the inter-comparison using different temporal resolutions, only ERA5 was adopted and the following methodology was used: (i) for each grid point of the ERA5 model, a reference WPD value is computed using the corresponding atmospheric parameters (this value is not interpolated); (ii) for the same grid point, another WPD value is derived using the corresponding atmospheric parameters of the grids 1 hour before and 1 hour after (2-h interval), interpolated in time to the instant of the actual grid; (iii) another WPD value computed as the latter, but using the grids 2 hours before and after (4-h interval); (iv) another WPD value interpolated in time using the grids 3 hours before and after (6-h interval).

Using these four global WPD values for a period of 4 years, three differences are calculated between non-interpolated WPD and the other three values (interpolated using atmospheric parameters from ERA5 at 2-h, 4-h and 6-h intervals). These global sets of WPD differences have been binned into classes of latitude and a Root Mean Square (RMS) value is calculated for each WPD difference and for each class of latitude. Left panel of Figure 2 shows these RMS values in cm for latitude classes of 3º. Blue bars represent the RMS of the differences between non-interpolated WPD and those interpolated using ERA5 atmospheric parameters at 6-h intervals. Red and green bars represent the corresponding values when 4-h and 2-h intervals are used, respectively.

The same global sets of WPD differences were binned for each day, computing daily weighted RMS of the differences (weights function of the co-sine of latitude) for the whole globe. These are shown in the right panel of Figure 2 using the same colour code, allowing to observe the time evolution of the various WPD differences (RMS) and to determine a global RMS for each difference.

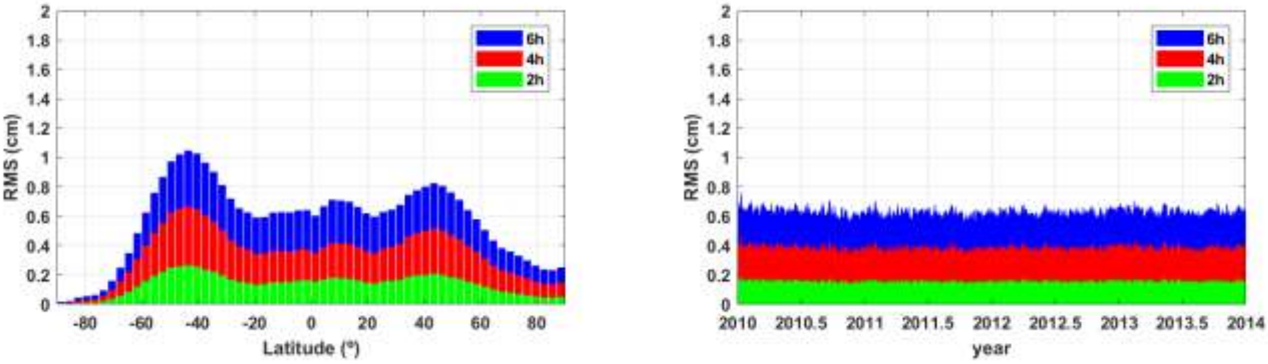

Figure 2 – RMS (cm) of the WPD differences function of latitude for classes of 3° (left panel) and function of time computed for weighted daily differences (right panel)

Figure 2 shows that, as expected, the differences increase with the time interval used to interpolate the WPD. These differences show maximum values around latitudes ±40°, larger in the southern hemisphere (latitudes 40°-50°S), with a maximum RMS value of about 1.0, 0.6 and 0.2 cm for the 6-h, 4-h and 2-h intervals, respectively. These values are indicators of the accuracy when different time intervals are used to compute WPD from ERA5. The right panel of Figure 2 shows a constant pattern and global RMS values for the WPD differences of about 0.2, 0.4 and 0.6 cm, when 2-h, 4-h and 6-h intervals are used, respectively.

To observe the spatial distribution of the differences between reference (non-interpolated) WPD and the corresponding interpolated values using 6-h intervals (depicted in blue in Figure 2), the left panel of Figure 4 represents the same RMS values for tiles of 3°x3°. The left panel of Figure 2 is a representation of the temporal variability of the WPD function of latitude, while the left panel of Figure 4 is a global representation of the spatial pattern of this temporal variability. The high differences observed in the left panel of Figure 2 in the southern hemisphere are observed in the left panel of Figure 4 for latitudes ranging from 40° to 50°S. This figure also shows regions with RMS values larger than 1 cm and zones with low temporal variability of the WPD (such as South Atlantic Ocean close to the coast of Africa and South Pacific Ocean close to Peru and Chile).

These results show that the use of atmospheric parameters with intervals smaller than 6-h has an impact less than 1 cm (~0.6 cm) in the global WPD computation (right panel of Figure 2), however in some regions this value can reach 1 cm (left panel of Figure 2) or can be larger than 1 cm (left panel of Figure 4).

3.2 Spatial resolution

For the inter-comparison using different spatial resolutions, ECMWF Operational and ERA5 models were used. The following methodology was adopted: (i) for all grid points of each model, a WPD value is computed using the corresponding atmospheric parameters; these values, which are not interpolated, are the reference values for each model; (ii) for the same grid points, a WPD value is interpolated in space, from atmospheric parameters, at the four neighbouring grid points, which are the corners of a square with centre in the previously mentioned grid points and with size twice the highest resolution of each model (0.6°x0.6° for ERA5 and 0.25°x0.25° for ECMWF Operational); (iii) another WPD value computed as the latter, but using a square with a size of 4 times the models resolution (1.2°x1.2° for ERA5 and 0.50°x0.50° for ECMWF Operational); (iv) another WPD computed value as the latter, only for the ECMWF Operational model, using a square with a size of 6 times the model resolution (0.75°x0.75°). This analysis was performed globally for the period 2010.0 - 2014.0.

Using these several sets of WPD, differences have been calculated between non-interpolated WPD, i.e. reference WPD, and those interpolated using different spatial resolutions as explained above. Figure 3 represents the RMS of these differences for ERA5 (top panels) and ECMWF Operational model (bottom panels).

As in the analysis using different temporal resolutions, these WPD differences were binned into classes of latitude (3º) and for each day, calculating the RMS for each class. The top left panel of Figure 3 represents these values for ERA5, function of latitude, showing a maximum value (RMS) of about 1.3 and 0.8 cm for differences between reference (non-interpolated) WPD and those interpolated at 1.2ºx1.2º (blue) and at 0.6ºx0.6º (red), respectively, occurring in the equatorial region. Concerning the time evolution of the global WPD values from ERA5 (top right panel), the same differences have global RMS of about 0.8 and 0.4 cm, respectively. This time evolution also reveals the existence of an annual signal in these differences, with maximum values during boreal summer, due to the WPD seasonal variability.

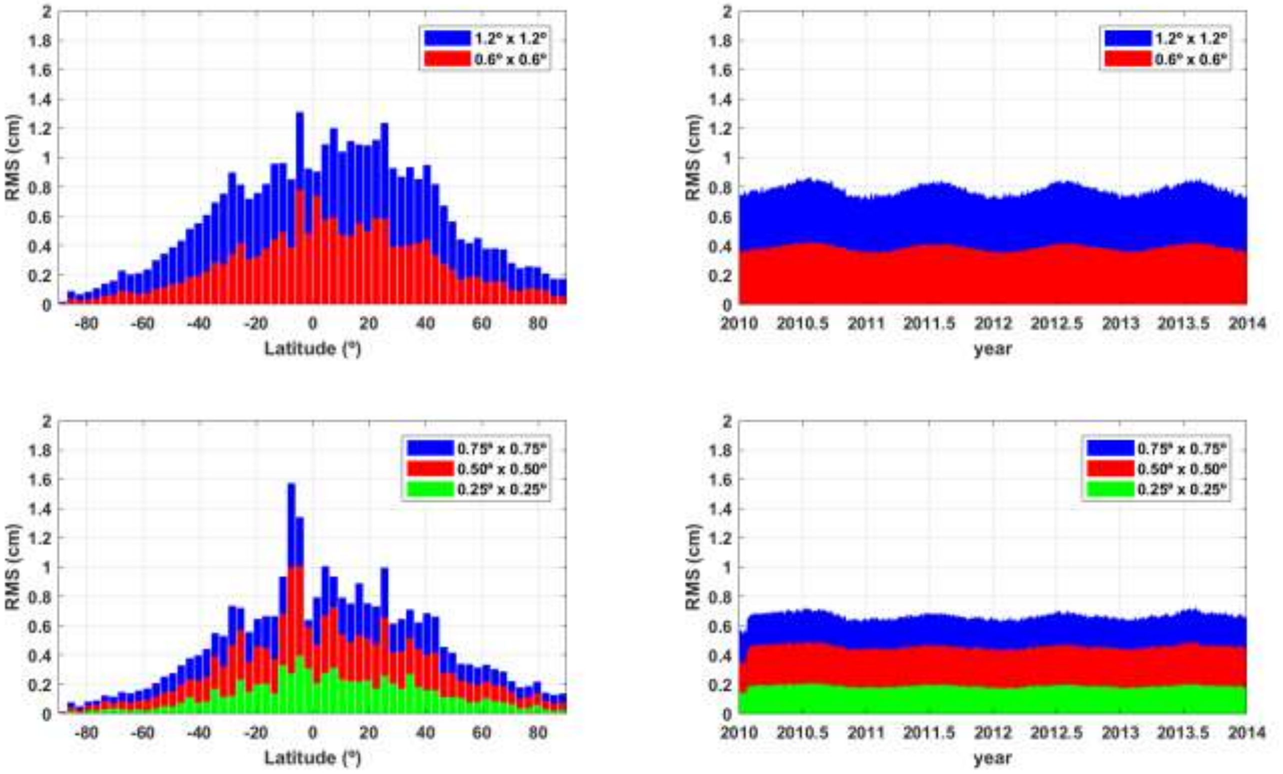

Figure 3 – RMS (cm) of the WPD differences function of latitude for classes of 3º (left panels) and function of time computed for each day (right panels) for ERA5 (top panels) and for ECMWF Operational (bottom panels)

Regarding the same analysis using WPD from ECMWF Operational model, maximum RMS values of about 1.6, 1.0 and 0.4 cm are found for WPD differences between WPD reference values and those interpolated at 0.75ºx0.75º, 0.50ºx0.50º and 0.25ºx0.25º, respectively (bottom left panel of Figure 3). The same differences calculated globally (bottom right panel of Figure 3) have RMS values of about 0.7, 0.5 and 0.2 cm, respectively. The same annual signal is observed in this panel.

The results represented in the bottom right panel of Figure 3 show a jump in the beginning of 2010, after which the three WPD differences become larger. The instant where this jump occurs coincides with the change in the orography of the ECMWF Operational model (January 26, 2010). This means that this change leads to a better modelling of the troposphere, since the differences are larger. When WPD differences between different spatial samplings are examined, low differences mean that the increase in spatial resolution does not conduct to significant improvement in the modelling of the WPD spatial variation. On the contrary, large differences indicate a better modelling of the WPD spatial variation, only depicted by the finest resolutions.

The same WPD differences represented in blue in the top panels of Figure 3, were computed globally for tiles of 3ºx3º and illustrated in the right panel of Figure 4. These differences are between non-interpolated WPD and those interpolated from ERA5 at 1.2ºx1.2º spatial sampling. This figure allows to observe the spatial pattern of these differences showing the spatial variability of the WPD. Observing the right panel of Figure 4, the most striking feature is the latitudinal dependence of these differences, in agreement with the top left panel of Figure 3, with RMS larger than 1.0 cm in some regions, with high values mainly over land and coastal zones in low latitudes.

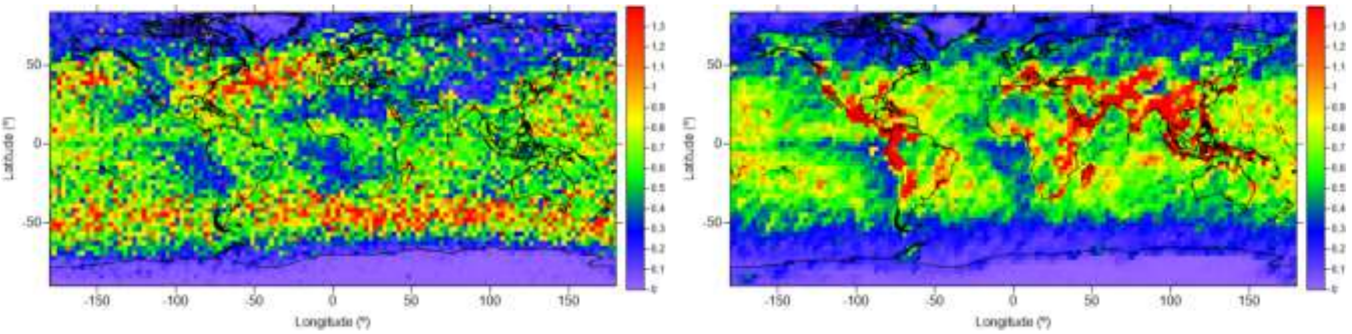

Figure 4 – RMS (cm) of the WPD differences when WPD is interpolated from ERA5 grids 6-h apart (left panel). RMS (cm) of the WPD differences when WPD is interpolated with 1.2ºx1.2º spatial sampling from ERA5 (right panel)

These results reveal global WPD differences with RMS smaller than 0.8 cm (right panels of Figure 3), however values larger than 1 cm exist in some regions (left panels of Figure 3 and right panel of Figure 4). Concerning ERA5, when 0.6ºx0.6º spatial sampling is used, differences have a global RMS of about 0.4 cm, being smaller than 0.8 cm over the equator. Regarding the ECMWF Operational model, when 0.75ºx0.75º spatial sampling is used, differences have a global RMS of about 0.7 cm and RMS values can reach 1.6 cm close to the equator. Concerning these differences using the 0.50ºx0.50º spatial sampling, the RMS values are not larger than 1 cm.

All results presented in this section, showing significant RMS differences up to 1.6 cm at low latitudes, but with insignificant global values, are provided by inter-comparisons, using different temporal and spatial resolutions of the models. For a complete analysis, an independent assessment is required, namely using WPD retrieved from MWR measurements.

4. Independent comparison between ERA5 and MWR-derived WPD

Using a time span of one full year (2010), WPD from two on-board MWR measurements have been compared with those computed from ERA5 considering different spatial and temporal samplings. For each along-track measurement of MWR, three WPD values are interpolated from ERA5: (i) using 0.3ºx0.3º and 1-h, the best resolutions; (ii) 0.3ºx0.3º and 6-h, as the former, but degrading the temporal resolution; (iii) 0.6ºx0.6º and 6-h, as the second, but degrading the spatial resolution. For these comparisons, only MWR-derived WPD measurements flagged as valid and with latitudes in the range [-60º 60º] were used. Since MWR-derived WPD measurements are referred to sea level, for this comparison all ERA5-derived WPD values are reduced to sea level using an empirical expression (Kouba, 2008).

This independent comparison was performed using WPD measurements from Jason-2 and EnviSat. The various WPD differences were binned into classes of latitude (3º) and RMS values were calculated for each class. Figure 5 represents these RMS values, function of latitude, for WPD differences between MWR on board Jason-2 and ERA5 (top panels) and between MWR on board EnviSat and ERA5 (bottom panels). The left panels show the effect of using the same spatial sampling (0.3ºx0.3º) and different temporal resolutions (1-h or 6-h), while the right panels show the effect of using the same temporal resolution (6-h) and different spatial samplings (0.3ºx0.3º or 0.6ºx0.6º), when compared with an independent WPD source.

When compared with independent measurements from on-board MWR (Jason-2 and EnviSat), the results show that there is no significant effect when WPD derived from ERA5 are interpolated at 0.6ºx0.6º, instead of 0.3ºx0.3º (right panels of Figure 5). Concerning the use of different temporal resolutions, results shown in the left panels of Figure 5 reveal a small effect when WPD values are interpolated at 1-h intervals, instead of 6-h. This small effect corresponds to RMS differences lower than 0.2 cm, only in some regions (approximately 30º-60ºS and 30º-60ºN). These results are in agreement with those shown in the left panel of Figure 2, where the WPD differences are larger in the same regions.

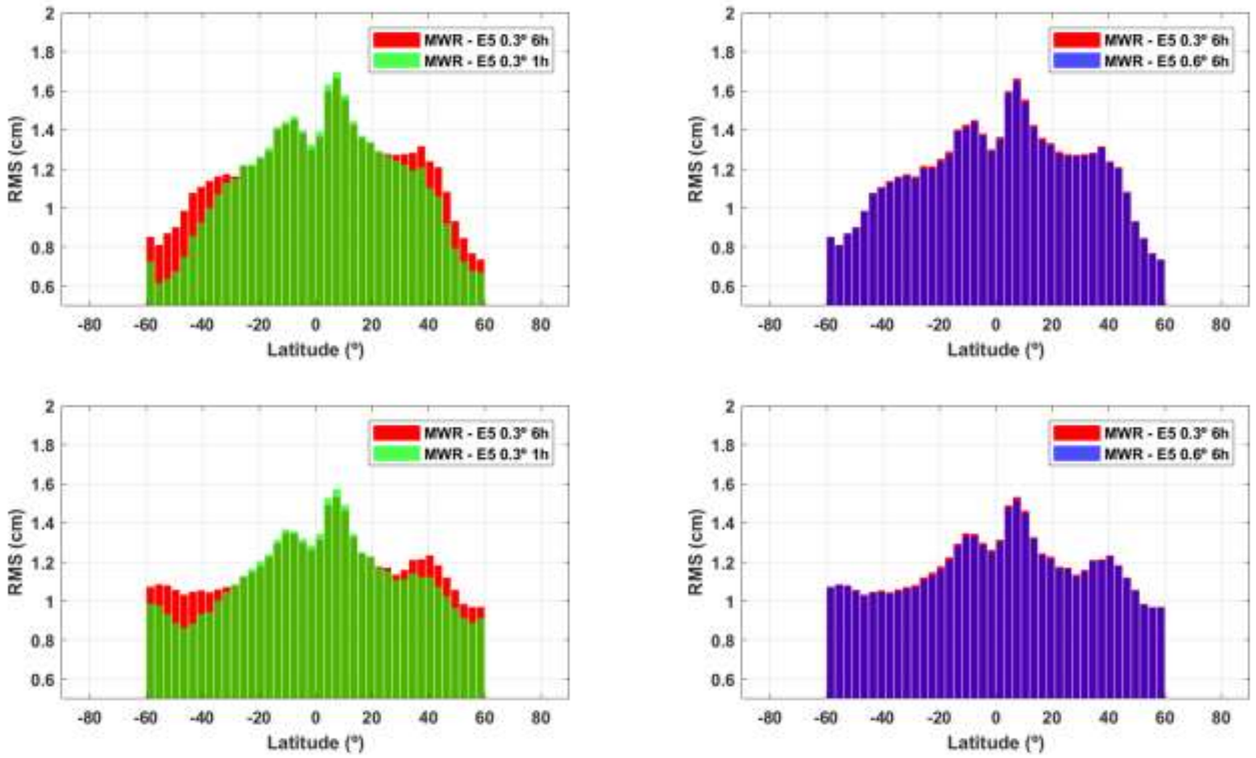

Figure 5 – RMS (cm) of the WPD differences between MWR on board Jason-2 (top panels) and EnviSat (bottom panels) and ERA5 at different spatial (right panels) and temporal (left panels) resolutions

Globally, the three WPD differences represented in Figure 5 have an RMS value of about 1.2 cm, without significant differences between them. The previous analyses performed with inter-comparisons show a global RMS of about 0.6 cm when 6-h intervals are used and a global RMS of about 0.4 cm when 0.6ºx0.6º spatial sampling is used. These last two RMS values are very low, compared with the RMS of the differences between MWR and ERA5. For this reason, the effect of using different spatial (0.3ºx0.3º or 0.6ºx0.6º) and temporal (1-h or 6-h) resolutions to derive WPD from ERA5, when compared with MWR, is insignificant or very small. These results are explained by the fact that the NWM are not able to model the smaller spatial and temporal scales of variability of the WPD. This can be observed when analysing the various WPD from satellite MWR and from ERA5 at different spatial and temporal samplings along satellite tracks, as exemplified in Figure 6.

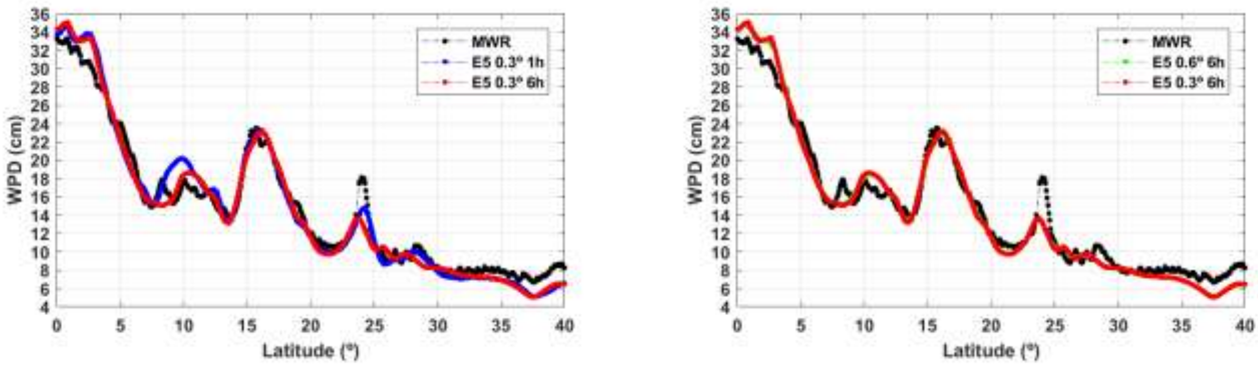

Figure 6 – Example of the WPD (cm) from EnviSat MWR (black) and interpolated from ERA5 at 0.3ºx0.3º and 1-h (blue), 0.3ºx0.3º and 6-h (red) and at 0.6ºx0.6º and 6-h (green)

Figure 6 shows very small differences between WPD interpolated from ERA5 at 0.3ºx0.3º and 0.6ºx0.6º (right panel) and some WPD variability not modelled by this model, either at 6-h or 1-h intervals (left panel).

5. Conclusions

This paper describes the impact of using atmospheric parameters from NWM (ERA5 and ECMWF Operational models) at different spatial and temporal resolutions in the computation of the WPD for application in satellite altimetry.

Inter-comparisons reveal WPD differences with global RMS values of about 0.6, 0.4 and 0.2 cm, when 6-h, 4-h and 2-h intervals, instead of non-interpolated 1-h values, are used in the WPD computation from ERA5, respectively. However, using 6-h intervals, the RMS can be larger than 1 cm in some regions (mainly in the southern hemisphere). For the spatial resolution, the same analysis reveals WPD differences with global RMS of about 0.4 cm, when 0.6ºx0.6º spatial sampling of ERA5 is used instead of the original 0.3ºx0.3º spacing, being the maximum of this RMS smaller than 0.8 cm close to the equator. Using the ECMWF Operational model, results show WPD differences with global RMS values of about 0.2, 0.5 and 0.7 cm, when 0.25ºx0.25º, 0.50ºx0.50º and 0.75ºx0.75º spatial samplings are used in place of the original 0.125ºx0.125º spacing. However, the same values can reach 0.4, 1.0 and 1.6 cm in some regions (mainly low latitudes), respectively.

The independent comparisons with WPD derived from MWR (on board Jason-2 and EnviSat) show a small effect when WPD is interpolated from ERA5 at 0.6ºx0.6º, instead of 0.3ºx0.3º spatial sampling, indicating that to optimize the calculation time, 0.6ºx0.6º spatial sampling may be used. Concerning the temporal sampling, the effect of using 1-h instead of 6-h intervals is significant only in some regions (latitudes larger than ±30º) and this effect is smaller than 0.2 cm in the RMS values of the differences MWR-ERA5. These results show that 1-h intervals do not have any significant effect in the WPD accuracy from ERA5, being a temporal resolution slightly better than 6-h (e.g. 3-h or 4-h) enough to remove this small effect of only 0.2 cm in the RMS. This is due to the inability of the model to represent the smaller scales of variability, both in space and time.

These results and conclusions are important to ensure the best accuracy of the WPD derived from NWM for application in satellite altimetry and, at the same time, to identify the spatial and temporal resolutions required to ensure this accuracy and the best computation time.

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