Authors' response to the Interactive comment on "A coastally improved global dataset of wet tropospheric corrections for satellite altimetry" by Clara Lazaro et al.

Anonymous Referee #2

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We would like to start by thanking the Reviewer for his or her careful reading of our manuscript and for taking the time to assess it.
The main changes introduced in the manuscript following the comments and suggestions of the two Reviewers can be summarised as:

- Sections containing the Abstract and the Conclusions have been updated to accommodate the new results presented in the revised version of the manuscript.
- Some parts of the text have been moved to new sections or were rewritten/completed to be clearer and more informative.
- Figures 1 as well as figures 11, 12 and 13 have been updated, the latter to include the results for the comparison of the GPD+ WTC with the MWR-derived WTC, instead of that for the Comp WTC, following the concerns raised by Reviewer#2.
- Previous Figure 5 has been divided into Figures 7 and 8 and the geographic location of the Envisat tracks have been added, following the recommendation of Reviewer#1.
- New figures have been added to the revised version (Figures 2, 3 and 14).
- Tables 1 and 4 have been updated, the former to include more information, the latter in the sequence of the last update of the GPD+ database (performed to include more data for the recent missions).
- A new table (Table 2) has been added in the revised version.
- All figures and tables have been renumbered.
- Section 3.2 has been divided into sections 3.2.1 and 3.2.2 describing the global and the regional (coastal) results, respectively, and the text has been extended.
- Reference Vieira et al. (2019c) has been updated, since at the time of this revision it has already been published.
- Reference AVISO (2017) has been removed.
- Five new references (Bevis et al. (1994), Rudenko et al., (2017), Valladeau et al. (2015), Dinardo et al. (2020) and Escudier et al. (2017)) have been inserted in the revised version.

We have responded to all the comments and suggestions raised by the Reviewer as follows.

The paper presents a dataset of wet tropospheric correction applicable to altimetry and the methodology used to product it. The wet tropospheric correction is one of the correction applied to the altimeter range to compute the Sea Level Anomaly. The WTC is traditionnaly provided by on board microwave radiometer, measuring in appropriate frequencies bands to correct for the excess path delay. The estimation of the WTC from the MWR measurements can be degraded by extreme rains events, ice surface, land contamination in coastal areas,

instrument malfunctions. The author proposes a method named GPD+ that intend to improve the MWR-based WTC of operational processing, or propose a correction for mission without MWR on-board (Cryosat-2).
The method consists first in the filtering of the invalid WTC estimation from the operational product and second, by the estimation based on the objective analysis using external data such as GNSS data, MWR Imaging data (providing water vapour), Numerical Weather Prevision model (ECMWF, ERA interim). The method is applied to almost all conventional missions.

The dataset used for the algorithm is rather well defined. The section about the GNSS dataset lack a discussion about the coverage of this network. Although the paper states otherwise, GNSS stations don't seem to be distributed globally over the globe.
R: The GNSS stations used in the methodology belong to several international GNSS networks (IGS, EPN, SuomiNet); some stations from national networks have also been used by the authors (e.g., in Indonesia, German Bight, etc.). The Reviewer is right saying that GNSS stations providing atmospheric products are not well distributed over the globe. The authors only say that GNSS stations all over the world are used, provided their atmospheric products are made available to users.

The section about the Imaging radiometer seems more dedicated to the filtering step of the method than to the description of the input dataset itself and the added value of this dataset.
R: By filtering step the reviewer may refer to the calibration step. This is a very relevant step, as it is important to ensure that the corrections are stable in time and do not introduce spurious trends in the SLA. In the revised version, information about the SI-MWR products have been inserted as well as the added value of this dataset.

The NWP dataset is slighlty described, and lack a discussion of the difference between ERA Interim and ECMWF. The paper don't say if one mission can be covered by only one model or if two are needed, if there is a bias between the two models that shall be corrected. Also the paper stated that NWM data are provided as output from GPD+ for northernmost latitudes, but the method to adjust the model to measurements is not clearly defined (is it a simple bias computed over each cycle?).
R: As ECMWF operational model has undergone several updates, this model does not have the same accuracy over time. For example, the RMS of the differences between MWR-derived WTC and NWM-derived WTC, in points with valid MWR values, is in the range 1.2-1.4 cm after 2004. Before that date, the RMS of differences increases as we go back in time, reaching 2.8-3.0 cm in 1995. On the contrary, ERA Interim is fairly uniform, with RMS of WTC differences with respect to the MWR WTC in the range 1.2-1.4 cm, including the period of the first altimeter decade. For this reason, for all missions with data before 2004 (T/P, Jason-1, ERS-1, ERS-2, Envisat and GFO), ERA Interim is used in GPD+, while for the most recent missions the Operational model is adopted. More details can be found in Legeais et al. (2014), cited in this manuscript. A sentence clarifying this has been added in the revised version of the paper.
The question concerning the adjustment of the WTCs derived from the model and GPD+ is addressed below.

The algorithm is well described and the workflow provides a clear overview of the processing. The method is assessed for Envisat only in this paper. The paper introduces Full Mission Reprocessing (FMR v3.0) but compare GPD+ dataset to the Composite Correction extracted from L2P products issued from an older reprocessing (FMR v2.1). According to the L2P product handbook available on AVISO, there is no composite correction in the L2P products, only MWR-derived correction. This point must clarified. In the validation section, both corrections (MWR-based and composite) are used for comparisons. it is difficult to follow which version of the Envisat MWR-based correction is used for the generation of the GPD+ and which one is compared to the GPD+.

R.: The Composite correction has been developed also aiming at getting a WTC with validity extended up to the coast. According to personal communication of colleagues from CLS, the AVISO products usually adopt this correction. However, it is difficult to find a proper reference for this product. Moreover, the Reviewer is right when states that the MWR-derived WTC used to generate the Composite WTC is different from the one provided in FMR V3.0 dataset.

Therefore, in the revised manuscript we dropped the comparison with the Composite WTC for Envisat. Now, GPD+ WTC is compared with both the ERA-derived WTC and the MWR-derived WTC (from Envisat V3.0), the later therefore has replaced the comparison with the Composite correction. In the present comparisons between GPD+ and MWR, the points for which the MWR observations are not set (NaN values) or are out of the limits of the WTC range (-50 cm to 0 cm) in the GDR products, have been discarded from the analysis. This has been clarified in the paper.

The number of 30% of invalid WTC data over ocean for Envisat is stated but not justified. This number seems quite high.

R.: This question is addressed below.

Moreover, the criteria to select valid SLA points is not discussed. The paper shall define the criteria of validity of the SLA. The L2P products provide a validity flag that could be used.

R.: The following sentence has been introduced:

"The criteria to select valid SLA are those recommended in the literature and adopted in the standard RADS processing (Scharroo et al., 2012, cited in this manuscript) and include: application of thresholds for all involved fields (satellite orbit above reference ellipsoid, altimeter range, all range and geophysical corrections), altimeter ice and rain flag (whenever set) and SLA within ±2m.".

The comparison of GPD+ with GNSS is more a validation of the method than a performance assessment. This section can gain in clarity in the method used for this comparison. GNSS data are not independent of GPD+ data. Is the GNSS data cited in this section also used in the generation of the GPD+ dataset (data from another network for example)? In the first sections, one of the criteria for rejection of MWR-based correction is the distance to coast, but it is not clear if this criteria is used in this section. The fact that the method is not clear makes the figure 7 difficult to understand.

R.: As stated in the paper (line 353 of original manuscript), GNSS data are not independent from the GPD+ WTC, as they have been used in their computation. Nevertheless, the analysis of the root mean square (RMS) value of the GNSS-derived and GPD+ WTC differences, function of distance from coast, is valuable to inspect the correction in coastal regions since it allows us to derive a threshold value of the distance to coast where the radiometer correction starts to become invalid (even if not flagged as invalid in the original GDR). Once this threshold value is obtained, it can and should be used in the GPD+ algorithm. This has been done for the Envisat FMR V3.0 used in this paper (more details are given below). The authors have detailed the methodology used in this comparison in the revised paper.

The paper provides a performance assessment (and not accuracy) of the section 3.2 using analyses of Sea Level Anomaly variances. In this section, the author compares the composite correction which is not part of the L2P products to the GPD+ correction. The method used is to select all valid SLA points, and for the points with the composite outside limits or invalid, the ERA interim WTC value is used. These points shall be discarded from the analysis as they do no represent a fair comparison with the MWRbased correction as the use of the model correction will degrade it.
R.: As stated before, the assessment with respect to the Composite WTC has been replaced by the corresponding comparison with the MWR-derived WTC. Since in this comparison we cannot assess the performance of the GPD+ WTCs in the points where these corrections are not set, we have now removed these points from the analyses. We believe that the assessment of the GPD+ through comparison with the model WTC is important for the users, who must rely on model data when the correction from the on-board radiometer is invalid/absent.

The previous sections have already shown that the GPD+ retrieve some invalid points.
R.: The GPD+ methodology retrieves a WTC estimate for all points with an invalid MWR-derived WTC. In the absence of observations (valid MWR-, GNSS- and SI-MWR-derived WTCs), the GPD+ output is the first guess (ERA Interim WTC) adjusted to the valid MWR-derived WTCs, as explained here. Therefore, all GPD+ estimates are valid. The GPD+ products provide a flag identifying the model-derived WTCs.

The color scales for figure 9 is not well chosen and is difficul to read.
R.: In Figure 9 (now Figure 12), blueish colours have been chosen to show an improvement from the use of the GPD+ WTC in the computation of SLA, compared to the use of other WTC correction, while the yellow to red colours show a degradation of the SLA dataset when the GPD+ WTC is used. The green colour is used for differences around zero. Since this colour can be difficult to see in the colour scale, a note has been added to the caption of the figure.

Figure 10a shows a strong peak, with not physical values, for latitude around 50°N that is not explained in the paper.
R.: This comment is addressed below.

For this diagnosis, it is not stated if data cover open-ocean only, or ocean and coastal areas. Moreover the figure shows a reduction of the SLA variance from 200km up to the cost but it is difficult to see the improvement close to the coast.
R.: For the diagnoses described in the paper, global data have been used (please refer to former Figures 9 and 10 (Figure 12 and 13 of the revised paper), which show that data for the whole ocean, including coastal regions, have been used). This has been written clearly in the revised paper. The improvement in the closest 20 km to the coast can be as high as 3 cm^2 for

the GPD+ and MWR-derived WTCs comparison and 1 cm^2 for the comparison with ERA. We believe that in both cases the improvement in SLA dataset is significant, by reducing the SLA error introduced by the WTC in a few centimetres.

Although the paper title is “A coastally improved global dataset”, there is no real focus on coastal areas. It is not stated clearly in the paper but it seems that the dataset is based on 1Hz data where 20Hz data are more adequate for studies on coastal areas.
R.: In response to the Reviewer’s concern, results for three coastal regions selected, on the one hand, due to the large number of available GNSS stations (North American and European coasts) and, on the other hand, due to the fact of being a challenging region for coastal satellite altimetry (Indonesia region), have been added to the revised version of the manuscript, as an attempt to show the potential of the GPD+ dataset along the coastal waters. Section 3.2.2 has been added in the manuscript to present these results.
The rate of the altimetry measurements is not a limitation to the GPD+ methodology. In the scope of a current research project in which the University of Porto (UPorto) is involved, the GPD+ methodology will be used to estimate the WTC for the coastal (and inland waters) zone for CryoSat-2 and Sentinel-3 missions. The outcome of this project will be a GPD+ WTC product at high rate (20 Hz), intended to be used for applications over the coastal zone (i.e., no ocean values included for distances larger than ~100 km off the coast). However, the GPD+ WTCs presented in this manuscript have been computed to be incorporated in altimetry products providing observations at 1 Hz rate, still the most used by the altimetry community databases. They are intended for users who want to have a consistent and continuous WTC correction, from open ocean to coasts (and polar regions as well). The correction can be extended up to the coast since a valid WTC value is provided for the first along-track measurement over land. Users can therefore use this measurement to interpolate the valid GPD+ WTC up to the coast, for the location and time instant of the 20 Hz data. Moreover, as the onboard radiometer data are not available at a higher than 7 Hz rate, neither these data nor the third-party data have enough resolution to be provided at 20 Hz. Therefore, and for the time being, the strategy for those users who want to focus on coastal ones, would be to interpolate these 1-Hz data to the location and time instant of the 20 Hz data.
For high-frequency MWR, expected in the future, high-rate WTCs are definitely advisable, and the authors intend to exploit this possibility. A sentence has been added in the section with the conclusions.

Minor comments
Row 118: “GNSS network of stations distributed globally along the coastlines”: GNSS stations don’t seems to be distributed globally over the globe. A map could be added to show the position of the GNSS stations used for the generation of the dataset.
R.: Following the suggestion of the Reviewer, a figure showing the location of the coastal and island GNSS stations used in this study has been added in the revised version (Figure 2).

Row 195: “values of 15km have been used for Jason-1/2/3”: 15km seems quite small for this serie of MWR knowing that they measure at three frequencies, including a 18.7GHz with a large footprint. What is the reason for that?
R.: The quoted values refer to those used currently in the GPD+ processing. For the Jason series of satellites, a smaller value has been adopted since the WTC provided in their products

are already improved in the coastal regions using the methodology developed by Brown (2010), cited in the text. However, the assessment of the MWR-derived WTCs through their comparison with GNSS-derived WTCs in the coastal zone has shown the existence of contaminated measurements for distances larger than 15 km off the coast. The result from this assessment for Envisat (30 km), shown in current Figure 10, has already been used in the GPD+ processing described in this paper. The same value was obtained for E1, E2 and GFO, which is the value in use in the GPD+ processing. For the reference missions (T/P, J1, J2 and J3), however, the assessment using GNSS data has shown land contamination up to 25 km off the coast. Therefore, the threshold value currently set (15 km) will be updated in the forthcoming GPD+ processing for these missions. For SARAL and Sentinel-3, the outcome of this assessment were thresholds of 15 and 25 km, respectively, that have been already implemented in GPD+. It should be emphasized that the distance from coast is a rejection criterion applied after a set of other criteria, such as the radiometer land flag, that, if efficient, should have already rejected land contaminated points. So, these distances must be large enough to ensure the rejection of contaminated points, but also conservative to avoid rejection of good MWR observations.

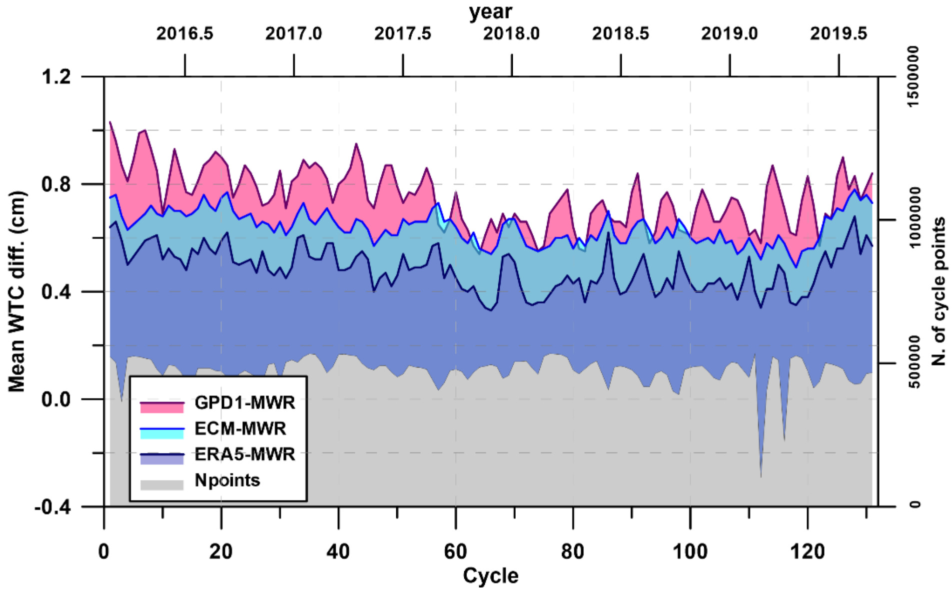
Row 201: Talking about Envisat datat from latest reprocessing, the author states “30 % of the oceanic points have an invalid WTC value”: This seems quite a large number of invalid points when focusing on ocean surface only (with a valid SLA). From Figure 2, it does not look like one third of the points are invalid. How do you explain that number?
R.: Altimeter data are acquired along satellite tracks only, therefore at low latitudes the distance between adjacent tracks is maximum, with large diamond-shaped regions without altimeter points. Therefore, the quantity of points sampled by the altimeter varies with latitude, being maximum over polar regions where WTCs are usually invalid. Also, the points within a strip of width 30-50 km along the coasts have usually invalid WTCs. Additionally, as depicted in Figure 2 (now Figure 4), there are generally full tracks with invalid WTCs. The percentage of ocean points with invalid WTC for Envisat cycle 12 is 29.5%. The corresponding number when only points with valid SLA are selected is 10.9%. These figures have been added to the text.

Row 209: the author states “Data from the reference missions”. For a non-specialist audience, the author should explain which are the reference missions.
R.: The explanation has been added in the revised version of the manuscript.

Row 219: for the intercalibration processing, the difference at cross-over points with a time-lag of 180 minutes between reference missions and other altimetry missions are computed. Is that time span not too large for WTC ?
R.: As explained in Fernandes et al. (2013b), cited in the text, this value has been chosen to guarantee the existence of enough crossovers to perform the analysis i.e., it is the best compromise between the number of crossovers and the minimum time interval.

Row 229: “In addition, to reduce data discontinuities, : : :.” : from this sentence it seems that a bias is computed between the MWR and the NWM correction for each cycle. What is the rationale for a simple bias? How is computed that bias?

R.: The bias is computed, for each cycle, as the mean difference between MWR and model WTC, for all points where the former correction has been considered valid. The rationale behind this comes from the observation that the differences between the WTC from MWR and that from models, in addition to the small scales observed in Figures 7 and 8 in the revised version, have long-wavelengths from yearly to decadal signals. See for example in the figure below, the mean cycle differences between Sentinal-3A (S3) MWR and ECMWF operational (cyan) and between S3 MWR and ERA5 (blue). Although these differences are small (only a few mm) the application of a mean bias per cycle helps to reduce these small discontinuities.



The method used to adjust the NWM-derived and GPD+ WTCs has been described in more detail in the revised version of the manuscript.

Row 274-275: "To prevent the loss of points when interpolating to 20 Hz points, in addition to ocean points, the closest land point is included, provided it is within a distance less than 50 km from the ocean." Can you clarify the processing here? what is the closest land point?

R.: This means that, for each track crossing a coastal zone, a GPD+ WTC at sea level estimate is also computed for the first altimeter measurement point located over land. This WTC estimate and the previous one over ocean, allow the user to perform the interpolation of the WTC field if high-rate data are to be used. The sentence has been rewritten to "To prevent the loss of points when interpolating to 20 Hz points, in addition to ocean points, the closest point over land is included, provided it is within a distance less than 50 km from the ocean. This guarantees that observations over ocean necessary to compute the WTC for this location are still available within the radiuses of influence centred on the point. The WTC estimated for the closest points over land are also estimated at sea level." to become more clearer to the reader.

Row 320: ""The GPD+ WTC is here compared to the ECMWF Reanalysis WTC (ERA Interim, GDR field mod_wet_tropo_cor_reanalysis_01) and with the WTC present in the AVISO CORSSH L2P products in July 2019 (AVISO, 2017). The latter dataset is usually called Composite Correction ". You state here that you compare the GPD+ to Composite correction, but latter (line 334). But according to the L2P products handbook (https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_L2P_all_missions_except_S3.pdf), there is no composite correction in these products. And latter, the author says that he used the field 'rad_wet_tropo_cor_sst_gam_01'. This point shall be clarified

R.: As stated before, the comparison with the Composite WTC has been removed.

The MWR-based correction used in the generation of the GPD+ Envisat files is the 'rad_wet_tropo_cor_sst_gam_01' field provided in Envisat FMR V3.0 GDR dataset, based on a five-input algorithm, according to reference:

Collecte Localisation Satellites (CLS). Surface Topography Mission (STM) SRAL/MWR L2 Algorithms Definition, Accuracy and Specification; S3PAD-RS-CLS-SD03-00017; CLS: Ramonville St-Agne, France, 2011.

Row 330: "Anomalies in this field have been found, with the field out of limits in a set of points, most of them concentrated on certain passes," : Do you mean that you found anomalies in the ERA interim product for WTC field?

R.: Yes, please see sentence below, added to the paper:

"Anomalies in this field have been found, with the field out of limits in a set of points, most of them concentrated on certain passes. This is due to the fact that this correction has been computed from 3D model fields at the altimeter measurement altitude. Therefore, whenever the altimeter-derived surface height is not set (NaN value), the corresponding model-derived WTC will also be NaN. As our goal is to be able to provide continuous WTC, without data gaps, this field is unsuitable for use in the GPD+ estimations."

Row 334: "The MWR-based correction used in the generation of these files" : Which files?

R.: The sentence has been rewritten in the revised version of the manuscript to make it clearer to the reader.

Row 342: The author found 30% of points with a rejected MWR-derived WTC. This figure seems quite large. It could be interesting to discuss that number and provides some insights of the repartition within the different causes. It seems this number is estimated over ocean. Does it include coastal regions? Which latitudes?

R.: The analysis is global, including coastal zones and the whole range of latitudes. This can be verified from Figure 2 (Figure 4 in the revised version), which shows an example of all points with invalid MWR-derived WTCs. This figure allows the reader to inspect the causes that led to the occurrence of all invalid WTCs. A sentence emphasizing that the reader, when analysing Figure 6 (Figure 9 in the revised version) can also refer to Figure 2 has been included. Moreover, the percentage of points contaminated due to each cause has been included in the text for Envisat cycle 12 (the same cycle used to generate Figure 2).

Row 362: "Only GPD+ estimates retrieved using observations are selected." Which observations? MWR? GNSS?

R.: WTC from along-track MWRs, SI-MWRs and GNSS stations are considered observations. The referred sentence has been rewritten as "Only GPD+ estimates retrieved using observations (valid MWR-, GNSS- and SI_MWR- derived WTCs) are selected, GPD+ estimates based on model have been discarded from this analysis.".

Row 370-376: Methodology difficult to understand

R.: The authors have included a more detailed explanation of the methodology.

Row 381: “On the contrary”: -> Moreover, Additionaly …
R.: The suggestion has been accepted.

Row 384: “Accuracy assessment” ==> Performance assessment
R.: The suggestion has been accepted.

Row 420: “third party data”: what are those third-party data?
R.: Third-party data are WTC observations, other than those from the on-board MWRs. The explanation has been included in the manuscript, where the term is used for the first time.

Figure 5: b) and c) look quite similar with land/ice contaminated pass. Outliers are not obvious in c).
R.: In general, all tracks have land and ice contamination. We decided to keep both figures because the referred tracks cover different oceans and therefore show different WTC variability. This has been highlighted in the text. Also, the discussion of former Figure 5, which has been divided into figures 7 and 8 to add plots showing the geographical coverage as recommended by Reviewer#1, has been extended in the text. The caption of Figures 7 and 8 includes now a brief description of the issues in the MWR-derived WTC.

Figure 7: why is there an increase in the number of points for the GNSS-GPD+ comparison but not for the GNSS-MWR one?
R.: As the tracks gets closer to the coast, the MWR-derived WTC become invalid or are inexistent, therefore the number of valid MWR-derived WTC diminishes. The GPD+ methodology computes a WTC estimate for these along-track points, therefore allowing SLAs to be computed at these locations and epochs. Therefore, the number of valid WTCs in the coastal region increases, being this one of the advantages of the GPD+ methodology.

Figure 9: The green color cannot be seen on the color scale.
R.: The green colour is used for the SLA variance differences with values around zero. A note has been added in the caption of the figure to help the reader interpreting this result.

Figure 10: What is this peak around latitudes 50_N?
R.: The peak in latitudes 50ºN is related to the large reduction in SLA variance when the GPD+ WTC is used instead of the Comp WTC or the MWR-derived WTCs. This can be seen in the original Figure 9, as dark blue pixels (GPD+ WTC performs better than Composite WTC or MWR-derived WTC) are found in the westernmost coastal regions of the oceanic basins (e.g., in the Gulf of Saint Lawrence or in the Sea of Okhotsk sea).