Dear reviewer,

Thank you for the constructive and encouraging comments regarding our manuscript. We have enclosed a carefully revised manuscript according to the comments and suggestions provided. We also provide an item-by-item response to all comments.

Yours Sincerely,

Zhilu Wu

Response to Reviewer #1

108-110 and Fig1. I am not sure if there is a point to include this information. Height correction is simply necessary due to the characteristic of vertical distribution of water vapor and it is obvious that higher differences in elevation results in higher differences in PWV.

Response: Thank you for the suggestion. The height correction is necessary for GNSS PWV because the vertical distribution of water vapor. The correction method we used may affect the further validation, therefore it is necessary to briefly present the efficiency/precision of this method. The information from Figure 1 is needed.

Line 252-253 "validation could still suffer from contaminated CMR data by the signal on the land, long distance between GNSS station and footprint, and GNSS height, especially for data of higher precision" – I am quite confused here. Several lines above it is show (on Figure 6) and pointed in the text, that distance up to 90 km has no significant impact on the differences, as well as station height due to the proper correction conducted at the beginning of calculations. Therefore I am not sure what author would like to say here. What kind of "long distance" is it (more than 90 km?). What GNSS elevation is mentioned here as a source of error, since as it was written in line 244-246 "The right panel confirms that the PWV differences have no correlation with station height, which means that the PWV height correction at ground-based GNSS stations is effective". Maybe it would be more clear if the Author would specify this "data of higher precision". Without specifying these information this paragraph is in contradiction with what the Authors have wrote before.

Response: Thank you for the suggestion. In the line 252-253 " validation could still suffer from contaminated CMR data by the signal on the land, long distance between GNSS station and footprint, and GNSS height, especially for data of higher precision" , the Figure 6 shows the land contamination of satellite-borne PWV is corrected properly, and the reconstruction method used in the paper shows no relation with the distance. In this figure we show no significant differences with the distance varying from 40 km to 90 km, which does not mean that the differences are comparable to that of co-located points (e.g., less than 5 km).The ground-based GNSS sites are still far away from ocean with tens of kilometers (minimum distance of 40 km), therefore the distance between sub-satellite points and GNSS sites is still exist. Since the characteristic of horizontal distribution of water vapor, this part of error can affect the comparison. On the other hand, Figure 6 shows that the PWV differences between shipborne GNSS and HY-2A increase

significantly (from 0.89 mm to 1.53 mm) with the distance criteria increases from 50 km to 100 km. As there is no land containment in the shipborne case, it indicates that the PWV agreement is sensitive to the horizontal distance. In the case of ground-based GNSS, however, we do not have so many observations within 50 km to the HY-2A footprint, and we have to consider the coupled effects of potential land containment, distance-induces bias, the model errors of height correction and reconstruction. We have revised the line of 244: "… are free of land contamination. **However, it should be noted that in the left panel the distance is varying from 40 km to 90 km, thus this conclusion does not indicates the case of distance less than 40 km**. The right panel …"
Also, the vertical distribution of water vapor effect the comparison, the height correction is processed before comparing ground-based GNSS PWV and satellite-borne PWV.
We revised "especially for data of higher precision" to "especially for higher accuracy of validation based on GNSS".

line 264 - "The RMS within 200 km, 150 km, 100 km, and 50 km are 2.89 mm, 1.78 mm, 1.53 mm, and 0.89 mm, respectively". Here Authors underline that the distance has impact on the differences between HY-2A and shipborne GNSS. This is in contrast to what they have wrote in line 242 – 243 "both the average value and STD of the PWV differences between HY-2A and GNSS show no correlation with the averaged distance ranging" (the mean RMS for ground-bases GNSS was 2.67 mm). Of course at this point we have larger distance (up to 200 km), but the RMS for distance 100 km is for about 70% higher than for distance 50 km, while for similar distance during comparison HY-2A to land GNSS (45 km to 90 km) it was 'no correlation'. There is also no comment about differences obtained for ground-based and shipborne GNSS. The mean RMS for shipborne would be about 1.4 mm (Authors did not provide this value), which is two times smaller than the mean RMS for ground base GNSS. In my opinion this indicate that procedure for PWV coastal reconstruction is not without errors. There is no 'ideal' way to reconstruct valid data, but this should be clearly pointed by the Authors. I would appreciate if Authors could provide some explanation about this.
Response: Many thanks for the advice. In the line 264 - "The RMS within 200 km, 150 km, 100 km, and 50 km are 2.89 mm, 1.78 mm, 1.53 mm, and 0.89 mm, respectively", we discussed the agreement between shipborne GNSS and HY-2A in different distance. While in line 242 – 243 "both the average value and STD of the PWV differences between HY-2A and GNSS show no correlation with the averaged distance ranging", we discussed the mean value and STD of difference between ground-based GNSS and HY-2A after the reconstruction, which mainly focus on evaluation of the reconstruction method. When ground-based GNSS sites and sub-satellite points are closer, the HY-2A data are more easily be contaminated. Therefore, when the distance is closer, the agreement between ground-based GNSS and HY-2A might be getting worse. Figure 6 shows no correlation between the agreement and the distance (varying from 40 km to 90 km), which means the reconstruction method is effective in this distance region.
Indeed there is no 'ideal' method to reconstruct the valid data. Thanks for your advice. We have clearly pointed out this in the revised manuscript after line 272: "It should be pointed out that there is no 'ideal' method to reconstruct the valid PWV data in coastal region, but it is still necessary to spare no efforts to investigate any useful method to derive 'clean' data for inter-technique comparison and validation."

Line 267 " The average bias is 0.32 mm, meaning that there is no obvious systematic bias between HY-2A PWV and shipborne GNSS PWV." In case of ground-base GNSS the mean bias was -0.03 mm. Since this value (-0.03mm) was expressed as 'good agreement', and 0.32 is also expressed as 'no obvious bias' where according to the Authors is a threshold, after which we can talk about systematic bias? In addition, the information about RMS w.r.t. distance were provide – why there is no information about bias w.r.t. distance?

Response: Thanks a lot for your comments and we are truly sorry for the misleading interpretation. The 0.22 mm PWV bias between HY-2A and shipborne GNSS is indeed much larger the -0.03 mm bias between ground-based GNSS and HY-2A. We have added new information about the bias w.r.t. the distance in the revised manuscript after line 267: "When the distance is getting closer (from 200 km to 100 km), the mean bias between shipborne GNSS and HY-2A is getting closer to zero (varies from 0.22 mm to -0.01 mm). The average bias is -0.22 mm within 50 km, which might be caused by the limited sample number (49 crossovers)."

According to Figure 7, mean difference between HY-2A and GNSS is 0.22 mm, 0.20 mm, -0.01 mm and -0.30mm, for threshold distance equal to 200 km, 150 km, 100 km an 50 km. Since 'mean differences' are simply biases, where the value of mean bias equal to 0.32 come from? In addition from what Authors mention results that the biases are not obvious and rather indicate high compliance between PWV from shipborne GNSS and from HY-2A. In my opinion the bias is clearly positive and clearly negative between the two extreme thresholds (50 km and 200 km). I do not see any comment about that. This is strongly related to the Authors 'threshold' for significance bias, which I mention before.

Generally, the results for ground-based and shipborne GNSS should be rewritten to avoid such misunderstandings as I mentioned above.

Response: Thank you so much for your advice again, we are truly sorry for the mistake. The mean bias 0.32 mm should be 0.22 mm for the distance of 200 km. In line 267, we revised the manuscript accordingly: "The average bias is 0.22 mm for the distance of 200 km with a much larger STD value (2.80 mm)."

The mean bias in different distance changed from positive to negative between the two extreme thresholds (50 km and 200 km), we added the explanation after line 267 as mentioned in the last comment.

Section 5 is not conclusions section. Is rather a (very) short summary of obtained results, without critical and interesting findings which are necessary in such section. There is also no references to similar studies.

After all, could Authors provide more explanation about including shipborne GNSS in this paper. It is not clear why they decided to analyze this data, since (from the selection of only coastal ground-based GNSS stations) the main activity of this study is rather related to the 'problematic' coastal area, than to the clear oceans. Please add some information to the text.

Response: Thank you so much for the suggestion. We revised the manuscript accordingly:

"Water vapor over oceans is essential for both the altimeter correction and the understanding of climate system and weather processes. Therefore, retrieving and validating HY-2A CMR PWV become critical. HY-2A PWV is mainly validated with NWM and other satellite (Wang et al., 2014; Zhao et al., 2016). Liu et al. (2019) investigated the agreement of shipborne GNSS and HY-2A CMR PWV, where more attention was paid to the GNSS-PWV uncertainty.

In this study, we focus on the HY-2A PWV evaluation on a global scale validation with GNSS observations. The HY-2A PWV observations in coastal regions were carefully checked and those suffer from land contamination were reconstructed using PWV products from NWM. The PWV height correction was applied to the ground-based GNSS stations to remove the height-related variations. The result shows that HY-2A PWV agrees well with the ground-based GNSS PWV with an RMS value of 2.67 mm with no obvious system bias. Besides, we compared shipborne-GNSS-derived PWV and HY-2A PWV, which shows the difference of 1.53 mm in RMS within 100 km. The shipborne-GNSS reveals a better agreement than the ground-based result, which because the residual error from the HY-2A reconstruction and ground-based GNSS PWV height correction, and the complex topography in coastal regions could be another reason.

Since HY-2A, after its operation for more than seven years, is facing the problem of inaccurate CMR data, e.g., biased PWV and ZWD caused by the aging of observation device. Although the agreement between HY-2A and ground-based GNSS is relatively worse, the ground-based could provide long-term observation globally with relatively high accuracy. With the supplement of shipborne GNSS observations, the new validation method using GNSS observation can play a critical role in the calibration of HY-2A CMR data, and improve the accuracy of HY-2A data for both altimeter correction and meteorological study."

We added the explanation the reason to analyze shipborne GNSS after line 254:

"The coastal GNSS can be combined with shipborne kinematic GNSS, which can also obtain high accuracy WTC (Wang et al. 2019), and shipborne GNSS observations in open-sea regions provide an accurate and direct method for the satellite altimetry comparison and validation, which is free of any land contamination or height correction error. The shipborne GNSS observations could be a very good supplement for the validation using GNSS observation and extend the method to open-sea. More than 160,000 vessels are sailing across the ocean daily (https://www.marinetraffic.com), and these data can also be used for calibration if the vessels are equipped with geodetic GNSS receiver and antenna. "

Wang, J., Zhang, J., Fan, C., and Wang, J.: Validation of the "HY-2" altimeter wet tropospheric path delay correction based on radiosonde data, Acta Oceanologica Sinica, 33, 48-53, 2014.

Wang J et al. (2019) Retrieving Precipitable Water Vapor From Shipborne Multi-GNSS Observations. Geophysical Research Letters, 46(9):5000–5008.

Zhao, J., Zhang, D., Wang, Z., and Li, Y.: The validation of HY-2A ACMR retrieval algorithms and product, Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International, Beijing, China, 2016, 411-413, 2016.

Liu, Liu, Y., Chen, G., and Wu, Z.: Evaluation of HY-2A satellite-borne water vapor radiometer with shipborne GPS and GLONASS 355 observations over the Indian Ocean, GPS Solutions, 23, 87, https://doi.org/10.1007/s10291-019-0876-5, 2019.

Figure 1, Please avoid in legend such shortcuts as "With" and "Without". The Figure should be prepare in the way, which will make it possible for anyone to understand it content, without referring to the text.

Response: Thank you for the suggestion. We revised the Figure 1 as suggested.

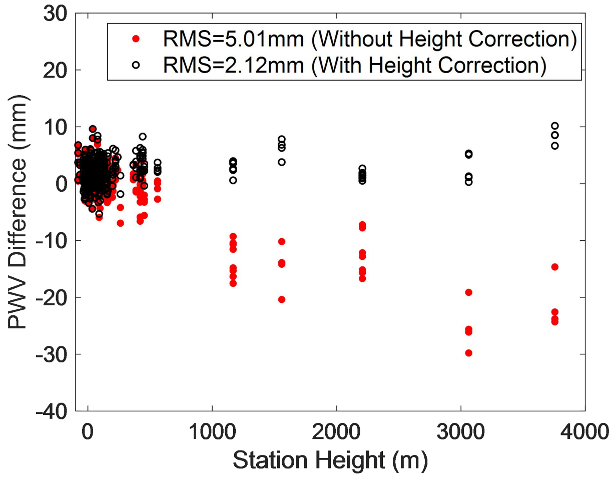
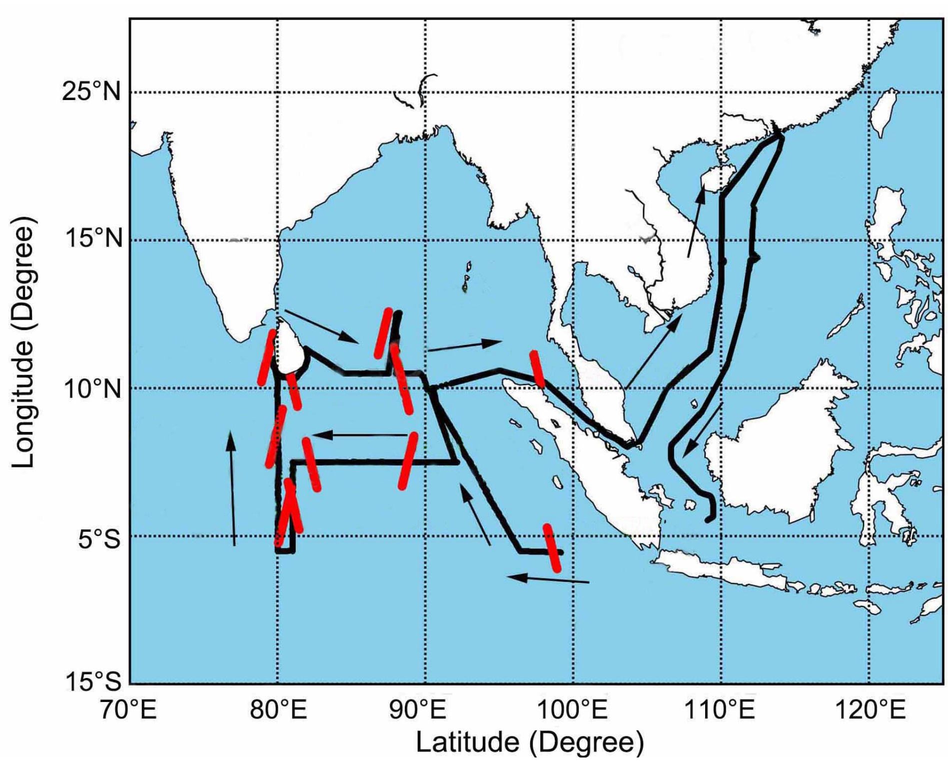


Figure 4 has to be improved. The crossover time cannot overlap the crossover point, especially when green and red colors are used, because it makes it difficult to read them. The crossover time should not also overlap with the ship trajectory.

Response: Thank you for the suggestion. We revised the Figure 4 as suggested.



Response to Reviewer #2

The author needs to read the guidelines for acronyms. Where should you use them and where should you define them in manuscript is a basic background knowledge for scientific writing. Line 12, please provide the full name of acronym PWV. Line 14, I understand HY-2A is Haiyang-2A, but you need to add this to the end of Haiyang-2A for clarification. Line 18, what is RMS? Line 30, Acronyms MODIS, FY-2C? SSM/I, TMI?

Response: Thank you for the suggestion. We are so sorry about our mistake. We revised the manuscript accordingly:

Line 12 is revised as "Ground-based Global Navigation Satellite Systems (GNSS) provide precise precipitable water vapor (PWV) with high temporal resolution"

Line 10 is revised as "The calibration microwave radiometer (CMR) onboard Haiyang-2A (HY-2A) satellite"

Line 15 is revised as "... using ground-based GNSS observations of 100 International GNSS Service (IGS) stations along ..."

Line 18 is revised as " Geographically, the root-mean-square (RMS) is 1.12 mm in the polar region ..."

Line 29 is revised as "satellite-borne infrared sensors (e.g. Moderate-resolution Imaging Spectroradiometer, Fengyun-2C) and microwave radiometers (Special Sensor Microwave/Image, Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI))"

The result section is largely based on the separation of clean and contaminated pixels. But I don't see a clear validation and explanation of how the author did this.

Response: Thanks a lot for your comments. Before the validation, the raw HY-2A PWV observations were processed with a outlier detection method, and coastal observation reconstruction was implemented. The reconstruction method of contaminated HY-2A PWV is described from line 150 to line 160, and the HY-2A CMR observations (DOY 123 and 128, 2014) in Southeast Asia were used as an example to illustrate the coastal PWV reconstruction (line 161 to 175).

The separation from 200km, 150km, until 50km is nice, but the data points are too little. Overall 600+ points is quite small for this kind of comparison. Since you already have the automatically methods for running this analysis, I would highly suggest to extend the running to at least one full year.

Response: Thanks a lot for your comments. We acknowledge the number of cross-points was limited in this study due to original GNSS observations. The limiting aspect of the study is the small number of points examined. And even fewer number of days which make the result not very much representative of general conditions. To better assess the HY-2A CMR bright temperature measurements and the PWV retrieving algorithms, more spatially distributed open-sea GNSS observations are needed, including those from various kinds of ships or buoys.Thank you so much for your advice again and we are planning to collect more GNSS observations (more than one year) to extends my research.

Line 15, coastline along China or India? Before you submit a paper, it is always a good practice to get a second opinion. You are familiar with all the acronyms and station set ups, but not the readers.

Response: Thank you for the suggestion. We revised the manuscript accordingly:

"100 IGS stations along the global coastline "

Line 25, reference is needed here

Response: Thanks a lot for your suggestion. We revised the manuscript accordingly:

"Sea surface height measurement is mainly implemented by satellite altimetry, where the precise tropospheric delay is required to correct the atmosphere propagation error in the measured distance between satellite and sea surface (Obligis et al., 2011) "

Obligis E, Desportes C, Eymard L, et al. Tropospheric corrections for coastal altimetry[M]//Coastal altimetry. Springer, Berlin, Heidelberg, 2011: 147-176

Line 51, over the sea and over the land.

Response: Thanks a lot for your comments. We revised the manuscript accordingly:

"where it happens very often that one footprint covers partly over the sea and partly over the land "

Line 71, delete the first and. The full sentence from line 71-72 needs to be rewritten. Grammar mistake.

Response: Thank you so much for your advice again, we are truly sorry for the mistake. We revised the manuscript accordingly:

"In this section, we introduced the processing strategy of ground-based and shipborne GNSS observations. The height correction for PWV of ground-based GNSS was also discussed. "

Line 74, ECMWF is a large dataset, what exactly did you based on here?

Response: Thank you so much for the comment. We revised the manuscript accordingly:

"Then we presented the HY-2A CMR retrieval method and the reconstruction algorithm of coastal HY-2A CMR contaminated data based on European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim layer data"

Line 123-127, more detailed coefficients calculation used here is needed. If you are using any standard lookup table, the reference should be provided

Response: Thank you for the suggestion. The data we used is level 2 product, which is from National Ocean Satellite Application Center (NSOAS), Ministry of Natural Resources (MNR) of China, and our paper is focus on the validation of level 2 product (PWV data). We revised accordingly:

"This procedure is referred as the calibration of CMR data and should be carried out carefully and updated in time in order to obtain accurate PWV observations. In our study we used the product from National Ocean Satellite Application Center (NSOAS), Ministry of Natural Resources (MNR) of China."

Line 139-141, you named all the potential problem, what is you solution? Just say be careful is not enough.

Response: Thank you for the suggestion. We find the potential problem of CMR PWV data, therefore, we propose a method to reconstruct the contamination CMR data after line 143:

"...Therefore, a linear fitting of HY-2A CMR PWV could be used for quality control in principle. ..."

Line 158-159, what is clean points? On both side how? How did you get the clear points? Figure 2 Still what defines a clean point? Contaminated points? The better way is to first describe how the points are classified (more figures), then show a scatter plot of the PWV point' s correction result. The current figure is very confusing.

Response: Thank you for the suggestion. The contaminated points are the CMR abnormal PWV data causing by the signal from land. The clean points are original HY-2A CMR PWV without contamination. We revised the manuscript accordingly:

"In this study, the vertical integral of water vapor (VIWV) from ERA-Interim surface product was used, where the PWV differences between HY-2A CMR and ECMWF at crossover points should be small and stable. Those with extremely large values (differences over three times of the standard deviation value of the differences) were considered as contaminated points, and the remaining CMR data were taken as clean points."

Line 176-179, consider delete this paragraph, the sentences are useless and contain several gramma mistakes.

Response: Thank you for the suggestion. We deleted this paragraph.

Line 184, the word complicated will raise concerns. Please elaborate on the advantage and disadvantages of the processing algorithm or packages.

Response: Thank you for the comment. Before the validation, we need to pre-process raw CMR data. The CMR data flagged with "land" and "ice" were removed firstly, and then CMR data that the footprints within 100 km to GNSS sites were selected. The integral of water vapor (VIWV) from ERA-Interim surface product was used, and those with extremely large values (differences over three-time of the STD value of the differences) were considered as contaminated points. The pre-processing can help to find the coastal contaminated points and make preparation for the reconstruction, which make the validation result realiable.

Line 193, mislabeling Figure 3. Check the rest of figure labeling, most of them needs updates.

Response: Thank you for the suggestion. We revised the label of the Figure 3 and other figures in the manuscript.

Line 203, how did you come up with the criteria of 200 km and 2 hours, any histograms to show the overlapping points so that these criteria can be trusted?

Response: Thank you for the comment. Research shows that successive zenith wet delay estimates are significantly correlated for up to 1.7 hours (El-Mowafy A et.al., 2011). And a troposphere delay resolution of 1 or 2 hours is usually used in GNSS processing (Snajdrova K et . al., 2006; Geng J et. Al., 2012). Larger temporal resolution might miss the real signals, while too small temporal resolution might cause low robustness of the solution (especially for kinematic platforms). Wet delay is nearly proportional to the PWV. Therefore, we take 2 hours as the time criteria. There are only 49 crossovers when the distance criteria is 50 km, so we loose the distance criteria to 200 km to have more crossover points for comparison.

El-Mowafy A, Lo J. Prediction of troposphere wet delay [J]. Journal of Applied Geodesy, 2011, 5(3-4): 163-173.

Geng J, Williams S D P, Teferle F N, et al. Detecting storm surge loading deformations around the southern North Sea using subdaily GPS[J]. Geophysical Journal International, 2012, 191(2): 569-578.

Snajdrova K, Böhm J, Willis P, et al. Multi-technique comparison of tropospheric zenith delays derived during the CONT02 campaign [J]. Journal of Geodesy, 2006, 79(10-11): 613.

Validating HY-2A CMR Precipitable Water Vapor Using Ground-based and Shipborne GNSS Observations

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Abstract. The calibration microwave radiometer (CMR) onboard Haiyang-2A (HY-2A) satellite provides wet tropospheric delays correction for altimetry data, which can also contribute to the understanding of climate system and weather processes. Ground-based Global Navigation Satellite Systems (GNSS) provide precise precipitable water vapor (PWV) with high temporal resolution and could be used for calibration and monitoring of the CMR data, and shipborne GNSS provides accurate PWV over open oceans, which can be directly compared with uncontaminated CMR data. In this study, the HY-2A CMR water vapor product is validated using ground-based GNSS observations of 100 International GNSS Service (IGS) stations along the global coastline and 56-day shipborne GNSS observations over the Indian Ocean. The processing strategy for GNSS data and CMR data is discussed in detail. Special efforts were made to the quality control and reconstruction of contaminated CMR data. The validation result shows that HY-2A CMR PWV agrees well with ground-based GNSS PWV with 2.67 mm in root-mean-square (RMS) within 100 km. Geographically, the RMS is 1.12 mm in the polar region and 2.78 mm elsewhere. The PWV agreement between HY-2A and shipborne GNSS shows a significant correlation with the distance between the ship and the satellite footprint, with an RMS of 1.57 mm for the distance threshold of 100 km. Ground-based GNSS and shipborne GNSS agree with HY-2A CMR well ~~with no obvious system error~~.

1 Introduction

Sea surface height measurement is mainly implemented by satellite altimetry, where the precise tropospheric delay is required to correct the atmosphere propagation error in the measured distance between satellite and sea surface (Obligis et al., 2011). Since the wet delay which can also be quantified by precipitable water vapor (PWV) in meteorology changes rather fast in space and time, the wet delay is measured with onboard water vapor radiometers. On the other hand, PWV is an essential factor in weather and climate system (Randall et al., 2007), especially PWV over oceans plays a paramount role, as more than 80% of atmospheric water vapor comes from the marine. Until now, PWV over ocean is mainly obtained by satellite-borne infrared sensors (e.g., Moderate-resolution Imaging Spectroradiometer, Fengyun-2C~~MODIS, FY-2C~~) and microwave radiometers (e.g., Special Sensor Microwave/Image, Tropical Rainfall Measuring Mission ' s Microwave Image~~SSM/I, TMI~~) (Nelson et al., 2016), and its spatial and temporal resolution can be improved if PWV of altimeter satellites, such as Haiyang-2A (HY-2A) can be included.

HY-2A is a Chinese ocean observation satellite launched on August 15, 2011, operating in a sun-synchronous orbit. The objective of HY-2A is to monitor the dynamic ocean environment, with microwave sensors to detect sea surface wind field, sea surface height, and sea surface temperature. It is equipped with a dual-frequency (13.58 GHz and 5.2 GHz) altimeter, a calibration microwave radiometer (CMR), a microwave scatterometer, and a scanning microwave radiometer (Jiang et al., 2012). The HY-2A CMR is a nadir-looking passive radiometer with three frequencies (18.7 GHz, 23.8 GHz, and 37 GHz) and the footprint of CMR is ~40 km (Wang et al., 2014). The wet delay and PWV retrieved from CMR measured brightness temperature (TB) were used for satellite altimetry observations correction and marine weather observation as well (Zhang et al., 2015).

Although HY-2A CMR was calibrated in the laboratory before launching (Zhang et al., 2014), due to the quite different space environment, in-orbit validation was carried out subsequently. The onboard validation was mainly conducted by comparing the PWV of HY-2A CMR with that of other altimetry satellites, e.g., Jason 1/2 (Zheng et al., 2014a), or using numerical weather model (NWM) and radiosondes (Wang et al., 2014;Zhao et al., 2016). Furthermore, microwave components will inevitably have aging phenomena, for instance, the Jason-1 and ENVISAT wet tropospheric delay have a drift of 1 mm per year (Brown, 2013;Obligis et al., 2006). The HY-2A altimetry values also show systematic biases in space and time (Peng 2015; Yang et al. 2016), and the wet tropospheric delay drift is confirmed as one of the reasons (Peng 2015). Moreover, a hardware problem of 18.7 GHz band since June 2017 was reported (Wu et al., 2019). Therefore, the long-term validation and calibration of CMR data are vital for HY-2A applications.

Furthermore, in the observation of HY-2A CMR, only TB measurements over the ocean can be converted into PWV, the measurement in transition areas, where it happens very often that one footprint covers partly on the sea and partly on the land surface, will be contaminated. Special handling and specific quality control measures should be imposed (Brown, 2010;Fernandes et al., 2003;Fernandes et al., 2010).

GNSS observations have been used for atmosphere sounding since the 1990s (Bevis et al., 1992;Bevis et al., 1994;Manandhar et al., 2018). PWV of an accuracy of 2 mm can be retrieved from ground-based GNSS observations (Gendt et al., 2004;Li et al., 2015;Wang and Liu, 2019) and has been successfully used for NWM assimilation (Gutman et al., 2004). Meanwhile, GNSS PWV retrieval using moving platforms over the ocean, such as ship and buoy, has been demonstrated with an accuracy of 1-3 mm (Kealy et al., 2012;Rocken et al., 2005;Wang et al., 2019). Therefore, GNSS PWV from coastal stations and especially that from moving platforms over the ocean could be a resource with higher accuracy and resolution for validating and potential calibrating HY-2A CMR data. Liu et al. (2019) investigated the agreement of shipborne GNSS PWV over the Indian ocean and HY-2A CMR PWV, where more attention was paid to the GNSS-PWV uncertainty, i.e., the influence of ZTD estimates from different software, the potential error induced by weighted mean temperature and atmospheric pressure, etc. And a strict criteria was applied when choosing the crossovers to ensure the best agreement, which results in only 4 crossovers used. In this paper, we focus more on the HY-2A PWV evaluation on a global scale using 100 ground GNSS stations, and the potential agreement between shipborne GNSS PWV and HY-2A observation under different distance criteria was also discussed.

The paper is arranged as follows. Section 2 presents the data processing strategy, including the PWV retrieval from both ground-based and shipborne GNSS observations, and the reconstruction and quality control of HY-2A PWV of coastal footprints. Section 3 introduces the data used in the study including HY-2A CMR PWV, ground-based and shipborne GNSS observations. Section 4 summarizes the major achievements and conclusions.

2 Processing method

In this section, we ~~first~~ introduced the processing strategy of of ground-based and shipborne GNSS observations.~~PWV retrieval from ground-based and shipborne GNSS, and t~~The height correction for PWV of ground-based GNSS was also discussed. Then we presented the HY-2A CMR retrieval method and the reconstruction algorithm of coastal HY-2A CMR contaminated data based on European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim layer data.

2.1 GNSS data processing

The ground-based and shipborne GNSS (GPS+GLONASS or GPS) data were processed using the Position And Navigation Data Analyst (PANDA) (Liu and Ge, 2003;Shi et al., 2008) in static and kinematic Precise Point Positioning (PPP) mode, respectively.

GNSS data from 100 IGS stations during DOY 91-147 in 2014 were collected. In the processing, ionosphere-free pseudo-range and phase observations were used with a cut-off elevation angle of 7°. The precise satellite orbit and clock products from GeoForschungsZentrum (GFZ) were used. Satellite and station antenna phase center offsets and variations were corrected using the IGS antenna file (igs08.atx), and the phase wind-up was fixed (Wu et al., 1993). The station displacements caused by solid earth tides, ocean tides, and pole tide were removed following the IERS 2010 Convention (Petit and Luzum, 2010).

The pressure and temperature from global pressure and temperature (GPT) (Böhm et al., 2007) were used to derive a priori hydrostatic and wet zenith delays with Saastamoinen model (Saastamoinen, 1972). Global mapping function (GMF) (Böhm et al., 2006) was used to map zenith delay to the satellite signal transmitting path. ZTD was estimated as a random walk process with a noise power density of 5 mm/$\sqrt{h}$ (Kouba and Héroux, 2001), and the horizontal tropospheric gradients every two hours as random walk parameters with 1 cm/$\sqrt{h}$ power density.

For the 30-sec resampled shipborne GPS+GLONASS observations, the processing strategy is similar but in kinematic mode, where the receiver antenna coordinates were estimated as epoch-wise parameters. The pressure data was from the shipboard equipment.

Afterward, ZWD was derived by subtracting ZHD from the estimated ZTD where ZHD was calculated from the ERA-Interim layer pressure data provided by ECMWF (Dee et al., 2011). Then ZWD was converted to PWV with the following equation:

$$\mathrm{PWV} = \frac{10^6}{\rho_w R_v [(k_3 / T_m) + k_2']} (\mathrm{ZTD\text{-}ZHD}) \rho_\omega \tag{1}$$

where ρ_w is the liquid water density, R_v = 461.495 J/(kg•K), which is water vapor specific gas constant, k_2' =22.97 K/hPa, k_3 =375463 K^2/hPa (Böhm and Schuh, 2013). T_m is the atmosphere weighted mean temperature derived from the ERA-Interim product (Davis et al., 1985). The uncertainty of ground-based GNSS PWV is less than 1 mm (Ning et al., 2016) and the uncertainty of shipborne GNSS PWV is less than 3 mm (Liu et al., 2019).

For comparison, GNSS derived or PWV must be aligned to the same elevation as the HY-2A PWV observations. The orthometric height of stations were calculated as the ellipsoid height from GNSS positioning minus the geoid undulation from the Earth Gravitational Model 2008 (EGM2008). The height correction based on ERA-Interim layer data is as follows: (1) for each station, calculating the ERA-Interim PWV values at the station elevation and at sea level (2) the PWV difference between these two elevations is used as the PWV height correction; (3) realigning the GNSS PWV to sea level by adding the ERA-Interim derived PWV height correction to the original GNSS PWV.

Fig. 1 shows the biases between ECMWF PWV and GNSS PWV before and after the height correction on all the GNSS stations along with station height. The apparent height-related bias is reduced significantly, especially for the five stations over 1000 m. It should be mentioned that the PWV difference scatters at each station are also improved because of height correction. In general, the corresponding PWV RMS is reduced to from 5.01 mm to 2.12 mm.

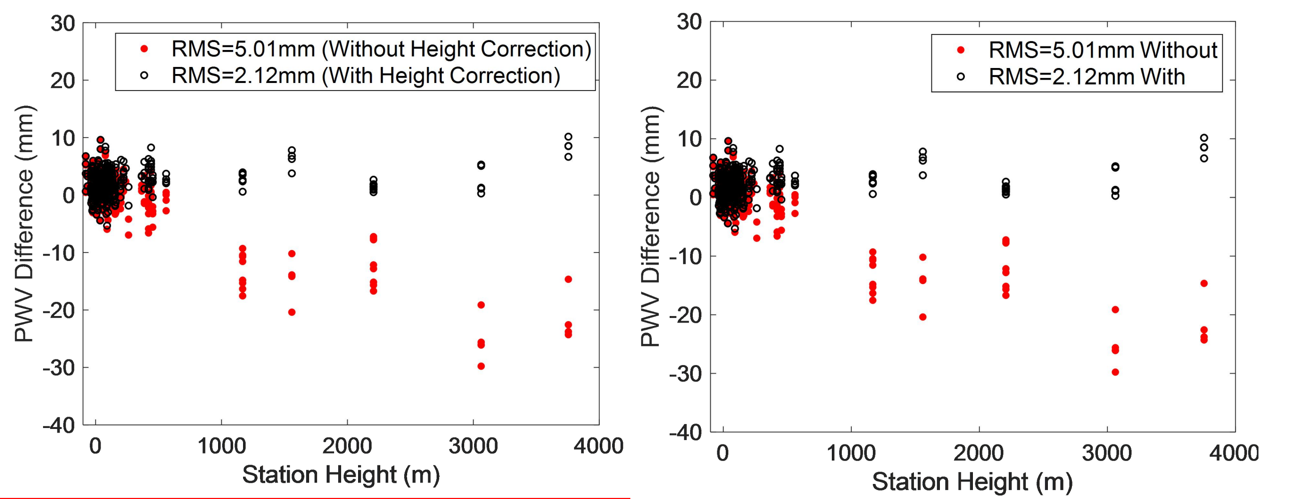


Figure 1. PWV biases between GNSS and ECMWF at all the GNSS stations without (red dots) and with (black cycles) height correction.

2.2 HY-2A PWV observation processing

The processing of HY-2A CMR contains three steps: antenna temperature calibration, TB adjustment, and PWV retrieval. The first two steps have been done by the data provider during the conversion from level 0 to level 1 data, which are not discussed in detail here. In this study, we focus on the validation of level 2 data.

The PWV retrieval algorithm of HY-2A CMR uses an empirical regression model based on the TB values from level 1 and PWV from the global database (Robinson, 2004). There are mainly two regression models to retrieve water vapor products: neural network algorithm and log-linear regression (Brown et al., 2004;Obligis et al., 2006;Thao et al., 2015). For HY-2A CMR data, the log-linear regression algorithm is widely used (Wang and Zhang, 2008;Zheng et al., 2014b). The model reads as:

$$\mathrm{PWV} = a_0 + a_{18.7} \cdot \ln(b_{18.7} - \mathrm{TB}_{18.7}) + a_{23.8} \cdot \ln(b_{23.8} - \mathrm{TB}_{23.8}) + a_{37} \cdot \ln(b_{37} - \mathrm{TB}_{37}) \tag{2}$$

where $TB_{18.7}$, $TB_{23.8}$, TB_{37} are the TB in K of the three frequencies (18.7 GHz, 23.8 GHz, and 37 GHz), respectively. a_0, $a_{18.7}$, $b_{18.7}$, $a_{23.8}$, $b_{23.8}$, a_{37}, b_{37} are the coefficients in the retrieval models. These coefficients must be estimated using external PWV datasets, e.g., NWM, radiosonde profiles, or previous satellite altimetry missions. This procedure is referred as the calibration of CMR data and should be carried out carefully and updated in time in order to obtain accurate PWV observations. In our study we used the product from National Ocean Satellite Application Center (NSOAS), Ministry of Natural Resources (MNR) of China. The uncertainty of the CMR PWV dataset is less than 3 mm according to the 7 years in-flight CMR observations (Wu et al., 2019).

For each transit of HY-2A to a ground GNSS station, there are a number of crossover points at different distances to the station. To avoid the potential large bias caused by a single point, the crossover points within 100 km to the GNSS station are used with the inverse distance weighting (IDW) interpolation:

$$\mathrm{PWV}(s) = \frac{\sum_{i=1}^{N} \omega_i(s)\,\mathrm{PWV}_i}{\sum_{i=1}^{N} \omega_i(s)} \tag{3}$$

$$\omega_i(s) = \frac{1}{d(s, s_i)} \tag{4}$$

where $\mathrm{PWV}(s)$ is the virtual measurement of HY-2A CMR at the GNSS station, $\omega_i(s)$ is the weight value, PWV_i is the PWV of HY-2A crossover point. $d(s, s_i)$ is the distance between the crossover point and the GNSS station, which is always larger than 0 since the GNSS stations locate several kilometers away from the coastline.

From the weight in Eq. (3), we need the CMR observations of the crossover points geometrically close to the ground station. However, the quality of these observations could be rather poor, as they may contain the contribution of reflected signals from both land/ice and ocean, which have different emissivity character. Therefore, HY-2A CMR data quality control is very crucial. First of all, the footprints flagged as “land” and “ice” must be excluded in advance. Then, the footprints flagged as "ocean" close to coastal regions should be checked carefully, due to the potential land contamination where the 40 km footprint may cover both ocean and land but flagged as "ocean".

The sampling interval of HY-2A CMR is 1s and the moving speed of the footprint is approximately 6 km/s, thus the variation of HY-2A CMR PWV between consecutive epochs should be very smooth. Therefore, a linear fitting of HY-2A CMR PWV could be used for quality control in principle. However, for the regions with complex terrain, such as archipelago, where there are more outliers than useful crossover points, the linear fit does not work. Therefore, a reliable external dataset is necessary for quality control. In this study, the vertical integral of water vapor (VIWV) from ERA-Interim surface product was used, and the PWV differences between HY-2A CMR and ECMWF at crossover points should be small and stable.T~~ and t~~hose with extremely large values (differences over three times of the standard deviation value of the differences) were considered as contaminated points, and the remaining CMR data were taken as clean points.~~invalid points.~~

The reconstruction of contaminated HY-2A PWV is usually implemented in the following two scenarios: (1) near the coastline where clean points are available only on the ocean side; (2) near the peninsula or small islands, where clean points before and after the contaminated point are available. The algorithm for the reconstruction of contaminated HY-2A CMR PWV can be summarized as follows (Fernandes et al., 2003):

$$PWV_{hy\_rec} = PWV_{ecmwf} + f(PWV_{hy\_clean}, PWV_{ecmwf\_clean}) \tag{5}$$

where PWV_{hy_rec} is the reconstructed HY-2A PWV at the crossover point, and PWV_{ecmwf} is the ECMWF PWV at this crossover point.

In Eq. (5), $f(PWV_{hy\_clean}, PWV_{ecmwf\_clean})$ is a linear function to calculate the PWV differences between HY-2A CMR and ECMWF at the contaminated crossover points based on the differences of all the clean points. For the first case, the difference is extrapolated using the PWV differences of the clean points on one side; while for the second case, it is interpolated using the PWV differences of clean points on both sides.

The HY-2A CMR observations (DOY 123 and 128, 2014) in Southeast Asia were used as an example to illustrate the coastal PWV reconstruction. The two trajectories of HY-2A traversed Malaysia and Indonesia in parallel, shown in the right panel of Fig. 2, including three representative terrain types, i.e., continental coast, peninsula, and islands. Meanwhile, as the PWV value in this low-latitude coastal area is rather large (>50 mm), a careful reconstruction should be implemented. The reconstruction of contaminated HY-2A CMR data was carried out with the ECMWF as the background field. As shown in the left panel of Fig. 2, the HY-2A PWV observations at coastal areas could be largely biased up to 100 mm, marked with red dots from the clean observations with green dots. By applying the aforementioned reconstruction algorithm, the reconstructed PWV observations show a much better agreement with the clean observations. The average value of the PWV biases between HY-2A CMR and ECMWF was reduced from 5.52 mm to 2.78 mm, while the standard deviation (STD) was reduced from 13.18 mm to 2.71 mm.

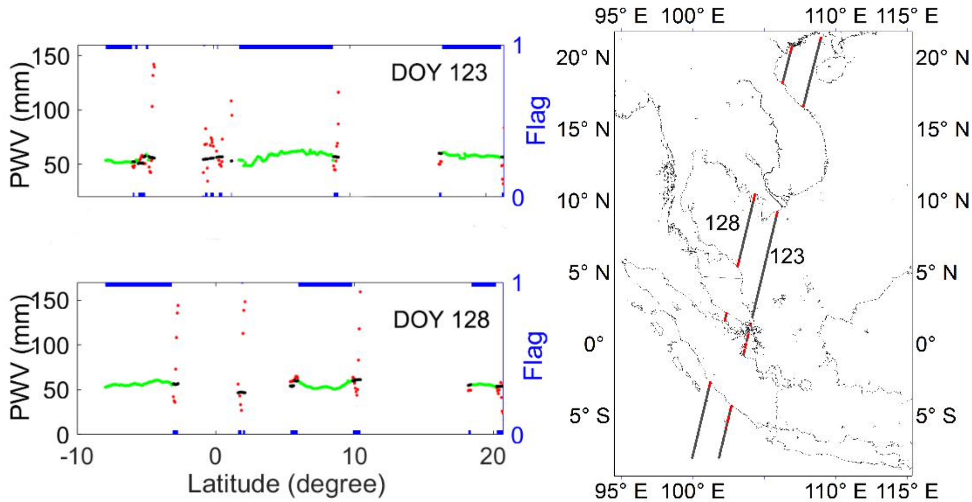


Figure 2. HY-2A PWV observations on DOY 123 (left-upper) and DOY 128 (left-bottom) in 2014, where the clean, contaminated, and reconstructed observations are shown as green dots, red dots, and black dots, respectively. The right Y-axis is the label of clean points (value 1) and contaminated points (value 0). The right panel illustrates the satellite trajectory on DOY 123 and DOY 128, where the clean and contaminated footprints are shown in gray and red dots, respectively.

3 Dataset

~~In this study, the HY-2A CMR PWV was compared to the ground-based and shipborne GNSS PWV. The ground-based GNSS data on the period of DOY 091-146, 2014 was collected and used, which is the same as the ship cruise. In this section, the datasets, i.e., the HY-2A CMR PWV observations, the ground-based GNSS observations, and the shipborne GNSS observations, are introduced.~~

3.1 HY-2A CMR PWV observations

The CMR PWV products used were provided by the ~~National Ocean Satellite Application Center (~~NSOAS~~)~~, ~~Ministry of Natural Resources (~~MNR~~)~~ of China. Two months HY-2A CMR in-orbit data for the period of DOY 91-147, 2014 were used. The raw HY-2A PWV observations were processed with a complicated outlier detection method and coastal observation reconstruction was implemented on the HY-2A PWV observations, as mentioned in Section 2.2.

3.2 Ground-based GNSS observations

Fig. 3 shows the distribution of 100 IGS stations used for the HY-2A CMR PWV comparison, including 46 stations located on islands and 54 stations located on mainland coastline. Each station has at least one crossover point within 100 km compared with the HY-2A sub-satellite point during the experiment period. Most of the stations are below 200 m, and five stations are above 1000 m. The GPS observations were used for all these stations, and the GLONASS observations were used whenever available.

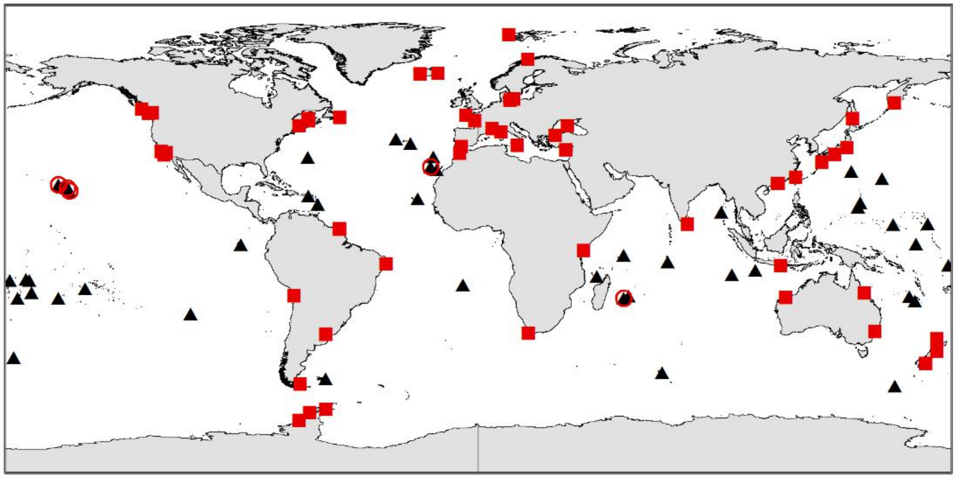
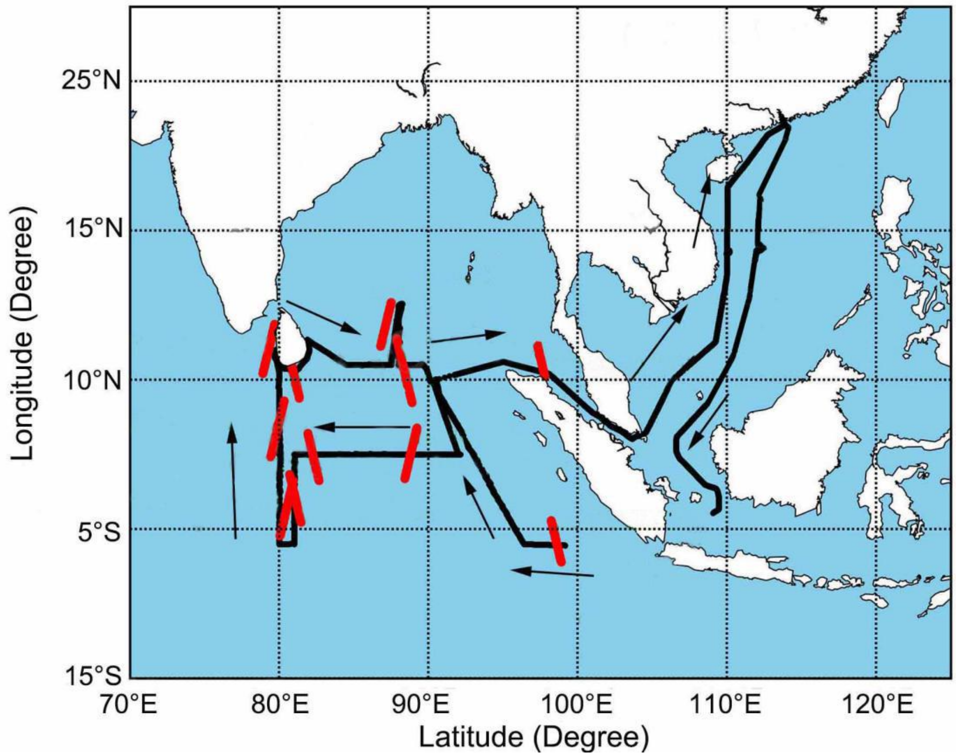


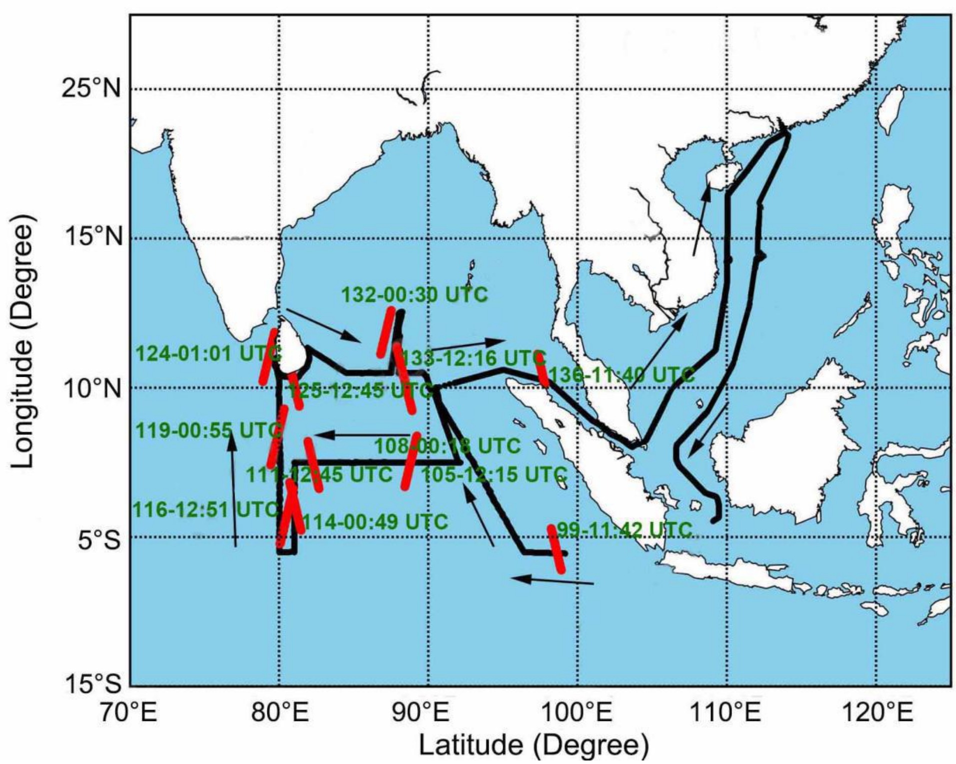
Figure 3. The distribution of GNSS sites within 100 km compared to HY-2A sub-satellite points, including 46 on islands (black triangle) and 56 on the mainland coastline (red square). Five of them (red circle) are higher than 1000 m.

3.3 Shipborne GNSS observations

The scientific survey of the Indian Ocean during DOY 91-146 in 2014 and the ship trajectory is shown in Fig. 4. The voyage started from Guangzhou, China, and went through the Sunda Strait into the Indian Ocean, sailing along the equatorial and arrived in Sri Lanka, finally returned to Guangzhou via the Malacca Strait. The ship was equipped with a TPS NET-G3A GNSS reference receiver to collect 1 Hz GPS+GLONASS data, where the choke ring antenna was used to reduce the multipath effect.

HY-2A satellite moves very fast (~6 km/s) while the speed of the ship is low (maximum ~35 km/h) and the ship track lacks regularity, the crossover points between satellite footprint and ship track are scarce in both time and space. To have more crossover points for comparison, the thresholds in distance and time difference were set to 200 km and 2 hours, respectively. Applying the thresholds, finally, 11 crossover events with 629 crossover points were found, which are shown with red dots in Fig. 4. With such a large number of crossover points, we can also further analyze the impact of different distance thresholds on the PWV comparison. It should be noted that the discontinuity of ship track was caused by the missing of GNSS observations.


25°N
15°N
10°N
5°S
15°S
70°E
80°E
90°E
100°E
110°E
120°E
Longitude (Degree)
Latitude (Degree)


25°N
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90°E
100°E
110°E
120°E
Longitude (Degree)
Latitude (Degree)
132-00:30 UTC
124-01:01 UTC
133-12:16 UTC
136-11:40 UTC
125-12:45 UTC
119-00:55 UTC
108-00:18 UTC
111-12:45 UTC
105-12:15 UTC
116-12:51 UTC
114-00:49 UTC
99-11:42 UTC

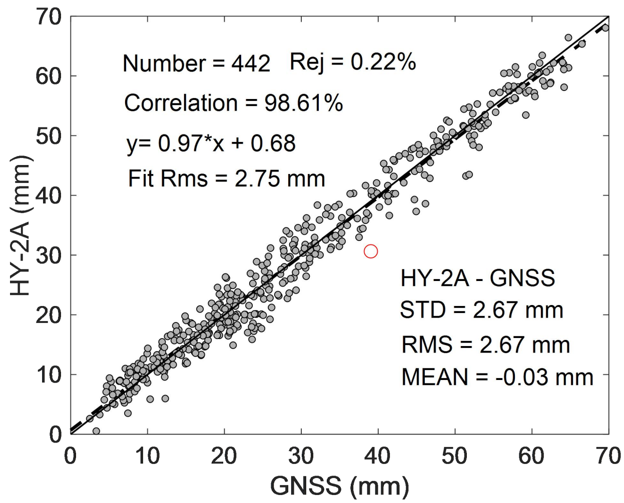
Figure 4. The ship trajectory (black line) and HY-2A crossover points (red dots). There are 11 crossover events.

4 Results and Discussion

In this section, the HY-2A CMR PWV was compared to GNSS PWV and the results were presented, including the comparison to ground-based GNSS PWV and shipborne GNSS PWV. The PWV height correction was applied to all the IGS stations comparison, and the HY-2A PWV observations in coastal regions were reconstructed to avoid the land contamination.

4.1 HY-2A PWV validation using ground-based GNSS

The HY-2A PWV observations of two months data were compared with the GNSS PWV on the 100 coastal stations. Analysis of the comparison results of the two sets is in the top panel of Fig. 5, while the detailed statistics of all crossover points in different latitude regions are shown in the bottom panel, where the PWV differences in polar regions (>66.5°), tropical area (23.5°N - 23.5°S) and mid-latitude regions (23.5° - 66.5°) were presented.



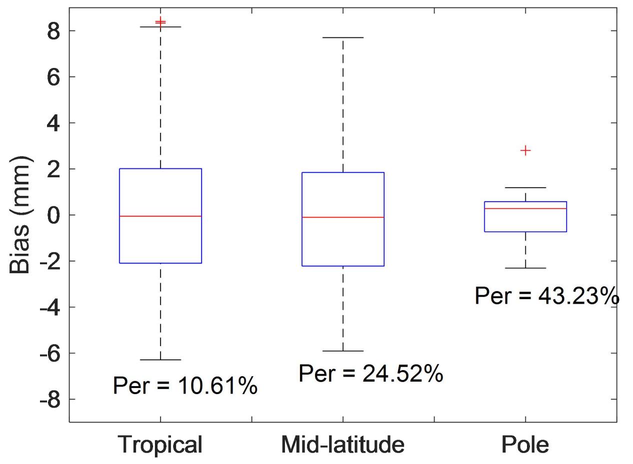


Figure 5. PWV difference between HY-2A and ground GNSS. The top panel shows PWV scatter diagram of HY-2A observations and GNSS results, the linear fit result is the solid line and the dashed line is the reference line, and red circles are outliers. The bottom panel shows boxplot of the difference between HY-2A and GNSS at tropical regions, mid-latitude regions, and pole regions. The blue box describes the upper and lower quartiles, the red line inside the box is median values, the whiskers are 1.5 times the interquartile range (IQR), and the red open cross-hatches describe data outliers, Per means the average ratio of the RMS to derived PWV of the region.

The top panel of Fig. 5 shows the scatter of HY-2A CMR PWV and ground-based GNSS PWV and linear fit result, in which about 0.22% of the total points with a difference larger than three times of STD were excluded. The HY-2A PWV shows a good agreement with the GNSS PWV with an average bias of -0.03 mm, and the RMS is 2.67 mm. No systematic bias is revealed and a high correlation coefficient of 98.61% is achieved. As shown in the bottom panel, the difference in polar regions is smaller than that in other regions; the upper and down quartile are -2.31 mm and 1.18 mm, respectively, with an average value of 0.27 mm and an RMS value of 1.12mm. The relative PWV error (PWV bias / PWV value) in polar region (43.23%) is much larger than that in other regions. On the other hand, the PWV RMS in lower and middle latitude regions is 2.78 mm, partially because of the large PWV content in these regions. It should also be noted that all the stations used in this comparison are located in coastal regions, which usually has a larger PWV. The PWV agreement between HY-2A and ground-based GNSS does not show an obvious correlation with latitude.

Moreover, for each GNSS station, the statistics of PWV differences of all the crossover points at different times were calculated and together with the average distance to the crossover points. The relationship between the PWV differences and the averaged distance and GNSS station height is shown in Fig. 6. As shown in the left panel of Fig. 6, both the average value and STD of the PWV differences between HY-2A and GNSS show no correlation with the averaged distance ranging from 40 km to 95 km, indicating that the HY-2A reconstructed PWV observations are free of land contamination. However, it should be noted that in the left panel the distance is varying from 40 km to 90 km, thus this conclusion does not indicates the case of distance less than 40 km. The right panel confirms that the PWV differences have no correlation with station height, which means that the PWV height correction at ground-based GNSS stations is effective.

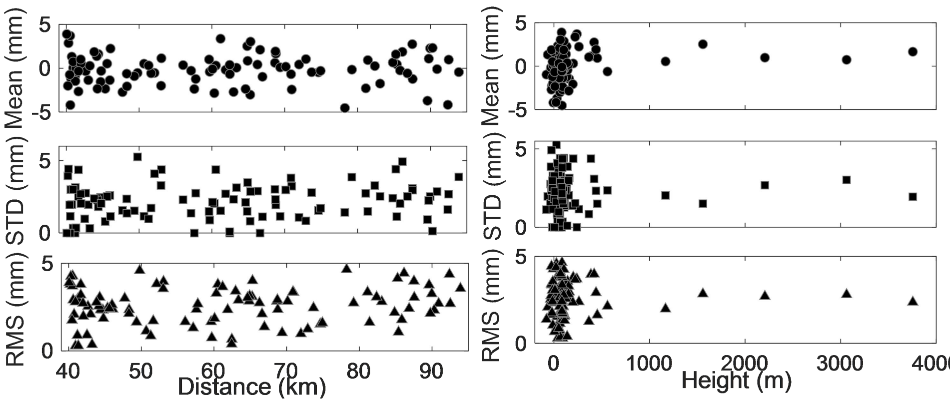


Figure 6. The statistics of PWV differences between HY-2A and ground-based GNSS w.r.t. the distance between HY-2A footprint (left panel) and GNSS stations and the station height (right panel).

4.1 HY-2A PWV validation using shipborne GNSS

Although ground-based GNSS can provide long-term PWV with certain accuracy for the validation of HY-2A CMR, the validation could still suffer from contaminated CMR data by the signal on the land, long distance between GNSS station and footprint, and GNSS height, especially for higher accuracy of validation based on GNSS~~data of higher precision~~. The comparison result could be affected by the residual error after correction. The coastal GNSS can be combined with shipborne kinematic GNSS, which can also obtain high accuracy WTC (Wang et al., 2019), and shipborne GNSS observations in open-sea regions provide an accurate and direct method for the satellite altimetry comparison and validation, which is free of any land contamination or height correction error. Therefore, the shipborne GNSS observations could be a very good supplement for the validation using GNSS observation and extend the method to open-sea. More than 160,000 vessels are sailing across the ocean daily (https://www.marinetraffic.com), and these data can also be used for calibration if the vessels are equipped with geodetic GNSS receiver and antenna.~~On the other hand, shipborne GNSS observations in open-sea regions provide an accurate and direct method for the satellite altimetry comparison and validation. The validation of HY-2A PWV using shipborne GNSS observations was presented in this section.~~

As mentioned before, with the threshold of 200 km and 2 hours, the number of the crossover events between HY-2A and GNSS are 11 days with 629 crossover points in total, which is shown in Fig. 4. For each crossover event, the PWV observations larger than three times of the STD value of the differences were removed as outliers, i.e., the 3σ criterion. Among the 629 crossover points, ~4.8% were removed as outliers and the useful number is 599.

To investigate the impact of the space threshold on the PWV validation, the PWV differences of the crossover points defined with space threshold of 200 km, 150 km, 100 km, and 50 km are presented in Fig. 7. As shown in Fig. 7, the PWV agreement between HY-2A CMR and shipborne GNSS decreases with the increase of the corresponding distance threshold.

The RMS within 200 km, 150 km, 100 km, and 50 km are 2.89 mm, 1.78 mm, 1.53 mm, and 0.89 mm, respectively, and the correlation increases from 77% to 98.2%. The outliers (red dots) decrease from 4.77% to 0% when the distance threshold is getting smaller. The linear fit also shows a better agreement when the distance is shorter.

The average bias is 0.22 mm for the distance of 200 km with a much larger STD value (2.80 mm). When the distance is getting closer (from 200 km to 100 km), the mean bias between shipborne GNSS and HY-2A is getting closer to zero (varies from 0.22 mm to -0.01 mm). The average bias is -0.22 mm within 50 km, which might be caused by the limited sample number (49 crossovers). ~~The average bias is 0.32 mm, meaning that there is no obvious systematic bias between HY-2A PWV and shipborne GNSS PWV.~~ Since the variation of PWV is relatively slow over the ocean, the average bias remains small even though the distance comes to 200 km. The agreement between shipborne GNSS and HY-2A data is better than that of the ground GNSS result, which could be caused by the potential residual error of the ground-based GNSS stations due to the PWV height correction and that of the HY-2A observations due to the data reconstruction; the complex topography in coastal regions could be another reason. It should be pointed out that there is no "ideal" method to reconstruct the valid PWV data in coastal region, but it is still necessary to spare no efforts to investigate any useful method to derive "clean" data for inter-technique comparison and validation. Overall, the PWV differences of HY-2A CMR data concerning ground and shipborne GNSS is 2.67 mm and 1.53 mm in RMS for the distance threshold of 100 km.

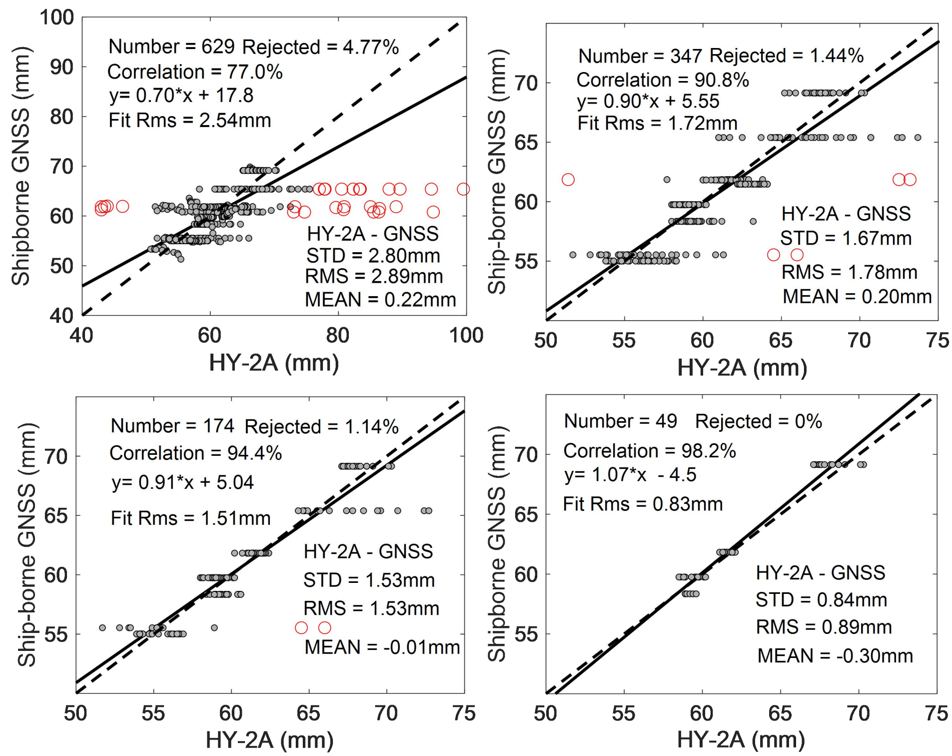


Figure 7. PWV comparison between HY-2A CMR and shipborne GNSS for crossover points with a distance threshold of 200 km (upper-left), 150 km (upper-right), 100 km (bottom-left), and 50 km (bottom-right). The red circles are for outliers, and the linear fit result is

presented as a solid line with its reference in dash line. For each panel, the linear fit is shown in upper-left and the comparison statistics are shown in lower-right.

5 Conclusion

Water vapor over oceans is essential for both the altimeter correction and the understanding of climate system and weather processes. Therefore, retrieving and validating HY-2A CMR WPV become critical. HY-2A PWV is mainly validated with NWM and other satellites (Wang et al., 2014;Zhao et al., 2016). (Liu et al., 2019) investigated the agreement of shipborne GNSS and HY-2A CMR PWV, where more attention was paid to the GNSS-PWV uncertainty.

In this study, we focus on ~~the validation of PWV from~~ HY-2A CMR PWV evaluation on a global scale validation with GNSS observations~~using GNSS PWV, including 100 ground GNSS stations and a 56-day shipborne GNSS observation campaign in 2014~~. The HY-2A PWV observations in coastal regions were carefully checked and those suffer from land contamination were reconstructed using PWV products from NWM. The PWV height correction was applied to the ground-based GNSS stations to remove the height-related variations. The result shows that HY-2A PWV agrees well with the ground-based GNSS PWV with an average bias of -0.03 mm and an RMS value of 2.67 mm. Besides, we compared shipborne-GNSS-derived PWV and HY-2A PWV, which shows the difference of 1.53 mm in RMS within 100 km. The shipborne GNSS reveals a better agreement than the ground-based result, which caused by the residual errors from the HY-2A reconstruction and ground-based GNSS PWV height correction, and the complex topography in coastal regions could be another reason.~~The PWV difference in polar regions is smaller than that in the other areas due to the low PWV content in the polar areas. Comparison with the shipborne GNSS PWV, HY-2A PWV shows an agreement of 0.89 mm in RMS for the 49 crossover points within 50 km, and an agreement of 2.89 mm in RMS for the 629 crossover points within 200 km. Both ground-based GNSS PWV and shipborne GNSS PWV show a good agreement with the HY-2A PWV observations without any obvious systematic bias.~~

~~Based on the validation result, GNSS PWV, especially that retrieved from shipborne data over open oceans, can play a critical role in the calibration of HY-2A CMR data.~~ Since HY-2A, after its operation for more than seven years, is facing the problem of inaccurate CMR data, e.g., biased PWV and ZWD caused by the aging of observation device. Although the agreement between HY-2A and ground-based GNSS is relatively worse, the ground-based could provide long-term observation globally with relatively high accuracy. With the supplement of shipborne GNSS observations, the new validation method using GNSS observation can play a critical role in the calibration of HY-2A CMR data, ~~The new calibration using GNSS PWV can provide precise~~and improve the accuracy ~~HY-2A CMR data~~ for both altimeter correction and meteorological study.

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Data availability. The source codes for the validation and the data of HY-2A and shipborne GNSS used in this study can be provided by the corresponding authors upon reasonable request.

Author contributions. ZW and JW co-designed this research; ZW, JW, XH, YL and XW conducted the data analyses; ZW wrote the manuscript. All authors discussed the experimental results and helped revise the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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