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Comparison of Satellite-derived Precipitable Water Vapor through Near-Infrared Remote Sensing Channels

Jia He, Zhizhao Liu

***Abstract*— The retrieval accuracies of three typical Near-Infrared (NIR) precipitable water vapor (PWV) products are thoroughly discussed in this research. The NIR PWV data are obtained from three satellite sensors: the MODIS/Terra, the MERIS/Envisat, and the MERSI/FY-3A. Collocated GPS PWV data from GPS network are employed as the reference dataset because of its high precision in water vapor measurement. Relative difference and RMS difference are computed for 'Clear', 'Cloudy' and 'All Weather' categories for each NIR water vapor product. The results reveal that PWV derived from NIR sensors tend to underestimate the water vapor values with the existence of cloud, as NIR signals cannot penetrate the cloud. Under 'Clear' condition, the overall RMS for remote sensors are close to the expected goal accuracies, namely, with RMSE of 5.480 mm for MODIS/Terra, 3.708 mm for MERIS/Envisat, 8.644 mm for MERSI/FY-3A. MERIS/Envisat has the highest PWV retrieval accuracy, while MODIS/Terra PWV product has the best correlation with GPS PWV (R^2 is 0.951). The MODIS/Terra tends to overestimate PWV value while MERSI/FY-3A tends to underestimate PWV value. Moreover, a comprehensive comparison of seasonal variation and wet/dry variation for each NIR PWV product is also performed in this study. The results indicate that the RMSE increases significantly under wet condition (PWV larger than 20 mm) than dry condition (PWV smaller than 20 mm) for all remote sensing PWV products.**

***Index Terms*—GPS, Remote Sensing, PWV**

I. INTRODUCTION

Water vapor is one of the most important but also poorly described and least understood components of the atmosphere. It has both direct and indirect influence on weather [1], climate [2] and environment [3]. It contributes significantly to moisture transportation and atmospheric energy exchange [4]. In addition to its importance in determining the sensitivity of Earth's climate, water vapor is also the fundamental driving force behind the formation of clouds and precipitation. The fidelity of its representation in weather forecast models has remained a topic of debate for more than one decade [5]–[8]. Water vapor is also a primary error source for repeat-pass Interferometric Synthetic Aperture Radar (InSAR), especially for long wavelength signals [9]. It is essential to make accurate global water vapor measurements while evaluating the uncertainties in forecast model results, cloud parameterizations and other applications that use water vapor as an input parameter.

Space-based remote sensing technique is an effective way for water vapor observation at a global basis, as it can provide measurements with global coverage at a high spatial resolution and reasonable temporal resolution. For instance, polar-orbiting satellites can sample the whole earth surface, and its water vapor observations can be used for global, long-term climatological studies. Previous studies show that multi-sensory precipitable water vapor data can be employed to identify the characteristics of water vapor [10]–[12].

Remote sensing technique and instrumentation are two major factors that influence the accuracy of water vapor retrieval. Remote sensors are often divided into three categories based on their propagation signals: visible/Infrared (IR) [13], [14] and Near-Infrared (NIR) [15]–[17] observes water vapor with high precision under clear condition, while Microwave [18], [19], as a complement of the optical remote sensing, could provide water vapor information in cloudy condition. Scientists initially retrieved water vapor through IR channels [20], [21]. The NIR observation has been the most popular technique over the past few decades [15], [22], [23]. Moderate Resolution Imaging Spectro-radiometer (MODIS) from Terra and Aqua satellites [15], POLDER from ADEOS [24] and AVHRR from NOAA satellites [25] are all NIR sensors used for precipitable water vapor retrieval globally. Validations of NIR PWV retrieval have been performed at various observation sites and during periods [15], [17], [26]. Research has shown that the root-mean-squares-error (RMSE) between water vapor

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Jia He is with the Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hung Hum, Hong Kong (e-mail: gail.he@connect.polyu.hk).

Zhizhao Liu is with the Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hung Hum, Hong Kong (e-mail: lszzliu@polyu.edu.hk).

retrieved from Global Positioning System (GPS) and MODIS/Terra NIR varies from 5.87 mm to 9.37 mm at two stations in India [26]. Another validation on MODIS NIR product was performed over high altitude region (~4,500 m) of Himalayan, with the RMSE value of 1.37 mm, compared to GPS observation [23]. Moreover, validations on MODIS PWV product in the Iberian Peninsula against GPS data indicated that MODIS strongly overestimated PWV under 5 mm, and the overestimation decreased quickly as PWV increased [27].

Evaluation of multi-sensor water vapor retrieval has been discussed in previous studies using GPS PWV as reference data [10], [12], [17], [28], [29], indicating the similarities and differences among these measurements. However, the problem was that as the study sites vary spatially and temporally, it was difficult to have a reliable analysis of the retrieval accuracy among different satellites. Moreover, some of the previous evaluations were conducted just over a limited area or even a few sites.

In this study, three types of NIR water vapor products from three satellite missions are inter-compared over 370 GPS stations in a large area (lat.: 20°N to 50°N, long.: 63°W to 130°W). The GPS PWV used as reference data are provided by NOAA National center for Environmental Information (NCEI), USA. Products obtained from MODIS operated by the National Aeronautics and Space Administration (NASA), USA [15], [21], Medium Resolution Imaging Spectrometer (MERIS) operated by the European Space Agency (ESA) [30], and Medium Resolution Spectral Imager (MERSI) operated by the China Meteorological Administration/ National Satellite Meteorological Center (CMA/NSMC) [22] are analyzed against the standard reference GPS PWV dataset.

In section 2, the climate condition of the research area is described in detail. Section 3 gives a detailed description of datasets used in this research, including sensor types and observation channels. Section 4 discusses the retrieval algorithms of each PWV product, along with GPS PWV calculation method. Section 5 conducts a comprehensive comparison between NIR remote sensing dataset and GPS PWV results.

II. STUDY AREA

The research area covers a large portion of the North America, with latitudes from 20°N to 50°N, and longitudes from 63°W to 130°W. Its landscape covers land, ocean, and lake/river. A total of 370 observation sites equipped with both GPS receivers and meteorological observation equipment are utilized in this study. To further analyze the performance of NIR water vapor retrieval over different surface types, the stations were classified into two groups by using the MODIS land-mask data. Among them, 271 stations were located over the land/desert surface, and 99 stations were over the water area (lake/river and coastal region). These stations distributed over United States, Canada, and Mexico, and provided continuous water vapor observation data for comparison and quality control. The location of these GPS stations in the study area is displayed in Fig. 1.

As the study region covers both tropical and mid-latitude areas, the climate and geographic features vary from place to place. Geographically speaking, the western continental area is semi-arid to the desert, while it is humid continental in the east part of this area. Most of this study area is in the subtropical zone with warm temperature, hence the precipitation characteristics across the research area differ significantly.

This area has four distinct seasons, winter (December to February), spring (March to May), summer (June to August), and autumn (September to November) [31]. To be specific, it is warm and humid in summer, as the southwest monsoon combines with the moisture from the Gulf of Mexico moving around the subtropical ridge in the Atlantic Ocean, and the humid will spread to the southern part of the research area. Meanwhile, tropical cyclones enhance the precipitation across the southern and eastern sections of the region. Over the northern part of this region, the jet stream brings a summer precipitation maximum to the Great Lakes, and mesoscale convective complexes move through the Plains, Midwest and Great Lakes during the warm season [32].

III. DATASET

Four types of datasets are employed in this comparison, including three PWV products derived from different near-infrared sensors onboard three satellites, and GPS PWV from the GPS network as reference data for inter-comparison. The PWV data for the whole year 2010 are used. A summary of the data characteristics is listed in Table 1 concerning platform, orbit altitude, equator crossing time (ECT), spatial resolution, launch time and observing time. As shown in the table, the three satellites have similar orbital altitudes, and all satellites cross the equator at around ten solar time of descendent orbit. PWV products with spatial resolution around 1,000 m are selected, in order to have a consistent spatial resolution in the comparative analysis.

MODIS is a passive whisk-broom scanning imaging spectro-radiometer onboard the Terra and Aqua satellites operated by NASA. It provides observation of earth atmosphere and earth surface with a global coverage every day using 36 spectral bands at moderate resolution (250-1,000 m). Five NIR channels are used for water vapor measurement. These channels can retrieve water vapor over clear land areas and ocean areas with sun glint [15]. PWV product used in this research is from the Terra platform, with the spatial resolution of 1,000 m.

The MERSI onboard China’s second generation of polar-orbit meteorological satellites is a MODIS-like sensor. It has 20 bands in both visible and NIR channels with a resolution from 250 to 1,000 m. It also has 5 NIR water vapor related channels [22]. Similar to MODIS, only clear areas and extended ocean areas with sun glint can produce PWV retrieval results. In this research, PWV product with the spatial resolution of 1,000 m is obtained from FY-3A satellite.

The MERIS from the Envisat satellite is a passive push-broom imaging instrument measuring surface reflectance in visible and NIR spectral channels during the daytime. It is the core mission of European Space Agency (ESA) for earth observation. MERIS has 15 spectral channels, two NIR channels of which are used in water vapor measurement. In fact, MERIS measures the earth surface with a full-resolution

(300 m) and provides three levels of processing resolutions: full-resolution, reduced resolution (1,200 m) and low-resolution (4,800 m) [33]. The theoretical accuracy for the water vapor estimated from images of MERIS/Envisat is 1.7 kg/m^2 over land and 2.6 kg/m^2 over water for full resolution (FR) [33], [34], and the specified error at reduced resolution (RR) is smaller than 20% [35]. Although the FR product allows for small-scale water vapor measurement with high accuracy, the RR product is the regular operation mode for MERIS [36]. Therefore, the product with reduced resolution is employed in this research, as its spatial resolution is the closest to that of MODIS and MERSI water vapor products.

Details on the spectral information of the three sensors are summarized in Table 2. It shows that the channel design for each sensor is different regarding band center and bandwidth. In addition, both MODIS/Terra and MERSI/FY-3A have three NIR water vapor absorption channels and two window channels, while the MERIS/Envisat has only one absorption channel and one window channel.

These satellites pass the research area between 14:00 to 20:00 UTC and monitor water vapor under either clear or cloudy condition. As NIR cannot penetrate the thick cloud, thus identification of the cloud condition is needed prior to the NIR water vapor retrieval. In this research, the cloud mask from each NIR water vapor product is used to determine the possibility of cloudiness in each pixel. For MODIS and MERSI, the cloud mask algorithm determines if the observing pixel is ‘clear’ by considering several spectral threshold tests [37]. Pixels with the confidence level of 95% clear are defined as ‘clear’, while the rests are considered as cloudy. For the MERIS, the mask is limited to a smaller range of wavelengths and is less robust compared to MODIS. Neither thermal information nor information on liquid and ice water is provided from MERIS cloud mask products.

GPS observed water vapor data are used as reference in this research, as it could provide observations with high spatial and temporal resolution with respect to radiosonde observations [38], [39]. It should be noted that though radiosonde PWV data are used as reference to evaluate GPS PWV, the radiosonde PWV data themselves are not error free. The accuracy of radiosonde PWV is also at mm level. The GPS-derived precipitable water vapor data are obtained from 370 ground-based stations in a GPS network managed by the National Centers for Environmental Information (NCEI), National Oceanic and Atmospheric Administration (NOAA) and U.S. Department of Commerce. All sites are equipped with a GPS receiver, and many are equipped with surface meteorological instrumentation packages. The GPS data are recorded at a temporal resolution of 30 minutes and are processed with the GAMIT software package with precise GPS orbit to estimate zenith tropospheric delay (ZTD). ZTD delays are then combined with surface meteorological information to estimate the precipitable water vapor. The PWV data from this observation network can achieve millimeter accuracy with a sub-hourly temporal resolution [40].

Satellite pixels collocated with GPS stations were extracted to assess the PWV retrieval accuracy of these products. As remote sensors observe the earth surface in a swath, there is a time lag when remote sensing satellites overpass the GPS stations. To reduce errors resulting from the time lag, the allowable time difference between GPS PWV measurements and remote sensing PWV is less than or equal to 15 minutes.

IV. WATER VAPOR RETRIEVAL ALGORITHM DESCRIPTION

Near-infrared channels have been widely used in water vapor retrieval through satellite-based remote sensing technology in many occasions [15], [21], [41], [42]. NIR channels are more sensitive to the precipitable water vapor, in which the apparent surface temperature is close to the mean temperature of the boundary layer, compared to infrared and microwave remote channels [21].

The interpretation of water vapor satellite imagery is based on the radiative transfer theory. The water vapor amount is measured through its effect on transmission absorption when the radiance is transmitted down to the earth surface and reflected to the sensor. The ratio of the NIR channels approximately equals to water vapor transmittance in the Sun-surface-sensor ray path [15]. So, the transmittance in NIR water vapor retrieval is usually calculated by measuring the mean radiance ratio of absorption channel and one or more window channels. Then, through a priori radiative transfer model derived from a large number of atmospheric profiles, the relationship between the measured radiance ratio and the amount of water vapor can be established. Through further calculation with either a lookup table, a regression method, or an artificial neural network, the inverted water vapor amount is estimated [43]. In this case, the accuracy of water vapor retrieval depends on the relationship between the column water vapor content and the radiance ratio of NIR channels.

The quality of NIR water vapor products has been continuously improved throughout these years, attributing to rapid development in sensors and computing methods [15], [44], [45]. In this research, a comparison of three typical NIR water vapor products is discussed in details.

A. *MODIS PWV Products from Terra*

The NIR water vapor data from MODIS/Terra are estimated through sunlight transmittance between 860 nm and 1240 nm, which include three absorption bands and two adjacent channels in atmospheric windows [21].

The radiance at the NIR sensors are approximated as:

$$L_{sensor}(\lambda) = L_{path}(\lambda) + [\mu_0 E_0(\lambda)/\pi] T(\lambda)\rho(\lambda) \quad (1)$$

where $L_{sensor}(\lambda)$ is the radiance at the sensor, λ is wavelength, $L_{path}(\lambda)$ is the path scattered radiance, μ_0 is the cosine of solar zenith angle, $E_0(\lambda)$ is the extra-terrestrial solar flux, $T(\lambda)$ is the total atmospheric transmittance, and $\rho(\lambda)$ is the surface bidirectional reflectance. It should be noted that $\pi L_{sensor}(\lambda)/[\mu_0 E_0(\lambda)]$ is defined as apparent reflectance, denoted as $\rho^*(\lambda)$ [15], [46]. As the influence from aerosol optical thickness is negligible in NIR bands, the $L_{path}(\lambda)$ will be ignored.

Both two-channel and three-channel ratio techniques have been used in MODIS atmospheric transmittance to derive PWV amounts over clear land areas and ocean areas with sun glint. If the surface reflectance is constant with wavelength, a two-channel ratio between an absorption channel and a window channel is considered as the water vapor transmittance. On the other hand, if the reflectance varies linearly with wavelength, a three-channel ratio between an absorption channel and two window channels is considered as water vapor transmittance. Look-up tables for interpolation of MODIS PWV data are generated with a line-by-line radiative transfer program HITRAN2000 spectroscopic database [47].

These absorption channels have different sensitivity reactions over different water vapor concentrations in the atmosphere. The 935 nm channel is a strong absorption channel that is sensitive under dry condition, while the 905 nm channel is a weak absorption channel that is sensitive under wet condition. The water vapor product value (W) is estimated as:

$$W = f_1 W_1 + f_2 W_2 + f_3 W_3 \tag{2}$$

where W_1, W_2 and W_3 are water vapor values retrieved from 905 nm, 935 nm and 940 nm, respectively. f_1, f_2 and f_3 are the corresponding weighting functions written as:

$$f_i = \eta_i / (\eta_1 + \eta_2 + \eta_3) \tag{3}$$

while

$$\eta_i = |\Delta T_i / \Delta W| \tag{4}$$

where T_i is sensitivity of the transmission in each channel.

B. MERSI PWV Product from FY-3A

MERSI onboard of the Chinese FY-3A satellite has20 channels, in which five NIR channels are used for atmospheric water vapor observation [22]. Two channels centered at 865 nm and 1030 nm are window channels, and three channels centered at 905 nm, 940 nm, and 980 nm are water vapor absorption channels.

Water vapor data from MERSI/FY-3A are also calculated using the radiance ratio method. The look-up table, which correlates the transmittance and precipitable water vapor, is pre-computed using atmospheric transmittance code MODTRAN [48]. Ratios observed from MERSI NIR channels are inverted into column water vapor with the look-up table [49]. Based on different sensitivities of absorption channels, each channel can derive one water vapor value. Similar to MODIS PWV product, the MERSI/FY-3A PWV product is also a weighted sum of the water vapor results from three absorption channels [49].

C. MERIS PWV Product from Envisat

The MERIS/Envisat uses two NIR channels centered at 885 nm and 900 nm for water vapor retrieval. Water vapor product from this platform has two spatial resolutions: 300 m for full-resolution (FR) mode and 1,200 m for reduced-resolution (RR) mode. It observes water vapor over land and ocean surfaces under ‘clear’ condition [34], or above the highest cloud level under cloudy condition [50]. The general approach of retrieving the PWV product is to relate the PWV content to the transmittance ratio of MERIS channels [33]. This retrieval model assumes that a logarithmic relation exists between the absorber mass and extinction. Therefore, it reflects Lambert’s law for idealized non-scattering atmosphere, unsaturated absorption and monochromatic radiation [34]. To simplify the calculation process, a neural network, which is trained with Matrix Operator Model (MOMO), is employed over land and water region [51].

Water vapor retrieval algorithm is based on the water vapor content at MERIS channels 14 and 15. The general form of the retrieval algorithm is:

$$\mathrm{W} = k_0 + k_1 \log(R) + k_2 \log^2 (R) \tag{5}$$

$$R = L_{15} / L_{14} \tag{6}$$

where W is the precipitable water vapor, and R is the ratio between L_{14} and L_{15}, which are the radiances measured in MERIS channels 14 and 15, respectively. k_0, k_1 and k_2 are regression parameters [52].

D. GPS PWV

GPS PWV is calculated based on the propagation delays caused by the neutral atmosphere [53]. First, GPS observations with satellite precise orbit and satellite precise clock information are employed to estimate GPS signal zenith tropospheric delay (ZTD) [54]. Signal delays are then combined with surface meteorological information to calculate precipitable water vapor [40].

ZTD can be decomposed into zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). The ZHD calculation equation is as follow [54]:

$$\mathrm{ZHD} = (2.2997 \pm 0.0024)\, P_s / f(\varphi, \mathrm{H}) \tag{7}$$

$$\mathrm{f}(\varphi, \mathrm{H}) = 1 - 0.00266 \cos 2\varphi - 0.00028\mathrm{H} \tag{8}$$

where P_s is the atmospheric pressure (unit: hPa), and φ and H are the latitude and height (unit: m) of GPS site, respectively. Then, ZWD can be calculated using:

$$\mathrm{ZWD} = \mathrm{ZTD} - \mathrm{ZHD} \tag{9}$$

Accordingly, the PWV can be calculated using:

$$\mathrm{PWV} = \Pi \times \mathrm{ZWD} \tag{10}$$

where Π is a scale factor that is usually derived using empirical functions through radiosonde / GPS comparisons [53]. The Π is strongly dependent on the geographic location and the surface temperature measured at the location [55].

V. INTER-COMPARISON OF WATER VAPOR PRODUCT

Daily mean PWV values obtained from GPS, MODIS/Terra, MERSI/FY-3A and MERIS/Envisat are shown in Fig. 2, indicating that PWV data follow a specific seasonal variation trend, PWV values higher during summer months.

GPS PWV results are considered as the baseline as they have better accuracy than remote sensing PWV [29], [40]. The figure indicates that although the variation trend of daily averaged remote sensing PWV agrees well with the GPS results, the PWV derived from MERSI usually underestimates the value while MODIS typically overestimates it. The MERIS PWV results have the best agreement with the GPS-derived ones.

From a seasonal point of view, the daily mean PWV gradually increases from January to May and stays below 20 mm for most of the time. Then the PWV value is consistently above 20 mm during the period from June to August, and then slowly decreases to the level below 20 mm after September. It is reasonable to conclude that water vapor in the study area is associated with the seasonal monsoon in summer (June to August). Further analysis of seasonal observation accuracy is carried out below, and the details of the calculation are shown in Table 3. Winter (December to February), spring (March to May) and autumn (September to November) have relatively low PWV values (we define dry season having a daily mean PWV below 20 mm) while the summer (June to August) has high PWV values (we define wet season having a daily mean PWV above 20 mm).

A. Statistical Metrics

Three statistic metrics are employed to evaluate the retrieval results. They are the root mean square error (RMSE), mean bias (MB), and coefficient of determination (R^2). The root mean square error is defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{N}(PWV_{GPS} - PWV_{RS})^2} \tag{11}$$

where n is the number of data pairs; PWV_{RS} is the PWV column obtained from remote sensors; PWV_{GPS} is the PWV observed from GPS network. The RMSE is used to quantify the PWV differences between remote sensing and reference data.

The MB is used to estimate the mean bias between two sets of PWV data It is defined as:

$$\text{MB} = \frac{1}{n}\sum_{i=1}^{n}(PWV_{GPS} - PWV_{RS}) \tag{12}$$

The coefficient of determination (R^2) can provide strength information between PWV retrieved from remote sensing dataset and GPS data. It is calculated as:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(PWV_{GPS}-\overline{PWV}_{GPS})(PWV_{RS}-\overline{PWV}_{RS})}{\sqrt{\sum_{i=1}^{n}(PWV_{GPS}-\overline{PWV}_{GPS})^2(PWV_{RS}-\overline{PWV}_{RS})^2}}\right]^2 \tag{13}$$

where $\overline{\text{PWV}}_{\text{GPS}}$ and $\overline{\text{PWV}}_{\text{RS}}$ indicate the average values of GPS PWV and remote sensing PWV, respectively.

B. GPS PWV and Water Vapor Product from NIR Channels

As different remote sensing satellites pass a given ground observation site at different times, a direct comparison among NIR retrieval products is challenging due to the un-synchronization problem. In this research, the GPS PWV are introduced as the reference data for its high precision under all weather conditions, its high temporal resolution, and its stable accuracy in measuring PWV [40]. The validation results between MODIS/Terra, MERSI/FY-3A and MERIS/Envisat with GPS data under clear, cloudy and all weather conditions are shown in Fig. 3.

The results displayed in Fig. 3 show that the annual RMSE values under ‘All Weather’ conditions are 10.473 mm, 15.524 mm and 12.386 mm for MODIS/Terra, MERSI/FY-3A and MERIS/Envisat, respectively. Meanwhile, the RMSE values for all the three sensors exceed 10 mm under ‘Cloudy’ condition (13.066 mm, 19.396 mm and 19.428 mm from MODIS/Terra, MERSI/FY-3A, and MERIS/Envisat, respectively). Previous studies showed similar results over other research sites [26], [56]. The tendency of underestimation under ‘Cloudy’ area implies that NIR remote sensing only measures water vapor contents above the cloud layer as the clouds obstruct the satellite’s view of atmospheric water vapor below them. Moreover, the correlations are weak under ‘Cloudy’ condition, with R^2 of 0.456 for MODIS/Terra, 0.165 for MERSI/FY-3A and 0.281 for MERIS/Envisat. Therefore, water vapor products from NIR sensors under ‘Cloudy’ condition are intrinsically less reliable.

On the other hand, the analysis under ‘Clear’ condition from Fig. 3 shows that the annual RMSE values are 5.480 mm, 8.644 mm and 3.708 mm for MODIS/Terra, MERSI/FY-3A and MERIS/Envisat, respectively. The MERIS/Envisat sensor has the smallest RMSE value and the best NIR PWV product, while the MERSI/FY-3A performs the worst among these three sensors. Furthermore, Fig. 3 also indicates that the remote sensing retrieved PWV have a strong correlation with GPS data under ‘clear’ condition, with R^2 of 0.951 for MODIS/Terra, 0.799 for MERSI/FY-3A and 0.927 for MERIS/Envisat.

The detailed description of seasonal statistics on NIR water vapor retrieval under ‘Clear’ condition is shown in Table 3. In comparison, the RMSE values are the smallest during winter months (3.219 mm, 3.785 mm and 2.504 mm for MODIS/Terra, MERSI/FY-3A, and MERIS/Envisat, respectively), and the values are high during summer months (7.608 mm, 12.378 mm and 4.751 mm for MODIS/Terra, MERSI/FY-3A, and MERIS/Envisat, respectively). The results further confirm that the MERIS/Envisat gives the best retrieval results under ‘Clear’ condition during daytime as it has the smallest RMSE and MB values at all seasons.

Previous studies reported that the accuracy of water vapor retrieval is associated with retrieval location [26], [56]. Thus, the annual mean bias under the ‘Clear’ condition is calculated for each station, and the results are displayed in Fig. 4. The figure shows the distribution map of MB for the MODIS/Terra, MERSI/FY-3A, and MERIS/Envisat PWV products. For MODIS/Terra, all stations have negative MB (overestimated), while the MB from MERSI/FY-3A have positive values (underestimated). Besides, stations in the southern part of the study area show more substantial biases of column water vapor throughout the year. In fact, the stations that have the most significant annual mean bias for MODIS/Terra and MERSI/FY-3A are in the ocean area of the Gulf of Mexico and North Atlantic Ocean. This bias may attribute to differences in the meteorological conditions over those stations, such as temperature, rainfall, humidity and wind field.

To interpret the effect of land surface type on the retrieval accuracy of water vapor, the GPS stations are classified into “land/desert” sites and “water” sites based on the estimation of surface reflectance. Since the land mask product from MODIS has a better representation of the surface types [57], the collocated GPS stations are flagged using the MODIS land/water mask. In this case, 271 GPS stations are classified as “land” sites and 99 GPS stations are classified as “water” sites. Fig. 5 shows the correlation between remote sensing retrieved water vapor and referenced GPS PWV over both land area and water area. The figure indicates that water vapor extracted from MERSI/FY-3A and MERIS/Envisat over the land area outperform the results obtained from water area. For MERSI/FY-3A, the RMSE is increased from 8.308 mm over land area, to 9.706 mm over water area. And for MERIS/Envisat, the RMSE is increased from 3.469 mm over land area, to 8.253 mm over water area. However, for MODIS/Terra the RMSE is decreased from 5.566 mm over the land area, to 5.216 mm over water area. Our results also reveal that the correlation of these NIR PWV products is higher over the land than the water area. With the R^2 values over the land area of 0.964, 0.852 and 0.936 for MODIS/Terra, MERSI/FY-3A and MERIS/Envisat, respectively, the R^2 over the water areas are 0.927, 0.659 and 0.658 for MODIS/Terra, MERSI/FY-3A and MERIS/Envisat, respectively.

As the retrieval accuracy of NIR PWV decreases significantly with the increase of water vapor concentration, analysis is conducted to evaluate the retrieval accuracy by categorizing the PWV into dry condition (PWV value less than 20 mm) and wet condition (PWV value more than 20 mm). Table 4 shows the statistical results under dry and wet conditions from different NIR products. The RMSE for MODIS/Terra under the dry condition is 3.372 mm. It increases to 8.938 mm under the wet condition. For the MERSI/FY-3A, the RMSE is 4.212 mm under the dry condition, and it increases to 14.715 mm in the wet condition. For the MERIS/Envisat sensor, the RMSE is 2.453 mm under dry condition, and it increases to 5.445 mm in wet condition. The growth rates of RMSE under wet condition are 165.07%, 249.36% and 121.97% for MODIS/Terra, MERSI/FY-3A and MERIS/Envisat, respectively. Generally, water vapor extracted from NIR channels under the dry condition is more reliable than under wet condition. The MERIS/Envisat sensor has the highest accuracy under both dry and wet conditions among the three sensors.

VI. CONCLUSION

A comprehensive comparison of three typical NIR PWV products (MODIS/Terra, MERSI/FY-3A, and MERIS/Envisat) and GPS PWV has been conducted. The analysis on for ‘All Weather’ conditions shows that the RMSE values for MODIS/Terra, MERSI/FY-3A and MERIS/Envisat are 10.473 mm, 15.524 mm and 12.386 mm, respectively. Under ‘Cloudy’ condition, the results show that all of the NIR products are inclined to underestimating the PWV value, with RMSE values of 13.066 mm, 19.396 mm and 19.428 mm for MODIS/Terra, MERSI/FY-3A and MERIS/Envisat, respectively. And all of these products have a low correlation with GPS PWV data over the cloudy area, with R^2 of 0.456 for MODIS/Terra, 0.165 for MERSI/FY-3A and 0.281 for MERIS/Envisat. This is because the NIR signals cannot penetrate the thick cloud. Thus the PWV retrieved from ‘Cloudy’ pixels are unreliable.

On the other hand, the analysis under ‘Clear’ condition shows that the RMSE values are 5.480 mm, 8.644 mm and 3.708 mm for MODIS/Terra, MERSI/FY-3A and MERIS/Envisat, indicating that the MERIS/Envisat NIR water vapor is the most reliable dataset compared to other NIR retrieved results, while the MERSI/FY-3A has the worst performance among the three sensors. Furthermore, the analysis also indicates that the NIR PWV datasets have a strong correlation with GPS data under ‘Clear’ condition, with R^2 of 0.951 for MODIS/Terra, 0.799 for MERSI/FY-3A and 0.927 for MERIS/Envisat.

Analysis of the three sensors also reveals the spatial and temporal dependence of the retrieval accuracy of water vapor. For instance, the RMSE of MERIS/Envisat over the land area is 3.469 mm, but the value increases to 8.253 mm over water sites. Meanwhile, the RMSE during summer months is 4.751 mm, and it decreases to 2.504 mm during winter months. The effects of dry/wet atmospheric conditions are clear. The RMSE values of PWV retrieval under wet conditions are 165.07%, 249.36% and 121.97% of those under dry conditions for MODIS/Terra, MERSI/FY-3A, and MERIS/Envisat, respectively.

Although an extensive comparison has been conducted in this research for the North America continent, the availability of the dataset is still limited from a global point of view. Further analysis of water vapor products at a global scale can help us understand the global retrieval accuracy of remote sensing water vapor and evaluate the remote sensing PWV products for different surfaces.

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REFERENCES

[1] B. J. Soden, R. T. Wetherald, G. L. Stenchikov, and A. Robock, “Global cooling after the Eruption of Mount Pinatubo: A test of climate feedback by water vapor,” *Science*, vol. 296, no. 5568, pp. 727–730, Apr. 2002.

[2] T. R. Karl and K. E. Trenberth, “Modern global climate change,” *Science*, vol. 302, no. 5651, pp. 1719–1723, Dec. 2003.

[3] D. J. Gaffen, T. P. Barnett, and W. P. Elliott, “Space and time scales of global tropospheric moisture,” *J. Clim.*, vol. 4, no. 10, pp. 989–1008, Oct. 1991.

[4] A. Raval and V. Ramanathan, “Observational determination of the greenhouse effect,” *Nature*, vol. 342, no. 6251, pp. 758–761, Dec. 1989.

[5] G. Liu, J. A. Curry, and R.-S. Sheu, “Classification of clouds over the western equatorial Pacific Ocean using combined infrared and microwave satellite data,” *J. Geophys. Res. Atmospheres*, vol. 100, no. D7, pp. 13811–13826, Jul. 1995.

[6] H. Nakamura, K. Koizumi, and N. Mannoji, “Data assimilation of GPS precipitable water vapor into the JMA Mesoscale Numerical Weather Prediction Model and its impact on rainfall forecasts,” *J. Meteorol. Soc. Jpn. Ser II*, vol. 82, no. 1B, pp. 441–452, 2004.

[7] T.-J. Zhou and R.-C. Yu, “Atmospheric water vapor transport associated with typical anomalous summer rainfall patterns in China,” *J. Geophys. Res. Atmospheres*, vol. 110, no. D8, p. D08104, Apr. 2005.

[8] Y. Shoji, M. Kunii, and K. Saito, “Assimilation of nationwide and global GPS PWV data for a heavy rain event on 28 July 2008 in Hokuriku and Kinki, Japan,” *Sola*, vol. 5, pp. 45–48, 2009.

[9] R. F. Hanssen, T. M. Weckwerth, H. A. Zebker, and R. Klees, “High-resolution water vapor mapping from interferometric radar measurements,” *Science*, vol. 283, no. 5406, pp. 1297–1299, Feb. 1999.

[10] A. I. Bokoye *et al.*, “Multisensor analysis of integrated atmospheric water vapor over Canada and Alaska,” *J. Geophys. Res. Atmospheres*, vol. 108, no. D15, p. 4480, Aug. 2003.

[11] J. Van Baelen, J.-P. Aubagnac, and A. Dabas, “Comparison of near–real time estimates of integrated water vapor derived with GPS, Radiosondes, and microwave radiometer,” *J. Atmospheric Ocean. Technol.*, vol. 22, no. 2, pp. 201–210, Feb. 2005.

[12] Z. Liu, M. S. Wong, J. Nichol, and P. W. Chan, “A multi-sensor study of water vapour from radiosonde, MODIS and AERONET: a case study of Hong Kong,” *Int. J. Climatol.*, vol. 33, no. 1, pp. 109–120, Jan. 2013.

[13] C. Francois and C. Ottle, “Atmospheric corrections in the thermal infrared: global and water vapor dependent split-window algorithms-applications to ATSR and AVHRR data,” *IEEE Trans. Geosci. Remote Sens.*, vol. 34, no. 2, pp. 457–470, Mar. 1996.

[14] H. Ren *et al.*, “Atmospheric water vapor retrieval from Landsat 8 thermal infrared images: Water vapor estimate from L8,” *J. Geophys. Res. Atmospheres*, vol. 120, no. 5, pp. 1723–1738, Mar. 2015.

[15] B.-C. Gao and Y. J. Kaufman, “Water vapor retrievals using Moderate Resolution Imaging Spectroradiometer (MODIS) near-infrared channels,” *J. Geophys. Res. Atmospheres*, vol. 108, no. D13, Jul. 2003.

[16] K. B. Mao *et al.*, “Estimation of water vapor content in near-infrared bands around 1 μm from MODIS data by using RM–NN,” *Opt. Express*, vol. 18, no. 9, pp. 9542–9554, Apr. 2010.

[17] K. Gui *et al.*, “Evaluation of radiosonde, MODIS-NIR-Clear, and AERONET precipitable water vapor using IGS ground-based GPS measurements over China,” *Atmospheric Res.*, vol. 197, pp. 461–473, Nov. 2017.

[18] D. D. Turner, S. A. Clough, J. C. Liljegren, E. E. Clothiaux, K. E. Cady-Pereira, and K. L. Gaustad, “Retrieving liquid water path and precipitable water vapor from the Atmospheric Radiation Measurement (ARM) microwave radiometers,” *IEEE Trans. Geosci. Remote Sens.*, vol. 45, no. 11, pp. 3680–3690, Nov. 2007.

[19] J. Du, J. S. Kimball, and L. A. Jones, “Satellite microwave retrieval of total precipitable water vapor and Surface Air Temperature Over Land From AMSR2,” *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 5, pp. 2520–2531, May 2015.

[20] W. P. Menzel, W. L. Smith, and L. D. Herman, “Visible infrared spin-scan radiometer atmospheric sounder radiometric calibration: an inflight evaluation from intercomparisons with HIRS and radiosonde measurements,” *Appl. Opt.*, vol. 20, no. 20, pp. 3641–3644, Oct. 1981.

[21] Y. J. Kaufman and B. C. Gao, “Remote sensing of water vapor in the near IR from EOS/MODIS,” *IEEE Trans. Geosci. Remote Sens.*, vol. 30, no. 5, pp. 871–884, Sep. 1992.

[22] X. Wang, D.-Z. Zhao, X. Su, J.-H. Yang, and Y.-J. Ma, “Retrieving precipitable water vapor based on FY-3A near-IR data,” *J Infrared Millim Waves*, vol. 31, no. 6, pp. 550–555, Dec. 2012.

[23] N. S. Shantikumar, S. Jade, T. S. Shrungeshwara, and H.-J. Song, “Validation of water vapor retrieval from Moderate Resolution Imaging Spectro-radiometer (MODIS) in near infrared channels using GPS data over IAO-Hanle, in the trans-Himalayan region,” *J. Atmospheric Sol.-Terr. Phys.*, vol. Vol. 137, pp. 76–85, Jan. 2016.

[24] M. Vesperini, F.-M. Breon, and D. Tanré, “Atmospheric water vapor content from spaceborne POLDER measurements,” *IEEE Trans. Geosci. Remote Sens.*, vol. 37, no. 3, pp. 1613–1619, May 1999.

[25] J. A. Sobrino, N. Raissouni, J. Simarro, F. Nerry, and F. Petitcolin, “Atmospheric water vapor content over land surfaces derived from the AVHRR data: application to the Iberian Peninsula,” *IEEE Trans. Geosci. Remote Sens.*, vol. 37, no. 3, pp. 1425–1434, May 1999.

[26] A. K. Prasad and R. P. Singh, “Validation of MODIS Terra, AIRS, NCEP/DOE AMIP-II Reanalysis-2, and AERONET Sun photometer derived integrated precipitable water vapor using ground-based GPS receivers over India,” *J. Geophys. Res.*, vol. 114, no. D5, Mar. 2009.

[27] J. Vaquero-Martínez *et al.*, “Validation of MODIS integrated water vapor product against reference GPS data at the Iberian Peninsula,” *Int. J. Appl. Earth Obs. Geoinformation*, vol. 63, pp. 214–221, Dec. 2017.

[28] M. S. Wong, X. Jin, Z. Liu, J. Nichol, and P. W. Chan, “Multi-sensors study of precipitable water vapour over mainland China,” *Int. J. Climatol.*, vol. 35, no. 10, pp. 3146–3159, Aug. 2015.

[29] J. Vaquero-Martínez *et al.*, “Inter-comparison of integrated water vapor from satellite instruments using

reference GPS data at the Iberian Peninsula," *Remote Sens. Environ.*, vol. 204, pp. 729–740, Jan. 2018.

[30] L. Guanter, L. Gómez-Chova, and J. Moreno, "Coupled retrieval of aerosol optical thickness, columnar water vapor and surface reflectance maps from ENVISAT/MERIS data over land," *Remote Sens. Environ.*, vol. 112, no. 6, pp. 2898–2913, Jun. 2008.

[31] R. W. Higgins, Y. Yao, and X. L. Wang, "Influence of the north american monsoon system on the U.S. summer precipitation regime," *J. Clim.*, vol. 10, no. 10, pp. 2600–2622, Oct. 1997.

[32] W. S. Ashley *et al.*, "Distribution of mesoscale convective complex rainfall in the United States," *Mon. Weather Rev.*, vol. 131, no. 12, pp. 3003–3017, Dec. 2003.

[33] J. Fischer and R. Bennartz, "Retrieval of total water vapor content from MERIS measurements," *Algorithm Theor. Basis Doc. PO-NT-MEL-GS-005*, 1997.

[34] R. Bennartz and J. Fischer, "Retrieval of columnar water vapour over land from backscattered solar radiation using the Medium Resolution Imaging Spectrometer," *Remote Sens. Environ.*, vol. 78, no. 3, pp. 274–283, Dec. 2001.

[35] R. Lindenbergh, M. Keshin, H. van der Marel, and R. Hanssen, "High resolution spatio-temporal water vapour mapping using GPS and MERIS observations," *Int. J. Remote Sens.*, vol. 29, no. 8, pp. 2393–2409, Apr. 2008.

[36] R. Lindstrot, R. Preusker, H. Diedrich, L. Doppler, R. Bennartz, and J. Fischer, "1D-Var retrieval of daytime total columnar water vapour from MERIS measurements," *Atmospheric Meas. Tech.*, vol. 5, no. 3, pp. 631–646, Mar. 2012.

[37] S. W. Seemann, E. E. Borbas, J. Li, W. P. Menzel, and L. E. Gumley, "MODIS atmospheric profile retrieval algorithm theoretical basis document," *Version*, vol. 6, p. 25, 2006.

[38] S. Rózsa, "Uncertainty considerations for the comparison of water vapour derived from radiosondes and GNSS," in *Earth on the Edge: Science for a Sustainable Planet*, C. Rizos and P. Willis, Eds. Springer Berlin Heidelberg, 2014, pp. 65–78.

[39] J. Nash, T. Oakley, H. Vömel, and L. Wei, *WMO Intercomparison of High Quality Radiosonde Systems*. WMO Instruments and Observing Methods, Report No. 107, 2011.

[40] D. E. Wolfe and S. I. Gutman, "Developing an operational, surface-Based, GPS, water vapor observing system for NOAA: network design and results," *J. Atmospheric Ocean. Technol.*, vol. 17, no. 4, pp. 426–440, Apr. 2000.

[41] B.-C. Gao, A. F. H. Goetz, E. R. Westwater, J. E. Conel, and R. O. Green, "Possible Near-IR channels for remote sensing precipitable water vapor from geostationary satellite platforms," *J. Appl. Meteorol.*, vol. 32, no. 12, pp. 1791–1801, Dec. 1993.

[42] P. Dubuisson, D. Dessailly, M. Vesperini, and R. Frouin, "Water vapor retrieval over ocean using near-infrared radiometry," *J. Geophys. Res. Atmospheres*, vol. 109, no. D19, p. D19106, Oct. 2004.

[43] P. Albert, R. Bennartz, R. Preusker, R. Leinweber, and J. Fischer, "Remote sensing of atmospheric water vapor using the Moderate Resolution Imaging Spectroradiometer," *J. Atmospheric Ocean. Technol.*, vol. 22, no. 3, pp. 309–314, Mar. 2005.

[44] C. Prabhakara, H. D. Change, and A. T. C. Chang, "Remote sensing of precipitable water over the oceans from Nimbus-7 microwave measurements," *J. Appl. Meteorol.*, vol. 21, pp. 59–68, Apr. 1981.

[45] K. E. Trenberth and C. J. Guillemot, "Evaluation of the Global Atmospheric Moisture Budget as Seen from Analyses," *J. Clim.*, vol. 8, no. 9, pp. 2255–2272, Sep. 1995.

[46] B.-C. Gao and A. F. H. Goetz, "Column atmospheric water vapor and vegetation liquid water retrievals from Airborne Imaging Spectrometer data," *J. Geophys. Res. Atmospheres*, vol. 95, no. D4, pp. 3549–3564, Mar. 1990.

[47] L. S. Rothman *et al.*, "The HITRAN molecular spectroscopic database and HAWKS (HITRAN Atmospheric Workstation): 1996 edition," *J. Quant. Spectrosc. Radiat. Transf.*, vol. 60, no. 5, pp. 665–710, Nov. 1998.

[48] A. Berk, L. S. Bernstein, and D. C. Robertson, "MODTRAN: a moderate resolution model for LOWTRAN," Jul. 1987.

[49] X.-Q. Hu, Y.-B. Huang, Q.-F. Lu, and J. Zheng, "Retrieving precipitable water vapor based on the near-infrared data of FY-3A satellite," *J. Appl. Meteorol. Sci.*, 2011.

[50] P. Albert, R. Bennartz, and J. Fischer, "Remote sensing of atmospheric water vapor from backscattered sunlight in cloudy atmospheres," *J. Atmospheric Ocean. Technol.*, vol. 18, no. 6, pp. 865–874, Jun. 2001.

[51] R. Santer, F. Zagolski, D. Ramon, J. Fischer, and P. Dubuisson, "Uncertainties in radiative transfer computations: consequences on the MERIS products over land," *Int. J. Remote Sens.*, vol. 26, no. 20, pp. 4597–4626, Oct. 2005.

[52] R. Bennartz and J. Fischer, "Retrieval of columnar water vapour over land from backscattered solar radiation using the Medium Resolution Imaging Spectrometer," *Remote Sens. Environ.*, vol. 78, no. 3, pp. 274–283, Dec. 2001.

[53] M. Bevis, S. Businger, T. A. Herring, C. Rocken, R. A. Anthes, and R. H. Ware, "GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system," *J. Geophys. Res. Atmospheres*, vol. 97, no. D14, pp. 15787–15801, Oct. 1992.

[54] T. Iwabuchi, I. Naito, and N. Mannoji, "A comparison of Global Positioning System retrieved precipitable water vapor with the numerical weather prediction analysis data over the Japanese Islands," *J. Geophys. Res. Atmospheres*, vol. 105, no. D4, pp. 4573–4585, Feb. 2000.

[55] I. Juni and S. Rózsa, "Developing a global model for the conversion of zenith wet tropospheric delays to integrated water vapour," *Acta Geod. Geophys.*, vol. 53, no. 2, pp. 259–274, Jun. 2018.

[56] Z. Li, J.-P. Muller, and P. Cross, “Comparison of precipitable water vapor derived from radiosonde, GPS, and Moderate-Resolution Imaging Spectroradiometer measurements,” *J. Geophys. Res. Atmospheres*, vol. 108, no. D20, p. 4651, Oct. 2003.

[57] M. L. Carroll *et al.*, “Development of an operational land water mask for MODIS Collection 6, and influence on downstream data products,” *Int. J. Digit. Earth*, vol. 10, no. 2, pp. 207–218, Feb. 2017.

Jia He received the B.Sc. degree in geography from Beijing Forestry University, Beijing, China, in 2013, and M.Sc. degree in Geo-Information Science from the Chinese University of Hong Kong, Hong Kong, China, in 2015. She is currently working toward the Ph.D. degree in the Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong, China.

Her current research interests include water vapor retrieval with multi-sensor observations.

Zhizhao Liu received the B.Sc. degree in surveying engineering from Jiangxi University of Science and Technology, Ganzhou, China, in 1994, the M.Sc. degree in geodesy from Wuhan University, Wuhan, China, in 1997, and the Ph.D. degree in geomatics engineering from the University of Calgary, Calgary, AB, Canada, in 2004.

He is currently an Associate Professor with the Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong. He is a guest Professor with Liaoning Technical University, Huludao, China, and Wuhan University. His research interests include new algorithm development for precise Global Positioning System (GPS) and Global Navigation Satellite System (GNSS), GPS/GNSS precise point positioning (PPP), ionosphere modeling and scintillation monitoring, tropospheric remote sensing and modeling, and GPS/GNSS meteorology. He has over 20 years of experience in GPS/GNSS research. His group developed China’s first GPS PPP-based Precipitable Water Vapor Real-time Monitoring System in the Pearl-River-Delta region in 2012. His research group established Hong Kong’s first GPS/GNSS-radiosonde water vapor sounding collocation system in 2013 in collaboration with Hong Kong Observatory. In 2012, his group developed Hong Kong’s first GPS/GNSS-based ionosphere scintillation monitoring system (two stations deployed in South and North Hong Kong) with his collaborators.

Dr. Liu was the recipient of the inaugural Early Career Award of the Hong Kong Research Grants Council (RGC), Hong Kong, in 2012 and was the recipient of the inaugural Best Conference Paper of the China Satellite Navigation Conference (CSNC), China, in 2013. In 2014, he was nominated by the Hong Kong Observatory for the World Meteorological Organization (WMO) “Norbert Gerbier-MUMM International Award for 2015” for his paper that has developed a method to evaluate the absolute accuracy of water vapor measurements.