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A total precipitable water retrieval method over land using the combination of passive microwave and optical remote sensing

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ABSTRACT

Atmospheric water vapor plays an important role in hydrologic cycle and climate change of the Earth. A number of studies have focused on retrieval of the total precipitable water (TPW) using microwave or optical remote sensing. In this paper, the global quarter-degree gridded TPW over land was retrieved using water vapor sensitivity parameter $\Delta Tb_{18.7}/\Delta Tb_{23.8}$ based on the combination of AMSR-E and MODIS observations. There are two major improvements in the retrieval algorithm, including optimization of the estimation model of surface emissivity $\Delta\varepsilon_{18.7}/\Delta\varepsilon_{23.8}$ and correction of the terrain influence to the retrieval of TPW using DEM. To obtain a high resolution TPW, we also developed an algorithm to downscale the retrieved quarter-degree gridded TPW to a fine scale of 0.05° × 0.05° using DEM and NDVI. In addition, the downscaled TPW was further calibrated using high precision TPW from MODIS in the clear-sky condition to improve its accuracy. Finally, both quarter-degree and 0.05° × 0.05° gridded TPW were validated against SuomiNet GPS retrieved TPW on a global scale. The RMSE for the retrieved quarter-degree gridded global TPW is 3.45 mm, with a correlation coefficient of 0.95. In addition, the RMSE for the downscaled 0.05° × 0.05° gridded global TPW is 4.18 mm, with a correlation coefficient of 0.95. An obvious advantage of our algorithm compared with MODIS TPW product is that it can retrieve TPW under cloudy sky condition over land. The algorithm developed in this study can be easily transferred to AMSR2 on board GCOM-W1 and provides the long-term global daily TPW over land since the launch of Aqua to present day to support hydrologic cycle and climate change studies.

1. Introduction

Atmospheric water vapor plays an important role in the hydrologic cycle and the climate change of the Earth. Water vapor enters into the atmosphere by way of evaporation and absorbs heat from the surrounding environment. It is further transported by advection and convection of the atmosphere, and finally forming clouds and precipitation in the process of condensation and releasing latent heat into the atmosphere. Without water vapor, the circulation of water between ocean and land would not exist. Water vapor is also the most important greenhouse gas in the Earth's atmosphere. Water vapor accounts for approximately 70% of the total atmospheric absorption of radiation and 60% of the total natural greenhouse effect in clear-sky cases (Lindstrot et al., 2014). The changes in water vapor in the upper troposphere are especially important for climate change. Some changes in water vapor in the upper troposphere from human influences contribute to radiative forcing on the order of 0.1 Wm^{-2} (Trenberth et al., 2005). In addition, the radiative contribution or attenuation of water vapor to the radiance from the surface in microwave bands has an obvious influence on the retrieval of land surface parameters, for example, the retrieval of Soil Moisture (SM) and Microwave Vegetation Index (MVI), which are discussed in Drusch et al. (2001) and Ji et al. (2014b), respectively. Thus, precise understanding of the variation and change of water vapor in spatial and temporal scales is of high importance. For clarity, we will use the term "total precipitable water (TPW)" as the total water vapor contained in an air column from the Earth's surface to the top of the atmosphere throughout this paper.

Observations of the TPW can be categorized into two types, one is ground-based observation, the other is observation from satellite remote sensing. Radiosondes and GPS have been widely used as ground-based equipment to observe TPW, and the data are further used for water vapor variability and trends study (Bevis et al., 1992; Ware et al., 2000; Wang et al., 2001; Wang et al., 2007). The ground-based observations usually have high precision and good continuity in the temporal scale for research regarding long-term trends. However, the disadvantage of ground-based observations is low quality in space coverage, which limits their ability for spatial distribution analysis. Satellite remote sensing provides an effective way for large-scale observation of TPW. Both infrared and passive microwave remote sensing have been used to retrieve TPW on a regional or global scale. Usually, infrared remote sensing using near-infrared or thermal infrared observations

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provides estimation of TPW with high accuracy under clear conditions, especially in the near-infrared region; the error of the retrievals is approximately 5% to 10% (Chesters et al., 1987; Jedlovec, 1990; Guillory et al., 1993; Knabb and Fuelberg, 1997; Kaufman and Gao, 1992; Gao and Kaufman, 2003). The major drawback of infrared remote sensing is its inability to acquire water vapor information under cloudy conditions. As a complement, passive microwave provides an effective way to retrieve TPW under cloudy conditions, because radiation from microwave channels can penetrate clouds.

Considerable efforts have been devoted to the development of TPW retrieval algorithms since the launch of first passive microwave radiometer. Generally, these algorithms can be classified into four groups. 1) Statistical algorithms. TPW is retrieved by establishing statistical relationship between TPW and brightness temperature of one or more microwave bands (Grody, 1976; Grody et al., 1980; Alishouse et al., 1990). 2) Semi-statistical algorithms. This type of algorithm uses a regression formula to relate TPW and brightness temperature but under the guidance of radiative transfer model (Deeter, 2007; Wang et al., 2009). 3) Physical algorithms. This type of algorithm uses simplified assumptions to solve radiative transfer equation for water vapor (Tjemkes et al., 1991; Wentz, 1997). 4) Neural network algorithms. TPW is retrieved by training a neural network using simultaneously observed atmosphere and land surface data (Aires et al., 2001; Bobylev et al., 2010). Most of these algorithms were developed for ocean areas. In addition, great progress of these algorithms has been achieved with the development of radiometers, from the early Special Sensor Microwave Imager (SSM/I) to the current Advanced Microwave Scanning Radiometer 2 (AMSR2) and GPM Microwave Imager (GMI). The accuracy of these algorithms is sufficient to produce products for scientific research.

However, there are still many challenges for estimating TPW from passive microwave remote sensing sensors over land areas, due to high land surface emissivity and heterogeneity. High emissivity and variability of land in the microwave bands severely suppresses the signal of atmosphere received by space-based microwave radiometer, making it difficult to retrieve TPW over land, especially under an area of cloud cover. Lack of accurate water vapor estimation under cloud covered areas over land makes it difficult to provide high quality and spatially continued daily TPW data on the global scale. For example, in the NASA Water Vapor Project (NVAP) data set, the inability to perform retrievals in areas of thick clouds can cause a “dry bias” (Randel et al., 1996), which may have a great influence on the study of global water vapor variability and changes. In the newly published global TPW from SSM/I and MERIS, daily composites of TPW are available on rectangular latitude-longitude grids with a spatial resolution of 0.05° × 0.05° over land (Lindstrot et al., 2014), but they are only available in clear-sky conditions because of the limitation of Medium Resolution Imaging Spectrometer (MERIS), which brings great limitation to spatial variability analysis of water vapor on daily basis. Thus, it is of vital importance to provide a global and full coverage of TPW dataset over land without the influence of clouds.

Aimed at the characteristic of microwave radiation of the land surface and the atmosphere, Deeter (2007) proposed a sensitive parameter $\Delta Tb_{18.7}/\Delta Tb_{23.8}$ (ratio of brightness temperature polarization difference at frequencies 18.7 and 23.8 GHz) to retrieve TPW over land and ocean areas. However, the problem is that the surface emissivity parameter $\Delta\varepsilon_{18.7}/\Delta\varepsilon_{23.8}$ (ratio of surface emissivity polarization difference at frequencies 18.7 and 23.8 GHz) is set to 1 in the retrieval, which may introduce great uncertainty in the retrieved TPW. In view of the limitation of passive microwave remote sensing in the retrieval of TPW over land, it is difficult to further improve the accuracy of algorithms based only on microwave radiometer; introducing observations from other sensors, such as MODIS or AIRS, may improve the retrieval algorithms. Ji and Shi (2014a) and Du et al. (2015) proposed new TPW retrieval algorithms based on the sensitive parameter $\Delta Tb_{18.7}/\Delta Tb_{23.8}$ with the help of introducing ancillary data observed from other sensors. Both methods have substantially improved the accuracy of retrieved TPW over land, and the RMSE of retrieved TPW respectively reached up to 4.85 mm in Ji and Shi (2014a) and 4.7 mm in Du et al. (2015). Although great progress has been achieved in both algorithms, the retrieved TPW is not accurate enough for long-term climate change and water cycle research, and the spatial resolution (0.25 lat-lon degree) is too coarse for the study of climate change and weather forecast in local areas.

The new research in this study is an extension of the work by Ji and Shi (2014a). There are two obvious improvements compared to the former work. One is the improvement in the accuracy of the estimated land surface emissivity parameter $\Delta\varepsilon_{18.7}/\Delta\varepsilon_{23.8}$ by introducing new ancillary data and new optimization methods, which finally improves the precision of the retrieved TPW. The other is that a downscale method is developed to resize the newly retrieved globally distributed TPW with a spatial resolution of 0.25° × 0.25° over land into 0.05° × 0.05° latitude-longitude grids data. As a validation, the TPW observed from globally distributed GPS is used to validate the retrieved TPW over land. The description of data and methods used in this study are provided in Sections 2, 3 and 4, while the results of the retrieval and the validation part are discussed in Section 5. Finally, Section 6 concludes this study.

2. Data used in the study

The satellite remote sensing datasets used in the study were from observations of AMSR-E and MODIS. These two sensors were selected because both of them are aboard the same satellite Aqua, and they have synchronous observations for the same location on the Earth's surface; thus, it is possible to take full advantage of the two sensors to retrieve TPW. The algorithm developed in this study can be easily transferred to the combination of AMSR2 and MODIS, both of which belong to A-Train Satellite series and have quasi-synchronous observation of same location on the Earth's surface. The ancillary datasets used in the retrieval algorithm in this study include DEM, NDVI, and the atmosphere profiles from RAOB and TPW observed from GPS.

AMSR-E is a twelve-channel, six-frequency total power passive microwave radiometer system onboard the Aqua satellite. AMSR-E measures the brightness temperatures at 6.925, 10.65, 18.7, 23.8, 36.5 and 89.0 GHz. Vertically and horizontally polarized measurements are taken at all channels (JAXA, 2006). Both horizontally and vertically polarized brightness temperatures of 18.7 GHz and 23.8 GHz will be used to calculate the water vapor sensitive parameter to retrieve TPW in this study. The 36.5-GHz vertically polarized brightness temperature will be used to estimate land surface temperature, which is an important parameter in the retrieval of TPW. In addition, the brightness temperatures from 6.925 GHz, 10.65 GHz and 18.7 GHz will be used in the estimation of land surface parameter, which is crucial in the retrieval of TPW. The AMSR-E Daily Global Quarter-Degree Gridded Brightness Temperatures (Knowles et al., 2006) will be used to retrieval coarse resolution TPW in all-weather conditions.

MODIS is a key instrument aboard the Terra and Aqua satellites. On the Aqua satellite, MODIS and AMSR-E provide synchronous observations of the Earth's surface, which makes it possible to improve the retrieval of water vapor using AMSR-E by introducing MODIS observations. In this study, TPW retrieved using MODIS thermal infrared bands and MODIS land surface temperature product (Wan, 1999) will be used together with AMSR-E brightness temperature data to estimated land surface emissivity parameter $\Delta\varepsilon_{18.7}/\Delta\varepsilon_{23.8}$ in the clear sky condition. The high precision TPW data retrieved from MODIS near-infrared bands in the clear sky condition (Gao and Kaufman, 2003) will be used to downscale the retrieved TPW to further improve its precision. The land surface temperature from MODIS LST product (Wan, 1999) is also used in the estimation of $\Delta\varepsilon_{18.7}/\Delta\varepsilon_{23.8}$ and TPW.

Both DEM and NDVI are ancillary data in the retrieval of TPW. As SRTM DEM (Jarvis et al., 2008) is only available from 56°S to 60°N, the rest area is filled with MODIS geolocation product (MOD03/MYD03). For the overlapping area of SRTM DEM and MOD03/MYD03, the DEM is an arithmetic average combination of the two. The DEM data will be