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An improved physical split-window algorithm for precipitable water vapor retrieval exploiting the water vapor channel observations

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ABSTRACT

This paper presents a new atmospheric precipitable water vapor (PWV) retrieval method based on three thermal infrared band observations from geostationary satellites. The proposed method is similar to the traditional physical split-window (PSW) retrieval technique, but a water vapor channel observation near 6.7 μm was included. Sensitivity analyses and simulation retrievals were carried out respectively according to the instrument characteristics of the Stretched Visible and Infrared Spin Scan Radiometer onboard FengYun-2G (SVISSR/FY-2G) and the Moderate Resolution Imaging Spectroradiometer aboard Terra (MODIS/Terra). The results indicate that the proposed 3-band algorithm can significantly reduce PWV retrieval errors caused by surface emissivity uncertainty and observation errors, especially in dry atmospheric conditions (i.e., PWV < 2 cm). The proposed algorithm was validated using SVISSR/FY-2G and MODIS/Terra observations, and was compared with radiosonde and GPS PWV. The determination coefficient (R^2), root mean square error (RMSE), and bias between the SVISSR retrieved PWV and the radiosonde PWV are 0.87, 0.43 cm and 0.14 cm, respectively. The R^2, RMSE and bias of the MODIS retrieved PWV are 0.89, 0.10 cm and −0.042 cm, respectively, which are slightly better than the MODIS L2 thermal infrared and near-infrared PWV products.

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1. Introduction

Water vapor is the most abundant greenhouse gas in the Earth's atmosphere. Water vapor and its variations are the main driving forces of weather and climate change (Solomon et al., 2007; Zveryaev and Allan, 2005). It plays an important role in the study of climate change, hydrological cycle, energy budget and biogeochemistry at global and regional scales (Dessler et al., 2008; Raval and Ramanathan, 1989). Precipitable water vapor (PWV), which is the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending from the Earth's surface to the top of the atmosphere, is an important parameter for the climate analysis of energy budgets, hydrological cycles and numerical weather prediction (Nakamura et al., 2004; Smith et al., 2000; Trenberth et al., 2009). Moreover, PWV is one of the main geophysical parameters that affects surface remote sensing applications, such as land surface temperature (LST) retrieval and atmosphere correction of satellite data (Li et al., 2013; Qin et al., 2001; Sobrino et al., 1993; Vermote et al., 2002).

A number of techniques have been used to obtain the PWV such as radiosonde, GPS, ground-based sun photometer and microwave radiometer, as well as polar-orbiting and geostationary satellite observations (Alshawaf et al., 2015; Czajkowski et al., 2002; Firsov et al., 2013; Li et al., 2003; Wang et al., 2015). Satellite observations, given its unique temporal and spatial resolution advantages, can effectively provide global or regional PWV distributions (Justice et al., 2002). Geostationary satellites can provide continuous observations of certain areas on the Earth's surface generally every 15 to 30 min (Maini and Agrawal, 2010; Suggs et al., 1998). One geostationary satellite can cover almost 1/3 of the Earth's surface, and a constellation of three equally spaced satellites can provide full coverage of the Earth (except the polar regions). Consequently, using geostationary satellite observations is an effective way to obtain high temporal and spatial resolution PWV at regional or global scales.

At present, PWV retrieval algorithms of geostationary satellites have been mainly based on thermal infrared data given the lack of observations in the near infrared and microwave bands (Cziczo et al., 2013; Julien et al., 2015; Schroedter-Homscheidt et al., 2008; Suggs et al., 1998). In past decades, a number of algorithms have been proposed to derive PWV from thermal infrared observations. In general, these algorithms are mainly based on the water vapor differential absorption within the split-window channels, and can be classified into the linear split-window algorithm, split-window covariance-variance ratio method, physical split-window (PSW) algorithm, and look-up table approach (Dalu, 1986; Guillory et al., 1993; Labbi and Mokhnache, 2015; Ottle et al., 1997; Schroedter-Homscheidt et al., 2008; Sobrino et al., 2002;

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Sobrino and Romaguera, 2008). The accuracy of these algorithms are easily affected by the surface emissivity uncertainty, first-guess field error, instrument noise and calibration error (Barton and Prata, 1999; Knabb and Fuelberg, 1997), especially for dry atmospheric conditions (i.e., PWV < 2 cm) (Hulley et al., 2012; Sun et al., 2013).

Based on the PSW technique (Guillory et al., 1993), the present study aimed to develop an improved PWV retrieval algorithm by adding a water vapor channel observation which has been included in most of the imagers onboard the geostationary satellites such as the Visible-Infrared Spin-Scan Radiometer onboard GOES (VISSR/GOES), Spinning Enhanced Visible and Infrared Imager onboard MSG (SEVIRI/MSG), and Stretched Visible and Infrared Spin Scan Radiometer onboard FY-2G (SVISSR/FY-2G). The water vapor channel observations mainly respond to middle and upper tropospheric water vapor, which is useful in determining locations of moisture and atmospheric circulations (Laurent, 1993; Roca et al., 1997). Furthermore, the water vapor channel can also provide atmospheric temperature information if there is enough moisture in the atmosphere which is helpful to improve the accuracy of PWV retrievals (Seemann et al., 2003; Tang and Li, 2008). To our knowledge, few studies have been reported on the retrieval of PWV by combining a water vapor channel and split-window channel measurements. We expect our proposed algorithm to reduce the PWV retrieval uncertainty due to the surface emissivity uncertainty, first-guess field uncertainty, and observation errors, especially under dry atmospheric conditions.

Section 2 describes the dataset used in this study. Section 3 first introduces the PSW retrieval technique, and then presents the sensitivity analysis and proposed 3-band PWV algorithm. The new algorithm is evaluated using the simulated SVISSR/FY-2G and MODIS/Terra radiances in Section 4. Validation of the proposed algorithm for the actual satellite observations is shown in Section 5. Finally, the conclusion is given in Section 6.

2. Datasets

SVISSR/FY-2G and MODIS/Terra data were used to evaluate the proposed algorithm. The reference data, including GPS and radiosonde PWV data were used for validation. In addition, the ECMWF reanalysis data were used for the numerical simulation and first-guess field for the proposed algorithm.

2.1. SVISSR/FY-2G and MODIS/Terra data

FengYun-2 (FY-2) is the first generation of Chinese geostationary meteorological satellite series, and currently includes seven satellites (Hu et al., 2013). One of the FY-2 satellites, FY-2G, was launched on December 31, 2014 with a main payload SVISSR. SVISSR/FY-2G observes the Earth every 30 min in 5 spectral channels, including two split-window channels, one water vapor channel, one mid-infrared channel, and one visible channel (Table 1).

As compared with previous instruments from the FY-2 satellite series, the SVISSR/FY-2G has been improved from the following three aspects: reduced stray infrared radiation, uplifted observation frequency for the blackbody, and improved telemetry resolution of optical components. These improvements are conducive in improving the accuracy of FY-2G quantitative products. Combining with previous FY-2 satellites

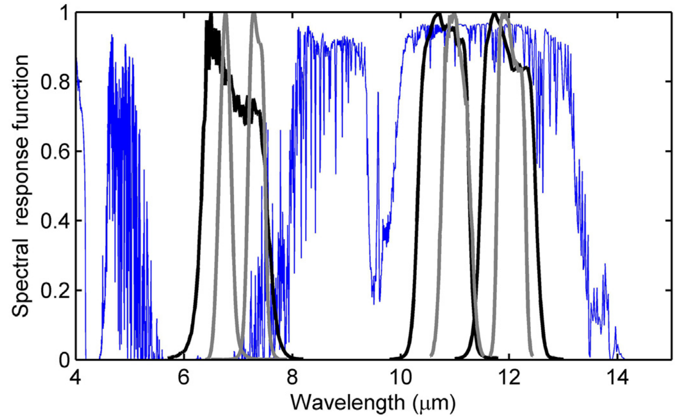

Fig. 1. Spectral response functions of SVISSR/FY-2G (in black) and MODIS/Terra (in gray) along with the calculated transmittance (blue line) of the standard mid-latitude winter atmosphere by MODTRAN 5.2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

data, the FY-2G satellite observations can provide long-term climatologies of PWV information over the Eastern Hemisphere. The FY-2G products used in this study are mainly comprised of the SVISSR L1B radiance and L2 cloud mask data, which are provided by the Fengyun Satellite Data Center (http://satellite.nsmc.org.cn/PortalSite/Data/Satellite.aspx).

Similar to SVISSR/FY-2G, MODIS/Terra has split-window and water vapor bands, and with higher spatial resolution, lower instrument noise, and a narrower spectral response function (SRF) (Fig. 1) (Justice et al., 2002; Wan, 2008). MODIS has two water vapor bands centered at 6.7 μm (band 27) and 7.2 μm (band 28) (Table 2). Band 27 is almost centrally located in the water vapor absorption region and only monitors the radiation from higher level atmosphere. In contrary, band 28 is located closer to the wings of the absorption region, which allows the sensor to detect radiation from lower layers. Given its relatively weak absorption, MODIS band 28 observations were used in this study. The MODIS L1b radiance, L2 cloud mask, near-infrared and thermal infrared PWV data were used.

2.2. Radiosonde and GPS PWV data

The radiosonde and GPS-derived PWV data were used as the reference data to evaluate the retrieved PWV. The radiosonde data used in this study was obtained by the L-band sounding system (1675 MHz) of the China Meteorological Administration (CMA), and was collected from the University of Wyoming website (http://weather.uwyo.edu/upperair/sounding.html). The CMA sounding system is composed of a GTS1 digital electronic radiosonde, a secondary wind-finding radar and a ground-check set. It is widely used to measure the air pressure, temperature, relative humidity, and wind from the ground to about 30 km in radiosonde sites across China (CMA, 2010). The accuracy of the measured pressure, temperature, and relative humidity is 1–2 hPa, 0.2–0.3 °C and 4–5%, respectively (CMA, 2010). The radiosonde PWV was derived by integrating the specific humidity from the surface to the top of the sounding profile.

SuomiNet hourly GPS PWV was used to validate the PWV retrievals across North America. SuomiNet is funded by the National Science

Table 1
Instrument specifications for SVISSR/FY-2G.

Band	Wavelength (μm)	SNR/NEΔT	IFGOV	Spatial resolution
VIS	0.55–0.75	>1.2 (ρ = 1%)	35	1.25 km
IR1	10.3–11.3	0.2–0.4 K@300 K	140	5 km
IR2	11.5–12.5	0.2–0.4 K@300 K	140	5 km
IR3	3.50–4.00	0.3–0.6 K@300 K	140	5 km
WV	6.30–7.60	0.3–0.6 K@260 K	140	5 km

Table 2
Instrument specifications for MODIS/Terra.

Band	Wavelength (μm)	NEΔT	IFGOV	Spatial resolution
27	6.53–6.89	0.25 K@240 K	55	1 km
28	7.17–7.47	0.25 K@250 K	55	1 km
31	10.78–11.28	0.05 K@300 K	55	1 km
32	11.7–12.27	0.05 K@300 K	55	1 km

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