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Retrieval of column-integrated water vapour from MODIS and analysis of its monthly and seasonal variability over several typical cities in China

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सार – कॉलम-एकीकृत जल वाष्प, जिसे वर्षणीय जल वाष्प (पी डब्ल्यू वी) भी कहा जाता है, वैश्विक जलवायु परिवर्तन को प्रभावित करने वाला एक मुख्य प्राचल है। अपनी उच्च स्थानिक और कालिक परिवर्तिता के कारण पी डब्ल्यू वी वायुमंडलीय गतियों का अच्छा ट्रेसर है। मध्यम विभेदन इमेजिंग स्पैक्ट्रो रेडियोमीटर (MODIS) ऑकड़ो से प्राप्त करने से उच्च स्थानिक विभेदन और कम लागत लगने का फायदा है। इस शोध पत्र में कई मॉडिस नियर आई आर चैनल ऑकड़ो का उपयोग करके पी डब्ल्यू वी प्राप्त करने के लिए एल्गोरिथिम को पहले प्रस्तुत किया गया है। इस अध्ययन के लिए विभिन्न जलवायु वाली चीन की छह शहरों का चयन किया गया है। यह है बीजिंग, शंघाई, गुआंगजू, चेगडू, वुहान और लानजू। इन छह शहरों में हाल के 13 वर्षों (2001-13) में पी डब्ल्यू वी की परिवर्तिता का विश्लेषण किया गया। इस अध्ययन से हाल के 13 वर्षों में इन शहरों में जल वाष्प के वार्षिक औसत की बढ़ती हुई प्रवृति का पता चला है। इस अध्ययन से यह भी पता चला है कि उच्चतम मान ग्रीष्म ऋतु में होते है और यह शरद ऋतु में कम हो जाता है और फिर वसंत ऋतु में और कम तथा शीत ऋतु में सबसे कम होता है। हाल के 13 वर्षों में इन छह शहरों में ग्रीष्म ऋतु में पी डब्ल्यू वी में वृद्धि हो रही है परन्तु वुहान और बीजिंग जैसे शहरों में पी डब्ल्यू वी शरद ऋतु और शीत ऋतु में कम हो रहा है। इस शोध पत्र में ऐसी प्रेक्षित प्रवृतियों के संभावित कारण प्रस्तुत किए गए है।

ABSTRACT. Column-integrated water vapour also called Precipitable Water Vapour (PWV), is one of the main parameters influencing the global climate change. Due to its high spatial and temporal variability PWV has been found to be a good tracer of atmospheric motions. Retrieving PWV from Moderate Resolution Imaging Spectroradiometer (MODIS) data has the merits of high spatial resolution and low cost. In this paper, an algorithm for retrieving PWV using several MODIS near-IR channels data is first presented. Six typical cities in China with different climate are selected for study. These are Beijing, Shanghai, Guangzhou, Chengdu, Wuhan and Lanzhou. The variations of PWV in recent 13 years (2001-2013) over six cities have been analyzed. The study brings out an increasing trend of annual average of water vapour over these cities in recent 13 years. The results also indicate that PWV reaches the highest value in summer, decreases in autumn, further decrease in spring, and is lowest in winter. PWV in summer over the six cities have been increasing in recent 13 years, but PWV in autumn and winter have been decreasing over inland cities, such as Wuhan and Beijing. Possible reasons for such observed trends are given in this paper.

Key words – Precipitable water vapour, MODIS, Near-IR, Trends.

1. Introduction

Water vapour in atmosphere is an important factor which affects the weather and the application of remote sensing. It influences a wide variety of meteorological processes, including small-scale weather systems and global climate change, particularly having significant impact on the development of weather fronts (Gong *et al*., 2011; Wang *et al*., 2013). Furthermore, water vapour is the main greenhouse gas which plays a vital role in the study of climate change. It's also used as an input parameter in the application of satellite remote sensing because of its effects on radiation transfer (Li *et al*., 2003).

Global distribution of water vapour is significant for the understanding of the hydrological cycle, biosphere-atmosphere interactions, and energy budget (Kaufman and Gao, 1992). The Precipitable Water Vapour (PWV) is an indicator to signify the condition of atmospheric water vapour, which is defined as an equivalent length of liquid water column to the vertically integrated water vapour in the unit area over a site (Wang *et al.*, 2005). The 1 cm PWV is equal to 1g/cm^2 water column (Liu *et al.*, 2006).

Data products generated by using MODIS data are freely available on a global scale. The PWV retrieved from MODIS has high spatial resolution. MODIS data can therefore reflect variability of PWV in detail.

China is in the period of urban modernization, large scale constructions have been started in most cities. The filling of lakes, the transfer of a large number of people from rural to urban, the development of industry and the pollution have great influence on the atmosphere, particularly on atmospheric water vapour.

Several typical cities in China are selected for this research. Analyses of the seasonal PWV and the annual PWV over these cities are made in recent 13 years (2001-2013). The reasons for the variability of PWV are analyzed.

2. Methods of retrieving PWV from MODIS data using near IR channels

2.1. *Introduction of MODIS*

MODIS is an earth-viewing sensor on board the Earth Observing System Terra and Aqua satellites, launched in 1999 and 2002 respectively. Terra and Aqua satellite are sun synchronous, in near polar orbit at an altitude of around 705 kilometers and pass over respectively at 10:30 in descending node and at 13:30 in ascending node at these local times every day. MODIS is designed for global monitoring of land, ocean, and atmospheric properties. MODIS scans a swath width of 2330 km that is enough to provide nearly the whole global coverage every 2 days. MODIS provides images in 36 spectral bands between 0.415 and 14.235 µm with spatial resolutions of 250 m (channels 1~2), 500 m (channels 3~7), and 1000 m (channels 8~36). Design of its channels enables MODIS to improve the precision of water vapour, aerosol and atmospheric profile retrieval (Gao and Kaufman, 2003; Gong *et al*., 2011). MODIS is especially well suited to global monitoring of atmospheric properties. Data collected by MODIS can provide information about the climatology and dynamics of atmospheric properties, the impact of human activity on the regional and global environment, and the subsequent impact of man on terrestrial and oceanic biota (King *et al*., 1992). Three near-IR channels located within the 0.94 µm water vapour band absorption region were implemented on MODIS for water vapour remote sensing.

The MODIS Near-Infrared Total Precipitable Water Product (MOD05) consists of column water vapour amounts over clear land areas of the globe, and above clouds over both land and ocean. Techniques employing ratios of water vapour absorbing channels centered near 0.905, 0.936 and 0.94 mm with atmospheric window channels at 0.865 and 1.24 mm are used. The column water vapour amounts are derived from the transmittances based on theoretical radiative transfer calculations and using look-up table procedures. Water vapour values can be determined with errors typically in the range between 5% and 10% (Gao *et al*., 2003). Kaufman and Gao have described the algorithm for retrieving atmospheric water vapour from MODIS in detail (Kaufman *et al*., 1992; Gao *et al*., 2003). King *et al*. (2003) also introduced the retrieval methods of cloud, aerosol and water vapour properties from MODIS (King *et al*., 1992).

Zhao youbing analyzed the PWV by two-channel ratio weighting method and three-channel ratio weighting method. By comparing the results of the two methods with the PWV of SONDE, it was found that the PWV of three-channel ratio weighting method have higher dependability (Zhao, 2008). Dai qiangling compared the PWV from MODIS with MOD05. The relative error from three-channel ratio was 4.88% and it was 5.03% from two-channel ratio. It showed that PWV retrieved from three-channel ratio weighting method had better accuracy (Dai *et al*., 2008).

2.2. *Description of the Algorithm*

The remote sensing method is based on detecting the absorption by water vapour of the reflected solar radiation after it has been transmitted down to the surface, reflected at the surface and transmitted up through the atmosphere to the sensor. The equivalent total vertical amount of water vapour can be derived from a comparison between the reflected solar radiation in the absorption channel and the reflected solar radiation in nearby non absorption channels. Retrieving techniques of water vapour from MODIS near IR data are described (Gao *et al*., 2003; Kaufman *et al*., 1992).

Among 36 Channels of MODIS, five near infrared channels 2, 5, 17, 18 and 19 in the 0.8-1.3 µm spectral region are useful for remote sensing of water vapour. The channel 2 and 5 with centre wavelength 0.865 and 1.24 µm are atmospheric windows to avoid gaseous absorption. The channel 17, 18 and 19 with centre wavelength 0.905, 0.936 and 0.940 µm are water vapour absorption channels. The positions and widths of these channels from the original MODIS design specification are given in Table 1.

TABLE 1

Positions and widths of five MODIS near-IR channels used in water vapour retrievals

MODIS channel	Position / µm	Width / µm
2	0.865	0.040
5	1.240	0.020
17	0.905	0.030
18	0.935	0.010
19	0.940	0.050

The radiance at the sensor can be written with a good approximation as

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

where, λ is wavelength, $L_{sensor}(\lambda)$ is the radiance at the sensor, μ_0 is the cosine of solar zenith angle, $E_0(\lambda)$ is the extra-terrestrial solar irradiance, $\tau(\lambda)$ is the total atmospheric transmittance, which is equal to the product of the atmospheric transmittance from the Sun to the Earth's surface and that from the surface to the satellite sensor, $\rho(\lambda)$ is the Earth's surface bi-directional reflectance, so $[\mu_0 E_0(\lambda)/\pi]\tau(\lambda)\rho(\lambda)$ denotes the solar radiation reflected directly from the Earth's surface. $L_{path}(\lambda)$ is the path scattered radiance, and near 1 µm, Rayleigh scattering is negligible and the main contribution to $L_{path}(\lambda)$ is scattering by aerosols. $L_{path}(\lambda)$ in the 1 µm region is usually a few percent of the direct reflected solar radiation. Because most aerosols are located in the lower 2 km of the atmosphere and the same is true for atmospheric water vapour, the single and multiple scattered radiation by aerosols is also subjected to water vapour absorption. As a result, $L_{path}(\lambda)$ contains water vapour absorption features and is treated approximately as an unspecified fraction of directly reflected solar radiation when the aerosol concentrations are low. Hence, Equation (1) can be converted to $\tau(\lambda) = \rho^*(\lambda)/\rho(\lambda)$, where $\rho^*(\lambda)$ is the apparent reflectance at top of atmosphere $\rho^*(\lambda) = \pi L_{sensor}/[\mu_0 E_0(\lambda)]$ (Gao *et al.*, 2003; Kaufman *et al.*, 1992).

Most land is either covered by soils, rocks, vegetation, snow, or ice, so the surface reflectance is either constant or varies in a linear fashion with wavelength. Water vapour can be retrieved by a two or three channel ratio method. When the surface reflectance is constant and independent of wavelength, the water vapour transmittance of the absorption channel can be expressed as a two-channel apparent reflectance ratio of an absorption channel with a window channel. For example, the transmittance of the channel at 0.94 µm can be expressed as

$$\tau_{obs}(0.94\mu m) = \rho^*(0.94\mu m)/\rho^*(0.865\mu m) \quad (2)$$

When surface reflectance varies linearly with wavelength, the water vapour transmittance of the absorption channel can be written as a three-channel ratio of an absorption channel with a combination of two window channels. For example, the transmittance of the channel at 0.94 µm can be expressed as

$$\tau_{obs}(0.94\mu m) = \rho^*(0.94\mu m) / \left[C_1.\rho^*(0.865\mu m) + C_2.\rho^*(1.24\mu m)\right] \quad (3)$$

where, C_1 is equal to 0.8 and C_2 is equal to 0.2. The transmittance of other absorption channels at 0.936 µm and 0.905 µm is the same as that at 0.94 µm.

Using radiative transfer programs, such as LOWTRAN7 and MODTRAN, an exponential formula can be found between the water vapour transmittance $\tau_{obs}(0.94\,\mu m)$ and the total water vapour (W) and it can be expressed by

$$\tau_{obs}(0.94\mu m) = \exp\left(\alpha - \beta\sqrt{W}\right) \quad (4)$$

For a mixture of all surfaces, α= 0.020 and β = 0.651. If the surface reflectance would have been spectrally neutral, α is 0. Vegetation covers and soils have different spectral reflectance in the near IR. As a result, the coefficient α is different for these two groups of surface covers: such as $\alpha = 0.012$ for vegetation and $\alpha = -0.040$ for soil.

As a result, we can obtain three water vapour contents, W_1, W_2 and W_3 from three absorption channels 17, 18 and 19 of MODIS images because atmospheric water vapour has very different absorption coefficients in different absorption channels. The strong absorption channel at 0.936 µm is most sensitive under dry conditions, while the weak absorption channel at0.905 µm is most sensitive under humid conditions. Under a given atmospheric condition, the derived water vapour values from the three absorption channels can be different. A mean water vapour value (W) will be obtained according to the equation:

$$W = f_1 W_1 + f_2 W_2 + f_3 W_3 \quad (5)$$

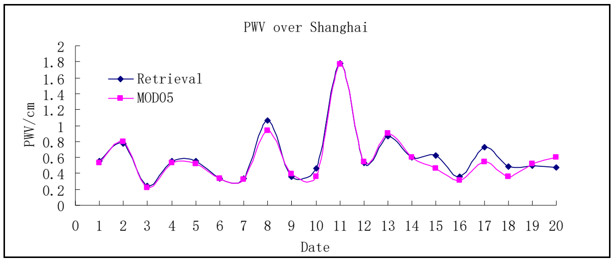

Fig. 1. Comparison between PWV retrieved from MODIS and MOD05 (Total Precipitable Water Vapour Products)

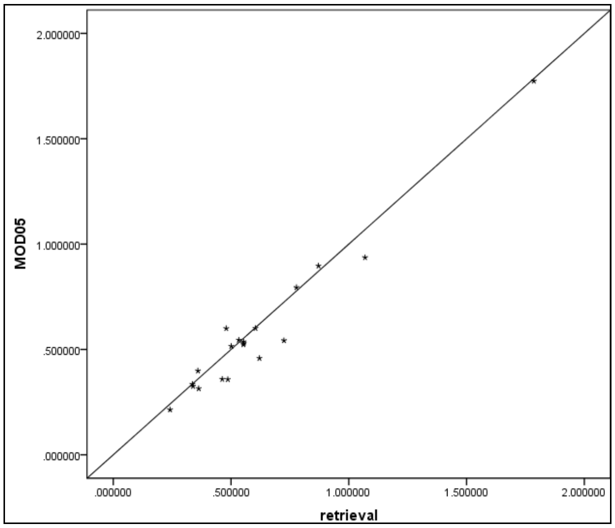

Fig. 2. Scatter plots of MODIS PWV and MOD05 under cloud-free condition

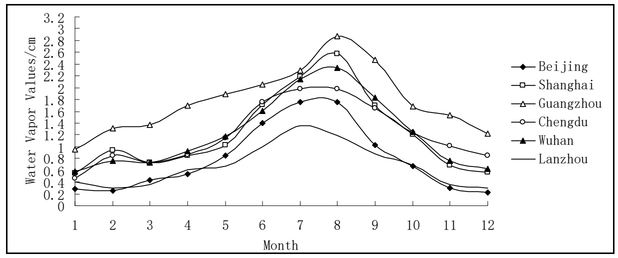

Fig. 3. Comparison of monthly average content of water vapour over six cities in 2009

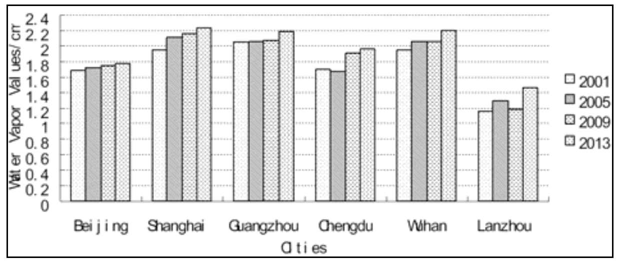

Fig. 4. Comparison of seasonal average content of water vapour over six cities in summer

where W_1, W_2 and W_3 are water vapour values derived from the 0.936, 0.940 and 0.905 µm channels, respectively, and f_1, f_2 and f_3 are the corresponding weighting functions. Based on the sensitivity of the transmittance (τ_i) in each of the channels (i) to the total water vapour (W): $\eta_i = \left|\Delta\tau_i / \Delta W\right|$. The weighting functions, f_i, are defined as the normalized values of η_i

$$f_i = \eta_i / (\eta_1 + \eta_2 + \eta_3) \quad (6)$$

These weighting functions are computed numerically from simulated curves of transmittances versus water vapour (Gao *et al*., 2003; Kaufman *et al*., 1992).

3. Quantitative assessments

PWV retrieved from MODIS near-IR channels data and MOD05 (Total Precipitable Water Vapour Test Results) are compared in Figs. 1&2. Terra-MODIS data of 20 days over Shanghai are selected. The PWV from MODIS data retrieval is very close to that from MOD05. There is a little bigger gap in some day, it is because that there are clouds in the day and the clouds affect the data collection. Generally, there are in good agreement. Their correlation coefficient is higher than 0.97, which indicates that the PWV can be effectively retrieved from MODIS data.

It has been verified by the experimental data that the Column-integrated Water Vapour over other five cities also obey the above conclusion.

4. Results and discussions

4.1. *Cities*

Six cites at different climate zones, including Beijing (north temperate semi-humid continental monsoon climate), Shanghai (north subtropical humid monsoon climate), Guangzhou (subtropical monsoon climate), Chengdu (subtropical humid monsoon climate), Wuhan (subtropical monsoon climate), Lanzhou (temperate continental climate) are selected and the content of column-integrated water vapour in recent 13 years (2001-2013) are retrieved.

4.2. *Analysis*

Geographic latitude, altitude and atmospheric circulation are the three main factors that affect the column-integrated water vapour (Han *et al*., 2012).

The monthly average content of water vapour over six cities in 2009 are shown in Fig. 3 and the highest content of column-integrated water vapour is in summer,

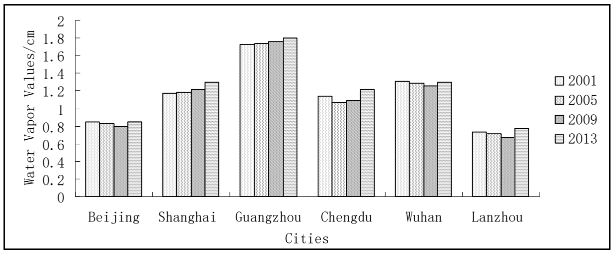

Fig. 5. Annual mean content of water vapour over six cities

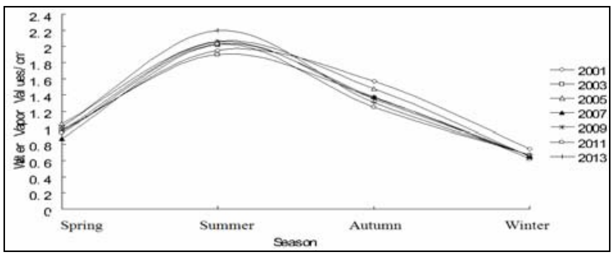

Fig. 6. Seasonal changes of column-integrated water vapour content over Wuhan (2001-2013)

decreases in autumn, further decrease in spring and it is lowest in winter.

Among six cities, the highest of the monthly average content is at Guangzhou. It is close to 3 cm in August and about 1 cm in January. Next is Shanghai, Wuhan and Chengdu, and the monthly average content of water vapour over the three cities is similar except in July and August. It is highest over Shanghai and lowest over Chengdu in July and August. Coastal condition and influence of marine climate lead to high PWV over Guangzhou and Shanghai. Yangtze River goes across Wuhan and lot of lakes are widely distributed in Wuhan, which lead to high PWV over Wuhan. Compared with these four cities, the content of water vapour over Beijing and Lanzhou is lower. The highest monthly average content of water vapour over Lanzhou is about 1 cm, close to the lowest over Guangzhou.

It is obvious that content of water vapour increases with the decrease of the geographic latitude and altitude.

It is indicated in Fig. 4 that the values of water vapour over six cities in summer have increased in recent years. The content in summer increases under the influence of abundant rainfall, monsoon, El-nino, global warming and atmospheric circulation. Global warming affected by greenhouse effect speeds up evapouration and rainfall in summer is very rich. In recent years, rainfall is great in many provinces in china. Waterlogging occurs often in many cities, such as Beijing and Wuhan. For example, during July 22 to July 24 in 2015, there has been heavy rainfall in Anhui, Hubei, Jiangxi and Fujian province. It has been the strongest rainfall in recent 50 years in many provinces. And a lot of cities' drainage system can not cope with. So, in recent several years it is popular in china to say "go to the city to see the sea".

According to the China Meteorological Department information, in recent years, adequate rain in summer, this year, a lot of rainfall in the province exceeded the highest level in history, the occurrence of water logging in many cities.

As is known in Fig. 5, the annual average content of PWV over Shanghai and Guangzhou increased year by year in recent 13 years. By contrast, over inland cities, including Beijing, Chengdu, Wuhan, and Lanzhou PWV had decreased every year before 2013. But, the annual average content over the six cities have increased in 2013. The data of China Meteorological Administration shows that the average of rainfall and temperature in 2013 are higher as compared to that at the same time in previous years.

Meanwhile the abnormality of the atmospheric circulation may affect the temperature and rainfall in a long time significantly.

It is illustrated in Fig. 5 that the comparison of the annual average content of water vapour over these cities is shown. The highest is Guangzhou, about 1.8 cm. The second is Wuhan, about 1.3 cm. The third are Shanghai and Chengdu, about 1.2 cm. The lowest are over Beijing and Lanzhou, especially it is below 0.8 cm over Lanzhou. The annual average content of water vapour had increased in recent 13 years.

Guangzhou, situated in the southeast coast of China and close to the South Sea, its temperature is high all through the year. Based on the above mentioned several reasons, the content of water vapour is high over Guangzhou all through the year.

Wuhan, Shanghai and Chengdu are at the same latitude, which is subtropical monsoon climate, characterized by high temperature and rainy in summer and moderate, humid in winter. As Shanghai is under the influence of maritime climate, the content of water vapour over Shanghai is higher than Chengdu in summer. It is higher over Wuhan than that over Chengdu because of lot of lakes in Wuhan.

Lanzhou is located inland and bears typical continental monsoon climate, characterized by less precipitation. Weather in Lanzhou is so terrible that sand storms are regular feature. The above conditions lead to low water vapour over Lanzhou.

Next, Wuhan located in center of China is selected and PWV over this station are analyzed.

According to the Fig. 6, content of water vapour in autumn and winter declined as compared with that in 2001. Column-integrated water vapour mainly comes from evapouration of rivers, lakes and oceans, and loss from plants and so on. High temperature speeds up evapouration, so the content of water vapour is higher in large tracts of warm waters. Terrain, climate, vegetation coverage, and distance far away from the water vapour sources make it different in the horizontal direction. And so the content of water vapour increases in summer. Greenhouse effect leads to rising global temperature, and rising temperature helps to speed up evapouration. It is obvious that PWV in autumn and winter decreased. Column-integrated water vapour mainly comes from the evapouration of rivers and lakes in autumn and winter. It suggests that rivers and lakes in Wuhan have reduced in recent 13 years.

5. Conclusions

In this paper, the data about PWV retrieved from MODIS near-IR channels have been analyzed over six different typical climate cities in China in recent 13 years (2001-2013). The conclusions are summarized as follows.

(*i*) The highest content of Column-integrated water vapour over these cities was in summer, decreasing in spring, further decrease in autumn and is the lowest in winter.

(*ii*) Overall, the values of PWV over six cities have increased in summer in recent 13 years. The main factors responsible for this include abundant rainfall, monsoon, El-nino, global warming and atmospheric circulation. And the abnormality of the atmospheric circulation also played a major role.

(*iii*) The annual average content of PWV over coastal cities (Guangzhou and Shanghai) increased in recent 13 years. But it decreased over inland cities before 2013.

(*iv*) The content of column-integrated water vapour over Wuhan decreased in autumn and winter under the influence of water area reduction.

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