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Using GPS PWV as a New Approach to Correlate Solar-Induced on Antarctic Climate

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Abstract: This paper observes the characteristics of Antarctic precipitable water vapor (PWV) as a climate parameter affected by solar radiation at Scott Base (77.85°S, 166.76°E), Davis (68.58°S, 77.97°E) and Syowa (69.00°S, 39.58°E) using the ground-based GPS and the surface meteorological measurements. As the Sun plays a central role in the hydrological cycle and precipitation, the associations between water vapor and solar radiation have been studied to understand the current global climate change. Analysis of data gathered for the period from 2003 to 2008 showed that the observations between PWV and solar radiation shows strong relationships with correlation coefficients 0.84 for diffuse and 0.79 for global radiation. Based on their strong relationship, PWV data and analysis have done suggests that GPS can be used as a new approach to study the interaction of solar-induced climate change.

Key words: GPS PWV, Solar radiation, Antarctica, Correlation

INTRODUCTION

As seen in the latest report of the Intergovernmental Panel on Climate Change (IPCC), increased in the global surface temperature of 1.1 to 6.4 °C during the twenty-first century, is expected due to the anthropogenic greenhouse gas concentrations (IPCC, 2007). In this report, human activity has played a major role in increasing the atmospheric greenhouse gases. The main greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Water vapor is the biggest contributor to the 'natural greenhouse effect', and their 'positive feedback' lead water vapor plays a critical role in the global climate system. Water vapor is expected to increase due to changes in the intensity of severe weather and solar activity. The natural forcing of solar variability brings annual and seasonal impacts of water vapor, which change the character of each hemisphere. Hence, water vapor circulation on the globe and its variability had a growing concern in many parts of the world owing to apparently contributed to the amplification of global warming. Thus characterizing water vapor on the surface radiation budget and their relationship are critical for a better understanding of the processes of solar-induced on climate change.

Previous studies have shown that the investigation of the vertical water vapor circulation and the horizontal global solar irradiances were concentrated at location between 60°N and 60°S. Recently, the challenging of water vapor investigation has focused in the polar regions. Due to the Polar regions (i.e. Antarctica) unique situation in terms of weather and climate, they offer a privileged position for the studying solar-climate relationships. Despite the opportunity of doing research in Antarctica to support the International Polar Year (IPY) program, this work is motivated by two recent reports: the absorption of solar radiation in the atmosphere in the presence of clouds (e.g., O'Hirock and Gautir, 2003) and the estimation of atmospheric turbidity for assessing the air pollution in a local area (e.g., Lopez and Batlles, 2004). According to Lopez and Batlles (2004), they use of surface parameters such as air temperature, dew point and relative humidity to estimate the precipitable water. However, for solar-terrestrial interaction studies, the vertical resolution of PWV will be imprecise quantified, especially in Antarctic region due to unexpected weather conditions. Connolley and King (1996) report that traditional moisture sensors in a cold environment had shown less reliable for measure the surface parameters on the ground. Thus, measurement of water vapor content in the atmosphere is now being addressed using the Global Positioning System (GPS) technology. Considerable developments in the GPS analysis lead to remarkable improvements in the accuracy of PWV estimation. The comparisons of

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GPS PWV with radiosondes and water vapor radiometers have demonstrated that GPS-sensed PWV has achieved consistent with an accuracy of about 1~2 mm (Elgered *et al*., 1998; Tregoning *et al*., 1998; Liou *et al*., 2001). The high quality of GPS PWV allows to be used for meteorology applications such as solar-climate relationship studies (e.g., Suparta *et al*., 2008).

The objective of this paper is to analyze the characteristics between the water vapor variability and the solar radiation at Scott Base station, Antarctica (SBA). To give clear the characteristics of GPS PWV pattern, the GPS PWVs at Davis and Syowa stations are compared with GPS PWV at SBA. The physical process of solar radiation affecting on water vapor is discussed. This paper is structured in the following manner: in Section 2 briefly describes the data and methods with covers the state-of-the-art in retrieval of PWV from GPS observations, in Section 3 discusses the results of the data observed and finally in Section 4 concluded the paper.

Data and Methods:

Brief PWV determination, the measurement system and data processing are elucidated in this section. The analyses are based on the data gathered from January 2003 to December 2008 over Antarctic region.

PWV Determination from GPS and Surface Meteorology:

To make use of advances in GPS signals for atmospheric studies, a ground-based GPS receiver together with the surface meteorology measurements is employed to measure the vertical content of water vapor. The GPS sensed water vapor is determined as follows:

When the GPS signal propagates through the Earth's atmosphere, it is severely affected by the propagation delays, mainly in the Earth's troposphere and ionosphere. This causes an excess delay of the signal, and the changes in the refractive index with height cause the bending of the signal. The total delay along the slant path is composed of two parts: ionospheric delay (I) and tropospheric delay (D). The ionospheric delay is frequency dependent, and it can be nearly corrected by observing both frequencies transmitted by the GPS satellites (L_1 and L_2). Besides the use, the dual-frequency GPS receiver, the ionospheric delay effect in the GPS processing can be minimized by adopting the precise point positioning (PPP) strategy, as implemented in the JPL GIPSY-OASIS software (Zumberge *et al*., 1998). The remaining delay is the tropospheric delay or neutral delay, and is not frequency dependent, but depends on the constituents of the atmosphere. As such, this delay along the path of the radio signals to a receiver on the ground is sensitive to local surface pressure, temperature and water vapor variations. Based on this assumption, the atmospheric delay caused by the neutral atmosphere can be determined from the "hydrostatic" delay and a "wet" delay. The tropospheric delay (D) for this work is calculated using the Modified Hopfield model (Hofmann-Wellenhof *et al*., 2001) as expressed in Eq. (1). To meet a consistency solution for tropospheric delay calculation, equation (1) has been corrected (see Eq. (11) in Suparta *et al*., 2008).

$$D = 10^{-6} N_{j,0} \left(\sum_{k=1}^{9} \frac{\beta_{k,j}}{k} r_j^k \right) \tag{1}$$

where $N_{j,0}$ is the total refractivity at the Earth's surface, which subscript j represents for the hydrostatic and wet components, respectively. Radius r_j is the length positions vector instead of height for hydrostatic and wet components respectively, b is the series expansion and k is the tropospheric layer.

To obtain the total tropospheric delay in the zenith direction or zenith tropospheric delay (ZTD), the right side of (1) is mapped to the satellite elevation angle using an appropriate hydrostatic mapping function. Based on this estimation, the ZTD is sum of the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD). The ZHD is mainly caused by the dry part of the gaseous in the atmosphere, which depends solely on local pressure and the position of GPS receiver, while the ZWD depends on mainly on the total amount water vapor along the paths of the radio signals to all satellites from a GPS receiver position. The ZWD is obtained by subtracting the ZHD from ZTD. Finally, total PWV is calculated using Bevis *et al*. (1994) formula as expressed in Eq. (2).

$$PWV = \alpha \ ZWD \quad , \quad \text{where } \alpha = \left(A + \frac{B}{C + DT} \right)^{-1} \tag{2}$$

where the dimensionless a parameter is a conversion factor that varies with local climate such as location, elevation, season and weather, A = 0.102 and B = 1725.6 are constants which both calculated from weighted molecule gases and refraction constants, C = 70.2 and D = 0.72 are intercept and regression coefficient for estimation of mean weighted temperature respectively, and T is the local surface temperature (in Kelvin). Detail determination of GPS PWV for this work can be found in Suparta *et al*. (2008).

The surface meteorological data, primarily on surface pressure, temperature and relative humidity combined with GPS signals are used to calculate the PWV. Accurate measurements of the third surface variables at adjacent the GPS antenna would isolate the errors in GPS determined PWV at the Earth's surface. Therefore, a Vaisala HMP45D is employed to measure the air temperature (T) and the relative humidity (H), and a Vaisala PTB 100A analog Barometer is used to measure the surface pressure (P). The units for P, T and H are mbar, degrees Celsius and percent, respectively. Besides the wind speed and direction measurements, the meteorology system at SBA consists of a broadband pyranometer (Kipp & Zonen CM11) that can be used to measure the amount of direct, diffuse and global solar radiations on a level surface (in Wm^{-2}).

Data Processing:

Figure 1 shows the location of GPS PWV observation in Antarctica. SBA is at a distance of about 3 km from McMurdo station (US Base), or 1,353 km from South Pole with Mt. Erebus behind it. It is near the tip of Hut Point Peninsula on Ross Island. At SBA, the GPS was installed at geographically (77.9°S, 166.8°E) with a height of 28.2 m at sea level. GPS signals are measured at a 30s interval and mean surface meteorological data collected are logged at 10-min intervals. The average minimum and maximum elevations looking towards the GPS satellites are about 39 and 61 degrees, respectively. The annual mean values for temperature and wind speed are about -19 °C and 6 ms^{-1}, respectively. As shown in Fig. 1, two sets of GPS and meteorological data at Davis and Syowa stations were also processed. The GPS position at Davis station (DAV1) is located at 68.58°S, 77.97°E and 44.40 m altitude ellipsoid, on the Ingrid Christensen Coast of Princess Elizabeth Land (known as the Vestfold Hills). The GPS system at Syowa station (SYOG) is at positions 69.00°S, 39.58°E and at 45.00 m altitude ellipsoid, located on East Ongul Island, Lutzow-Holm Bay, East Antarctica, 4 km from the seashore. In this work, GPS data for both stations were obtained from GARNER archives at SOPAC homepage (http://sopac.ucsd.edu).

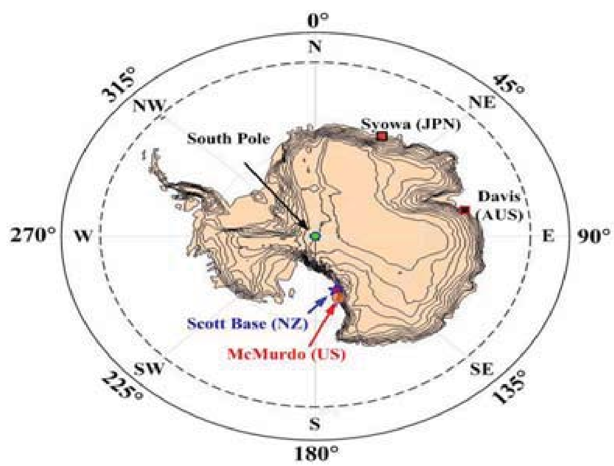

Fig. 1: Location of Scott Base (SBA), Davis (DAV1) and Syowa (SYOG) stations in Antarctica

As introduced in Section 2.1, the PWV is determined from GPS signals and the surface meteorological data. In this work, the ZTD calculated using the improved Modified Hopfield model (namely ZTD_{cal}) is validated with ZTD product (namely ZTD reference, ZTD_{ref}) obtained from AIUB (Astronomical Institute of the University of Berne) Data Center (ftp://ftp.unibe.ch/aiub/CODE/). This ZTD_{ref} is processed by Bernese GPS Software Version 5.1 and available in 2h intervals. In this work, the ZTD_{ref} at DAV1 was used to compare the ZTD_{cal} at same station. Results showed that a positive bias of ZTD_{cal} was about 0.32 cm with standard deviation errors to be 0.12~0.20% based on ZTD data in 2008. To calculate the PWV in Eq. (2), the GPS-sensed water vapor observables (ZTD, ZHD, ZWD) at SBA are computed every 10 minutes using self-developed data analysis software, namely the tropospheric water vapor program (TroWav) written in Matlab.

Overall, the accuracy of ZTD product at SBA in a 10 min average was at the level of 1.2 ~ 1.60 cm, which corresponds to 2~3 mm in PWV accuracies.

RESULTS AND DISCUSSIONS

This section presents a surface meteorological condition, since the meteorological phenomena forces the PWV. After that, I will deals association between GPS PWV and solar radiation.

Surface Meteorological Variations:

Figure 2 shows the temporal variations of surface meteorological data for 6-year at SBA. The results are averaged at the one-day intervals. On the top panel of Fig. 2 presents the variation of surface pressure, which is fluctuated between 952 and 1029 mbar (989 mbar, on average). The surface temperature on the second panel, its value varies from -46 to 2 °C with a mean value of -19 °C. While relative humidity on the third panel has a discrepancy with value varies from 34 to 101% (70.5%, on average). Wind speed on the fourth panel representing a micro-scale climate show increased their speed to a maximum value at 20 ms^{-1} during the Austral winter (June, July and August, JJA) and decreased their speed to about 2 ms^{-1} at Austral summer (December, January and February, DJF) periods. The prevailing wind in the bottom panel of Fig. 2 was blowing from the North-Northeast (from the Ross Sea). The winds coming from the Ross Sea and is possibly affecting the evapotranspiration. The wind brings heat energy into an area and removing the vaporized moisture then warms the surface of Scott Base circumstances.

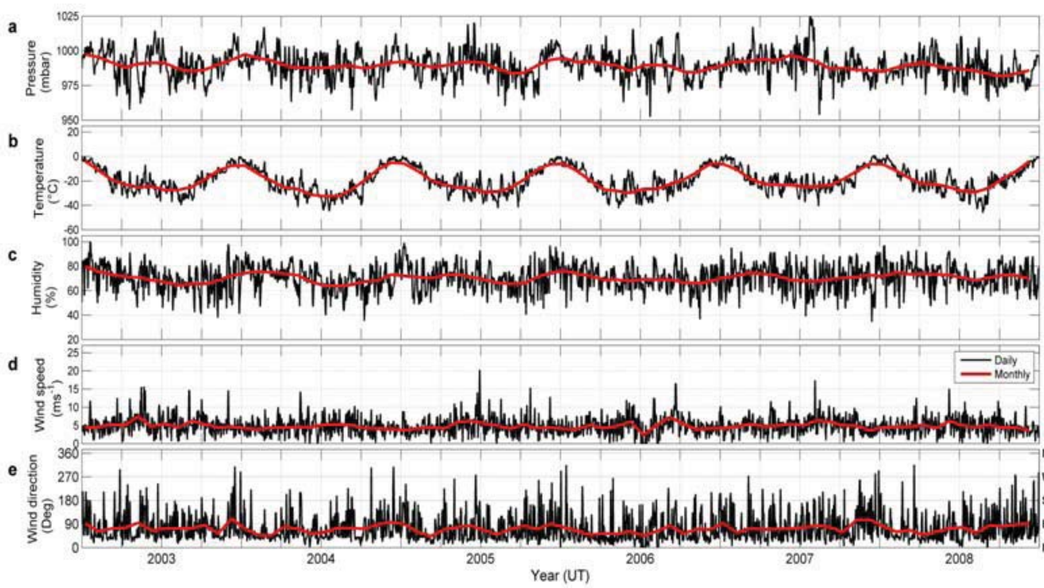

Fig. 2: Temporal variations of daily-mean surface meteorological measurement for the period from 2003 to 2008 at Scott Base station, Antarctica. Note that the red solid lines show for monthly-mean values, and the year marks on the figure denotes the middle of the year

From a monthly-mean variation of Fig. 2, the surface meteorological parameters (surface pressure, temperature, relative humidity and wind speed) were apparent forces the GPS PWV variability. This evident has shown that the temperature and wind speed is the biggest components to influence the PWV content. The temperature pattern was observed in seasonal variation, which maximum in Austral summer and minimum in Austral winter. As shown in Fig. 2d, the wind speed pattern seems an opposite variation to that of surface temperature. The strong wind speed above 10 ms^{-1} was observed decreased the PWV content (Suparta *et al*., 2009).

PWV Profiles at Polar Cap:

Figure 3 shows the temporal variations of PWV content at three stations in Antarctic coasts. Their variation exhibits almost similar characters following the local temperature patterns. At SBA, the range of daily-mean estimated PWV value was 0 to 11 mm (~3.3 mm, on average) with a standard deviation of 2.1 mm. Similar to SBA, the maximum PWV values were 10.40 mm for DAV1 and 11.00 mm for SYOG with standard deviations of 2.1 mm and 2.3 mm, respectively. Mean PWV values for DAV1 and SYOG during the observation period were 4.1 mm and 4.5 mm, respectively. PWV at SBA was observed lower by about 25% compared with PWV at DAV1. The difference daily mean PWV value between SBA and SYOG was about 36%, which PWV at SYOG was higher compared to PWV at SBA and DAV1, respectively. The high fluctuations of PWV variation on daily means for Austral winter in 2005 at DAV1 and SYOG, and during Austral spring in 2006 for DAV1 are due to unknown effects on the actual surface meteorological data. At all stations, the pattern of the monthly averaged PWV obtained at DAV1 is similar to that obtained at SYOG. However, the pattern of PWV obtained at SBA seems to differ from those obtained at both DAV1 and SYOG. In other words, the PWV pattern in Antarctica shows a large seasonal variation, largest in the Austral summer and lowest in the Austral winter.

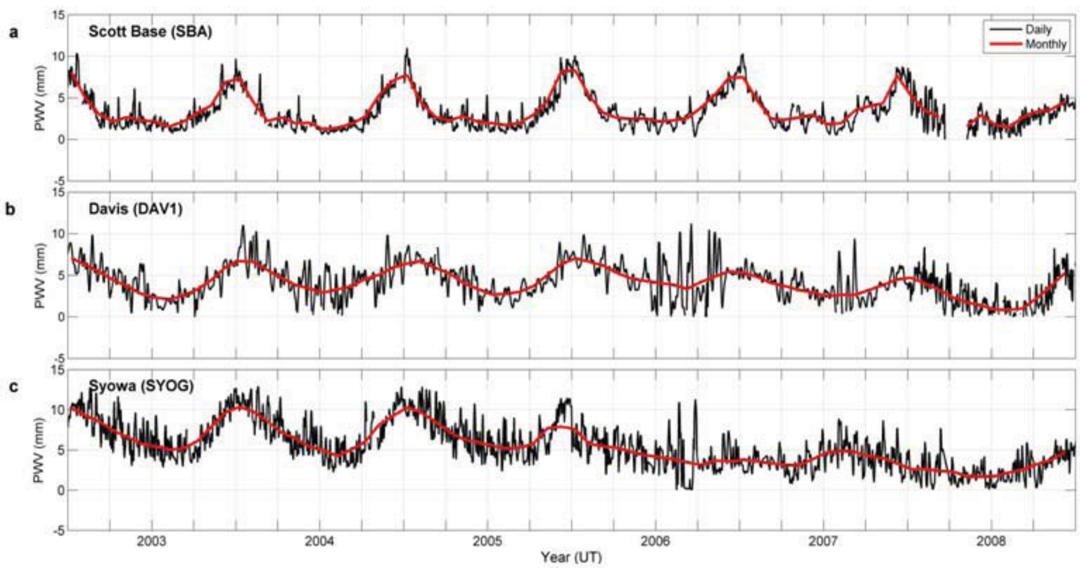

Fig. 3: PWV variability for the period of 2003 to 2008 at Scott Base (SBA), Davis (DAV1) and Syowa (SYOG) stations, Antarctica

The seasonal effects of PWV in the monthly-mean patterns were clear seen in Fig. 3. The PWV rapidly rises from its winter until late spring and continues to rise at a faster rate to reach the summer peak at around December, then minimum in July, and finally forming an annual cycle signal. The unusual PWV at around May/June (Austral winter) pronounced by a maximum peak and repeat at around September/October at every year is indicative of coreless winter resulting from inversion of the temperature gradient variation (e.g., Hudson and Brandt, 2005). One or more can see from monthly mean variation, the PWV and temperature on monthly-mean variation follow each other better than the temperature and relative humidity (see Figs. 2 and 3 for a comparison). The PWV pattern during the observation period demonstrates descending trend, whereas the time of this observation is coincident with declining phase of solar cycle 23.

Solar Radiation Influence on PWV:

Figure 4 shows the temporal variations of solar radiation received at the ground surface at SBA, which is composed of direct, diffused (skylight) and net global components. The direct solar radiation (DSR) is the amount of solar radiations reaching the Earth's surface emitted from the solid angle of the Sun, mainly on unscattered and unreflected solar insolation. The intensity of DSR was observed maximum of 1005.93 Wm^{-2}. The daily mean DSR was recorded about 886 Wm^{-2} during the Austral winter and about 0 Wm^{-2} from April to September. The indirect or diffuse (FSR) and the global solar radiation (GSR) values were notable maximum in summer and minimum in winter, in which their amount lies in the ranges of 0 to about 448 Wm^{-2}. On the other hand, the DSR value and its intensity during this period were higher by a factor of two compared to FSR and GSR, respectively. The high amount of solar radiation received on the surface (the surface-absorbed solar flux) during the Austral summer is associated with low cloud cover (e.g., Keevallik *et al*., 1994). While low irradiance values measured during the Austral winter is being associated with cloudy periods. Thus, the presence of snow cover in the sky absorbs a substantial amount of solar radiation and as a result, only scattered (diffused) radiation can reach the Earth's surface.

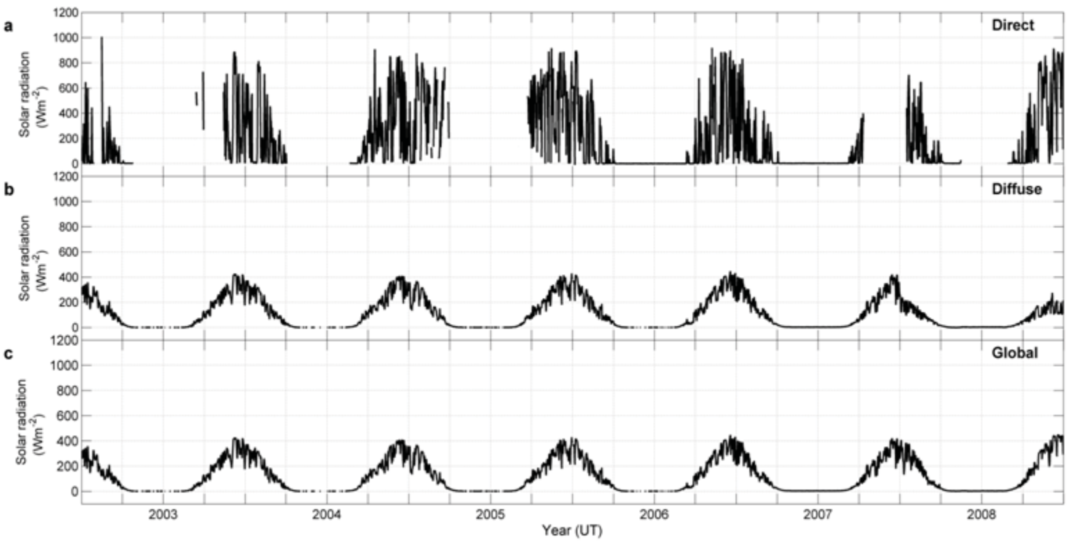

Fig. 4: Temporal variations of solar radiation for direct, diffuse and global measurements during the period of 2003 to 2008 at Scott Base station, Antarctica

As seen in Fig. 4, the incoming of solar energy (insolation) is usually depending on the solar elevation angle, time of day and atmospheric conditions. By comparing Figs. 3 and 4, it revealed that the PWV low occurs at high latitude of the Southern Hemisphere in Austral winter because of the low of the solar radiation. In the Austral summer, the high PWV occurs because the high rates of evaporation depend on the temperature. Since the saturation of water vapor pressure increase, this will increases the amount of water vapor in the atmosphere. On the other hand, the intensity of radiation from the Sun affecting the Earth's atmosphere varies with seasonal cycle of the Earth, so the strongest is occurring on the dayside of the Earth (polar summer), and the lesser is during the dark side (polar winter). The annual variations of PWV and solar radiation are plotted in Fig. 5. One important thing to see from the figure that the PWV variation over Antarctica had closely been following the solar radiation patterns, which is characterized by U-distribution. Although both DSR and FSR shown sudden changes in September (so-called the 'Polar morning'), due to the ozone-hole event involves in the seasonal variation of Antarctic atmospheric temperature, the two quantities are seen to be strongly associated.

The dependencies of PWV on solar radiation are displayed in Fig. 6. Their association is characterized by correlation coefficients (r), which are all calculated at the 99% confidence level. The autocorrelation in the data series has been taken into account when statistical significance established. The degree of coupling between the PWV and the solar radiation in the observation data can be read in the slope of the correlation charts. Atmospheric conditions can reduce direct beam radiation reaching the Earth's surface. The low of their correlation does not necessarily mean that there is no water vapor feedback, although there was no sunlight in the polar region during Austral winter. From the figure, the lack of incoming solar radiation during Austral winter (see Fig. 5) means results in cooling of the stratosphere to global record lows and the net radiation is dominated by long-wave radiant energy and the radiation balance is outgoing. The low level of significant impacts of solar radiation on the PWV variety during the Austral winter season is a possibility caused by atmospheric turbidity and a substantial of solar radiation was attenuated by clouds (high cloud cover). Referring to that, the strongest correlation between PWV and solar radiation indicating that the abundance of water vapor more absorbs the incoming of solar radiation during the Austral summer and less absorbed during the Austral winter. The absorbed energy changes partly into heat and produces a change of temperature in the clear sky. Warmest the temperature during summer to many air molecules excited (evaporation process) above Earth's surface that would be increased the PWV content in the atmosphere.

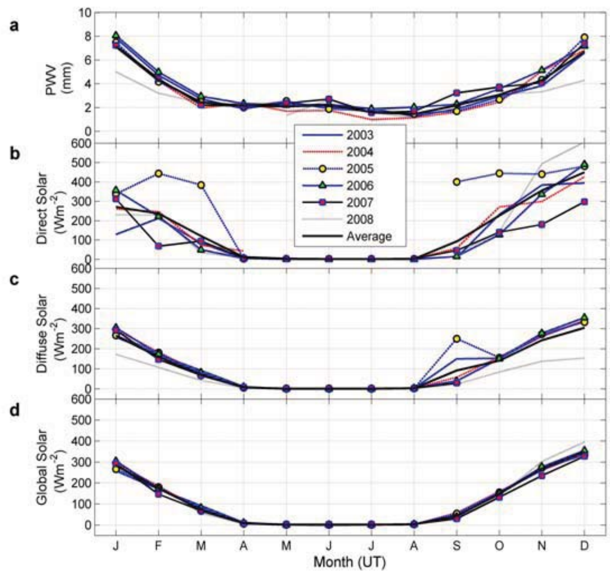

Fig. 5: Annual PWV and solar radiation variations averaged over the year of 2003-2008

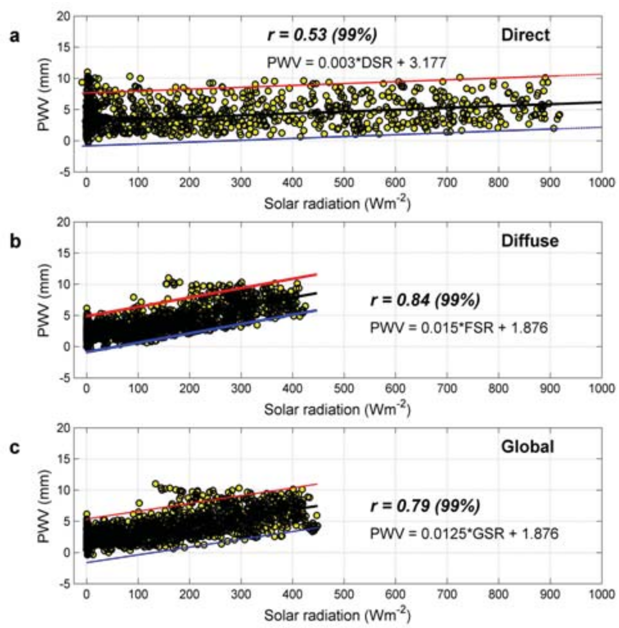

Fig. 6: Scatterplot of daily-mean values of PWV and solar radiation observed for the period from 2003 to 2008 at Scott Base station, Antarctica. In each figure, r is the correlation coefficient calculated at the 99% confidence level.

Conclusions:

The vertical integrated PWV and its characteristics within the polar cap were observed by using the ground-based GPS receivers and the surface meteorological measurements. From the data collected, a daily mean analysis was made to construct a climatology response to the solar radiation activity during which is coincident with descending phase of solar cycle 23. Analysis shows that there is a strong relationship between Antarctic PWV and solar radiation with correlation coefficients of 0.84 for diffuse and 0.79 for the net global solar radiation, significantly at 99% confidence level. In addition, a number of Antarctic meteorological variables show a strong annual cycle, suggesting that a strong relationship between PWV and solar radiation can be formulated in a mathematical expression of interest. This high correlation reflects the fact that high solar radiation toward warmer the temperatures and the amount of water vapor transported into the upper troposphere becomes large and thereby drives the atmospheric circulation as well as warming effect on Earth. Furthermore, the increase in surface temperature and solar radiation means to increase the energy available for evaporation which in turn increases the PWV content in the atmosphere. In addition to interesting results and continuous PWV data with high resolution presented here, will give useful to improve our understanding of radiation-climate interactions through the GPS approach.

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