

Atmospheric sounding with ground-based and Balloon-based GNSS RO for atmospheric study



Xiaoming Wang, Cong Qiu

Academy of Opto-Electronics, Chinese Academy of Sciences

Corresponding Email: wxm@aoe.ac.cn



Introduction

GNSS has been widely used as an atmospheric observing system to measure the water vapor and temperature in the atmosphere for both climate studies and meteorology. Atmospheric sounding with GNSS can be divided into two categories based on the way signal is received and used, i.e. the ground-based GNSS remote sensing and the space-born GNSS remote sensing, which is also known as GNSS radio occultation (GNSS-RO). Both ground-based and space-based GNSS techniques can give information on the atmosphere by analyzing the atmospheric refraction effect on the L-band signal transmitted from GNSS satellites to the receivers on the ground or to the receivers in a low-earth orbit. Ground-based GNSS remote sensing is used to derive the precipitable water vapor (PWV) from the delay of the radio waves caused by the atmosphere when transmitting from GNSS satellites to receivers on the Earth. Space-based GNSS-RO techniques can provide vertical profiles of refractivity, temperature, and water vapor on a global scale. The concept of GNSS atmospheric sounding was proposed in the 1990s with the establishment of the GPS. After almost 30 years of development, both ground-based and space-based GNSS techniques have been widely adopted as established atmospheric remote sensing systems due to their all-weather and 24-hour availabilities, high spatial-temporal resolution, and relatively low cost. GNSS remote sensing has been used not only for weather forecasting but also for climate studies due to the data accumulation of 30 years of global observations. With the development of long-duration balloon, balloon-based GNSS RO becomes a practical and promising technique in the remote sensing of the atmosphere for a specific region. We recently initiated a 5-year project to investigate the atmosphere structure and properties in the mid-latitude region and the Qinghai-Tibet Plateau with balloon-based, ground-based, and satellite-based GNSS remote sensing techniques.

Ground-based GNSS for climate study

Water vapor is the most abundant atmospheric greenhouse gas, and it plays a vital role in the evolution of the Earth's climate. As El Niño–Southern Oscillation (ENSO) is an ocean-atmosphere interaction phenomenon, in addition to sea surface temperature (SST), water vapor in the atmosphere can be used to trace ENSO evolution. PWV, which is highly correlated with precipitation but which increases much faster than the volume of total precipitation as the climate warms, can serve as an additional measure for better understanding the outcomes of ENSO events. Fig. 1 shows the non-linear trend obtained from PWV time series at 6 stations. Although the non-linear trends in different PWV time series show different properties, obvious turning points at around 1998 and 2000 were found in these non-linear trends. These turning points might be caused by the strong 1997–98 El Niño and 1999–2000 La Niña events, as shown in Fig. 2. In the ocean, ENSO is most commonly monitored by observing SST within a boxed region of the central and eastern tropical Pacific known as NINO3.4. While in the atmosphere, ENSO is monitored via the SOI, a measure of atmospheric circulation that takes the difference of atmospheric pressures between Darwin and Tahiti.

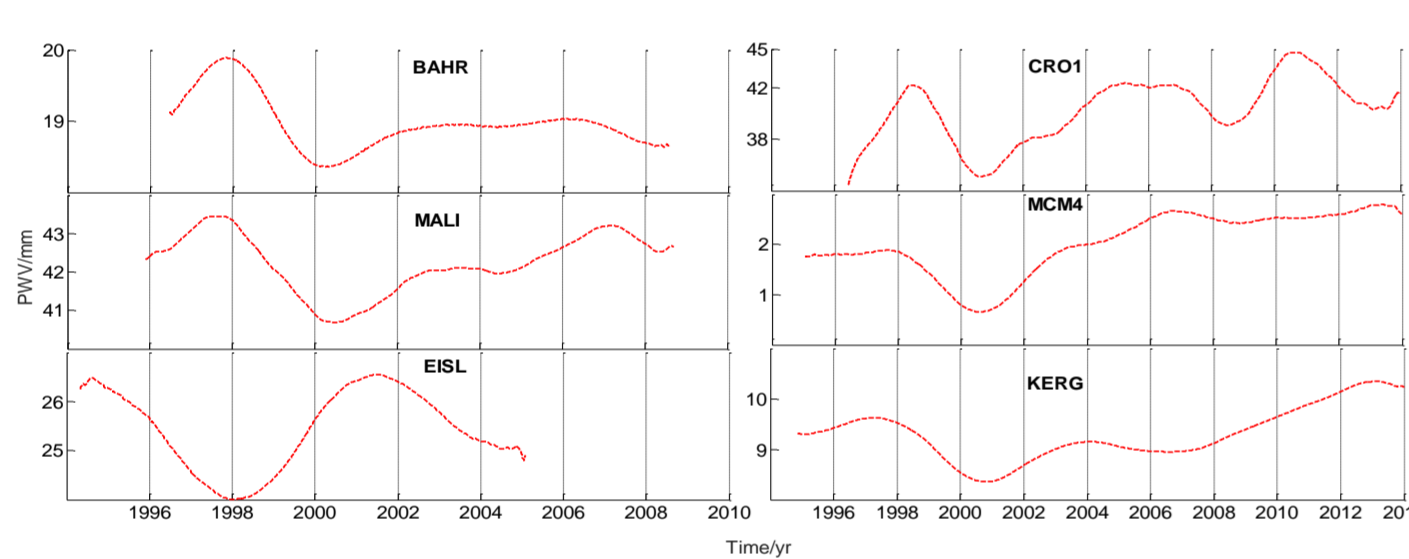


Fig. 1 Non-linear trend in the PWV time series at 6 stations

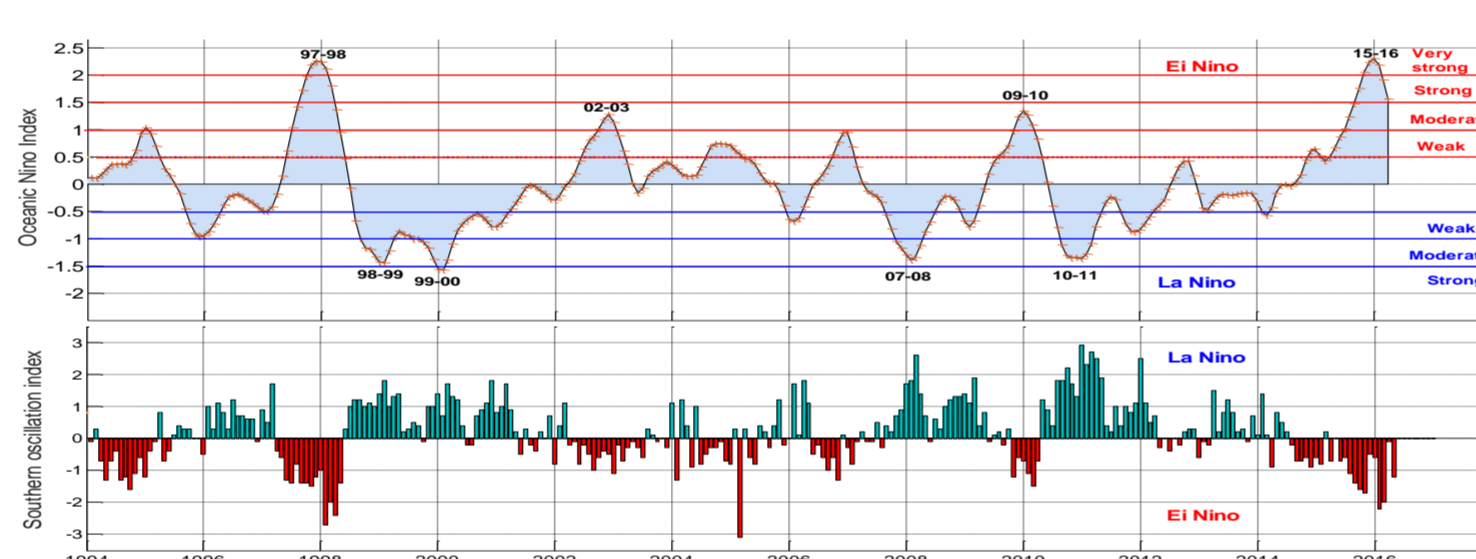


Fig. 2 SOI and ONI for the period 1994–2016

As shown in Fig.3, the correlation coefficients between PWV and SST are larger than 0.7 at 91 % of the stations and larger than 0.8 at about 66 % of the stations. The 5 stations that have a correlation coefficient under 0.7 are located in a region with either a large annual precipitation or a strong wind. The heavy precipitation would decrease the PWV and the strong wind would blow the PWV to other regions, both of which have a large impact on the correlation between PWV and SST. Fig. 3 (b) indicates that a 1 K increase in SST leads to a 5.2 mm increase in PWV in the tropical regions and a 1.5 mm increase in the other regions. Fig. 3 (c) shows that a 1 K increase in SST leads to a 11.2 % increase in PWV across all 56 stations.

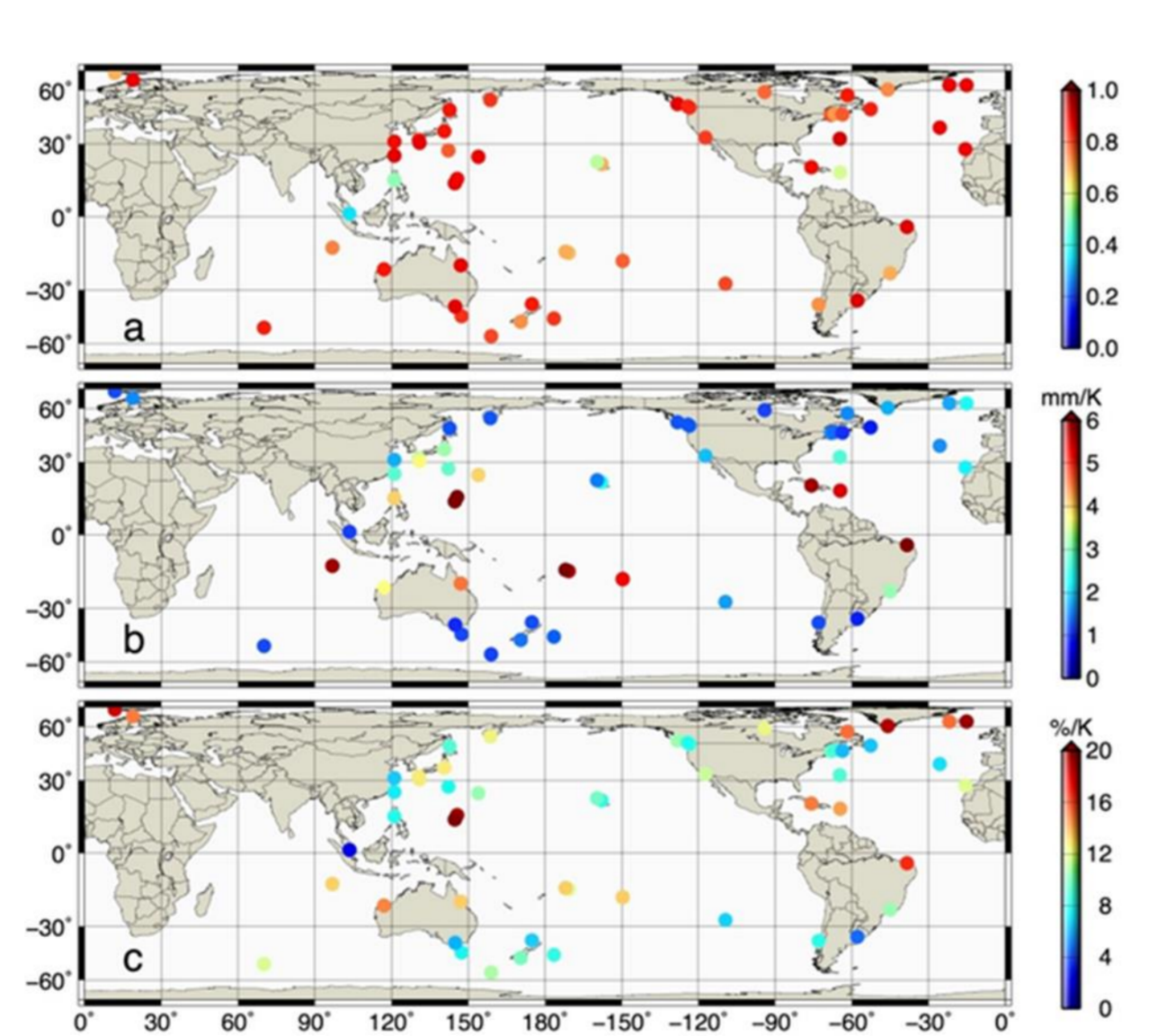


Fig. 3 Correlation coefficients between SST and PWV (a); the increase of PWV caused by 1 K increase in SST (b); the relative increase of PWV caused by 1 K increase in SST (c)

The variations in Total Precipitation (TP) and PWV over the TOW2 station were taken as an example for investigating the regional outcome of ENSO events during the period 1995–2014. TOW2 is located in Cape Ferguson, a city in central of Queensland on the Coral Sea which is part of the South Pacific Ocean. Fig. 4 shows the regional annual and seasonal TP anomaly during this period. The annual/seasonal anomaly is defined as the deviation of annual/seasonal TP from its long-term annual/seasonal average of the whole period (1995–2014). As shown in Fig. 4, there is considerable event-to-event variability in the impacts of ENSO events on TP. For example, although the 1997–98 El Niño was regarded as one of the most powerful ENSO events in recorded history, the TP during the event did not show a significant decrease as expected. However, due to the effect of 1998–99 and 1999–2000 La Niña events, a significant increase in the TP in 2000 was observed. Because of several El Niño events (2002–03, 2004–05 and 2006–07), the annual TP decreases significantly and remains obviously under its long-term (1994 – 2013) average value of 1227 mm. This severe drought was stated as the worst drought in record of southeast Australia by several measures. With the development of the 2010–2011 La Niña event, the annual TP is noticeably (63%) larger than the long-term annual average, which leads to large-scale flooding in many parts of southeast and east Australia. Fig. 5 shows the annual and seasonal PWV anomaly during the period 1995–2013 observed at TOW2. The main features of the PWV variations are in a very good agreement with that of TP. For example, during the severe drought period, the annual PWV and most seasonal PWVs are below the long-term annual and seasonal average. Before the 2010–2011 flood occurred, a obvious rapid increase in PWV of 2010 is found (Fig. 5 (b)) and the winter and spring in 2010 was also most humid winter and spring during the period 1995–2013. The period from summer 2010 to autumn 2011 is also the longest period (6 seasons) that has a continuous positive seasonal PWV anomaly.

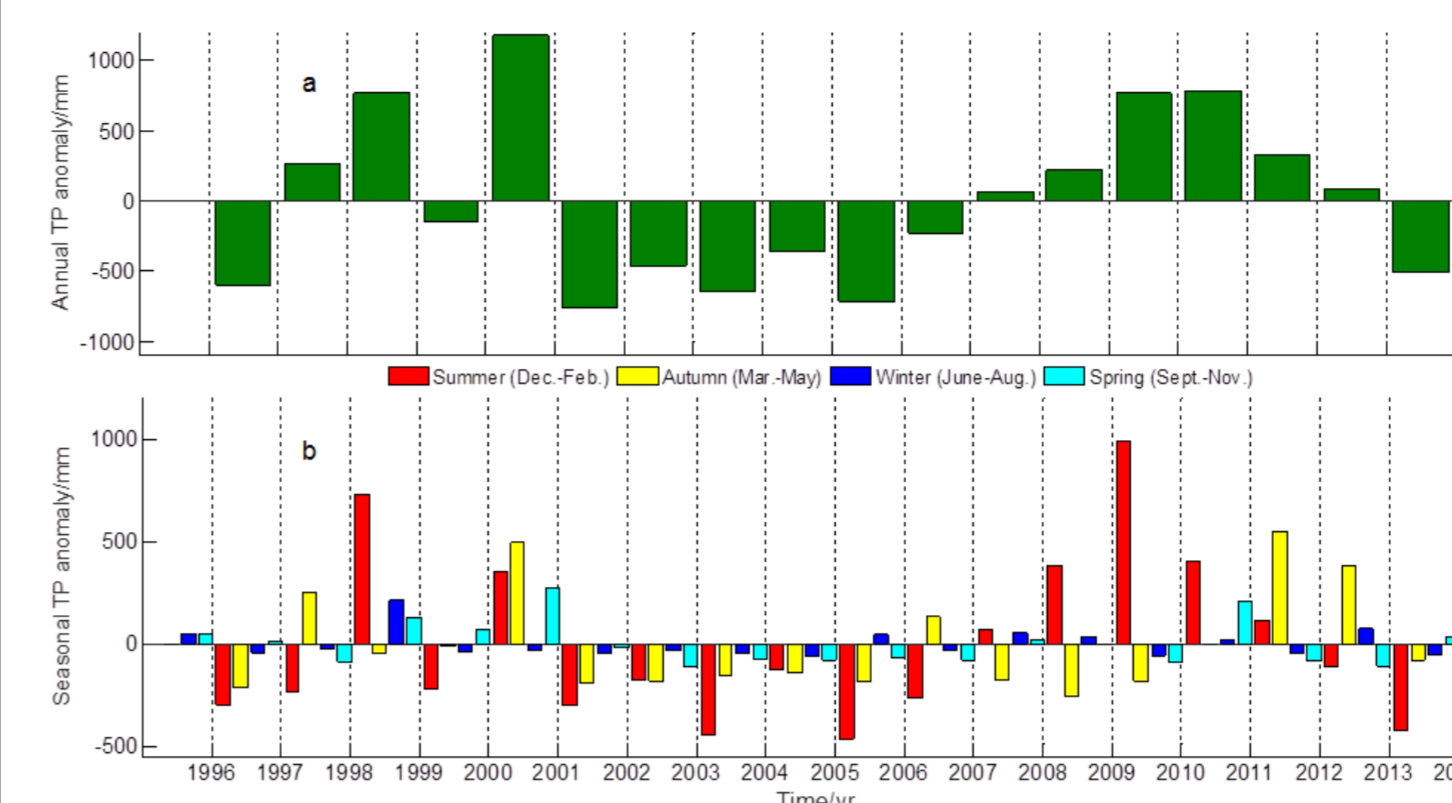


Fig. 4 Annual TP anomaly (a) and seasonal TP anomaly (b) at TOW2 during the period 1995–2014

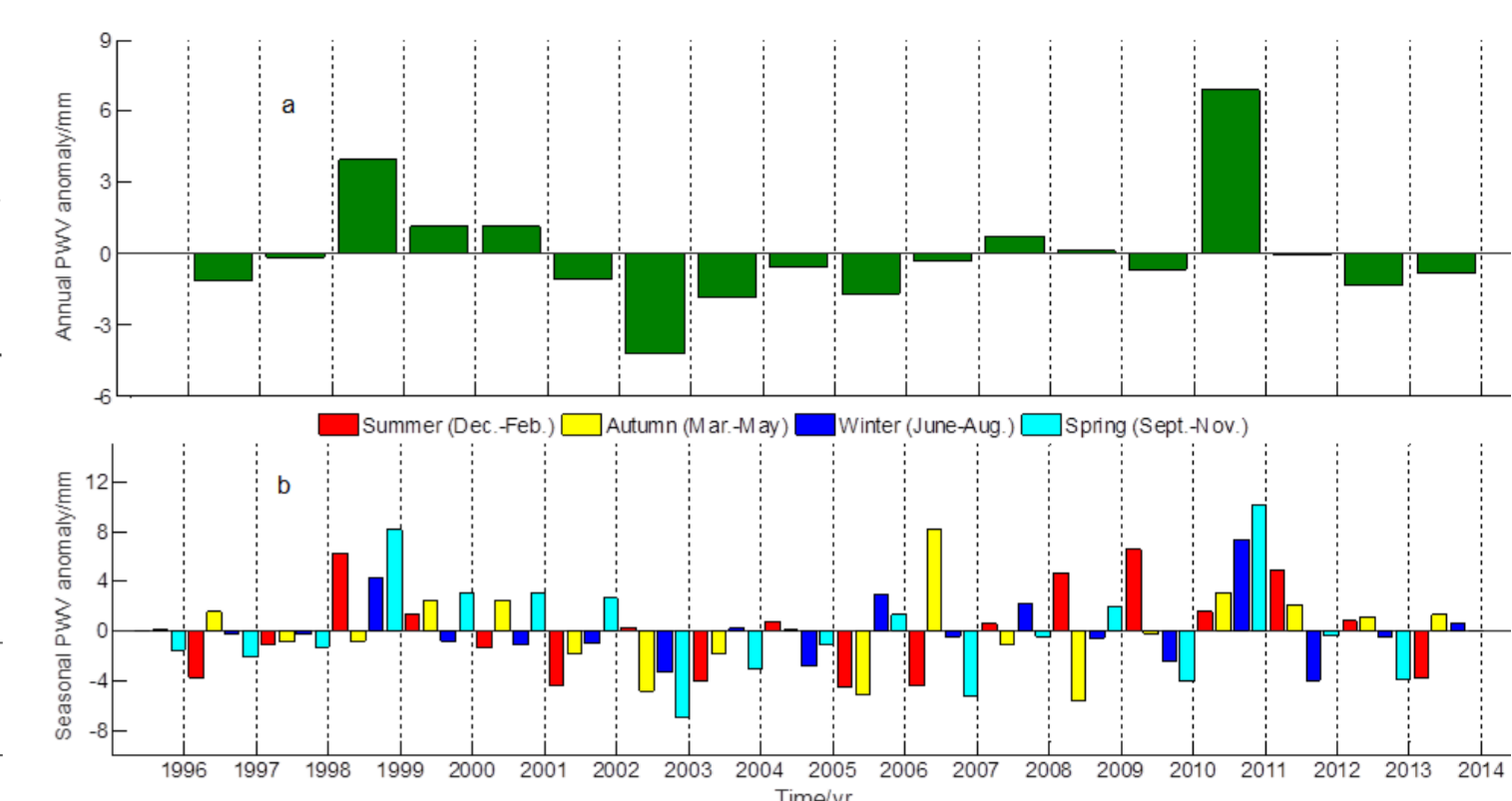


Fig. 5 Annual PWV anomaly (a) and seasonal PWV anomaly (b) at TOW2 during the period 1995–2014

Fig. 6 shows the non-linear trend extracted from the PWV time series. Although the 2002–2007 drought began from around 2001–2002, the PWV started decreasing since 1998 and reached the average value shortly before 2001 and remained below the average until mid-2007. Therefore, through tracing the variation trend in PWV time series, it is likely to predict the occurrence of drought and flood events.

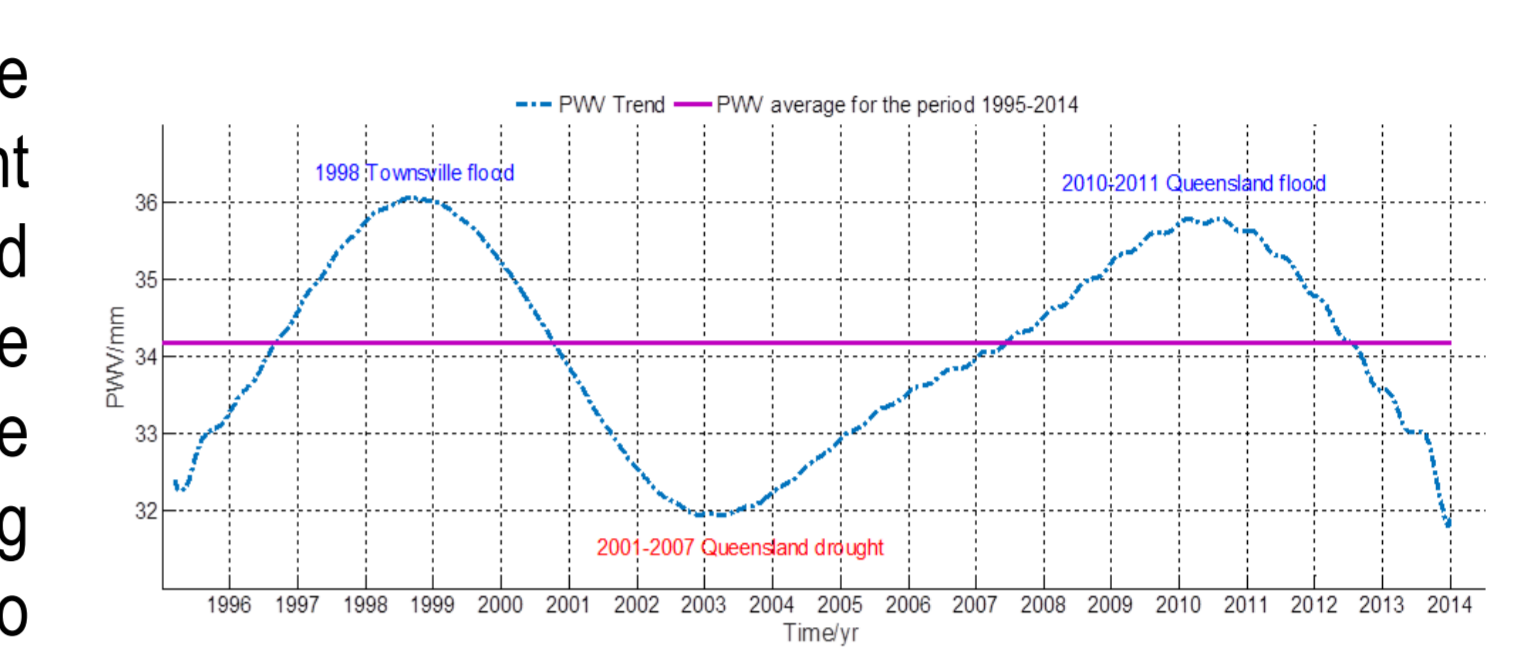


Fig. 6 Non-linear trend of PWV at TOW2 during the period 1995–2014

Balloon-based GNSS Radio Occultation

The RO technique was proposed in 1962 to probe the atmospheric structures of Mars with NASA's Mariner 3 and 4 missions, and it then became an essential means of remotely sensing almost all planets in the solar system. With the establishment of a fully operational GPS in the 1990s, it became popular to use the GNSS signals to study the structure of the Earth's atmosphere. Following the first RO satellite that GPS/MET launched in 1995, a series of GNSS-RO missions have been launched since then, including CHAMP, SAC-C, GRACE, METOP-A, TerraSAR-X, FORMOSAT-3/COSMIC and FY3. The satellite-based GNSS-RO technique has also been proven to be a good complementary data source for weather forecasting, especially over the sea and the land area with sparse radiosonde sites. However, because of funding issues, the FORMOSAT-7/COSMIC-2 decided not to execute the second 6 satellites, which will have a large impact on the development of the satellite-based GNSS RO technique. In this case, an alternative way is to fully use those low-orbit communication satellites that are designed mainly for global communication and other services by putting a receiver with low weight and low power consumption on those satellites. The retrieval of the humidity in the low troposphere is still a challenging issue because of the high dynamic variation of water vapor in this area, which then needs to be investigated more comprehensively in the future since this information is quite important for weather forecasting and thus will attract more attention from the meteorology community. Although the satellite-based GNSS RO technique can provide an important data source for weather forecasting on a global scale, it cannot be used to monitor the atmospheric condition of a specific small interesting region for specific event evolution, e.g., a typhoon. The airborne or balloon-based GNSS RO technique can then be used as a comprehensive method for this kind of application, which has been assessed in some experiments but still needs more studies before it becomes a well-established technique for atmospheric monitoring.



Fig. 7 Balloon-based GNSS RO

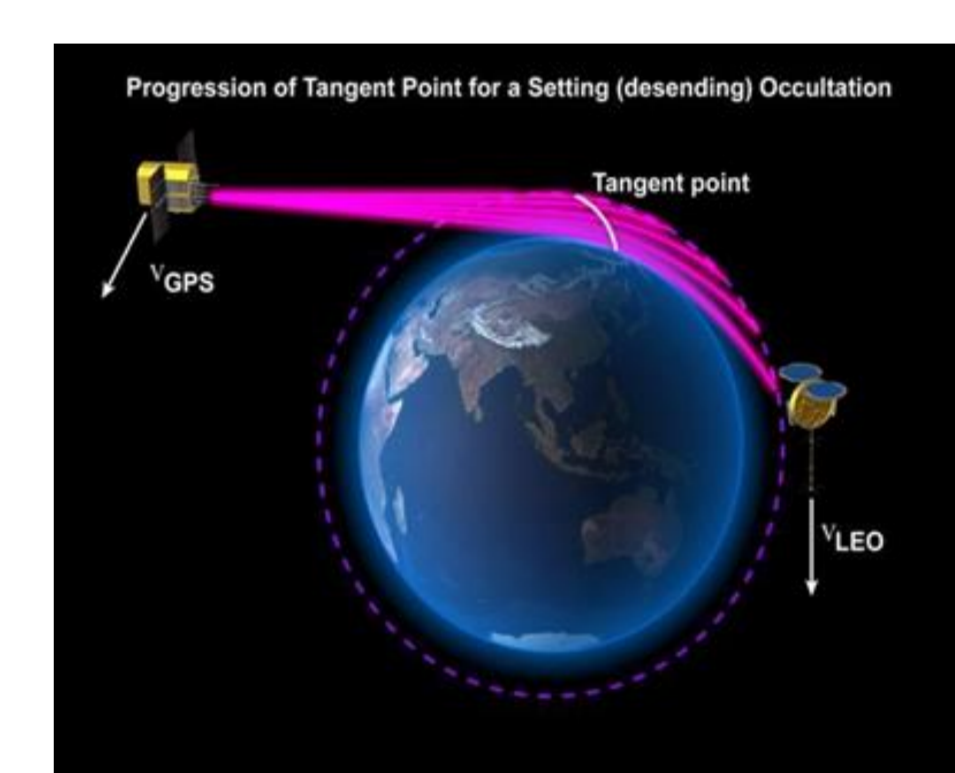


Fig. 8 Satellite-based GNSS RO

With the development of long-duration balloon, balloon-based GNSS RO becomes a practical and promising technique in the remote sensing of the atmosphere for a specific region. We recently initiated a 5-year project supported by Chinese Academy of Sciences to investigate the atmosphere structure and properties in the mid-latitude region and the Qinghai-Tibet Plateau with balloon-based, ground-based, and satellite-based GNSS remote sensing techniques.

Conclusion

Because the GNSS-derived water vapor information has a relatively short time span (less than 30 years), instead of linear trend estimation, the new novel method needs to be developed to fully use this short-range data for short-term climate pattern studies, e.g., ENSO. Although the satellite-based GNSS RO technique can provide an important data source for weather forecasting on a global scale, it cannot be used to monitor the atmospheric condition of a specific small interesting region for specific event evolution, e.g., a typhoon. The airborne or balloon-based GNSS RO technique can then be used as a comprehensive method for this kind of application, which has been assessed in some experiments but still needs more studies before it becomes a well-established technique for atmospheric monitoring.

References

- Cai, W., S. Borlace, M. Lengaigne, P. Van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santos, M. J. McPhaden, and L. Wu (2014), Increasing frequency of extreme El Niño events due to greenhouse warming, *Nature Climate Change*, 4(2), 111–116.
- Nilsson, T., and G. Elgered (2008), Long-term trends in the atmospheric water vapor content estimated from ground-based GPS data, *Journal of Geophysical Research: Atmospheres* (1984–2012), 113(D19).
- Trenberth, K., J. Fasullo, and L. Smith (2005), Trends and variability in column-integrated atmospheric water vapor, *Climate Dynamics*, 24(7–8), 741–58.
- Foster, J., M. Bevis, T. Schroeder, M. Merrifield, S. Businger, S. Dorn, S. Marcus, J. Dickey, and Y. Bar-Sever (2000), El Niño, water vapor, and the global positioning system, *Geophysical research letters*, 27(17), 2697–2700.
- Wang, X., Zhang, K., Wu, S., Li, Z., Cheng, Y., Li, L., & Yuan, H. (2018). The correlation between GNSS-derived precipitable water vapor and sea surface temperature and its responses to El Niño–Southern Oscillation. *Remote Sensing of Environment*, 216, 1–12