GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 17, PAGES 2679-2700, , SEPTEMBER 1, 2000

El Niño, water vapor, and the Global Positioning System

James Foster, Michael Bevis, Thomas Schroeder, Mark Merrifield, Steven Businger, and Susanne Dorn

SOEST, University of Hawaii, Honolulu, HI 96822, USA

Steven Marcus, Jean Dickey, and Yoaz Bar-Sever

Jet Propulsion Laboratory, Pasadena, CA 91109

The 1997-1998 El Niño had a profound impact on atmospheric circulation in the tropical Pacific and affected weather patterns world-wide. Precipitable water estimates from Global Positioning System (GPS) sites in the western tropical Pacific capture the sudden onset of large-scale subsidence, a phenomenon proposed as a possible mechanism driving the eventual decline of El Niño episodes. The atmospheric drying associated with this anomalous high-pressure ridge and the turnabout as the warm episode transitions into the subsequent La Niña are clearly visible in the GPS observations.

1. Introduction

The importance of water vapor in the climate system can hardly be overstated, and knowing its distribution in space and in time is crucial to a better understanding of climate and climate change [*Starr and Melfi*, 1991]. Networks of continuous Global Positioning System (or CGPS) stations can be used to measure the radio propagation delay associated with the atmosphere, and thus the precipitable water (PW), i.e. total-column integrated water vapor, overlying each GPS station in the network [*Bevis et al.*,, 1992; *Duan et al.*, 1996]. While considerable attention has been focused on using this capability to support operational weather analysis and prediction [*Businger et al.*, 1996; *Wolfe and Gutman*, 2000], much less emphasis has been placed on the climatological uses of ground-based GPS networks. We illustrate this latter class of applications by presenting GPS measurements that manifest atmospheric changes associated with the 1997 - 1998 El Niño event.

The propagation delay of the GPS signal as it travels through the neutral atmosphere has wet and hydrostatic (or 'dry') components. The hydrostatic delay is proportional to the total mass of atmosphere along the radio path, and hence to surface pressure, while the wet delay is nearly proportional to the total amount of water vapor along the radio path. Both delays increase in a predictable fashion as the path's elevation angle decreases, thereby increasing the length of the path within the atmosphere. Geodesists usually parameterize delays in terms of zenith (vertical) path delays. GPS measures the total neutral delay. Given surface pressure at a GPS station, we can compute the zenith hydrostatic delay and subtract this from the zenith neutral delay (ZND), and thus isolate the zenith wet delay which, in turn, can be transformed into an estimate of PW [*Bevis et al.*, 1994].

Copyright 2006 by the American Geophysical Union.
0094-8276/06/$5.00

2. Results

Two CGPS sites located on islands in the western tropical Pacific (Figure 1) recorded the influence of the 1997-1998 El Niño on precipitable water. KWJ1 (Kwajalein) and GUAM (Guam) are located to the northwest of the western Pacific warm pool. KWJ1 sits in the zone where winds from both hemispheres normally converge resulting in a wet climate with relatively little annual variation. Prior to the 1997-1998 El Nino the PW timeseries for KWJ1 (Figure 2a) exhibits little seasonality. There is no clear influence of the El Niño, which began in May 1997 (Figure 2b), on PW through most of 1997, however the onset of drying associated with the formation of the pressure ridge and atmospheric subsidence is dramatic. Beginning in November 1997 the GPS observations show a precipitous fall in PW that reached a low from January through March 1998. The PW drop coincided with the out-going longwave radiation (OLR) increase and the drop in sea-surface temperature (SST) as colder, drier air from higher latitudes cooled the sea-surface. This pressure ridge, much more pronounced during this event than a similar feature that forms in non-El Niño years, may be linked to the anomalous anticyclone identified by Wang et al., [2000]. The formation of this anticyclone during the boreal winter is attributed to a combination of local cooling and remote forcing from the El Niño-related central Pacific warming. Its persistence is postulated as a possible mechanism for the reversal of the El Niño warming trend, as its easterly winds at the equator force upwelling (cold) Kelvin waves to propagate into the eastern Pacific [*Wang et al.*, 2000].

Further north and west, GUAM shows a much stronger annual cycle than KWJ1 with PW, SST, OLR and rainfall all clearly correlated with the East Asian monsoons (Figure 2c). The monsoons are seasonal weather patterns driven by the pressure differences caused by the different heat capacities of the continents and the oceans. These pressure differences induce regional wind fields that flow towards the continent during summer and away from it during winter, creating an annual cycle at GUAM with high rainfall during summer/fall and dryer conditions during winter/spring. Because the drop in PW occured during GUAM's dry season it is somewhat masked and less dramatic, however there is a clear, sudden reduction, starting slightly later than at KWJ1. Although the relative magnitude of the drop was smaller at GUAM, the PW fell to a minimum value similar to that observed at KWJ1 and the OLR and rainfall data both exhibit strong coincident changes. In this case the PW anomaly is uncorrelated with any SST anomaly. This unusually pronounced dry season is consistent with the El Niño-related regional-scale anticyclone modeled by Wang et al. [2000] which is triggered by the winter tradewinds that cause GUAM's normal dry season and then acts to enhance them.

Of particular note for GUAM and KWJ1 is that while both have a normal seasonal drop in median PW during the winter, the variability of their PW estimates (shown by the width of the gray areas in Figures 2a and 2c) usually increases during this period. The El Niño-induced drop in median value, however, was accompanied by a substantial reduction in the PW variability, reflecting the consistent influence of the subsidence.

GUAM recovered slowly to normal PW levels by summer 1998, and, although KWJ1 remained dry longer than GUAM, it recovered more quickly and also returned to normal values by summer as the high-pressure ridge weakened and the central Pacific warm water anomaly cooled (Figure 2b). In both cases the PW begins to recover sooner than the OLR and normal rainfall does not resume until PW reaches near-normal levels.

The following year (1998) KWJ1 shows a longer than normal dry season, extending into the spring of 1999 as the subsequent La Niña episode impacted the region. Interestingly this La Niña did not lead to increased rainfall but instead the drought experienced by these islands was compounded as the center of deep convective activity moved westward during January 1999, away from KWJ1, drying the atmosphere, and stronger surface winds cooled the water. GUAM, in contrast, was now closer to the locus of atmospheric convection so the PW did not drop as low as previous years and the SST remained warmer than normal through this period. The most recent data available for both sites at the time of writing suggest that PW levels had returned to normal values by the end of the spring 1999.

3. Conclusions

GPS-derived PW estimates from two west Pacific sites capture the impact of El Niño-driven atmospheric changes on PW. During the mature phase of El Niño, an anomalous, high-pressure ridge over the West Pacific resulted in a sharp drop in PW and rainfall over the sites. This anomalous ridge has also been linked to ENSO turnabout. These results illustrate the potential contribution of GPS to climatological investigations. GPS is an accurate, all-weather system, and its high temporal resolution, inherently drift-free nature, and independence from external calibration requirements make it a powerful tool for climate research. The global, and rapidly densifying, International GPS Service (IGS) network provides the framework for both global and regional scale studies.

Acknowledgments. We thank Dr. Bin Wang for useful discussions and Seth Gutman and an anonymous reviewer for their comments. GPS data are from the IGS combined tropospheric solutions where available, augmented with data from JPL and the Pacific GPS Facility. Interpolated OLR data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their web site at http://www.cdc.noaa.gov. SST data are from the National Meteorological Data Center. Rainfall data provided by Ray Tanabe. El Niño indices are from the NOAA Climate Prediction Center.

References

Bevis, M., S. Businger, T. A. Herring, C. Rocken, R. A. Anthes, and R. H. Ware, GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System, *J. Geophys. Res., 97,* 15787-15801, 1992.

Bevis, M., S. Businger, S. Chiswell, T. A. Herring, R. A. Anthes, C. Rocken, and R. H. Ware, GPS meteorology: Mapping zenith wet delays onto precipitable water, *J. Appl. Meteorol., 33,* 379-386, 1994.

Businger, S., S. Chiswell, M. Bevis, J. Duan, R. A. Anthes, C. Rocken, R. H. Ware, M. Exner, T. v. Hove, and F. S. Solheim, The promise of GPS in atmospheric monitoring, *Bull. Amer. Meteorol. Soc., 77,* 5-18, 1996.

Duan, J., M. Bevis, P. Fang, Y. Bock, S. Chiswell, S. Businger, C. Rocken, F. Solheim, T. v. Hove, R. H. Ware, S. McClusky, T. A. Herring, and R.W. King, GPS meteorology: Direct estimation of the absolute value of precipitable water, *J. Appl. Meteorol., 35,* 830-838, 1996.

Starr, D. O'C., and S. H. Melfi (Eds.), The role of water vapor in climate, *NASA Conference Publication 3120,* 50 pp., NASA, Easton, Maryland, 1991.

Wang, B., R. Wu, and X. Fu, Pacific-East Asian teleconnection: How does ENSO affect East Asian climate?, *J. Clim., 13,* 1517-1536, 2000.

Wolfe, D. D., and S. I. Gutman, Developing an operational, surface-based, GPS, water vapor observing system for NOAA: Network design and results, *J. Atmos. Oceanic Technol., 17,*, 426-440, 2000.

J. Foster, M. Bevis, T. Schroeder, M. Merrifield, S. Businger, and S. Dorn, SOEST, University of Hawaii, Honolulu, HI 96822, USA. (e-mail: jfoster@soest.hawaii.edu)

S. Marcus, J. Dickey, and Y. Bar-Sever, Jet Propulsion Laboratory, Pasadena, CA 91109.

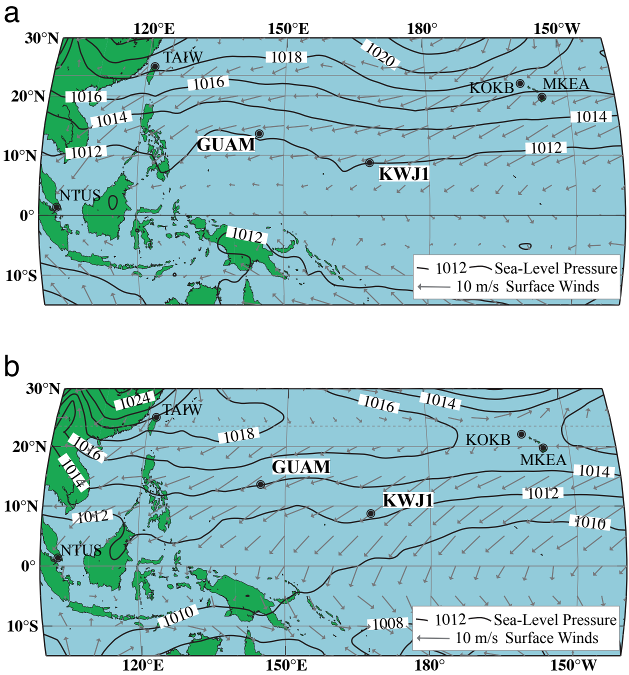

Figure 1. Locations of existing IGS CGPS sites in the western tropical Pacific with sea-level pressure and surface winds for (a) November 1997, just prior to the onset of atmospheric drying and (b) January 1998 when the drying episode was fully developed. Sites discussed here have white boxes under their names. (GPS data from the Hawaiian sites KOKB and MKEA show anomalies similar to GUAM. NTUS was installed in 1998 and TAIW has data only until 1997).

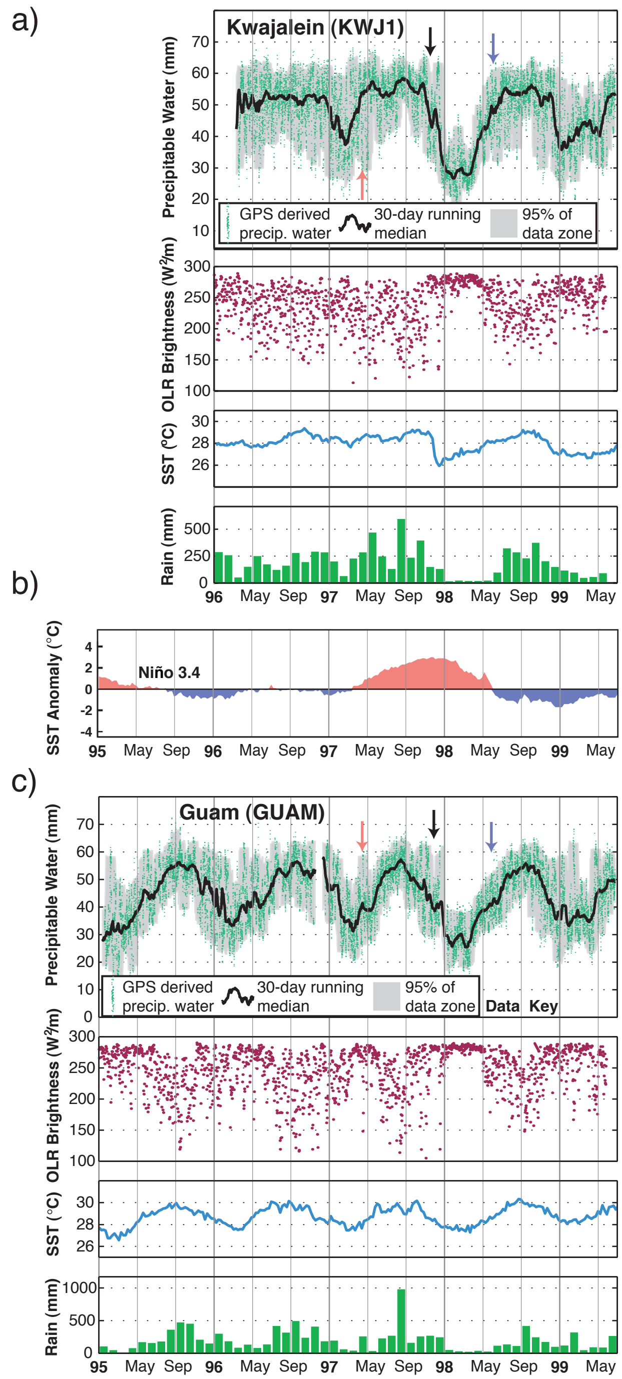

Figure 2. a) GPS-derived precipitable water (PW) series for KWJ1. Green dots are PW estimates, the thick black line is the running 30-day median PW value and the grey shading represents the area encompassing 95% of the estimates. Also plotted is outgoing long-wave radiation (OLR), sea-surface temperature (SST) and rainfall time series for the same period. Red arrows show the onset of El Niño conditions indicated by (b). Black arrows indicate the sudden onset of drying. Blue arrows mark the beginning of La Niña. OLR is used as a measure of convection. Deep, strong convection carries clouds higher, cooling the tops and lowering their thermal emittance, thus low OLR values reflect a moist, deeply convecting atmosphere while high values indicate a dry, cloudless and non-convecting atmosphere. (OLR data are linearly interpolated to each site from the 2.5° grid of daily-averaged data measured by AVHRR on NOAA 14). Reduction of ZND to PW used predicted meteorological data from a 3-D global weather model. b) Niño 3.4 Index. Niño 3.4 is an indicator for El Niño/La Niña conditions. It is the sea-surface temperature anomaly averaged over the area 5° N - 5° S, 120° - 170° W. c) GPS derived precipitable water (PW) and other time series for GUAM. Details as for (a).