Precipitable Water from GPS Zenith Delays Using North American Regional Reanalysis Meteorology

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ABSTRACT

Precipitable water or integrated water vapor can be obtained from zenith travel-time delays from global positioning system (GPS) signals if the atmospheric pressure and temperature at the GPS site is known. There have been more than 10 000 GPS receivers deployed as part of geophysics research programs around the world; but, unfortunately, most of these receivers do not have collocated barometers. This paper describes a new technique to use North American Regional Reanalysis pressure, temperature, and geopotential height data to calculate station pressures and surface temperature at the GPS sites. This enables precipitable water to be calculated at those sites using archived zenith delays. The technique has been evaluated by calculating altimeter readings at aviation routine weather report (METAR) sites and comparing them with reported altimeter readings. Additionally, the precipitable water values calculated using this method have been found to agree with SuomiNet GPS precipitable water, with RMS differences of 2 mm or less, and are also generally in agreement with radiosonde measurements of precipitable water. Applications of this technique are shown and are explored for different synoptic situations, including atmospheric-river-type baroclinic storms and the North American monsoon.

1. Introduction

Precipitable water (PW), or integrated water vapor, is a useful meteorological quantity in many different contexts. It is defined as the “total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels” (Glickman 2000, p. 591). Typically, the levels chosen are the surface and the top of the atmosphere, or some height sufficiently high that there is very little water vapor above that level. Its value can be given as either an areal mass density or as the depth of water that would exist on a unit surface if all the water vapor in the column above were condensed. In this paper, we give its value in millimeters.

In forecasting, it can be used to estimate the rainfall potential for a weather system, or to estimate rain rate, given a knowledge of the upward vertical velocity (Carlson 1998). Accurate knowledge of precipitable water not only improves precipitation forecasts, but it may also improve weather forecasting in general because water vapor is a key element of the energetics of weather systems, through the latent heat of condensation (Emanuel 1988). The positive impacts of assimilation of precipitable water values into numerical models have been demonstrated by Smith et al. (2007). Their study noted improvements in forecasts of water vapor content in the 20-km Rapid Update Cycle model (RUC20) for 3–12-h forecasts. The importance of such an improvement was shown in a case study of forecasting of a tornado outbreak in the Midwest, for which the operational model was compared against one that assimilated global positioning system (GPS) precipitable water. The operational model underestimated the convective available potential energy (CAPE) of the situation, while the model that assimilated GPS precipitable water had higher CAPE, which more accurately portrayed the severe storm threat.

With the advent of GPS, people realized that atmospheric water vapor could affect measurements, and in the early 1990s the idea of using the GPS signal delay in order to determine atmospheric column water vapor was suggested (Bevis et al. 1992). Most of the applications to date have used collocated or nearby meteorological observations to provide the surface pressure and
temperature necessary to calculate GPS precipitable water. A notable exception is the global study by Wang et al. (2007), which uses National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis to derive the surface temperature while still incorporating surface observations to derive the station pressure.

The goal of this paper is to demonstrate how reanalysis can be used to derive both the station pressure and surface temperature, and hence provide the meteorological information necessary to compute GPS precipitable water, when combined with the zenith delay. This technique can be applied to the archived delays of the more than 10 000 GPS receivers that have been deployed worldwide for geophysical applications. We have chosen to focus on California and Nevada because of the very high density of GPS sites, but similar concentrations of GPS receivers can be found in the Pacific Northwest, Hawaii, Japan, and other areas of active geophysical investigation. The high density of GPS receivers and frequency of observations enable precipitable water to be resolved on spatial and temporal scales that were not previously possible, albeit at the expense of the easily quantifiable accuracy available at GPS sites with collocated meteorological stations.

Travel-time delays between satellites and fixed ground-based GPS sites vary due to a number of factors, but most importantly because of the amount of air and water vapor between the GPS receiver and the satellite. This is a consequence of the nonunit index of refraction of air (Hopfield 1971; Smith and Weintraub 1953). From the index of refraction, the delay due to the dry air can be calculated if the atmospheric pressure is known at the site (station pressure) and then the delay due to the integrated atmospheric water vapor (precipitable water) can be simply related to the total delay, as given in Duan et al. (1996):

$$\zeta_t = \zeta_h + \zeta_w.$$  

Here, $\zeta_t$ is the total delay, $\zeta_h$ is the “hydrostatic” delay, entirely due to the amount of dry air above a site and easily related to the atmospheric pressure, and $\zeta_w$ is the “wet” delay, due to the amount of water vapor above a site. An accurate approximate expression (Saastamoinen 1973) for the hydrostatic delay is

$$\zeta_h = 77.6 \times 10^{-6} R P_s / g_0,$$

where $R$ is the gas law constant for dry air; $g_0$ is the acceleration of gravity; and $P_s$ is the station pressure measured in millibars (hectopascals), that is, the pressure measured at the GPS site and not reduced to mean sea level. If one knows the wet delay, station pressure, and temperature, then the precipitable water at the GPS site can easily be calculated. To effect this calculation, we use the following formula relating precipitable water and wet delay (Bevis et al. 1994):

$$PW = \Pi \times \xi_w.$$  

The derivation of this relation relies on an assumption of azimuthal symmetry, since different slant paths to different GPS satellites are combined. Azimuthal symmetry implies that there are not strong lateral gradients in the pressure, temperature, and moisture field, so the relationship will hold best in quiescent weather situations and may have significant errors in the vicinity of fronts.

The following expression for the semiempirical function $\Pi$ is given by Bevis et al. (1992):

$$\Pi(T_m) = \frac{10^5}{461 \times \left[ \left( \frac{3.776 \times 10^5}{T_m} \right) + 17 \right]}.$$  

Here $T_m$ is the integrated mean temperature, defined in terms of the partial pressure of water vapor, $P_v$, as

$$T_m = \int \frac{(P_v/T) \, dz}{\int (P_v/T^2) \, dz},$$

where the integrals are taken over the total height of the atmosphere. A good approximation for $T_m$ has been given by Bevis et al. (1992) and is

$$T_m = 70.2 + 0.72 T_s,$$

where $T_s$ is the surface temperature. We use this approximation in our calculation of $\Pi(T_m)$.

The virtue of being able to infer temperature and pressure from reanalysis is that it opens up many more GPS sites for precipitable water measurements than would be available otherwise. Geophysicists and geodisists have deployed large numbers of fixed GPS receivers in order to track motions of lithospheric plates, as well as decipher local crustal deformation resulting from earthquakes. In some areas of the world, particularly California, these stations are spatially dense. In California and Nevada there are over 500 GPS sites (see Fig. 1), many of which have been operating since 2003. The delay information from these sites is archived at the Scripps Orbit and Permanent Array Center (SOPAC, http://sopac.ucsd.edu/). These delays are recorded on an...
hourly basis and are generally available in the archive within a few days of observation. If the station pressures and temperatures were available for these sites, then the precipitable water could be calculated and the archived delay data would provide a unique resource of climate information. By comparison, there are only six radiosonde sites in California and Nevada from which precipitable water data can be obtained, and only at 12-h intervals. It is also possible through microwave imagers to make all-weather retrievals of precipitable water over the oceans (Schluessel and Emery 1990); however, such techniques are limited by the time of and swath of the satellite overpass.

In the rest of this paper, we will demonstrate how reanalysis can be used to estimate temperature and pressure at GPS sites that do not have observations available for these sites, then the precipitable water could be calculated and the archived delay data would provide a unique resource of climate information. By comparison, there are only six radiosonde sites in California and Nevada from which precipitable water data can be obtained, and only at 12-h intervals. It is also possible through microwave imagers to make all-weather retrievals of precipitable water over the oceans (Schluessel and Emery 1990); however, such techniques are limited by the time of and swath of the satellite overpass.

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2. Methodology

We have used the North American Regional Reanalysis (NARR) to estimate historical pressure and temperature at the GPS sites. The NARR provides geopotential height and sea level pressure at 32-km resolution over its domain (Mesinger et al. 2006), which includes North America and surrounding regions. The NARR data are available for every 3 h from 1979 to the present. Since at a given level surface pressure is usually a fairly slowly varying function of horizontal position, the NARR geopotential height grids can be interpolated horizontally to the GPS site and then the hypsometric equation is used to calculate the station pressure at the elevation of the GPS receiver, shown as

$$Z_2 - Z_1 = H \ln(p_1/p_2).$$

The geopotential heights $Z_1$ and $Z_2$ are known for standard pressure levels $p_1$ and $p_2$, respectively, from the NARR output. The scale height $H$ can then be calculated for that particular layer, and the station pressure can be determined by extrapolating upward (or downward) from the elevation of that pressure level. For example, if a station lies at an elevation $Z_{\text{station}}$, where

$Z_{\text{station}} = Z_1 + \Delta Z$,

then the pressure at $Z_{\text{station}}$ can be found from

$$p(Z_{\text{station}}) = p_1 \exp\left(-\frac{\Delta Z}{H}\right).$$

A one-sided extrapolation is used for those stations with elevations below sea level. For the surface temperature at the GPS sites, we use a simple two-dimensional interpolation of the reanalysis gridpoint surface temperatures. It would also be possible to modify this horizontally interpolated surface temperature to the elevation of the GPS site by using an assumed local lapse rate, but we have chosen not to do that here because of the number of assumptions that must be invoked in determining the lapse rate. The next section will show that the calculation is relatively insensitive to errors in temperature, so that little is gained in precipitable water accuracy by a small increase in the accuracy of surface temperature.

3. Implementation and error analysis

The accuracy of the above technique for estimating pressure has been checked by comparing more than a quarter of a million NARR-estimated altimeter readings with those reported hourly at all reporting aviation routine weather report (METAR) sites within California and Nevada, for the year 2006. A plot of the difference between these values is shown in Fig. 2. It was found that the NARR-estimated altimeter readings had a negative bias of 0.4 hPa compared to the METAR altimeter readings, with a standard error of 2.1 hPa. This value of bias in estimated versus observed pressures
translates to an error in precipitable water of less than
1 mm (Bevis et al. 1994), which would mean an average
accuracy of 5% or better for typical values of precip-
itable water. Using standard propagation of errors, we
can estimate the error in calculation of precipitable
water due to errors in the zenith delay, temperature, and
station pressure.

From this analysis, we assume the errors in tempera-
ture and pressure are independent, although this is
certainly not strictly correct for the actual measurements
(temperature measurements may require correction for
temperature, etc.) or for the errors in the model. How-
ever, we believe it is reasonable to assume that these
cross terms will be substantially smaller than the in-
dependent error terms, so we proceed here as if they
were strictly independent. Then the errors \(\sigma_{\pi w}, \sigma_{\pi T},\)
and \(\sigma_{\pi H}\) are related by

\[
\sigma_{\pi w} = \sqrt{\sigma_{\pi T}^2 + \sigma_{\pi H}^2}.
\]

We can estimate the error in the hydrostatic delay from
the error in the station pressure using

\[
\sigma_{\pi H} = \frac{77.6 \times 10^{-6} R}{g_0} \sigma_P.
\]

From the comparison with altimeter readings, the esti-
mated uncertainty in station pressure is 2.1 mb. This
equates to about 4.8 mm in hydrostatic delay and ap-
proximately 0.7 mm of precipitable water. The un-
certainty in the total delay has been reported to be

10 mm or less (Bevis et al. 1992), and while the errors
reported for our delays are substantially lower than this,
we will use 10 mm as a conservative estimate. When
combined with the uncertainty due to pressure, this
would yield an uncertainty in the precipitable water of
approximately 1.8 mm.

The errors associated with the multiplicative function
\(\Pi(T_m)\) depend on the error in \(T_m\) as shown:

\[
\frac{\partial \Pi}{\partial T_s} = \frac{\partial \Pi}{\partial T_m} \frac{\partial T_m}{\partial T_s}.
\]

So, for the first term we get

\[
\frac{\partial \Pi}{\partial T_m} = \frac{8.19089 \times 10^7}{\left(\frac{3.776 \times 10^5}{T_m} + 17\right)^2 T_m^2}.
\]

Combining with the second term gives

\[
\sigma_{\Pi} = 0.72 \times \frac{8.19089 \times 10^7}{\left(\frac{3.776 \times 10^5}{T_m} + 17\right)^2 T_m^2} \times \sigma_{T_m}.
\]

This shows that \(\sigma_{\Pi}\) is quite insensitive to surface tem-
perature; for a (large) 5-K error in surface temperature,
the error in precipitable water is approximately 0.3 mm.

Combining all these into a single expression for the
uncertainty of precipitable water, we get
This yields errors of less than 2.5 mm for all reasonable values of precipitable water and measurement uncertainties. Since $\sigma_{\Pi}$ and $\sigma_{s_w}$ have finite lower bounds as the precipitable water goes to zero, the fractional uncertainty must go up as the precipitable water magnitude goes down. So, for very dry conditions, with precipitable water of 5 mm, the uncertainty will be about 20% of the measurement; but, during wet conditions with precipitable water of 40 mm, it will be about 6%.

The relatively large spread in the estimation of station pressure is a bit troublesome, but perhaps not too surprising considering that the wide variation in elevations at METAR sites, ranging from below sea level to more than 2 km above sea level. An inspection of the errors indicates that errors are larger for higher-elevation stations. This is actually somewhat convenient, since water vapor is concentrated in the lower parts of the atmosphere, the errors will be proportionally smaller where the values are of most interest.

After estimating the station pressure and temperature at the GPS sites, the precipitable water can be calculated in a straightforward way, given the GPS delays at the sites. This technique was used to develop a database of precipitable water at 3-h intervals for 2003–09. In the following sections, we compare precipitable water obtained through our technique with conventional GPS estimations of precipitable water and with radiosonde estimates.
4. Comparison with SuomiNet GPS PW data

A test of the NARR GPS technique is to compare the value of precipitable water calculated for a site where barometric pressure and temperature are measured (or inferred from nearby sites) and precipitable water is already calculated. Such a comparison was made for nine sites (see Fig. 3) where precipitable water is calculated as part of the SuomiNet (Ware et al. 2000) (http://www.suominet.ucar.edu/). The values calculated by SuomiNet were compared with our own calculated values for the year 2009. Their method of calculation is essentially the same as the one used here (Wolfe and Gutman 2000), but SuomiNet uses pressure and temperatures either measured at the GPS sites or at a nearby Automated Surface Observation System (ASOS) site, while we infer the temperature and pressure from reanalysis. Also, SuomiNet uses GPS zenith delays obtained from a high-speed evaluation of orbits, while we use zenith delays that are not available in real time but instead are available a few days later and are typically more accurate. The sampling intervals were also somewhat different: values of precipitable water from the SuomiNet observations are taken at 15 and 45 min after the hour, while the reanalysis values were calculated at the times of the reanalysis data, which is every 3 h starting at 0000 UTC.

Figure 4 shows the time series of the NARR and SuomiNet precipitable water overlaid for site p499. The agreement is very close, especially considering that the sampling intervals are different. As a further comparison of SuomiNet PW and NARR PW values, we have plotted calculated linear fits and show scattergrams for three of the six sites in Fig. 5. To compensate for the difference in sample times, the SuomiNet times at 15 min before and after the hour were averaged to produce a value appropriate for sampling on the hour, and then plotted against the NARR values at 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC for the entire year.

Scattergram plots are shown in Figs. 5a–c. The linear relation is obvious, with only a few outliers.

The fitting parameters, Table 1, represent a nearly one-to-one relationship between the SuomiNet and NARR values of precipitable water, with high \( r \) correlations between the two estimates. Precipitable water, like many meteorological variables, shows persistence and is also strongly correlated with itself. For time series that have strong autocorrelations, it is necessary to use a reduced number of degrees of freedom, since consecutive observations are not independent. We follow the procedure given in Quenouille (1952) referencing Bartlett (1935) and use the following:

\[
N_{\text{ind}} = \frac{N}{\sqrt{1 + 2r_1r_1^* + 2r_2r_2^* + \cdots}}
\]

Here, \( N_{\text{ind}} \) is the effective number of independent observations in testing between two series, with each having \( N \) observations with autocorrelation coefficients \( r_1, r_1^* \) for lag 1, \( r_2, r_2^* \) for lag 2, and so on. In practice this sum is taken until the autocorrelations become small. In Fig. 6 we show the autocorrelations for these sites.

![Fig. 6. Autocorrelation plots of GPS PW anomalies plotted for the sites cnpp, sio3, and p066 for the calendar year 2009.](image-url)
calculated from the NARR precipitable water values (autocorrelations calculated from the SuomiNet precipitable water values are very similar). While there is little variation of the autocorrelation between the SuomiNet and NARR values for precipitable water, there are distinct variations from site to site that may be connected to the climatic setting of the site. They all show a persistence that drops off rapidly over a time scale of about one week (~50 observations) and then more slowly after that, until approaching zero at a time lag of about 60–80 days. In Table 1 we have taken the sum out to lag 500 (~62 days) to calculate the effective observations and from that the effective degrees of freedom (D.F.), which range from 41 to 210.

5. Comparison with radiosonde data

As a further test of this technique, NARR GPS precipitable water values are compared with the twice-daily values of precipitable water obtained from balloon soundings for five radiosonde sites in California and Nevada (see Fig. 3). For the year 2006, the NARR GPS precipitable water values have been interpolated to the radiosonde sites, using the times when the GPS observations and balloon soundings were coincident. Since each GPS site is at a different elevation than the launch site for the balloon, there is an elevation dependence that we have partially compensated for by adjusting according to the scale height of precipitable water obtained by Means (2011). Each sounding is actually representative not of a vertical sounding centered at the radiosonde site but instead of the complex three-dimensional path the balloon followed until its burst point, so there is some uncertainty in the interpolation. Also, the accuracy of the interpolation will depend on how close the GPS sites are to the radiosonde site. This

![Graphs showing comparison between GPS and RAOB precipitable water at different sites](image)

**FIG. 7.** NARR GPS precipitable water for 2006 interpolated to radiosonde (raob) locations and plotted against PW from radiosondes. Radiosonde measurements are twice daily, and NARR GPS data are from the same times.
will cause some variance between the two values, but the overall shape of the time series should be similar. An important aspect for comparison of the two time series is the similarity of the amplitude and temporal structure of specific events, such as winter storms, summer moist pulses, and very dry Santa Ana episodes.

Fitting parameters for NARR GPS versus radiosonde precipitable water are given in Table 2, and scatterplots are shown in Fig. 7. As with the comparison of the SuomiNet values, it is clear that the NARR and radiosonde values are highly correlated, and the $F$ statistic yields a significance level for the correlation greater than 99.9% at all the sites, as would be expected for measurement of the same quantity using different techniques.

Even so, the agreement is not nearly as good as might be expected, especially for the coastal sites of Okland (OAK), Vandenberg (VBG), and San Diego (NKH), California. The scatterplots show that many of the values for the radiosonde precipitable water are less than those seen for GPS. There have been suggestions of hygristor problems on the current generation of radiosondes (Maddox 2012), resulting in precipitable water values that are too low in certain situations, and it is possible that the differences seen are evidence of that. A systematic study with a GPS collocated at the radiosonde launch site would be the best way to understand what is causing these differences.

6. Applications of the technique

In this section three applications of the GPS NARR database of precipitable are examined: 1) the spatial and time variation of precipitable water across the region, 2) the precipitable water associated with landfalling atmospheric rivers, and 3) the variation of precipitable water with the North American monsoon. These examples, while not exhaustive, demonstrate the possibilities for exploiting the precipitable water database.

Considering how much the climate varies across California and Nevada, it is not surprising that the precipitable water varies greatly from site to site. Here, we give a few examples of the temporal variation of precipitable water across the time span of this study. The plots in Fig. 8 show time series of precipitable water for the 2004–10 period at a variety of stations across the region. Most show a strong annual cycle with precipitable water peaking in late summer and reaching minimum values in midwinter. There is also a clear dependence on latitude and elevation, with southern lowland stations showing the greatest precipitable water and the northern and mountain stations showing the least.

In Fig. 8 the Southern California coastal site sio5 shows a strong summer increase, with precipitable water values over 50 mm during intrusions of monsoonal air. Peaks during the winter season correspond to baroclinic storm passages. The southern desert site iid2 has a similar annual cycle to sio5 but with much larger summer amplitude because the North American monsoon exerts a stronger influence in the southeastern deserts. The strong annual cycles seen at the southern sites contrast to the much weaker annual signal seen at the north coast site farb on Farallon Island. The weak annual signal is most likely due to strong and frequent baroclinic storm passages, little monsoon influence, and the small annual temperature range. Nearby onshore sites have similar annual cycles but with more seasonal variation than is seen at farb.

Also shown are maps of California and Nevada that display the data as dots color coded by the magnitude of
the precipitable water (Fig. 9b) and as color-shaded contour maps (Figs. 10a and 10b). The NARR GPS technique opens the door to making high-resolution analyses of precipitable water on land, which can yield insights into both precipitating and nonprecipitating systems. It offers an advantage over Geostationary Operational Environmental Satellite (GOES) sounder images, in that it can be made in all weather conditions and that it complements Special Sensor Microwave Imager (SSM/I) water vapor images because it allows plots to be made over land surfaces, while the SSM/I only works over bodies of water. As an example of how
this might be applied. Figs. 9a and 9b show precipitable water snapshots of a baroclinic system that caused extensive damage throughout California. The system was of the type that is characterized as an “atmospheric river” (Ralph et al. 2004; Zhu and Newell 1994) because of the relatively narrow band of high moisture content air that arises from a connection between the deep tropics and the midlatitudes. The SSM/I image of Fig. 9a shows the structure of the atmospheric river impinging on the coastline, but previously there was no good way of seeing what happened over land; Fig. 9b shows the NARR GPS precipitable water image for the day of the storm, clearly showing the same high water vapor content air. The large number of GPS sites available to this technique and the 3-hourly availability of data enable high temporal and spatial resolution of precipitable water in these storms, which could be key in understanding the occurrence of flooding associated with these systems.

While such midlatitude baroclinic systems as atmospheric rivers are usually quite obvious in satellite images, it is sometimes difficult to recognize incursions of moisture associated with the North American monsoon, and the dearth of observational data in the U.S. Southwest and Mexico can make analysis and forecasting of summer-monsoon-related phenomena difficult. GPS water vapor measurements offer the ability to directly image the water vapor of the monsoonal flow and detect the moisture necessary for deep convection and determine its horizontal structure. Figure 10 shows water vapor images before and after the onset of the monsoon in the California and Nevada region: Fig. 10a shows dry conditions over all of California and Nevada for 21 June 2006, while Fig. 10b shows the situation approximately five weeks later, with approximately the southern one-third of California and Nevada covered with a deep moist layer, with precipitable water values exceeding 40 mm.

7. Conclusions and future directions

Using the NARR dataset has been shown to be an effective method for generating GPS PW data at sites that do not have meteorological instrumentation, and it provides spatial density and temporal coverage that are not available with conventional measures of precipitable water at an accuracy that is comparable to radiosonde or traditional GPS precipitable water. The database of GPS water vapor maps for California and Nevada is being extended backward through the GPS archive and forward as more data becomes available. However, we do not believe the present level of accuracy is sufficient to ascertain long-term trends in water vapor. Nevertheless, within the limitations of its accuracy, it can

![Fig. 10. (a) Contoured NARR GPS PW vapor on 21 Jun 2006, prior to the onset of the monsoon. Interpolation is performed using NCAR Command Language (NCL) and is based on a triangular mesh algorithm. (b) Contoured NARR GPS PW vapor on 27 Jul 2006, showing fully developed monsoon with sharp moisture gradient from south to north. Interpolation is performed using NCL and is based on a triangular mesh algorithm.]
provide insight into the statistics of precipitable water at a site and help in the understanding of particular synoptic events.

Additionally, a real-time version of the algorithm has been implemented in order to take advantage of the large number of low latency, high bandwidth (1 Hz) GPS sites that have been installed in connection with automated earthquake warning networks. By using the Rapid Update Cycle (RUC) model for the pressure and height data instead of the NARR, precipitable water maps can be generated every hour, or more often if desired. Assimilation of GPW precipitable water into numerical weather prediction models has already shown to improve forecasting skill (Gutman et al. 2004; Kuo et al. 1993; Marcus et al. 2007; Smith et al. 2000, 2007), and the availability to forecasters of real-time high-resolution water vapor images should improve forecasts. It is expected that this might improve operational forecasting and possibly result in more accurate forecasts of incipient flooding situations.

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