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Comparison of precipitable water over Hawaii using AVHRR-based split-window techniques, GPS and radiosondes

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Abstract. Precipitable water vapour (PWV) was estimated over Lihue, Kauai, from AVHRR data using split-window techniques. The predicted values using the satellite sensor data were compared to precipitable water vapour amounts obtained from radiosondes and corrected GPS measurements. Compared to the corrected GPS precipitable water, the Dalu and RV satellite methods had rms errors of 7.3 and 3.8 mm, respectively. Typical values of PWV over Hawaii are approximately 27.5 mm, suggesting errors of about 14% in values estimated using the satellite split window technique near Hawaii.

1. Introduction

Real time precipitable water vapour (PWV) calculated from satellite sensor images can provide useful information to understand the meteorological processes occurring near Hawaii. In order to use these PWV images it is necessary to have some understanding of the accuracy of the PWV values. Here we investigate several split-window techniques by comparing their results to GPS and radiosonde measurements.

The AVHRR on the NOAA polar orbiting satellites has two thermal channels, near 11 μm and 12 μm, which are designed to correct for water vapour effects when predicting sea-surface temperatures (McMillan and Crosby 1984). Several investigators have employed these thermal channels in estimating total column water vapour (or PWV) from the AVHRR sensor ($\sim$1.1 km at nadir) in a technique referred to as the split-window technique (Dalu 1986, Kleespies and McMillin 1990, Rogers and Vermote 1998). The split-window technique uses the differential water vapour absorption at two adjacent thermal channels under clear sky conditions to produce PWV estimates.

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Dalu (1986) used a radiative transfer model along with standard moisture and temperature profiles to show that over oceans, where the surface emissivity is nearly constant for both thermal channels, PWV can be estimated without *a priori* information using AVHRR channel 4 and 5 brightness temperatures and the satellite zenith angle. More recently, Roger and Vermote (1998) compared SSM/I microwave estimates of PWV with estimates from the Dalu method and concluded that this algorithm works well for nadir viewing angles but should be modified for off-nadir viewing angles. They further verified this relationship with MODTRAN calculations. Here we compare the accuracy of predictions made using the Dalu, and Rogers and Vermote (hereafter referred to as RV) algorithms against PWV derived from radiosondes and Global Positioning System (GPS) receivers (Bevis *et al.* 1994, Duan *et al.* 1996), at Lihue, Kauai (21° 58.8′N, 159° 20.4′W) in the Hawaiian islands.

2. Satellite sensor algorithms

Dalu found that PWV could be estimated from split-window brightness temperatures and the satellite sensor view angle using the following equation:

$$\mathrm{PWV} = A(T^{11} - T^{12}) \cos(\theta) \quad (1)$$

where the regression constant, $A = 19.6\ \mathrm{kg\,m^{-2}\,K}$), T^{11} and T^{12} are the brightness temperatures at 11 μm and 12 μm, respectively, and θ is the satellite sensor zenith angle. By comparing PWV estimates from ship-based radiosondes and satellite sensor data, Dalu concluded that this method could provide PWV estimates with an accuracy of approximately ± 5 mm.

Rogers and Vermote examined the Dalu method by comparing PWV estimates from SSM/I (microwave based) and AVHRR data. They found that $A(0) = 19.8$ kg ($\mathrm{m^{-2}\,K}$) at the nadir view angle; however, at a viewing angle of 60°, this coefficient became $A(60) = 15.3$ kg ($\mathrm{m^{-2}\,K}$). Using MODTRAN code and standard atmospheric soundings, they found a similar viewing angle dependence. These results showed that the coefficient A could be modified by changing the form of the $\cos(\theta)$ term used in the Dalu equation as follows:

$$\mathrm{PWV} = A(T^{11} - T^{12}) \cos(\theta)^{\mathrm{B}} \quad (2)$$

RV suggested that over dark target regions, like oceans, $B = 0.4$ and $A = 15.0$ kg ($\mathrm{m^{-2}\,K}$) where PWV is in units of mm.

3. Satellite sensor versus radiosonde comparisons

Radiosonde reports are one of the primary tools for measuring atmospheric water vapour; however, there are problems associated with using radiosonde as atmospheric data. First, the temporal frequency of radiosonde reports is generally limited to two launches per day. Secondly, radiosonde instruments can typically only measure temperature and relative humidity with a precision of about 0.2 degK and 3.5%, respectively (Elliot and Gaffen 1991). Resulting errors in PWV may be in the range of 5 to 10%. Nevertheless, radiosonde reports still represent the most accurate means for verifying atmospheric water vapour amounts. Here we derive PWV from radiosonde data by integrating the specific humidity with respect to pressure following the approach described by Elliot and Gaffen (1991).

Data from channels 4 (10.76 μm) and 5 (11.97 μm) of the AVHRR instrument flown on the NOAA-14 polar orbiter obtained from September 1998 to June 1999 were compared with radiosonde reports released at the Lihue, Kauai, airport. Clear sky images were selected manually using visible (daytime) and thermal (nighttime) images for an open ocean region approximately 15 km east of Lihue, Kauai. Three by three pixel averages of temperatures and satellite sensor zenith angles were saved from these images. PWV was derived using the Dalu and RV methods when the satellite overpass was within one hour of the sounding, resulting in 44 cases. The results of the comparisons between the soundings and the Dalu and RV method are correlation coefficients (*R*) of 0.50 and 0.72 and root-mean-square (rms) errors, of 5.86 mm and 3.13 mm. The satellite-predicted PWV was slightly greater than the radiosonde PWV with biases of 0.66 mm and 1.34 mm for the Dalu and RV methods, respectively.

4. Satellite sensor versus ground-based GPS comparisons

The radiosonde and satellite sensor comparison was limited because few satellite overpasses occurred within one hour of the radiosonde launches. To increase the number of comparisons, GPS-derived PWV values were used for comparison. Microwave radio signals transmitted by GPS satellites are delayed (refracted) by the atmosphere as they propagate to Earth-based GPS receivers. This delay in the GPS signal is nearly proportional to the PWV amount along the signal path. Bevis *et al.* (1994) show that PWV can be estimated from GPS data using the relationship

$$\mathrm{PWV} = \Pi(\mathrm{ZWD}) \tag{3}$$

where ZWD is the zenith wet delay or the estimated delay in the GPS signal due to PWV above the GPS receiver. Π is an empirical constant that is a function of the atmospheric virtual mean temperature along the signal path. Here Π was derived from the form presented by Bevis *et al.* (1994) and had a mean value of 0.15 for our Kauai measurements. Duan *et al.* (1996) showed that GPS-based estimates of PWV have rms errors of less than 1 mm and a bias of less than 1 mm.

GPS estimates at Lihue of PWV were compared to coincident radiosonde launches from September 1998 through June 1999 giving 143 pairs of observations. Thirteen outliers were removed from the data set, which probably correspond to soundings passing through clouds. Radiosonde and GPS data (figure 1) were found to be highly correlated, $R = 0.91$, with relatively little scatter as indicated by an rms error of 1.76 mm. The GPS data were found to have a positive bias compared to radiosondes of 1.85 mm, which may be caused by using a retrieval scheme, based on globally averaged variables. Based on this GPS and radiosonde comparison, the bias in the Lihue GPS data was corrected using the regression equation:

$$\mathrm{PWV_c} = 3.1424 + 0.8252(\mathrm{PWV}) \tag{4}$$

where PWV represents the initial GPS estimate and $\mathrm{PWV_c}$ is the corrected estimate in mm. These corrected GPS-based estimates of PWV were used in the following analysis.

Satellite sensor PWV estimates from the Dalu and RV algorithms were compared to the corrected GPS data from September 1998 through June 1999. This comparison resulted in 186 observations. The corrected GPS and RV estimates of PWV are compared in figure 2 and yield a correlation of 0.64, an rms error of 3.80 mm, and a bias 1.12 mm. The Dalu method (not shown) had a correlation of 0.46, an rms error of 7.30 mm and a bias of 2.82 mm.

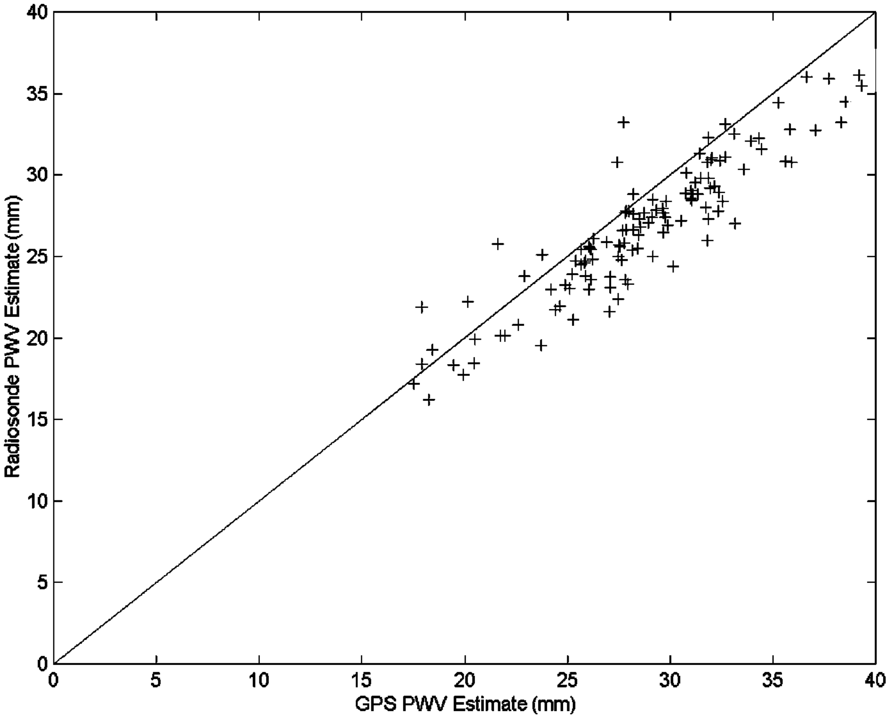

Figure 1. Comparison between radiosonde measured and GPS derived precipitable water.

To see if new coefficients would increase the accuracy of satellite sensor estimation of PWV near Hawaii, new coefficients were derived using the Lihue data fitted to the RV algorithm:

$$\mathrm{PWV} = 14.24(T^{11} - T^{12}) \cos(\theta)^{0.22} \tag{4}$$

Compared to the corrected GPS, this equation increases the accuracy of the prediction of PWV only slightly increasing the correlation to $R = 0.66$ and decreasing the rms error to 3.53 mm. This small improvement suggest that the original RV coefficients are adequate for PWV retrievals near Hawaii. The rms errors in the RV method (3.8 mm) are $\sim$14% of the typical PWV values we found over Hawaii ($\sim$27.5 mm). This error is not much greater than the uncertainty in our radiosonde estimates. Without more absolute measurements, further increase in accuracy is difficult. Despite these limitations, PWV images derived near Hawaii can provide useful information on the synoptic and meso-scale processes occurring near Hawaii.

5. Summary

This Letter tests the Dalu and Roger and Vermote (RV) methods to derive PWV using the split-window technique. Compared to corrected GPS, the Dalu and RV algorithms predicted PWV with correlation coefficients of 0.46 and 0.64 and yielded rms errors of 7.30 mm and 3.80 mm. Additional analysis showed that new coefficients for the RV approach using local data decreased the rms error only slightly to 3.53.

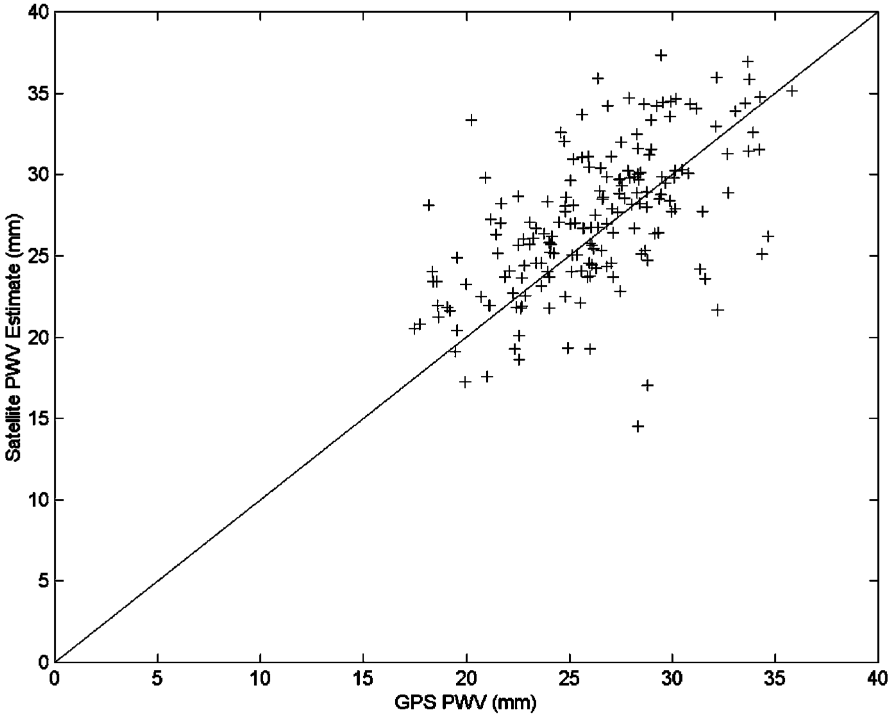

Figure 2. Comparison between GPS-derived and AVHRR satellite-derived estimates of precipitable water based on the Roger and Vermote algorithm (rms error and bias in mm).

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