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GPS-DERIVED INTEGRATED PRECIPITABLE WATER COMPARED WITH THE AFWA MM5 MOISTURE FIELDS

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1. INTRODUCTION

GPS-derived precipitable water is a tool that provides unprecedented spatial and temporal resolution of water vapor, a highly variable parameter that is currently very difficult to accurately initialize. By measuring the "wet delay" of a transmission to a GPS receiver, where the delay is proportional to the integrated water vapor, it is possible to remotely sense a line-of-sight precipitable water amount for a given transmission time and receiver location. This parameter can be normalized into an estimate of a vertically integrated precipitable water value. In order to produce the most accurate water vapor measurement, the GPS receiver must have a means to measure temperature and sea level pressure concurrently.

The goal of this research is to perform statistical comparisons of raw precipitable water measurements from existing GPS-Meteorology sensor networks (networks of sensors with temperatures and SLP measurement devices in place) in five regions worldwide. This data will be compared with Air Force Weather Agency Mesoscale Model 5 (AFWA MM5) moisture output. This information will be presented to AFWA as evidence regarding future integration of GPS precipitable water measurements into their model initialization schemes.

2. BACKGROUND

2.1. *Global Positioning System*

The Global Positioning System was established by the U.S. government in the early 1980s as a crucial element in navigation and relative positioning. Today, GPS includes a constellation of 24 low-earth-orbit (LEO) satellite vehicles that transmit signals in the L-band (1.2 and 1.6 GHz) to terrestrial users equipped with receivers. These signals are converted into information to aid in navigation, timing, and positioning, not only for military assets, but also for many civilian uses (Trimble 1996).

2.2. *Delays in the GPS signal*

Due to the requirement for highly accurate GPS readouts in every transmission, post-processing has been developed to write out signal delays from each of these transmissions. These delays are excess path lengths due to the phase shifting between the standing signal and the transmission signal. They are calculated out of the signal through post-processing at the receiver end of the transmission. There are two major components of the GPS signal delay, the hydrostatic delay and the wet delay.

Hydrostatic delay arises from the induced dipole moment of the atmosphere. This part of the delay factors in all constituents of the neutral atmosphere (to include nitrogen, oxygen, argon, and other trace gases) *except* water vapor. These constituents have relatively uniform composition in the troposphere. Using a surface pressure measurement, the hydrostatic delay is calculated:

$$ZHD = \frac{(2.2779 + 0.0024)\cdot P_s}{f(\phi, H)}.$$

Ps is the surface pressure, and f is the variation of the gravitational constant with latitude and height (Borbas 1997). With surface pressure measurements, the hydrostatic delay can be measured to better than 1mm. (Businger 1996).

The wet delay arises from the refractivity of the water vapor in the neutral atmosphere. Due to the variability of water vapor in the tropopause, the wet delay can vary from 10mm in desert regions to more than 400mm in more humid regions. Not only is there a significant spatial variability in wet delay, but there also exists a significant temporal variability. When the wet delay is measured in the zenith direction, an amazingly simple relationship exists:

$$PW := \Pi \cdot ZWD.$$

PW is precipitable water in a vertical column, and ZWD stands for zenith wet delay, which is typically a

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slant-wise wet delay measurement that has been normalized with a basic mapping function: ZWD = WD*(sin θ), where θ is the elevation angle.

$$\Pi = \frac{10^6}{\rho \cdot R_v \cdot \left[\left(\frac{k_3}{T_m} \right) + k_2 \right]}.$$

R_v is the gas constant for water vapor, ρ is the density of liquid water, T_m is the mean temperature through a vertical layer, and k_2 and k_3 are constants related to the refractivity of water (Bevis 1994).

2.3. *Research Efforts in GPS Meteorology*

Exploiting the GPS signal delay for meteorological applications is a relatively young endeavor. The GPS network has only been operational since the mid-1980s. GPS meteorology shows considerable promise for both short- and long-term forecasting, including climatology. In addition, research is ongoing for the assimilation of GPS water vapor data into larger-scale forecast models, the mapping of global water vapor patterns in a manner similar to computerized axial tomography (CAT scanning), and the measurements of atmospheric refractivity soundings via radio occultation to gather information about temperature, humidity and ionospheric structures (Ware 2000).

2.4. *Fifth Generation Penn State/NCAR Mesoscale Model*

The MM5 is a three-dimensional, non-hydrostatic, primitive-equation, nest-grid model with a terrain following vertical coordinate system (σ) (Grell 1995). It is the Air Force Weather Agency's (AFWA's) weather forecast model of choice. As of this writing, AFWA runs MM5 windows over 29 worldwide mission critical theaters of operations. AFWA maintains 18 parent domains, from which 11 inner nest windows are derived (Applequist 2001, personal communication).

2.5. *Precipitable Water in the MM5*

Kuo (1993) has already shown that precipitable water, although a two-dimensional variable, can be aptly assimilated into the MM5. Therefore, it is plausible that with its exceptional temporal and spatial resolution, the GPS-derived precipitable water can be a valuable input for modeling the tenuous water vapor variables.

Gutman (2001) has offered theories on how GPS PWV can be integrated into mesoscale models by using a vertical aliasing technique, similar to the one mentioned above by Kuo (1993). He shows a case study in which GPS PWV was assimilated into the National Center for Environmental Prediction's (NCEP's) Rapid Update Cycle 2 (RUC-2) mesoscale forecast model. In addition, he cites previous studies in which it has been shown that the most vertical variability in the integrated vertical moisture profile is in the lower 4000m.

Currently, data is assimilated into AFWA's MM5 for analysis using the Multivariate Optimal Interpolation (MVOI) scheme. MVOI uses point analyses in the vertical to derive vertical profiles of temperature, winds, and moisture. GPS-derived moisture products are currently not assimilated into the MM5 (partly due to the form of assimilation technique). By summer 2002, AFWA's analysis scheme will transition from MVOI to the 3-Dimensional Variational Analysis (3DVAR) system. This method is designed to employ more data sources along with parallelization techniques to compile more information in a comparable amount of time (Ritz 2001). This future transition provides more validity to my research, for 3DVAR may be able to ingest the GPS-derived products for initialization.

3. METHODOLOGY

Four locations have been selected that each must meet the following two criteria: (1) the region has an existing GPS Meteorology network whose resolution is better than the existing rawinsonde network and (2) AFWA must have an existing MM5 grid in place and operating daily. For each location, a period of time will be selected to study the location in a significant weather event. Eight to ten days should be enough time to gather a variety of weather conditions. Barring an anomalous long-term weather pattern (such as an Omega block), a significant synoptic scale system should impact each area, giving the network a chance to gather potentially significant precipitable water data.

NOAA's Forecast Systems Laboratory is providing the CONUS GPS meteorology data for this research. In addition, representatives in the GPS meteorology office have been coordinating through international channels the use of some of the international GPS meteorology networks. For research with the most Air Force applicability, access to the international locations will be important, so it can be seen how this information will fare in more significant warfighting locations.

For each area, the following tasks will be accomplished to prepare the data for analysis:

- Gather GPS readings from the network sites every 3 hours and process the data into precipitable water values.
- At each data time, a grid-to-station linear interpolation will be performed to match each GPS observation to a corresponding MM5 forecast value.
- MM5 data at 3-hour intervals will be used. Each of these runs will have an analysis and 3 hour forecasts for 48 hours.

Various statistical measures will be conducted to compare the GPS-derived moisture profiles with MM5 analysis and forecast data. While the statistical measures that will need to be performed have not been finalized, analyses should include bias, RMS error, and correlations. These parameters will be calculated for each location, and then compared – both with the MM5 output and with each other. Output will include both tabular and graphical methods.

4. EXPECTED RESULTS

This project will likely further verify what Powers (2000) and Spangenberg (1997) have shown in related studies involving MM5 moisture: significant shortcomings exist in the MM5 moisture prognoses. In fact, Powers demonstrated that assimilating DMSP precipitable water data into the MM5 could reduce errors by more than 30%! If a significant difference between the GPS moisture plots and MM5's precipitable water plots can be shown, perhaps AFWA will allow this research to continue by testing true incorporation of GPS-derived precipitable water into the model.

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