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MONITORING CLIMATE CHANGES ON SMALL SCALE NETWORKS USING GROUND BASED GPS AND METEOROLOGICAL DATA

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ABSTRACT. The total zenith tropospheric delay (ZTD) and its components, hydrostatic and wet parts are important parameters of the atmosphere and directly or indirectly reflect climate processes. This possibility can be more adaptive when meteorological data are combined to co-located meteorological sensors with GPS stations. In this paper eighteen months with one hour time interval ZTD estimates of a permanent GPS station are analyzed with the associated atmospheric parameters provided from a co-located meteorological sensor. The mathematical relationship through the multiple stepwise regression analysis reflects the plausible physical link of temperature and relative humidity values with ZTD's. This regression equation is assessed by a second data set performed by a small GPS baseline few months later for the same study area. It was found that mainly due to the zenith wet delay variations and with the help of fundamental meteorological equations the behavior of water vapor pressure can be monitored and estimated. This is possible when an appropriate setup of GPS stations and a co-located meteorological sensor exist and if the GPS stations sound the same part of atmosphere. Therefore, the GPS tropospheric products are good indicators for a climate monitoring tool and can help address the physics of a climate model.

Keywords: GPS data, Ground Meteorological data, Zenith Tropospheric Delay, Stepwise regression analysis, water vapor pressure, Climate variation.

1. INTRODUCTION

The Global Positioning System (GPS) consists of a constellation of satellites that transmit radio signals to every user engaged in navigation, time transfer, and relative positioning. Over the past 20 years, the applications of GPS technologies have been developed in many different areas. One of these areas is the GPS meteorology, which means the use of GPS data for climate monitoring through analysis of several atmospheric parameters, such as the water vapor. The principle is that the atmospheric gases, including water vapor in atmosphere cause an additional delay (range error) in GPS observations as the broadcast signals from satellites travel through the neutral atmosphere to gps receiver's antennae. This delay can be modeled and estimated by a parameter called total Zenith Tropospheric Delay (ZTD). The zenith tropospheric delay of the signal can be divided into a Zenith Hydrostatic (ZHD) term and a wet term caused by the refractivity of the (Zenith) Water vapor (ZWD) (Hofmann-Wellenhof et.al. 1997, Schüler 2001, Fotiou and Pikridas 2012). Therefore ZTD is an important parameter of the atmosphere, which reflects the weather and climate processes, variations and atmospheric motions.

Due to recent progress in GPS tropospheric delay estimation techniques and improvements in orbit quality and receiver technology it is possible to monitor Earth's troposphere and its parameters using ground based GPS receivers. At the recent years continuously operating GPS stations exist in large numbers and with a wide spatial distribution. Several research projects using continuous observations from GPS permanent networks stations were initiated in Europe and overseas for mapping and predict the state of the atmosphere and as a consequence the climate changes (van der Marel 2004, Bennitt and Jupp, 2012).

Climate change monitoring over the coming decades is of high relevance since there is a global concern that the Earth's climate is increasingly influenced by human activities (e.g., IPCC, 1995). The atmosphere plays an important role to the climate system and changes in atmospheric composition, such as the increase in greenhouse gases, cause modifications of the thermal structure. Improved knowledge of atmospheric parameters is needed for a variety of atmospheric research applications and for improved weather forecasting. The potential use of GPS measurements for meteorological purposes would enable more accurate forecasts of rainfall and severe weather and would contribute to several studies of climate change (Bevis et al. 1992, van der Marel, 2004).

In this paper we examine the sensitivity of the estimated ZTD values and its components, derived from a small GPS baseline formed by (two) stations equipped with meteorological sensors, to any site climate changes. It was found that GPS product data are a good climate monitoring tool and must help address the physics of a climate model so as to make it better able to predict future climate.

2. GPS NETWORK DATA PROCESS

The first part of GPS study data covers a period of 18 months starting from June 1st of 2011 until December 31th of 2012. A number of four permanent IGS stations in Austria, Italy and Cyprus which also contribute to the European Reference Frame (EUREF, http://www.epncb.oma.be) Network (Bruyninx, 2004) and one in Greece forming long baselines were selected. Figure 1 shows the geographical locations (red bullets) of the selected GPS stations from which data are used to obtain ZTD values for the test site named IOA1 (NW Greece). All permanent GPS stations are equipped with dual frequency receivers and have an observation recording data rate of 30 seconds.

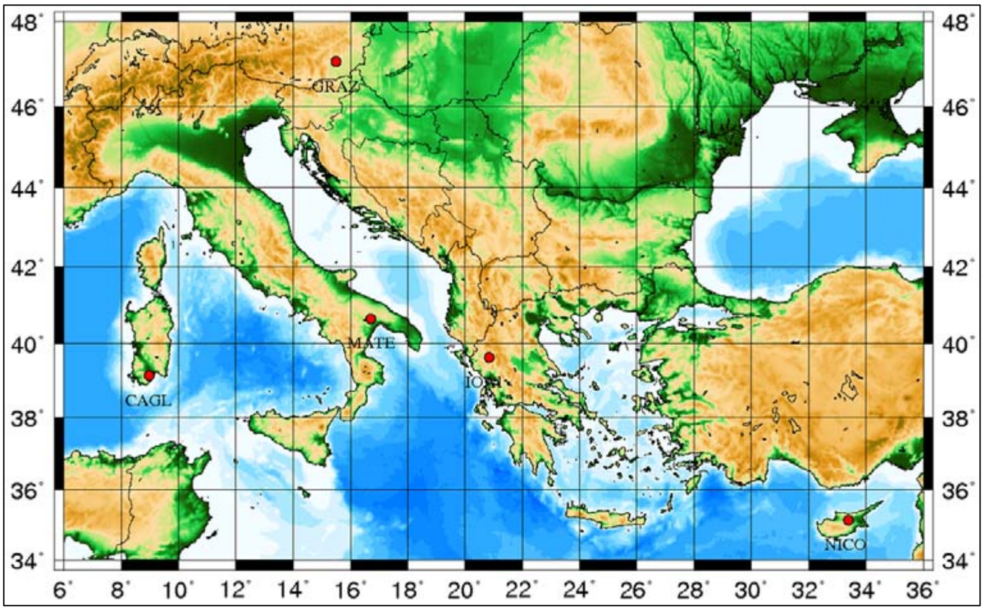

Fig. 1. Geographic distribution of the used permanent GPS stations.

The primary goal of this processing step is to estimate the ZTD values extracted from GPS data process for the station IOA1. Therefore, ZTD values were estimated over one hour time intervals, using the Bernese v5.0 software which was developed at Astronomical Institute of the University of Bern in Switzerland (Dach et. al. 2007). The ZTD estimates can be split into zenith hydrostatic (ZHD) and zenith wet (ZWD) component of the delay using the relation (Schuler 2001):

$$\mathrm{ZTD} = \mathrm{ZHD} + \mathrm{ZWD} \tag{1}$$

The hydrostatic component (ZHD) is modeled based on the pressure, temperature, height at the GPS stations which might be obtained from standard atmosphere models, as well as numerical weather prediction models or alternatively from ground meteorological observations. While, the wet component (ZWD) is highly variable due to the presence of water vapor content above GPS stations and is difficult to model. Unfortunately only few GPS stations of global networks like IGS, EPN have meteorological sensors which can directly obtain the real ZWD.

In this study, near to IOA1 permanent GPS station a meteorological sensor is located. This sensor also participates to the Weather Underground weather station network. The Weather Underground network started in 2001 to address the growing need for meteorologists to gain access to more granular data. Today is one of the world's largest networks including over 25000 personal weather stations. The specific station includes a thermometer, barometer, anemometer and wind vanes and is sending weather conditions to a server. From the relevant data server (http://www.wunderground.com) the hourly records, including temperature, relative humidity, pressure and precipitation for all the days of the test period are downloaded. It is worth to be mentioned that the city of Ioannina and its broader area is considered an area of significant meteorological interest due to extreme variations in seasonal weather (Houssos et al. 2012, Sindosi et al. 2012). Also due to the area's unique weather and important agricultural sector, there is an increased interest to complement current meteorological sensor network observations with GPS product data, like the ZTD values.

Referring the basic information for processing parameters, the GPS data was analyzed with a satellite elevation cut-off angle of 10 degrees, final precise orbit information was used from IGS directory (available after 12 days) which refers to the IGb08 reference frame and the new IGS_08.atx model with absolute antenna calibration values was applied. It is important to note that, in order to derive absolute ZTD estimates the average length of baselines included in processing should be over 500 km. This rule was applied for the selection of the four EUREF stations. Long baselines reduce the high level of correlation of the tropospheric delays which occurs on short baselines (Duan et al. 1996). The ZTD of our network is of absolute estimate values because almost all of the baselines are longer than 500 km. For the account of the tropospheric refraction, the Saastamoinen model (Saastamoinen, 1972) with Niell mapping function (Niell, 1996) was used in processing. Mapping functions currently used to map slant delays to zenith delays using a relationship depending on geographical position and time of year in order to estimate the most probable moisture profile. Finally, all the initial phase ambiguities of carrier frequencies were resolved at a level >98% using the QIF strategy (Dach et. al. 2007). As it is known, carrier phase data are biased by an integer number of carrier wavelengths which called initial phase ambiguity and must be estimated from the data. If phase ambiguity resolution is succeeded then high accuracy results are obtained. As a consequence, ZTD estimates were obtained with an accuracy of a few millimeters. More specific, ZTD RMS values were not exceeded the 4 millimeters.

3. ANALYSIS OF ZTD AND METEOROLOGICAL DATA

There are two main methodologies for predicting climate change caused by critical parameters. One is to describe the atmospheric system analytically and construct a general circulation model, but this kind of models requires extensive data and massive numerical computations. A second option is to define statistical relationships between different climate parameters which is relatively easy to apply. The stepwise regression method has been applied to the analysis of possible climate change combining correlated atmospheric parameters using various scenarios. (Hashino and You, 1994). The principle of a stepwise regression method was described in detail by Enslein et al. (1977) and enables the most significant independent variables to be selected and coefficients of regression equations to be estimated.

More specifically, multiple stepwise regression analysis generates a linear equation that predicts a dependent variable as a function of several independent variables. In this study the hourly ZTD values estimated through GPS data processing for IOA1 station (through differential process) were selected as the dependent variable, while the independent variables were also the hourly values of temperature, pressure, relative humidity and precipitation which had been downloaded from wunderground server. It is assumed that these meteorological variables have a plausible physical link with ZTD estimates.

The multiple stepwise equation is of the general form,

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \ldots + b_nX_n \tag{2}$$

where Y is the predicted dependent variable, b_0 to b_n are partial regression coefficients, and X_1 to X_n are independent variables (Brown, 1996). For the application of the multiple stepwise regression, the SPSS software package was used (Norusis, 2005). The F-statistic is used to test whether the values of the coefficients for the entire equation are equal to zero, and if the p-value (statistical significance) for the F-statistic is less than 0.05, the equation is statistically significant. To assess statistical validity of the predictive equation, we also computed the root mean squared error (RMSE) of regression process which was found equal to 0.02 and coefficient of multiple determination (r^2 and r^2 adjusted for n-2 degrees of freedom).

Another critical factor for the correctness of the selected model parameters is the correlation factor. Correlation measures the dependability of the relationship (the goodness of fit of the data to the mathematical model relationship). It is a measure of how well one variable can predict the other (given the context of the data) and determines the precision you can assign to a relationship. Table 1 shows the derived correlation values between the tested variables.

Table 1. Correlations values between dependent and independent variables of multiple stepwise regression analysis

		ZTD	Tempe-rature	Relative Humidity	Pressure	Precipitation
Pearson Correlation	ZTD	1.000	.742	-.336	-.119	-.007
	Temperature	.742	1.000	-.702	-.250	-.204
	Rel.Humidity	-.336	-.702	1.000	.252	.426
	Pressure	-.119	-.250	.252	1.000	-.146
	Precipitation	-.007	-.204	.426	-.146	1.000

Because there is no statistically significant correlation between precipitation and ZTD values, this parameter was excluded from the final relationship. Also the small (negative) correlation value (-0.119) of atmospheric pressure with ZTD shows that pressure variations do not significantly influence the ZTD estimates. As a consequence this parameter was not included to the final relationship. The derived equation from multiple stepwise regression is defined as follows:

$$ZTD = 2.163 + 0.005 * T_{emp} + 0.001 * RH_{umidity}$$

Therefore, it was found that the statistical relationship of ZTD with other climate factors, derived from big numerous data records, is temperature and relative humidity. So, this relationship is assumed as representative (from the test period) of the specific weather process of both the present and the near future. This remark was also one of major topic to investigate on the next application. On this point it is worth to be mentioned that climate analysis usually needs much longer observation period data so this study period is mainly based on local weather conditions but if it extents with longer time span of GPS and meteorological sensor observations it'll clearly illustrate the climate signature.

4. SMALL SCALE GPS NETWORK AND METEOROLOGICAL DATA COMBINATION

The second part of GPS study data covers a period of seven days starting from March 3rd until 10 but in year 2013, two months later after the first test period. The GPS network consists of the same four EUREF permanent GPS stations and IOA1 but in addition, one more is installed for the purposes of the study about 18 Km away at NW direction and almost at the same height with station IOA1 (only four meters height difference). The new station is named KLHM, it was equipped with dual frequency receiver and had same observation recording data rate. Under this installation, the forming baseline (IOA1-KLHM) is characterized as a small scale GPS distance (Dach et. al. 2007). For research purposes a Personal Meteorological station (PM) was installed exact near to KLHM GPS station storing its simultaneous measurements to internal memory. This PM station was a 4500 model of Kestrel company (http://kestrelmeters.com/products) and measured the same atmospheric parameters like the meteorological sensor of station IOA1. In addition and in order to avoid bias and drift problems the PM station was (first) calibrated according to manufacturer instructions. Also, for this test GPS network, the same processing scenario was used and the related accurate ZTD values every one hour time interval, for the interesting stations, were estimated. As it concerns the ambiguity resolution, for this kind of baseline length the Sigma strategy was used according to (Bernese) manual guidelines (Dach et. al. 2007). Figure 2 depicts the ZTD values of the stations IOA1 and KLHM during the test period.

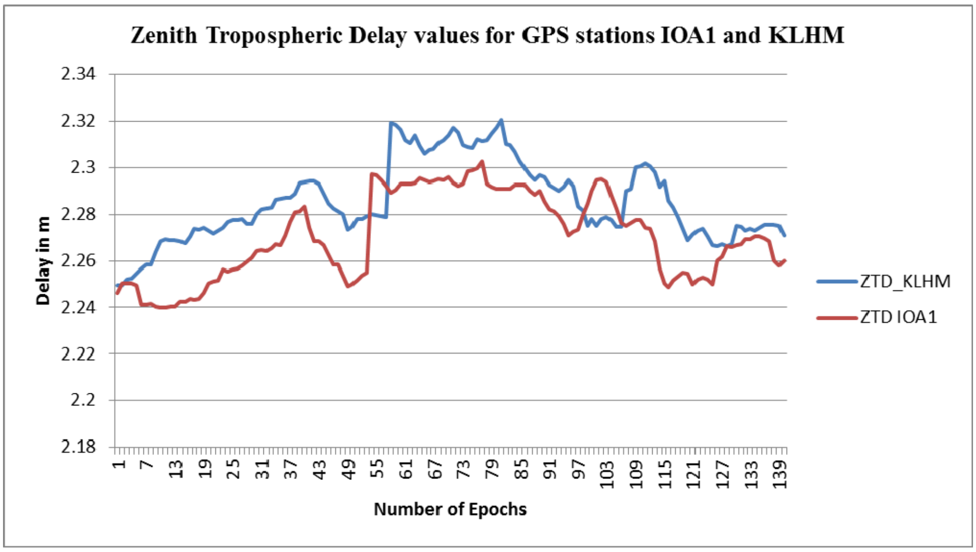

Fig. 2. Zenith Tropospheric Delay (ZTD) values for GPS stations IOA1 and KLHM during the test period.

Focusing on the above figure 2 it becomes clear that a big sudden jump occurs for stations IOA1 and KLHM starting from epoch 52 and ends at epoch 58. This epoch interval relies on March 7th and time from 12:00 to 6:00 am. Searching in detail the meteorological data values of both sensors (at IOA1 and KLHM) it was found that within this interval the relative humidity was changed from 55% to 82% and from 33% to 72% for stations IOA1 and KLHM respectively. While, the temperature values showed was much smaller variation, only 1.7 ^{0}C difference (from 9.8 to 8.1 ^{0}C) for IOA1 and from 11.3 to 7.4 C^{0} at KLHM. A sample plot of KLHM meteo sensor data records is illustrated as follows where the big change of relative humidity (RH) values are clearly shown. TP and BP represents the Temperature (in^{0}C) and Barometric Pressure (in hPa) respectively, while RH is the Relative Humidity values in scale of hundred percent (%).

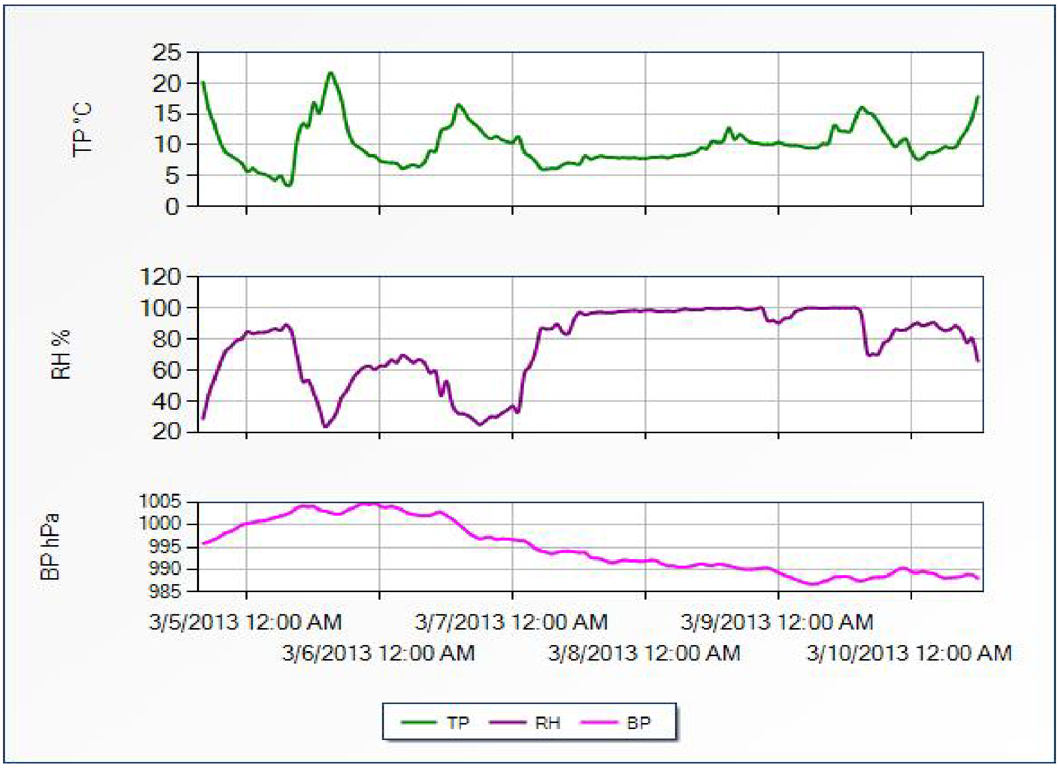

Fig.3. Temperature, Relative Humidity and Barometric Pressure values of station KLHM for the test period

As far as the difference of pressure values between the two stations is concerned, these remained almost unchangeable. Table 2 presents the correlation results between the major atmospheric parameters which make clear how well the data pairs match each other and confirm that both sites are founded under the same atmospheric layer.

Table 2. Correlations values between atmospheric parameters of stations IOA1 and KLHM

		ZTD (KLHM)	Temperature (KLHM)	Rel.Humidity (KLHM)	Pressure (KLHM)
Correlation	ZTD (IOA1)	**0.732**	-0.319	0.376	-0.368
	Temperature (IOA1)	-0.181	**0.912**	-0.429	-0.187
	Rel.Humidity (IOA1)	0.424	-0.544	**0.962**	-0.582
	Pressure (IOA1)	-0.181	-0.072	-0.650	**0.999**

As a consequence, we can consider that the multi stepwise regression model of IOA1 station is representative for the outskirts of Ioannina city and reflects the weather change. Investigating more the occurred variation for the estimated ZTD values, the ZWD values were derived through the equation 1 for stations IOA1 and KLHM. The related ZHD component was estimated according to the following formula which is based on Saastamoinen model (Saastamoinen 1972, Tregoning and Herring 2006).

$$\mathrm{ZHD}(\mathrm{P},\Phi,\mathrm{h})=\frac{0.0022768\mathrm{P}}{1-0.00266\cos(2\Phi)-0.00028\mathrm{h}} \tag{3}$$

where, P is the surface pressure, Φ is the station latitude and h the orthometric station height. It must be noted that the relevant pressure values were used as input data to the above equation for parameter P. This choice was mandatory in order to obtain the real ZHD. Figure 4 depicts the calculated ZWD values.

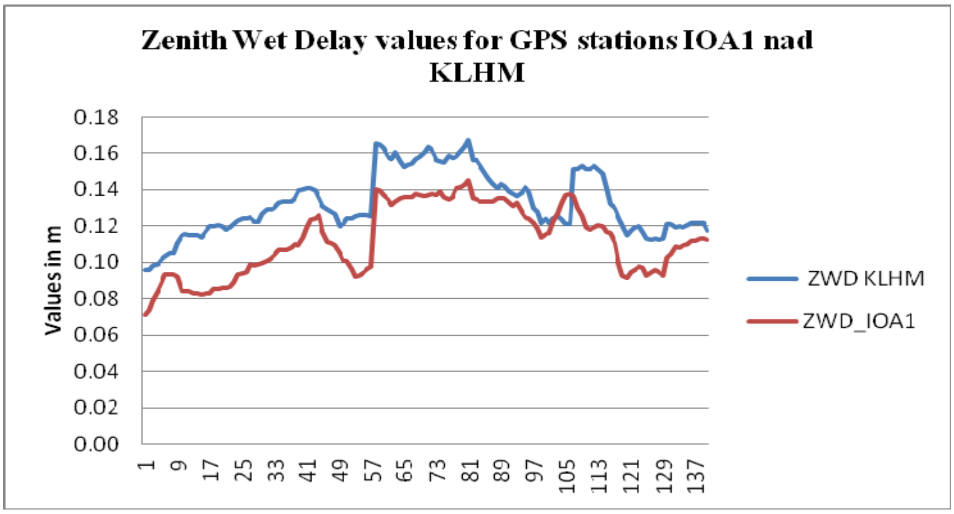

Fig. 4. Zenith Wet Delay (ZWD) values for GPS stations IOA1 and KLHM during the test period

It becomes clear that the ZWD component is the main factor for this event which reflects the water vapor percentage of the atmosphere. Therefore the potential contribution of GPS data products have to be more analyzed.

As it is known, the clausius-clapeyron equation (4a) allows us to estimate the vapor pressure at another temperature, if the vapor pressure is known at some temperature, and if the enthalpy of vaporization is known.

$$\frac{\mathrm{de_s}}{\mathrm{dT}}=\frac{\mathrm{e_s L_u}}{\mathrm{R_u T^2}} \tag{4a}$$

or the equivalent parameterized relations (Flokas,1997)

$$\log e_s = 9.4041-\frac{2354}{T} \tag{4b}$$

$$e_S = \exp^{(21.65-\frac{5417}{T})} \tag{4c}$$

where, e is the vapor pressure and e_s the (maximum) vapor pressure to the saturation amount of the air and T the temperature in Kelvin scale. Conversion from Celsius to Kelvin scale is done using the formula $T_K=T_C+273.15$. As it is known from literature, the more is the water vapor in the air, the higher the relative humidity is at a given temperature. So, relative humidity (RH) is related with e and e_s as follows,

$$\mathrm{RH} = \frac{\mathrm{e}}{\mathrm{e_s}}\times 100 \tag{5}$$

The next step of this study was the calculation of the vapor pressure at both observing sites using the equations (4c) and (5). In order to relate the vapor pressure, with the water vapor content factor derived through GPS data process, the ratio of ZWD to pressure (e) was determined. Figure 5 depicts the ratio values of both sites for the tested period and in addition the best fitting line. This equation (y= 0.4635 x+0.0051) gives a linear dependence between the two computed ratios. Calculating the correlation factor between (stations) ratios values, this was found equal to 0.92 which qualifies how well the data pairs match each other. So we can conclude that when the GPS stations sound the same part of atmosphere we can estimate from the one site the other site atmospheric parameters (like in our case, the vapor pressure) with desirable accuracy at least for several weather reports (like in e.g. agriculture), establish only one co-located meteorological sensor. In case of site dependent bias, they must be taken into account in order to get more accurate estimations. As a consequence, a GPS permanent network could contribute to the meteorological ground networks activities. The knowledge of the atmospheric distribution of water vapour is of key importance in weather prediction and climate research. It has to be noted that, assuming a single atmospheric layer an operational weather volume observed by a (single) GPS receiver with a cutoff angle of 10^0 and a tropospheric height of 5 km is an area with radius of 27 km. Difficulties for this station separation plays the complex topography of the earth's surface, so maybe a more dense GPS stations network could be more adaptive for this kind of studies. Also, due to internet capabilities of GPS receivers operation, the computation of ZTD and its related components could be applied in almost real time mode. The nature and stability of the GPS measurements could provide a long term homogeneous data set largely free of calibration and instrument drift problems. On the other hand and in order to perform an operational weather forecast, a fast and reliable data flow from GPS observations is required and high accuracy satellite ephemeris data must be used.

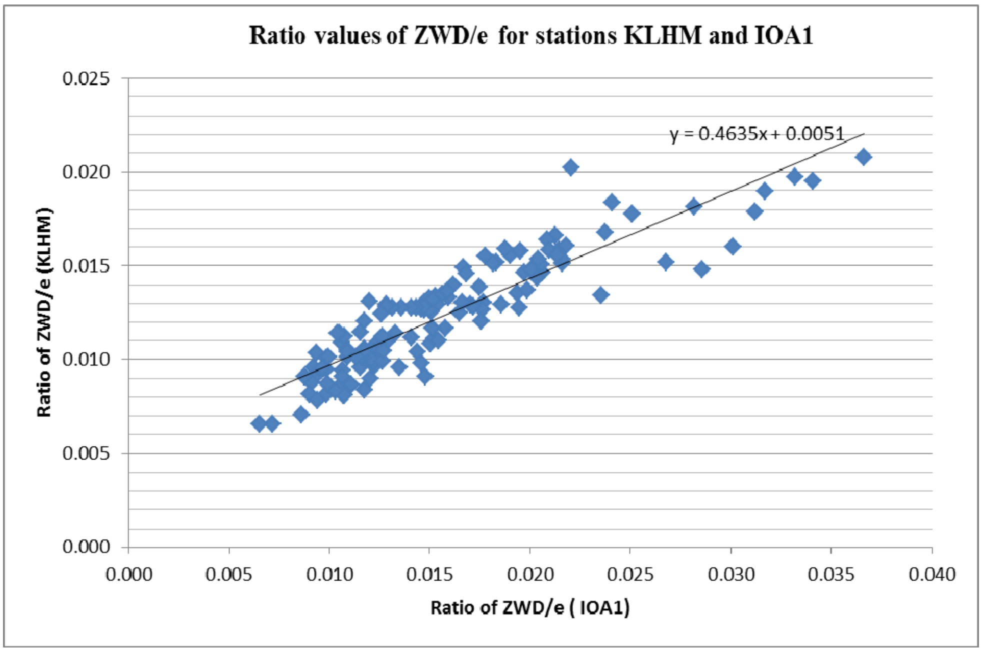

Fig. 5. Ratio values of ZWD to water vapor pressure (e) of stations KLHM and IOA1 during the test period

CONCLUSIONS

In this study eighteen months meteorological data of a collocated sensor with a GPS reference station were used in order to derive the mathematical relationship between the zenith tropospheric delay and atmospheric parameters. It was found, for the study area, through the multiple stepwise regression analysis that the statistical parameters related with ZTD estimates are temperature and relative humidity. These parameters and its components (like the water vapor pressure) were more analyzed in order to relate their behavior with ZTD products such as the zenith wet delay under certain circumstances.

A new data set of a small GPS baseline with specific setup and with meteorological sensors was collected in order to assess the relationship as representative of the specific climate system. During analysis, it was concluded that site-specific atmospheric parameters can be monitored and estimated with sufficient accuracy for a weather report if both GPS stations sound the same part of atmosphere. Therefore, the GPS tropospheric products estimated through GPS network data process are good indicators for a weather monitoring status tool and can help address the physics of a climate model. This advantage could be applied in a near real time manner using the derived products from the relevant GPS analysis centers.

In addition, a longer time span of test period data (5~10 years) could be more useful to analyze in order to indicate if the GPS signals through ZWD values are more strong correlate with the climate change parameter.

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