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# MEASURING AND FORECASTING OF PWV ABOVE LA SILLA, APEX AND PARANAL OBSERVATORIES

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RESUMEN

El contenido de vapor de agua precipitable (PWV) en la atmósfera es muy importante en las regiones espectrales del infrarrojo y radio (sub-milimétrico). Por esto, el grupo de Astrometeorología de la Universidad de Valparaíso, ha desarrollado diferentes métodos para derivar el valor de esta variable desde mediciones con instrumentos hasta utilización de un modelo meteorológico para obtener su pronóstico. El objetivo de utilizar un modelo así es poder predecir las condiciones atmosféricas y apoyar la programación de las observaciones astronómicas. ESO posee varios medios para determinar PWV, utilizados en los observatorios, tales como radiometros infrarrojos (IRMA) y espectrógrafos ópticos e infrarrojos. Al poseer estas herramientas se realizó una investigación para comparar las estimaciones de PWV con las mediciones *in-situ* entregadas por los radiosondas. Cuatro campañas dedicadas fueron realizadas durante el año 2009 en los observatorios La Silla, APEX y Paranal. Además, el grupo de astrometeorología implementó el modelo de pronóstico e investigación meteorológico (WRF) con el propósito de simular el estado de la atmósfera (cada 6 horas) y pronosticar el valor de PWV. Con estas simulaciones, los datos medidos por las campañas de radiosondas pueden ser clasificadas sinópticamente y al mismo tiempo puede ser validado el modelo respecto al PWV.

ABSTRACT

The content of precipitable water vapor (PWV) in the atmosphere is very important for astronomy in the infrared and radio (sub-millimeter) spectral regions. Therefore, the astrometeorology group has developed different methods to derive this value from measurements and making forecasts using a meteorological model. The goal is to use that model to predict the atmospheric conditions and support the scheduling of astronomical observations. At ESO, several means to determine PWV over the observatories have been used, such as IR-radiometers (IRMA), optical and infrared spectrographs. Having these tools a study was undertaken to compare the accuracy of this PWV estimate with the *in-situ* measurements provided by radiosondes. Four dedicated campaigns were conducted during 2009 at the La Silla, APEX and Paranal observatory sites. In addition, the astrometeorological group employs the WRF meteorological model with the goal of simulating the state of the atmosphere (every 6 hours) and forecasting the PWV. With these simulations, radiosonde campaign data can be classified synoptically and at the same time the model can be validated with respect to PWV.

*Key Words:* atmospheric effects — site testing

## 1. GENERAL

The European Southern Observatory (ESO), in collaboration with Institute for Space Imaging Science (ISIS) and the Astrometeorology Group from the Universidad de Valparaíso, conducted a series of dedicated measurement campaigns to characterize the PWV[5] environment over three observatories in central and northern Chile. PWV is the principle source of opacity in infrared and radio (submillimeter) spectral regions. These campaigns were performed using an IRMA[6] (Naylor et al. 2008), several high-resolution facility spectrograph and series of radiosondes launches. The Astrometeorology group conducted the radiosonde launches over the three observatories: La Silla, APEX[7] and Paranal.

To assist the PWV measurement campaign, the Astrometeorology group used the Weather Research and forecasting (WRF) meteorological model. This model can simulate the state of the atmosphere, forecast meteorological variables and conditions. With all this data was able to calculate and compare the

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[5]Precipitable Water Vapor.

[6]Infrared Radiometer.

[7]Atacama Pathfinder Experiment.

forecasted of PWV with the value measured by the radiosondes, with the objective of identifying the synoptic patterns, especially those in the PWV. This study is organized as follow: a brief overview of the instrument used in the radiosonde campaign (§ 2), mesoscale model (§ 3), methodology (§ 4), results (§ 5) and conclusion (§ 6).

## 2. RADIOSONDES CAMPAIGNS

To measure the vertical profile of the atmosphere above the observatories sites, were used Vaisala radiosondes RS92-SGP. The radiosonde is a self contained instrument package with sensors to measure, e.g. temperature and humidity combined with a GPS receiver and a radio transmitter that relays all data in real-time to a receiver on the ground. The radiosonde is tied to a helium filled balloon and after launch ascends at a rate of a few m/s following the prevailing winds. On its ascent trajectory the sonde will sample the local meteorological variables up to a height ∼20 km, when the balloon will burst. By that time it has traveled horizontally ∼100 km from the launch site. Since it relays its 3D location based on GPS location every two seconds, the wind vector exerting force on the balloon can be deduced from the change in GPS position. Using this device, four radiosonde campaigns were develop in 2009, the schedule of each was: La Silla Site between May 5th to 15th, APEX site between July 7th to 16th and Paranal site two campaigns first between July 29th to August 10th and second between November 9th to 19th, between 00, 06 and 12 UTC hours.

## 3. THE WRF MESOSCALE MODEL

The development of the Weather Research and Forecasting (WRF) modeling system is a multiagency effort intended to provide a next-generation mesoscale forecast model and data assimilation system. The model is being developed as collaboration between the National Center for Atmospheric Research (NCAR), University Corporation for Atmospheric Research (UCAR), Mesoscale and Microscale Meteorology (MMM) Division, between other (Skamarock et al. 2005). This model is a limited-area, non-hydrostatic and terrain following sigma-coordinate. This model can simulated and predict mesoscale atmospheric circulation. The model also has the nesting capabilities (Domains). The boundary conditions used in this model were the FNL model[8] and resolutions used in this study were 27 km, 9 km, 3 km and 1 km in APEX Site. For La Silla and Paranal site were: 30 km, 10 km, 3.3 km and 1.1 km.

[8] http://dss.ucar.edu/datasets/ds083.2/.

## 4. METHODOLOGY

In order to develop this study the following steps were taken:

1. Calculated the value of PWV directly from the radiosonde data, using the next equation:

$$\mathrm{PWV} = \frac{1}{g}\int_{P_1}^{P_2} q_{vs}\, dP\,, \qquad (1)$$

where $q_{vs}$ is the mixing ratio at a given pressure level, $P$, then the PWV contained in a layer bounded by pressures $P_1$ and $P_2$ and $g$ is the acceleration of gravity. This equation was used with the data measured by the radiosondes and the values simulated using the WRF mesoscale model.

2. Extract the vertical profiles of the meteorological values from the WRF model, using a linear interpolation based on each location in the study.

3. Perform a statistical analysis, correlation analysis (Cor), root mean square error (RMSE) calculation. Determine the bias and cumulative distribution function (CDF).

4. To classify the synoptic pattern, the study was based on the classification made by Cuevas et al. (2008).

## 5. RESULTS

The WRF model validation was performed comparing data from domain 4 (highest resolution ∼1 km) with radiosondes. § 5.1 will present the results from the PWV comparison and § 5.2 will show the vertical profiles comparison. § 5.3 present the meteorological study.

### 5.1. *Validation of PWV*

The WRF model simulations were run 72 hours every day during the periods of radiosonde campaigns. Radiosondes were launched at just 00, 06 and 12 UTC in each campaign. Since the model performance during the 72 hours of forecasts was evaluated everyday, simulations were compared with radiosondes at 00, 06, 12 UTC for the first day, at 24, 30 and 36 forecast hours for the second day and at 48, 54 and 60 forecast hours for the third day.

The first campaign was conducted in La Silla site, Figure 1a shows the time series comparison of PWV measured by the radiosonde and the PWV calculated by WRF model. This figure displays the values from the model overestimate the PWV by more than 2 mm. The second day of forecast present the lowest errors, with RMSE and BIAS of 2.80 mm and 2.48 mm, respectively. The CDF function shows that 50% of the forecast from the second day shows an

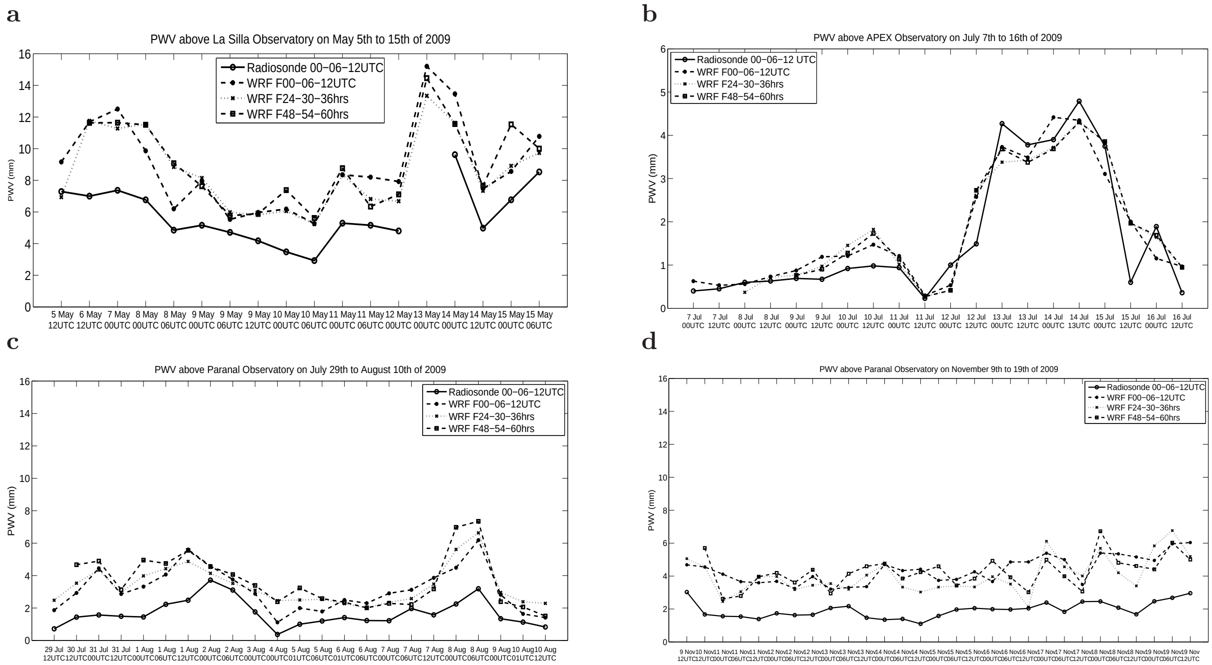


Fig. 1. Comparison of PWV measurment by the radiosonde and PWV from WRF model from (a) La Silla Observatory, (b) APEX Observatory, (c) Paranal Observatory (first campaign) and (d) Paranal Observatory (second campaign).



error less than 2.3 mm. The second PWV campaig was conducted at APEX Observatory, the location where the radiosondes were launched moved to San Pedro de Atacama in the middle of APEX campaign. However, the analysis was focused on APEX location. Figure 1b shows very good agreement between values simulated by the WRF model and those from radiosondes. The PWV from the model is overestimate by not more than 0.15 mm, with average RMSE of 0.6 mm and a Cor of 0.93, in the three days of forecast. The CDF function indicate that errors are less than 0.58 mm in 75% of the data. The third PWV campaign was conducted at Paranal site, in mid-winter season. Figure 1c shows that PWV from WRF model overestimates the radiosondes by more than 1 mm during the three days of forecast. The lowest RMSE (1.47 mm) and BIAS (1.66 mm) is observed in the first day of forecast, where CDF functions indicate that 50% and 75% of data show errors less than 1.15 mm and 1.86 mm, respectively. The fourth campaign was conducted at Paranal but during spring season. The objective was to obtain the PWV for this site during different seasons. Figure 1d indicates that the model does not show the same tendency than radiosondes and overestimates the PWV values by more than 2 mm. This campaign shows the lowest RMSE (2.27 mm) anss BIAS (2.09 mm) during the second day of forecast with the largest Cor (0.61). The CDF function for the second day of forecast shows the largest number of data with small errors (50% of data with errors less than 1.9 mm). The comparison of WRF simulations during two different seasons in Paranal the model can better predict the cold season than the warm season but this supposition should be further investigated. The WRF model overestimates the time evolution of PWV during La Silla and both Paranal campaigns all though it shows the same tendency than observations. A possible source of error in this comparison could be the fact that geographical coordinates used to extract the values from the WRF model are not the same were the radiosondes were launched.

### 5.2. *Validation of Vertical Profiles*

An average vertical profile from WRF simulations and radiosondes were calculated and used for comparison. The temperature vertical profiles from WRF are similar to the profiles measured by the radiosondes. The RMSE are larger than 1°C between 750 hPa and 600 hPa at La Silla and Paranal. However, at APEX, the model mostly overestimates temperature, but by less than 1°C. The comparison between relative humidity profiles shows that the RMSE is less than 20% below 300 hPa although the

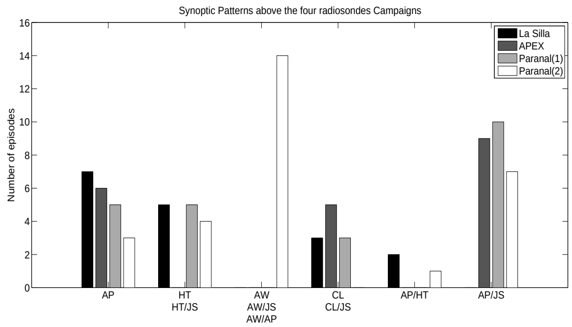


Fig. 2. Histogram of the synoptic pattern over La Silla, APEX and Paranal Observatories.

third and fourth campaigns show errors less than 10%. In the vertical profiles of mixing ratio, WRF model overestimates the vertical profiles in the four campaigns. The best simulation of this variable were performed over the APEX site with RMSE between 0 and 0.5 mm. This may be due to the very dry conditions present at that site. The largest errors are found below 600 hPa with RMSE as large as 2 g/g in the fourth campaign. In the four campaigns the average WRF vertical profile of the wind speed shows the same tendency than that from radiosondes. The best performance was obtained at APEX site and at the second campaign over Paranal site, with RMSE less than 2 m/s (except at upper pressure levels in APEX). In the case of wind direction vertical profiles, the agreement between the model and radiosondes is very good, except below 700 hPa at the second campaign in Paranal site where WRF shows RMSE larger than 60° and around 600 hPa in La Silla with RMSE near 45°.

### 5.3. *Meteorological study*

The synoptic patterns analyzed are the same than those presented in the study of Cuevas et al. (2008): Anticyclonic Predominance (AP), High Trough (HT), Cut-off Low (CL), Altiplanic Winter (AW) and Jet Stream (JS). In addition, combinations of two synoptic patterns (e.g. AP/JS, HT/JS) are also found. The four campaigns were individually analyzed since they were scheduled on different seasons of the year. Figure 2 shows the histogram of the number of synoptic patterns found during the four campaign of radiosondes. For the first campaign the AP configuration was more frequent and related to low values of PWV. Large values of PWV were associated to HT, HT/AP and CL configuration. The second campaign, the AP and AP/JS configurations predominated on 15 from total of 20 radiosondes launches. Those configuration showed the lows values of PWV with an average of 0.99 mm (AP/JS) and 0.49 mm (AP). The largest value of PWV were observed during the presence of CL with an average PWV of 4.1 mm. The AP pattern (AP and AP/JS) predominated over the third campaign mainly associated to relatively low values of PWV. The HT-HT/JS and CL-CL/JS were found less times but related to a PWV increase. The frequency of occurrence of synoptic patterns during the fourth campaign, where AW and HT predominated with relatively high values of PWV (1.78 mm and 2.79 mm, respectively).

## 6. CONCLUSIONS

The radiosondes camapigns were successfully conducted on La Silla, APEX and Paranal observatories, obtaining good quality data. In the evaluation of PWV forecasts, the best agreement were obtained during the APEX campaign, showing very small errors. As for the two campaigns develop in Paranal site the best model performance was obtained during winter on the first campaign. The analysis over La Silla and Paranal sites show larger errors than APEX. A possible explanation for this could be that APEX is located at ∼5100 m of altitude, farther away from the coast than the other sites and with a smaller PWV seasonal variation. The comparison of vertical profiles from WRF and radiosondes shows a good agreement at upper levels and the largest errors near the surface in the four campaigns. This could be related to the fact that the three observatories are located over complex terrain. Realted to the synoptic classification, AP was the synoptic pattern that predominated during most of the radiosonde launching times but was associated to a dry atmosphere with low PWV values. AW and HT were less frequent but were associated to periods of PWV increase and maximum PWV values.

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