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A dense GNSS meteorological network for observing deep convection in the Amazon

David K. Adams,[1]* Rui M. S. Fernandes,[2] E. Robert Kursinski,[3] Jair M. Maia,[4] Luiz F. Sapucci,[5]
Luiz A. T. Machado,[5] Icaro Vitorello,[6] João Francisco Galera Monico,[7] Kirk L. Holub,[8] Seth I. Gutman,[8]
Naziano Filizola[9] and Richard A. Bennett[10]

[1] *C.E.S.T.U., Universidade do Estado do Amazonas, Amazonas, Brazil*
[2] *University da Beira Interior, Institute Geophysical D. Luíz, Covilhã, Portugal*
[3] *Department of Atmospheric Sciences, University of Arizona, Tucson, AZ, USA*
[4] *Instituto Nacional de Pesquisas da Amazônia/LBA and Universidade do Estado do Amazonas, Amazonas, Brazil*
[5] *Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, São Paulo, Brazil*
[6] *Divisão de Geofísica Espacial, Instituto Nacional de Pesquisas Espaciais, São Paulo, Brazil*
[7] *Departamento de Cartografia, Universidade Estadual Paulista, São Paulo, Brazil*
[8] *Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO, USA*
[9] *Dept. de Geografia, Universidade Federal do Amazonas, Amazonas, Brazil*
[10] *Department of Geosciences, University of Arizona, Tucson, AZ, USA*

**Correspondence to:
David K. Adams, C.E.S.T.U., Universidade do Estado do Amazonas, 3578 Av. Djalma Batista, Manaus, Amazonas 69050-010, Brazil.
E-mail:
dave.k.adams@gmail.com*

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Abstract

A dense Global Navigation Satellite System (GNSS) meteorological network (∼20 stations) in the central Amazon Basin in Brazil is being developed for long-term studies of deep convection/water vapor interactions and feedback. In this article, the network is described and preliminary results are presented: GNSS-derived precipitable water vapor is useful for tracking water vapor advection and in identifying convective events and water vapor convergence timescales. Upon network completion (early 2011), 3D water vapor field analyses and participation in the intensive field campaign GPM-CHUVA will provide unique data sets for initializing, constraining or validating high-resolution models or refining convective parameterizations. Copyright © 2011 Royal Meteorological Society

Keywords: **precipitable water vapor; cold pools; water vapor tomography; GPS; Brazil**

1. Introduction

A sizeable literature has focused on the complex relationship between water vapor variability and deep convection in the tropics (see Sherwood *et al.*, 2009 for a review). Unlike higher latitudes, rotational dynamical constraints are weak and precipitation-induced heating perturbations are rapidly communicated over great distances (Bretherton and Smolarkiewicz, 1989; Mapes, 1997). Water vapor, on the other hand, is highly variable in space and time; its spatial distribution depending on much slower advective processes above the boundary layer and on deep convection itself. Furthermore, deep convection, through vertical transport of water vapor and evaporation of cloud droplets and hydrometeors, serves as the free tropospheric water vapor source. And deep convection is itself sensitive to the free tropospheric humidity distribution through local moistening of the environment which favors further deep convection; a positive feedback (Tompkins, 2001a, 2001b; Grabowski and Moncrieff, 2004; Holloway and Neelin, 2009).

Water vapor fields also play a role in deep convection through the generation of parcel thermodynamic energy, namely, convective available potential energy (CAPE). CAPE essentially depends on boundary layer moisture, but is also sensitive to parcel level of origin, thermodynamic path, ice phase inclusion and to free tropospheric humidity through virtual temperature effects (Williams and Rennó, 1993; Adams and Souza, 2009). Traditional ‘quasi-equilibrium’ convective parameterizations generally employ CAPE as both a trigger of and closure for deep convection. In continental tropical regions, these parameterizations poorly represent the diurnal cycle, convecting too early and too often, altogether skipping the shallow-to-deep convection transition (Betts and Jakobs, 2002; Grabowski *et al.*, 2006). The timing and quantity of upper-tropospheric heating with these overactive parameterizations are therefore unrealistic and have consequences for model dynamics and cloud/radiation fields (Betts and Jakobs, 2002). Given that free tropospheric humidity is critical in modulating the transition from shallow-to-deep convection (Derbyshire *et al.*, 2004), convective parameterizations should be sensitive to tropospheric humidity through adequately representing entrainment of environmental air (Kuang and Bretherton, 2006).

The formation of cumulonimbus clouds into lines and clusters is even tied to the humidity distribution. Under conditions of weak dynamical forcing, cloud-resolving models have indicated that convective downdrafts/cold pools act prominently during the shallow-to-deep transition and mesoscale organization (Tompkins, 2001b; Khairoutdinov and Randall, 2006). The strength of convective downdrafts and cold pool formation are strongly linked to vertical humidity profiles through entrainment and evaporatively driven negative buoyancy acceleration below cloud base (Tompkins, 2001a, 2001b). Nevertheless, cold pool formation and mesoscale organization, in general, are mostly absent from convective parameterizations [however, refer Grandpeix and Lafore (2010)]. Below synoptic scale, interactions between individual cumulonimbus clouds, organized convective complexes and associated mesoscale circulations can cover several model grid cells, muddying the separation of large-scale forcing (grid-scale) from convective response (subgrid-scale) (Mapes, 1997; Moncrieff, 2004; Moncrieff and Liu, 2006). Most 'quasi-equilibrium' parameterizations, however, retain this arbitrary large-scale/convective-scale separation even though it most likely holds only from the synoptic-scale to the entire deep tropics (Mapes, 1997; Adams and Rennó, 2003).

In the very moist equatorial regions, deep convection can be suppressed by the intrusion of low-to-mid tropospheric dry layers of subtropical origins (Mapes and Zuidema, 1996; Yoneyama and Parsons, 1999). These lower-to-mid tropospheric dry layers can suppress convection through radiatively induced thermal inversions and entrainment of free tropospheric air (Mapes and Zuidema, 1996). The dynamical origins may result from the breaking of extra-tropical Rossby waves leading to potential vorticity anomalies which suppress convection under dry slots (Russell *et al.*, 2008; Allen *et al.*, 2009) Though their origins may be on the synoptic scale, these dry intrusions may have dimensions of a few hundred kilometers, a scale too small to be observed by synoptic-scale soundings (Mapes and Zuidema, 1996).

From the above discussion, and given the present observational capacity in the deep tropics, the complex multi-scale interactions/feedbacks between deep convection/humidity are obviously exceedingly difficult to unravel and to represent in large-scale models. To gain insight into convective/humidity interactions processes at the mesoscale ($\sim$100 km) and below requires observations on the order of minutes and kilometers. Presently, no such mesoscale meteorological network exists in an equatorial continental region. In what follows, we provide motivation for, present preliminary results from and define the specific goals for the embryonic Global Navigation Satellite System (GNSS) meteorological network in the Amazon Basin. Briefly, this network will probe water vapor/convection interactions with emphasis on the shallow-to-deep convection transition and mesoscale organization. We summarize the variables derived from GNSS meteorological techniques, overview the network organization and observational capacity and offer preliminary results pertaining to water vapor transport and identification of convective events. We then conclude by outlining the goals for the network.

2. Amazon dense GNSS network: description

In the Amazon, important, but temporally limited, field campaigns have explored aspects of deep convection such as the diurnal cycle, the morphology of mesoscale complexes and tropical squall line formation and propagation [e.g. WETAMC, TRMM/LBA, Silva Dias *et al.* (2002)]. Long-term, continuous observations/statistics on tropical deep convection are, however, necessary to gain further insight into the water vapor/convection interactions noted in Section 1. With this in mind, we propose the creation of a long-term ($>$1 year), dense meteorological network comprising GNSS receivers and surface meteorological stations around Manaus, in the central Amazon Basin. Before considering the details of the GNSS network, we briefly review GNSS meteorological variables.

2.1. GNSS ground-based meteorology

For well over a decade, GNSS ground-based meteorology has provided all-weather, relatively inexpensive, high frequency (5–30 min), accurate measurements of atmospheric water vapor (for space-based occultation technique, refer Kursinski *et al.*, 2000) Applications of GNSS meteorology are wide ranging; for example assimilation into Numerical Weather Prediction (NWP) models (Gutman and Benjamin, 2001), meteorological case studies (Champollion *et al.*, 2009) and water vapor transport (Kursinski *et al.*, 2008). Precipitable water vapor, PWV, the principal variable,

$$\mathrm{PWV} = \frac{1}{g\ \rho_w} \int_{p_\mathrm{t}}^{p_\mathrm{s}} q \frac{dp}{g} \tag{1}$$

is derived from water-vapor-induced delays in the radio signals from the satellite to the ground-based receiver (refer Bevis *et al.*, 1992). GNSS PWV accuracy is on the order of 1 to 2 mm (Sapucci *et al.*, 2007).

More generally, PWV relates to the water conservation equation per unit area as follows:

$$\frac{\partial \mathrm{PWV}}{\partial t} + \frac{\partial}{\partial t} \int_{p_\mathrm{t}}^{p_\mathrm{s}} q_c \frac{dp}{g} + \nabla \cdot \int_{p_\mathrm{t}}^{p_\mathrm{s}} q\mathrm{V} \frac{dp}{g} = E - P. \tag{2}$$

In both Equations (1) and (2), the variables have their typical meteorological meanings with the subscript s for surface and t for top of the atmosphere and, $\mathbf{V}$ is the horizontal wind vector, ρ_w is liquid water density. Prior to precipitation (ignoring local evaporation, E, and horizontal fluxes of condensed water, q_c), the time-rate-of-change of PWV is determined by column water vapor convergence and cloudy air formation.

The characteristic PWV signal then indicates the column water vapor convergence timescale. Although small, the cloud-water term may be significant on the scale of 5 to 10 km. In principle, with radiosondes and liquid water measurements (see Section 4.2), either the second (total cloud water) or third term (water vapor convergence) could be estimated for an area within the GNSS network.

Clearly, PWV is only an integral measure and lacks the necessary vertical structure to investigate how water vapor profiles modulate deep convective activity. However, with a dense network of GNSS receivers, slant path views in the direction of all orbiting satellites may be estimated to characterize 3D water vapor structure (Braun *et al.* 2001). Dense GNSS networks in concert with additional information and constraints on solutions also lend themselves to water vapor tomography which has successfully described 3D temporal evolution of water vapor fields; for example the diurnal cycle (Bastin *et al.*, 2007) and mesoscale thunderstorm development (Champollion *et al.*, 2009). With more available satellites, the tomographic technique is expected to improve (Bender and Raabe, 2007) and the deep convective regime of the Amazon provides an ideal region developing, testing and refining such 3D techniques.

2.2. The Amazonian dense network

Logistics in the Amazon are extremely difficult and often compete directly with scientific goals. For the Amazon dense network, dealing with a multi-scale phenomenon also adds another layer of complexity. Moreover, the requirements for GNSS observational platforms are stringent; lack of obstruction, isolated from emitting antennas and stable platforms. However, Adams *et al.* (submitted) have shown that accurate PWV values can be captured from a very non-ideal rainforest flux towers allowing the expansion of dense network into very remote forest locations. Furthermore, given the available meteorological resources (see below), scientific personnel present and the continuation of long-term atmospheric science experiments (e.g. INPA/LBA), locating the dense network within the Manaus area more than compensates for any possible logistical difficulties.

The dense network will consist of at least 20 GNSS receivers with coupled meteorological stations. Average distance between receivers will range between 5 and 10 km, covering an area of ~70 km × 70 km (Figure 1). Theoretical calculation and experiments confirmed that, for the deep tropics, a 5-km distance is then the minimum separation distance between stations for distinguishing PWV values. Clearly, this spatial/temporal resolution is not adequate for resolving the most energetic convective boundary layer eddies (~1 km) during the initial stages of transition to deep convection. However, sub-mesoscale variations in thermodynamic variables reflective of important vertical and horizontal gradients in water vapor (e.g. moist static energy) or surface air temperature (e.g. cold pools) can be resolved (see Figure 5, Khairoutdinov and Randall, 2006). Manaus is advantageous in that it enjoys twice-daily radiosondes, an S-band Doppler radar, a hydrometeorological network (http://remethi.org/site/) and GOES 12 satellite data (near nadir, 15-min resolution).

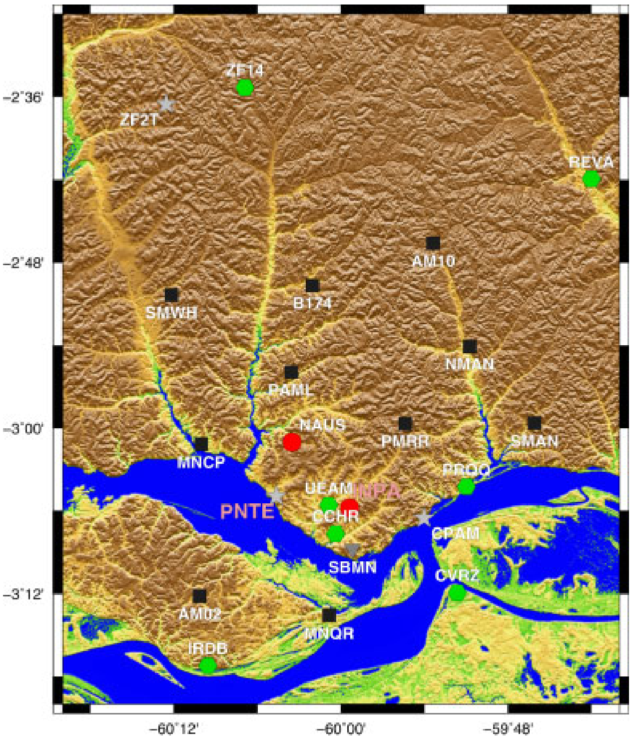

Figure 1. Map of Manaus, Amazonas and surrounding environs, ~70 km × 70 km. The red dots represent permanent GNSS stations; grey stars represent stations tested. Green hexagons represent next stations to be tested and the black squares represent probable locations. The Manaus radiosonde (SBMN) and SIPAM Radar are also shown. PNTE and INPA (Figure 3) are indentified by lavender colour.

3. Preliminary results

Given the embryonic stage, we provide two simple examples of the information on water vapor and convective events that can be extracted from one or two GNSS meteorological stations. The observational capabilities will expand vastly, particularly 3D, once the entire network is in place.

3.1. Column water vapor advection

With two or more GNSS stations, propagating column water vapor can be tracked. The dominant wind vector which advects the bulk of the column water vapor column, the *PWV-weighted wind* (Kursinski *et al.*, 2008) can be calculated as follows:

$$\mathbf{V}_{\mathrm{PWV}} = \frac{1}{\mathrm{PWV}\rho_w}\int_{p_t}^{p_s} q\mathbf{V}\frac{dp}{g} \qquad (3)$$

where PWV is defined by Equation (1) and ρ_w is liquid water density. From the 12Z sounding (decimal day 57.5), the PWV-weighted wind vector, $\mathbf{V}_{\text{PWV}}$, is East–Northeast with magnitude $|\mathbf{V}_{\text{PWV}}| \approx 3\ \text{ms}^{-1}$. An approximately 45-min delay between INPA and PNTE PWV is found near decimal day 57.55. Assuming the 12Z radiosonde wind and vapor profiles are representative, a PWV-advection distance of 8 km results. The actual distance of 11 km would suggest that advection is the dominant process water vapor transport between the two stations, with perhaps local convergence also contributing.

3.2. Deep convection and the PWV signal

To identify a 'typical' deep convective event signal in PWV, 37 precipitation events were examined for the dry and dry-to-wet transition season from July to December 2008. To select only deep convective events, several criteria were employed; a minimum cloud top temperature (CTT) of 230 K, and averaged $\frac{\partial \text{CTT}}{\partial t}$, the presence of convective downdrafts and precipitation. Amazonian convective activity is complex – the different types of convective events include squall lines, mesoscale complexes and 'simple' diurnally forced convective activity (Machado *et al.*, 2002; Silva Dias *et al.*, 2002). These selected convective events reflect this complexity. Fourteen events occurred during the afternoon; however, 15 occurred between 0500 and 0900 UTC entirely out of phase with diurnal heating. Early morning convective storms are perhaps related to the passage of long-lived, propagating squall lines (Silva Dias *et al.*, 2002) or other mesoscale convective complexes.

For simplicity, we focused on the 14 diurnally forced deep convective events where obvious large-scale forcing is not present (e.g. no strong wind shear). Figure 3 shows the PWV signal for one representative afternoon deep convective event. Its deep convective nature is confirmed by the rapid decrease in CTT, concomitant fall in surface temperature (~7 °C) and spike in wind speed. This clearly indicates the cold air outflow associated convective-scale downdrafts.

For these events, PWV convergence 'ramp-up' times are around 5 h for diurnally forced convective activity. The ramp-up time was calculated as the slope between the initial increase and decrease in PWV (values at upper/lower triangles in Figure 3) coincident with the precipitous drop in CTT. A cursory examination of wet-season convective events (January–April), convergence times appear shorter, somewhat greater than 2 h (Figure 2). High wet-season PWV (>60 mm), deep convection apparently require little water vapor convergence which is consistent with recent work that argues for a critical PWV value above which precipitation rises sharply (Holloway and Neelin, 2010). It should be considered that this analysis with one/two receivers is essentially a 'proof of concept'. The advantage of employing 20 or more GNSS meteorological stations is that when used in concert with existing observational systems, it will enable effective categorization of convective events, their intensity, their thermodynamic environment, and cold pool formation with respect to temporally and spatially evolving water vapor fields.

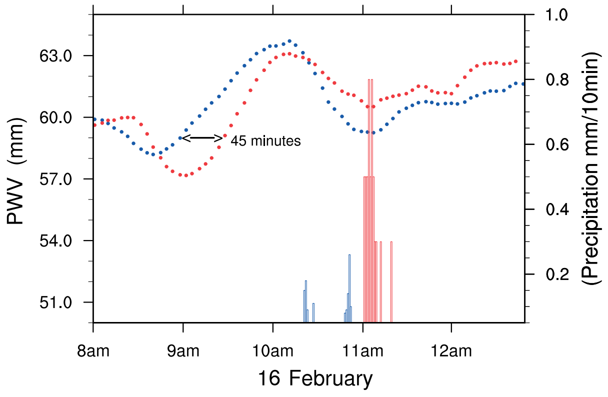

Figure 2. Propagation of convective event as seen in GNSS PWV at INPA (blue) and PNTE (red) (separation distance ~1 km). PWV values are represented by coloured dots and precipitation rate by coloured bars. Station names follow typical GNSS naming convections (usually using local toponymy).

4. The dense network: aims and campaigns

As noted in Section 1, observational studies are necessary to unravel the complex water vapor convection interactions, particularly with respect to convective organization and 'thermodynamic control' of convection through the vertical structure of water vapor. And this provides the overarching framework for dense network. More specifically, we summarize below the three principal aims of the network.

4.1. Convection climatology

The dense network, unlike previous campaigns, is intended to develop long-term observations, a 'convection climatology', of the shallow-to-deep convection transition, mesoscale organization and the interaction with water vapor fields. In particular, we will examine the following:

1. The structure and spatial/temporal scales of cold pools in convective transition and organization
2. The vertical humidity structure in the suppression, enhancement/intensification and organization of deep convection

Convective downdrafts will be identified via surface stations (Figure 3), while PWV fields, radar and GOES 12 data will specify water vapor convergence/advection, the growth, organization and propagation of cumulonimbus lines/clusters. Tomographic analysis, constrained vertically by soundings, radio

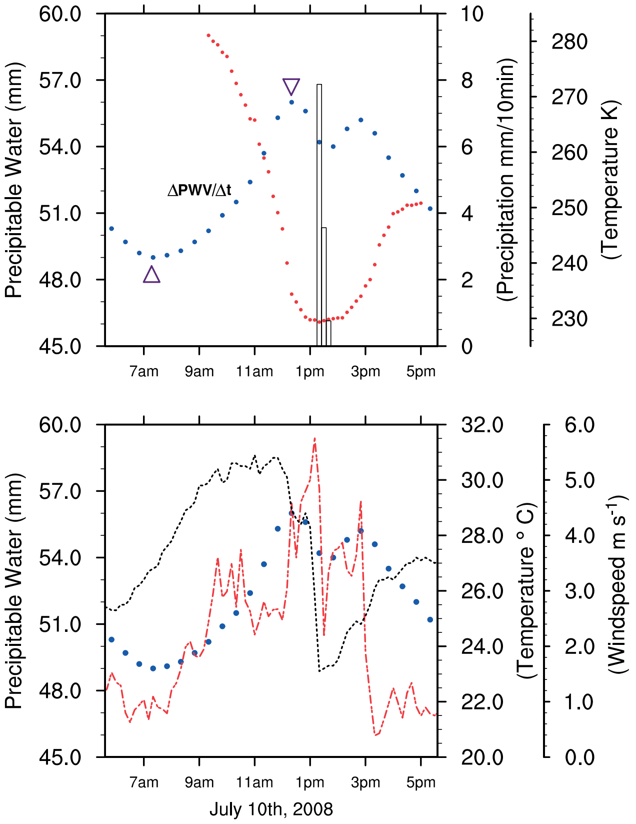

Figure 3. A typical afternoon deep convective event over INPA GNSS/meteorological station. The upper plot contains PWV (blue dots) *versus* average cloud top temperature (red) and precipitation rate (bars). The 'ramp-up' time calculated for the average $\Delta PWV/\Delta t$ (between triangles) represents the timescale of column convergence (see Equation (2) and text for discussion). The bottom graph plots wind speed (red), temperature (black) and PWV(blue) for the deep convective event.

occultations and satellite sounders, will characterize 3D water vapor evolution.

4.2. Campaigns: GPM-CHUVA

The GPM-CHUVA (http://gpmchuva.cptec.inpe.br/) campaign coincides with the dense network (2012) providing a plethora of additional instruments including: dual polarization, Doppler radar, radiometers, lidar, soundings and aircraft. The field campaign in Manaus will focus principally on studying cloud liquid water/ice content and precipitation for warm and deep convective clouds in the central Amazon Basin. This provides an unprecedented opportunity to research:

1. The atmospheric hydrological cycle with high temporal resolution PWV, water vapor profiles, cloud liquid water and precipitation
2. Water vapor convergence and convective intensity through PWV, multiple simultaneous radiosondes, radiometers, satellite imagery and radars

4.3. Assimilation/modeling

Assimilation of GNSS data is advancing in NWP models at the CPTEC-INPE (Brazil) and will benefit greatly from the dense network as conventional humidity measurements are lacking. The high temporal resolution means PWV values will be available for all assimilation cycles. Previous experiments in CPTEC-INPE using PWV from the AQUA satellite show that PWV assimilation corrects the humidity overestimation in the Amazon region and positively impact precipitation forecasts (Sapucci *et al.*, submitted). Furthermore, the dense network will contribute useful water vapor field data particularly for initializing, constraining or validating high-resolution regional down to cloud-resolving models. With GPM-CHUVA, a potentially rich data set could be used for model intercomparison studies similar to the LBA data set (Grabowski *et al.*, 2006). Moreover, long-term observations under a variety of meteorological conditions will lend themselves to refining convective parameterization particularly those including cold pool generation and upscale organization.

5. Concluding remarks

The development of this unique equatorial tropical network will proceed over the next 6 months, yielding a functional network by 2011. The minimum lifetime (1 year) should further the understanding of the complex convection/water vapor relationship. GNSS dense networks are relatively inexpensive, dependable observational tools; and we offer this work to motivate the creation of other dense tropical networks for point of comparison as well as to encourage input from the atmospheric sciences community for this present effort.

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