The DOI for this manuscript is doi: 10.1175/BAMS-D-13-00171.1

The final published version of this manuscript will replace the preliminary version at the above DOI once it is available.

If you would like to cite this EOR in a separate work, please use the following full citation:

Adams, D., R. Fernandes, K. Holub, S. Gutman, H. Barbosa, L. Machado, A. Calheiros, R. Bennett, R. Kursinski, L. Sapucci, C. DeMets, G. Chagas, A. Arellano, N. Filizola, A. Amorim, R. Araujo, L. Assuncao, G. Cirino, T. Pauliquevis, B. Portela, A. Sa, J. Sousa, and L. Tanaka, 2015: The Amazon Dense GNSS Meteorological Network: A New Approach for Examining Water Vapor and Deep Convection Interactions in the Tropics. Bull. Amer. Meteor. Soc. doi:10.1175/BAMS-D-13-00171.1, in press.

The Amazon Dense GNSS Meteorological Network: A New Approach for Examining Water Vapor and Deep Convection Interactions in the Tropics

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ABSTRACT

The complex interactions between water vapor fields and deep atmospheric convection remain one of the outstanding problems in Tropical Meteorology. The lack of high spatial/temporal resolution, all-weather observations in the Tropics has hampered progress. Numerical models have difficulties, for example, in representing the shallow-to-deep convective transition and the diurnal cycle of precipitation. GNSS (Global Navigation Satellite System) meteorology, which provides all-weather, high frequency (5 minutes), precipitable water vapor estimates, can help. The Amazon Dense GNSS Meteorological Network experiment, the first of its kind ever in the Tropics, was created with the aim of examining water vapor and deep convection relationships at the mesoscale. This innovative, Brazilian-led international experiment consisted of two mesoscale (100km x 100km) networks: (1) a one-year (April 2011 to April 2012) campaign (20 GNSS meteorological sites) in and around Manaus, and (2) a 6 week (June 2011) intensive campaign (15 GNSS meteorological sites) in and around Belem, this latter in collaboration with the CHUVA Project in Brazil. Results presented here from both networks focus on the diurnal cycle of precipitable water vapor associated with sea breeze convection in Belem and seasonal and topographic influences in and around Manaus. Ultimately, these unique observations may serve to initialize, constrain, or validate precipitable water vapor in high resolution models. These experiments also demonstrate that GNSS meteorology can expand into logistically difficult regions such as the Amazon. Other GNSS meteorology networks presently being constructed in the Tropics are summarized.

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1. Capsule

The Amazon Dense GNSS Meteorological Network provides high spatial/temporal resolution, all-weather precipitable water vapor for studying the evolution of continental tropical and sea-breeze convective regimes of Amazonia.

2. Introduction

The meteorology and climate of the equatorial Tropics are dominated by atmospheric convection, which presents a rather challenging range of spatial and temporal scales to capture with present-day observational platforms (Mapes and Neale 2011; Moncrieff et al. 2012; Zhang et al. 2013). Over a period of a few hours, shallow convection (order 1-10km in horizontal scale) can transition to deep precipitating convection (order 10-100km) and then organize into mesoscale convective systems (order 100-1000km) with lifetimes ranging from several hours to greater than one day. Furthermore, complex feedbacks exist between atmospheric convection and the thermodynamic environment, particularly water vapor fields, in which convection develops (see Sherwood et al. (2009) for a review of convection and water vapor interactions).

Understanding and modeling tropical convection have been hampered by the dearth of long-term observations resolving the mesoscale. For example, large-scale models where convection is parameterized have poorly represented the diurnal cycle of convective precipitation, particularly over land, possibly resulting in the degradation of model clouds, radiation fields and large-scale dynamics (Betts and Jakob 2002a,b; Bechtold et al. 2004). While single column models and high resolution models (cloud resolving to large eddy simulations) are a useful tool (Betts and Jakob 2002b; Grabowski and Moncrieff 2004; Grabowski et al. 2006), they are not a substitute for observations. Many efforts have focused on what controls the shallow-to-deep convection transition, a process often missing in coarse models with separate shallow and deep convection schemes (Betts and Jakob 2002b,a; Grabowski et al. 2006;

Kuang and Bretherton 2006; Khairoutdinov and Randall 2006; Waite and Khouider 2010; Wu et al. 2009; Hohenegger and Stevens 2013). Mechanisms to explain the shallow-to-deep transition include: cold pool formation (Kuang and Bretherton 2006; Khairoutdinov and Randall 2006; Schlemmer and Hohenegger 2014), cumulus congestus moistening of the free troposphere (Waite and Khouider 2010), increasing cloud buoyancy (Wu et al. 2009), and dynamically forced, large-scale vertical motions and attendant water vapor convergence (Hohenegger and Stevens 2013). Whatever the mix of these model-elucidated physical mechanisms, even high resolution models must somehow be evaluated with real-world observations which, unfortunately, are sorely lacking in the Tropics at the necessary temporal/spatial scale.

Geostationary satellites are the backbone of observational studies of the evolution and life cycle of tropical convection (Sherwood and Warhlich 1999; Masunaga 2013). Visible and IR cloud imagery can document the evolution of cumulus fields at high spatial resolution and adequate temporal resolution (15 to 30 minutes). However, water vapor is more challenging to measure from space. IR radiometers for measuring column water vapor are limited to clear-sky conditions while microwave observations, although all-weather, are unreliable over land and sporadic over water. Long-term, surface-based, mesoscale meteorological networks thus have a unique role to play. Unfortunately, only brief field campaigns in the continental Tropics, such as the Amazon, have been carried out due to logistical difficulties (e.g., ABLE 2B, Garstang et al. (1990), TRMM/LBA, Silva-Dias et al. (2002); Betts et al. (2009) and currently GOAmazon). Global Navigational Satellite System (GNSS) meteorology ("GPS", Global Positioning System being the most commonly used) can help in this regard.

For two decades, GNSS/GPS meteorology has offered relatively inexpensive, high frequency ($\sim$5 minutes), *all-weather*, "precipitable" or column integrated water vapor (PWV) values within 1 to 2 mm accuracy compared to radiosondes and radiometers (Bevis et al. 1992; Rocken et al. 1993; Duan et al. 1996; Wolfe and Gutman 2000; Sapucci et al. 2007). A related space-based technique, GPS radio occultation provides water vapor profiles, but is too infrequent to capture water vapor field evolution at a given location, see (Kursinski et al. (2000)). Estimation of the effects of cloud liquid/ice water, precipitation and atmospheric aerosols/dust on GNSS signals can be found in (Solheim et al. 1999). For process-oriented, mesoscale studies of water vapor/convection interactions, a network of sites is needed. The GNSS cone of observation has an approximately 10km radius, covering the spatial and temporal scale at which the shallow-to-deep transition occurs and upscale convective organization begins (Moncrieff et al. 2012). With GNSS meteorology arranged in a network, mesoscale convective organization and associated water vapor fields can be documented. Surprisingly, after two decades, most GNSS studies have focused on the technique itself, validating radiosondes, radiometers or satellite platforms, or as ancillary data for large-scale studies or numerical weather data assimilation/prediction. Mesoscale, process-oriented GNSS studies are few, and even less so for the deep Tropics.

The Amazon Dense GNSS Meteorological Network (ADGMN) was created to address these issues of water vapor/convection interactions. In this brief overview of the ADGMN, we encapsulate the motivations and goals (Section 3) as well as the experimental design (Section 4) for both the Belem and Manaus networks. An example of the diurnal cycle of sea-breeze convection for Belem and ideas for future work for this network are presented in Section 5. Results from the Manaus network (Section 6) also describe the diurnal cycle with respect to topographic effects and the seasonal evolution given that the data set spans one year. Prospects for expanding large-scale GNSS networks in the Tropics, specifically in the Caribbean and Mexico, are then surveyed. A secondary goal is to demonstrate that GNSS meteorology is viable even in regions fraught with logistical difficulties such as the Amazon.

3. The ADGMN: Motivations and Aims

Dense GNSS meteorological networks are not new in Europe (Champollion et al. 2005; Bastin et al. 2007; Brenot et al. 2013), Japan (Seko et al. 2004) nor the US (Champollion et al. 2009); neither are GNSS studies of deep convection (Mazany et al. 2002; Kursinski et al. 2008; Brenot et al. 2013). However, the deep tropics offer new challenges as well as unique weather situations to explore. Establishing any type of meteorological network in the Amazon is a challenging logistical task as suitable sites are few and far between. Fortunately, the GNSS site infrastructure for deriving GNSS PWV is not nearly as demanding as for geodetic or plate tectonics studies. Highly non-ideal platforms such as flux towers (Adams et al. 2011a) or even moving oceanic vessels (Rocken et al. 2005; Kealy et al. 2012) can be utilized (see Sidebar).

The overarching motivation for the creation of the ADGMN was to address convection-humidity interactions, a major scientific challenge (Derbyshire et al. 2004; Kuang and Bretherton 2006; Waite and Khouider 2010; Hohenegger and Stevens 2013). Convective parameterizations are too insensitive to tropospheric humidity due to inadequate representation of entrainment of environmental air into convective updrafts (Kuang and Bretherton 2006; Genio 2012). Entrainment in clouds remains a vital research question (Romps and Kuang 2010; Yeo and Romps 2013; Sherwood et al. 2013), and is a leading source of climate model uncertainty (Rougier et al. 2009). Furthermore, upscale growth and convective organization, also poorly represented with parameterized convection, are strongly linked to convective downdrafts/cold pools which, in turn, are sensitive to the vertical humidity structure (Tompkins 2001a,b). A few convective parameterizations are beginning to address these effects (Rio et al. 2009; Mapes et al. 2009; Park 2014). Although neither entrainment nor the vertical humidity structure (however, see Section 6a) can be directly captured with GNSS dense meteorological networks, they can provide target relationships modified parameterization schemes must be able to replicate.

Diagnostic studies are needed to turn raw data into such model target results and suggest which physical processes are dominant (e.g., surface latent heat fluxes, horizontal advection, water vapor convergence, etc.) in the evolution of water vapor fields at these newly seen spatial and temporal resolutions. Adams et al. (2013) inferred using GNSS PWV from a single station, a 4-hour water vapor convergence timescale indicative of the shallow-to-deep transition for the equatorial continental Tropics. With dense mesoscale networks, cross-correlations and other techniques will be able to identify the spatial/temporal scales of variability in PWV fields, putting mechanistic deductions on a firmer basis. Furthermore, PWV, in itself, is actually a much more valuable quantity than its integral nature might suggest (Holloway and Neelin 2009; Lintner et al. 2011). Empirical PWV/precipitation relationships are surprisingly strong (Zeng 1999; Bretherton et al. 2004) and theoretical views of tropical convection such as "self-organized criticality" (Neelin et al. 2009; Peters et al. 2009) or that of large-scale "thermodynamic control" (Raymond 2000) depend critically on PWV. These types of studies, all over oceanic regions, could be greatly expanded with GNSS meteorology and data over land may provide unique tests of such theories.

4. Experimental Design, Instrumentation and Data

The ADGMN consisted of two experiments: a 6-week campaign in and around Belem, which coincided with the CHUVA Belem campaign (Machado et al. 2014), and a one-year campaign in and around Manaus. As originally proposed (Adams et al. 2011b), the ADGMN was intended to coincide in Manaus with the CHUVA campaign in 2012. However, with the confirmation of the U.S. Department of Energy GOAmazon (Green Ocean Amazon) Campaign (see http://campaign.arm.gov/goamazon2014/), an elaborate experiment for examining atmospheric chemistry, aerosols, cloud microphysics and convective precipitation in a tropical continental setting, CHUVA Manaus was postponed until 2014 when more instrumentation was deployed. Nevertheless, constructing one phase of the ADGMN in Belem was fortuitous in that it was a successful demonstration of a dense GNSS meteorological network in a distinctive tropical convective regime driven by the sea breeze.

a. The Belem Dense Network

Convective development in the tropical sea-breeze regime has been studied in theoretical, modeling work and observationally in a wide variety of locales around the globe (Moncrieff and Liu 1999; Carbone et al. 2000; Mapes et al. 2003; Fovell 2005; Robinson et al. 2013). The sea breeze, driven by differential land/sea heating, orchestrates the timing and location of convective cell initiation (Moncrieff and Liu 1999; Fovell 2005; Robinson et al. 2013). However, once the convective cells begin to precipitate, cold pool/gust fronts and the environmental thermodynamical/shear conditions then determine whether upscale growth into propagating squall lines or mesoscale convective systems occur (Moncrieff and Liu 1999; Carbone et al. 2000). The Belem coastal region, unlike many previous tropical sea-breeze studies, such as Florida (Ulanski and Garstang 1978), is the coast of an enormous continental region. The Belem area has two particularities: the striking punctuality [1] of the late afternoon convective activity (Kousky 1980; Angelis et al. 2004), and acting as the initiation point of spectacular, long-lived squall lines up to 2000 km in length penetrating, and even crossing, the Amazon Basin (Greco et al. 1990; Garstang et al. 1994; Cohen et al. 1995; Alcântara et al. 2011).

The Belem Dense GNSS Meteorological Network was initiated May 25th and dismantled July 7th. The network was composed of 15 GNSS/meteorological stations which provided high frequency (5 minutes) PWV as well as surface meteorological variables (Figure 1). Two nearly perpendicular transects were constructed: (1) southeast to northwest along the dominant lower-to-mid tropospheric east-southeasterly winds (BSMG-BSPC-BMSQ-BSOR ~150km) and, (2) southwest to northeast, essentially perpendicular to the Atlantic coastline (BABT-BSSG ~100km). A cluster of stations, centered in Belem with approximately 10km separation distance were collocated with the CHUVA instrumentation array, described next.

The CHUVA project consisted of 6 field campaigns in different convective regimes in

[1] A common expression in Belem is "A gente se encontra antes ou depois da chuva?" (Should we meet before or after the rain?)

Brazil; including the sea-breeze regime of Belem and the continental tropical rainforest regime of Manaus. CHUVA was motivated by the need to better observe cloud microphysics in both warm and cold clouds and their associated precipitation processes in the Tropics (Calheiros and Machado 2014). The CHUVA Belem campaign included a suite of instrumentation for documenting environmental thermodynamic conditions and cloud evolution and microphysics. Three radiosonde sites supplied thermodynamic stability variables, water vapor and wind profiles. A microwave radiometer furnished high frequency vertical water vapor structure and cloud liquid water profiles. An X-band dual polarization radar (X-Pol) was utilized to capture the development of convective clouds. Surface meteorological stations and disdrometers characterized rainfall intensity and hydrometeors, respectively. Twice-daily (8am and 8pm LT) radiosondes were launched (SBBE 82193, Belem Airport, near station BEMA) through the duration of the experiment. In addition, a 7-day intensive observational period included 4 extra launches per day (00:00, 06:00,12:00 and 18:00 UTC) in a triangular arrangement with approximately 120 km separation distance between SBBE, São Miguel (BSMG) and further to the south at Tomé Açu (2.4167° S, 48.1500° W), (not seen in Figure 1). Details can be found in (Machado et al. 2014) and at http://chuvaproject.cptec.inpe.br.

b. The Manaus Dense GNSS Meteorological Network

The area around Manaus (2.61° S, 60.21° W) (see Figure 2), in the central Amazon, in many respects is the quintessential continental tropical regime. Rainfall totals are large ($\sim 2500 mm yr^{-1}$) and distributed throughout the year, but with a notable dry season from July through September and the most frequent precipitation from January through April (Machado et al. 2004). Topographic variation across the network, from Amazon River stations to forest stations is greater than Belem, but small nonetheless ($\sim$ 150m). It has been noted that these weak topographic gradients can induce local circulations with impacts on the precipitation distribution (Fitzjarrald et al. 2008; Betts et al. 2009). Typical of continental tropical regimes, there is a strong afternoon peak in convective rainfall; however, nocturnal events are not infrequent and travelling squall lines can arrive in or out of phase with diurnal surface heating (Greco et al. 1990; Angelis et al. 2004; Adams et al. 2013).

The Manaus network commenced in April 2011 with 12 GNSS meteorological stations. With the termination of the Belem campaign, the Manaus network expanded to 22 stations for the last 9 months (August 2011 to April 2012). Although the profiling instrumentation of CHUVA was not available, twice-daily radiosondes were launched from SBMN (see Figure 2). In addition, the station at Embrapa (EMBP, green, north of Manaus), included a UV Raman Lidar (beginning September 2011) for frequent $\sim$ 5 minute nighttime water vapor profiles, as well as disdrometer and additional surface meteorological equipment. The station distribution can be categorized as low-lying river sites (CMP1, CHR5, CTLO, EMIR, HORT, MNCP, MNQI, PDAQ, TMB7), interior stations (CDN2, CDN4, GOAM, INPA, IRAN, JPL6, NAUS, PNT8) and forest-transition stations (EMBP, RDCK, RPDE, TRM3). Site ZF29 (blue, northern-most site), a rainforest GNSS site, was rather unconventional being located atop a 55m flux tower (K34) (see Figure 5) of the *Large Scale Biosphere/Atmosphere Experiment in Amazonia* (LBA), thereby offering an unprecedented look at rainforest PWV (Adams et al. 2011a). Although the network's primary goal was to study the mesoscale evolution of convection, indirect measures of local circulations (e.g., between the Amazon River and surrounding forest) and their intensity can also be gauged. Furthermore, the network's one-year duration means that the dry, wet and transition seasons were observed and seasonal effects on convective organization and PWV fields are available for analysis.

5. Belem Results: The Diurnal Cycle of Sea-breeze Convection

For the 6 week duration of the Belem experiment, days were categorized as "convective" (22 days) or "non-convective" (19 days), based solely on a minimum cloud top temperature of 240K or below over the central portion of the network and a report of precipitation at at least one site during the afternoon or evening. Composites of the temporal evolution of PWV and cloud top temperature are shown in Figure 3. To gauge the environmental conditions in which convection developed (or not), average thermodynamic stability (CAPE and CIN), water vapor profiles and wind shear magnitude were calculated. The Belem network lacks any significant variations in topography along the coast and bay and boundary layer thermodynamics are also quite uniform. During the intensive observational period, the standard deviation of mixing ratio and temperature averaged over the lowest 50hPa in all soundings from all 3 sites and all launch times, were $1.1gkg^{-1}$ and $1.0°C$, respectively. The reasons for convective development on any given day are quite subtle.

The composites of GNSS PWV and cloud top temperature for 3 stations (BSSG, BBNV and BABT), aligned SW/NE almost perpendicularly to the broadscale coastline and advancing sea-breeze lines, are shown in Figure 3. Morning values of PWV and cloud top temperature are similar for convective and non-convective days, but differences begin to appear about 10am. $\frac{\Delta PWV}{\Delta t}$, mostly a measure of water vapor convergence (Adams et al. 2013), was estimated between the upward and downward pointing triangles for each site in Figure 3. The propagation speed of the convective perturbation between BSSG/BBNV and BBNV/BABT was calculated by dividing between-station distance by the time difference between maximum PWV at each site (upward pointing triangles). These two propagation speeds were then averaged. $\frac{\Delta PWV}{\Delta t}$ is more than 50% greater for convective days and the convective propagation speed is nearly twice as large (see Table 1).

What promotes or inhibits the development and propagation of convection in Belem's sea-breeze regime? In addition to propagation speed and water vapor convergence, environmental conditions, including moist stability as measured by CAPE/CIN, the windshear magnitude between the steering level and near-surface layer (Carbone et al. (2000)) and water vapor, both near surface and from 850 to 500hPa were calculated from the 8am LT soundings (Table 1). The vertical water vapor distribution and wind shear magnitude (and direction, not shown) are essentially the same for both convective and non-convective days. However, morning CAPE is twice as large on convective days. Nevertheless, a $1gkg^{-1}$ and $1°C$ increase in surface mixing ratio and temperature; that is, the observed standard deviations, would increase CAPE by more than $1000Jkg^{-1}$, larger than the convective-nonconvective difference of $500Jkg^{-1}$. Although the number of cases is small, it would be difficult to argue that deep convection or its suppression are solely functions of environmental instability, wind-shear and water vapor structure.

Convective growth or suppression appears to be closely tied to the morning formation of convective lines within 30km or so of the coast (presumably along the sea-breeze front). Time loops of GOES 12 IR imagery over a much larger region than the Belem network support this contention. Figure 3 shows the average cloud top temperature at 12:30pm local time for convective and non-convective days. Convective days begin with the formation, by 10am, of near coastal cumulus cells. By noon, cumulus congestus develop above the freezing level, begin to coalesce and commence propagating inland. In contrast, for non-convective days, cumulus cells develop later in the morning, remain closer to the coast and only weakly coalesce, quickly dissipating before propagating further inland (See Supplemental Material (Caption: Animations of 15 minutes GOES 12 IR imagery over the northern Brazilian coast near Belem for Convective days (Left) and Non-convective days (right))). These impressions suggest a prominent role for gust fronts and cold pools and secondary development in the organization and propagation of these convective lines. What promotes the initial convective formation along the coast in the first place? Subtle changes in interactions between the sea-breeze front and synoptic-scale flow patterns may be at play, similar to seasonal variability in large-scale flow over the region (Kousky 1980).

a. Future Belem Network Studies

Given the soundings, surface meteorological and cloud microphysical data gathered by CHUVA and the ADGMN, the role of advancing cold pools/gust fronts forcing convection can be surmised in future work. Our portrait of the evolution of Belem sea-breeze convection presented in the previous section, although a bit speculative, is entirely consistent with a quiescent large-scale, but mildly thermodynamically unstable, environment where premoistening of the free troposphere to support deep convection is not required. Here, propagating cold pools provide the necessary kick for releasing convective instability leading to cloud growth and precipitation and further propagation. With the existing dense network and CHUVA data set, dynamic lifting provided by cold pools/gust fronts can be examined directly through cloud spatial/temporal evolution (X-pol radar) and visible and IR cloud fields (GOES 12 satellite). Surface meteorological stations will provide temperature drops and wind gusts for cold pool/gust front identification and, finally, GNSS stations will furnish $\frac{\Delta PWV}{\Delta t}$ at each station along the convective line trajectory. Adams et al. (2013) hypothesized, during the transition to deep convection and prior to heavy precipitation, cloud condensate formation and advection and surface evaporation are secondary in the total column water conservation budget. These ideas can be put to the test with the Belem data set. Furthermore, given the homogeneity in Belem low-level water vapor fields, horizontal advection is weak, and thus GNSS $\frac{d(PWV)}{dt}$ represents vertical water vapor advection, providing a window into vertical motion, which is very difficult to measure directly.

6. Manaus Results: Seasonal and Topographic Effects on the Diurnal Cycle

In light of the longer-term deployment of stations in and around Manaus, studies involving the seasonal influences on convection and topographically forced mesoscale circulation can also be addressed. Local topography and vegetated surfaces, perturbed and unperturbed, can induce mesoscale circulations along the Amazon River which influence cloud and precipitation distributions (Silva-Dias et al. 2004; Fitzjarrald et al. 2008). Local circulations driven by anthropogenic deforestation have especially received attention (Wang et al. 2009; Saad et al. 2010). Local mesoscale breezes can enhance cloud formation over vegetated zones, while suppressing it over the river due to subsidence. Enhanced cloud formation should be associated with increases in precipitation for typical diurnal cycle convection, all else being equal. Fitzjarrald et al. (2008) found that near-river sites do receive less afternoon rainfall as expected, but their nocturnal rainfall can be enhanced due to interactions with squall lines and local river geometry.

From the year of Manaus network data, Figure 4 presents the PWV diurnal cycle as a function of location and season. The diurnal cycle of PWV was calculated at an interior, forest and two river sites for the dry, dry-to-wet transition and wet season, the results of which can be seen in Figure 4. Based solely on the forest/river contrast, which is difficult to separate from the topographical effect, it is apparent that the forested site ZF29 experiences a more robust diurnal cycle, particularly when compared with CHR5, a river site. The seasonal effect on the PWV diurnal cycle is principally that water vapor convergence is earlier in the day (true for all sites) and generally less intense during the wet season. The dry season and dry-to-wet transition seasons have larger amplitude diurnal rises for both the interior site, JPL6, and ZF29. This is not true, however, for CHR5 where the dry season diurnal cycle is strongly muted. The behavior of all of the river sites is not consistent and appears to be strongly influenced by their very local setting with respect to the dominant lower tropospheric easterly winds and the Manaus "peninsula" (See Figure 2). For comparison purposes, an "upwind" river site (HORT) is also included in Figure 4. The diurnal cycle at HORT is much more pronounced than CHR5, mimicking other interior stations. The other river stations on the "downwind" side of the Manaus peninsula (CMP1, TMB7) share this seasonal behavior with CHR5. Recalling that $\frac{\Delta PWV}{\Delta t}$ is a glimpse of vertical motion, these results offer strong evidence that local topographic effects do indeed induce mesoscale circulations. How these local convergence patterns affect the development of convection still remains to be investigated. But, these results indicate that GNSS meteorology may also be an incisive test for model-generated mesoscale circulations, even for non-convective conditions.

a. *Future Work: Manaus*

The Manaus network lends itself to the study of cumulus congestus cold pools and their role in the shallow-to-deep transition to deep precipitating cumulonimbus cells and their organization on the mesoscale. Numerical modeling work by Khairoutdinov and Randall (2006), based on Amazonian-inspired boundary conditions, identifies the space and time scales that are associated with congestus cold pool formation, convergence and the shallow-to-deep transition. The density of stations in the central portion of the network is more than adequate to capture cold pool formation. Cold pools and convective downdrafts can be identified via surface stations, while PWV fields will indicate water vapor convergence/advection. Meanwhile, GOES 12 visible and IR document the growth, organization and propagation of cumulus into cumulonimbus lines/clusters. The frequent convective events over the Manaus network should furnish sufficient cases to ascertain the role of cold pools in the shallow-to-deep convective transition.

One exciting prospect is that with a dense network of GNSS receivers, 3D water vapor structure may be possible to retrieve (Braun et al. 2001; Bastin et al. 2007; Champollion et al. 2009). Tropospheric tomography divides the earth's atmosphere into small volume elements or "voxels" and uses the slant delays (between the satellite and the receiver) to estimate the refractivity in each voxel and, hence, a vertical profile of refractivity. This refractivity can be transformed through algebraic iterative techniques into 3D water vapor estimates (Bender et al. 2011). This tomographic software is currently being developed at the Departamento de Informática, Universidade da Beira Interior, Covilhã, Portugal. The ADGMN, both Belem and Manaus, are ideal for developing such 3D estimates given the available soundings for constraining and validating the technique.

7. GNSS Networks in the Tropics

Though mesoscale meteorological GNSS networks are absent in the Tropics, larger scale networks have been (Bock et al. 2008) and are presently being constructed. The COCOnet project (Braun et al. 2012) is constructing 139 GNSS meteorology sites for studying Caribbean climate and meteorology and tectonic activity in the region. These permanent real-time PWV stations (101 of which are currently online), scattered across the Caribbean, can serve as anchor sites for the development of both long-term and campaign mesoscale dense networks to study convection and water vapor fields in the tropical tradewind regime. Another promising development in the Tropics was the joint U.S./Mexico *North American Monsoon GNSS Transect Experiment 2013*, a mesoscale meteorological transect across the complex terrain of the Sierra Madre Occidental in northwest Mexico (Adams et al. 2014). Across the rest of Mexico, TlalocNet (http://www.unavco.org/projects/major-projects/tlalocnet/tlalocnet.html) aims to develop a large-scale geodetic and atmospheric infrastructure for geoscience studies. 18 new real-time GNSS meteorology sites, including a permanent extension of the *North American Monsoon GNSS Transect Experiment 2013* are being installed. Dense Networks anchored to these Mexican and Caribbean sites would offer a wide variety of topographic settings and meteorological regimes to complement sea-breeze and continental tropical data from Brazil described above.

Since unstable oceanic platforms can even be employed, the expansion of GNSS meteorology into viable tropical oceanic regions should be promoted over ocean, local surface evaporation is a small contributor to PWV and well-measured, strengthening the interpretation of dPWV/dt as representative of vertical motion (Yasunaga et al. 2008). Finally, for the long term, the precision of GNSS-derived PWV will increase as more satellites come online in addition to GPS (e.g. GLONASS, Galileo and Beidou), increasing the value of this stable platform for observing global climate variability.

a. Sidebar: GNSS Meteorology in Logistically Difficult Sites

As noted, the spread of GNSS meteorology into logistically difficult regions such as the Amazon requires compromises when it comes to GNSS installations. Geodetic requirements for antenna permanence, such as rigid monumentation, full-sky visibility, and absence of obstructions can be relaxed for GNSS meteorological applications without serious deterioration of the data collected. Even in the extreme case of installing a GNSS antenna on scaffolding above the forest canopy, useful data can still be collected if the motions of the scaffold were constrained to minimize vertical displacements of the antenna phase center over time. Relaxing these requirements also reduces the financial burden on the campaign, since local/indigenous resources can be exploited to accomplish the experimental objectives. For the Amazon Dense Network campaign sites, perfectly valid PWV values were captured from a 55 meter INPA/LBA Flux tower (ZF29), a chicken coop (HORT), housing on stilts "palafitas" suffering annual flooding (CTLO) and residential housing (BJRN) (see Figure 5). For permanent sites which serve both the Geodesy/Geophysics and the meteorology community, more stringent conditions exist and, clearly, these sites would not be adequate for measuring the necessary millimeter displacements in position.

For meteorological campaigns (longer than several weeks), the lack of need for stable monumentation drastically lowers installation costs. A geodetic grade receiver/antenna and a surface meteorological station (with real time capacity were internet available) is now less than 10,000 dollars (in the U.S.) for a meteorological campaign-ready installation. These receivers/antennas are extremely robust and durable and serve as a datalogger with greater than one year capacity for data storage at the typical data collection rate required. Energy requirements are small ($\sim 4W$) so solar panels and deep cycle batteries can be employed, although maintenance costs for deep cycle batteries depend on climatic regime. Given the frequent power outages in the Amazon and lack of solar panels for the the ADGMN, both Belem and Manaus, a workable energy set up consisted of a trickle charger plugged in to local current and two car batteries in parallel giving at least two days of independent power.

The entire process of installation, maintenance and data collection is relatively straightforward. Students from the graduate program *Clima e Ambiente* from the Universidade do Estado do Amazonas in Manaus participated in the installation of both the Belem and Manaus networks as well as the maintenance and data collection from these sites.

Acknowledgments.

We would like to thank Dr. Antônio Manzi, Hilândia Cunha e Cícero Leite of the INPA/LBA for financial, logistical and technical support for this project. Special thanks also go to Lúcia Soares de Oliveira, Edson Ferreira de Assunção, Carlos Vicente Ferreira, Francisco Paulo Santos, Prefeito of Manaquiri, Fundação Amazonas Sustentável Tumbira, Embrapa, and Reserva Ducke for hosting stations. We also thank Earle Williams and David Fitzjarrald for their comments on the original manuscript. Likewise, Brian Mapes greatly helped with the manuscript and the IDV animations. Figures were made with NCL. Support for this project and the Amazonian Dense GNSS Meteorological Network comes through cooperation project 0050.0045370.08.4 between PETROBRAS and INPE (Brazil) (Icaro Vitorello, Principal Investigator) and SMOG (PTDC/CTEATM/119922/2010) funded by FCT (Portugal). The CHUVA Project was funded by FAPESP grant No. 2009/15235-8. Also, we would like to thank UNAVCO's Equipment Loan Program for providing GPS receivers for the Belem Network. The ADGMN was carried out while the first author was faculty in the Programa de Pós Graduação em Clima e Ambiente, Universidade do Estado do Amazonas, Manaus, Amazonas, Brazil.

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TABLE 1. Thermodynamic and Dynamic Characteristics for the 22 Convective and 19 Non-Convective days. CAPE, CIN, PWV, PWV(850-500mb) and Shear were calculated from the 8am (12Z) soundings. $\frac{\Delta PWV}{\Delta t}$ representing "water vapor convergence" and Propagation Speed were calculated from the GNSS sites used in Figure 3.

	CAPE Jkg^{-1}	CIN Jkg^{-1}	PWV cm	PWV 850 to 500mb cm	$\frac{\Delta PWV}{\Delta t}$ $cmhr^{-1}$	Propagation Speed. ms^{-1}	Shear $10^{-3}s^{-1}$
Convective (22 days)	1121.0	2.44	4.35	1.74	0.094	10.9	2.2
Non Convective (19 days)	549.0	3.32	4.23	1.77	0.064	5.8	1.9

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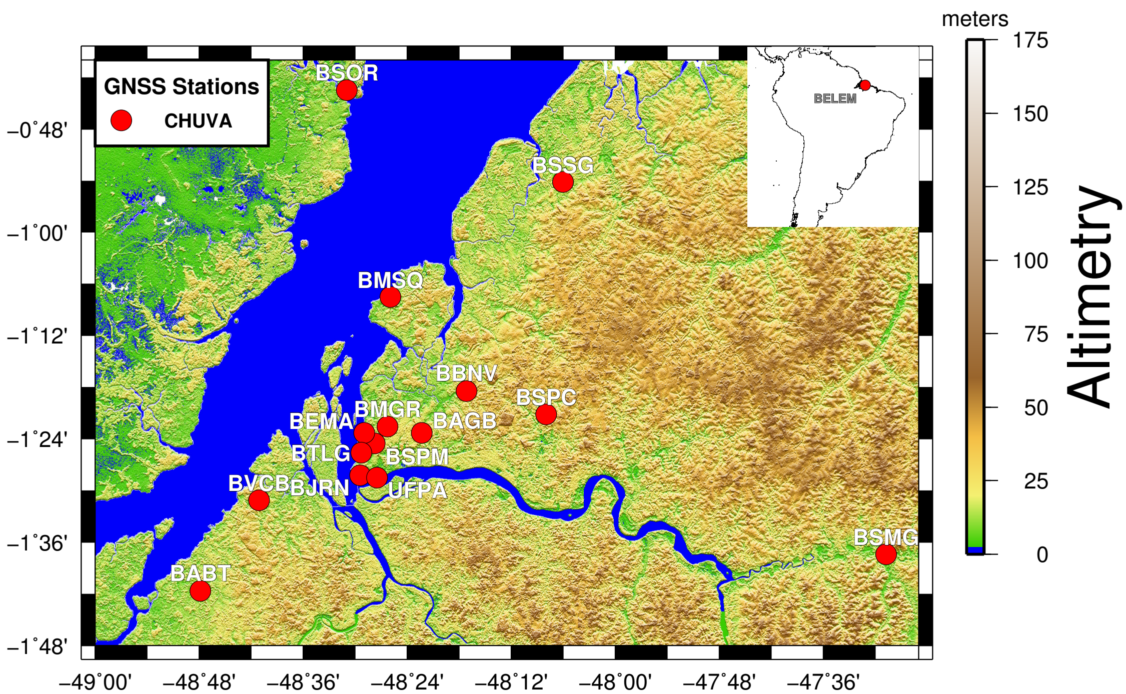

FIG. 1. Map of the Belem Dense GNSS Meteorological Network during the CHUVA experiment June 2011. Sounding sites were BSMG and BSSE (near BEMA). Tomé Açu is to the south of the mapped region. The large water body west of Belem is the Bahia de Marajó.

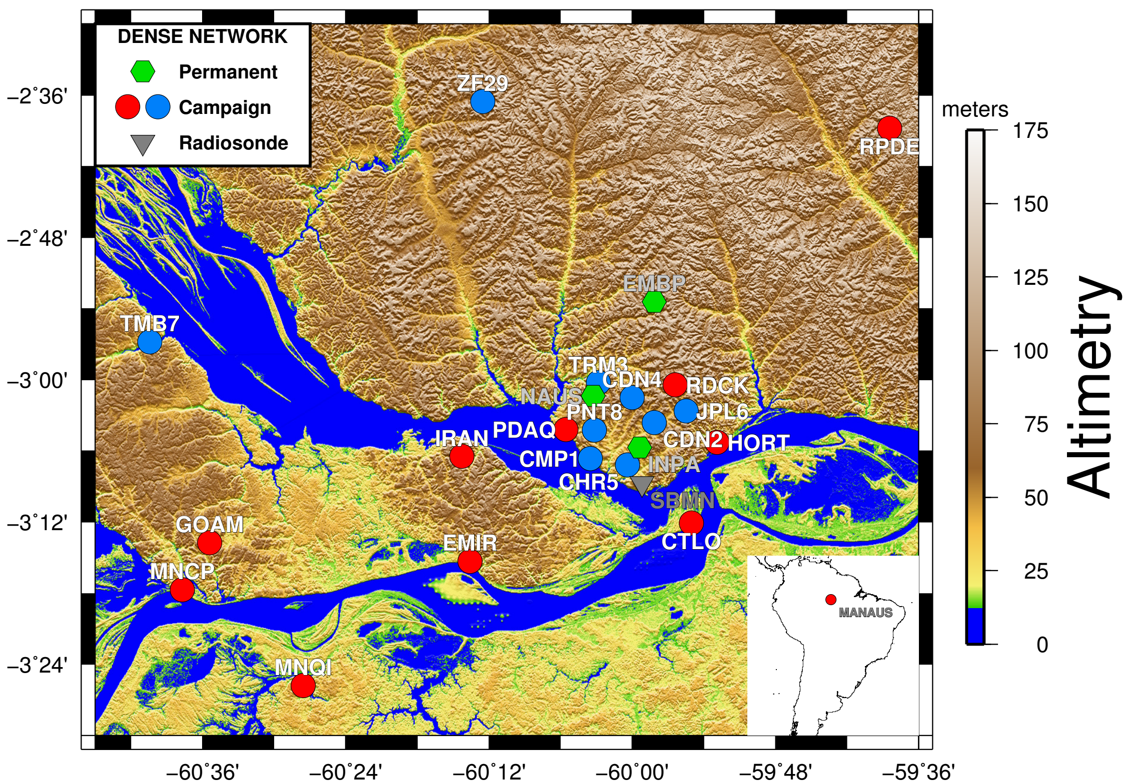

FIG. 2. Map of the Manaus Dense GNSS Meteorological Network, April 2011 - April 2012. Green and blue stations were present for the duration of the experiment. Red stations were present from August 2011 to April 2012. SBMN (82332) is the site for twice daily radiosondes and represents the tip of the Manaus "peninsula".

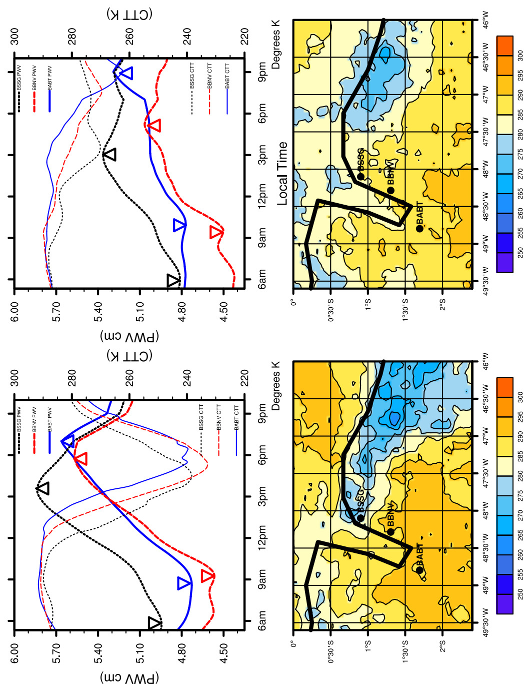

Fig. 3. Plot of timeseries of average PWV (every 5 minutes) BSSG (black,short dash), BBNV(red, long dash) and BABT(blue, solid) and average cloud top temperature (CTT) (every 15 minutes) (Identical patterns and colors, but thinner lines) for convective days (N =22) (upper left-hand plot) and non-convective days (N = 19) (upper right-hand plot). Triangles represent the times for which propagation speed and water vapor convergence values were calculated (See Table 1 and text). Bottom plots show cloud top temperature (degrees K, ranging from 245K (blue) to 305K(red)) at 12:30pm local time for convective (bottom left-hand plot) and non-convective (upper right-hand plot) days.

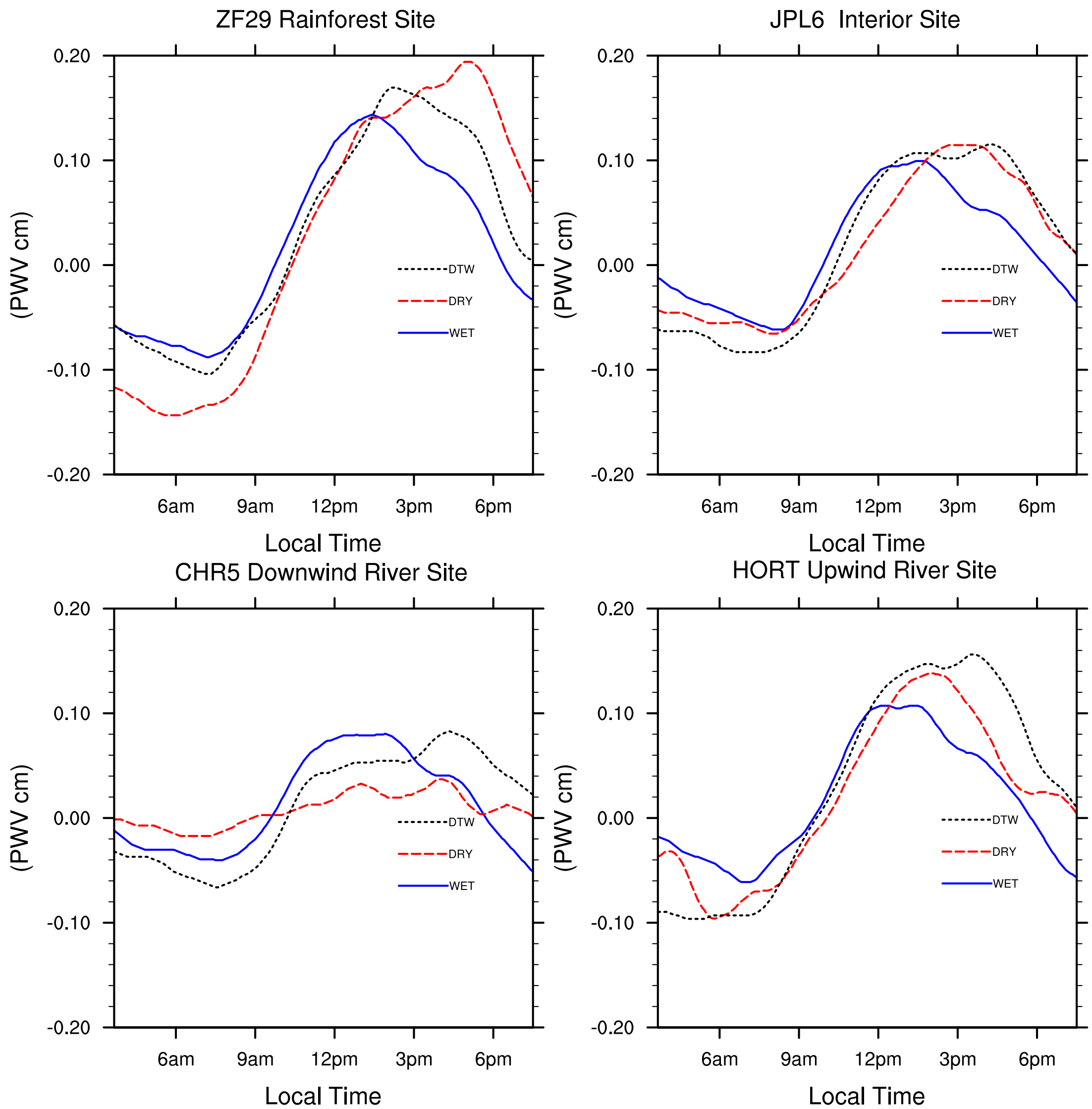

Fig. 4. Plot of diurnal cycle of PWV as a function of both season and location for Manaus stations: ZF29, JPL6, CHR5 and HORT representing a forest, interior and river sites, respectively (See Figure 2). The blue solid lines represent the wet season, black short dashed lines, the dry-to-wet transition and red long dashed, the dry season.

FIG. 5. Photos of ADGMN sites. Upper left-hand is Manaus station ZF29, upper right-hand is Manaus station HORT, bottom left-hand is Manaus station CTLO and bottom right-hand is Belem station BJRN.