12C.4 ANALYSIS OF HEAT AND MOISTURE BUDGETS FROM THE NAME ENHANCED SOUNDING NETWORK

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1. INTRODUCTION

Previous studies of the North American Monsoon (NAM) have been hampered by the lack of observations, particularly over Mexico. During the summer of 2004, the North American Monsoon Experiment (NAME) established an enhanced observational network over Mexico and the southwestern United States aimed at determining the sources and limits of predictability of warm season precipitation associated with the NAM (Higgins et al. 2006). Nested within the larger NAME observational network, an enhanced sounding network was deployed over the southern Gulf of California extending eastward into northwestern Mexico to examine the diurnal cycle over the core of the monsoon region. This study makes use of this unprecedented sounding dataset to analyze the heat and moisture budgets over the core of NAM region. Determination of the heating profiles over the NAM region is important due to considerable uncertainty observed in model-generated heating profiles in this region (Barlow et al. 1998) and the sensitivity of the large-scale circulation to the vertical distribution of heating (Hartmann et al. 1984).

2. SOUNDING NETWORK AND ANALYSIS METHOD

The NAME sounding network, shown in Fig. 1, consists of three nested domains: the Tier II Array (T2A) covering most of Mexico and the southwestern United States, the Tier I Array (T1A) covering the core of the monsoon region, and the Enhanced Budget Array (EBA) where a denser network of rain gauges and upper-air soundings was established to capture the diurnal cycle. This sounding network, which was in place from 1 July to 15 August 2004, consisted of operational sounding sites in the United States and Mexico, seventeen of which increased their launch frequency during ten Intensive Observing Periods (IOPs) and six additional sites that were temporarily established along the Gulf of California (GOC). These additional sites included three NCAR Integrated Sounding Systems (ISS) along the western Mexican coast, a GLASS sounding system at Loreto, Baja, the *RV* Altair stationed near the mouth of the GOC, and enhanced soundings at Yuma, AZ. Most of these additional sites did not become fully operational until July 7. The launch frequency for these sites is indicated in Fig. 1. All soundings were quality-controlled (QC'd) following procedures described in Johnson et al. (2006).

Gridded analysis of horizontal wind, temperature, specific humidity and geopotential height were created at 1° horizontal and 25 hPa vertical resolution using the QC'd sonde data and multiquadric in-

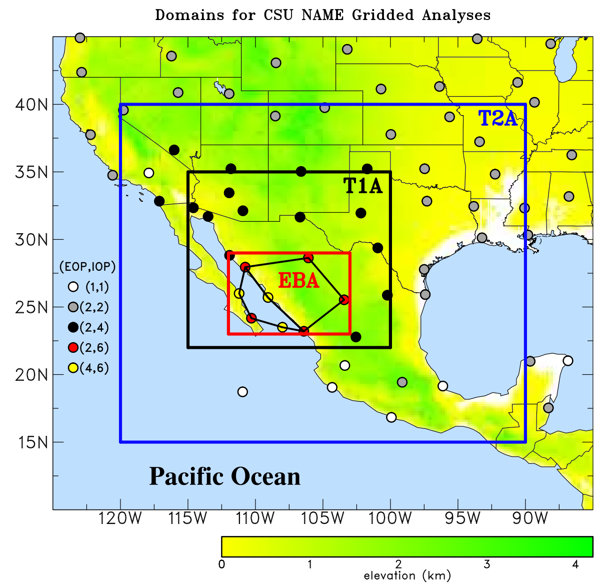

Figure 1: NAME sounding network and three grids used for sounding analysis: Tier 2 Array (T2a), Tier 1 Array (T1A), and the Enhanced Budget Array (EBA). Color of circles indicate frequency of routine sonde launches (left number) and frequency of sonde launches during the IOPs (right numver).

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terpolation scheme of Nuss and Titley (1994). Gridded analyses were produced at 00 and 12 UTC over the T2A domain for the period 1 July to 15 August. For the 40-day period from 7 July to 15 August, when the additional GOC sites were operational, gridded analyses were produced at 00, 06, 12 and 18 UTC. On the 18 IOP days with 6 sondes per day at the EBA sites, the gridded analyses were produced at 00, 04, 08, 12, 16 and 20 UTC over a domain slightly larger than the EBA (shown with a red box in Fig. 1). To aid the analysis over the data-sparse oceanic regions, NCEP reanalysis data were used. Use of the the model analysis over the oceans had little or no impact on the objective analysis over the GOC and the land portions of the analysis domains.

Using the objectively analyzed gridded fields described above, several derived quantities were computed on the grids shown in Fig. 1. The vertical p-velocity ω used in computing the atmospheric budgets was obtained through the kinematic method where horizontal divergence δ is integrated upward starting at the surface, where for the computations shown here, the condition $\omega = 0$ was used. We recogize that this assumption is not strictly valid over mountainous terrain. In future versions of our analyses we plan to incorporate pibal data, which just recently has become available, to better capture the flow along the slopes of the Sierro Madre Occidental (SMO). Next, the divergence field is mass balanced in the vertical by assuming adiabatic flow at the tropopause and using a constant divergence correction. Details on the computation of the apparent heat source Q_1 and the apparent moisture sink Q_2 (Yanai 1973) can be found in Johnson and Ciesielski (2000).

3. DERIVED FIELDS OVER THE ENHANCED BUDGET ARRAY

The time series of the derived fields: divergence, vertical motion, apparent heat source and apparent moisture sink are shown in Fig. 2 for the land portion of the EBA. From this diagram one can deduce several periods of strong convection characterized by significant upper-level divergence, upward vertical motion, and large apparent heating and drying rates. The IOPs, indicated by the gray shading in this figure, captured many of these convectively active periods. The strong intraseasonal modulation of these fields results from the passage of easterly waves, upper-level troughs and tropical cyclones which impact the NAM region through changes in the thermodynamic and shear environment.

We now consider vertical profiles of these derived fields partitioned by convective regimes identified in radar analyses. Based on a three-radar network with sites located along the southern GOC coast, Lang et al. (2006) identified two major disturbed precipitation regimes during the period from 8 July to 21 August 2004. Regime A was characterized by enhanced rainfall over the coast and GOC, especially overnight and during the early morning hours. Regime B had rainfall systems with significant along-coast movement. The occurrence of these regimes, in which there was considerable but not complete overlap, appears to be related to enhanced low-level environmental shear allowing systems to grow upscale and have long lifecycles. Overall, these disturbed regimes had convective features that tended to be larger, produce more rainfall, last longer, and be more organized. On non-A&B days, convection typically remained over the foothills and the higher peaks of the SMO and dissipated quickly before local midnight.

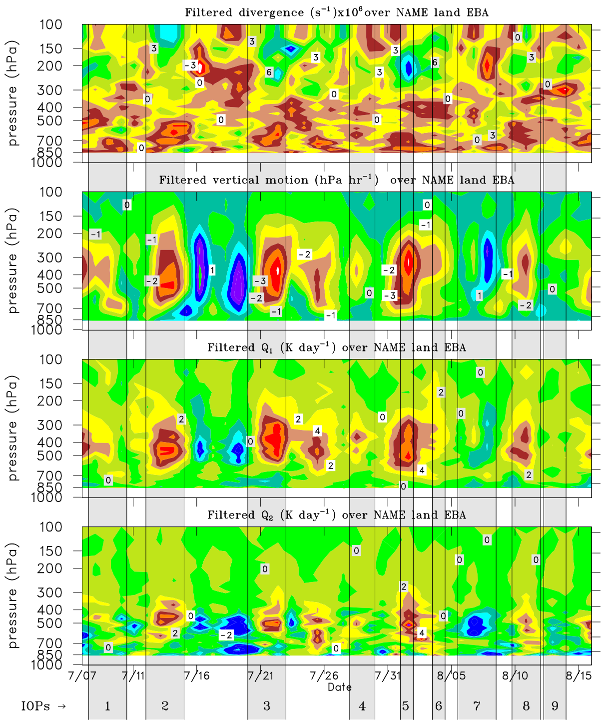

Figure 2: Time series of filtered (5-day running mean) divergence, vertical p-velocity, apparent heat source Q_1, and apparent moisture sink Q_2 averaged over the land portion of the Enhanced Budget Array (EBA) using the four-times daily T1A analyses. Shaded periods refer to Intensive Observing Periods (IOPs) during NAME. Warm colors indicate convergence, upward motion, apparent heating and apparent drying.

Figure 3 shows the vertical profiles of the derived fields computed using the four-per-day T1A

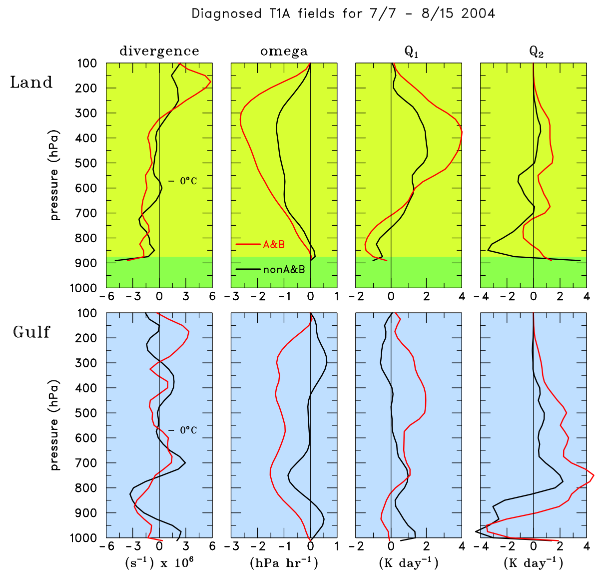

Figure 3: Vertical profiles of diagnosed fields computed from the T1A analysis for the period 7 July - 15 August 2004. Results are partitioned by convective regimes identified in radar analyses: A&B regime (red curves) and non-A&B regime (black curves). Top (bottom) panels represent averages computed over land (gulf) portion of the EBA. Land profiles are not shown at levels where more than half the area is below ground (denoted by darker green shading in top panels).

analyses for the regime A&B periods (red curves) and non-A&B periods (black curves). From the 40 days that T1A analyses were available, 15.5 days are classified as regime A&B, while the remaining 24.5 days as non-A&B. In Fig. 3 the results have been further stratified by averaging these fields over the land (upper panels) and gulf (bottom panels) portions of the EBA. From the profiles in Fig. 3 we note the following:

- Vertical profiles over land are indicative of deep moist convection with low-level convergence and upper-level divergence, and upward vertical motion with upper-level heating and drying. The level of peak vertical motion near 350 hPa is similar to that observed over the western Pacific warm pool (Lin and Johnson 1996). The strong low-level cooling and moistening, typically not seen in the mean tropical profiles, is related to relatively dry conditions (compared to the Tropics) in the lower troposphere which contribute to enhanced evaporation of falling rain.

- Convective forcing was much stronger over both land and gulf regions during the A&B regimes indicative of heavy rainfall and more organized long-lived systems that propagated over GOC consistent with radar analysis.

- The differences observed between the A&B and non-A&B mean profiles can be accounted for predominately by the 00 LT profiles (not shown). Namely, A&B profiles at 00 LT are characterized by much stronger convection with a prominent stratiform signature (large upper-level heating and drying with significant low-level cooling and moistening rates). This again corroborates the radar analysis which showed longer lasting, more robust nocturnal systems during the A&B regimes.

- The substantial near-surface moistening observed in gulf profiles is likely due to a large evaporative flux off the gulf waters (mean latent heat flux measured at the *RV* Altair was $\sim$110 W m^{-2}) combined with turbulent mixing in the boundary layer. The deeper low-level moistening extending to 850 hPa may result from a detraining, non-precipitating cloud field over the gulf.

- Non-A&B days over the Gulf are characterized by suppressed conditions with mean low-level subsidence indicative of a robust daytime sea-breeze circulation.

4. DIURNAL CYCLE: OBSERVATIONS VERSUS MODEL

During the 46 day period from 1 July to 15 August 2004, nine IOPs were conducted to address various scientific issues of importance to the NAME (Higgins et al. 2006). Since an important scientific consideration to the IOP missions was how convective systems and regional circulations in the core of the monsoon vary over the diurnal cycle, the sonde launch frequency in IOPs 2-9 was increased to 6/day for sites within the EBA.[1]

Figure 4, which is based on the EBA gridded objective analyses, shows the diurnal cycle of the derived fields partitioned over the land and gulf portions of the EBA for the 18 days over which IOPs 2-9 spanned. The land profiles show deep upward vertical motion peaking near 550 hPa at 18 LT transitioning to profiles with peaks near 350 hPa at 22 LT and 300 hPa at 02LT. The attendant Q_1 profiles show strong heating at 18 LT with a mid-level heating peak indicative of a large convective rain fraction. At subsequent times the magnitude of heating

[1]IOP 1 was used to test the enhanced sonde network and had a launch frequency of 4/day.

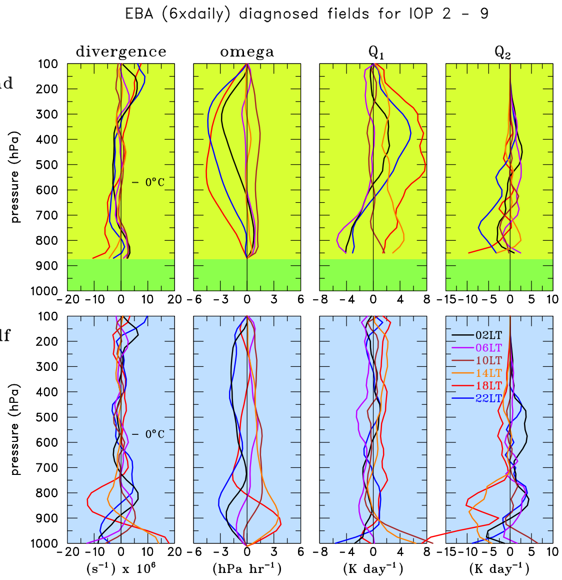

Figure 4: Diurnal cycle of diagnosed fields computed from the 6/day EBA analysis covering NAME IOPs 2-9 (~18 days). Top (bottom) panels represent averages computed over land (gulf) portion of the EBA.

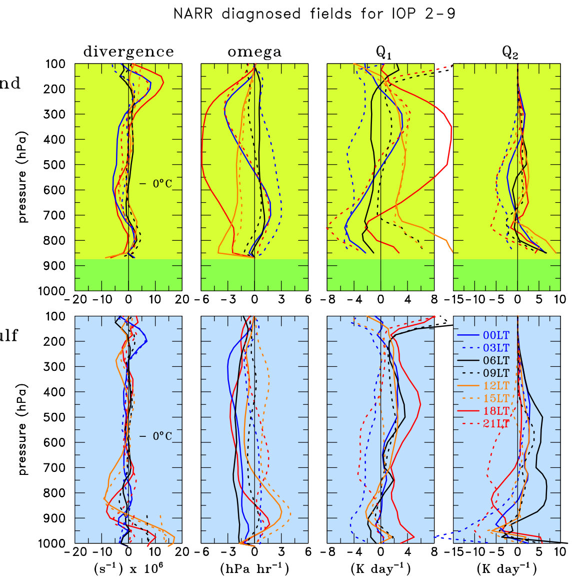

Figure 5: Diurnal cycle of diagnosed fields computed from the 8/day NARR analysis covering NAME IOPs 2-9. Top (bottom) panels represent averages computed over land (gulf) portion of the EBA.

gradually weakens as the level of peak heating rises, with concomitant cooling at low-levels, suggesting a transition to more stratiform rainfall at these latter hours. The early afternoon (14 LT) heating observed throughout the depth of the troposphere is likely due to short wave absorption by the atmosphere.

The diurnal features over the gulf are less prominent, except at lower-levels where afternoon and evening (14 LT and 18 LT) profiles show shallow subsidence associated with the daytime sea-breeze circulation, while the night-time land-breeze circulation results in shallow upward motion. The large moistening peaks around 850 hPa at 14 LT and 18 LT may be related to a shallow, detraining, non-precipitating cloud field. On the other hand, the large near-surface diurnal fluctuations in the Q_1 and Q_2 profiles should be regarded with caution, since diurnal surface heating and moistening effects from the coastal sites are aliased onto larger scale fields by the objective analysis scheme and overwhelm the weaker, low-level, diurnal signal over the gulf.

We now compare the diurnal profiles in Fig. 4 to a similar analysis in Fig. 5 computed from the eight-per-day North American Regional Reanalysis (NARR). To be consistent, the NARR results were computed over the same times as those for Fig. 4 (i.e., the periods spanning IOPs 2-9) and the NARR fields, which are at 32 km horizontal resolution, were regridded to same 1° grid as the objective analyses used in this study. The NARR data used here represent a special reanalysis performed for period 1 July - 15 August 2004 using all NAME soundings, multiplatform derived SSTs in the GOC, and precipitation data combining both RMORPH (a combined satellite and gauge product) and NAME Event Rain gauge Network (NERN) estimated rainfall. The NERN rainfall data are from a special rain gauge network established over the core of the NAM region (Gochis 2004). NARR fields, such as vertical motion and latent heating, are strongly constrained by the surface rainfall that is assimilated into the analysis system (Mesinger 2006). This ensures that reanalysis rainfall will closely match that observed.

While general features are similar between the NARR diurnal cycle (Fig. 5) and that based on the gridded objective analyses (Fig. 4), several notable differences also exist. The most obvious similarities include the convective to stratiform transition in the evening land profiles and the weaker convective forcing over the gulf with daytime low-level subsidence over this region. Some of the more noteworthy differences between these analyses include: (1) a tendency in the NARR towards a quicker build-up and decay of land convection, (2) a significant low-level upward motion and heating in the noon to early-evening land NARR profiles, and (3) the lack of low-level rising motion over the gulf at night. Some of the diurnal characteristics seen here in the NARR are consistent with previous observations that models tend to reach their convective maxima over land 2-3 hours earlier than observed (Higgins et al. 2006).

While the reasons for the differences noted here are still being investigated, some preliminary diagnostics indicate that the NARR is missing the night-time land-breeze circulation which is observed over the GOC. As a result, the day-time sea-breeze circulation appears to build up too quickly and strongly, resulting in an unrealistically strong low-level upward motion over the western slopes of the SMO in the late morning and early afternoon hours. This also may explain the lack of low-level rising motion over the gulf at night, which would be induced by a land-breeze circulation. Some of the descrepancies noted between Figs. 4 and 5 could also result from the use of $\omega = 0$ as the lower boundary condition in our diagnostic scheme. For example, the magnitude of the upward (downward) motion over the SMO will be underestimated by this current procedure when there are upslope (downslope) flows. Work is underway to improve this lower boundary condition.

5. SUMMARY

Sounding data collected during the 2004 North American Monsoon Experiment (NAME) were used to investigate the large-scale heat and moisture budgets over the core of the monsoon region. These budgets are strongly modulated on an intraseasonal time scale as the passage of easterly waves, upper-level troughs, and tropical cyclones affect the thermodynamic and shear environments, resulting in periods of suppressed and enhanced convection. During disturbed periods, convection over the SMO is characterized by deep convective heating at 18 LT, followed by a transition to stratiform-like heating and moistening profiles through the early morning hours. Examination of the diurnal cycle in a special model reanalysis for the NAME period shows the tendency for convection to fire prematurely and dissipate too quickly.

The results presented herein should be considered preliminary in nature, with further work currently underway to improve the diagnostic budgets in the NAME region. For those interested, the NAME QC'd sonde data and gridded analyses described in this paper are available at: http://tornado.atmos.colostate.edu/name/.

ACKNOWLEDGMENTS This research is supported by the National Science Foundation, Mesoscale Dynamics Program under Grant ATM-0340602 and the National Oceanic and Atmospheric Administration, Office of Global Programs, under Grant NA17RJ1228.

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