

J5.8 MEAN STRUCTURE AND VARIABILITY OF THE LOW-LEVEL JET ACROSS THE CENTRAL GULF OF CALIFORNIA FROM NOAA WP-3D FLIGHT LEVEL OBSERVATIONS DURING THE NORTH AMERICAN MONSOON EXPERIMENT

John F. Mejia, CIMMS/Univ. of Oklahoma, Norman, Oklahoma; and **M. Douglas**^{*}, NOAA/NSSL

1. INTRODUCTION

The North American Monsoon System (NAMS) is an atmospheric feature that produces a significant increase in rainfall during the summer months in Northwestern Mexico and Southwestern United States. The pronounced onset of the monsoon is attributed to a shift in the large-scale upper-level flow, and to the associated increase of moisture flux (Hales 1972; Brenner, 1974; Douglas et al. 1993, Higgins et al. 1997; Adams and Comrie, 1997; Fuller and Stensrud, 2000). The origins of the atmospheric moisture that feeds the NAMS is one of the natural questions that has persisted for some time because of the lack of sufficient detailed measurements over the region (Adams and Comrie, 1997; Schmitz and Mullen 1996; Berbery, 2001.) The Southwest Area Monsoon Experiment (SWAMP) carried out in 1990 (Reyes et al. 1994; Meitin et al. 1991) increased the research interest in gulf surges because several of them were observed by a research aircraft and special sounding network deployed during this field experiment (Douglas, 1995; Stensrud et al. 1997; Anderson et al. 2000). SWAMP-1990 and a second version of this one during 1993, evolving a special network operation (Howard et al. 1993), allowed for the first depiction of both the horizontal and vertical structure of the airflow and temperature field over the Gulf of California, Arizona and southwest California. Recent research using data of SWAMP-1990 and SWAMP-1993 (Douglas and Leal, 2003; Fuller and Stensrud, 2000; Anderson et al. 2000; Douglas and Li, 1996) provided serious evidence suggesting that the main source of moisture comes from the Easter Tropical Pacific and the Gulf of California with either tropical storms south of Baja California, cyclone perturbations propagating from the east, or a combination of these as the mayor forcing mechanisms that lead to the development of moisture surges. Most studies of gulf surges have involved case studies, with those of recent years being a blend of observations and modeling studies. However, most of the studies relied either on radiosondes that ignored the adjacent oceanic regions, or on coarse resolution gridded datasets or by not including the key physical processes, such as resolving the Gulf of California, a postulated moisture source for the NAMS.

This work describes lower tropospheric features over the Gulf of California and adjacent areas using NOAA WP-3D aircraft (P3) flight level observations made during July and August 2004 as part of the

North American Monsoon Experiment (NAME). The WP-3D was used to capture the 3-dimensional structure of the low level flow during both "strong" and "normal" monsoon flow conditions in this region. In particular, it was deployed to make observations to address questions related to moisture flux variability that cannot be resolved by other observation systems that were deployed in the northwestern Mexico during NAME (section 2.) We compare analyses produced by regional models to the aircraft measurements made during the flight days (section 3.) Comparison of the aircraft data with the mesoscale model output provides better insight into the moisture flux field over the Gulf and adjacent regions, and its spatial variability during different flow regimes.

2. AIRCRAFT OPERATIONS

2.1 The objectives

Questions related to the moisture flux field fall into several categories. Although the mean fields and seasonal evolution of the flux field are themselves somewhat uncertain, there are large synoptic time scale transient variations in the flux field over the region, commonly called "gulf surges" (Hales, 1972.) There are also somewhat longer periodic variations that might be associated with wet and dry periods of more than one week duration during the rainy season. The moisture flux variability, on time scales ranging from seasonal to diurnal, as well as mesoscale atmospheric features affecting the monsoon region are part of the scientific objectives of NAME.

To explore the moisture flux variability over the NAME domain the NOAA WP-3D research aircraft was used to conduct specific research activities, and was deployed to Mazatlan, Mexico for the period July 5 to Aug 4th, 2004. The aircraft operations had five principal objectives:

- 1) The measurement of lower tropospheric moisture fluxes into the Gulf of California from the eastern tropical Pacific. These flights will provide an accurate estimate of the horizontal transport of water vapor into the southern Gulf of California during enhanced rainfall events over the NAME Tier 1 domain (northwestern Mexico and southwestern U.S.), during periods of less rainfall over the Tier 1 domain, and during "typical conditions". These measurements compliment other NAME field observations and serve as validation data for NAME modeling activities.

^{*} Corresponding author address: Michael W. Douglas, National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK, 73069. Michael.douglas@noaa.gov

2) Describing the structure of the gulf surges and the Gulf of California low-level jet. As the gulf surge has been identified with variations of rainfall over the NAME domain these flights will provide the high spatial resolution data needed over the gulf to validate simulations of the phenomena. Observations over the lower gulf should help clear up the formative mechanism responsible for surge genesis.

3) Describing the structure and formative conditions for mesoscale convective systems and their associated potential vorticity anomalies over the Sierra Madre Occidental (SMO). This activity was not successful during the 2004 measurement campaign.

4) Describing aspects of the sea-land breeze circulations to measure horizontal gradients associated with low-level circulation features (e.g. along Gulf of California low-level flow, the coupling between the sea-breeze /land-breeze and mountain/valley circulations) at better resolution than can be provided by the NAME sounding network. These data are critical for comparisons with model simulations of the flow.

5) Describing moisture gradients in the vicinity of the SMO. These flights will extend across the axis of the SMO in an approximately east-west orientation to measure variations normal to the mountain axis from the strongly heated Mexican altiplano to the Gulf of California. One such flight was made during NAME.

2.2 The aircraft operations

The aircraft operations started on July 7th and continued through August 4th. This period was selected to overlap the operating period for other platforms deployed during NAME (the availability of the aircraft also constrained the period of operations). In general, the aircraft flew a pattern ranging from the lowest level of 500 ft (500 ft over the ocean and 1000 ft over the land) to a level varying from 3000 to 14000 ft. The flight level data was obtained doing a series of horizontal zig-zags (while porpoising) from Mazatlan, Sinaloa up the center to the upper Gulf of California (see Figure 1). Most porpoises extended to a 5000-6000 ft maximum altitude above sea level but ascents on six flights extended to 10,000 ft or higher (~695mb). Some difficulties were encountered operating with flexibility within 50 miles of different airports around the region, though these had only minor impact on the mission success. The flights were designed to cover some of the same legs shown in Figure 1, such as *aa'* and *bb'*, to measure the synoptic evolution of the moisture flux along the aircraft period of operations. Porpoising was done throughout every flight. A transect from the flight showed in Figure 1 (from 16:00 UTC to 17:40) is shown in Figure 2 to illustrate the vertical flight pattern of three

selected variables. Although the flight level data has a one second time resolution, the panel in Figure 2 shows 10-second average values. During low-level jet (LLJ) events the flight tracks were intended to provide cross sections at a number of places along the Gulf. The transects *aa'* and *bb'* were repeated while going back southeast (3–4 hours gap) to look for any diurnal or synoptic changes over the flight. No data problems were encountered during the flights.

Ten flights were carried out and they were focused mainly on measuring moisture fluxes and the LLJ flow along the Gulf of California as well as other features listed on numeral 2.1. Table 1 has a description of the flights including their objective emphasis and duration in hours. The relation of the flights along the mean daily meridional wind (along 22.5°N) from NCEP/NCAR Reanalysis data (Kalnay et al., 1996) is shown in Figure 4. As describe in Table 1, the flights were carried out during different synoptic settings, e.g., a surge genesis flight on July 12th was likely because a well-marked mid-tropospheric wave was propagating from the east across central Mexico since the pervious day. Figures of every flight for different horizontal levels, such as in Figure 3, and cross sections, can be obtained from the web page <http://www.nssl.noaa.gov/projects/pacs/web/html/NAME/P3/indexP3.html>.

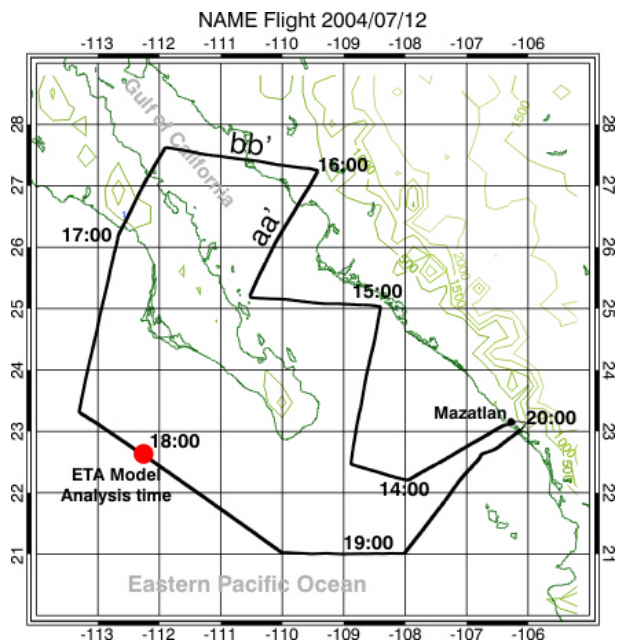


Figure 1 Horizontal track for the July 12th Surge genesis/Moisture flux flight. Take off and landing in Mazatlan, Sinaloa. Time marks are given in UTC.

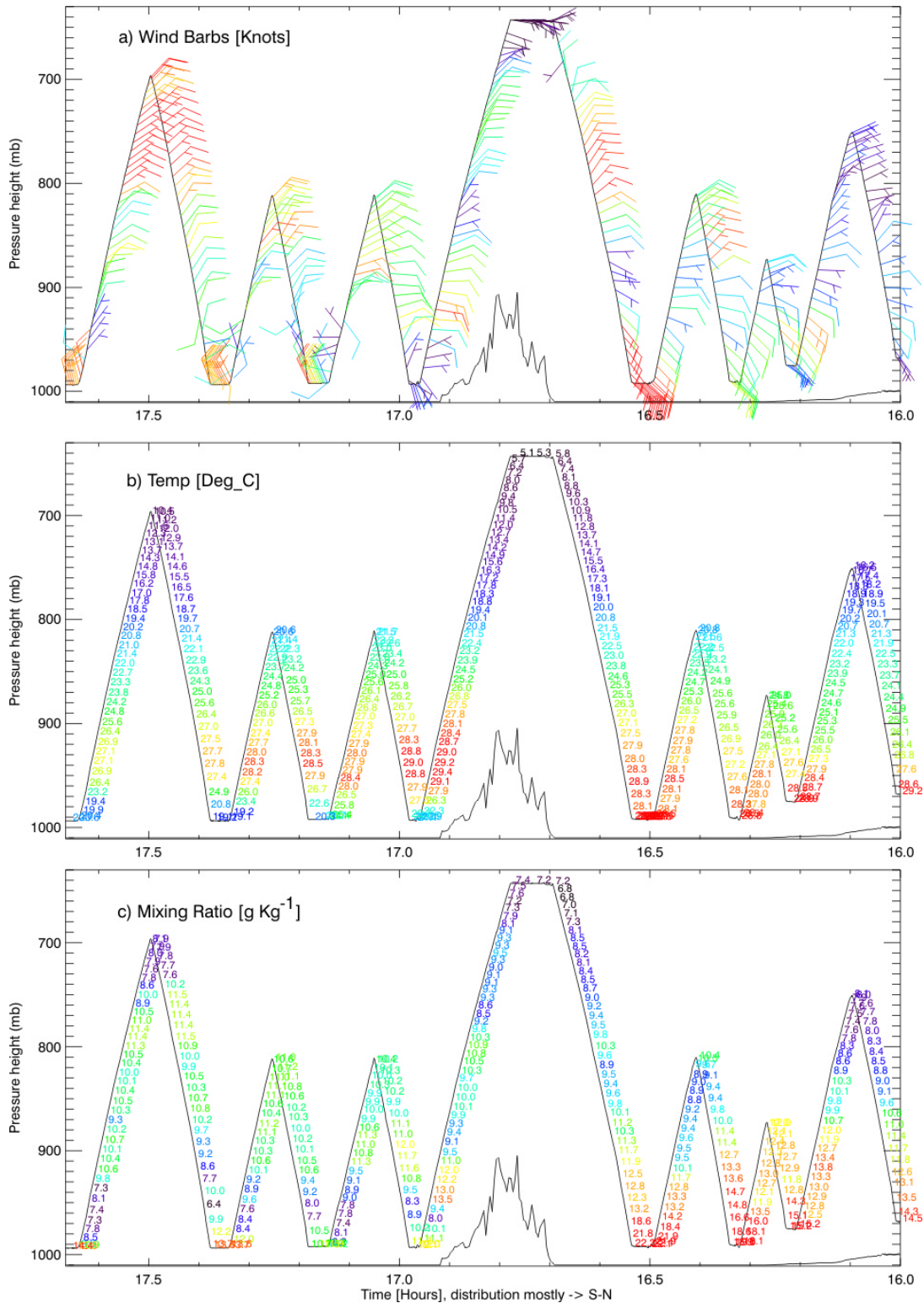


Figure 2 Vertical transect for the July 12th Surge genesis/Moisture flux flight between 16:00 to 17:40 UTC. Data averaged over a 10-second window. Red colors assigned for the higher values while blues for lower values. (a) Wind barbs in knots, (b) ambient temperature in °C, and (c) mixing ratio in g kg⁻¹. Solid black line at the bottom shows the topography height.

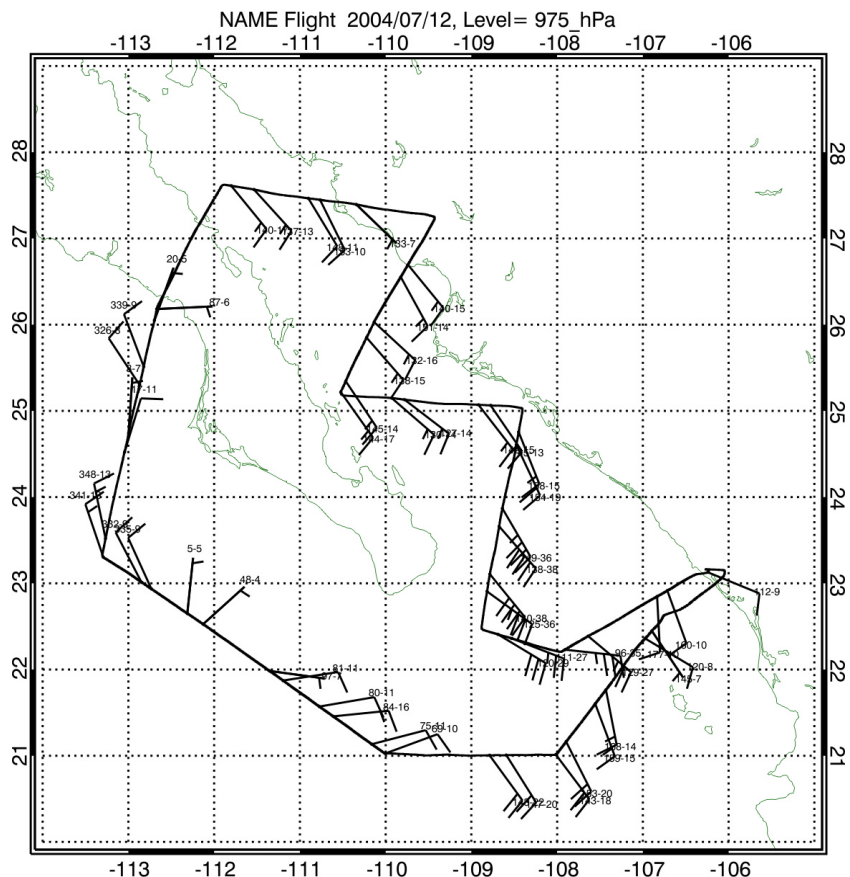


Figure 3 The NOAA WP-3D wind observations at 975 mb for the July 12th Surge genesis/Moisture flux flight.

Table 1 Description of the NAME NOAA WP-3D flight missions.

| Date 2004 | Emphasis | Hours UTC |
|-----------|---|----------------|
| 07/08 | Moisture Flux: The first NOAA P-3 flight was called to examine the low-level moisture fluxes into the southern part of the Gulf of California and to help determine the best pattern and operating altitudes for such missions. | 13 to 20 |
| 07/12 | Surge genesis/Moisture flux: investigate the possible genesis of a gulf surge (well-marked mid tropospheric easterly wave.) | 13 to 20 |
| 07/13 | Low-level Jet: Southerly winds were up the entire Gulf. The central gulf transects were the same as done during the previous two flights. Strong winds in the far northern Gulf, reaching 43 kts (1-sec data), with 34 kts winds at 500 ft above the surface. Strongest winds were close to Puerto Peñasco. Winds were also strong, to about 27 kts, over the central Gulf (west of Guaymas.) | 13 to 21 |
| 07/18 | Moisture flux flight (modified): Detailed flow structure around the southern part of the Baja California peninsula. Gap flow across the lowest part of the Peninsula near La Paz and the directional shift in the winds south of Cabo San Lucas. The effect of the significant SST gradient in this region on the depth of the PBL and its moistening was also of interest. | 13 to 18 |
| 07/22 | Moisture flux flight: The flight followed the flight track of the first flight on July 8th, with modifications to measure details of the flow around the tip of Baja California and a small additional leg near Kino Bay to describe the LLJ that was sampled. Overall, moderate LLJ conditions were observed over the central Gulf (~30-35+ kts at 950-990mb); this seemed associated with a decaying MCC that had occurred the night before over the central Gulf coastal plain. | 13 to 21 |
| 07/23 | Low-level Jet: Describe the LLJ that was forecast from Eta output, and observed the previous day. Weaker flow than the previous day but more uniformly up-Gulf (below 900mb). Mid-Gulf flow at 850mb and higher clearly shows a cyclonic vortex or cyclonic shear - a feature observed on various flights. | 13 to 21 |
| 07/24 | Moisture flux flight: Modified moisture flux flight, with additional legs over the northern Gulf to measure LLJ flow (weak). Strongest up-Gulf winds of about 20kts, but somewhat deeper and more Southeasterly than on previous 2 days. The region of cyclonic curvature over central Gulf evident on this flight as well. This flight, together with the previous two, occurring shortly after major MCC events over Sonora | 13 to 21 |
| 07/29 | Moisture flux and sea breeze: Unusually weak monsoonal flow up the Gulf of California. Sample the sea-breeze penetration along the eastern shore of the Gulf of California. | 16:30 to 23:30 |
| 08/02 | Sea-breeze and Moisture flux: A "non-typical" monsoon day, but in that sense. Interesting measures horizontal variations of the moisture flied across the Sierra Madre Oriental; measure the sea-land breeze circulation over the coastal plain and foothills of southern Sonora. The flight found very weak flow over the Gulf of California. | 17 to 23:30 |
| 08/03 | Surge genesis flight: Strong mesoscale convective complex south of Mazatlan. This flight described the cyclonic flow associated with a lower-mid tropospheric trough. In general, the flight was successful in capturing the synoptic environment of a major MCS complex over the lower Gulf and the subsequent surge-like feature. | 13:30 to 21:30 |

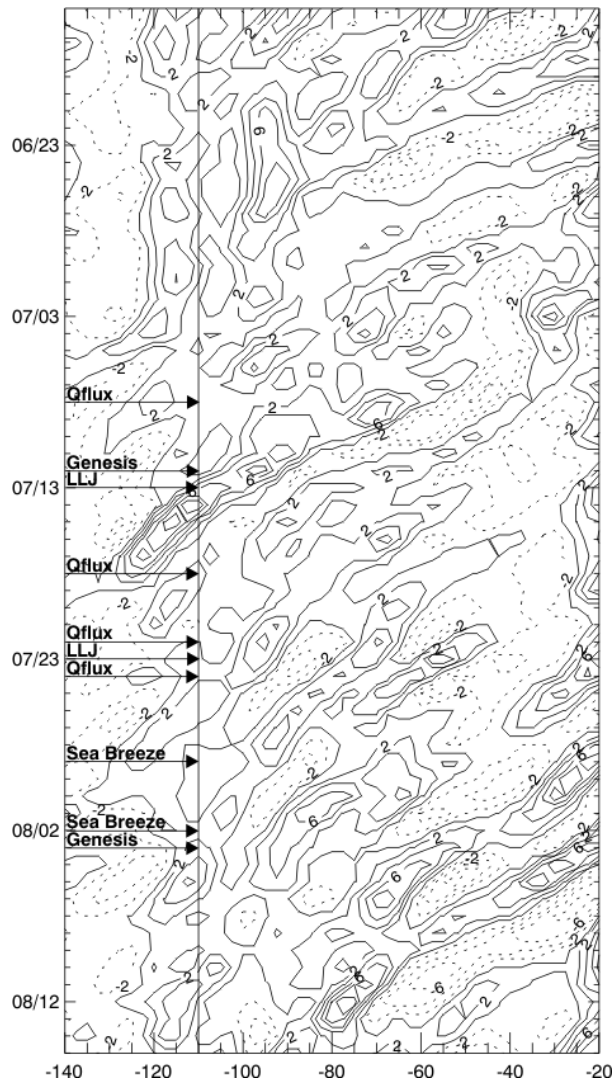


Figure 4 Hovmöller longitude-time diagram using NCEP/NCAR Reanalysis 700 mb meridional wind component (m s^{-1}) along the 22.5°N . The vertical solid line illustrates the location of the entrance of the Gulf of California (around 110°W , 22.5°N). The flight missions are located in their respective date.

3. MOISTURE FLUX: MODEL VERSUS AIRCRAFT OBSERVATIONS

In the past, the regional model analysis did not properly reproduce the monsoonal circulation of the southwestern U.S. and northwestern Mexico region, but significant changes have been done since then. Stensrud et al. (1997) compared model data (Pennsylvania State University-NCAR mesoscale model version 4 - MM4) and the observations from the NOAA WP-3D taken during SWAMP. In Stensrud et al. work,

they recognized the ability of the model to simulate many of the mesoscale features seen in the aircraft data, which gives some measure of confidence that the model used can simulate realistic surges. Stensrud et al. most important conclusion centers in the interaction between tropical easterly waves and midlatitude systems necessary to produce a strong gulf surge in the model simulation. Berbery (2001) used an improved NCEP's Eta Mesoscale Model simulations to reproduce realistic monsoonal circulations and also precipitation forecast that are closer to the observations. Despite the progress in Berbery's (2001) work to simulate the airflow circulation in the NAMS region, some deficiencies in the model precipitation were still unresolved. These simulations ended suggesting the need of incorporating the diurnal cycle and transient activity into the analysis of moisture flux associated with the monsoonal precipitation. Such model simulations are fundamental to understand the physical processes related to the monsoon circulation but more progress is still necessary to improve analysis and forecasting in the region.

Figure 5 shows a quick comparison between the NAME aircraft data and the NCEP 12 Km Eta Model for the July 12th flight (model data was obtained in the NOAA Operational Model Archive and Distribution System NOMADS-Rutledge et al., 2002.) Figure 5a shows the meridional moisture flux (q^*v in $\text{g kg}^{-1} \text{m s}^{-1}$, analysis valid at 1800UTC), which was produced by extracting the corresponding model grid points along the horizontal flight path (every 60 seconds). A bilinear interpolation was performed to bring the model grid points into the corresponding flight location (see Figure 1 to relate the time (hours) of the flight with the horizontal position). Figure 5b shows the analysis of the same variable as Figure 5a, but using the P3 observations. The P3 observational analysis was produced using a 2-pass Barnes interpolation scheme. The topography effect can be observed in both the model data and the P3 observations. Most of the discrepancies between the model analysis and the P3 analysis lie over the ocean where no or few observations exist. At the pacific side, from 1700 to 1830 UTC, the P3 observations show a deep northerly moisture flux component whereas this feature is barely captured by the model analysis, which also shows a southerly component aloft. The legs over the Gulf of California (1430-1640 UTC) show some similarities in the moisture flux magnitude below 900 mb. However, throughout this time period, the P3 observations show a significantly shallower moisture flux, such as observed from the $40 [\text{g/kg m/s}]$ meridional moisture flux line. The differences described above are enhanced if we compare the model analysis and the P3 vertical integrated moisture flux values between 975 and 900 mb (see Figure 6). Larger discrepancies are found south-southwest of the entrance of the gulf (take off-1500UTC and 1830-landing). In the case presented here, the estimation of the low level water vapor that

goes into the Gulf of California basin, using either model analysis or P3 analysis, is appreciably different.

4. FUTURE WORK

The use of NOAA P-3 research aircraft during the NAME will help to understand a variety of research objectives that can be addressed in no other feasible manner with the other platforms deployed during NAME. Future work using these data will focus on analysis of individual flights and extract relationships, and if data allows it, to make a conceptual model for the moisture surge and its forcing mechanisms (i.e., the impact of the MSCs, tropical cyclones, diurnal cycle, among others). In order to describe the surge genesis conditions over the southern Gulf of California and eastern Pacific, a synoptic analysis of the observations made by the aircraft combined with the other NAME soundings, would be required. The objective would be to produce a detailed synoptic analysis spanning the genesis event which could be used as a reference for comparison with other modeling activities that might attempt to reproduce the event. To establish a convincing link between a westward propagating tropical wave and the surge events, it would be necessary to produce analysis spanning nearly a week for each event that was sampled by the aircraft.

NOAA WP-3D observations will help to describe the association of tropical waves south the entrances of the gulf with moisture surge genesis. In general, the genesis flights were successful in capturing the synoptic environment of the major convective systems developed over the lower Gulf and the subsequent surge-like feature. Along with the other set of observation gathered during NAME, the NOAA WP-3D observation should help to attempt clarifying the hypothesis postulated in previous works.

From comparison of the aircraft observations and the sounding network observations it will be possible to determine how closely the sounding network tends to estimate the moisture flux along the Gulf of California. Different flights should be useful for describing the effect of the topography on the near-climatological moisture flow along the Gulf, offshore from the west coast of the Baja California, the variation in PBL structure about the SST gradient around the southernmost part of the peninsula, and other pertinent mesoscale features around the region.

Relatively small time-changes were observed on the common legs during different passes on the same flight (inbound and outbound), which should help to produce an easier and more confident analysis of the data.

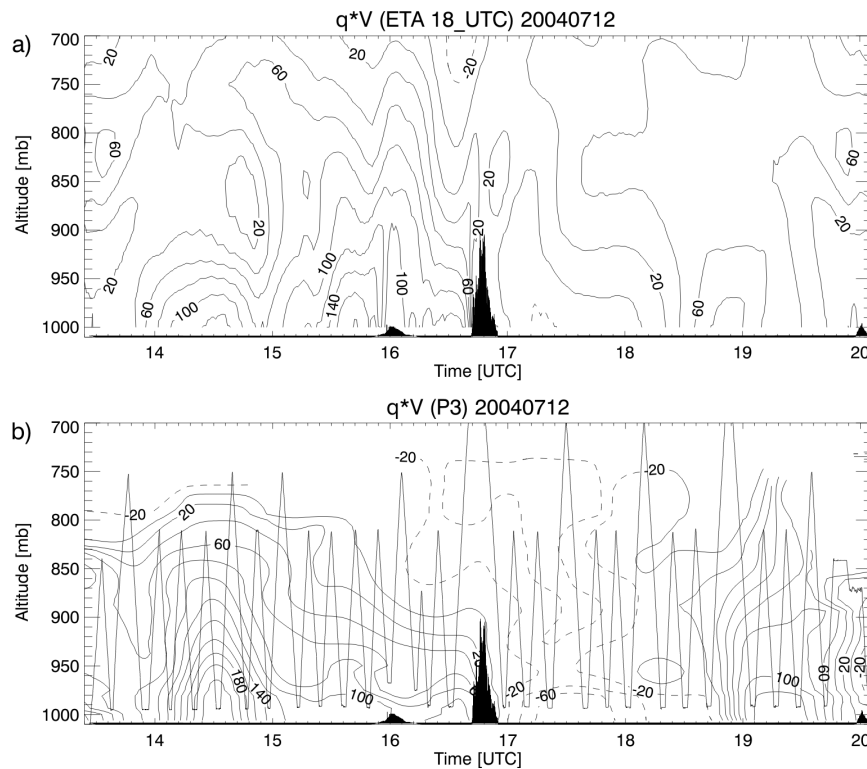


Figure 5 Medional moisture flux (q^*v in $\text{g kg}^{-1} \text{ m s}^{-1}$) for (a) the NCEP's 12 Km Eta Model (analysis valid at 1800UTC) and (b) for the NOAA WP-3D observations for the July 12th Surge genesis/Moisture flux flight. Solid lines (dashed) indicate positive (negative) values. Topography is shaded in black.

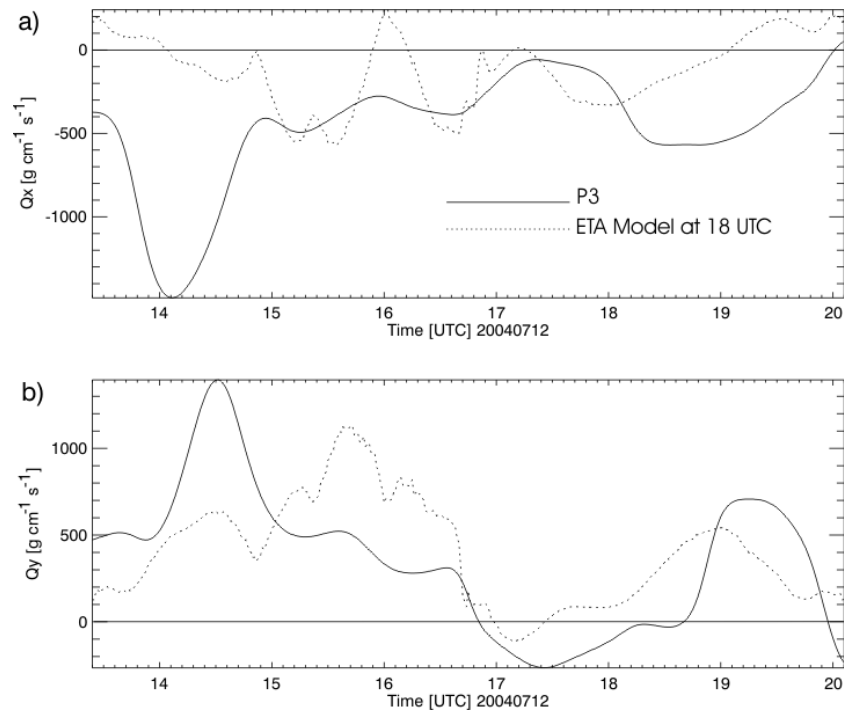


Figure 6 Vertical integrated moisture flux ($\text{g cm}^{-1} \text{s}^{-1}$) for the July 12th Surge genesis/Moisture flux flight. The integration was calculated between 975 and 900 mb. (a) and (b) were obtained integrating the moisture flux using the zonal and meridional wind components, respectively.

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NAME Field catalog:

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SWAMP Project page:

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SWAMP-90/SWAMP-93 Material:

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