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Mesoscale Moisture Analysis of the North American Monsoon

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ABSTRACT

The regional circulations that contribute moisture to the large precipitation over northwestern Mexico, the core region of the North American monsoon, are investigated using three summer seasons (July–September 1995–97) of Eta Model mesoscale analyses and forecasts. Analyses are produced by the Eta Model's own four-dimensional data assimilation system that includes a diverse mix of observations. Comparison of the forecast precipitation with satellite estimates and previous observational studies shows similarity in location, shape, and scale of the patterns over northwestern Mexico; the magnitude of the precipitation over the slopes of the Sierra Madre Occidental is also similar to that from climatologies based on rain gauge observations. Examination of the morning and evening forecast precipitation also reveals agreement with equivalent estimates from high-resolution satellites. Excessive model forecast precipitation is found over the Isthmus of Tehuantepec in eastern Mexico, which seems related, at least in part, to deficiencies in the convective parameterization scheme.

Special attention is given to the diurnal cycle that is needed to resolve the interactions between circulation and precipitation. The Gulf of California exhibits evaporation through the entire diurnal cycle. In contrast, moisture flux divergence has a marked diurnal cycle with the largest magnitude over the gulf during the afternoon; this divergence is associated with the afternoon sea and valley breezes that favor a net transport of moisture toward the western slopes of the Sierra Madre Occidental. At the same time, large convergence of moisture flux develops over the slopes of the Sierra Madre Occidental, and is followed by intense afternoon–evening precipitation. The reverse circulation during nighttime and early morning results in moisture flux convergence near the coastline and over water, where early morning precipitation develops.

Large divergence of moisture flux is found over the northern sector of the Gulf of California at all times, and it results almost equally from transients and the time mean flow. The time mean flow is characterized by a nighttime and predawn low-level jet whose intensity is weaker than the Great Plains counterpart, but still appears to transport a significant amount of moisture into the southwestern United States. Northward transport of moisture is also accomplished by the transient fluxes that include, but are not limited to, the episodic northward moist surges frequently discussed in the literature.

1. Introduction

The foothills and western slopes of the Sierra Madre Occidental of northwest Mexico during summer receive heavy precipitation with typical values of 200–250 mm month^{-1}, and even higher values at some locations (Mosiño and García 1974; Douglas et al. 1993; Reyes at al. 1994; Stensrud et al. 1995). This precipitation is at the core of a monsoon system sometimes referred as the North American monsoon system, whose processes span a broad range of scales, from continental to the smallest mesoscales. While the continental-scale upper-level circulation of the North American monsoon system is relatively well described by global analyses (see, e.g., Okabe 1995; Higgins et al. 1997; Barlow et al. 1998) the mesoscale features, particularly at lower levels, are less well documented.

The large spatial variability in the precipitation fields is evident from studies using high-resolution satellite estimates. Negri et al. (1993, 1994) showed that the great complexity of these patterns is related to topographical features, and, earlier, Mosiño and García (1974) pointed out that both orography and atmospheric disturbances are needed to explain the climatological patterns of precipitation over Mexico. Although no quantitative estimates have been offered, it is believed that mesoscale convective systems (MCS) contribute significantly to the total precipitation amount (Howard and Maddox 1988; Farfán and Zehnder 1994); MCS frequently develop over northwest and southwest Mexico, and as pointed out by Velasco and Fritsch (1987), they are not the extensions of tropical storms.

For decades, the origin of the moisture that feeds

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the monsoon was unclear. Nevertheless, recent observational and modeling studies have helped clarify the issue (see Stensrud et al. 1995 for a detailed discussion, and Adams and Comrie 1997 for a review). The current consensus is that the Gulf of Mexico supplies moisture at higher levels, but the most significant contribution occurs at lower levels associated with moisture flux from the Gulf of California and the Pacific Ocean. The observational studies of Douglas et al. (1993, 1998) and Douglas (1995) showed that local low-level circulations over the Gulf of California play a significant role in the development of the monsoonal precipitation. The existence of a northward low-level jet in the northern sector of the gulf that supplies moisture to the southwestern United States was noticed as well. Further support to their findings was provided by the model-based studies of Stensrud et al. (1995, 1997), who also discussed the role that northward moist surges along the Gulf of California play in transporting moisture to the southwestern United States (see also Hales 1972, 1974). These surges appear to be forced by interactions between tropical easterly waves and circulation systems in the lower-midlatitude westerlies (Stensrud et al. 1997).

Because of the mesoscale nature of these features, an increasing number of studies of the North American monsoon circulation using regional models is becoming available. Dynamical aspects of the low-level circulation over the Gulf of California were simulated using a nested regional model by Anderson et al. (2000a,b). Swanson (1998) also used a regional model to simulate the interactions between the monsoonal circulation and tropical storms in the eastern Pacific. Such model simulations are fundamental to understand the physical processes related to the monsoon. Nevertheless, models tend to drift toward their own climate, and the extent to which they still represent observed features needs to be carefully assessed.

This paper investigates the mesoscale circulations at the core region of the North American monsoon, and, more specifically, the regional processes contributing moisture to the monsoonal precipitation. To achieve this, a climatology of the mesoscale circulations was prepared using 3 yr of regional analyses and short-term forecasts derived from the National Centers for Environmental Prediction (NCEP) operational Eta Model. These results are also useful to reassess the performance of the model for a region where older versions failed to produce the correct patterns (Dunn and Horel 1994a,b). Section 2 describes the regional datasets and model suite in which they are based. Section 3 inspects the quality of the forecast fields, while section 4 examines the diurnal cycle and transient behavior of moisture fluxes as obtained from the regional analyses. The circulation over the northern part of the Gulf of California is diagnosed in section 5. Finally, a summary and conclusions are presented in section 6.

2. Model products and observations

a. Eta Model regional analyses and forecasts

The primary dataset for this study consists of 3-h regional analyses for July–September (JAS) of 1995–97. They were derived from the Eta Model's own four-dimensional data assimilation system, known as Eta Data Assimilation System (EDAS). The Eta Model has been run at NCEP for several years, and EDAS was implemented operationally in April 1995 (Rogers et al. 1996). The assimilation scheme begins with a global model 6-h forecast up to 12 h prior to the Eta Model forecast, and is followed by adjustments to observations by optimal interpolation at 3-h intervals. According to Rogers et al. (1996) and Lin et al. (1995), apart from synoptic observations, the assimilation ingests data from aircraft, wind profilers, and vertically integrated water vapor derived from satellites' measurements. The fewer observations outside the continental United States imply that in other regions the analysis may be more influenced by the first-guess field.

Analyses were used to estimate moisture and circulation fields because they are less influenced by the model physical parameterizations than the forecasts (due to the ingestion of observations at regular intervals). Precipitation and evaporation were not available from the assimilation cycle, but estimates from the 12–36-h forecasts of the Eta Model, available at 6-h intervals, are included for a more comprehensive discussion of the processes and for model evaluation purposes. Mixed use of analyses and forecasts would be inconsistent for moisture budget studies, but that was not attempted in this paper.

The Eta Model dynamic and physical methods are described in several articles (e.g., Mesinger et al. 1988; Janjić 1990, 1994; Rogers et al. 1996; Betts at al. 1997). Summaries of model changes during the period covered by this study and their expected effects on the model products can be found in Black et al. (1997), Betts et al. (1997), and Berbery and Rasmusson (1999). The model's domain covers all North America and large portions of the adjacent oceans at a horizontal grid spacing of 48 km (Fig. 1a). The large domain has two important advantages: first, no distinguishable negative boundary effects are detected over the region of interest (Fig. 1b; Pielke 1984; Staniforth 1997; Warner et al. 1997), and, second, the quality of the model forecasts is enhanced because interactions with larger scales are better represented (Mesinger 1998). Thirty-eight unevenly distributed vertical levels provide high resolution in the boundary layer (see distribution of vertical levels in Rogers et al. 1996, their Fig. 1). Over high terrain the spacing between levels is lower, and might not appropriately resolve the interaction between surface and atmospheric processes. All computations for this study have been performed in the model's original (Arakawa E) grid, and interpolations were done only for display purposes.

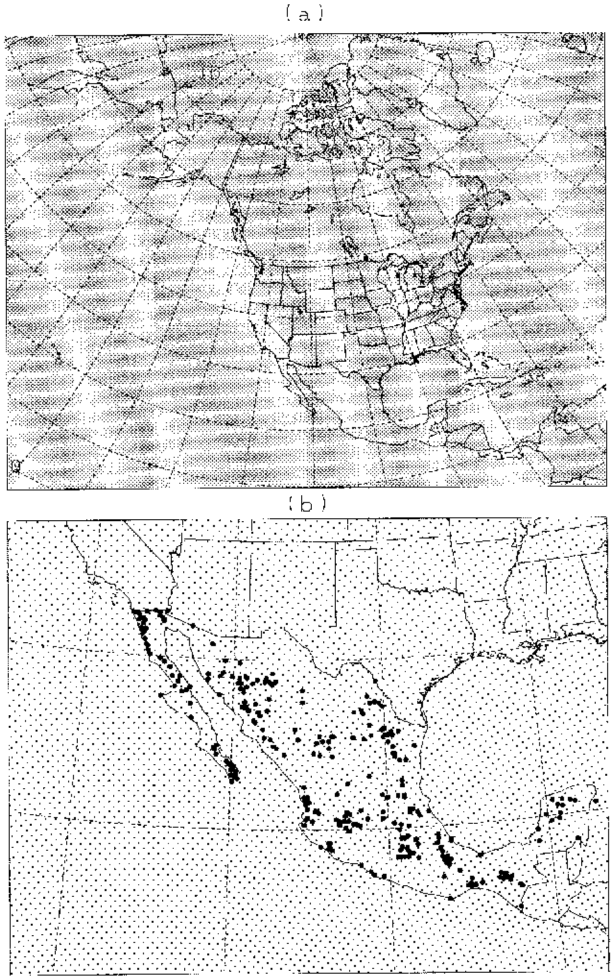

FIG. 1. (a) Domain and grid of the Eta Model; (b) close-up over Mexico. The thin dots represent the model's grid points, while the heavier dots are GHCN stations locations.

It is known that an earlier version (1992) of the Eta Model had difficulties reproducing the monsoon in Arizona (Dunn and Horel 1994a,b). Their study, from the perspective of an operational forecaster in Phoenix, Arizona, revealed important deficiencies. The model was unable to predict heavy precipitation over central Arizona and its forecast fields would not represent correctly the moist surges and low-level jet in southern Arizona. The failure was attributed to several reasons. First, the initial and lower boundary conditions were taken from the global model's forecasts that were too coarse to represent the Gulf of California and other small-scale features. As a result, sea surface temperatures used by the model would be about 6°–8°C below typical values, thus a large gradient existed between water and the nearby deserts, forcing unrealistically strong sea breezes. Second, the Betts–Miller convection scheme appeared to have reference profiles that were not adequate for arid regions. Finally, moisture in low and midlevels would not increase as expected before the occurrence of convection.

Since then, the Eta Model has undergone significant changes. Presently, the model has its own four-dimensional data analysis system that generates its initial conditions; it uses high-resolution satellite estimates of sea surface temperatures[1] that are of particular relevance for defining the mesoscale circulations in northwest Mexico. Several changes to the parameterization of convection and surface processes (Chen et al. 1997; Betts et al. 1997) are expected to alter the moisture content at the lower levels, although it is not yet clear how it may have affected the southwestern United States in particular.

Results by Berbery and Rasmusson (1999) suggest that there may still be a deficit in monthly accumulated forecast precipitation over Arizona (see their Fig. 2), but we are unaware of other recent studies evaluating the warm season day-to-day performance of the Eta Model over the southwest. The fact that Arizona is in the periphery of the monsoon region (Douglas et al. 1993) makes it more challenging for any numerical model to predict correctly the summer precipitation in that region.

b. Observations

The limited network of rain gauges over Mexico and the complexity of the terrain (see, e.g., Negri et al. 1993), makes it most difficult to carry out an observational climatology that will reliably show the spatial structure of the precipitation patterns. Therefore, rain gauge observations are included here only to complement the analysis of high-resolution satellite estimates. The Global Historical Climatology Network (GHCN version 1; see Barlow et al. 1998 for a description) has about 170 rain gauge stations over Mexico that were used to construct a JAS 1950–85 climatology used for general reference. This dataset is not available after 1990, and rain gauge observations during 1995–97 obtained from the National Climatic Data Center appear to lack the quality needed to produce a reliable comparison with the forecast precipitation.

The National Aeronautics and Space Administration produced a precipitation dataset (known as GPROF 4.0) at 0.5° × 0.5° latitude–longitude resolution, estimated from special sensor microwave/imager instruments on board polar-orbiting satellites. The algorithm, methodology, and a discussion of biases with respect to geostationary satellite estimates are presented in Negri et al. (1993). These products were used by Negri et al. (1993, 1994) to describe the climatological features of the precipitation of the Mexican monsoon. Garreaud and

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[1] Prepared at the National Environmental Satellite, Data, and Information Service of the National Oceanic and Atmospheric Administration.

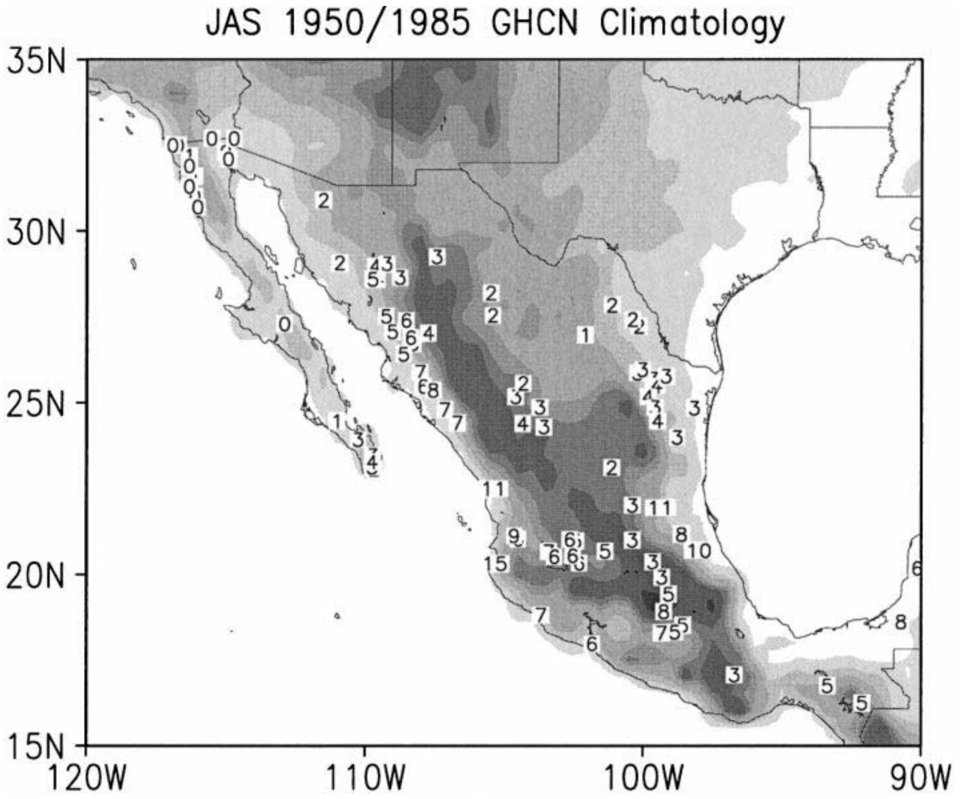


FIG. 2. JAS 1950–85 climatology of observed precipitation from GHCN dataset. Units are mm day^{-1}. The shades represent the topography. (Only stations that are at least 0.2° apart are represented here.)

Wallace (1997) compared Negri et al.'s climatology to their convective cloud (clouds with tops colder than 235 K) frequency estimated at 3-h intervals from geostationary satellites, and found similar patterns in both datasets. The satellite-estimated averages presented here do not include August and September 1997, since these two months are not available in the GPROF 4.0 dataset.

3. Consistency of the model forecasts

a. Precipitation

Figure 2 presents a climatology based on GHCN stations for JAS 1950–85, which shows that typical precipitation values over the western slopes of Sierra Madre Occidental are 6–8 mm day^{-1}, similar to those mentioned in the literature; coastal regions in western Mexico have values as high as 15 mm day^{-1}; large areas, including the northern sector of the Isthmus of Tehuantepec, are not covered by stations and thus no reliable observational estimates can be offered.

Quantitative evaluation of the model's performance in regions of scarce data is always difficult particularly during summer. In this article, satellite estimates are used to show that the model's performance is consistent with our current knowledge of the climate over the monsoon region. Figure 3a presents the JAS 1995–97 precipitation as estimated from GPROF 4.0. The pattern is similar to Negri et al.'s climatology, with the largest values found in an elongated maximum along the western slopes of the Sierra Madre Occidental. The precipitation maximum of about 20 mm day^{-1} seems high by a factor of 2 with respect to rain gauge climatologies (see Fig. 2; also Mosiño and García 1974; Barlow et al. 1998), even considering that the averaging period (3 yr) is relatively short. According to Negri et al. (1993) the excessive precipitation could be related to the evening satellite overpass that occurs at the time of maximum rainfall rate that is typically not expected to last but a few hours. Therefore, a simple average of morning and afternoon–evening precipitation will have a positive bias. Other regions of large precipitation are found toward the Tropics: the northern extension of the intertropical convergence zone (ITCZ) around 108°W, another near the west coast of Mexico, and yet another one over the Isthmus of Tehuantepec.

Figure 3b presents the JAS 1995–97 averaged precipitation fields from the Eta Model 12–36-h forecasts. The elongated maximum of the forecast precipitation along the western slopes of the Sierra Madre Occidental is similar in shape, location, and scale to the pattern obtained from the satellite estimates; it depicts small-scale centers (also similar to those observed in the satellite estimates) that could be associated with valleys and changes in orography. Maximum values of 8–10

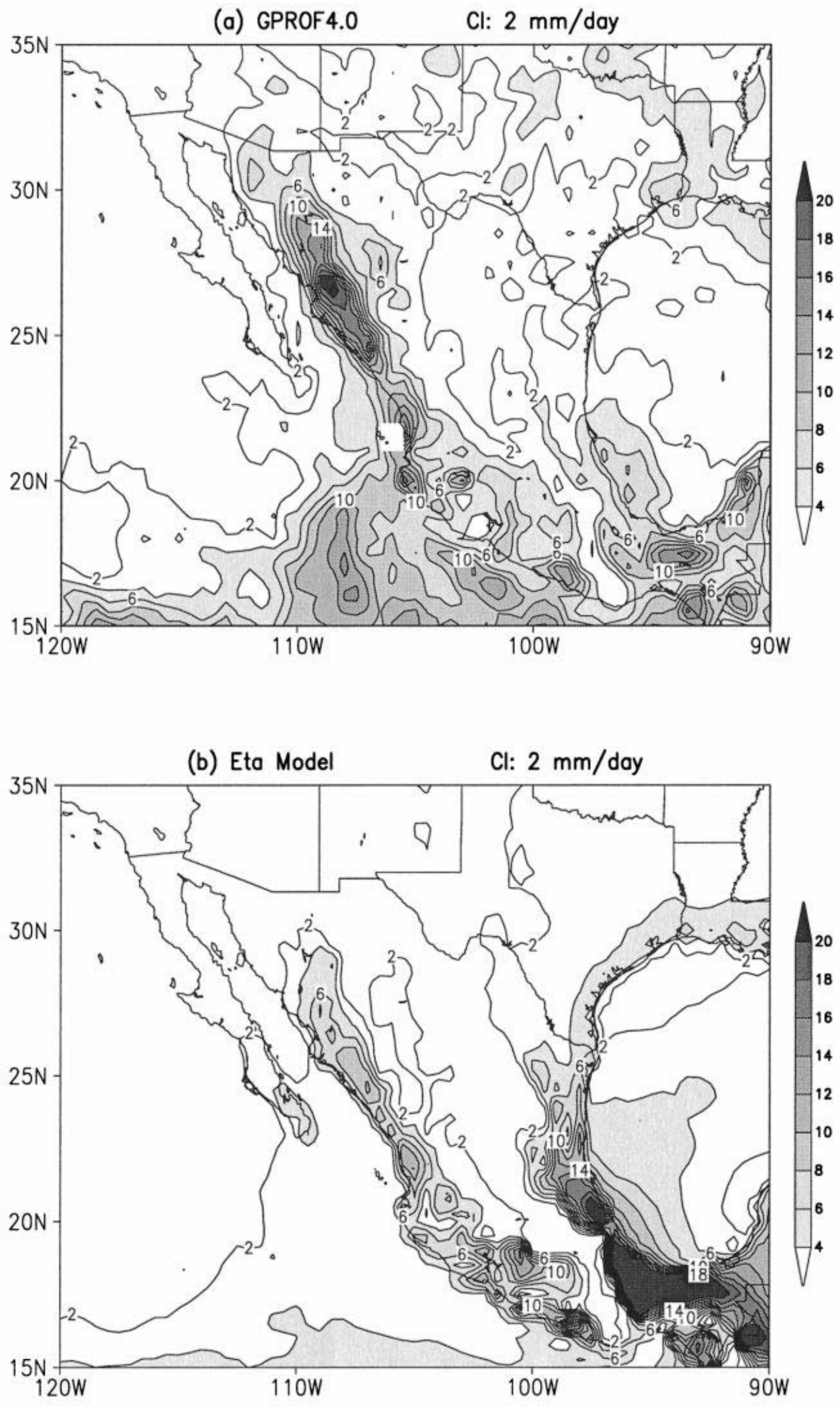


FIG. 3. Precipitation for JAS 1995–97 as estimated from (a) satellite measurements and (b) from Eta Model 12–36-h forecasts. Contour interval is 2 mm day^{-1}.

mm day^{-1}, are about half the intensity of satellite estimates, but in closer agreement to the climatologies based in rain gauges (Fig. 2; Mosiño and García 1974; Douglas et al. 1993).

Larger differences between forecast and satellite estimates of precipitation are found toward the Tropics. Over the ITCZ, the model appears to produce less rain than it is estimated from satellites; however, the most

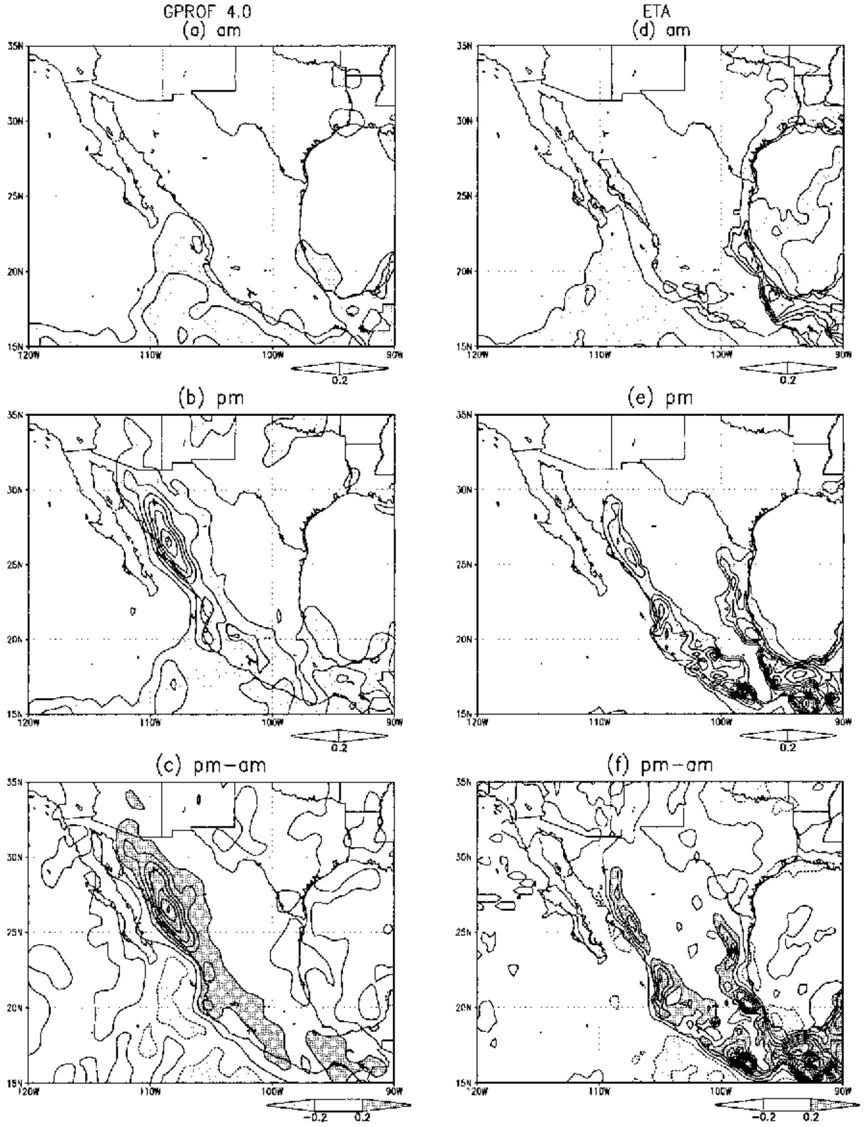


FIG. 4. (a) Morning (a.m. satellite pass) precipitation as estimated from satellite measurements; (b) same as (a) for the afternoon (p.m. satellite pass); (c) amplitude of the diurnal variability in precipitation as estimated from afternoon minus morning precipitation. (d), (e), (f) Same as (a), (b), (c) for the Eta Model forecast precipitation, where morning is defined as the period 0500–1300 LST and afternoon as 1700–0100 LST. Contour interval is 0.2 mm h^{-1} and the shades are specified below each figure.

notable differences are found over the northern part of the Isthmus of Tehuantepec (toward the Bay of Campeche) where precipitation up to a maximum of 27 mm day^{-1} is predicted by the model. It is likely that the large precipitation is related, at least in part, to a deficiency in the model's convective parameterization scheme as discussed by Manikin et al. (1998), who also found excessive precipitation along the northern coast of the Gulf of Mexico. (The results in Fig. 3b also show that the model produced precipitation along the coastline of the Gulf of Mexico, where satellite estimates do not exhibit precipitation.) Manikin et al. (1998) suggest that this deficiency is due to the assumption of different reference profiles over land and sea in the convective parameterization scheme, and by selecting one unique reference profile they obtained improvements along the coast of the Gulf of Mexico.

b. Amplitude of the diurnal cycle of precipitation

The diurnal cycle is one of the dominant modes of variability of the monsoon system; Figs. 4a–c depict the amplitude of the diurnal cycle of precipitation estimated for 1995–97 from GPROF 4.0 data. Morning precipitation is found over the Pacific Ocean connected to the ITCZ (Fig. 4a), while during the afternoon large precipitation develops over the western slopes of the Sierra Madre Occidental (Fig. 4b). The dominance of afternoon precipitation over land in western Mexico and morning precipitation over the oceans is further noted in the afternoon-minus-morning precipitation difference (Fig. 4c). This diurnal cycle pattern has been discussed earlier by Negri et al. (1994) and verified by Garreaud and Wallace (1997) using convective cloud frequency.

Figure 4d presents the 12–18-h Eta Model forecast precipitation that roughly corresponds to 0500–1100 LST. Some differences with satellite estimates of rainfall rate should be expected, since the latter are obtained from instantaneous values at the time of the satellite overpass, while the Eta Model forecast precipitation is the accumulation over a 6-h period. As with the satellite estimates, most model forecast precipitation in the morning occurs over the ocean and western coastal areas. (The model forecast precipitation along the east coast of Mexico responds to the model deficiency discussed earlier.) According to Fig. 4e, the 24–30-h forecast precipitation that corresponds to the afternoon–evening (about 1700–2300 LST) develops over land and achieves its maximum of about 0.6 mm h^{-1} over the Sierra Madre Occidental. At the same time, there is almost no precipitation over the oceans. The morning and afternoon patterns of precipitation resemble the first eigenmodes of the empirical orthogonal function analysis over ocean and land discussed by Garreaud and Wallace (1997). Except over the eastern coast of Mexico, the satellite- and model-estimated afternoon-minus-morning difference fields (Figs. 4c,f) have similar general features (but not magnitude).

c. Evaporation

Model evaporation was not available in the archives during 1995 and no attempt was made to derive it as a residual of the moisture budget equation (see, e.g., Berbery and Rasmusson 1999) because no reliable quantitative estimates of observed precipitation were available. Thus, the discussion here will focus on the fields for 1996 and 1997. Parameterizations in the Eta Model underwent changes that influenced evaporation during the period covered in this study: from January 1996 to February 1997, an extended Pan–Mahrt land surface scheme was used (see Chen et al. 1996). In February 1997 changes were made to soil moisture and bare soil evaporation (Black et al. 1997); with these changes, evaporation over land was increased and the low-level dryness was reduced. However, these changes are not expected to affect the estimates of evaporation over water.

Seasonal evaporation estimates obtained from the 12–36-h forecasts for 1996 and 1997 are presented in Figs. 5a,b, respectively. Evaporation over the plateau in central Mexico was about 1 mm day^{-1} during the summer of 1996 and about 2–3 mm day^{-1} during the summer of 1997, with the increase probably being the result of the aforementioned changes to the model parameterization. On the other hand, the evaporation fields over water are similar for the two years. The overall average (Fig. 5c) has largest values over the Gulf of Mexico (about 5 mm day^{-1}) and over the Gulf of California (about 4 mm day^{-1}). Estimates of evaporation derived from observations over coastal stations of the Gulf of California have reported annual values close to 2.7–3 mm day^{-1} (Castro et al. 1994), which could be consistent with the larger, summer-only, values from the model.

The spatial variability of evaporation over the Gulf of California deserves further discussion, since usually numerical model simulations of the Mexican monsoon assume a constant sea surface temperature along the gulf. Observational and ocean model studies have shown that the Gulf's physical characteristics are heterogeneous: ocean depth varies from about 1000 to 2000 m in the southern region to about 100–200 m to the north. Two islands near 29°N, *Angel de la Guarda* and *Tiburón*, produce notable heterogeneities in the ocean circulation (see, e.g., Beier 1997), and observational data obtained during cruises have shown intense upwelling at the same location (e.g., Roden and Groves 1959). Changes in sea surface temperatures have also been measured, with a local decrease of about 2°C (Robinson 1973). Badan-Dangon et al. (1991) also found significant changes in the local atmospheric circulations near the islands, affecting the dewpoint and temperature of the marine boundary layer.

The Eta Model products seem to capture the character of this region, as the (model) surface temperature is about 28°C in the northern gulf, but about 3°C lower near the islands (not shown). Similarly, the model evaporation has a minimum of about 1–2 mm day^{-1} close to the two islands (Fig. 5d).

4. Moisture flux diagnosis

Investigation of the moisture transports in the North American monsoon region has been pursued earlier using global analyses (e.g., Schmitz and Mullen 1996; Higgins et al. 1997; Barlow et al. 1998). These analyses have helped understand the large-scale features of the monsoon, but Schmitz and Mullen have suggested that even the European Centre for Medium-Range Weather Forecasts' global analyses at T106 resolution (about 1.125°) are too coarse to resolve local terrain features. Here, EDAS analyses are used to investigate the moisture transports near and around the Gulf of California.

a. Moisture availability

The water vapor content of the atmosphere over the Gulf of California is larger than over surrounding regions. Figure 6a shows that it ranges from about 35 mm on the northern sector of the gulf to about 50 mm to the south, where a moist tongue close to the shore of

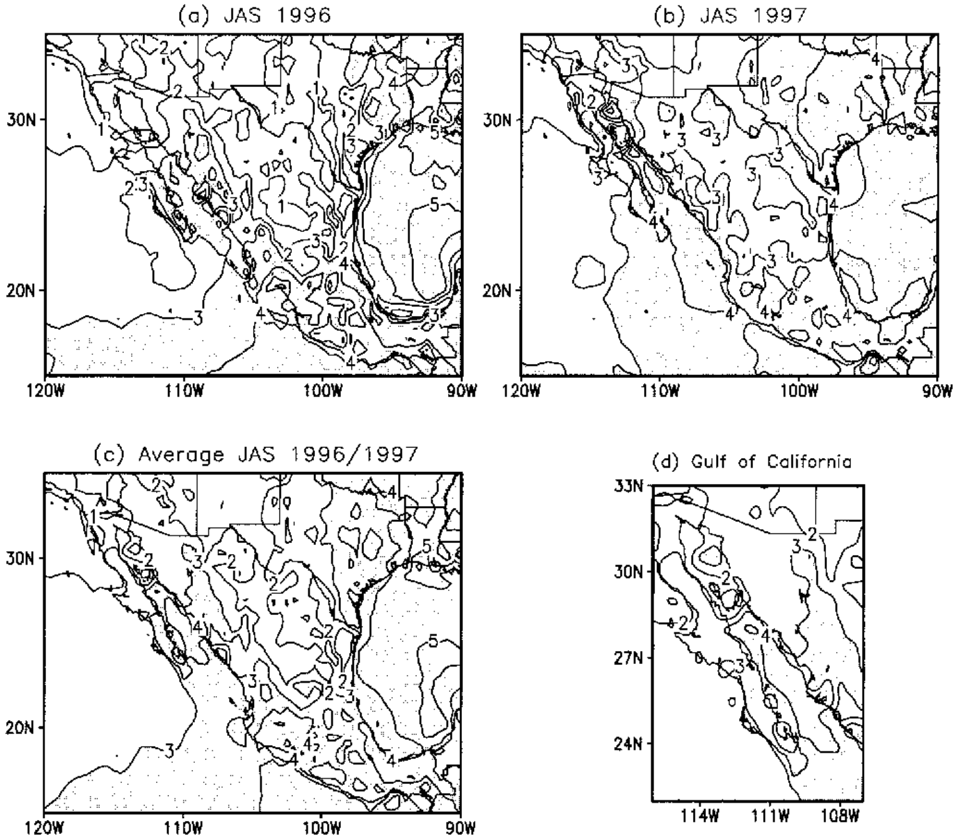


FIG. 5. Eta Model evaporation for (a) JAS 1996; (b) JAS 1997; (c) the average for JAS of 1996 and 1997; (d) same as (c) but detailed over the Gulf of California. Contour interval is 1 mm day^{-1} and values larger than 3 mm day^{-1} are shaded.

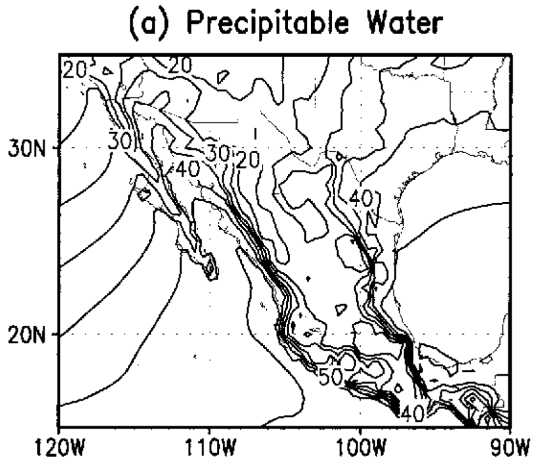
southern Mexico widens toward the ITCZ. The latter values are even larger than those found over the Gulf of Mexico, and larger by 5–10 mm than those over the Pacific Ocean at the same latitudes. Because of elevated terrain, the atmosphere over Mexico has less moisture content, with typical values of approximately 15–20 mm.

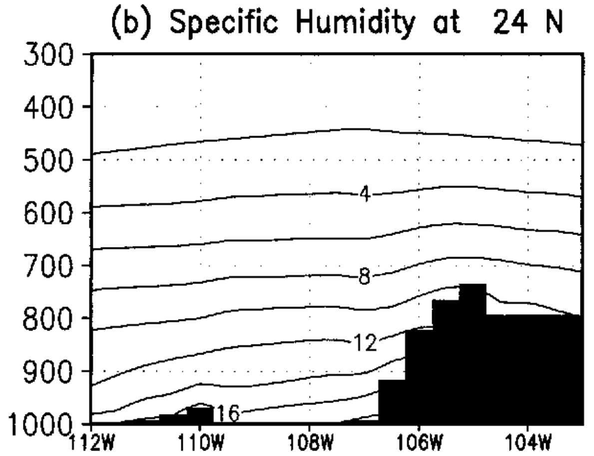
Figure 6b presents the vertical distribution of moisture over the southern–central part of the Gulf of California (at 24°N) where values as large as 18 g kg^{-1} near the surface are noticed. According to Fig. 6c, the northern sector (30°N) is less humid, with values of 15 g kg^{-1} near the surface. The two cross sections show that largest values are found toward the east of the gulf, that is, surfaces of specific humidity are upward sloping toward the east, as in the cross section discussed by Stensrud et al. (1995, their Fig. 14). Our results do not exhibit any effect that could be associated with terrain above 600 hPa as in Stensrud et al.'s results, which showed that topography could be felt up to 400 hPa. This difference could be due to the different vertical coordinates in the models.

b. *Total moisture flux*

The vertically integrated total moisture flux and its convergence are presented in Fig. 7. The easterly flow over the Gulf of Mexico branches out in two directions: the northward branch is related to the well-known Great Plains low-level jet; the southward branch crosses the Isthmus of Tehuantepec in southern Mexico, and then curves anticyclonically over the Pacific Ocean toward the Sierra Madre del Sur.

According to Fig. 7, large moisture flux convergence is found on the northern sector of the Isthmus where large model forecast precipitation is found; the convergence, along with divergence toward the south of the Isthmus, form a dipole pattern that may be partly a result of the mentioned convection parameterization scheme deficiency, probably augmented by topography effects similar to those discussed by Rasmusson and Mo (1996) for larger scales. A second, larger region of moisture flux convergence is found on the western slopes of Sierra Madre del Sur, also collocated with large values of precipitation (Fig. 2). While the location of the moisture





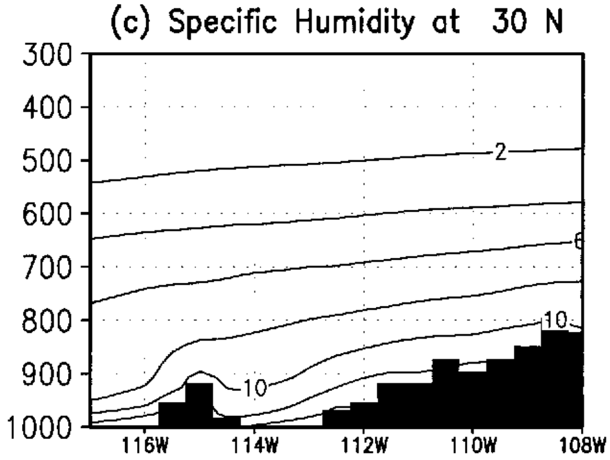


FIG. 6. (a) JAS 1995–97 mean precipitable water estimated from EDAS analyses. Contour interval is 5 mm; cross section of specific humidity at (b) 24°N and (c) 30°N. Contour interval is 2 g kg^{-1}.

flux convergence is consistent with that of the precipitation pattern, its intensity may be overestimated.

The central–southern part of the Gulf of California is marked by weak easterly fluxes and no clear convergence/divergence pattern. The direction of the fluxes is similar to that estimated by Schmitz and Mullen (1996) and Barlow et al. (1998), and, as it will be shown later, it is the result of having averaged all times of the diurnal cycle into the seasonal means: analysis of the total moisture flux will not provide clear patterns unless the diurnal cycle is taken into account (see section 4c).

Finally, the northern sector of the Gulf of California has divergence of moisture flux with a weak moisture flux emanating mostly toward Arizona, thus supporting the notion that the northern part of the gulf is a moisture source for the southwestern United States. This region will be discussed in section 5.

c. *Diurnally modulated circulations*

The moisture flux over the Gulf of California presented in Fig. 7 is the average of all analysis times without distinction of the diurnal cycle. However, the strong solar heating over land and slopes of the Sierra Madre Occidental during the afternoon forces a sea breeze, as discussed by Stensrud et al. (1995). The influence of the breeze on the vertically integrated moisture flux is illustrated in Fig. 8, where the moisture flux convergence is computed separately for daytime and nighttime hours. Daytime is defined as 1800–2400 UTC (1100–1700 LST) and nighttime is defined as 0600–1200 UTC (2300–0500 LST).

During daytime hours (Fig. 8a), an afternoon pattern of widespread divergence of about 0.4 mm h^{-1} is found over the Gulf of California, where large evaporation from the surface is taking place. A well-defined pattern of moisture flux convergence with maximum values of about 0.6 mm h^{-1} is located mostly over land along the western slopes of the Sierra Madre Occidental; large convergence is also found over the slopes of the Sierra Madre del Sur, with largest values of about 1.2 mm h^{-1}. In general, the maximum centers of convergence are collocated with those of maximum precipitation (see Figs. 2 and 4).

During nighttime hours (Fig. 8b) the circulation reverses and the opposite pattern emerges: the slopes of the Sierra Madre Occidental have divergence of moisture flux, and some convergence is noticed along the coast. Moisture flux convergence is still present toward the Sierra Madre del Sur in southwestern Mexico, suggesting that, apart from the diurnally modulated circulations, other effects are contributing to the development of precipitation. Similarly, the northern Gulf of California maintains a divergent pattern during the morning as well, again suggesting that other factors exist besides the diurnal variability. This will be discussed later in section 5. Over southern Arizona there is convergence during nighttime and divergence during day-

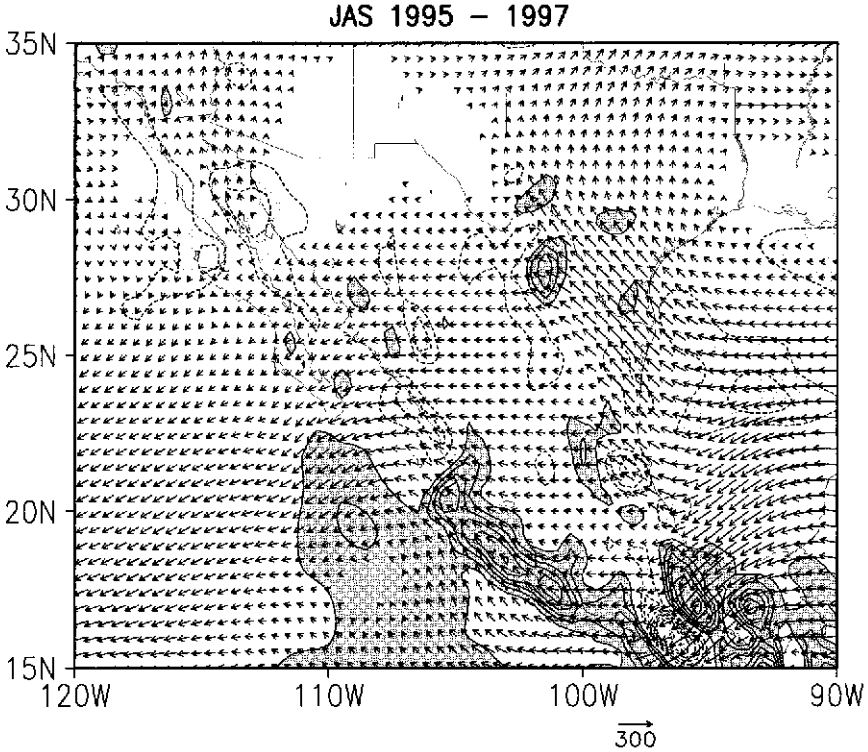


FIG. 7. Vertically integrated moisture flux (arrows) and its convergence (isolines and shades). The arrow scale at the bottom represents 300 kg m^{-1} s^{-1} and values smaller than 30 kg m^{-1} s^{-1} are not displayed; contour interval for the moisture flux convergence is 5 mm day^{-1}, with convergence shaded dark for values larger than 5 mm day^{-1} and light shades represent divergence also larger than 5 mm day^{-1}.

time, agreeing with Douglas et al. (1998). Convergence is found over the eastern Pacific Ocean at all times, but it is largest during nighttime, agreeing with the nighttime–early morning increase of precipitation over water.

The regional features are better depicted as the difference between daytime and nighttime convergence (Fig. 8c): the slopes of the Sierra Madre Occidental have an elongated area of convergence with values exceeding 1 mm h^{-1} while a weaker divergence pattern covers all the Gulf of California. The corresponding daytime–nighttime difference of vertically integrated moisture flux (Fig. 8d) clearly reveals the effect of a sea breeze that is further enhanced by the terrain of the Sierra Madre Occidental. (Note that the southward arrows over Texas represent a decrease of the northward moisture flux during the afternoon, which is the time of the day when the Great Plains low-level jet is at its minimum intensity.)

Therefore, an efficient mechanism exists by which the large evaporation over the Gulf of California increases the moisture content of the atmosphere; the afternoon sea breeze favors the moisture flux divergence over the gulf and transports moisture toward the slopes of the Sierra Madres, where large moisture flux convergence is followed by precipitation.

d. Time mean and transient moisture flux

It was shown earlier that inclusion of the diurnal cycle can help explain the moisture transports in the monsoon region. Similarly, decomposition of the total moisture flux in its time mean and transient components (defined as deviations from the mean diurnal cycle; see Berbery et al. 1996) may provide additional information about other acting processes.

Figure 9a shows that the time mean fluxes at 950 hPa are largest over the Gulf of Mexico. accounting for most of the total easterly flow, and the northward and southward branches over the United States and southern Mexico, respectively. The northern sector of the Gulf of California (about 30°N) has a northward component with some influx from the Pacific Ocean. Small *southward* fluxes are noted over the central and southern parts of the gulf, which seem to be in disagreement with earlier observational studies (e.g., Badan-Dangon et al. 1991; Douglas 1995).

The transient component of the moisture flux at 950 hPa (Fig. 9b) shows a different picture from the time mean component. The transient flux is northward all along the Gulf of California with some spreading toward land. Over other regions, the magnitude of the transient fluxes is smaller than the time mean component by 1

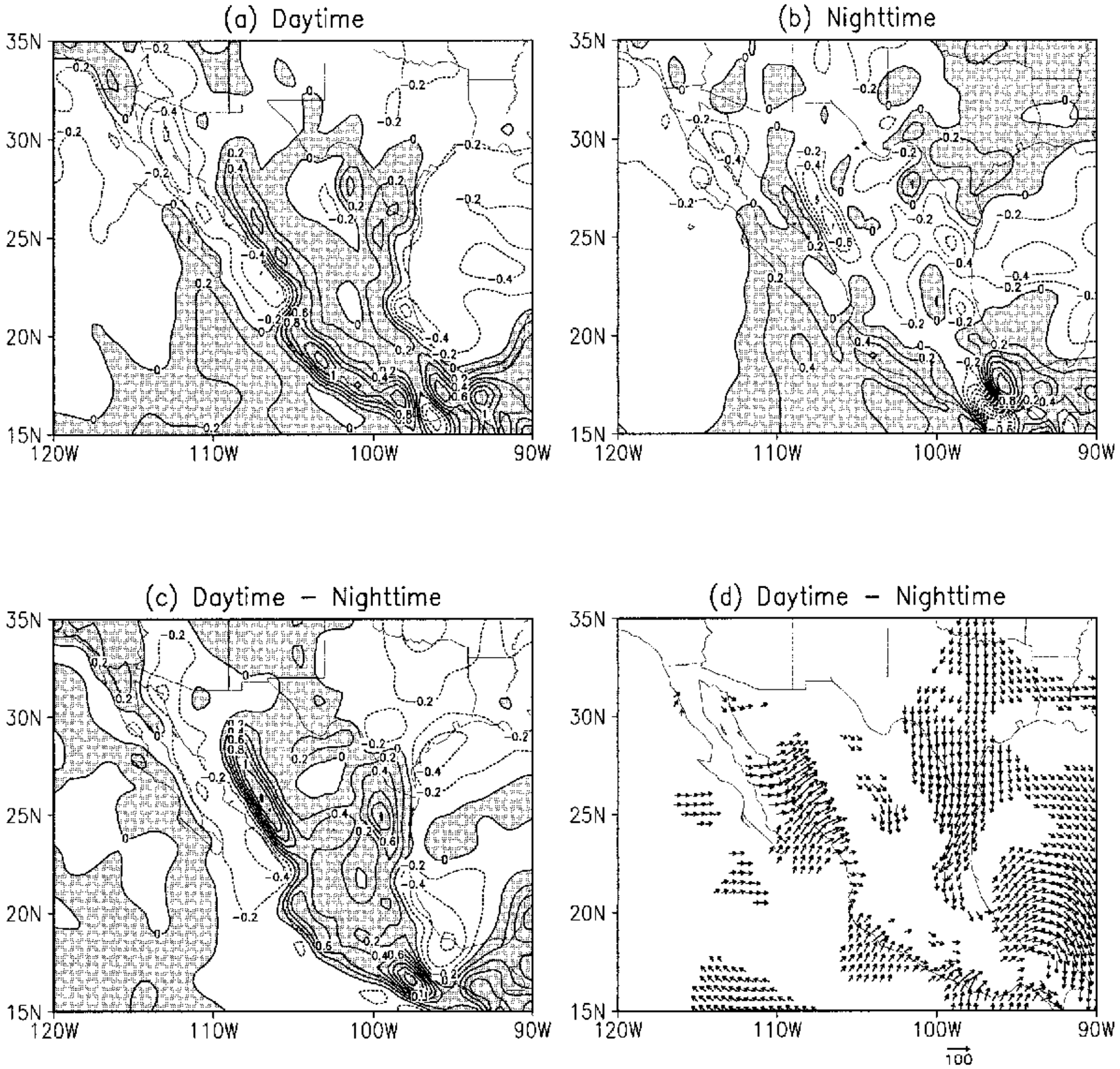


FIG. 8. Vertically integrated moisture flux convergence during (a) daytime, (b) nighttime; (c) their difference; (d) daytime minus nighttime difference in vertically integrated moisture flux. Daytime is defined as 1800–2400 UTC (1100–1700 LST). Nighttime is defined as 0600–1200 UTC (2300–0500 LST). Contour intervals in (a), (b), (c) are 0.2 mm h^{-1} and positive values are shaded. The arrow scale at the bottom of (d) is 100 kg m^{-1} s^{-1} and values smaller than 30 kg m^{-1} s^{-1} are not displayed.

order of magnitude, but over the gulf it is as large as one-third of the time mean flux. In the northern sector of the gulf, the transients and the time mean flux have the same northward direction, suggesting that the two components are supplying moisture to the southwestern United States.

The direction of the transients along the gulf is similar to that of the northward moist surges (Hales 1972, 1974) whose generation was discussed by Stensrud et al. (1997). This study will not analyze the contribution of the moist surges to the moisture transports, but their effect is included in the transients. The typical features of the moist surges are exemplified in Fig. 10a, where the August 1997 time–height section of the 3-h meridional moisture flux at 30°N, 113.5°W is presented. Episodes of large northward moisture flux are found with values as large as 120 g kg^{-1} m s^{-1}, corresponding to northward winds of about 10–12 m s^{-1}. One of these events (13–18 August) is associated with the northward progression of tropical storm Ignacio to the west of the Baja Peninsula. A Hovmöller (longitude–time) diagram of moisture flux at 900 hPa for the same period (Fig. 10b) suggests a mix of timescales, from diurnal to synoptic (modifications to the diurnal cycle by moist surges are discussed by Anderson et al. 2000b). The channeling effect of the gulf is notable, particularly during 13–16 August, when the northward flux is flanked by fluxes in the opposite direction.

The vertically integrated time mean and transient moisture fluxes and their respective convergences are

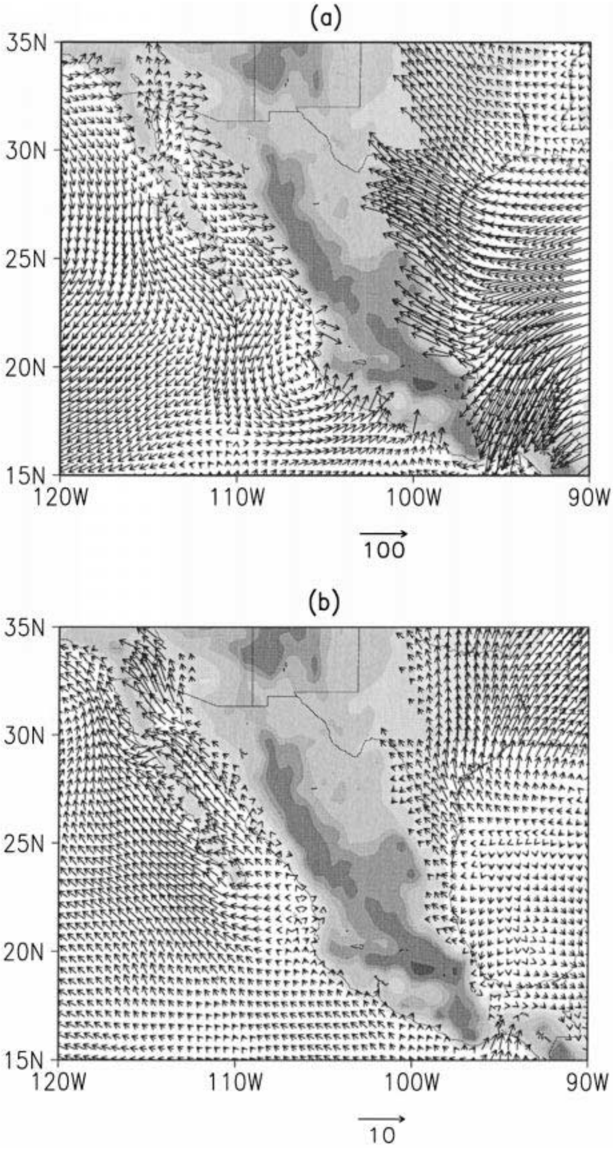


FIG. 9. (a) Time mean and (b) transient components of the moisture flux at 950 hPa. The arrow scales in g kg^{-1} m s^{-1} are depicted at the bottom of each figure. The shades represent the topography.

presented in Fig. 11. Figure 11b shows that large time mean moisture flux convergence is found along the slopes of Sierra Madre del Sur. Also, the time mean appears to carry all the signal for the pattern of moisture flux convergence (real or in error) over the Isthmus of Tehuantepec.

The time mean moisture flux (Fig. 11a) is usually larger than the transient component (Fig. 11c) by 1 order of magnitude. However, the difference is significantly reduced over the Gulf of California, and the same is true for the moisture flux convergence. Over the northern part of the gulf, the time mean vertically integrated moisture flux divergence is about 5 mm day^{-1}, while the transient component (Fig. 11d) has values ranging between 2 and 4 mm day^{-1}. This suggests that in the northern sector of the gulf time mean and transient contributions are about the same magnitude.

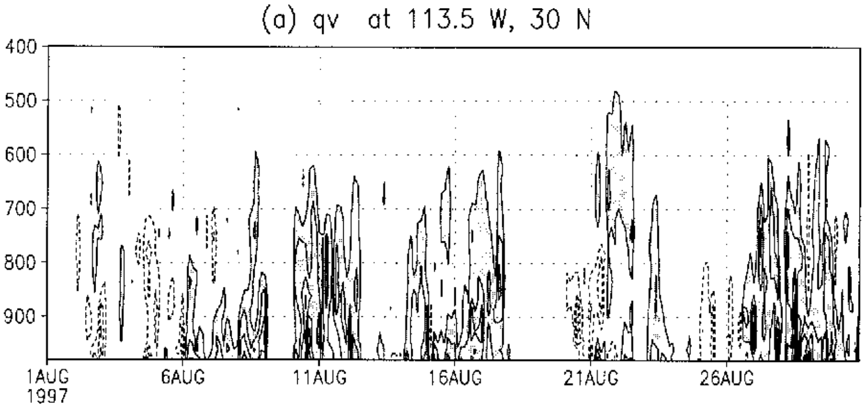
The previous description differs from earlier analysis of the transients (e.g., Schmitz and Mullen 1996, their Fig. 6b) that show generalized westward transient flux over the Gulf of California and a dominance of the time mean circulation over the transients. The differences can be explained by the mesoscale nature of the moisture transports within the gulf that are not properly resolved by the coarse grid spacing of the global analyses. Moreover, the improvement in the representation of the moisture fluxes (when compared to those from global analyses, even those at T106) could suggest that the Eta assimilation system supports physical mechanisms not included in the global analysis systems.

5. Northern gulf low-level circulations

The northern sector of the Gulf of California has distinct characteristics that are relevant for the southwestern United States climate. Douglas (1995) and Douglas et al. (1998) have given observational evidence of the local circulations as estimated from radiosondes and pilot balloons for short periods, and their results have been established as a benchmark for modeling studies. It is then of interest to compare patterns from the Eta Model analyses with those from Douglas' work. However, taking advantage that wind vectors do not differ in direction from the moisture flux, the discussion will be centered on the latter because they can be related better to the precipitation processes.

a. Vertical structure

Figure 12 depicts the moisture flux at four levels (980, 925, 850, and 700 hPa), which can be compared with the streamline analysis at equivalent levels discussed by Douglas (1995, his Fig. 2; see also Douglas et al. 1998, their Fig. 7). At 980 hPa (Fig. 12a) low-level winds from the gulf have an anticyclonic curvature and transport moisture toward Arizona. The eastern side of the subtropical anticyclone over the Pacific Ocean has a large southward moisture flux, which at this level is not connected to the Gulf of California. The moisture flux toward Arizona is more evident at 925 hPa (Fig. 12b) where two new features are noticed. First, moisture flux from the Pacific Ocean is seen to cross the Baja Peninsula into the Gulf of California (the model's topography is slightly lower than the actual one over the Baja Peninsula, thus it is not clear at what precise level the influx from the Pacific begins). Second, a new branch of the northward moisture flux is now found along the border between Arizona and California. At 850 hPa (Fig. 12c) the moisture flux shows a new influx of moisture from the Pacific Ocean toward Nevada at about 35°N. Finally, at 700 hPa (Fig. 12d) the circulation is predominantly anticyclonic, with a center over Arizona.



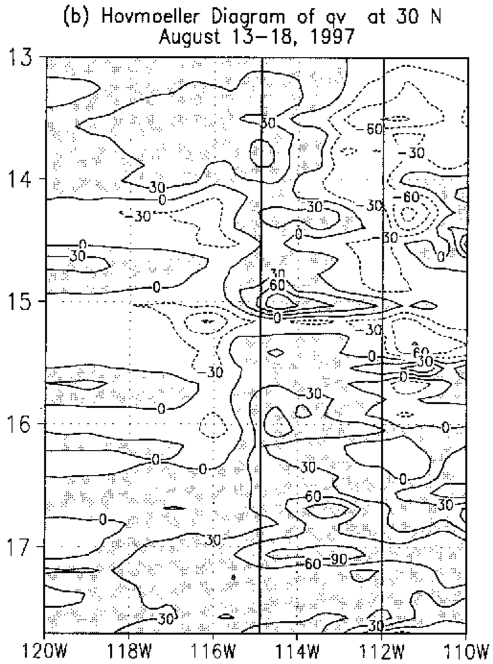


FIG. 10. (a) Time–height cross section of the meridional component of the moisture flux for Aug 1997 over the north of the Gulf of California (30°N, 113.5°W). Contour interval is 30 g kg^{-1} m s^{-1} and positive values are shaded. (b) Hovmöller diagram of the 900-hPa meridional component of the moisture flux at 30°N for 13–18 Aug 1997. Contour interval is 30 g kg^{-1} m s^{-1} and positive values are shaded. The vertical lines at 112°W and 115°W represent the boundaries of the Gulf of California.

Our results for the northern sector of the gulf, while agreeing with Douglas' (1995) observational study, suggest a more complex structure, particularly at the two midlevels (Figs. 12b,c).

b. The low-level jet over the northern gulf

The role of the low-level winds from the Gulf of California in supplying moisture to Arizona and New Mexico was discussed by Douglas (1995), who found a jet over the gulf with strongest intensity toward the north. A cross section along 31°N (Fig. 13a) effectively shows such a structure with most of the northward moisture flux occurring below 900 hPa. The moisture flux has a maximum of about 32 g kg^{-1} m s^{-1}, which corresponds to average wind speeds of about 3–4 m s^{-1} (about one-fourth of the intensity of the Great Plains low-level jet; Berbery and Rasmusson 1999). The magnitude of the meridional wind is also low when compared with the 5–7 m s^{-1} reported by Douglas et al. (1998), but it represents a three-summer season all-time average. Individual cases with speeds of 15 m s^{-1} are obtained, and they seem related to moist surges. Traces of a secondary maximum of northward moisture flux at

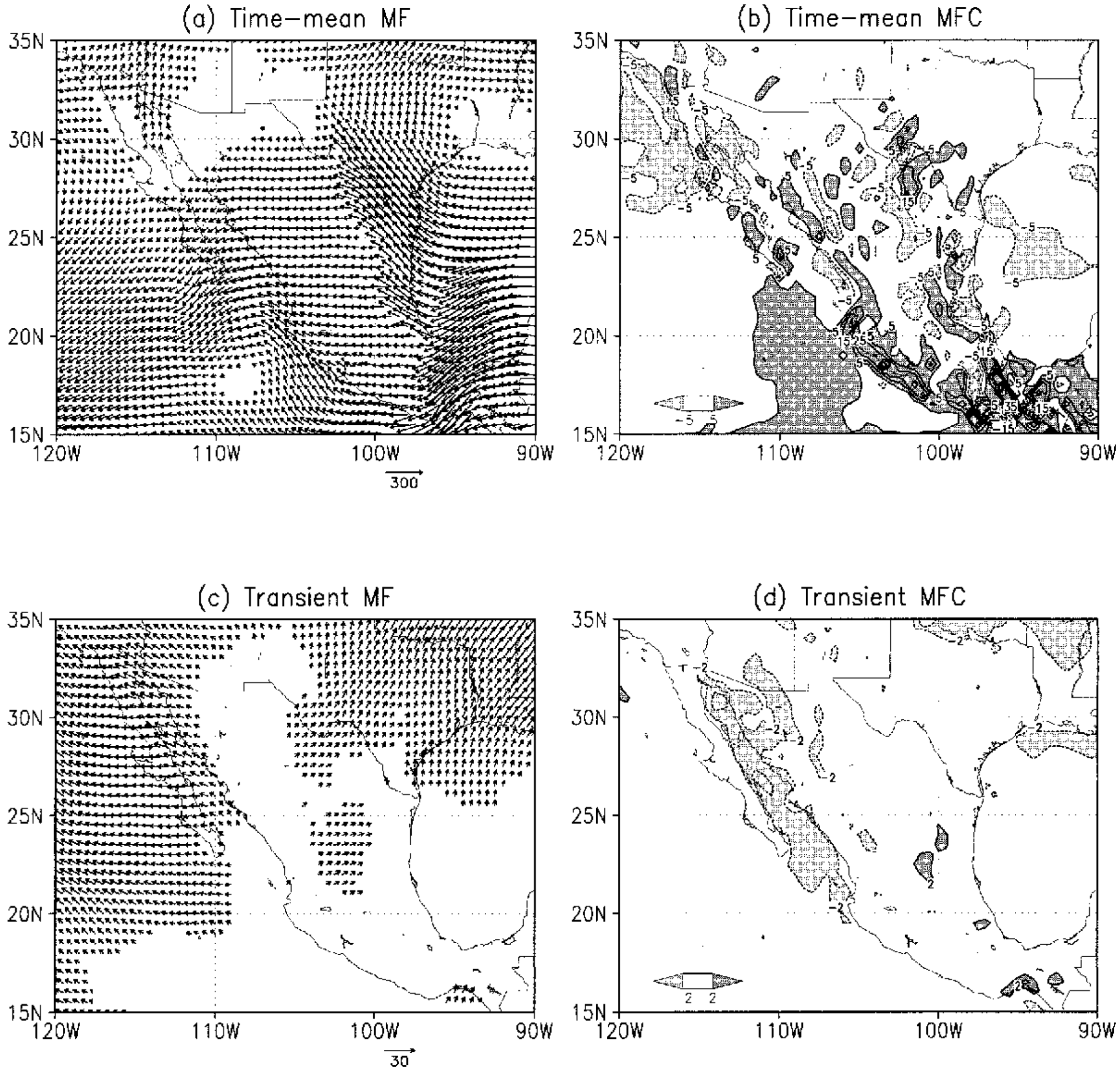


FIG. 11. (a) Vertically integrated time mean moisture flux and (b) its convergence. (c) Vertically integrated transient moisture flux and (d) its convergence. The arrow at the bottom of (a) and (c) is the scale in kg m^{-1} s^{-1}, and values smaller than 30 kg m^{-1} s^{-1} and 5 kg m^{-1} s^{-1}, respectively, are not displayed. Contour intervals in (b) and (d) are 5 mm day^{-1} and 2 mm day^{-1}, respectively.

700–600 hPa are noticed, and in fact can also be observed in the results of Rasmusson (1967), obtained from radiosonde observations.

Figure 13a also reveals that the core of the meridional moisture flux is slightly shifted toward the western coast of the gulf despite that the moisture content, shown in Fig. 6, increases toward the east. Thus, the meridional wind over the gulf must have some increase toward the west to compensate the moisture asymmetry (indeed this is the case as verified by the cross section of the meridional wind, not shown). This westward shift is consistent with the uncentered jet shown in the case study described by Douglas (1995) using special aircraft measurements.

As depicted in Fig. 13b, meridional moisture flux at the center of the jet (31°N, 114°W) has a marked diurnal cycle with largest intensity between 2000 and 0500 LST, and a maximum at about 2300 LST (0600 UTC). Observations have not been conclusive to establish the time of the maximum wind, although it has been regularly found during nighttime. Douglas et al. (1998), using observations during the summer of 1995, detected a maximum at Puerto Peñasco (31.3°N, 113.5°W) at about 0100 LST (0800 UTC). The 2-h phase difference could be related to the fact that the results in Douglas et al (1998) are based on a 2-week period (30 July–14 August 1995) while results reported here are based on three summer seasons.

Again according to Fig. 13b, between 1400 and 1800 UTC (0700–1100 LST) there is a rapid decay of the intensity of the meridional moisture flux at the lowest levels, while a deeper layer (up to 600 hPa) of northward

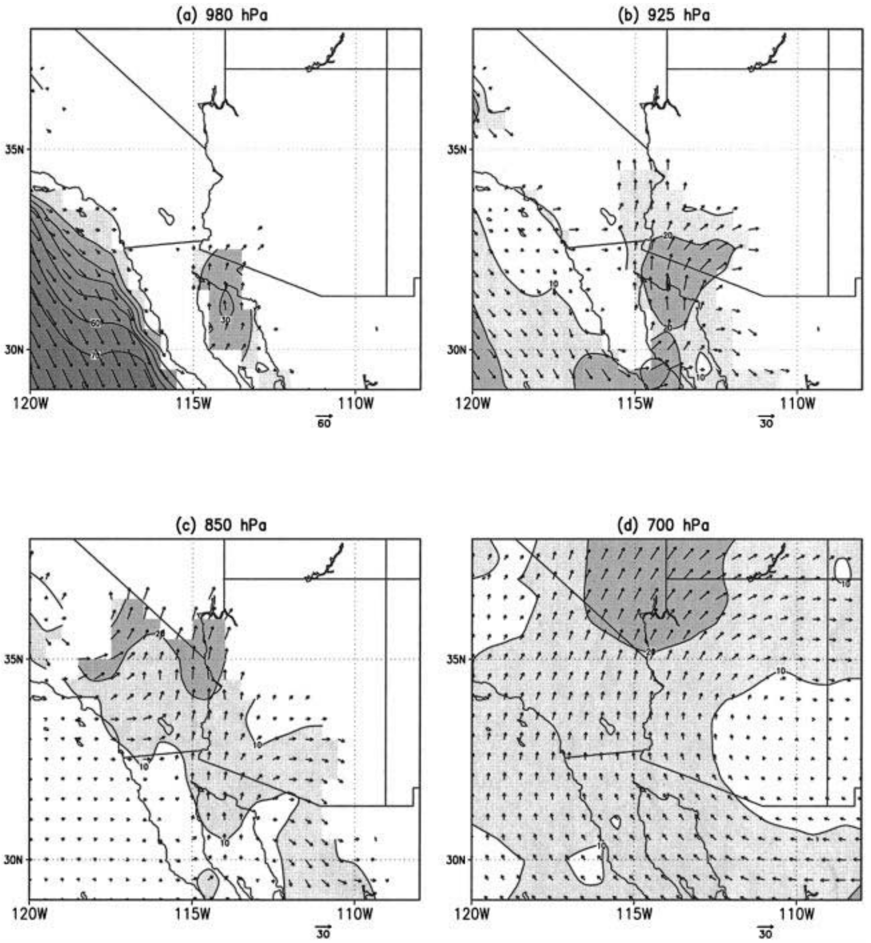


FIG. 12. Moisture flux and its magnitude at (a) 980 hPa, (b) 925 hPa, (c) 850 hPa, and (d) 700 hPa. Contour interval is 10 g kg^{-1} m s^{-1} and the arrow scales are depicted at the bottom of each figure.

moisture flux develops. The evolution of the vertical structure seems to agree with the morning destruction of a nighttime stable boundary layer due to vertical mixing of both wind and moisture. However, the fact that the vertical average is not conserved suggests that other mechanisms must be at work (e.g., horizontal advection). Douglas (1995) has suggested that there may be mixing over Yuma up to 2500 m above ground level, which is a similar depth as the one found here at 1500 UTC.

6. Summary and conclusions

Regional analyses from NCEP's Eta Model's four-dimensional data assimilation system, EDAS, and short-term forecasts during three summer seasons were employed to investigate the circulation and moisture transports over the core region of the North American monsoon. Three regions with distinct circulations were examined: the northern sector of the gulf, the central/southern part of the gulf, and southwestern Mexico. In the past the Eta Model did not properly reproduce the monsoonal circulations of northwestern Mexico and the southwestern United States, but significant changes have been done since then. The impact of such changes is reflected in more realistic circulations and forecasts that are closer to observations, as discussed here.

An evaluation of the forecast precipitation reveals that it agrees with the satellite estimates concerning location, shape, and spatial scales of the patterns. The magnitudes are similar to those from climatologies based on rain gauge observations, but over the northern part of the Isthmus of Tehuantepec and along the eastern coast of Mexico excessive forecast precipitation is found. The positive bias in the model precipitation seems to be, at least partially, due to deficiencies in the parameterization of convection, with the added effect of topography-related problems.

Precipitation over the Sierra Madre del Sur is related to the moisture flux that has a large sea and valley breeze influence; moisture flux also shows considerable persistence due to phenomena in other timescales, and, in

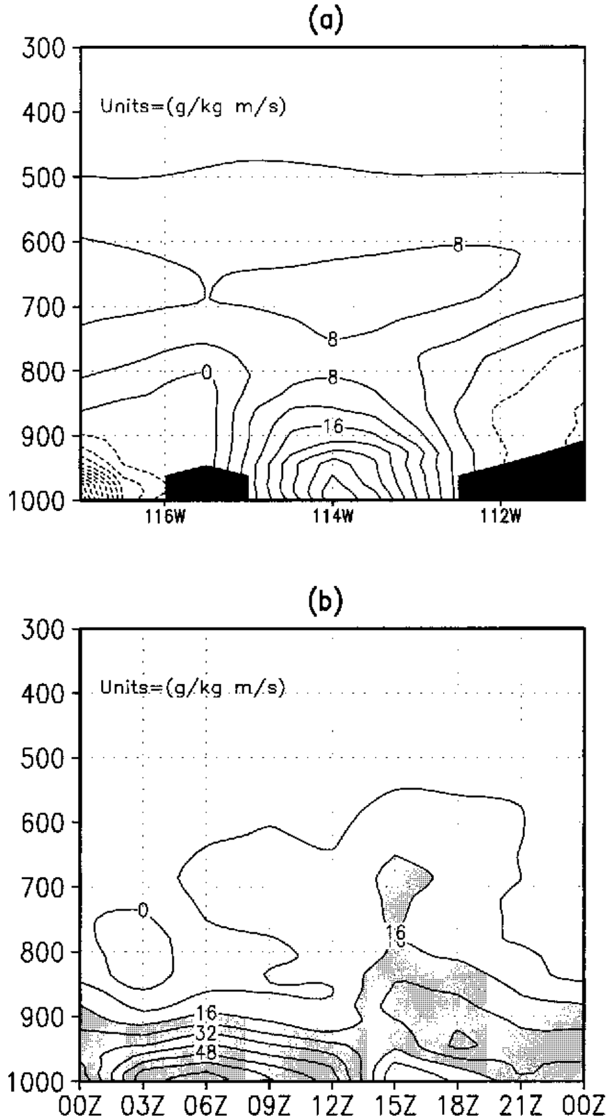


FIG. 13. (a) Cross section of meridional moisture flux at 31°N. Contour interval is 4 g kg^{-1} m s^{-1}; (b) diurnal cycle of meridional moisture flux at (31°N, 114°W). Contour interval is 8 g kg^{-1} m s^{-1} and values larger than 16 g kg^{-1} m s^{-1} are shaded.

particular, there are contributions from the easterly flow from the Gulf of Mexico that crosses the Isthmus of Tehuantepec.

The diurnal sequence of events associated with the monsoon precipitation over the slopes of the Sierra Madre Occidental can be summarized as follows: large evaporation from the Gulf of California is found throughout the diurnal cycle, and is collocated with a pattern of moisture flux divergence during the afternoon; the sea breeze favors moisture flux toward the slopes of the Sierra Madre Occidental, where large moisture flux convergence develops, and is followed by heavy precipitation. During nighttime and early morning hours, there is a circulation reversal with convergence of moisture flux near the coastline and offshore, where morning precipitation is found.

Our results show that northward transients of moisture flux along the Gulf of California, which tend to fan out over the coastal regions, also contribute to the divergence of moisture flux over the gulf. The transients' pattern, along with the moisture transports resulting from the sea breeze, support the notion of a local source of moisture from the Gulf of California. These diagnostics strongly suggest the need of incorporating the diurnal cycle and transient activity into the analysis of the moisture flux associated with the monsoonal precipitation, agreeing with arguments presented by Stensrud et al. (1995).

The primary mechanisms by which moisture is transported into the southwestern United States involve (a) a nocturnal and predawn low-level jet from the Gulf of California, and (b) transient effects, also from the Gulf of California (no attempt at separating the moist surges from other transients was done at this time). It is found that, unlike typical behavior at these latitudes, total divergence of moisture flux over the northern sector of the Gulf of California results almost equally from transients and the time mean flow.

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