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Alternative mechanisms of tropical cyclone formation in the Eastern North Pacific

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RESUMEN

Desde hace algún tiempo es sabido que el noreste subtropical del océano Pacífico, justo al oeste de la costa de México, experimenta una alta incidencia en la formación de ciclones tropicales.

Generalmente es aceptado un mecanismo de iniciación de ciclones tropicales en el Pacífico este, que involucra ondas del este, que se originan sobre Africa y se propagan a través del Atlántico. Recientes investigaciones indican que otros mecanismos, tales como la interacción del flujo de gran escala con la topografía o la formación de los sistemas convectivos de mesoescala (MCSs), pueden también ser importantes en la iniciación de ciclones tropicales en esta región.

El satélite de imágenes en infrarrojo es usado para ilustrar ejemplos específicos de los mecanismos descritos arriba, ocurridos durante la estación de huracanes de 1989. El huracán Lorena y la tormenta tropical Manuel parecen tener su origen en una misma región de tiempo perturbado, asociado con el flujo sobre la Sierra Madre; y la tormenta tropical Priscila, parece haberse formado de un MCS que apareció primero sobre México. Los datos convencionales de sondeo y viento, son usados para demostrar que el flujo incidente presente fue favorable para la generación de ciclones orográficos durante la formación de las tormentas Lorena y Manuel, y que el medio ambiente fue condicionado por formaciones de MCS anteriores al desarrollo de Priscila.

ABSTRACT

It has been known for some time that the subtropical Eastern North Pacific Ocean, just west of the coast of Mexico, experiences a high incidence of tropical cylone formation. One currently accepted mechanism for tropical cyclone initiation in the Eastern Pacific involves easterly waves that originate over Africa and propagate across the Atlantic. Recent investigations indicate that other mechanisms, such as the interaction of the large scale flow with the topography or the formation of mesoscale convective systems (MCSs), may also be important in initiating tropical cyclones in this region.

Infrared satellite imagery is used to illustrate specific examples of the alternative mechanisms described above that occurred during the 1989 hurricane season. Hurricane Lorena and Tropical Storm Manuel appear to have originated from a single region of disturbed weather associated with flow over the Sierra Madres and Tropical Storm Priscilla appears to have formed from an MCS that first appeared over Mexico. Conventional sounding and wind data are used to demostrate that the incident flow present was favorable for the generation of orographic cyclones during the formation of Lorena and Manuel and that the environment was conditioned for MCS formation prior to the development of Priscilla.

Introduction

It has been recognized that the subtropical Eastern Pacific Ocean, just off of the coast of Mexico, experiences and extremely high incidence of tropical cyclone activity. A climatological study by Renard and Bowman (1976) indicates that nearly 75% of the Eastern Pacific tropical cyclones form in the region bounded by 10°N latitude, 20°N latitude, 115°W longitude and the coast of Mexico. Comparisons with other tropical and subtropical regions show that the subtropical Eastern Pacific is the most prolific region in the world for the formation of tropical cyclones.

An explanation of this preferred geographic location for tropical cyclogenesis should be based on our current understanding of the dynamics and thermodynamics of tropical cyclone formation. At this time there are two competing theories of the instability mechanism which results in tropical cyclone intensification. The first involves the presence of a conditionally unstable atmosphere and forced vertical motion due to convergence at the surface. Rising air parcels are warmed relative to the environment by latent heat release and become buoyant, which enhances the vertical motion and drives the tropical cyclone circulation. This is referred to as Conditional Instability of the Second Kind (CISK) and is described by Charney and Eliassen (1964).

The second theory assumes that the atmosphere is conditionally neutral to forced ascent. The assumption of conditional neutrality of the maritime tropical atmosphere has been verified observationally by Xu and Emanuel (1989). In this theory the atmosphere is rendered unstable by increases in the equivalent potential temperature of parcels near the surface. The increase in equivalent potential temperature is due to latent and sensible heat flux from a suitably warm sea surface into parcels as they flow into a preexisting vortex. The resulting instability is referred to as the Air-Sea Interaction Instability (ASII) and is described by Emanuel (1984). Although the CISK and ASII theories differ in the instability mechanism responsible for intensification of the tropical cyclone circulation, both theories require the presence of convergence and forced vertical motion at low levels associated with an initial region of low pressure at the surface.

In addition to the difference in the instability mechanism, CISK and ASII also differ in the type of initial disturbance needed to trigger the instability. CISK is a linear instability theory, hence infinitesimally weak disturbances will grow by this mechanism. The ASII mechanism is sensitive to both the strength and the length scale of the initial disturbance. Rotunno and Emanuel (1986) describe a series of numerical simulations of the intensification of an initial finite-amplitude cyclonic vortex, assuming a conditionally neutral atmosphere and heat transfer from a warm sea surface. The result of these numerical simulations indicate that the initial vortex has to be sufficiently strong and have a length scale of a few hundred kilometers in order for a cyclone of hurricane intensity to develop in a realistic time. Weak, very large or very small initial vortices fail to develop. The selectivity of the ASII mechanism is an important result since it helps explain why so many of the disturbances observed in the tropics fail to intensify into tropical storms or hurricanes.

There have been studies which have attempted to identify the source of the initial disturbances that eventually become tropical cyclones in the Eastern Pacific. Frank (1976) suggests that a significant fraction of Eastern Pacific tropical cyclones are generated from "seedlings" that originate over the African continent and move across the Atlantic. While it is likely that some Eastern Pacific storms originate in this manner, it is difficult to explain phenomena such as the twin hurricanes described by Larson (1975). It would be difficult to get multiple "seedlings" associated with disturbances that originate near Africa into the Eastern Pacific at the same time.

Recent research has identified other possible mechanisms which may be responsible for the initiation of tropical cyclones in the Eastern North Pacific. These mechanisms involve the presence of the land mass and topography of central and northern Mexico in generating the initial disturbances which develop into tropical cyclones. One mechanism involves the generation of disturbances called Mesoscale Convective Systems (MCSs). The MCSs form over the mountains and eventually propagate over the warm ocean waters where they may eventually become hurricanes. A second mechanism involves large scale flow interacting with the mountains to generate cyclones over the Eastern Pacific near the west coast of Mexico.

An observational study by Velasco and Fritsch (1987) examines the initial location and subsequent trajectories of MCSs that form in both the northern and southern hemispheres at low and middle latitudes. Many of the systems that originate over Mexico propagate toward the west under the influence of the tropical easterlies and eventually move over the ocean. The MCSs have characteristic length scales which are consistent with those necessary for the formation of tropical cyclones by the ASII mechanism (Rotunno and Emanuel, 1986) hence it is likely that some of them will continue to intensify.

The details of the life cycle of MCSs in the subropics are examined in a study by Smith and Gall (1989, hereafter referred to as SG), who consider the development and subsequent propagation of three systems over southern Arizona and northwestern Mexico. There were a number of similarities of the environments in which each of the storms developed. The MCSs developed in the late afternoon in a vertical wind profile characterized by easterly flow aloft and westerlies confined to the level below 700 mb. There was also extremely dry air in the middle troposphere. SG believe that the dry air is associated with advection by the easterlies and/or subsidence at middle levels in the atmosphere. The exact role that the low level shear and the midtropospheric dry air play in MCS develpment in uncertain. There is evidence that subsidence associated with the dry air acts to suppress convection early in the day, causing it to occur later than elsewhere. The vertical shear may provide the initial relative vorticity characteristic of the MCS through vortex tilting by the convective updraft. The role that the mountains play in the formation of MCSs is also uncertain. The mountains may serve as initial sites for convection due to uneven solar heating of the surface or forced ascent. In addition, a thermally forced diurnal circulation may be the source of the low level shear needed for MCS formation.

SG found that the MCSs propagated in the direction of the prevailing easterlies and eventually moved across Baja California and into the Pacific Ocean at a latitude of about 30°N. Cloud track winds were used to identify a cyclonic circulation and average relative vorticities were estimated at 5×10^{-5} s^{-1} which is comparable to the maximum relative vorticity of the initial vortex used in the study by Rotunno and Emanuel (1986). There was no tropical cylone activity associated with the vortices examined by SG since the sea surface temperatures in the Pacific Ocean at 30°N are typically about 19°C during July and August and hence are too cold to support tropical cyclone development. However, a similar MCS occurring at lower latitudes, where sea surface temperatures exceed 26°C could trigger tropical cyclogenesis even by the more selective ASII mechanism.

There is evidence that topography may play another role in generating the initial cyclonic circulation necessary to initiate a tropical cylone. A recent theoretical study by Zehnder and Gall (1990, hereafter referred to as ZG) describes a mechanism through which large scale flow interacting with the Sierra Madres of Mexico may generate regions of enhanced cyclonic vorticity over the Eastern Pacific. ZG examines the effect of a steady, uniform flow which approaches a mountain ridge at a specific angle. The model topography consists of an infinite ridge that is located on a β-plane and is oriented at an angle with the north-south axis. The variable angle of attack of the incident wind serves to simulate the climatological northeast trade winds as well as the occasional southeasterlies associated with the propagation of large scale waves through the subtropics.

ZG find that northeasterly winds result in an anticyclone that is centered over the mountains. This result is consistent with an easterly zonal flow over an isolated mountain on a β-plane described by Janowitz (1975). However, ZG find that certain southeasterly flow configurations result in a stationary wave disturbance consisting of a series of cyclonic and anticylonic vorticity maxima oriented parallel to the ridge located at the surface and extending upward. The disturbances are present in the southwest quadrant of the model atmosphere, which corresponds to the Eastern Pacific North Pacific if the mountains are the Sierra Madres. For topographic widths that are characteristic of the Sierra Madre Occidental, the resulting cyclones have a length scale of about 300 km, which is consistent with disturbances that may grow by the ASII mechanism.

The cyclonic disturbances associated with flow over topography may explain the simultaneous formation of tropical cyclones in the Easter North Pacific. The orographically induced waves provide a series of cyclones at increasing distances from the mountains. In addition, the region of cyclonic vorticity nearest the ridge may consist of a number of individual circulation centers due to variability of the terrain height along the ridge. Both of these factors provide the possibility of a number of initial disturbances being present in the region simultaneously, in contrast to the single disturbances resulting from easterly waves (Frank, 1976) or MCSs (Velasco and Fritsch, 1987).

In this paper we present observations of Eastern Pacific tropical cylones that occurred during the 1989 hurricane season and that may illustrate two of the tropical cyclogenesis mechanisms described above. We are operating under the assumption that once a circulation center is present over the ocean a tropical storm is likely to develop and we investigate the possible origin of the initial circulation. In the second section we describe the simultaneous formation of Hurricane Lorena and Tropical Storm Manuel. These storms developed from a disturbance that appears to have been generated off the west coast of Mexico in a large scale flow configuration that is consistent with that described in ZG. The third section documents the formation of Tropical Storm Priscilla, which appears to have been initiated by an MCS that was generated over the mountains and eventually propagated over the ocean. There is strong evidence that the disturbances were initiated over the Eastern Pacific in the case of Lorena and Manuel and over the mountain in the case of Priscilla and did not propagate into the region from the Caribbean.

Hurricane Lorena and Tropical Storm Manuel

In this section we present observations which document various stages in the life cycles of Hurricane Lorena and Tropical Storm Manuel. We present a discussion of the history of each of the storms, accompanied by satellite imagery. An analysis of the observed winds prior to the formation of the storms indicates that the location of the initial disturbances relative to the mountains agrees with the relative vorticity distributions predicted by the steady state solution of ZG.

The sequence of events leading to the formation of Lorena and Manuel began when tropical depression fifteen-E was identified by the National Hurricane Center* (NHC) at a location of 13.7°N latitude and 104°W longitude at 1800 UTC on 27 August 1989. The depression moved slowly towards the northwest and was upgraded to Tropical Storm Lorena at 1800 UTC on 28 August while at a location of 15.9°N, 105.3°W. Lorena continued moving toward the northwest and reached hurricane intensity at 0600 UTC on 1 September.

*The National Hurricane Center is located in Miami, Florida, USA.

During the time that Lorena was present there was a second disturbance located in the Eastern North Pacific. A second tropical depression was identified by the NHC at 12.8°N latitude and 95.2°W longitude at 1800 UTC on 28 August 1989. The depression exhibited little motion over the next 24 hours and was upgraded to Tropical Storm Manuel at 1800 UTC on 29 August. At that time the storm was located at 13.4°N latitude and 99.4°W longitude. The scenario described above is representative of a fairly common occurrence in the Eastern North Pacific; the presence of multiple tropical cyclones generated almost simultaneously. In this case there is evidence that both storms formed from a larger scale area of disturbed weather.

Figure 1 shows a sequence of satellite images from the GOES 7 infrared window channel. These images provide a measure of the cloud top temperature, with high cold clouds appearing white and warm low clouds appearing grey. Warm land and sea surfaces appear black in the images. Figure 1a was taken at 1801 UTC on 27 August and corresponds to the time that tropical depression fifteen-E was identified by the NHC. There is an area of disturbed weather, marked by three distinct convective centers, oriented nearly parallel to the west coast of Mexico. The convective center labeled 1 is located at about 14°N and 104°W, which is approximately the location of tropical depression fiftheen-E. Convective center 2 is located at about 12.5°N, 100°W and center 3 is located at about 12°N, 95°W. The location of convective center 3 coincides approximately with the initial position of the tropical depression which will be identified by the NHC in 24 hours

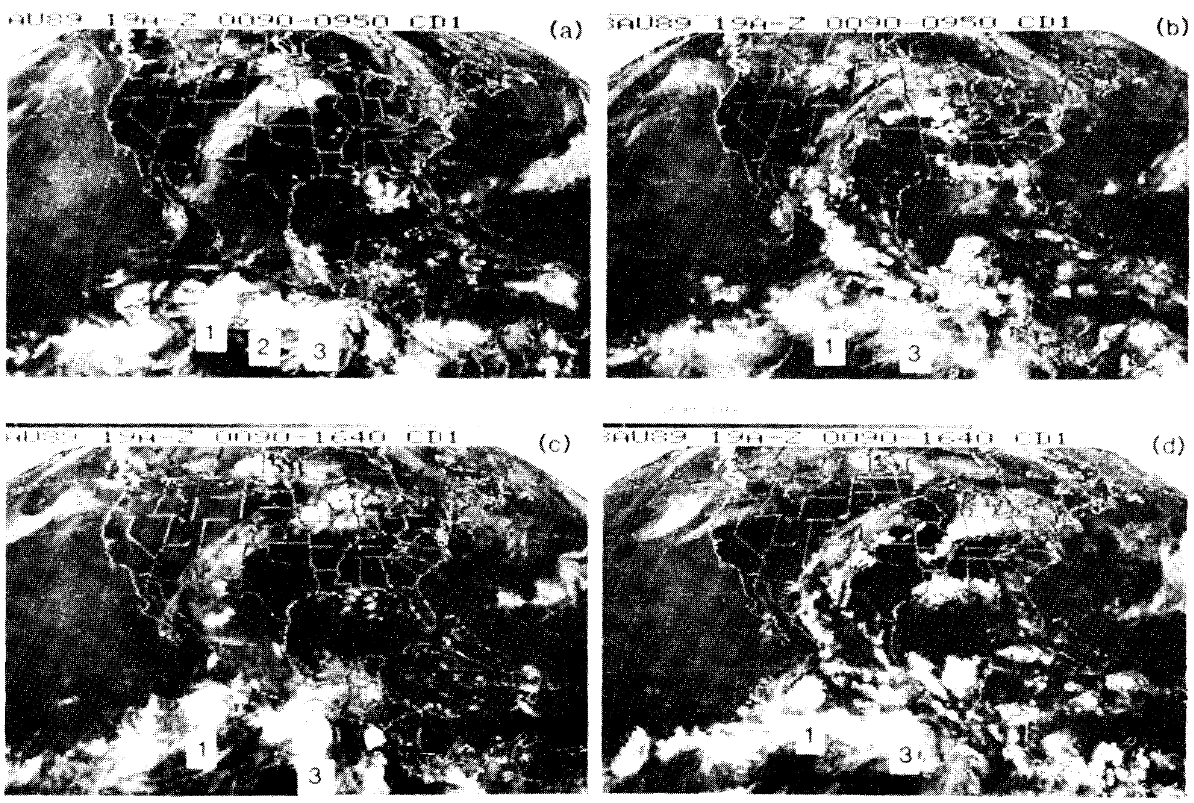

Fig. 1. Infrared satellite images for (a) 1801 UTC 27 August, (b) 0001 UTC 28 August, (c) 1201 UTC 28 August and (d) 1801 TUC 28 August 1989 corresponding to the formation of Hurricane Lorena and Tropical Storm Manuel. The labels indicate the initial convective centers discussed in the text.

and which will eventually become Tropical Storm Manuel. The observed area of disturbed weather is consistent with the presence of a cyclonic relative vorticity maximum oriented parallel to the mountain. An analysis of animated satellite images indicates a cyclonic circulation associated with convective center 3 in additon to that associated with tropical depression fifteen-E. Convective center 2 fails to develop and is not present in any of the subsequent satellite images.

Figure 1b shows the satellite image from 0001 UTC on 28 August. At this time the intensity of the convection associated with the area of disturbed weather has decreased relative to that in Fig. 1a. However, analysis of animated satellite images indicates a circulation centered about 14°N, 104°W which was the reported position of tropical depression fifteen-E, and a circulation at about 12°N, 95°W. It is important to note that even though the convection has decreased there is still a circulation present in each of the above mentioned regions.

Figure 1c shows the satellite image from 1201 UTC on 28 August. At this time the convection associated with both circulation centers 1 and 3 has been reestablished. Tropical depression fifteen-E is located at 15.5°N, 105°W and the other circulation center is still at about 12°N, 95°W. Both centers have remained more or less stationary in the 12 hours. The circulation center at 12°N, 95°W will be identified by the NHC as a tropical depression in 6 hours.

Figure 1d shows the satellite image taken at 1801 UTC on 28 August, corresponding to the time that the NHC identified a tropical depression at 12.8°N, 95.2°W. The tropical depression is visible as the region of enhanced convection located southwest of the Gulf of Tehuantepec. At this time Tropical Storm Lorena is located at 16°N, 105.5°W. During the following 24 hours both disturbances continued to intensify and move toward the northwest.

Figure 1 shows the development of two tropical cyclones from a single larger scale area of disturbed weather. The storms develped concurrently but not at the same rate. Tropical depression fifteen-E was upgraded to Tropical Storm Lorena at the time that the tropical depression associated with Manuel was first identified. However, it is important to note that circulation centers are visible in the locations where the tropical depressions will eventually be identified by the NHC during the entire time period represented in Figure 1.

We would like to identify the dynamical mechanism responsible for the precursory area of disturbed weather. In this case the existence and location of the initial disturbances which subsequently develop into tropical cylones are consistent with the steady state model of flow over topography of ZG. The streamlines of the large scale wind incident on the topography are obtained from the NHC operational ATOLL (Analysis of the Tropical Oceanic Lower Layer) analysis are shown in Figure 2. The data for the ATOLL streamline analysis are obtained from pibal winds, ship and aircraft reports and satellite derived cloud track winds, in addition to available radiosonde (RAOB) reports. The ATOLL analysis is typically associated with the 900 mb level. Figure 2a shows the streamlines for 27 August at 0000 UTC. The low level wind is southeasterly in the region between 90°W and 110°W longitude. A persistent southeasterly flow such as this is necessary to establish the steady regions of cyclonic vorticity described by ZG. The persistence of the southeasterly wind is demonstrated in Figure 2b, which shows the streamlines for 28 August at 0000 UTC. The southeasterly flow is still present along the coast near and just to the northwest of the Gulf of Tehuantepec. The wind direction over the ocean being modified by the presence of tropical depression fifteen-E.

An estimate of the strength and position of the orographically induced disturbance that results from the type of flow shown in Figure 2 is obtained by inputing incident wind values taken from

Figure 2a into the steady solution of ZG. The reported wind at 16°N, 97.5°W indicates a speed of 10 knots at an angle of 148° with the north. This wind direction and magnitude correspond to a zonal wind and meridional wind components of -2.7 m s^{-1} and 4.3 m s^{-1} respectively.

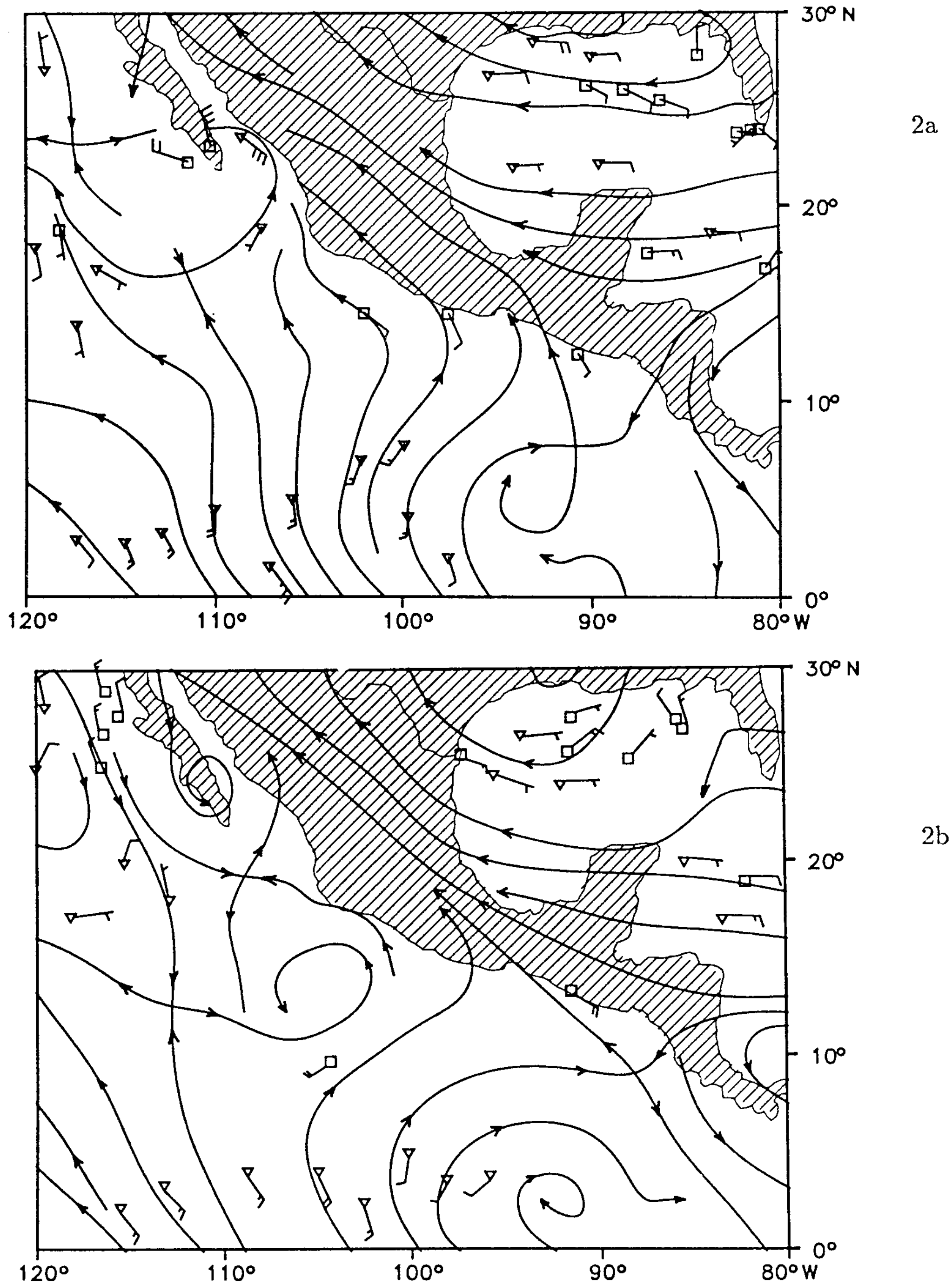

Fig. 2. Operational ATOLL streamline analyses for (a) 0000 UTC 27 August and (b) 0000 UTC 28 August 1989. The data sources are indicated by the shape of the station model head. Crosses indicated RAOBS, squares indicate aircraft reports and triangles indicate satellite derived cloud track winds.

Representative values of height, width and angle of orientation of the ridge with the north are also needed as input into the steady solution of ZG. The primary topographic feature of Mexico is the Sierra Madre Occidental, which extends from the Arizona, New Mexico, Mexican border in the north to the Isthmus of Tehuantepec in the south and which has maximum elevations above 2 km. The Sierra Madre Occidental is oriented at roughly a 45° angle with the north. This primary ridge is flanked to the east by the Sierra Madre Oriental, which extends from about 28°N to 20°N, and the Sierra Madre del Sur, which runs parallel to the west coast of Mexico between Manzanillo and the Isthmus of Tehuantepec. This systems of mountains ranges is approximated by a single ridge oriented at an angle of 45° with the north having a width of 600 km and a maximum height of 2 km. These parameter values adequately represent the large scale features of the topography.

The distribution of relative vorticity as a function of perpendicular distance from the ridge, obtained from the steady solution of ZG, is plotted in Figure 3. Figure 3 shows a region of anticyclonic relative vorticity located over the mountain and cyclonic relative vorticity to the southwest of the ridge (indicated by negative values of distance). The maximum relative vorticity is located about 900 km from the top of the ridge and this position agrees well with the perpendicular distance between the top of the Sierra Madre Occidental and the initial location of tropical depression fifteen-E. The half-width of the positive vorticity maximum is about 300 km, which is characteristic of tropical cyclones. Tropical Storm Manuel forms near the end of the ridge and Manuel's structure may be influenced by end effects. This may account for Manuel being a weaker tropical cyclone.

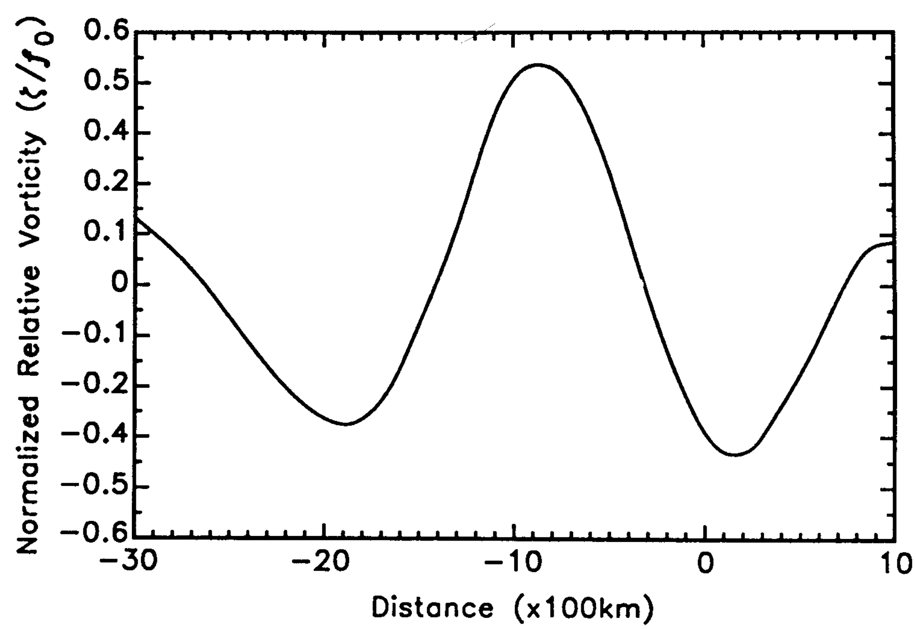

Fig. 3. Relative vorticity at the surface as a function of distance from the ridge as obtained from the solution described in Zehnder and Gall (1990). The topography has a maximum height of 2 km and a halfwidth of 300 km. The ridge is centered about the zero point of the horizontal axis.

There are other features of the development of Lorena and Manuel that are consistent with a steady, topographically forced region of cyclonic vorticity. The first is the minimal movement of the circulation centers during the initial stages of development. A comparison of the location of circular centers 1 and 3 in Figure 1a with those in Figure 1d shows that there is little movement of these features. This persistent, spatially fixed circulation is consistent with a steady state vorticity maximum associated with topographic forcing.

Tropical Storm Priscilla

In this section we present satellite images which illustrate the formation of Tropical Storm Priscilla. The large scale wind field and the origin of the initial disturbance associated with this storm are quite different from those associated with Lorena and Manuel. There is another mechanism operating in this case as Tropical Storm Priscilla seems to have originated from an MCS that formed over the Sierra Madre Occidental and moved over the ocean.

The tropical storm history began when the National Hurricane Center identified a region of organized convection located about 60 nautical miles south of Manzanillo at 18.1°N, 104.5°W as tropical depression nineteen at 0600 UTC on 21 September 1989. The tropical depression moved toward the northwest and was upgraded to Tropical Storm Priscilla at 1800 UTC on 21 September. Priscilla began to move due west at 1200 UTC on 22 September and continued moving toward the west until dissipating on 26 September.

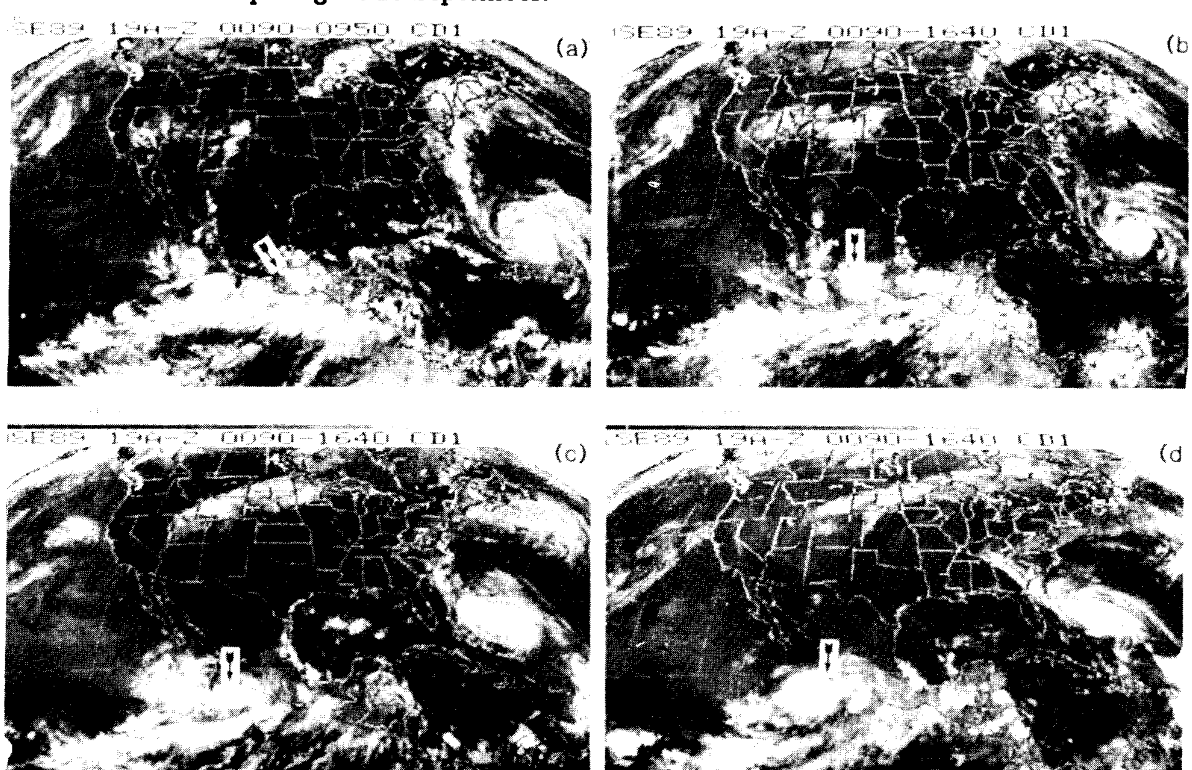

Fig. 4. Infrared satellite images for (a) 2101 UTC 19 September, (b) 0401 UTC 20 September, (c) 1801 UTC 20 September and (d) 0501 UTC 21 September 1989 corresponding to the formation of Tropical Storm Priscilla.

Figure 4 shows a sequence of GOES 7 infrared images corresponding to the time prior to the identification of tropical depression nineteen. Figure 4a was taken at 2101 UTC on 19 September. There is convection associated with the ITCZ in a band at about 13°N latitude. The convective band associated with the ITCZ is visible and remains in roughly the same position in all of the satellite images in Figure 4. There is also a convective cell located at about 18°N, 105.5°W. Analysis of animated satellite images reveals no discernable rotation associated with this disturbance and the cell dissipates rapidly. There is also convective activity in the Gulf of Campeche and over the Isthmus of Tehuantepec, but the convection appears to be spatially localized and dissipates rapidly.

Despite the presence of isolated convective activity in the Gulf of Campeche and the Isthmus of Tehuantepec, the area over the continent seems to be free of any synoptic scale regions of convection, which would indicate the presence of an easterly wave. The 2001 UTC image (not shown) indicates that the area over land to the northwest of the Isthmus of Tehuantepec is clear. However, Figure 4a shows a convective cell located at about 19°N, 98.5°W, and an examination of earlier satellite imagery confirms that the cell originated in that location. This convective cell grows rapidly into an MCS and eventually propagates over the water.

The cloud mass associated with the MCS was quite coherent and the position of the MCS as a function of time was determined from the satellite images. The position of the MCS, defined as the location of the center of the cloud mass, is plotted in Figure 5 from the time of its initial detection at 2101 UTC on 19 September, until 0800 UTC on 20 September, at which time it becomes sationary. The MCS moves almost due easterly during this time period.

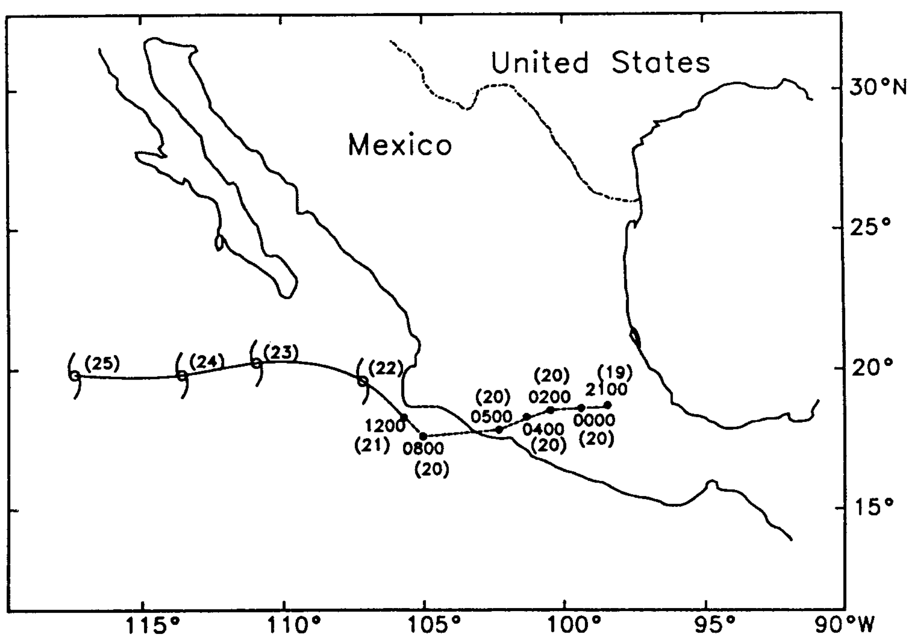

Fig. 5. Location of the MCS, tropical depression and Tropical Storm Priscilla from 19 September until 25 September 1989. The location of the MCS was determined by locating the center of the cloud mass on the infrared satellite images. Positions of the tropical depression and tropical storm are those reported by the NHC. Numbers in parentheses indicate the date. The tropical storm position, indicated by the tropical storm symbol, is given at 0000 UTC for 22 September and later.

Subsequent development of the MCS is shown in Figs. 4b-d. At 0401 UTC on 20 September (Fig. 4b), the center of the MCS is located at near the Mexican coast at about 18.5°N, 101°W. Figure 4c is taken at 1801 UTC on 20 September, and shows the remnants of the MCS located over the water at 18.5°N, 105°W, which is the final MCS position indicated in Figure 5. The intensity of the convection associated with the MCS has decreased compared with Figure 4b. However, as in the case of Lorena and Manuel, there is evidence of a circulation even though the intensity of the convection is variable. Figure 4d is taken at 0501 UTC on 21 September, one hour prior to the NHC identification of tropical depression nineteen. At this time there is a large region of convection centered at 18°N, 107°W. The center of the circulation, visible on the animated satellite imagery, is at 18°N, 104.5°W, which is near the initial position of tropical depression nineteen as reported by the NHC.

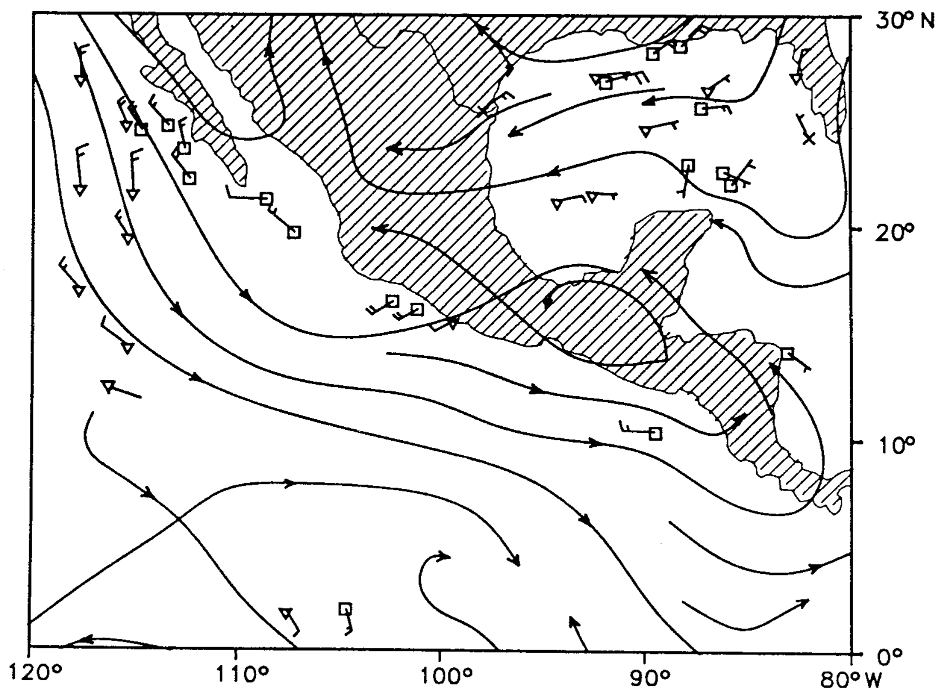

Fig. 6. Operational ATOLL streamline analysis for 0000 UTC 20 September 1989. Data symbols are as indicated in Figure 2.

The motion of the MCS during the initial stages of its life cycle can be explained by considering a representative distribution of the observed winds, obtained from the operational ATOLL analysis at 0000 UTC on 20 September shown as Figure 6. This figure corresponds to three hours after the initial convection associated with the MCS was first detected in the satellite image. The analyzed streamlines show that the winds at latitudes above 18°N are easterly over the continent and westerly over the Eastern Pacific. This analyzed wind distribution is consistent with the MCS initially moving toward the west and subsequently becoming stationary in the convergence zone located just off the coast near Manzanillo. The offshore convergence zone may also be responsible for the quasi-persistant convection that is present in Figure 4a. The ATOLL analysis at 1200 UTC on 20 September (not shown) indicates that the pattern of easterlies over the continent and westerlies over the ocean persists over the time that the MCS moves over the ocean.

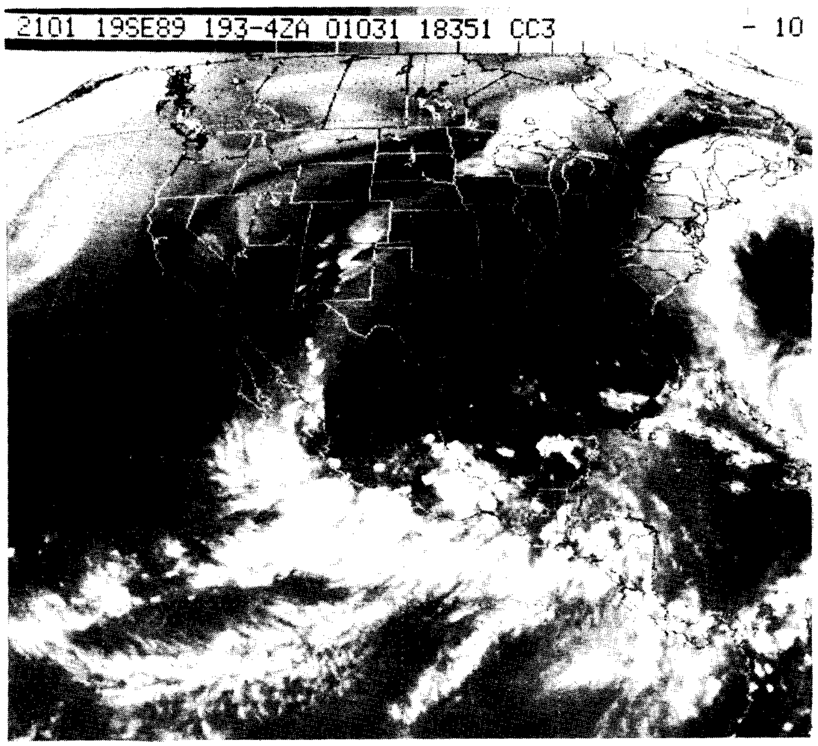

Fig. 7. The 6.7 μm water vapor image at 2100 UTC on 19 September 1989. The middle and upper tropospheric dry air is indicated by the dark area over central Mexico.

The appearance of a growing, propagating convective cell in the satellite imagery suggests the presence of an MCS. Observational evidence from two sources shows that favorable conditions for the formation of an MCS existed on 19 September in the region where the initial convective cell was first identified. Evidence of a vertical moisture profile conducive to the development of an MCS is presented in Figure 7, which shows the GOES 7 6.7μm water vapor image corresponding to 2101 UTC on 19 September 1989. This image provides a measure of the water vapor content of the air at the 400-500 mb level, with dry areas appearing dark and moist areas appearing light. The MCS first appears on the southern edge of a region of dry air similar to the mid-level dry air associated with the MCSs studied by SG.

The second necessary condition for MCS formation given by SG is a vertical wind shear associated with a wind reversal at low levels. Figure 8 shows a skew T- log P plot of RAOB data taken at Mexico City at 1200 UTC on 19 September. This time is the closest available representation of the precursor wind since the 0000 UTC RAOBs were suspended at this time. The sounding indicates conditions similar to those in the cases studied by Smith and Gall. The winds were predominantly easterly above the 700 mb level with a shift to northwesterlies below 700 mb. While there is some evidence of a dry region between 500 and 600 mb, it is not as pronounced as the dry air in the study of SG.

The ATOLL analysis (Figure 6) and the vertical wind profile at Mexico City (Figure 7) indicate that the mechanism described in ZG was probably not operating during the formation of Tropical

Storm Priscilla. The low level winds incident on the mountain are westerly and the resulting orographically induced cyclone would be very broad, weak and located to the east of the Sierra Madres. The lack of an orographic disturbances in the Eastern Pacific is consistent with the absence of a large scale area of disturbed weather, characterized by numerous convective cells (as in Figure 1) in Figs 4b-d.

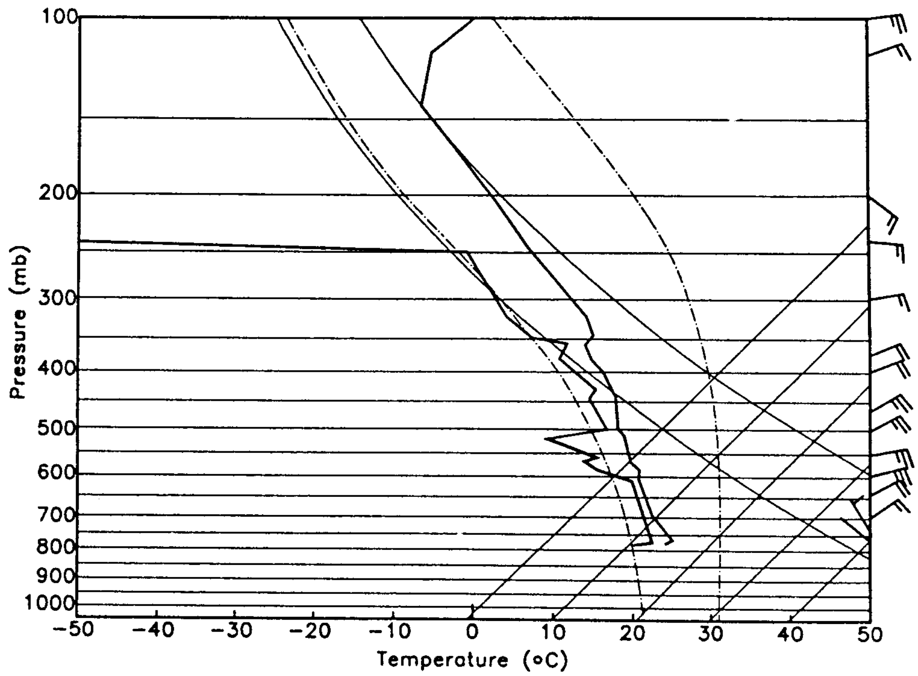

Fig. 8. Skew T-log P plots of the 1200 UTC Mexico City sounding from 1200 UTC on 19 September 1989. Isotherms are indicated by solid lines, dry adiabats by dashed lines and moist adiabats by dotted lines. Pressure values are given in millibars. The temperature data below 800 mb was not plotted due to an obvious error in the temperature value reported at 800 mb.

Conclusions

In this study we have presented two examples of tropical cyclone initiation in the Eastern North Pacific by mechanisms other than the propagation of easterly waves into the region (Frank, 1976). The identification of alternate cyclogenesis mechanisms helps to explain the fairly common occurrence of multiple tropical storms in the Eastern Pacific, as well as possible fate of the MCSs (Velasco and Fritsch, 1987), which are also common in the tropics and subtropics.

The generation of regions of cyclonic relative vorticity through interaction of the large scale flow with the topography of Mexico has been suggested by Zehnder and Gall (1990). The cyclonic relative vorticity described by Zehnder and Gall is in a band that lies parallel to the mountain, hence it provides the possibility of multiple initial disturbances. This mechanism helps to explain the occurrence of simultaneous tropical cylones in the Eastern Pacific.

An example of the simultaneous existence of tropical cyclones in the Eastern Pacific occurred during the 1989 hurricane season. Hurricane Lorena and Tropical Storm Manuel formed off of the west coast of Mexico and while Lorena was identified prior to Manuel, both storms were at tropical storm intensity during the same time period (1800 UTC on 29 August until 1200 UTC on 31 August). An analysis of GOES 7 infrared satellite imagery suggests that the tropical depressions which eventually became Lorena and Manuel formed from larger scale region of disturbed weather located off the west coast of Mexico.

An examination of the observed winds indicates that a southeasterly wind was incident on the Sierra Madres prior to the formation of Lorena and Manuel. This incident wind satisfies the criterion for the existence of a steady state cyclone described by Zehnder and Gall (1990). The reported wind speed and direction, along with topographic parameters representative of the Sierra Madre Occidental are used to predict the expected location of the cyclonic relative vorticity maximum described by Zehnder and Gall (1990). The steady state cyclone should be located about 900 km from the top of the mountain. This distance corresponds well with the perpendicular distance between the Sierra Madre Occidental and the initial location of tropical depression fifteen-E, which eventually becomes hurricane Lorena. During the initial stages of their life both Lorena and Manuel appear to be stationary, which is further evidence of their forming from a steady state disturbance.

An example of tropical cyclone initiation from an MCS that started over land, as suggested by Velasco and Fritsch (1989), occurred during the 1989 hurricane season with Tropical Storm Priscilla. An analysis of the GOES 7 satellite imagery shows an isolated convective cell that develops over the Sierra Madre Occidental near Mexico City, expands and propagates toward the west, eventually moving into the region where the tropical depression that eventually becomes Priscilla is first identified. An examination of the GOES 7 water vapor image and the RAOB from Mexico City indicate that the moisture and vertical wind profiles preceding the MCS formation are similar to those described in the study by SG.

The evidence supporting the proposed mechanisms in this study is far from conclusive. Our goal is to provide examples of mechanisms of tropical cyclone initiation other than the African waves described by Frank (1976). In both of the cases examined we have used the available data to show that atmospheric conditions are at least consistent with the proposed mechanisms for generation of the initial disturbances. There may be other factors which contribute to the subsequent development of the tropical cyclones. Further research is necessary to assess the importance of these alternate tropical cyclogenesis mechanisms, to better identify the precursory conditions associated with them and to identify any other mechanisms that may be active. Current research involves an in-depth analysis of observational data to provide a more accurate description of the initial conditions which are conducive to tropical cyclogenesis. Time dependent numerical models are being used to identify the dynamical mechanism active during the initial stages of tropical cyclone development. Both of these research efforts would be aided by enhanced observations in the Eastern Pacific and over Mexico.

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