Maximum Potential Intensities of Tropical Cyclones near Isla Socorro, Mexico

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ABSTRACT

The maximum potential intensity (MPI) of a tropical cyclone represents a theoretical upper limit to the strength of the storm imposed by the laws of physics and the energy available to the system in the atmosphere and the ocean. The MPI in this study was computed using a method in which the cyclone is assumed to consist of the environment, an eyewall, and an eye. Calculation of the MPI requires a vertical sounding of temperature, the surface pressure, and the surface air temperature. The soundings used in this study were taken at Isla Socorro, Mexico, during the period 1994–97. The MPIs were compared to the minimum surface pressures for seven tropical cyclones that passed near Isla Socorro. The MPI provided an accurate indication of the potential for the atmosphere to support the intensification of a tropical cyclone. The thermodynamically based MPI also proved to be superior to an SST-based MPI.

1. Introduction

Prediction of the intensity of a tropical cyclone remains one of the more challenging problems in operational meteorology. As stated by Avila (2000), ''While there has been a gradual improvement in track forecast accuracy, no significant change has been observed in the skill of the 72-h intensity forecast.'' More recently, DeMaria et al. (2002) demonstrated that while intensity forecasts have a comparable skill to track forecasts for a 12-h period, intensity forecasts have only one-third of the skill of track forecasts for a 72-h period. Continued research on the factors that affect the intensity of a tropical cyclone is needed to improve the skill of the intensity forecasts. Once a tropical cyclone forms, the rate of intensification and the ultimate intensity of a tropical cyclone are determined by the complex interaction of the system and its surrounding environment. The ability to specify the conditions in the surrounding environment and within the tropical cyclone is limited often by the paucity of data over the tropical oceans. Although case studies of storms like Hurricane Opal (1995) by Bosart et al. (2000) have investigated the interactions between tropical cyclones and their environments, questions still remain about the precise nature of the interactions.

The maximum potential intensity (MPI) of a tropical cyclone represents a theoretical upper limit on the intensity of the storm based on the energy available in the upper layer of the ocean and in the atmosphere. The MPI provides the operational forecaster with a worst-case scenario, since it represents the intensity a tropical cyclone may attain in the absence of inhibiting factors such as vertical wind shear or entrainment of drier air. Miller (1958) computed a minimum possible surface pressure based on the sea surface temperature (SST), the surface relative humidity, and a synthetic sounding. Emanuel (1986, 1988) used the Carnot cycle to develop a theoretical relationship between the minimum central pressure, the SST, and the outflow temperature at the top of the storm. Emanuel (1999) demonstrated that simulated tropical cyclones intensify to their MPIs when the magnitude of the vertical wind shear was small. DeMaria and Kaplan (1994) and Whitney and Hobgood (1997) related the maximum observed intensities of tropical cyclones to the SSTs for the Atlantic and eastern North Pacific Oceans, respectively. Holland (1997) developed a method for the estimation of the maximum possible decrease in the surface pressure ''based on hydrostatic balance with a saturated eyewall and a parameterized eye region.''

The eastern North Pacific Ocean experiences the greatest frequency of tropical cyclone occurrences per unit area of any ocean basin (McBride 1995). Although most of the tropical cyclones in this region move west-northwest and dissipate over cooler waters, storms that affect Mexico can produce heavy rainfall and significant flooding. Soundings taken at Isla Socorro, Mexico, are often the only in situ data representative of the atmospheric conditions over the eastern North Pacific Ocean. The purpose of this research is to determine if the soundings taken at Isla Socorro can be used in the method

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developed by Holland (1997) to provide useful estimates of the MPIs of tropical cyclones in this region. The Holland (1997) method is reviewed briefly in section 2, and the soundings from Isla Socorro are described in section 3. The results of the estimation of MPIs are discussed in section 4 and the conclusions are presented in section 5.

2. Computation of MPI

Holland (1997) developed a method to compute the maximum decrease of the surface pressure in a tropical cyclone that could be expected in an ideal thermodynamic environment. The components of the method that are most relevant to the research discussed in section 4 are reviewed here. Readers are referred to the original paper by Holland (1997) for a complete description of the method. The following primary assumptions were used to develop the method.

1) The tropical cyclone is symmetrical.
2) The decrease in surface pressure is computed hydrostatically based on the temperature anomaly of the column.
3) An eye forms in the tropical cyclone if the hydrostatic computation produces a decrease in the surface pressure of 20 hPa or more.
4) The equivalent potential temperature is constant within the eye.
5) The eyewall is vertical and the saturated equivalent potential temperature is constant with height within the eyewall.
6) Ice-phase processes and entrainment of midlevel air into the eye can be neglected.
7) The environment can be described with a single sounding, surface pressure, and surface air temperature.

The program to calculate the maximum decrease of surface pressure uses an interative approach to compute the hydrostatic reduction of pressure. The program requires the surface pressure and temperatures at the surface and 70, 100, 150, 200, 250, 300, 400, 500, 600, 700, 850, and 925 hPa. For reasons that are discussed in section 3, the SST − 1 (K) was used in place of the surface temperature. The surface relative humidity beneath the eyewall was set at 90%, which was the magnitude specified by Holland (1997) in his standard set of parameters.

After computation of the surface equivalent potential temperature, the environmental sounding is adjusted to the pseudoadiabat defined by the surface equivalent potential temperature. The resultant warming of the column and hydrostatic reduction of surface pressure are computed. Since a change of surface pressure produces a change of surface equivalent potential temperature, the process is repeated until convergence occurs. If the final reduction of surface pressure is at least 20 hPa, then a further reduction of pressure due to the processes in the eye and eyewall are computed. The previously computed hydrostatic reduction is added to the decrease of pressure due to the formation of an eye to yield the total decrease in pressure. Subtraction of the total decrease in pressure from the original surface pressure produces the MPI in terms of the minimum possible surface pressure for a tropical cyclone in the specified thermodynamic environment.

Sensitivity studies by Holland (1997) showed that the method was sensitive to changes in SST, surface relative humidity beneath the eyewall, and surface pressure. Tonkin et al. (2000) evaluated the method developed by Holland (1997) and an updated version of the method developed by Emanuel (1986). The methods were evaluated using mean monthly soundings for the Australia/southwest Pacific, the northwest pacific, and the North Atlantic basins. The study concluded that ''Both models provide reasonable estimates of the potential climatological/regional tropical cyclone hazard.'' In addition the study concluded that the method developed by Holland (1997) ''provided a realistic seasonality, but tended to underestimate the early and late season maximum in some regions.'' The previous studies cited here used monthly averaged soundings. Tonkin (1997) used daily soundings to estimate the potential intensity of actual storms near Willis Island, Australia. The results of that study provided a further indication that the method developed by Holland (1997) could successfully predict the potential intensity of tropical cyclones. The results presented in section 4 show the MPIs from individual soundings from Isla Socorro, Mexico.

3. Soundings from Isla Socorro

One of the significant problems in the prediction of the intensity of tropical cyclones is the lack of sufficient data to specify the environmental conditions over the tropical oceans. Most rawinsondes are released from stations on large bodies of land. Soundings from stations near oceans may sample air from continental regions and not provide a true depiction of the structure of the atmosphere over the oceans. The magnitude of the effects of the continental air depends on the direction and speed of the wind. Tonkin et al. (2000) found this contamination by continental air in some of the mean monthly soundings in their study. Rawinsondes released from small islands would seem to provide the best information on the state of the atmosphere over the surrounding oceans.

Isla Socorro, Mexico, is an island in the eastern North Pacific Ocean located at 18.7°N, 110.9°W. The island is approximately 700 km west of Manzanillo, Mexico, and approximately 500 km south southwest of Cabo San Lucas, Mexico. Isla Socorro occupies an area of approximately 285 km^2. The distance from the continental landmass and the relatively small size of the island minimize the contamination by continental air. Rawinsondes are released from a location 35 m above mean sea level.

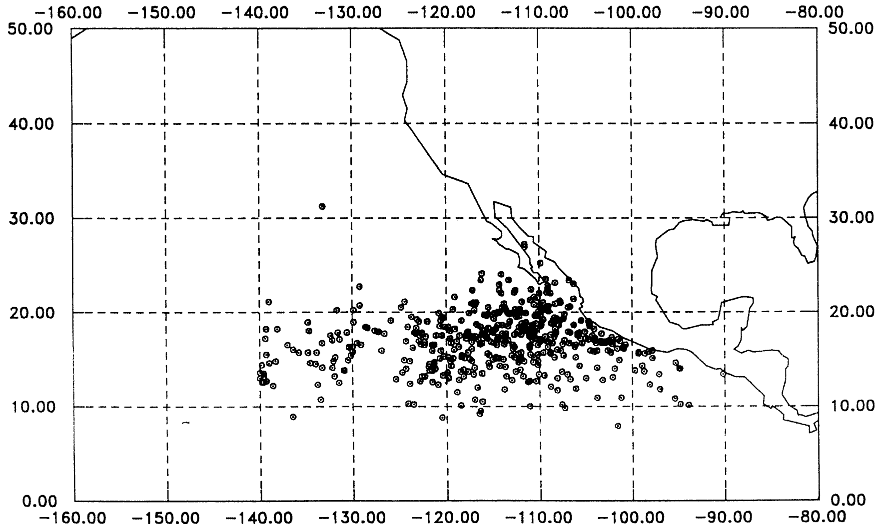

FIG. 1. Position where tropical cyclones between 1963 and 1993 first reached maximum intensity. From Whitney and Hobgood (1997).

Soundings obtained by the rawinsondes provide the best data on the state of the atmosphere over this portion of the eastern North Pacific Ocean. Figure 1, which was Fig. 6 in Whitney and Hobgood (1997), depicts the locations where tropical cyclones that occurred between 1963 and 1993 reached their maximum intensities. Numerous tropical cyclones reached their maximum intensities in the vicinity of Isla Socorro. This fact makes MPIs computed from soundings obtained at Isla Socorro potentially very useful to forecasters.

Archived soundings from Isla Socorro for the period from 1992 to 1997 were obtained from the Air Force Combat Climatology Center (Air Weather Service) in Asheville, North Carolina. There were very few soundings from 1992 to 1993 and those years were eliminated from the analysis. Most of the soundings were taken by rawinsondes released at 0000 UTC, although there were a few soundings from rawindsondes released at 1200 UTC. The soundings were examined to determine their suitability for the calculation of MPIs. Soundings that did not extend to the 100-hPa level were eliminated from the analysis. Any soundings that were missing too many levels and did not provide sufficient resolution of the vertical structure of the atmosphere were eliminated from the analysis. In practice soundings missing more than three levels required by the program used to compute the MPIs were rejected. Temperatures were not measured at the 600-hPa level in many soundings. When the temperature at 600 hPa was unavailable, the temperature at the nearest pressure level was used and the program used to compute the MPIs was modified accordingly. The soundings taken at 1200 UTC were not used in the analysis because they were so few in number. The exclusive use of soundings taken at 0000 UTC made comparison of the results internally consistent. Elimination of soundings based on the previously discussed criteria and restriction of the periods of analysis to the hurricane season over the easter. North Pacific Ocean left 96 soundings for 1994, 75 soundings for 1995, 129 soundings for 1996, and 68 soundings for 1997. The relatively small number of soundings from 1997 is partly attributable to damage caused during the passage of Hurricane Linda over Isla Socorro.

Although Isla Socorro is relatively small and is surrounded by the eastern North Pacific Ocean, there is a pronounced diurnal cycle in the air temperatures at the surface. Surface air temperatures at 0000 UTC showed the effects of daytime heating and exceed the temperatures that would be expected over a purely oceanic surface. Thus SST − 1 (K) was used in place of the air temperature at the surface. SSTs were obtained from a data archive at Columbia University. The SSTs were generated using the method described by Reynolds and Smith (1994). SSTs were available at a spatial resolution of 2.5° latitude by 2.5° longitude and a temporal resolution of 1 week. The SSTs for the grid points within 400 km of Isla Socorro were averaged spatially and then interpolated temporally to the date of the sounding.

4. MPIs

a. During the hurricane seasons

The official hurricane season for the eastern North Pacific Ocean runs from 15 May through 30 November. Figure 2 shows the MPIs computed from soundings for Isla Socorro for the hurricane season of 1994. The environment is only marginally favorable for the formation of weak tropical cyclones at the beginning of the season (Julian day 135). MPIs at the beginning of the season are near 1000 hPa. The environment remains thermodynamically capable of supporting only weak tropical

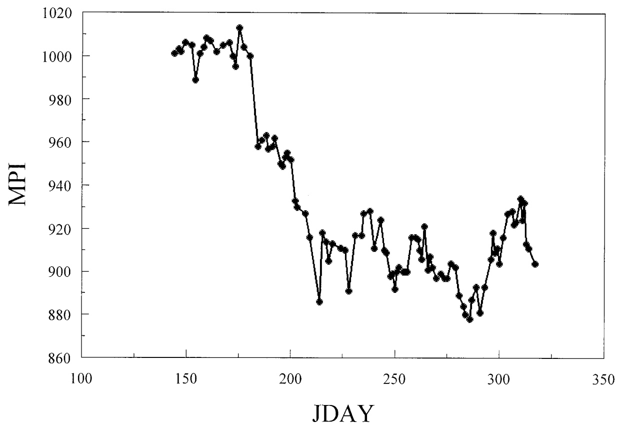

FIG. 2. MPIs for the 1994 hurricane season for Isla Socorro.

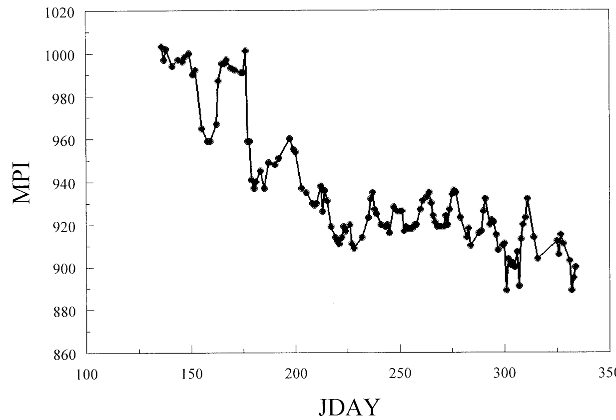

FIG. 4. MPIs for the 1996 hurricane season for Isla Socorro.

cyclones through the end of June. The SSTs have warmed sufficiently by early July to enable the environment to support the development of hurricanes. The sharp drop in the MPI curve on Julian day 184 in Fig. 2 represents the threshold at which the hydrostatic decrease in surface pressure computed by the Holland (1997) method reaches 20 hPa. An additional reduction of surface pressure occurs due to the computation of the effects of formation of an eye and the MPI decreases to 954 hPa. The MPI fluctuates between 880 and 960 hPa throughout the rest of the season.

Figure 3 depicts the MPIs for Isla Socorro for the hurricane season in 1995. The pattern is similar to 1994 in the early part of the season. The thermodynamic environment was not as favorable in 1994 during the most active part of the hurricane season. Cooler SSTs resulted in MPIs that were greater than 920 hPa throughout most of the season. The abrupt change in the MPIs on Julian days 242 and 243 in 1995 resulted from a 0.2-K decrease in the SSTs. The cooler SSTs resulted in a hydrostatic pressure drop of less than 20 hPa and the decrease of pressure due to the processes in the eye does not contribute to the MPI when that occurs. Figure 4 shows the MPIs for Isla Socorro for the 1996 hurricane season. The pattern for 1996 was very similar to the pattern for 1995. As was the case in 1995 MPIs ranged from 920 to 940 hPa for most of the season.

Warmer SSTs associated with the El Niño of 1997 are seen in Fig. 5. At the beginning of the season the environment was marginal for the development of hurricanes. The fluctuations of MPI between 960 and 1000 hPa reflect this state. Warmer SSTs in August and September created an environment capable of supporting intense hurricanes. The MPI computed for 11 September 1997 was 875 hPa. That pressure was the lowest computed for any of the soundings and preceded the passage of Hurricane Linda over Isla Socorro. A more detailed discussion of the MPIs of tropical cyclones that passed near Isla Socorro is contained in the next section.

b. For individual storms

The centers of 14 named tropical cyclones passed within 200 km of Isla Socorro between 1994 and 1997. Some of these storms were tropical cyclones that developed near Isla Socorro and moved out of the area before they had time to intensify to their MPI. In other

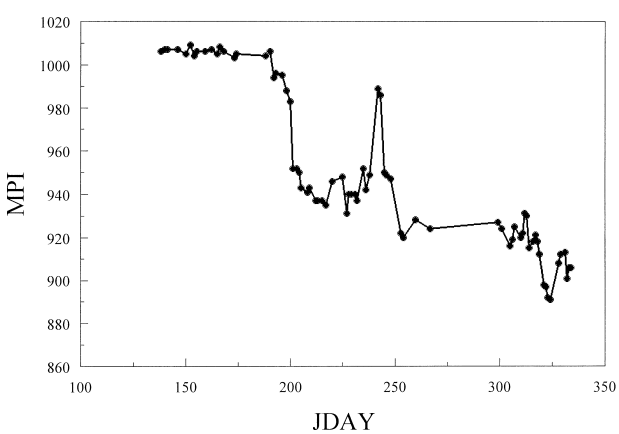

FIG. 3. MPIs for the 1995 hurricane season for Isla Socorro.

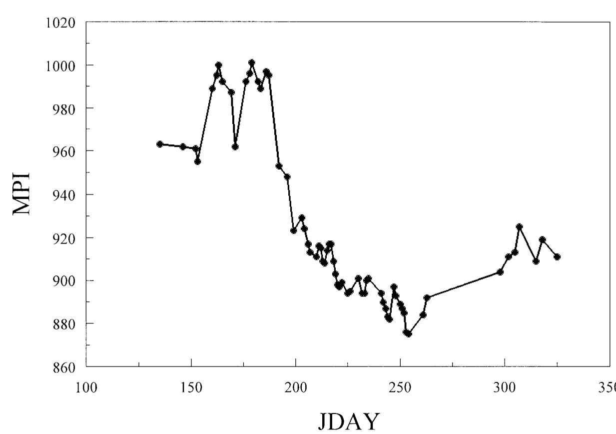

FIG. 5. MPIs for the 1997 hurricane season for Isla Socorro.

cases vertical shear of the horizontal wind affected the structure of the tropical cyclone and prevented the storms from reaching their MPIs. The vertical difference in the winds between 200 and 850 hPa in the soundings taken at Isla Socorro was computed for all tropical cyclones passing within 200 km of the island and was used to represent the vertical wind shear over those storms. Hurricane Nora (1997) passed within 60 km of Isla Socorro, but no usable soundings were available to compute the MPI due to prior damage from Hurricane Linda (1997). Brief summaries are given of six storms that passed near Isla Socorro, but did not have an opportunity to reach their MPIs near that location. Hurricane Nora is also discussed only briefly because a lack of usable soundings made it impossible to compute the MPIs. Seven other storms that did have an opportunity to attain their MPIs before reaching Isla Socorro are discussed in greater detail. Hurricane Guillermo (1997) is also discussed even though it passed 550 km from Isla Socorro, because it was one of the most intense tropical cyclones ever observed over the eastern North Pacific Ocean.

Hector (1994) was classified as a tropical storm at 1200 UTC on 7 August 1994, when the center of the storm was located 225 km from Isla Socorro. As the center passed within 200 km of Isla Socorro, the central pressure was estimated to be 1002 hPa. At that time the MPI was computed to be 913 hPa and the magnitude of the vertical difference of the wind between the 850- and 200-hPa levels at Isla Socorro exceeded 15 m s^{-1}. The large magnitude of the wind shear inhibited intensification and prevented the tropical cyclone from approaching its MPI. Ileana (1994) was classified as a tropical storm 4 days after Hector when the center of Ileana was located less than 400 km from Isla Socorro. At 1200 UTC on 12 August 1994 the center of Ileana passed within 150 km of Isla Socorro. The central pressure was estimated to be 990 hPa, while the MPI was computed to be 911 hPa. The storm was still intensifying as it moved away from Isla Socorro, although the magnitude of the vertical shear exceeded 8 m s^{-1}. Lane (1994) was classified as a tropical storm at 0600 UTC on 4 September 1994 when the center of the storm was less than 60 km from Isla Socorro. At that time the minimum surface pressure was estimated to be 1006 hPa, while the MPI was computed to be around 900 hPa. The environment was clearly capable of supporting a strong hurricane and Lane intensified into a major hurricane with a minimum surface pressure of 948 hPa, but by that time the center was located more than 1500 km west of Isla Socorro.

Gil (1995) was classified as a tropical storm at 0000 UTC on 21 August 1995 when the center of the storm was over 1000 km from Isla Socorro. The tropical cyclone moved toward Isla Socorro, but strong vertical wind shear of up to 15 m s^{-1} inhibited intensification. The center of Gil passed approximately 150 km southwest of Isla Socorro on 23 August 1995. The minimum

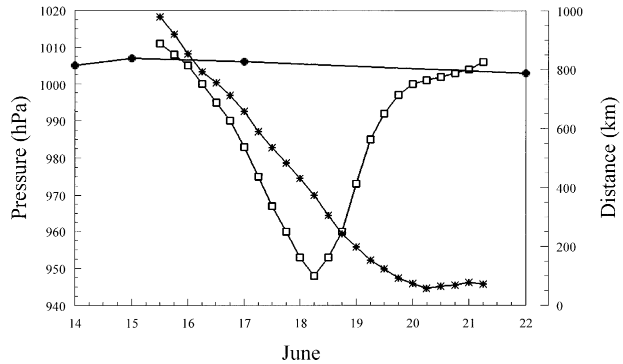

FIG. 6. MPIs for Isla Socorro (filled circles) and actual minimum surface pressures (open squares) for Hurricane Adolph (1995). Distances from Isla Soccorro are shown by asterisks.

central pressure was estimated to be 998 hPa, while the MPI was approximately 950 hPa. Elida (1996) was classified as a tropical storm at 0600 UTC on 2 September 1996 when the center was less than 100 km from Isla Socorro. At the time the minimum surface pressure was estimated to be 1005 hPa, while the MPI was computed to be 916 hPa. The storm moved away from the island and intensified before finally dissipating over cooler SSTs. Kevin (1997) was classified as a tropical depression at 1800 UTC on 3 September 1997. At that time the center was located within 200 km of Isla Socorro. The storm moved away from Isla Socorro before it had time to intensify to its MPI. Hurricane Nora (1997) would have been a good candidate for more detailed analysis, but damage caused by the passage of Hurricane Linda prevented the acquisition of soundings that could be used to compute the MPI.

Five of these seven storms formed near Isla Socorro and moved out of the area before they had time to intensify to their MPI. Strong vertical wind shear also played a role in the inhibition of the intensification of Hector, Ileana, and Gil. Although Nora would have been a good candidate for further analysis, usable soundings did not exist for that time period. Seven storms that did have sufficient time to attain their MPIs and moved within 200 km of Isla Socorro and major hurricane Guillermo (1997) are discussed in greater detail in the remainder of this section.

Hurricane Adolph developed off the coast of Mexico approximately 975 km to the southeast of Isla Socorro on 15 June 1995. Figure 6 shows the minimum surface pressures for Adolph taken from the National Hurricane Center's (NHC) best-track data and the MPIs computed from the soundings taken at Isla Socorro. Adolph was initially in a favorable environment and developed rapidly into a hurricane. Adolph had a minimum surface pressure of 948 hPa at 0600 UTC on 18 June 1995. At that time the center of the storm was approximately 400 km east-southeast of Isla Socorro. The MPIs based on the soundings taken at Isla Socorro indicated that the environment around the island was only capable of sup-

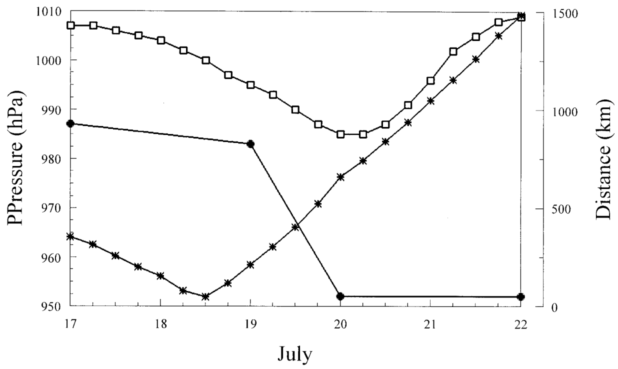

FIG. 7. Same as in Fig. 6 but for Hurricane Cosme (1995).

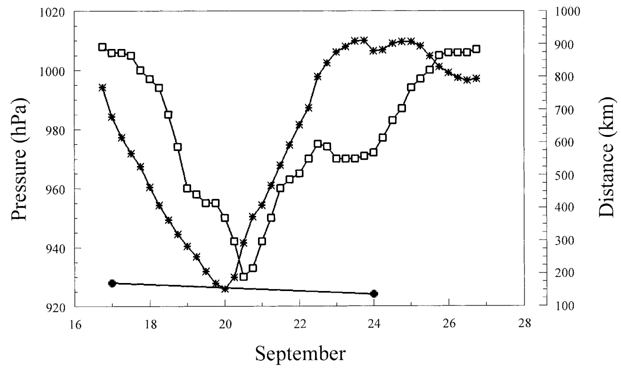

FIG. 8. Same as in Fig. 6 but for Hurricane Juliette (1995).

porting a weak tropical cyclone. As Adolph moved northwest toward Isla Socorro, the unfavorable thermodynamic environment appeared to produce rapid weakening that mirrored the earlier rapid intensification. By the time the center of Adolph passed within 50 km of the island at 0600 UTC on 20 June 1995 the minimum surface pressure had risen to 1001 hPa, which was very close to the MPI computed from the sounding taken at Isla Socorro. The MPI varied from 1003 to 1007 hPa during the period before and after the passage of Adolph. The effect of the proximity of Adolph and most other storms had a minimal effect on the computed MPIs.

Hurricane Cosme developed approximately 250 km southeast of Isla Socorro at 0000 UTC on 17 July 1995. The minimum central pressures for Cosme and the MPIs for Isla Socorro are shown in Fig. 7. The MPI suggests that the environment around the island was capable of supporting a minimal hurricane at the time of Cosme's development. The sharp drop in the MPI on 19 July 1995 indicates that the hydrostatic pressure decrease had exceed 20 hPa and the processes in the eye included in Holland's method produced an additional decrease of 30 hPa. Cosme intensified as it moved west of Isla Socorro. The storm achieved minimal hurricane status at 1800 UTC on 19 July 1995. Cosme's minimum surface pressure of 985 hPa occurred 6 h later. The storm subsequently weakened as it moved over cooler SSTs. The MPIs from Isla Socorro on Julian day 198 accurately presaged the development of the minimal hurricane.

Hurricane Juliette developed approximately 700 km southeast of Isla Socorro at 1800 UTC on 16 September 1995. The minimum central pressures for the storm and the MPIs from Isla Socorro are shown in Fig. 8. At the time of the storm's development the soundings at Isla Socorro indicated an environment capable of supporting the development of a powerful hurricane. The MPI at 0000 UTC on 17 September 1995 was 928 hPa. Juliette intensified rapidly as it moved toward the west-northwest. The storm was closest to Isla Socorro at 0000 UTC on 20 September 1995, when the center of the storm was approximately 150 km south of the island. At that time the minimum surface pressure of the storm was 955 hPa. Juliette continued to intensify as it moved west of the island. The hurricane reached its maximum intensity at 1200 UTC on 20 September 1995, when the minimum surface pressure reached 930 hPa. Juliette was the most intense hurricane to form over the eastern North Pacific in 1995. Once again the MPI computed using Holland's method accurately predicted the maximum intensity of the tropical cyclone.

Hurricane Douglas formed when the system that had been Hurricane Cesar in the Atlantic basin crossed central America and redeveloped over the warm waters of the eastern North Pacific Ocean. The minimum central pressures for Hurricane Douglas and the concurrent MPIs for Isla Socorro are shown in Fig. 9. The entries in the best-track file for Hurricane Douglas begin at 0000 UTC on 29 July 1996. At that time the system was more than 2000 km east-southeast of Isla Socorro. MPIs computed from soundings taken at the island fluctuated between 920 and 940 hPa and indicated that the environment was capable of supporting the development of a strong hurricane. Douglas intensified slowly, but steadily, as it moved west-northwest. The storm was classified as a hurricane at 1200 UTC on 29 July 1996. Douglas continued to intensify and became a major hurricane. The lowest minimum surface pressure of 946 hPa occurred as the center of the storm passed within 100 km of Isla Socorro. The MPIs based on the sound-

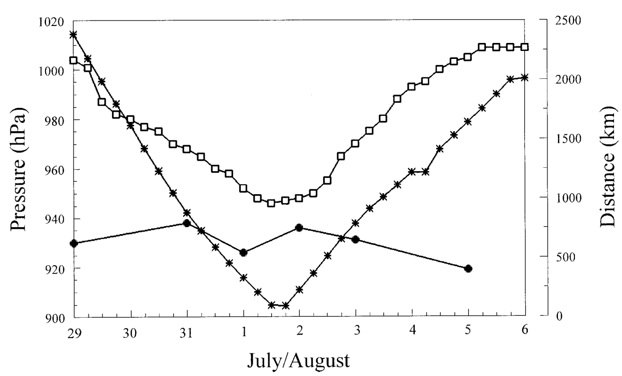

FIG. 9. Same as in Fig. 6 but for Hurricane Douglas (1996).

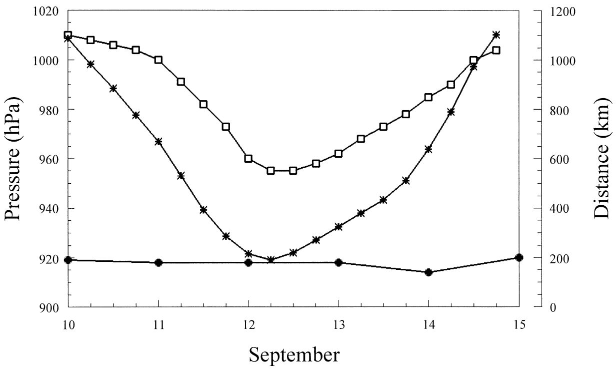

FIG. 10. Same as in Fig. 6 but for Hurricane Fausto (1996).

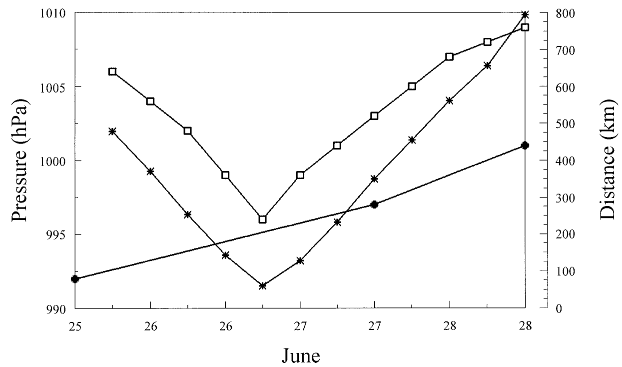

FIG. 11. Same as in Fig. 6 but for Tropical Storm Carlos (1997).

ings of the island provided a good indication of the potential intensity of Douglas.

Hurricane Fausto formed at 0000 UTC on 10 September 1996. The genesis of the system occurred approximately 1000 km east-southeast of Isla Socorro. The minimum central pressures for Fausto and the MPIs for the island are shown in Fig. 10. The tropical cyclone intensified steadily as is moved toward the northwest. MPIs based on the soundings from Isla Socorro were around 920 hPa and indicated that the thermodynamic environment was capable of supporting the development of a strong hurricane. Fausto reached its maximum intensity at 0600 UTC on 12 September 1996. The center of the storm was located approximately 200 km north-northeast of the island and the minimum surface pressure was 955 hPa. An approaching midlatitude trough turned the storm northward and the hurricane weakened as it approached Baja California. Hurricane Fausto represents an excellent example of how inhibiting factors in the environment, such as shear generated by the midlatitude trough, can prevent a tropical cyclone from reaching its MPI.

Tropical Storm Carlos developed at 0000 UTC on 25 June 1997. Carlos formed approximately 450 km southeast of Isla Socorro. The minimum surface pressures and the MPIs for Isla Socorro are shown in Fig. 11. The MPIs indicated that the thermodynamic environment around the island was only capable of supporting a strong tropical storm and the development of a hurricane was unlikely. Carlos intensified slowly and reached its maximum intensity at 0600 UTC on 26 June 1997. The minimum surface pressure in Carlos was 996 hPa when the storm was centered approximately 60 km from the island. As suggested by the MPIs, Carlos remained a tropical storm throughout its brief existence.

Hurricane Guillermo formed approximately 2000 km east-southeast of Isla Socorro at 1200 UTC on 20 July 1997. The minimum surface pressures of Guillermo and the MPIs for Isla Socorro are shown in Fig. 12. Guillermo intensified steadily and was classified as a hurricane at 1800 UTC on 1 August 1997. Guillermo began a period of rapid intensification at 0600 UTC on 2 August 1997. The minimum surface pressure decreased by 44 hPa to 935 hPa during the following 24 h. The hurricane intensified further and the minimum surface pressure was 927 hPa at 1800 UTC on 3 August 1997, when the center of Guillermo was closest to Isla Socorro. Although the center of the hurricane never came closer than 550 km of the island, the MPIs in the range of 900–920 hPa indicated that the thermodynamic environment was capable of supporting the development of a major hurricane. Guillermo reached its maximum intensity at 0000 UTC on 5 August 1997. The hurricane's minimum surface pressure of 919 hPa made it one of the most intense tropical cyclones that has ever been observed over the eastern North Pacific basin.

Hurricane Linda formed over the eastern North Pacific 5 weeks after Guillermo developed. Linda formed approximately 800 km southeast of Isla Socorro at 1200 UTC on 9 September 1997. The minimum surface pressures for Linda and the MPIs for the island are shown in Fig. 13. Linda intensified steadily after its formation and achieved hurricane status at 0000 UTC on 11 September 1997 with an estimated minimum central pressure of 987 hPa. A period of extremely rapid intensification commenced and over the next 24 h the minimum surface pressure in the hurricane decreased 81 hPa to 906 hPa. Since the intensity of Linda was estimated using satellite imagery, it is not possible to know the exact rate of deepening, but it seems clear that the rate

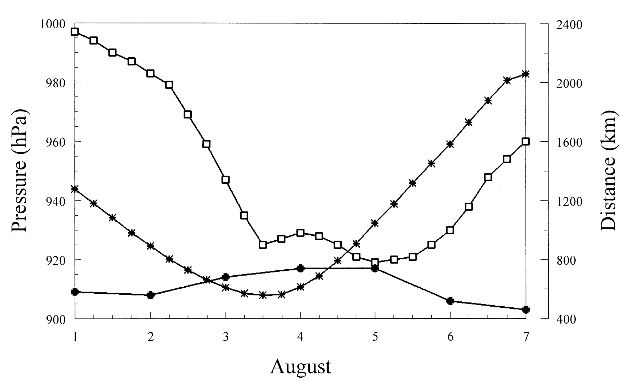

FIG. 12. Same as in Fig. 6 but for Hurricane Guillermo (1997).

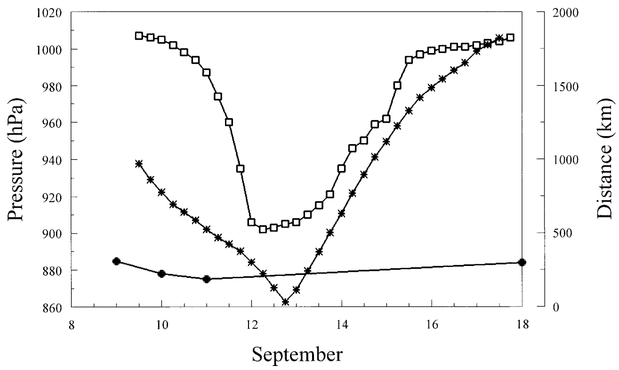

FIG. 13. Same as in Fig. 6 but for Hurricane Linda (1997).

of intensification was among the most rapid observed in a tropical cyclone. The MPIs based on the soundings taken at Isla Socorro show the impact of an El Niño in the form of warmer SSTs and suggest that the thermodynamic environment could have supported minimum surface pressures as low as 880 hPa. The hurricane attained its maximum intensity at 0600 UTC on 12 September 1997 when the minimum surface pressure was 902 hPa. The center of Hurricane Linda passed over Isla Socorro between 1800 UTC on 12 September 1997 and 0000 UTC on 13 September 1997. At that time the minimum surface pressure of 905 hPa was more than 25 hPa higher than the MPI. With the limited data available it may not be possible to determine if interaction with the topography of the island, upwelling of cooler water, or some other process kept Linda from further intensification. Although no in situ aircraft or other data were available at the time when Linda was at its peak intensity, it does seem likely that Hurricane Linda was the most intense tropical cyclone ever observed in the relatively short period of record for the eastern North Pacific and that the thermodynamic environment was primed to support an intense hurricane.

c. Thermodynamic versus SST-based methods

The computation of MPI using the method developed by Holland (1997) required a sounding of the thermodynamic environment. In some applications, including the research discussed in the previous sections, surface air temperature was replaced by SST − 1 (K). DeMaria and Kaplan (1994) and Whitney and Hobgood (1997) developed empirical functions that related the maximum wind speeds observed in tropical cyclones to SSTs for the Atlantic and eastern North Pacific basins, respectively. In this section the empirical MPI computed from the relationship developed by Whitney and Hobgood is compared to the MPIs computed from the Holland method.

Whitney and Hobgood (1997) related the maximum wind speeds for tropical cyclones over the eastern North Pacific Ocean to the SSTs under the cores of the storms for 31 yr of data. The data were aggregated into categories with a width of 1 k and a function was fit to the resulting curve. The relationship that resulted from the curve fitting was

$$\text{EPMPI} = C_0 + C_1(\text{SST}), \qquad (1)$$

where EPMPI was the eastern North Pacific MPI in meters per second, SST was in degrees Celsius, $C_0 = -79.17262\ \text{m s}^{-1}$, and $C_1 = 5.361814\ \text{m s}^{-1}\ {}^\circ\text{C}^{-1}$. Since EPMPI has units of meters per second, the intensity relationship from the Dvorak (1984) technique was used to convert from maximum sustained winds to minimum surface pressures. Although the conversion introduced some additional uncertainty into the analysis, it was consistent with most of the data used to develop (1), since most intensity estimates for tropical cyclones over the eastern North Pacific are based on the Dvorak technique.

The use of this method to develop an empirically based MPI has two potential weaknesses. First, the use of a dataset of finite length may mean that the strongest possible tropical cyclone has not yet occurred over a given SST and hence is not included in the data used to generate (1). The implication of this weakness is that the relationship may underestimate the MPIs for storms over higher SSTs. Hurricane Linda (1997) may represent an example of this problem and it is discussed in more detail later in this section.

Second, the tropical cyclones that passed over the cooler SSTs used in the development of (1) were systems that were dissipating, but had not yet spun down. The wind speeds and central pressures of those tropical cyclones had been generated when the systems were over warmer SSTs. As the systems moved poleward, the cooler SSTs were unable to sustain the intensity of the systems. However, dissipation of a tropical cyclone is not an instantaneous process and there is a lag time between the effects of an unfavorable thermodynamic environment and the decay of the wind field. The implication of this lag time is that the empirical relationship may overestimate the thermodynamic potential of the environment to sustain tropical cyclones at cooler SSTs.

The MPIs computed for Isla Socorro for 1997 using the two methods are shown in Fig. 14. The empirical MPI based on the SST alone exhibits a gradual decrease until the peak of the hurricane season followed by a gradual increase thereafter. This pattern results from the relatively gradual changes in SSTs that occur in the eastern North Pacific. The short increase in the empirical SST-based MPI around Julian day 180 may have been the result of some upwelling of cooler water associated with the passage of Tropical Storm Carlos.

In the early portion of the hurricane season the empirically SST-based MPIs were lower than the MPIs computed from Holland's method. This difference results from the data used to develop (1). At the beginning of the hurricane season the SSTs and environmental conditions around Isla Socorro were marginal for trop-

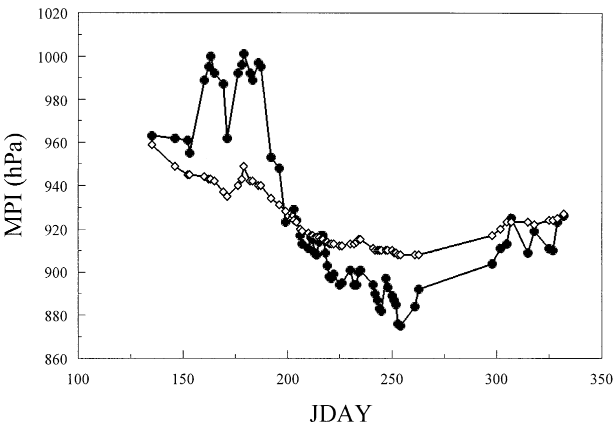

FIG. 14. SST-based MPIs (open diamonds) and thermodynamic MPIs (filled circles) for Isla Socorro for 1997.

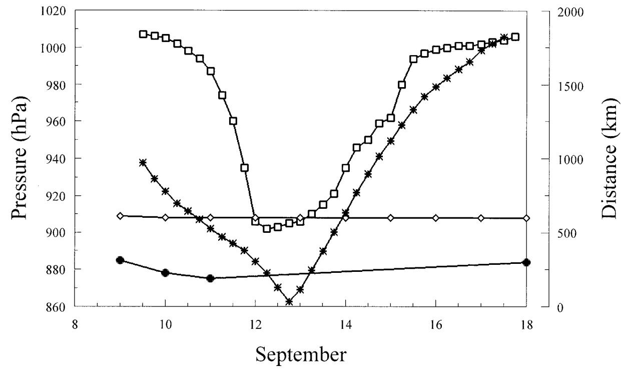

FIG. 16. Same as in Fig. 15 but for Hurricane Linda (1997).

ical cyclone development and these conditions are accurately reflected in the MPIs from Holland's method. However, the storms used to compute the SST-based MPI represented the strongest tropical cyclone observed at each SST. The strongest tropical cyclones occurring over cooler SSTs were those that intensified over warmer water before moving over the cooler SSTs. The lag time required for the system to experience the effects of cooler SSTs and spin down caused the SST-based MPIs to overestimate the potential intensities of tropical cyclones that could be supported by those SSTs. This problem can be clearly seen in Fig. 15. The SST-based MPIs indicated that the water around Isla Socorro could support a strong hurricane. However, the thermodynamically based Holland method predicts that the environment would only support a tropical storm. Carlos only achieved tropical storm status, which was well predicted by Holland's method.

By the middle of the hurricane season the MPIs computed using the Holland method were lower than the SST-based MPIs. This result can also be explained in terms of the data used to generate (1). Only 31 yr of data were used to generate the relationship between EPMPI and SST. It is entirely likely that this short length of record did not include the most powerful tropical cyclones that could occur over a given SST. This problem may be particularly relevant for anomalously warm SSTs that develop during an El Niño. An El Niño was occurring during 1997 and intense hurricanes Guillermo and Linda both developed over the eastern North Pacific. As can be seen in Fig. 16, the SST-based MPIs underpredicted the maximum intensity of Linda, because Linda was more intense than any tropical cyclone in the data used to develop (1). The Holland method clearly indicated that the environment around Isla Socorro was capable of supporting the development of a major hurricane, such as Linda.

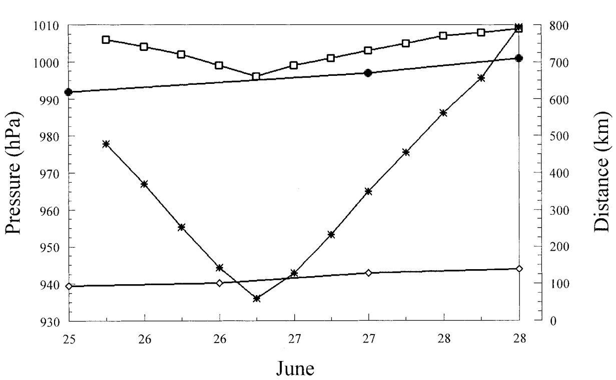

FIG. 15. SST-based MPIs (open diamonds), thermodynamic MPIs (filled circles), and minimum surface pressures (open squares) for Tropical Storm Carlos (1997). Distances from Isla Socorro are shown by asterisks.

Table 1 presents comparisons of MPI and EPMPI to the actual intensity (MSP) for the seven storms that had an opportunity to attain their MPI before they passed within 200 km of Isla Socorro. With the exception of Tropical Storm Carlos, MPI and EPMPI were based on soundings and SSTs 72 h prior to the time of the nearest location of the storm's center to Isla Socorro. Since no usable soundings existed for Carlos at either 72 or 48 h prior to the closest passage of the storm, a sounding 24 h prior to that time was used. The Holland method (MPI) overpredicted the maximum intensity by an average of 15.6 hPa, while the empirically based method (EPMPI) overpredicted the maximum intensity by an average of 34.4 hPa. EPMPI overpredicted the maximum intensity of the three storms that occurred in June and July by an average of 57.3 hPa, while MPI over-

TABLE 1. Comparisons of MPI and EPMPI.

Storm	Date	Distance (km)	MPI (hPa)	EPMPI (hPa)	MSP (hPa)
Adolph	20 Jun 1995	57	1006	950	1001
Cosme	18 Jul 1995	46	987	940	1000
Juliette	20 Sep 1995	153	929	920	950
Douglas	01 Aug 1996	94	930	926	947
Fausto	12 Sep 1996	191	917	923	955
Carlos	26 Jun 1997	60	992	935	996
Linda	12 Sep 1997	35	884	909	905

predicted the maximum intensity of those three storms by an average of 4 hPa.

Ideally any method used to estimate the MPI should come close to predicting the actual intensity without underpredicting it. Both methods underpredicted one of the seven storms. The Holland method underpredicted the minimum surface pressure of Tropical Storm Adolph by 5 hPa. At the time, Adolph was filling and the final pressure in the best-track file, which occurred 24 h later, is 1006 hPa, which was predicted exactly by the Holland method. The EPMPI underpredicted the minimum surface pressure of Hurricane Linda by 4 hPa. Although a difference of only 4 hPa may fall within the range of error due to the estimatation of intensity based on satellite imagery, it is an example of one of the limitations of an empirically based MPI resulting from the relatively short time period used to generate (1). The limited sample size prevents a more detailed statistical analysis of these results.

While the accuracy of the Holland method is affected by the assumptions used to develop it, the method was clearly superior to an SST-based approach. It more closely predicted the actual intensity of the storm in six of the seven cases and was more than 50 hPa closer to the actual intensity for the three early season storms. The combination of the atmospheric sounding with surface data provides a more comprehensive synopsis of the tropical environment than is provided by the SST. Empirical SST-based MPIs are useful and will become more accurate as the length of record increases and more extreme tropical cyclones are observed. The problem of the lag time before tropical cyclones weaken in response to cooler SSTs might be alleviated to some extent, if separate relationships were developed for intensifying and dissipating tropical cyclones.

5. Summary and conclusions

Soundings from Isla Socorro, Mexico, were used in the method developed by Holland (1997) to compute MPIs for 1994–97. The MPIs characterized an environment that is only minimally favorable to the formation of tropical cyclones in May and June, but which becomes conducive to the development of strong hurricanes in August and September. The El Niño conditions in 1997 produced low MPIs and saw the development of powerful hurricanes Guillermo and Linda. MPIs for tropical cyclones that passed near Isla Socorro accurately described the potential for intensification of those storms. In the cases of Adolph (1995), Cosme (1995), and Carlos (1997), the MPIs from Isla Socorro accurately demonstrated that the environment could only support weak tropical cyclones. For Juliette (1995), Douglas (1996), Guillermo (1997), and Linda (1997), the MPIs indicated the potential for the development of strong hurricanes. The MPIs also indicated the potential for the development of a strong hurricane in the case of Fausto (1996), but strong vertical wind shear prevented the storm from reaching its MPI.

The thermodynamically based MPIs proved to be superior to an empirically based MPI that was solely a function of SST. Early in the hurricane season the Holland method clearly indicated that the environment could not support strong tropical cyclones, while the SST-based MPI overestimated the potential for intensification. At marginal SSTs the MPIs from the SST-based method were more representative of previously strong tropical cyclones that were dissipating over cooler water, and the MPIs overestimated the potential for weaker systems to intensify over those same SSTs. A very intense hurricane, Linda (1997), was stronger than any storm used to determine the relationship between SST and MPI. Thus the SST-based MPI underestimated the potential for Linda's intensification.

The use of soundings from a small island such as Isla Socorro in conjunction with a thermodynamic technique for computation of MPI clearly provides a means to characterize the tropical environment. The soundings at Isla Socorro probably provide the only in situ representation of the environment over the tropical eastern North Pacific that is not significantly contaminated by continental air. The MPI gives forecasters an accurate indication of the worst-case scenario they should expect. The atmosphere in the Tropics exhibits less variability than conditions at higher latitudes. However, given the scale of a tropical cyclone, daily soundings provide superior vertical samples of the spatial and temporal variations that do occur in the Tropics. The results of this study indicate that the Holland method can provide useful information to forecasters when the center of the tropical cyclone is forecast to pass within 200 km of the location of the sounding. The importance of regular sampling of the tropical atmosphere is most important in the determination of when the atmosphere makes the transition from being thermodynamically favorable for the development of weak tropical cyclones to being favorable for the development of strong tropical cyclones.

The MPI is a useful variable that provides a vertically integrated measure of the state of the tropical atmosphere during the hurricane season. However, the MPI only provides a thermodynamic measure of the potential for the intensification of a tropical cyclone. Additional research is needed into the factors, such as vertical wind shear and oceanic–atmospheric interactions, that allow some tropical cyclones to approach their MPIs while inhibiting the intensification of other storms. It might be particularly instructive to examine the magnitudes of MPIs and these other factors prior to the onset of periods of rapid intensification of tropical cyclones.

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