Implications of Summertime Sea Level Pressure Anomalies in the Tropical Atlantic Region

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(Manuscript received 14 December 1995, in final form 23 September 1996)

ABSTRACT

This study explores the inverse relationship between sea level pressure and tropical cyclones in the tropical Atlantic (TA). Upper-air observations, the National Centers for Environmental Prediction (formerly the National Meteorological Center)/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, and regional SSTs provide clues as to the physics of this relationship using composite and regression methods. Stratification of upper-air data by sea level pressure anomalies in the TA yields several interesting results, including anomalously high (low) pressure association with relatively dry (moist) middle levels, cooler (warmer) midlevel temperatures, and stronger (weaker) 200–850-mb vertical wind shears. The configuration of these composite wind differences suggests that higher summertime pressure in the TA is associated with an anomalously strong tropical upper tropospheric trough (TUTT) circulation. The observations show systematic association between the composite moisture, temperature, and wind differences. Studies of longwave sensitivity using a two stream model show that the moisture field dominates the longwave radiative cooling; hence, dry midlevels enhance cooling of the atmosphere. The effects of SST variations and tropical cyclones on TA pressure anomalies suggest that summertime pressure in this region is strongly influenced by additional (unresolved) climate forcings. These findings lead to a hypothesis that explains both the persistent nature of the summertime pressure (in the TA) as well as how variations of this pressure modulate the TUTT circulation strength. The hypothesis states that positive feedbacks operate between pressure/subsidence variations, midlevel moisture, and differential longwave radiative cooling that affects local baroclinicity (i.e., TUTT). When pressures are anomalously high, subsidence is greater and middle levels are dryer, resulting in increased atmospheric cooling to space and increased baroclinicity. Hence, pressure-related variations of both the midlevel moisture field and the TUTT circulation result in modulations of the upper-level winds and vertical wind shears in the TA. These, in turn, are found to be the primary cause of the observed pressure–tropical cyclone relationship; higher tropical Atlantic pressure results in an environment that is dryer and more sheared and, thus, less favorable for tropical cyclone formation and development.

1. Introduction

It is well established that sea level pressure (SLP) anomalies in the tropical Atlantic (TA) (defined as the Atlantic Ocean south of a Charleston–Bermuda line and west of a Georgetown–Bermuda line) are closely related to both seasonal and shorter term, week-to-week variations of Atlantic tropical cyclone (TC) activity. As early as 1906 increased Atlantic TC activity was being attributed to low regional barometric pressure (Garriott 1906). Studies of the very active 1933 Atlantic hurricane season showed a clear relationship between tropical storm activity and prevailing SLP, both preceding and during the hurricane season (Ray 1935; Brennan 1935). In fact, Brennan's work notes that both regional pressure anomalies and the strength of the trade winds are inversely related to sea surface temperatures (SST).

More recent studies by Namias (1955, 1968) and Ballenzweig (1958) rediscovered the relevance of the TC-pressure relationship while attempting to explain year-to-year variations of tracks and numbers of TCs in the TA. Shapiro (1982a) identified cycles of year-to-year variations of TC activity associated with regional SSTs and Atlantic pressures and examined the dominant cycles of these variations for the possible causes (Shapiro 1982b). Shapiro's studies suggest that one-sixth of the Atlantic basin's TC activity is explained by variations of surface pressure in the tropical Atlantic. This is remarkable in that Shapiro's studies used only regional sea level pressures for locations north of 20°N. Gray (1984) demonstrated the utility of the preseason pressure–TC relationship noted by Shapiro (1982b) and Ray (1935) by using preseason pressures in the Caribbean Sea and Gulf of Mexico region plus El Niño–Southern Oscillation (ENSO) conditions and forward extrapolated values of the stratospheric quasi-biennial

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TABLE 1. Stations used in the July through September index of SLP in the tropical Atlantic. Listed along with the WMO number is the station name, location, and mean and standard deviation July through September sea level pressure in millibars.

WMO number	Station	Lat	Long	Mean	SD
72202	Miami, FL	25.8°N	80.3°W	1016.3	0.88
72206	Jacksonville, FL	30.5°N	81.7°W	1017.2	0.77
72208	Charleston, SC	32.9°N	80.0°W	1017.4	0.78
72231	New Orleans, LA	30.0°N	90.3°W	1016.1	0.76
78073	Nassau, Bahamas	25.0°N	77.5°W	1016.7	0.61
78897	Raizet, Guadeloupe	16.3°N	61.5°W	1014.8	0.49
78954	Seawell, Barbados	13.1°N	59.5°W	1014.0	0.65
78988	Curacao	12.2°N	69.0°W	1011.8	0.47
80413	Maracay	10.3°N	67.7°W	1013.8	1.68
80447	San Antonio Del Tachira	7.8°N	72.5°W	1011.3	1.39
81405	Cayenne	4.8°N	52.4°W	1013.1	0.39

oscillation (QBO) to predict seasonal TC activity for the Atlantic basin. The predictive utility of the pressure–TC relationship has been further refined by Gray et al. (1993, 1994).

Though SLP anomalies in the TA seem to be strongly related to Atlantic TC activity, it is not clear in a dynamic context how anomalous pressure variations of only a millibar or two can have such a strong modulating effect on hurricane activity.

This paper attempts to clarify this question by exploring several possible causes for the pressure–TC relationship. These possible causes include changes in vertical shear, low-level convergence/vorticity, and a possible decrease of basinwide convective instability. As will be shown, the observations strongly suggest that the pressure–TC relationship in the Atlantic basin is not solely the result of any single change but rather a complex interaction between several competing factors. In order to study these interactions, upper-air differences in the wind, temperature, and moisture fields for years with higher versus lower than normal pressures in the Atlantic TC basin are examined using composite and regression methods. The following section will discuss the data and methodology. Additional sections, in order, include a background section discussing TC environmental influences, a results section, discussion, a hypothesis to interpret all of the results is then offered, followed by a short summary.

2. Data and methodology

An index of July through September sea level pressure (SLP) in the TA was used as the selection criterion for various composites of regional upper-air data. The July through September period was chosen so as to limit the effects of intrusions of midlatitude weather systems. The SLP stations are listed in Table 1 along with each station's July–September (JAS) mean and standard deviation. Figure 1 shows the geographical location of these stations. These stations cover a much broader geographic region than previous studies of this nature, encompassing a large region that is more representative of the Atlantic TC basin. This index was created using the long-term mean ($\overline{x}_i$) to compute JAS anomalies at each station for each year. These anomalies are normalized as shown in Eq. (1) by the standard deviation (σ_i) of SLP variations at that station (i). The index (I_j) is found by summing the standardized deviations at each of the stations for each year (j):

$$I_j = \sum_{i=1}^{N} \frac{x_i - \overline{x}_i}{\sigma_i}, \qquad (1)$$

where N is the number of stations.

The archived surface data were obtained from the Global Historical Climatology Network (Vose et al. 1992). Figure 2 shows a time series and regression analysis of the resulting SLP index (average mean = 1014.8 mb; average standard deviation = 0.81 mb) along with an index of normalized hurricanes forming south of 25°N created using the same method as the pressure index [see Eq. (1)] (average mean = 2.67; average standard deviation = 2.18). The scatter diagram in Fig. 2 further illustrates the relationship. Tropical cyclone data were obtained from Neumann et al. (1993). Table 2 provides a detailed summary of TC activity during the ten highest and ten lowest pressure years. Note that in this table the wind bias for intense hurricanes (categories 3–5) prior to 1969 mentioned by Landsea (1993) has been removed. An inverse relationship between the pressure index and low-latitude tropical storm activity is apparent. Note also in the bottom of Table 2 that TC activity (tropical storms and weak hurricanes) tends to increase in regions north of 25°N when TA pressures are high.

Upper-air soundings were composited for 850, 700, 500, 300, 200, 150, and 100 mb. The monthly mean soundings for the stations listed in Table 3 came from two different archives. The first set consisted of monthly mean soundings; the other archive consisted of daily soundings from which monthly means and anomalies were calculated. Both of the datasets are available at the National Center for Atmospheric Research and are described in Shea et al. (1994). The years 1956, 1961, 1967, 1968, 1972, 1976, 1977, 1983, 1985, and 1986 are used for the high pressure composites and 1950,

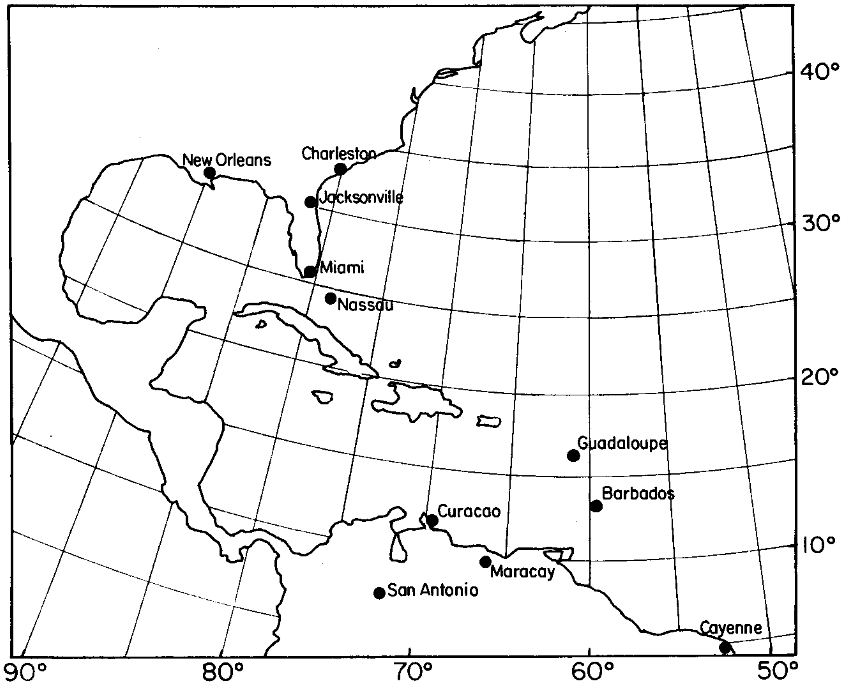

FIG. 1. Geographical location of SLP stations used to create the July through September index in the tropical Atlantic region.

1951, 1955, 1957, 1958, 1963, 1964, 1966, 1969, and 1979 are used for the low pressure composites. As noted previously, these are the ten highest and ten lowest years in the 39-yr 1950–88 record and, as such, approximate the upper and lower quartiles. Significance tests were performed on the composite results using the Student's t-test for the significance of means as described in Panofsky and Brier (1968). Since the time spaces of data varies between stations, this test provides an adequate intercomparison of the significance of means. The results of the composite analysis and their significance are discussed in section 4.

Because of the limited amount of upper-air data, areas showing large and significant differences between the high versus low pressure composites are tested using regression analysis to determine if the year-to-year variations of the phenomenon are also significant. This analysis also quantifies the pressure/environmental relationships as regression coefficients. These coefficients are expressed in terms of the ratio of the change of an environmental quantity to the pressure change in millibars. This analysis will allow for the use of all available data and thus may aid the establishment of significance for some of the composited results. The significance of these regression coefficients is also tested using the Student's t-test (Panofsky and Brier 1968); the results are also discussed in section 4.

Upper-air data were also composited to stratify daily soundings by surface pressure differences. This analysis focused on only one station (San Juan) for one month of the year (August) and is restricted to nighttime soundings only. Nighttime soundings are used to prevent biasing of results due to design problems of the moisture sensor, which yielded erroneously low moisture values during the daytime (Ruprecht 1975). The San Juan soundings for August are examined and stratified according to their surface pressure. This procedure is conducted for the years 1956–86. This analysis helps determine if the pressure-linked associations found in the monthly mean soundings are applicable on shorter term, weekly and daily basis.

Longwave radiative cooling rates and sensitivity calculations are performed to estimate differences in cooling rates as well as to determine the dominant radiational effects. These calculations are accomplished by inserting the resulting mean from the daily soundings stratified by pressure into a two stream radiative transfer model discussed in Stackhouse and Stephens (1991) with 350 ppm CO_2 concentrations. The results of this analysis and the simple radiation calculations are also discussed in section 4.

In addition to the standard rawinsonde data discussed above, this study utilizes the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center) monthly reanalysis data discussed by Kalnay et al. (1996). Using thirteen years (1982–94) of this reanalysis, I performed the same composite analysis as was applied to the rawinsonde data. Using the methodology discussed in section 2, it is found that the low pressure years are 1984, 1987, and 1989 and the high pressure years are 1986, 1991, and 1992. This again roughly represents the lowest and high-

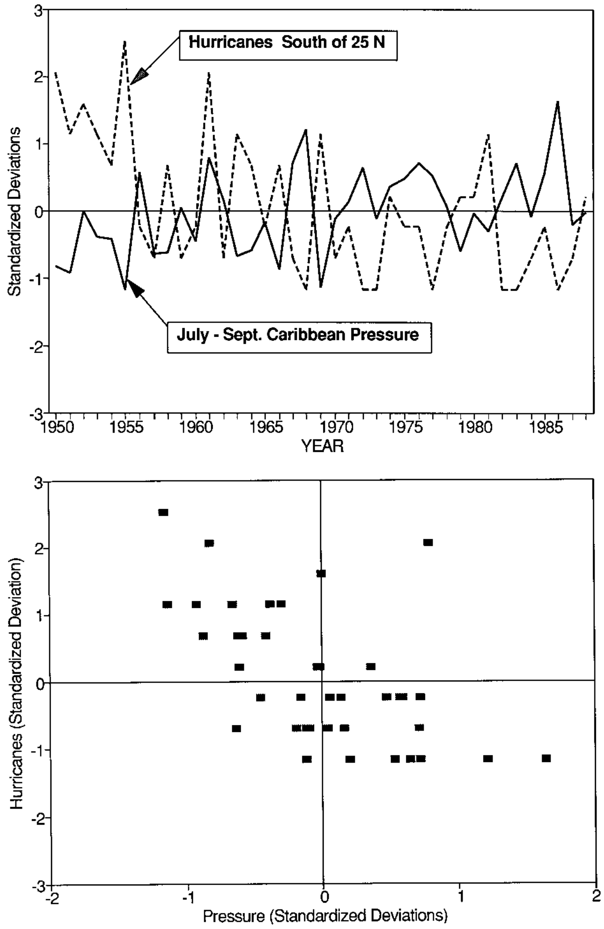

FIG. 2. (Top) Time series of July through September Caribbean sea level pressure index expressed as standardized deviations (solid line) versus normalized values of hurricane activity south of 25°N (dashed line). (Bottom) Scatter diagram of the data points contained in the top panel. The correlation coefficient for the analysis in the bottom panel is $r = -0.58$ for the 1950–88 period. Mean pressure is 1014 mb with a standard deviation of 0.81 mb; hurricane activity has a mean value of 2.52 and a standard deviation of 2.19.

est quartiles of the data. Using the reanalyzed fields, it is possible to look at the wind, moisture and temperature fields in much greater spatial detail than was possible with monthly soundings. The model calculated radiative properties of the atmosphere associated with the two different SLP conditions can also be examined. And though this part of the study is limited by the length of the data time series, it is nevertheless interesting to compare reanalysis results to results obtained solely from the rawinsonde data.

Climatological values of SLP and of SST from the Comprehensive Ocean Atmosphere Data Sets (COADS) (Shea et al. 1994) are used for diagnosing the strength of SST–SLP relationships. These fields are also used in a limited manner to examine the relationship between SST and hurricanes as discussed in section 5.

TABLE 2. Summary of tropical cyclone activity parameters and indices stratified by both latitude and pressure. Included are named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), intense hurricanes (i.e., categories 3, 4, and 5) (IH), and intense hurricane days (IHD). Early period wind bias effects have been removed from the hurricane data using the methodology described by Landsea (1993). The numbers shown are mean values for the ten lowest and ten highest pressure years (see text for years) and the ratio of low to high pressure periods for the regions south and north of 25°N, respectively.

	NS	NSD	H	HD	IH	IHD
	Formation south of 25°N					
Ten lowest SLP	65	516	46	265	19	58
Ten highest SLP	30	208	14	86	7	21
Ratio low/high	2.17	2.48	3.28	3.08	2.71	2.76
	Formation north of 25°N					
Ten lowest SLP	21	106	19	69	6	11.3
Ten highest SLP	30	123	22	69	4	4
Ratio low/high	0.70	0.86	0.86	1.0	1.5	2.88

3. Tropical cyclones and upper-air environments

I begin by describing environmental upper-air features that inhibit TC development and maintenance. Gray (1968) showed that a major inhibiting factor for TCs is tropospheric vertical wind shear (VWS); see Eq. (2) below. Namely, when large vertical differences occur between horizontal winds in the lower-troposphere (near 850 mb) and the upper-troposphere (near 200 mb), storms can neither form nor maintain themselves:

$$\mathrm{VWS} = \sqrt{(U_{200} - U_{850})^2 + (V_{200} - V_{850})^2}. \quad (2)$$

Recent work by Zehr (1992) and Fitzpatrick (1995) shows that net VWS becomes an inhibiting factor on tropical cyclone intensification at values greater than approximately 8.5 m s^{-1} and retards formation at values exceeding 10 m s^{-1}. DeMaria et al. (1993) found that shear, along with sea SST, are the primary factors involved in determining tropical cyclone intensification.

TABLE 3. Summary of upper-air stations used for the July through September composite study in the Atlantic, Caribbean, and Gulf of Mexico. Listed along with the WMO number is the station name and coordinates.

WMO number	Station	Lat	Long
72202	Miami, FL	25.8°N	80.3°W
72208	Charleston, SC	32.9°N	80.0°W
72250	Brownsville, TX	25.9°N	97.4°W
78016	Bermuda	32.4°N	64.7°W
78367	Guantanamo, Cuba	19.9°N	75.2°W
78384	Roberts Field, Grand Cayman	19.3°N	81.3°W
78397	Kingston, Jamaica	17.9°N	76.8°W
78501	Islas Del Cisne, Honduras	17.4°N	83.9°W
78526	San Juan, Puerto Rico	18.4°N	66.0°W
78897	Raizet, Guadeloupe	16.3°N	61.5°W
78954	Seawell, Barbados	13.1°N	59.5°W
78988	Curacao	12.2°N	69.0°W
80001	Georgetown, Guyana	6.8°N	58.2°W
80222	Bogota, Colombia	4.7°N	74.8°W

Another important upper atmospheric factor that inhibits the formation of tropical cyclones is reduced midlevel (300–700 mb) moisture (low relative humidity) values. Humidity of the midlayers is reduced (increased) by mean subsidence (rising motion). Gray (1968, 1975, 1979) states that drier midlevels act to suppress (or retard) formation of intense convection and, hence, TCs. The entrainment of drier environmental air into developing TC systems results in less buoyancy for the system as well as diminished upper-level warming due to decreased release of latent heat. These two resulting effects can, by themselves, effectively limit the formation of TCs.

Other factors both which actively influence TCs on seasonal and day-to-day timescales are the presence of low-level relative vorticity and convergence, coupled with upper-level divergence and negative relative vorticity (Gray 1975; Zehr 1992). In the Atlantic basin (where a monsoon trough seldom forms), most low-level positive relative vorticity and convergence is forced by transient vorticity features such as easterly waves and stalled frontal boundaries (Zehr 1992; Gray 1968). It is felt that the effects of seasonal variations of large-scale vorticity in the Atlantic are not as important to TC activity as are the short-lived transient sources of synoptic vorticity associated with easterly waves and midlatitude weather systems. Most Atlantic TCs form in an easterly regime (low or negative large-scale vorticity) from African easterly wave systems (Gray 1968). In other regions such as the Northwest Pacific, where nearly half of all tropical storm genesis is associated with the monsoon trough (Zehr 1992), the variation of the seasonal strength of large-scale vorticity or the monsoon trough would likely be a more dominant modulator of TC activity on a seasonal basis. In addition, the divergence and vorticity fields also require more extensive spatial data that are not available for the tropical Atlantic at this time. Because of all the above-stated reasons, the seasonal variation of low-level vorticity is not considered in this study.

4. Results

a. Composite and regression results

Results of the compositing tests provide much information on upper-air conditions for different pressure regimes in the TA. The most dramatic results are found in the upper troposphere in and around the Caribbean Sea. The high pressure minus the low pressure zonal wind differences shown in Fig. 3 indicate that the 300–100 mb zonal winds are increased, with the most significant differences occurring in the Caribbean Sea at the 200-mb level. The notable exception to the results is at Bermuda where the wind differences are significantly from the northeast. These differences portray a trough extending from the subtropical Atlantic to the western Caribbean Sea wherein higher pressure is associated with stronger westerly winds in the region containing the Caribbean Sea.

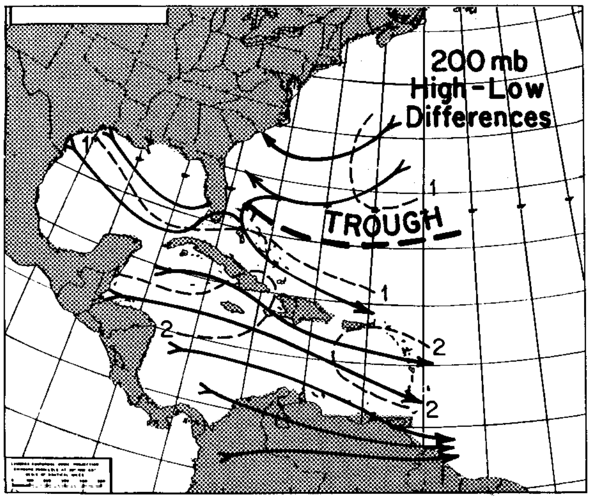

FIG. 3. Composite differences of the 200-mb wind field during July through September for periods of high pressure minus periods of low pressure in the tropical Atlantic. Isotachs are drawn every m s^{-1}.

Consistent with this trough in the wind field differences are also found in the temperature field at all TA stations. Temperatures at 100-mb stations located in the Caribbean Sea region (with the exception of Guadeloupe) are positive, though only Kingston shows a significant difference. On the other hand, temperature differences at 300, 500, and 700 mb show cooler temperatures throughout the TA, roughly 50% of which are significant. Temperature differences for the 300-mb pressure level that are representative of differences occurring in the 700–300 mb deep layer are shown in Fig. 4. Note again these temperature differences are greatest in and around the Caribbean Sea.

Consistent with these cooler temperatures in the midtroposphere are changes observed in atmospheric moisture content. Figure 5 shows both the 500 and 700 mb composite high-minus-low SLP mixing ratio differences. Approximately 60% of these differences are significant and all are negative or zero. This result indicates that periods of higher pressure in the TA are correlated with reduced midlevel moisture. Lesser amounts of midlevel moisture are important in relation to atmospheric radiative cooling; less moisture indicates more subsidence and decreased deep convection is occuring during periods of higher pressure in the TA. The combination of midlevel cooling along with drying suggests that the radiative effect of moisture is likely dominating the temperature findings.

The bulk of the significant composite differences occur in and around the Caribbean Sea region. As illustrated in Fig. 6 using just the stations located in the Caribbean region. These stations include Guantanamo, Grand Cayman, Kingston, Islas Del Cisne, San Juan, Guadeloupe, Barbados, and Curacao. The average differences in zonal wind show a maximum in the upper troposphere where average zonal winds are nearly 2 m s^{-1} greater during the 10 yr with higher than normal

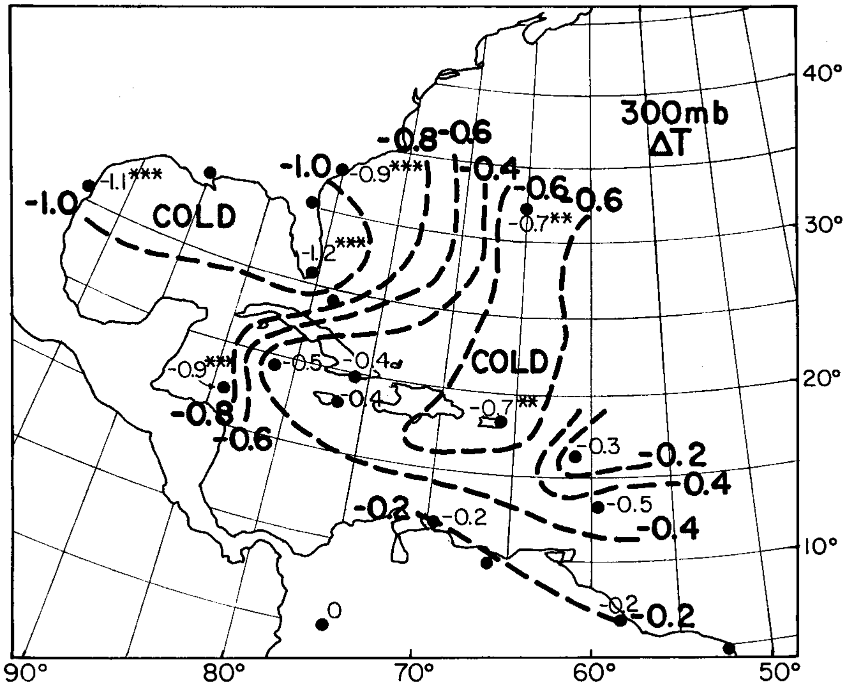

FIG. 4. Composite temperature differences at 300 mb during JAS showing distinctly cooler temperatures to be occurring at 300 mb during 10 yr of higher than normal SLP in the tropical Atlantic when compared to 10 yr of lower than normal SLP. Significances of these differences are given by *, **, and ***, representing 10%, 5%, and 1% levels, respectively.

SLP. The temperature differences of nearly 0.5°C occur at 200 mb wherein they are cooler during the 10 high pressure yr. The mixing ratio differences are also pronounced in the midlayer where differences average nearly 0.3 g kg^{-1} drier in the high pressure composite.

Likewise, the average differences for three subtropical stations (Miami, Charleston, and Bermuda; all located north of the Caribbean) temperature and moisture are similar but the zonal winds are more easterly during the 10 high pressure yr, also shown in Fig. 6. This tendency is a further indication that a trough in the upper-level winds accompanied by dryer and cooler middle-level conditions is present during the 10 high pressure yr.

There is clear evidence of a weak upper-level wind trough maximizing near 200 mb as shown by the upper-level temperature and wind and the midlevel temperature and moisture differences. Warming associated with the wind trough is above 200 mb and cooling occurs below 200-mb levels. This configuration clearly mimics the summertime midoceanic Tropical Upper Tropospheric Trough (TUTT) (Sadler 1976) in the Atlantic, shown in Fig. 7 (Fitzpatrick et al. 1995). The high-minus-low SLP composite differences of 200-mb wind in Fig. 3 show a clear and distinct trough extending from the midlatitudes into the Tropics, resulting in increased westerly (easterly) winds in the Tropics (subtropics). This trough has a significant reflection through the midlayers and is evident to some degree at 700 mb. The 200-mb differences shown in Fig. 3 are remarkably similar to the climatological TUTT shown in Fig. 7. Therefore, all indications are that a more robust mean climatological TUTT is associated with high SLP periods in the tropical Atlantic.

The composite analysis shows several locations/levels with notable differences in the upper-air circulation during the two different surface pressure regimes. As noted, these include zonal winds at 200 mb, mixing ratio at 500 and 700 mb, and temperatures throughout the midlevels of the troposphere. Because of the limited number of realizations in the composites, the significance of these results are slightly understated. To emphasize the above results, regression analysis and significance testing is also performed over all of the existing data at these stations. The regression coefficients along with their significance values are shown in Table 4. These results emphasize the composite findings showing that higher JAS Caribbean pressure is accompanied by dry and cooler midlevels and stronger upper-level westerly winds, especially in and around the Caribbean Sea.

It is also evident in both the composite and regression analyses that vertical wind shear and midlevel moisture are distinctly different during the different pressure conditions in the TA. These differences are known to be important to TC development. Cooling and decreased mixing ratios in the middle levels tend to offset one another to some degree. However, the net result appears

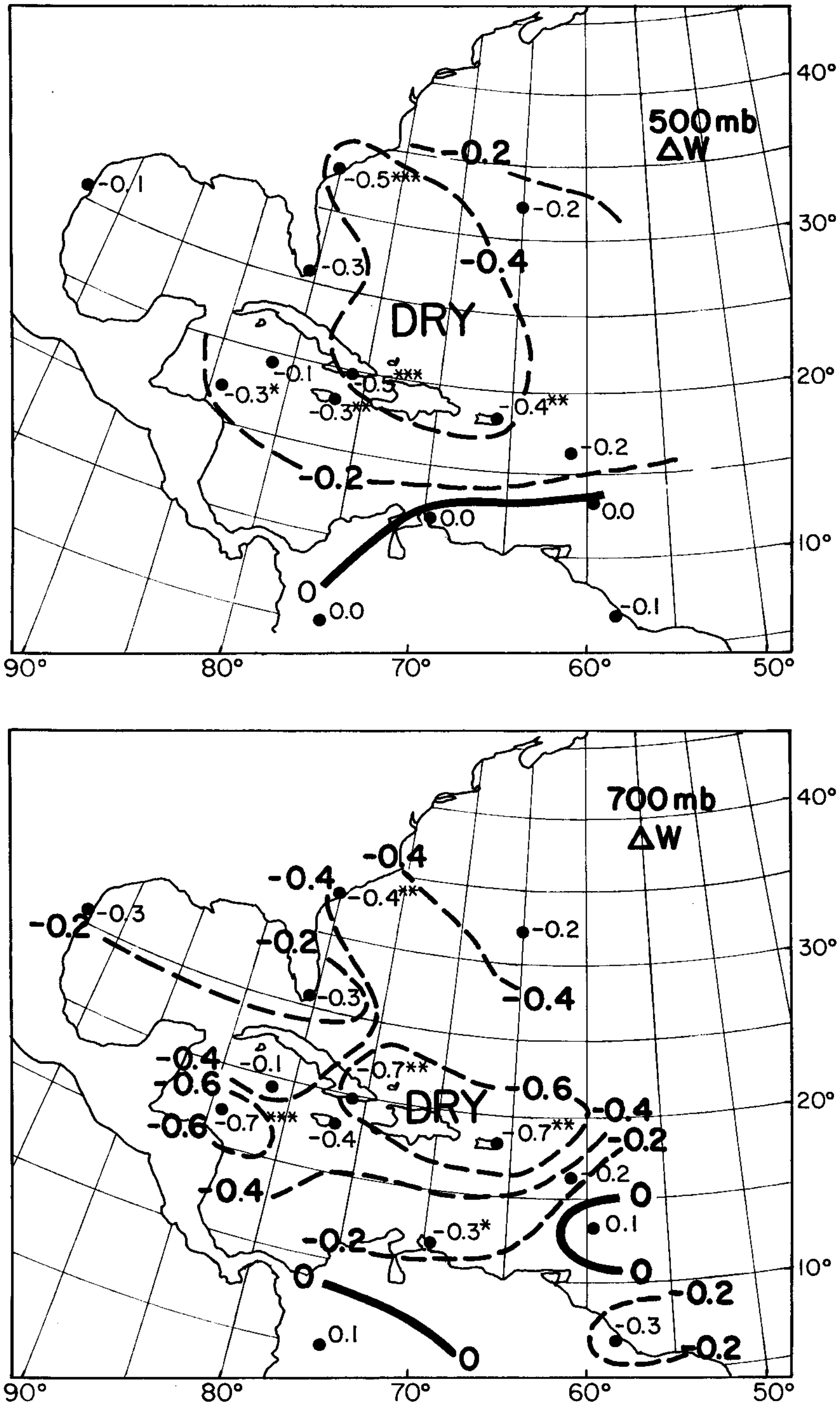

FIG. 5. Composite differences showing the distinct dryness of July through September 500 mb (top) and 700 mb (bottom) mixing ratios during periods of high tropical Atlantic pressure minus low pressure years. Significances of these differences are given by *, **, and ***, representing 10%, 5%, and 1% levels, respectively.

to be a reduction of ambient relative humidity of approximately 2%–4% at 700 mb and 4%–6% at 500 mb. Although these midlevel moisture differences are greatest over the Caribbean, it is clear that decreased moisture in midlevels accompanies higher pressure throughout the TA. This "moisture deficit" is likely the combined result of increased subsidence and diminished deep convective activity. The resulting conditions act to further

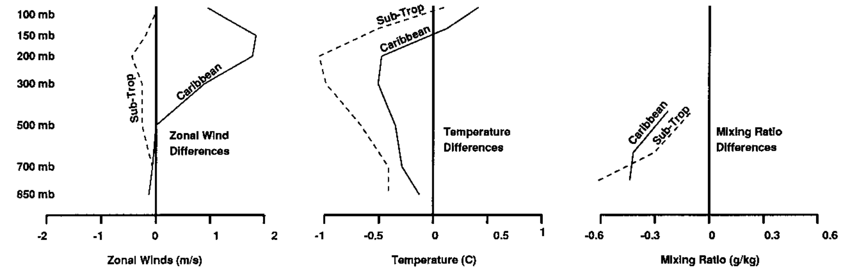

FIG. 6. Vertical profiles of average zonal wind, temperature, and mixing ratio calculated from high minus low pressure composite differences for stations in and around the Caribbean Sea (Guantanamo, Grand Cayman, Kingston, Islas Del Cisne, San Juan, Guadeloupe, Barbados, and Curacao) and stations located north of the Caribbean or in the subtropics (Miami, Charleston, and Bermuda).

suppress convective activity in general through increased entrainment of dry air from the environment and strengthening of the trade wind inversion.

Changes in tropospheric vertical wind shear or baroclinicity are also related to SLP variations. Figure 8 shows a map of the high-minus-low SLP stratified differences of VWS obtained from the composite analysis. For comparison, Table 5 shows the VWS composite differences and regression coefficients at each station. These shears are increased when regional pressures are anomalously high, particularly in the tropical regions south of the climatological TUTT axis where most TCs form. This greater VWS condition is less likely to allow vertical stacking of convection as is necessary for TC maintenance and formation.

Although the number of realizations is limited, various reanalysis products have proven useful in the examination of the spatial details of the general circulation associated with differing pressure regimes in the TA. Most interesting is the general agreement between the rawinsonde composite results and the composite results obtained using the reanalysis. Reanalysis temperatures show high-minus-low SLP stratified differences on the order of 0.5°C throughout the middle troposphere. The moisture field, though largely a model dependent quantity, indicates dryer midlevel conditions exist in the vicinity of the TUTT when the TA pressures are high. Going further, the reanalysis data allow tests of the atmosphere longwave upward flux differences between the high and low pressure composites, as shown in Fig. 9. These differences indicate that the outward flux at the top of the atmosphere increases with the decrease in midlevel moisture, which suggests that the TA radiates more energy to space during periods of high pressure.

It is inferred that these midlevel temperature and mois-

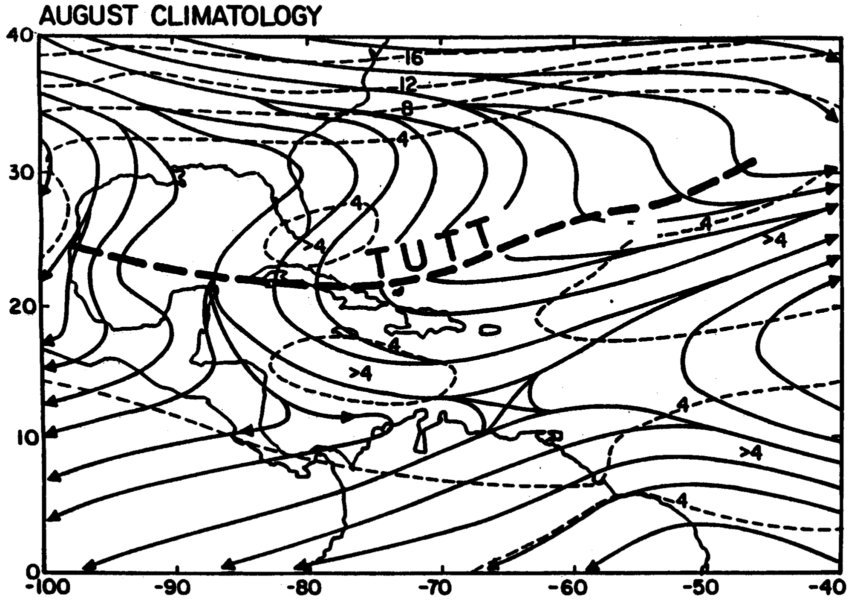

FIG. 7. August 200-mb streamline and isotach analysis adopted from a 1975–91 climatology by Fitzpatrick et al. (1995). Wind speeds are contoured at 4 m s^{-1} intervals. The dark dashed line represents the mean TUTT axis.

TABLE 4. Regression coefficients for 200-mb zonal wind, 700-mb mixing ratio, 500-mb mixing ratio, and 500-mb temperature versus the index of July through September Caribbean SLP discussed in section 2. Significance is indicated by *, **, ***, and **** for 10%, 5%, 1%, and 0.1% significance levels, respectively.

Station	U 200 mb (m s^{-1} mb^{-1})	*w* 700 mb (g kg^{-1} mb^{-1})	*w* 500 mb (g kg^{-1} mb^{-1})	T 500 mb (°C mb^{-1})
Miami	−0.16	−0.35*	−0.26**	−0.60****
Charleston	−0.32	−0.23**	−0.30***	−0.40**
Brownsville	0.66*	−0.23*	−0.05	−0.63****
Bermuda	−0.40	−0.30	−0.23*	−0.33*
Guantanamo	1.13***	−0.54***	−0.42****	−0.20
Grand Cayman	0.79**	−0.28*	−0.19**	−0.43**
Kingston	1.75****	−0.33*	−0.21***	−0.34**
Islas Del Cisne	1.04**	−0.54***	−0.30****	−0.55****
San Juan	1.13***	−0.63***	−0.28***	−0.42***
Guadeloupe	0.98**	−0.22	−0.05	−0.36**
Barbados	1.41**	0.15	0.02	−0.16
Curacao	1.53***	−0.21	0.00	−0.19
Georgetown	0.85	−0.32	−0.07	−0.32**
Bogota	0.43	0.17	−0.04	−0.25

ture differences during periods of higher pressure, along with the resultant radiative flux, create conditions suitable for the existence of strong climatological TUTT circulations during JAS. This seems to be confirmed in the limited amount of realizations available in the reanalysis composited in Fig. 10. This figure shows the composite 200-mb wind results for the average high and low SLP conditions. It is clear that the TUTT circulation is much stronger in the high pressure composite average, extending much deeper into the tropical regions of the Caribbean Sea. Along with these variations in TUTT strength with pressure, we expect similar variations in the amount of VWS with the SLP. The sense of this variation is such that higher pressure would result in greater VWS. In fact, the correlation between VWS and SLP in a box bounded by 10°N to 20°N, 100°W to 50°W was 0.53, significant at the 5 percent level for 11 degrees of freedom.

The August daily composite soundings for San Juan confirm the results of the monthly spatial composites in Figs. 3, 4, 5, and 8. Higher surface pressures are closely

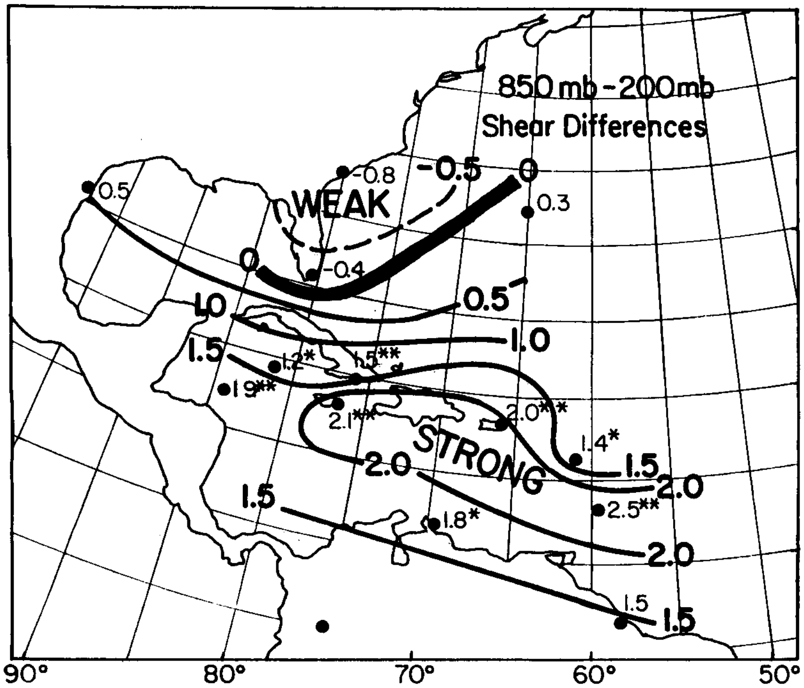

FIG. 8. Composite differences of 850-mb to 200-mb VWS differences during July through September for periods of high pressure minus periods of low pressure in the tropical Atlantic. Significances of these differences are given by *, **, and ***, representing 10%, 5%, and 1% levels, respectively.

TABLE 5. Summary of composite and the regression analyses of VWS. The composite differences (ms^{-1}) in the middle column are obtained by subtracting the low pressure composite from the high pressure composite. Values in the third column are the regression coefficients ($m\ s^{-1}\ mb^{-1}$) obtained for 200–850-mb shear versus the July–September Caribbean SLP index. Note the significance of these results are given by *, **, and ***, representing the 10%, 5%, and 1% significance levels, respectively.

Station	Composite difference	Regression coef.
Miami	−0.40	−0.25
Charleston	−0.80	−0.57
Brownsville	0.50	0.47
Bermuda	0.25	0.30
Guantanamo	1.51**	0.90**
Grand Cayman	1.21*	0.80**
Kingston	2.09**	1.79***
Islas Del Cisne	1.91**	0.83
San Juan	2.00**	1.05**
Guadeloupe	1.40*	0.96*
Barbados	2.56**	1.93**
Curacao	1.80*	1.93***
Georgetown	1.44	1.95*

tied to less moisture, colder midlevels temperatures, stronger upper-level westerlies and increased VWS. Figure 11 shows mean composite vertical profiles of relative humidity, temperature differences, and zonal winds during very low pressure (≤1013 mb) and very high pressure (≥1017 mb) conditions. The significant composite differences in Fig. 11 (99 percent confidence) are denoted by the vertical bars to the right of each panel. The high pressure dataset contains 115 soundings while the low pressure set contains 184 soundings. Because of the enhancing effects of serial correlation, the effective degrees of freedom (independent data samples) are taken to be 52 for the high pressure composite and 84 for the low pressure composite. These numbers are determined by the method proposed by Leith (1973), utilizing the field which exhibited the largest degree of autocorrelation (zonal wind at 850 mb). It is clear from Fig. 11 that midlevels are significantly cooler and drier in the mean composite profiles for high pressure conditions. This condition results in large differences in the vertical profiles of potential temperature (not shown). The soundings during high pressure conditions are somewhat more unstable but have much lower midlevel moisture values and, thus, support less deep convective activity than do the low pressure soundings. Along with these changes in temperature and moisture, the mean high pressure profile has much larger vertical zonal wind shear when compared to the lower pressure profile. These results are consistent with the monthly composite findings suggesting that the same processes responsible for the seasonal differences are also at work on shorter timescales.

b. Radiation model results

Differences in the vertical distribution of temperature and humidity result in subtle but very important changes in the longwave radiative cooling structure of the lower troposphere. Cooling profiles for the soundings shown in Fig. 11 were calculated with a two stream radiative transfer model (Stackhouse and Stephens 1991). The radiative cooling rates are clearly different near the surface and and in midlevels near 600 mb. The sharper vertical moisture gradient in the high pressure composites results in greater low-level and midlevel cooling rates. Sensitivity studies conducted using the temperature for the low pressure soundings in combination with the moisture values of the high pressure soundings and vice versa suggest that moisture changes are the dominant radiative driver of this system. This suggests that

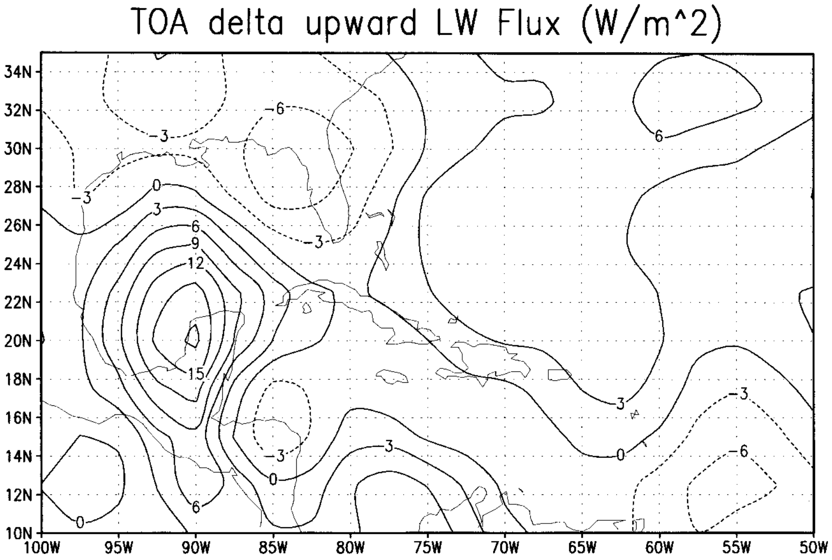

FIG. 9. Upward longwave radiative flux differences (W m^{-2}) at the top of the atmosphere between the high pressure and low pressure reanalysis composites.

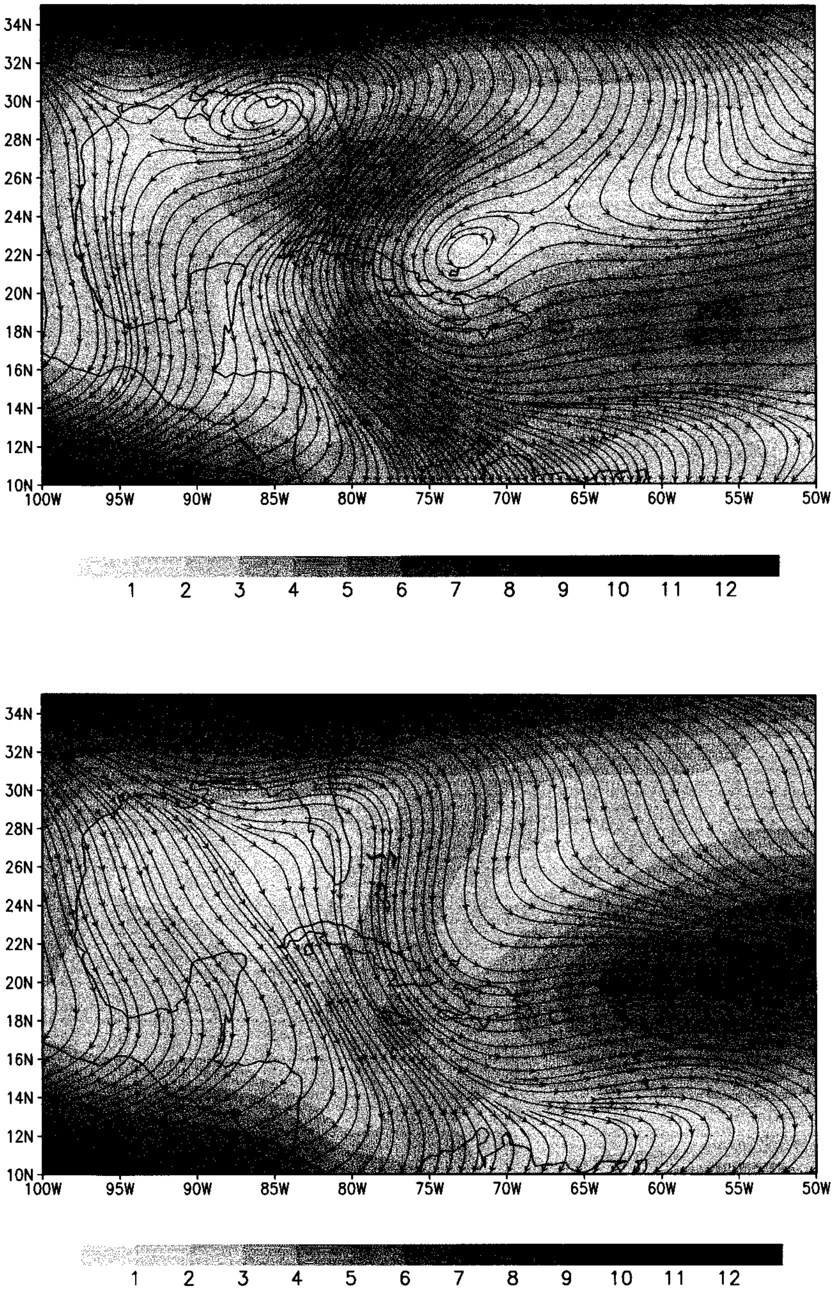

FIG. 10. The 200-mb streamlines and isotachs from the reanalysis composites for the high pressure years (top) and the low pressure years (bottom).

the lower temperatures during the higher pressure days are a result of the temperature adjusting to the drier moisture profiles. Furthermore, the atmosphere in the higher pressure case cools at a slightly greater rate (-0.15°C day^{-1}, or 5.5%) through the layer 1000–400 mb, despite the 0.5°C cooler temperature profile. This difference must be overcome, probably through increased subsidence since convection is suppressed by the somewhat drier environment.

5. Discussion

Summertime sea level pressure in the tropical Atlantic exhibits variability on the interannual to interdecadal timescale. These SLP variations have been shown by several authors to be related to the TC activity. Specifically, when the pressures in the TA are anomalously low, TC activity is increased and vice versa. These variations in SLP could be due to several factors. First, it is

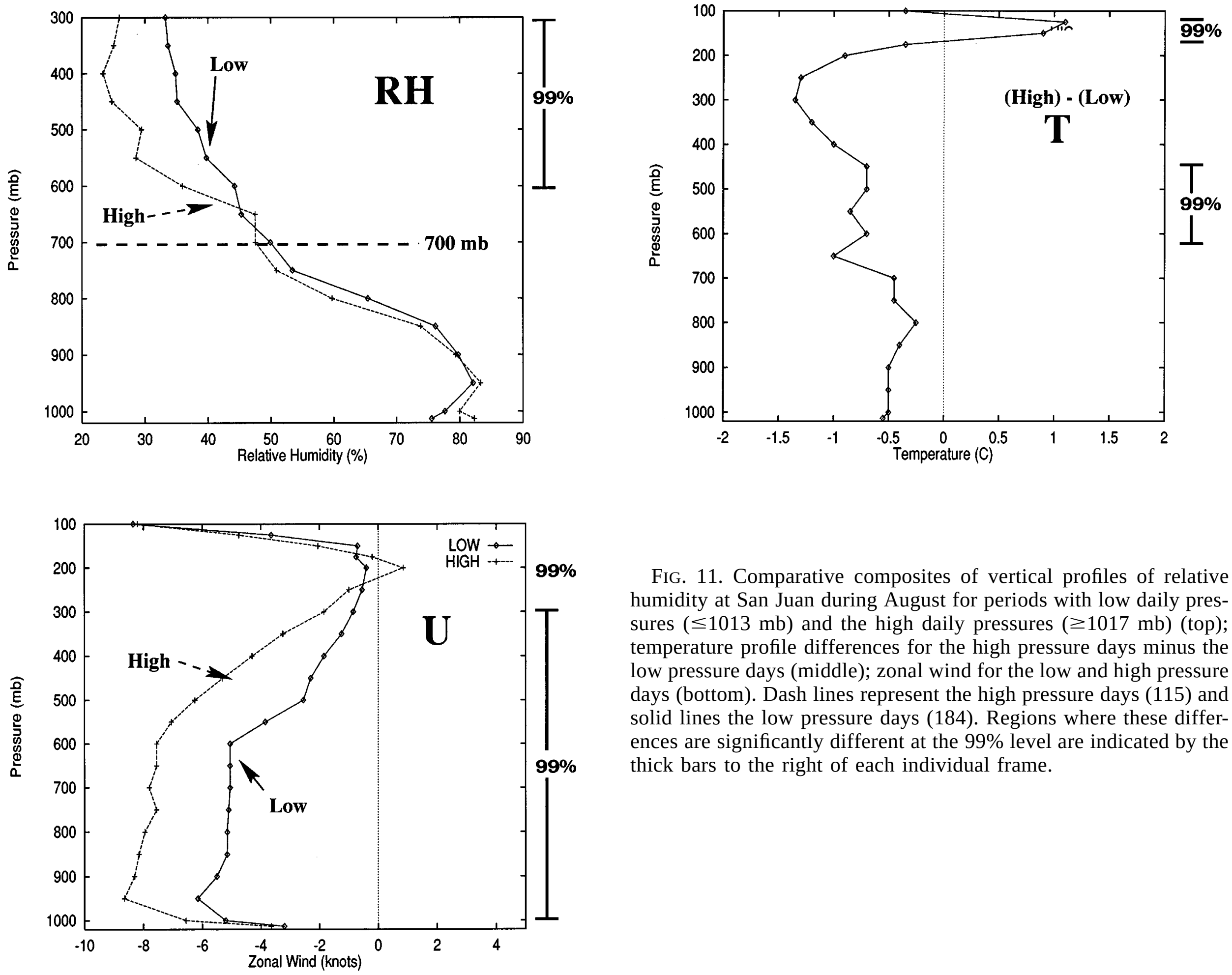

FIG. 11. Comparative composites of vertical profiles of relative humidity at San Juan during August for periods with low daily pressures (≤1013 mb) and the high daily pressures (≥1017 mb) (top); temperature profile differences for the high pressure days minus the low pressure days (middle); zonal wind for the low and high pressure days (bottom). Dash lines represent the high pressure days (115) and solid lines the low pressure days (184). Regions where these differences are significantly different at the 99% level are indicated by the thick bars to the right of each individual frame.

conceivable that the summertime SLP anomalies in the TA are largely due to the hurricane and tropical storm activity; but is this the case? Because daily SLP data are not available, an alternative method of assessing the impact of hurricanes and tropical storms on the pressure field must be used. Here I employ TC rawinsonde composites for Atlantic hurricanes and tropical storms (Gray 1981). Using average 850- and 1000-mb heights and virtual temperatures, an SLP field can be calculated from these composites. From these SLP fields, the potential impact of a hurricane and tropical storm upon the pressure field can be estimated. It is assumed that the environment is represented by the areas in the composite data that are greater than 10° latitude (~1110 km) from the center of the composite storm. Subtracting the environment from the composite SLP inside 10° results in an anomaly field from which an average anomaly can be estimated. This analysis determines the impact of the average hurricane averaged over the 10° radius storm to be approximately 3.6 and for an average tropical storm to be 2.4 mb.

Using the above values along with the number of named storm days, number of hurricane days (see Gray et al. 1994), and the size of the Atlantic tropical storm basin (10°–35°N; 100°–45°W), a basinwide impact of tropical cyclone activity upon the TA pressure during the months of July through September is created and applied to the JAS SLP index discussed in section 2. Assuming a 10° storm occupies one quarter of the TA, that one named storm or hurricane day is equal to one tropical storm or hurricane lasting one day in duration, that 92 calendar days occur in the July through September period, and the effect on the pressure field is represented by the above composite 10° estimates, a correction is created and applied to the SLP index. This corrected index, along with the original SLP index are shown in Fig. 12.

The corrected index of SLP shows that TC activity can have a strong impact on the seasonal SLP index in the TA. However, the impact of TC induced pressure anomalies is minimal to those changes associated with the more interannual and decadal timescales. In fact, the exclusion of TC-related SLP anomalies in the composite analysis would have no effect whatsoever on this analysis. The same ten highest and ten lowest pressure years

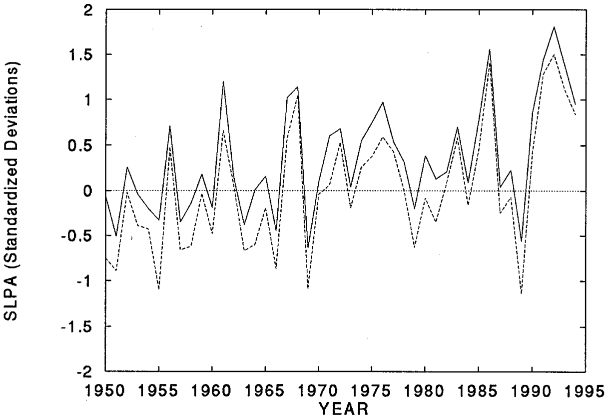

FIG. 12. Time series of the JAS SLP index (dashed) in the TA along with a corrected SLP index (solid) created by removing the effect of tropical storms and hurricanes.

would be chosen and the same results forthcoming. Thus, the impact of TC induced SLP anomalies is believed secondary in this study.

Whereas TCs impact on the SLP is found to be secondary, the year-to-year and decadal variations of TA SSTs seem more important. The correlation between the average SST from COADS over the TA and the SLP index discussed in section 2 yields a correlation coefficient of -0.31; barely significant at the 10% level. This result can be compared with correlation of area average COADS pressure with the SLP index that yields a correlation coefficient of 0.48. This analysis suggests that the SSTs have a slight influence on the pressure in the TA. This analysis does not, however, show the details of the SST–SLP relationship in the TA. To address this question, I look at point to point correlations between SST and SLP during the JAS season. These correlations, along with the significance (indicated by the shading) are shown in Fig. 13. A weak relationship is observed between SST and SLP fields, primarily south of the Greater Antilles.

A question occurs concerning the role SST variations in seasonal hurricane activity. Using simple correlation analysis, it can again be shown that the correlation between TA area average SSTs and the number of hurricanes south of 25°N is 0.26. On the other hand, a similar area average of pressure correlates with hurricanes south of 25°N with a correlation coefficient of $r = -0.43$ while the SLP index discussed in section 2 correlates at $r = -0.58$. Hence, there is a weak relationship between TA basinwide SSTs and hurricane activity, and this relationship is a limited one at best.

With the previous information at hand, a hypothesis can be formed as to why SLP affects hurricane activity. First, it is best to review the results of this study. The results presented in the previous section show that two upper-air TC inhibiting factors are closely associated with higher SLP in the tropical Atlantic region. These include 1) vertical wind shear [which increases in the Tropics with positive SLP anomalies, especially in and around the Caribbean Sea; as the pressure increases, so do the upper-level (200 mb) westerlies]; and 2) drier midlevels

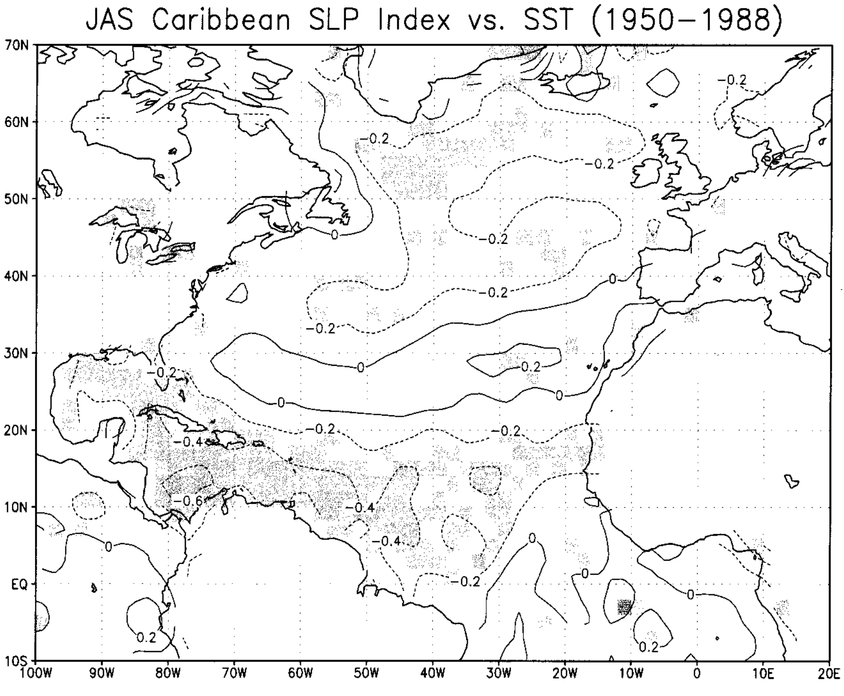

FIG. 13. Point to point correlation coefficients between SST and SLP during JAS. Both fields come from the COADS datasets. Significance of 10% or greater is indicated by the shading.

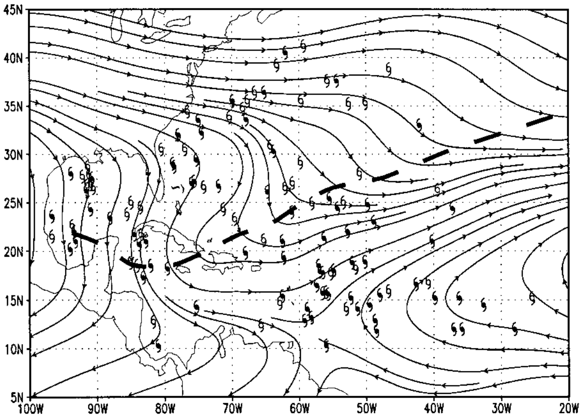

FIG. 14. Diagram depicting where TCs were first named hurricanes during the 10 yr with the highest (tropical storm symbols), and the ten lowest (hurricane symbols) SLP anomalies in TA along with the climatological TUTT axis during JAS.

become established. The amount of midlevel moisture is significantly reduced over large portions of the tropical Atlantic, especially in regions where tropical storms form and intensify. From the composite analysis there is evidence that the radiative cooling, caused by reductions of midlevel moisture, dominates the increased subsidence warming occurring during high pressure periods in this region. These results are supported by both sensitivity studies and the reanalysis. More specifically, the TUTT and all the circulation features associated with it are more robust when the pressures in the TA are higher than normal. The strength of the TUTT modulates the strength of the upper-level westerlies in the regions of the Atlantic south of 25°N. Figure 14 shows where TCs first became hurricanes during the 10 high pressure and 10 low pressure yr, along with the climatological TUTT axis. Note that nearly four times as many hurricanes form south of the TUTT when the pressure is low while the numbers north of the TUTT hardly change. It seems that these changes in VWS and midlevel moisture associated with SLP anomalies and an enhanced TUTT are enough to modulate basinwide storm activity.

6. Hypothesis

Differences found between high and low pressure composites show that the middle-level temperature and moisture profiles dramatically change with SLP. Along with these temperature and moisture changes are large differences in the wind fields. The observed midlevel drying during periods of high pressure are thought to be associated with increased subsidence, diminished low-level convergence and decreased deep convective activity. Associated with this increased subsidence is a stronger trade wind inversion, which would also work to suppress deep convection while further drying the middle levels. These differences are accompanied by other changes including warmer 100-mb temperatures and decreased 300–700 mb temperatures which point to a stronger mean climatological TUTT. Consistent with this thinking, stronger upper-level westerly winds exist in the tropical regions of the Atlantic. These westerly winds result in increased VWS in the Tropics where most TCs form.

A schematic diagram showing how these factors are likely related is shown in Fig. 15. As the pressure anomalies intensify in the tropical Atlantic in the late spring and early summer, so does subsidence. This subsidence results in drying of the middle and upper layers as well as a stronger trade wind inversion. This increased upper and midlevel drying creates a steeper moisture gradient. On a seasonal basis, a steeper vertical moisture gradient works to cool the midlevels through longwave radiation flux divergence while at the same time inhibiting deep convection. The stronger trade inversion also acts to limit deep convective activity. Reducing the net amount of cloudiness further acts to increase the amount of atmospheric longwave cooling to space (Stephens et al. 1994). The extra cooling caused by the combination of a steeper moisture gradient and less cloudiness then results in increased surface pressure and greater upper and midlevel subsidence. The subsidence from the stratosphere above would result in warming the region near the tropopause (i.e., 100 mb). This yields the temperature difference profile (warm tropopause, cool troposphere) shown in both the daily and seasonal composite results. Dynamically this results in a more robust TUTT circulation. The results presented here suggest a positive feedback between surface pressure, subsidence, and the maintenance of the TUTT is occurring in the TA.

The two-stream radiation calculations showed a 5.5% greater IR cooling rate in the 1000–400-mb layer using the high pressure vertical profile of moisture shown in Fig. 8 with clear sky conditions. A similar percentage is found in the reanalysis composites. The effect of clouds is (in general) to warm the column, resulting in a 50% reduction of column cooling rates (Stephens et al. 1994). So, a simple 10% increase of cloudiness can lead to a 5% decrease in column cooling. From this standpoint, the conditions in the TA—a trade wind region of mean subsidence is very conducive to the proposed feedback between pressure and longwave cooling.

This proposed positive feedback operates as shown in the flow chart in Fig. 16. Higher (lower) pressure results in increased (decreased) mean subsidence. This leads to a stronger (weaker) trade wind inversion and less (more) mean midlevel moisture. The stronger (weaker) trade wind inversion results in less (more) deep convection which reinforces the drier (more moist) midlevels. The combined effect of drier (more moist) midlevels and lesser (greater) convective activity results in increased (decreased) amounts of radiative cooling to space. This relative cooling (warming) acts to further reinforce the conditions that resulted in the increased subsidence by further increasing (decreasing) the surface pressure. This mechanism occurs with diminishing effect with the sea surface temperatures acting as a gov-

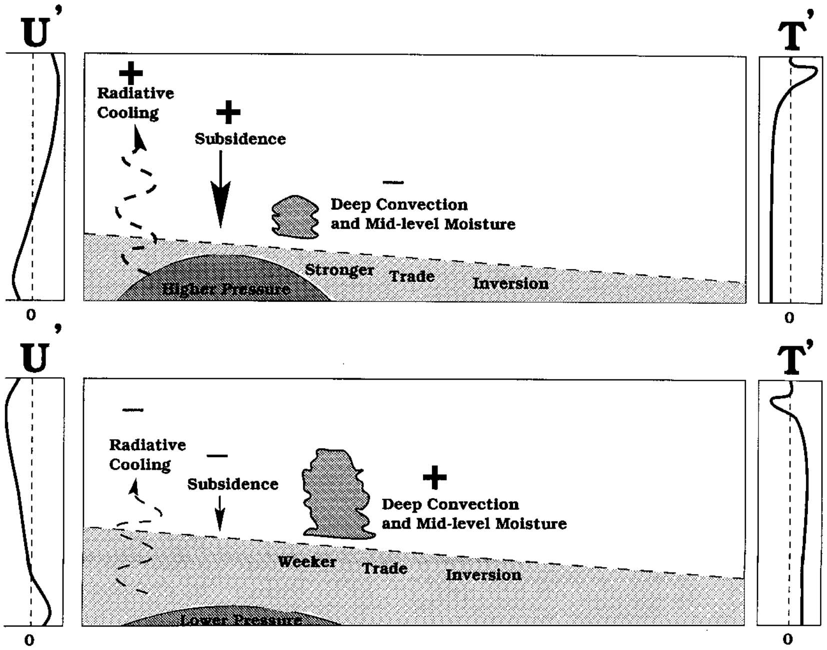

FIG. 15. Idealized schematic of the conditions characteristic of anomalously higher pressure (top) and anomalously lower pressure conditions (bottom) in the the tropical Atlantic. When pressures are anomalously high (low), increased subsidence (decreased) has the effect of reducing (increasing) midlevel moisture and strengthening (weakening) the trade wind inversion. The combined effects of relative reduction (increase) of convection and midlevel moisture enhances (suppressed) IR cooling to space. This anomalous cooling (warming) of the midlevels enhances upper-level westerly (easterly) and lower-level easterly (westerly) zonal wind anomalies.

ernor, preventing the system from running away in one direction or the other. Enhanced cooling (warming) also affects the dynamics of the TA by creating a greater (lesser) baroclinicity. This feedback association helps to explain the tendency for pressure conditions in the Caribbean to persist over an entire season. This hypothesis requires more study to confirm the exact mechanism maintaining the noted sequence of cause, effect, and feedback. However, evidence presented here suggests that SLP variations in the TA are the fundamental modulator of TC activity and the strength of the TUTT.

7. Summary

Tropical cyclone formation requires enhanced midlevel moisture values. Hence, formation becomes more difficult when environmental moisture values are low. The combination of cooling and drying at midlevel and warming and drying at the upper-levels associated with periods of higher pressure result in relatively low pressure heights in the vicinity of 300–200 mb above tropical regions experiencing the increased upper-level radiative cooling. This configuration (Fig. 3) is very similar to the observed structure (Fig. 7) of the climatological Atlantic TUTT (Fitzpatrick et al. 1995) and causes increased 200-mb westerlies over the Caribbean Sea and increased 200-mb easterlies in the subtropical Atlantic. These effects ultimately create increased VWS pattern shown in Fig. 8 and Table 5. Hence, pressure conditions in the tropical Atlantic are thought to persist throughout the summer by maintaining themselves through a positive feedback between midlevel moisture, deep convective activity, and radiative cooling to space. Furthermore, it appears that these higher summertime SLPs are related to the 1) increased mid and upper-level subsidence (inferred), 2) decreased midlevel moisture, 3) increased radiative cooling in the midlevels associated with the increased vertical gradient of moisture (inferred), 4) a more robust climatological TUTT, and 5) increased vertical shear in the Tropics south of the TUTT axis and decreased shear north of the TUTT axis. Collectively, enhanced values for these factors strongly inhibit low-latitude (≤25°N) TC formation and maintenance and thus offer an explanation for the observed pressure–TC relationship in this basin.

Acknowledgments. I wish to thank Professor William Gray, John Sheaffer, Tom Chase, Pat Fitzpatrick, Chris Landsea, and the two anonymous reviewers for their discussions and comments regarding this research. I would also like to thank Barbara Brumit for her assistance in document preparation and Judy Sorbie-Dunn for drafting several of the figures. Funding for this research was provided by the NSF under Contracts ATM-9417563 (William Gray PI) with supplemental support

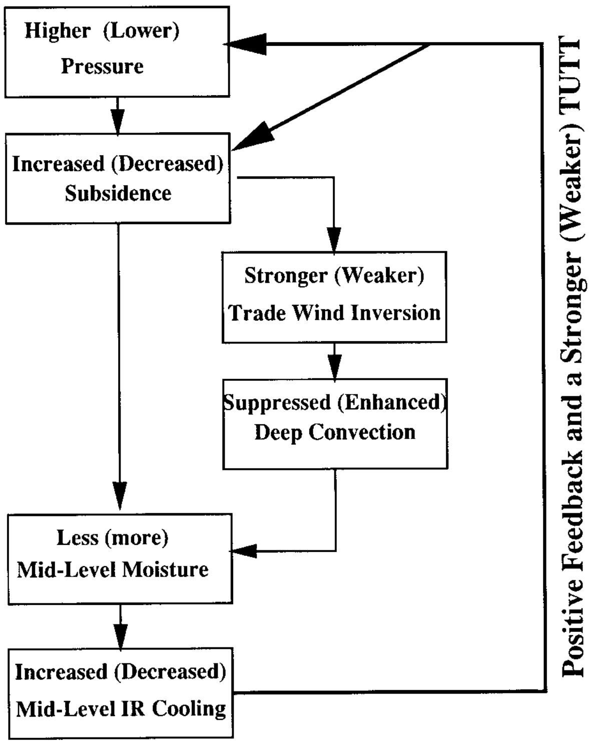

FIG. 16. Flow chart depicting the major elements of the hypothesized positive feedback loop between SLP pressure, midlevel moisture and convection and IR cooling to space. During periods of anomalously high (low) surface pressure, subsidence is increased (decreased). This change in the rate of sinking acts twofold to reduce (increase) midlevel moisture while at the same time decreasing (increasing) deep convective activity. The combination of larger (smaller) moisture gradients in the vertical and the decrease (increase) in convective activity result in more (less) IR cooling to space. This increase (decrease) in cooling acts to reinforce the high (low) pressure condition.

given by NASA Global Change Fellowship under Contracts NGT-30147.

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