

FORECASTER'S FORUM

Documentation of a Systematic Bias in the Aviation Model's Forecast of the Atlantic Tropical Upper-Tropospheric Trough: Implications for Tropical Cyclone Forecasting

PATRICK J. FITZPATRICK, JOHN A. KNAFF, CHRISTOPHER W. LANDSEA, AND STEVEN V. FINLEY

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

(Manuscript received 15 March 1994, in final form 27 January 1995)

ABSTRACT

This study uncovers what appears to be a systematic bias in the National Meteorological Center's aviation (AVN) model at 200 mb over the Caribbean Sea. In general, the 48-h forecast in the vicinity of the Tropical Upper Tropospheric Trough (TUTT) underpredicts the magnitude of the westerly 200-mb winds on the order of 5–10 m s⁻¹. This unrealistic weakening of the TUTT and associated cold lows by the AVN results in erroneous values of the vertical (850–200 mb) wind shear. These systematic errors are in the same order of magnitude as the minimum shear threshold for tropical cyclone genesis and development. Thus, 48-h tropical cyclone formation and intensity forecasts based upon the AVN model are often incorrect in the vicinity of the TUTT. Knowing the correct future upper-wind regime is also crucial for track forecasting of more intense tropical cyclones, especially in cases of recurvature.

It is shown that simple persistence or climatology of the 200-mb winds south of a TUTT axis is superior to the AVN model's 48-h forecast. Until this bias in the AVN is successfully removed, the tropical cyclone forecaster for the Atlantic basin should be aware of this systematic error and make subjective changes in his/her forecasts. For 200-mb west winds greater than or equal to 10 m s⁻¹, forecasts based on persistence are best, while for west winds less than 10 m s⁻¹, half climatology and half persistence is the preferable predictor. If the TUTT is weak such that 200-mb easterly winds occur, climatology tends to be the best predictor as it nudges the forecast back to a normal westerly wind regime.

1. Introduction

In the science of tropical cyclone (TC) forecasting, three key components—genesis, intensification, and movement—are dependent upon an accurate assessment of current and future upper-tropospheric (200 mb) winds. Therefore, knowing the strength and location of the Tropical Upper Tropospheric Trough (TUTT; Sadler 1976b) is crucial information for the TC forecaster.

TUTTs often can inhibit the formation of TCs by allowing large amounts of vertical wind shear (VWS) to be positioned directly over the prestorm disturbance. VWS can be quantified in the following manner:

$$\text{VWS} = [(u_{200} - u_{850})^2 + (v_{200} - v_{850})^2]^{1/2}, \quad (1)$$

where u and v are the zonal and meridional wind components at each grid point, respectively, for the 200- and 850-mb levels. According to (1), westerly flow at 200 mb superimposed over easterly trade wind flow at

850 mb will give high VWS values. Therefore, VWS south of a TUTT axis is usually large. Likewise, a tropical disturbance in a deep tropospheric easterly flow has a better chance of development if u_{850} and u_{200} are similar in magnitude, since this will yield low VWS values. Values of VWS greater than or equal to 10 m s⁻¹ are generally considered to be great enough to inhibit TC genesis by advecting upper-level moisture and temperature anomalies away from the low-level disturbance center (Zehr 1992).

In contrast, the TUTT and associated cold lows may enhance the possibility of genesis by importing upper-level angular momentum (Pfeffer and Challa 1992) and/or upper-level potential vorticity (Montgomery and Farrell 1993) over the prestorm disturbance if the VWS remains below the 10 m s⁻¹ threshold. Sadler (1976a) also found that directly below the divergence sector of the TUTT a surface disturbance may be induced in a trade wind regime that could then develop into a TC. Sadler (1976b) proposed a comparable genesis mechanism for the monsoon trough region. Ramage (1959) also found that a TUTT cell could transform itself into a TC.

Similarly, the competing effects of VWS and angular momentum eddy fluxes by TUTTs and midlatitude

Corresponding author address: Patrick J. Fitzpatrick, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.

E-mail: kjun@typhoon.atmos.colostate.edu

troughs are also hypothesized to affect TC intensification (Molinari and Vollaro 1989) once genesis has occurred. In a quantitative treatment of the problem, DeMaria et al. (1993) found that VWS has a strong negative influence on intensification and that the momentum eddy fluxes have a positive yet much weaker effect on TC intensity change. Sadler (1978) notes that the proper positioning of a TC's outflow channel with respect to a TUTT may encourage intensification by efficiently removing mass from the eyewall region, especially for a dual outflow situation. Additionally, Chen and Gray (1986) have extensively discussed the different upper-tropospheric outflow characteristics associated with TC intensification.

Finally, it is generally accepted that the motion of the TC is primarily the result of the deep layer flow in which it resides, usually taken to be from 850 to 200 mb (Elsberry 1987). Velden and Leslie (1991) have suggested, however, that tropical storms and weak hurricanes (central pressure > 975 mb) are generally

guided by flow lower (850–500 mb) in the atmosphere. While TUTTs are primarily maximum in strength at 200 mb, many times they can extend into the midtroposphere. Thus, they can often influence the current and future motion of a nearby TC of any intensity. It has also been shown recently that the infringement of a deep baroclinic layer of westerly winds upon a TC can be a precursor to recurvature, since this usually precedes encroachment of deeper westerly flow close to the poleward side of the storm center (Hodanish and Gray 1993). Therefore, poor forecasting of any upper-level wind characteristic can result in degraded motion predictions.

From this discussion, it is clear that the upper-tropospheric flow is very important in many forecasting aspects of TCs. The aim of this paper is to examine the forecasting skill of the National Meteorological Center's aviation (AVN) model with respect to the tropical North Atlantic 200-mb flow and its handling of the TUTT and embedded cold lows. The next section

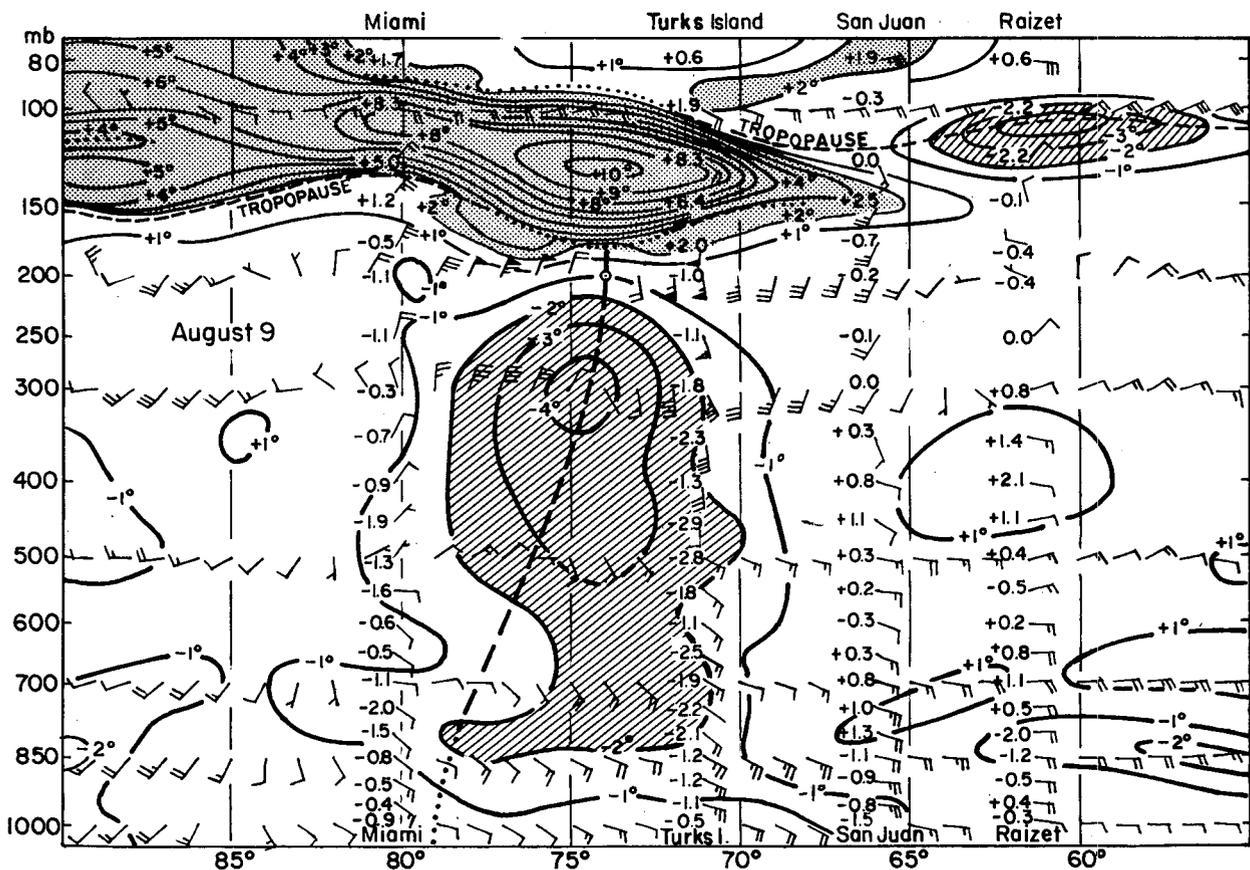


FIG. 1. Vertical cross section for 1200 UTC 9 August 1966, along a line through Miami, Florida, and Raizet, Guadeloupe. Isolines are temperature deviations (1 K) from mean Caribbean atmosphere for August (Jordan 1958) and are based on smoothed analyses at constant pressure levels. Gray shading indicates warm temperature anomalies exceeding +2 K. Hatching indicates cool temperature anomalies below -2 K. Unsmoothed data are plotted at four individual stations. Intermediate winds along standard isobaric levels are interpolated from streamline isotach analyses. All winds are plotted in the standard synoptic convention (one full barb equals 5 m s^{-1}). Heavy dashed lines near 75° and 70°W are axes of upper-level cyclonic curvature and low-level waves, respectively, [from Erickson (1969) as displayed in Krishnamurti (1979)].

AUGUST CLIMATOLOGY

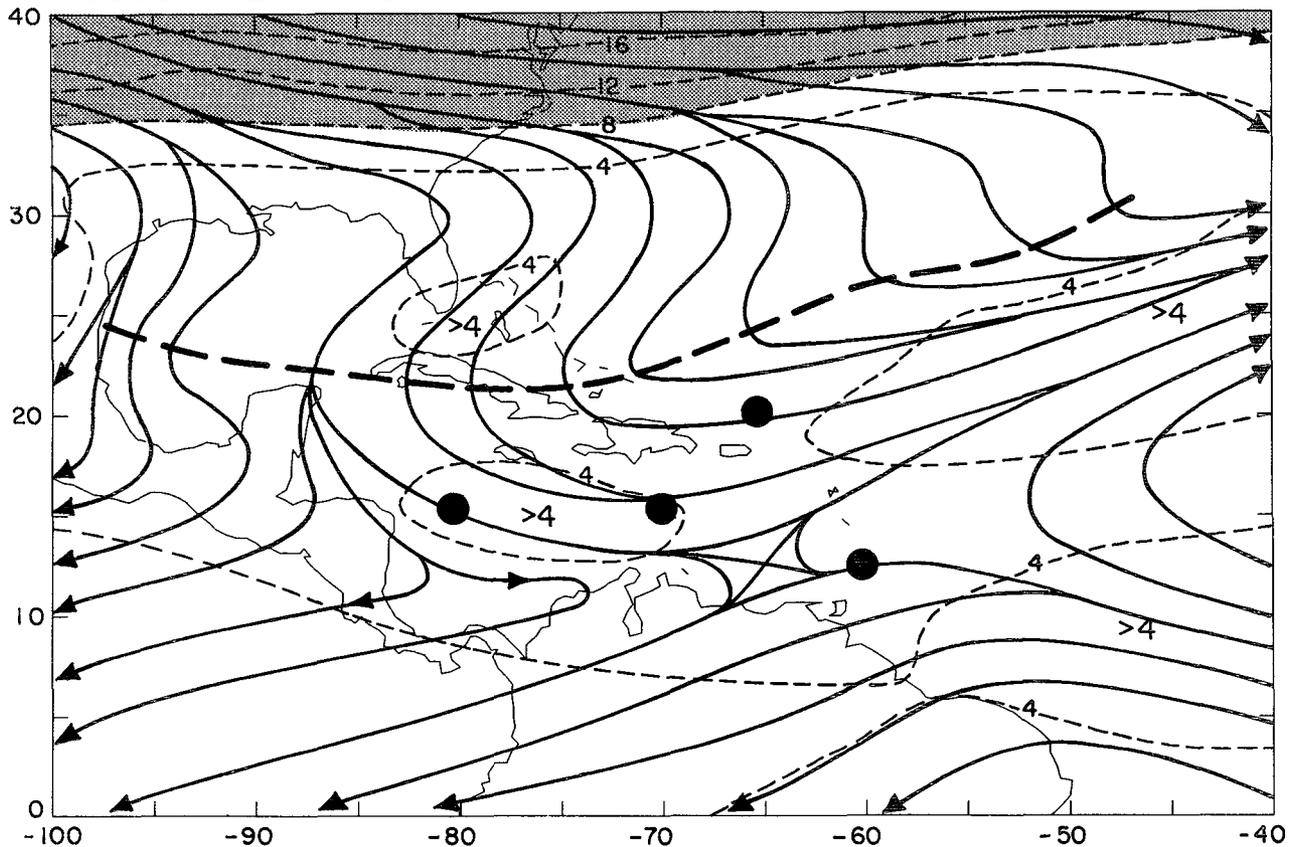


FIG. 2. The 200-mb streamline and isotach analysis from a 1975–1991 climatology for the month of August. Wind speeds are contoured every 4 m s^{-1} with shading added for those winds greater than 8 m s^{-1} . The dark dashed line indicates the mean TUTT axis. Closed circles denote regions where AVN 48-h wind errors were calculated. Climatological data are provided by the archive of tropical North Atlantic 200-mb winds courtesy of the National Oceanographic and Atmospheric Administration's Hurricane Research Division. Details on the dataset are available in Shapiro (1987).

will discuss the structure, climatology, and hypothesized causes of the TUTT, and it describes the AVN model and the systematic biases that have been identified in the tropical predictions of this model. Section 3 details a 200-mb AVN easterly wind bias in the Caribbean basin during the peak hurricane season and shows that currently persistence and climatology are better 200-mb wind forecast tools. The final section relates these findings to the context of TC forecasting and provides hypotheses that may explain the biases found.

2. Background

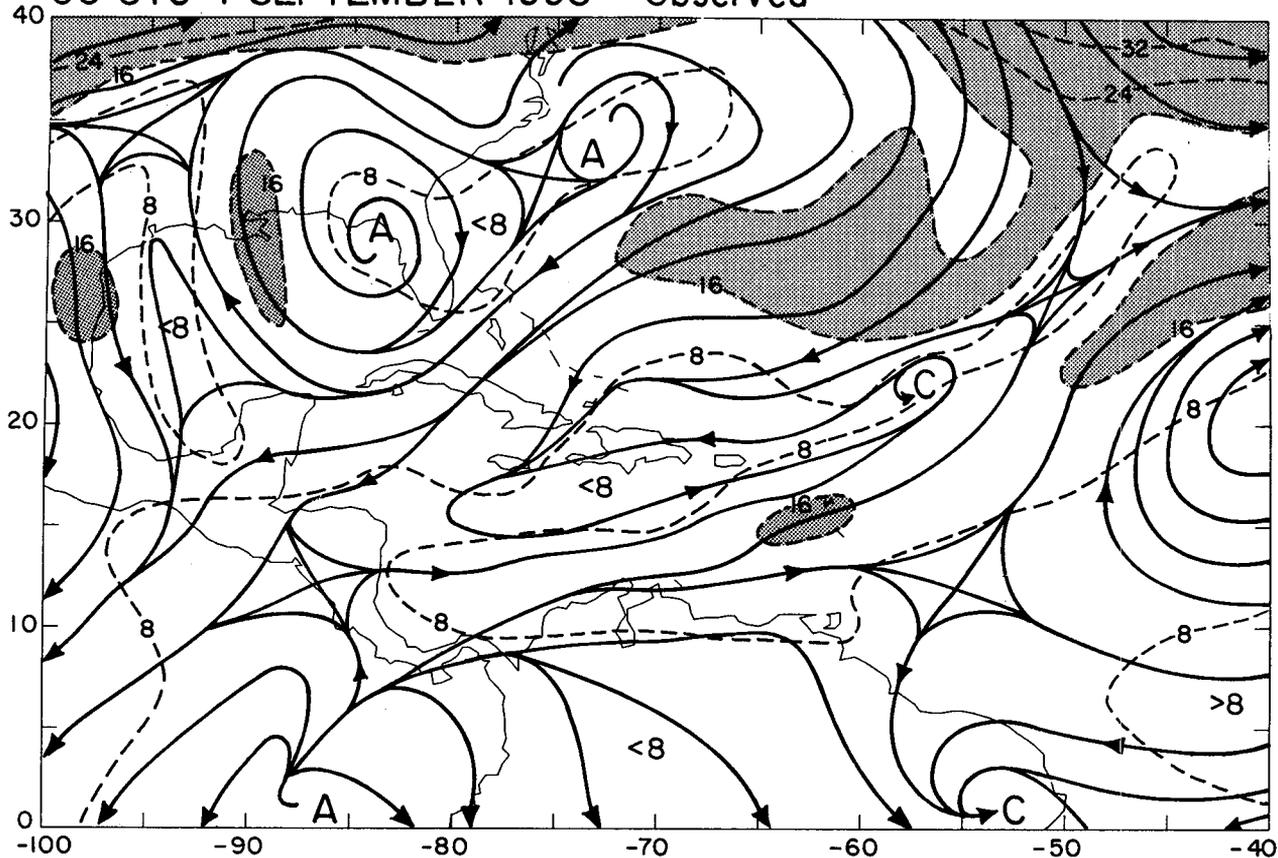
a. The tropical upper-tropospheric trough

One of the more intriguing tropical weather features in the summer oceanic climatology is the TUTT. The TUTT is a semipermanent summertime feature of the North Atlantic, South Atlantic, North Pacific, and South Pacific. It is a shallow, cold-core trough that is

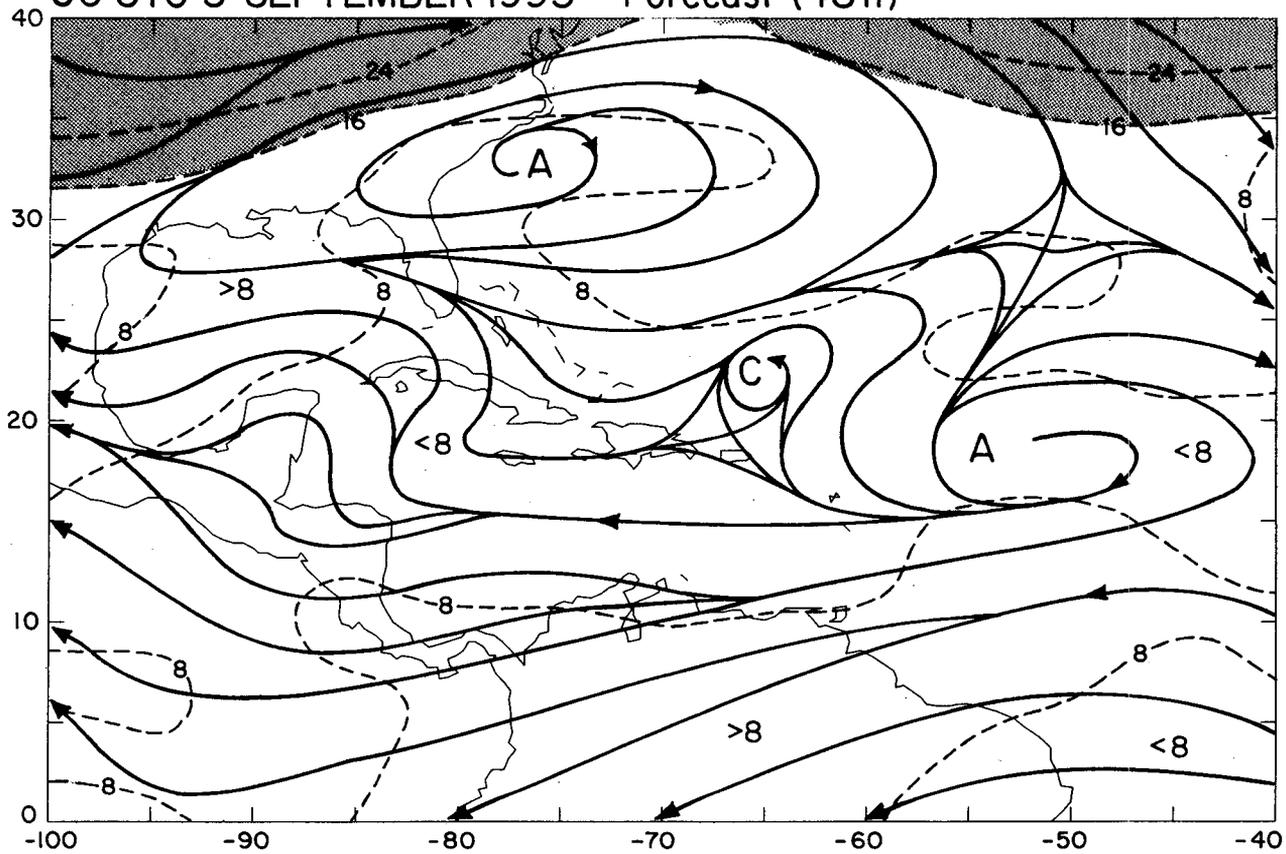
oriented across the subtropical and tropical portions of these oceans (Whitfield and Lyons 1992). The maximum intensity of the cold core of the TUTT exists at roughly 300 mb, while the vorticity maximum is located approximately at 200 mb below strong upper-tropospheric and lower-stratospheric subsidence-forced warming, as shown in Fig. 1. TUTTs and associated cold lows are thought to be maintained by radiational cooling that causes this upper-tropospheric subsidence, as is required to maintain atmospheric thermal balance in the midocean regions during the summer. Defining Q as the contribution from sensible, latent, and radiative heating rates and c_p as the specific heat at constant pressure, estimates of the total diabatic heating rate per unit mass Q/c_p are as strong as -6 K day^{-1} in the vicinity of the TUTT (Geller and Avery 1978).

Little research has been conducted to explain the seasonal cycle of the TUTT, but one possible scenario for the North Atlantic is as follows. During the summer, continental convection increases due to higher sensible

00 UTC 1 SEPTEMBER 1993 – Observed



00 UTC 3 SEPTEMBER 1993 – Forecast (48 h)



00 UTC 3 SEPTEMBER 1993 – Observed

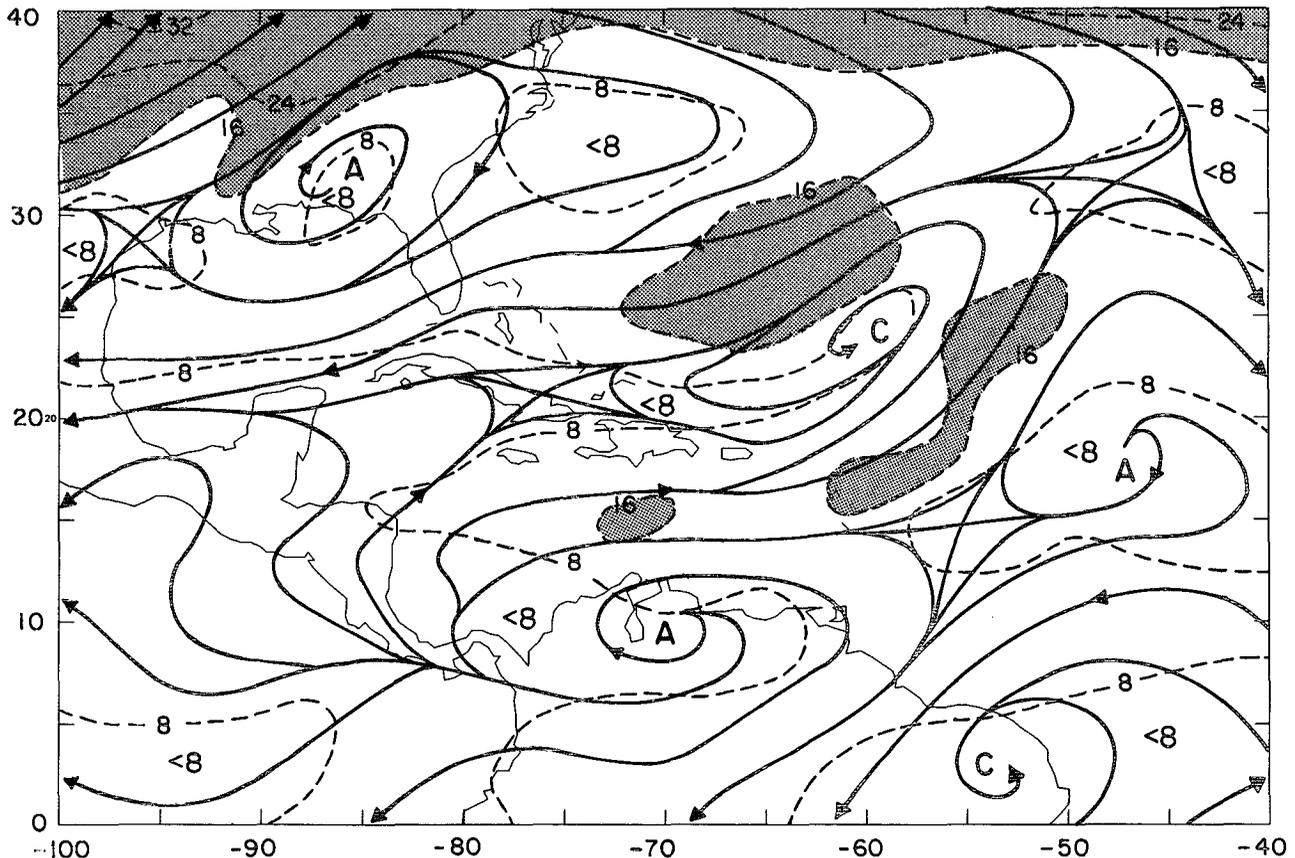


FIG. 3. Strong TUTT case. (a) AVN analysis of 200-mb winds at 0000 UTC 1 September 1993. (b) AVN 48-h forecast of the 200-mb winds that verifies at 0000 UTC 3 September 1993. (c) AVN analysis of 200-mb winds at 0000 UTC 3 September 1993. Wind speeds are contoured every 8 m s^{-1} with shading added for those winds greater than 16 m s^{-1} .

heat flux (Jaeger 1976; Peixoto and Oort 1992), transporting heat and moisture upward (in the form of latent heat), which more than balances radiational cooling. Observations show that Q/c_p in the mid- and upper troposphere over continents are about $1\text{--}2 \text{ K day}^{-1}$ in the summer (Schaack et al. 1990; Geller and Avery 1978). However, precipitation decreases (on average) over the subtropical ocean in the warmer months. For example, at the climatological position of the TUTT maximum (30°N and 50°W), seasonal winter rainfall is 300 mm compared to 170 mm in the summer (Dorman and Bourke 1981).

Therefore, the upper tropical atmosphere experiences net cooling due to radiational losses in the summer, and subsidence occurs to maintain thermal balance. In turn, this upper-tropospheric subsidence dries the atmosphere, creating large longwave radiation flux divergence that further enhances cooling. It is through this feedback process and the strong continental-oceanic gradient of Q/c_p that the TUTT may be initiated. The TUTT dissipates in the fall as $\nabla Q/c_p$ decreases due to less continental convection, increasing

oceanic convection, and baroclinic intrusions into the Tropics. More research on the summer genesis and maintenance of the TUTT needs to be conducted to determine the specific role of these and other processes.

In the North Atlantic, the TUTT first develops in June, strengthens in July and August, and dissipates in September and October. In its climatological position, the trough axis tilts from the central North Atlantic into the Gulf of Mexico as shown for mean August conditions in Fig. 2. Smaller-scale (few hundred kilometers) closed circulations—cold lows or TUTT cells—form within the TUTT and move to the south and west along the TUTT axis throughout the summer. It is these strong cold lows that are most important in regard to tropical cyclone forecasting, because they are associated with maxima in VWS and horizontal eddy momentum fluxes.

b. Aviation model description and known systematic tropical wind biases

The National Meteorological Center's AVN model has evolved through a number of changes and upgrades

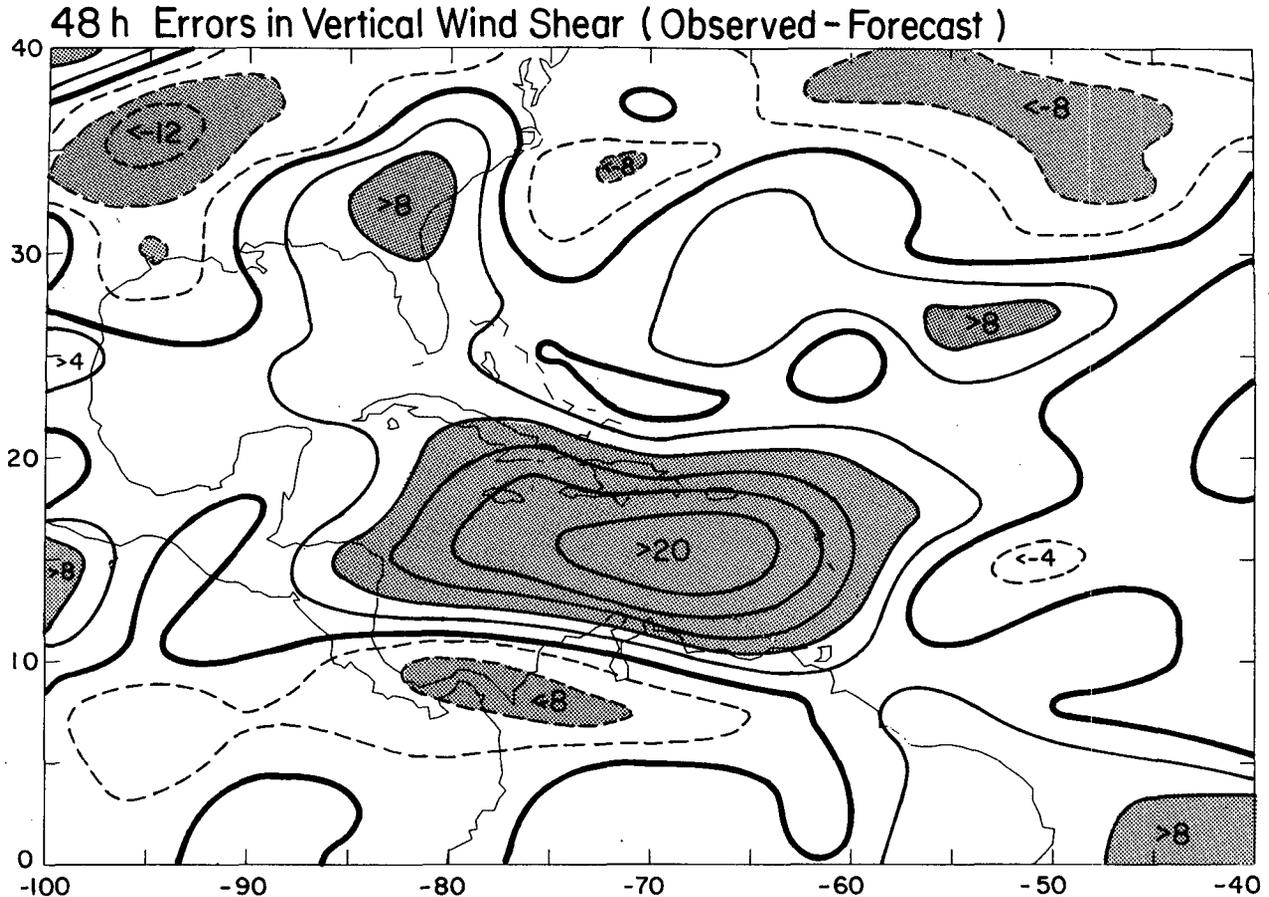


FIG. 4. Errors (in m s^{-1}) in the vertical wind shear (VWS) for the strong TUTT case associated with the AVN 48-h forecast that verifies at 0000 UTC 3 September 1993. Errors are expressed as the magnitude of the observed minus the forecast VWS. Errors greater than 8 m s^{-1} in magnitude are shaded. Contour intervals are 4 m s^{-1} . Bold line is 0 m s^{-1} .

during its existence. It is a global spectral model run on a 12-h cycle after assimilating all available data 2 h 45 min after the synoptic time (Peterson and Stackpole 1989). The analysis-forecast-postprocessing then takes about 2 h to complete. Forecasts are generated out to 72 h from the initialization time. The medium-range forecast model (MRF) is essentially the same model in regard to its construction as the AVN, except that the MRF is run only once daily from 0000 UTC after collecting 9 h worth of data. As of 1990, the AVN had a horizontal resolution of T126 that corresponds to a horizontal resolution of 105 km, mean orography, and observed 2° resolution sea surface temperatures updated once a week (Kanamitsu et al. 1991). According to Kanamitsu et al., changes were made to the marine stratus parameterization, mass conservation was improved, and horizontal diffusion was reduced in medium scales. In addition, on 11 August 1993, the number of levels in the vertical was increased to 28 and an Arakawa-Schubert convective parameterization scheme with moist downdrafts was implemented in the model. This new scheme is a slight modification

of that described in Grell et al. (1991), which further enhances boundary-layer forcing and modifies downdraft levels in accordance with the greater resolution near the surface of the AVN (H. Pan 1994, personal communication).

In a study on the systematic errors of the MRF model, Rosen et al. (1991) found that the model experienced a large bias in the tropical upper troposphere with the easterlies becoming much too strong when the MRF was run out to 10 days. They also found that this bias was observable even in a 2-day forecast. Apparently, this type of systematic error is a common one for operational global spectral models, as the same unrealistic overproduction of tropical upper-level easterlies was identified in the European Centre for Medium-Range Weather Forecasts (ECMWF) model (Bengtsson 1991). According to Rosen et al., it is unlikely that new computational procedures introduced in the last few years have created this bias, as earlier versions of global forecast models have also experienced this problem.

However, beyond this general identification of an easterly bias in the tropical troposphere, specifics about the longitudes, times of year, and synoptic conditions (including periods when the TUTT is present) when this problem was most severe are, to our knowledge, lacking. The next section details our findings for the tropical North Atlantic during the hurricane-prone months of August and September for 1993.

3. Methodology and results

Real-time AVN output data for the following analyses were received locally via the Numerical Products Service (NPS) satellite broadcast through the Alden/Zephyr Weather Incorporated downlink system. Uni-data's Local Data Management (LDM) Version 4 software decoded the incoming NPS gridded data to General Meteorological Package (GEMPAK) Version 5.1 format (desJardins et al. 1991). The data were provided to us with a grid spacing of 2.5° latitudinally and 5° longitudinally. Graphical hard copy GEMPAK images were generated automatically when the AVN output arrived.

Starting in early August 1993, AVN analyses and forecast fields for the 48-h forecast for 850 and 200 mb were saved when data were received. (Note that over 90% of the data analyzed in this study was collected after the implementation of the new convective parameterization scheme on 11 August 1993.) The 48-h forecast fields were selected, since this lead time provides key information for crucial tropical cyclone forecast decision making, such as the placement of watches and warnings (Sheets 1990). From early August through late September 1993, a total of 63 cases that contained the analyses, forecast fields, and their verification were available.

On the whole, data availability for the initial time analyses were very good. Within the region of the climatological TUTT axis, there exists several reliable rawinsonde stations, numerous jet aircraft reports, and many cloud track wind vectors (from cirrus) at 200 mb every synoptic time. A typical analysis contains between 15 and 25 observations in the crucial 10° – 30° N, 60° – 80° W region. No systematic difference between the 0000 and 1200 UTC data availability was detected. Thus, the ability of the AVN analysis was more than adequate to pick out synoptic-scale features, such as the TUTT.

It was found that the upper-tropospheric forecast flow fields in the vicinity of the climatological position of the TUTT were biased toward stronger easterlies than what was verified. The low-level forecast flow fields were, in general, observed to have very little systematic bias.

Figure 3 provides an example of the behavior of the AVN when a strong TUTT is observed in the initial analysis time. On 0000 UTC 1 September, the 200-mb

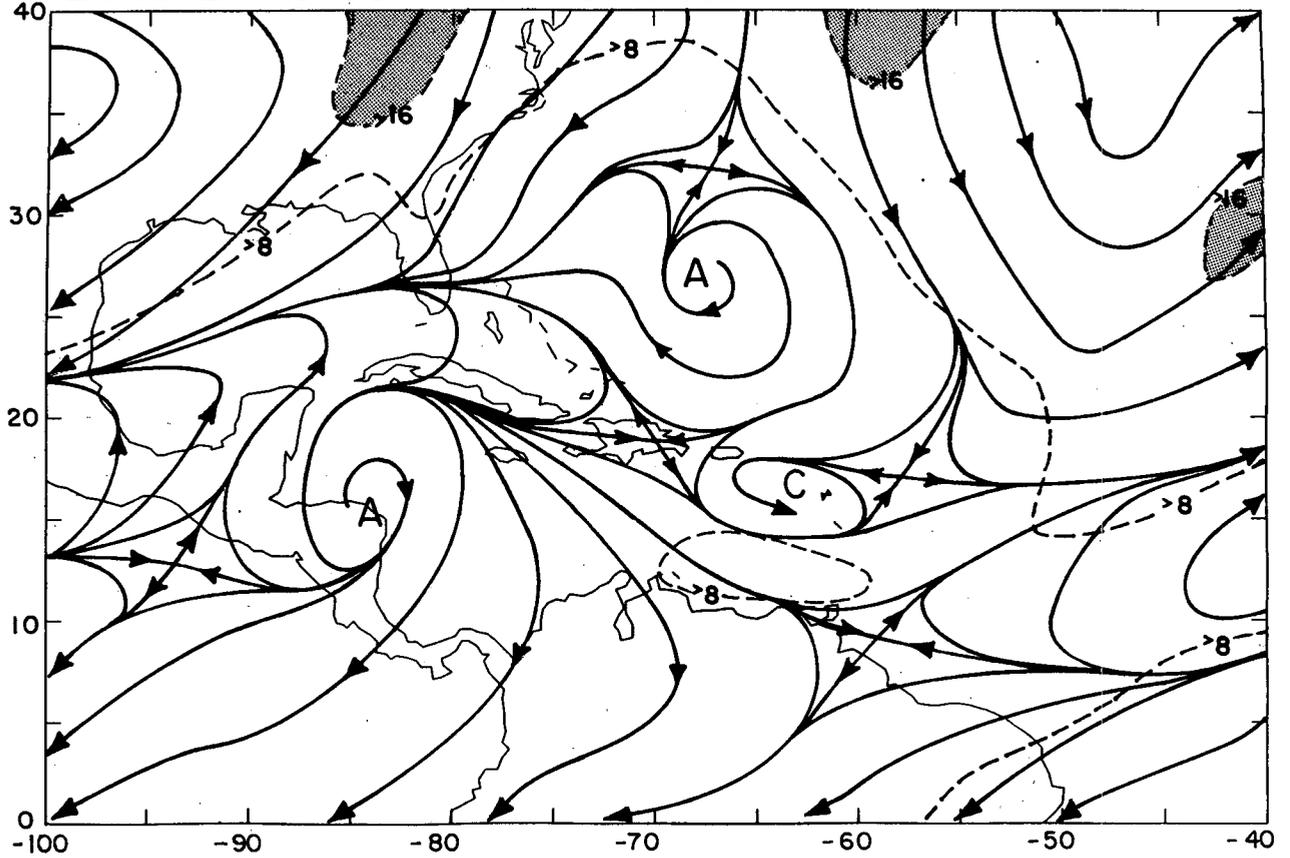
flow shows a strong TUTT extending from near 30° N and 50° W southwestward into the Caribbean Sea, westward to Central America, and then northwestward into eastern Texas (Fig. 3a). The TUTT also has a cold low along its axis centered at 22° N and 58° W. Maximum westerly winds south of the TUTT axis in the Caribbean Sea are on the order of 15 m s^{-1} . Figure 3b shows the 200-mb forecast field valid at 0000 UTC 3 September. The AVN completely dissipates the TUTT, leaving only a weak cold low near 23° N and 65° W, replacing the TUTT westerlies with weak to moderate easterly flow associated with the subtropical ridge to the north. However, in the verification of the 200-mb forecast field (Fig. 3c), the TUTT is still strongly present at 0000 UTC 3 September. The TUTT axis is in nearly the same location with the same magnitude of westerlies south of the axis. One new feature is the anticyclone over northern South America. This feature also was not forecast by the AVN.

Since the 850-mb forecast was observed to have very little bias (not shown), errors in the vertical wind shear (VWS)—the critical measure for TC genesis and intensity forecasting—are dominated by the errors at 200 mb. Shear values were calculated from the AVN for the initial time period and the 48-h prediction fields by using (1). Figure 4 demonstrates the large magnitude of error (observed minus forecasted VWS) that was found for the 48-h AVN forecast verifying at 0000 UTC 3 September. A wide region near the Caribbean Sea experienced 8 m s^{-1} or greater error in the forecast VWS field. Note that the locations of large positive errors correspond extremely well with the regions of observed westerly winds south of the TUTT axis. It is also possible that the unanticipated development of the South American anticyclone contributed to the shear errors in this particular case, but in general such errors were observed to be associated with the AVN's improper handling of the TUTT.

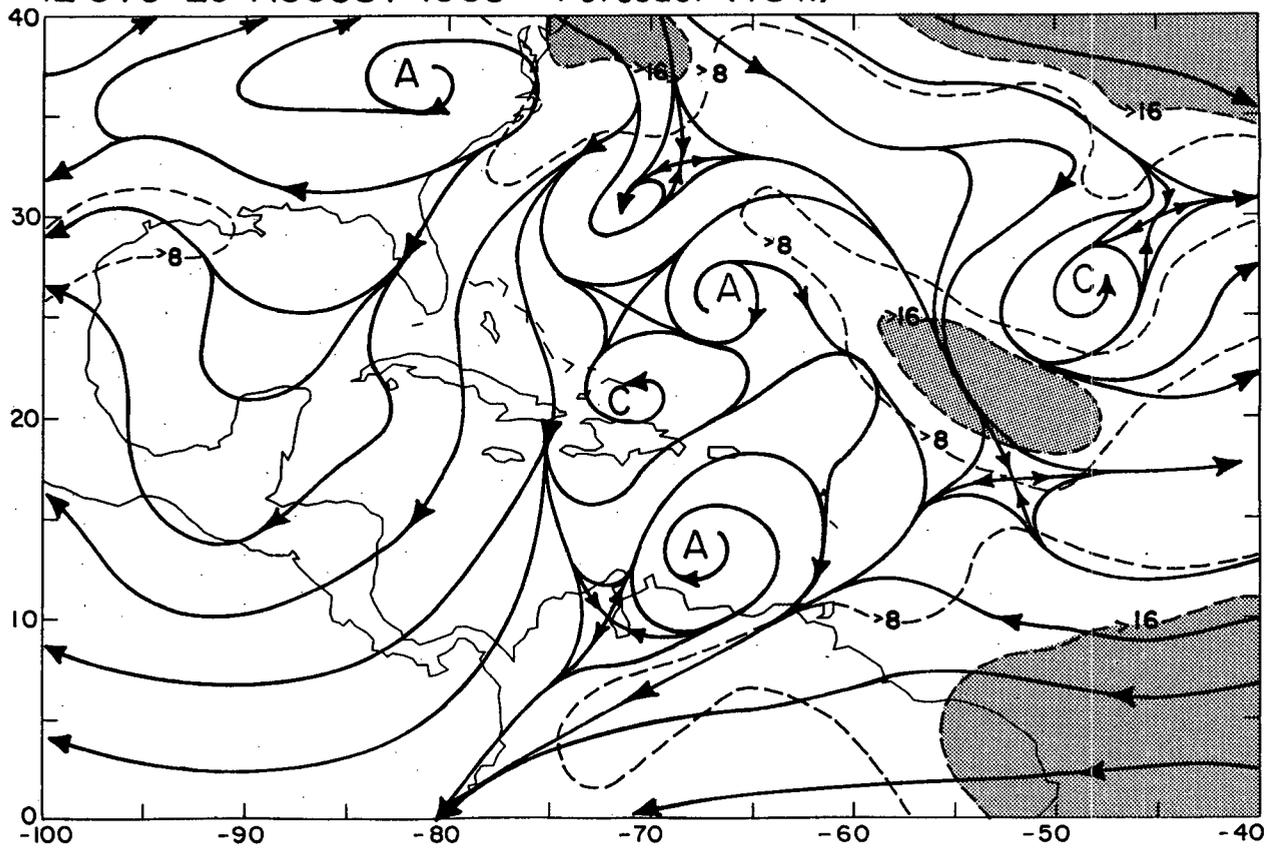
While Figs. 3 and 4 have presented the errors found in conjunction with one of the stronger TUTTs that were present in the 2-month time period, 48-h forecast errors in the vicinity and south of the TUTT axis typically were on the order of 10 m s^{-1} . However, when the TUTT was either very weak or not present in the analysis, it was found that the errors were substantially reduced.

To contrast results shown in Figs. 3 and 4, a weak TUTT case was examined. Figure 5 provides an example of the forecast behavior of the AVN when only a very weak TUTT is observed in the initial analysis. At 1200 UTC 27 August 1993, the 200-mb flow shows a weak closed cold low at roughly 17° N and 63° W, which is attached to a midlatitude trough over the Azores and adjacent to a weak trough extending from the northeastern Pacific Ocean region (Fig. 5a). The normal climatological position of the TUTT (see Fig. 2) is occupied by two closed upper-level anticyclones: one located over eastern Honduras, and the other sit-

12 UTC 27 AUGUST 1993 - Observed



12 UTC 29 AUGUST 1993 - Forecast (48 h)



12 UTC 29 AUGUST 1993 - Observed

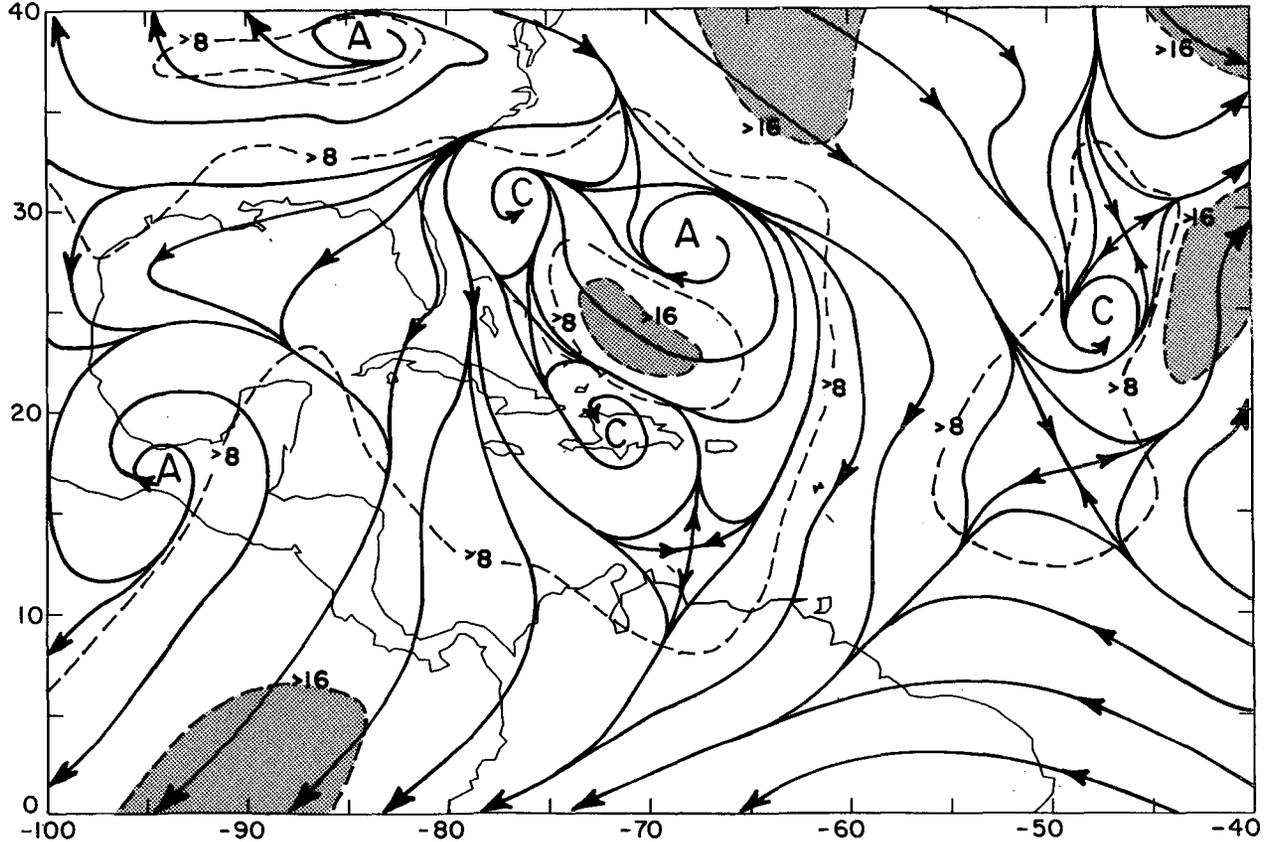


FIG. 5. As in Fig. 3 except for weak TUTT case. (a) AVN analysis of 200-mb winds at 1200 UTC 27 August 1993. (b) AVN 48-h forecast of the 200-mb winds that verifies at 1200 UTC 29 August 1993. (c) AVN analysis of 200-mb winds at 1200 UTC 29 August 1993.

uated about 7° north of Puerto Rico. The eastern half of the United States is under the influence of a strong subtropical ridge. Figure 5b shows the 48-h AVN forecast of 200-mb winds valid at 1200 UTC 29 August. When compared with the analysis at the verification time (Fig. 5c), the AVN forecast does well, specifically with respect to both positioning and strength of the cold low near Hispanola and the upper-level anticyclones in the Caribbean and over the U.S. mainland. It does, however, dissipate the 200-mb trough that extends from the eastern Pacific basin and washes out the closed anticyclone over Honduras.

Figure 6 shows the observed minus forecast VWS valid at 1200 UTC 29 August. The magnitude of errors is strikingly small ($<4 \text{ m s}^{-1}$), when compared to Fig. 4, throughout the entire Caribbean basin. The errors are smallest where easterly winds persisted throughout the analysis period and are small where westerly winds became northeasterly in the eastern Caribbean. There is only one region that has errors in excess of 12 m s^{-1} : the area of westerly winds just south of a weak east-west trough in the Gulf of Mexico. This feature is curiously eliminated in the forecast field (see Fig. 5b).

Note that with the exception of two small regions to the south of Honduras and one region over South Carolina all positive forecast errors shown are associated with observed upper-level westerly winds at verification time.

Table 1 documents the 48-h AVN model errors found at specific locations throughout the entire 2-month time period under analysis. The locations of these four points are shown in Fig. 2. All four locations show an underestimation of the VWS during the 2-month period for all cases with the largest errors occurring at the two westernmost points. When stratified by 200-mb westerly and easterly wind cases at the verification time (48 h), it becomes apparent that the easterly bias is strongest when westerly winds were observed. Typically, these westerlies occurred only when the TUTT axis was to the north of the location in question. When moderate ($<10 \text{ m s}^{-1}$) westerlies were observed at 48 h, this bias is on the order of 5 m s^{-1} . Furthermore, when strong ($\geq 10 \text{ m s}^{-1}$) westerlies were observed at 48 h, the underestimation in the VWS is on the order of 10 m s^{-1} . This implies that there is a consistent tendency for the AVN to unrealistically di-

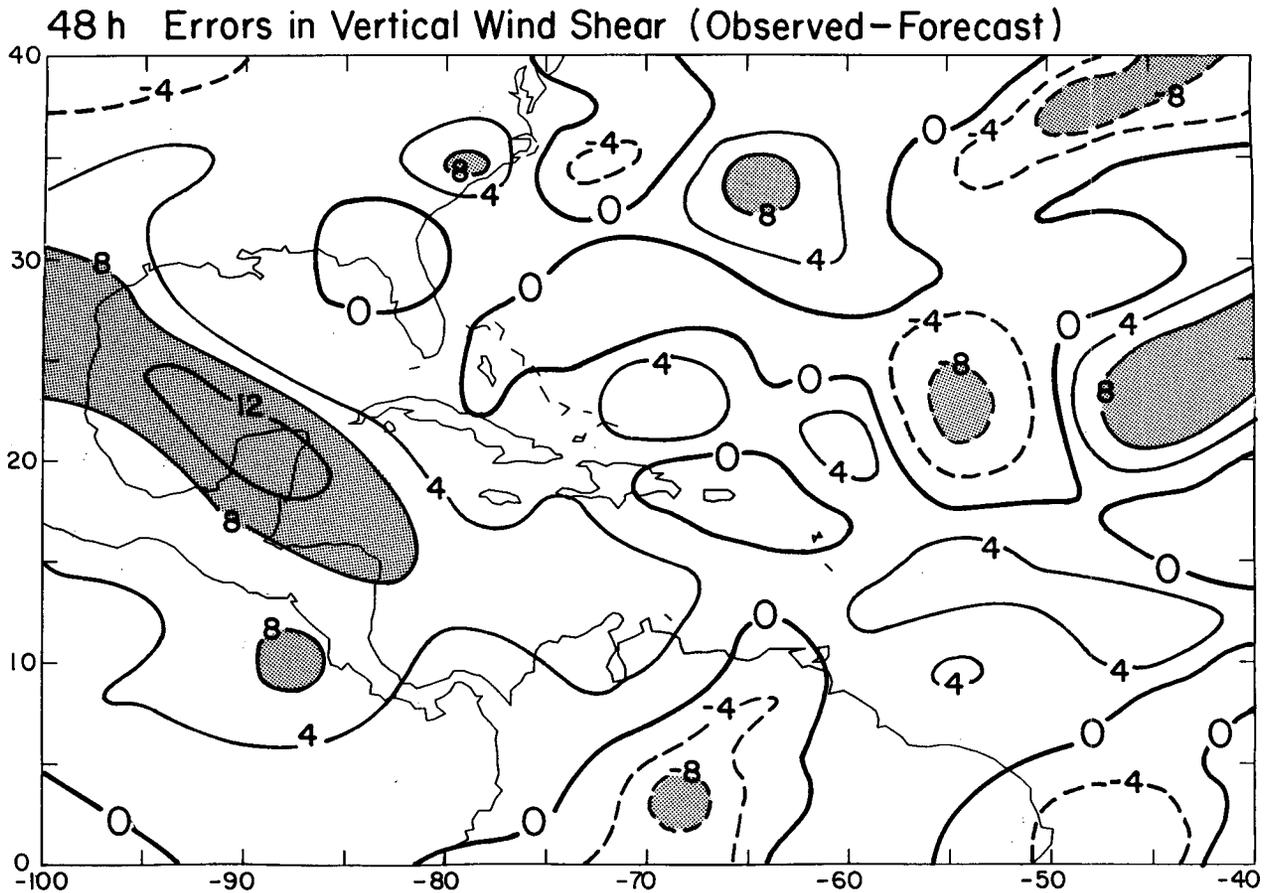


FIG. 6. As in Fig. 4 except VWS errors for the weak TUTT case associated with the AVN 48-h forecast that verifies at 1200 UTC 29 August 1993.

minish all westerly momentum, even for westerly winds with substantial strength, in the Tropics. However, when 200-mb easterly winds occurred at 48 h, the errors are small. This contrast is even more evident when the four locations in Fig. 2 are averaged together; the error associated with the strong westerlies is 7.8 m s^{-1} , while for the easterly case it is 1.1 m s^{-1} .

For an additional perspective, the 48-h forecast VWS errors are plotted in terms of 5 m s^{-1} classes for easterly, westerly, and strong westerly wind regimes at the 48-

h verification time (Fig. 7). As expected, when easterly winds were observed the AVN errors are semi-Gaussian. However, west winds experience a positive error bias, and in fact, very few errors are negative. For strong westerlies the bias is strongly positive.

To examine these errors in more detail, the AVN shear values were stratified by winds observed at model initialization and by winds observed at the 48-h verification time (Table 2). From this tabulation, it is clear that the AVN suffers a tendency to weaken or eliminate

TABLE 1. Relative errors for the 48-h forecasted vertical wind shear (VWS) from the AVN model for selected locations and the overall average during August and September 1993. Errors (in m s^{-1}) are expressed as observed minus forecasted VWS such that positive values indicate more VWS was observed than forecasted. The type of observed winds (west, east, west $< 10 \text{ m s}^{-1}$ and west $\geq 10 \text{ m s}^{-1}$) refer to the 200-mb wind flow at the particular location at the verification time 48 h ($t = 48$). Number of cases are in parenthesis.

Category	15°N, 80°W	15°N, 70°W	20°N, 65°W	12.5°N, 60°W	Avg
All cases ($t = 48$)	5.7 (63)	6.1 (63)	2.2 (63)	2.0 (63)	4.0 (252)
West ($t = 48$)	7.7 (37)	7.4 (43)	3.5 (47)	4.6 (30)	5.8 (157)
East ($t = 48$)	2.8 (26)	3.4 (20)	-1.6 (16)	-0.4 (33)	1.1 (95)
West $< 10 \text{ m s}^{-1}$ ($t = 48$)	7.3 (26)	5.2 (30)	2.6 (24)	3.5 (23)	4.7 (103)
West $\geq 10 \text{ m s}^{-1}$ ($t = 48$)	8.6 (11)	12.5 (13)	4.5 (23)	8.3 (7)	7.8 (54)

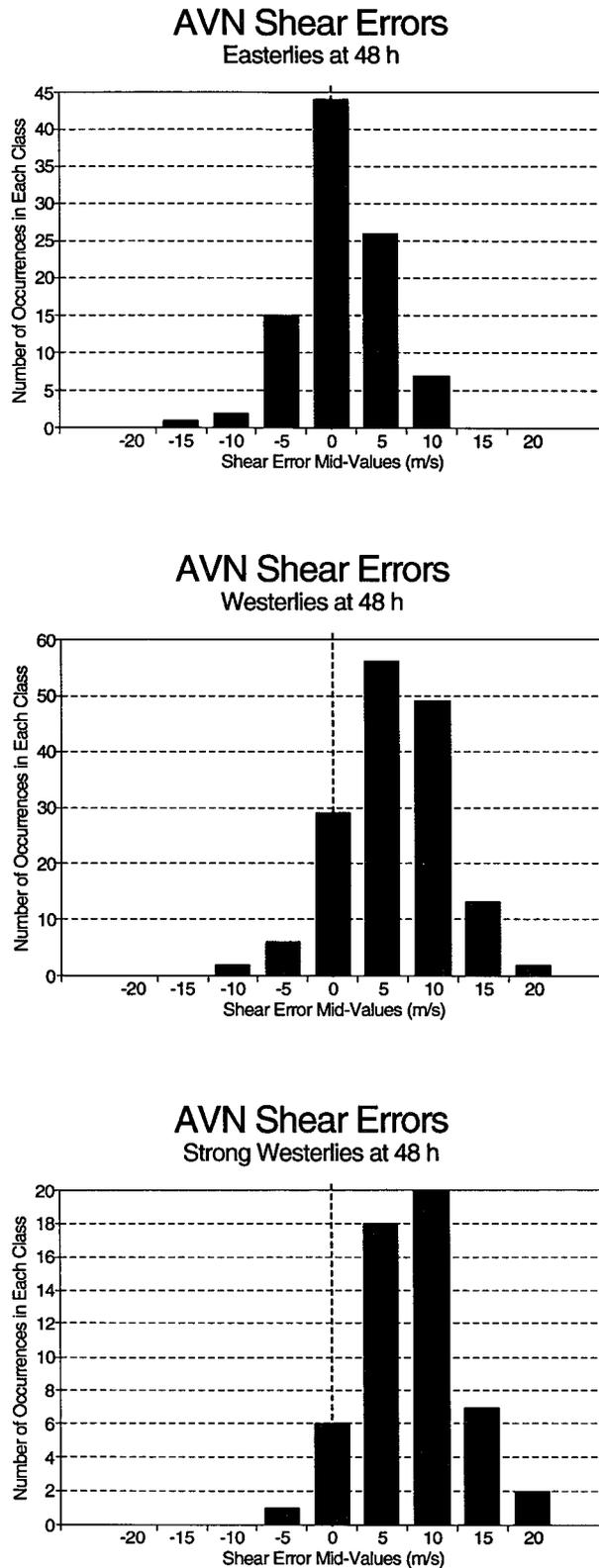


FIG. 7. AVN 48-h forecast VWS errors plotted in terms of 5 m s^{-1} classes for easterly, all westerly, and strong westerly wind regimes ($\geq 10 \text{ m s}^{-1}$) observed at the 48-h verification time.

200-mb westerly winds and/or to introduce 200-mb easterly winds in the Caribbean Sea. For example, the VWS errors are highest when 1) west winds were observed to increase with time, 2) east winds became westerly with time, or 3) west winds were observed to be steady state. This indicates the AVN model's inability to generate, maintain, or build westerlies associated with a steady-state or growing TUTT. It is also possible that the AVN is misplacing the location of the TUTT, but it was observed that the easterly bias was much more common. In contrast, for the cases when 1) easterlies were observed throughout the forecast period, 2) west winds weakened with time, or 3) west winds became easterly with time, the VWS forecast errors were small. This probably also reflects the model's bias toward generating 200-mb easterlies in most cases.

Although identifying such a bias provides useful information, the forecaster is left with a dilemma: How does one predict the 200-mb flow in the future for a tropical westerly wind regime? One approach is to assume that the TUTT is approximately a steady-state system and use persistence. Another approach is to use climatology to predict the future 200- and 850-mb wind flow. Both procedures are further investigated. The persistence scheme simply extrapolates the observed VWS into the future. The climatology scheme uses average 15-day climatological values for the verification time.

Climatological data were provided by the Climate Analysis Center's Global Tropical Climate Diagnostics for the years 1979–1988 (prepared by Muthuvel Chelliah at the National Center for Atmospheric Research). This 10-year VWS climatology is interpolated from 2.5° grid spacing to the four individual locations for the following time periods: 1) 10 August–20 August, 2) 21 August–9 September, 3) 10 September–20 September, and 4) 21 September–30 September. For this 10-year climatology, westerlies exist in all four time frames at 200 mb (not shown). The climatological VWS values are shown in Table 3. VWS tends to decrease south of the TUTT in early September because the trade winds are weakest at this time while (for this 10-year climatology) the 200 mb westerlies remained fairly constant in magnitude during August and September.

The effectiveness of these schemes is examined in Table 4, in which the average errors are stratified by winds observed at the initialization time. For this 2-month (August and September) period, both climatology and persistence experience smaller VWS errors than the AVN for all stratifications. Furthermore, all the AVN forecast errors are positive, again showing the model's tendency to diminish westerly momentum and therefore underforecast VWS. When all cases are considered, average persistence errors are approximately zero, implying that this procedure introduces no forecast bias. When subdivided by different wind

TABLE 2. Average relative forecast errors (in m s^{-1}) for the 48-h VWS from the AVN model during August and September 1993 stratified by winds observed at initialization ($t = 0$) and 48 h later ($t = 48$). Number of cases are in parentheses. Due to missing wind observations coinciding with model initialization, there are four fewer total cases than in Table 1 (248).

Category	East ($t = 48$)	West < 10 m s^{-1} ($t = 48$)	West \geq 10 m s^{-1} ($t = 48$)
East ($t = 0$)	1.4 (51)	5.8 (37)	8.8 (6)
West < 10 m s^{-1} ($t = 0$)	1.3 (33)	5.0 (44)	7.2 (25)
West \geq 10 m s^{-1} ($t = 0$)	-2.3 (8)	2.3 (21)	8.1 (23)

stratifications, the errors are smallest in magnitude compared to the other two predictive procedures (though it is the same as climatology for weak westerlies) except for observed easterlies at initialization. This implies that 200-mb easterlies often did not persist for two consecutive days during August and September 1993.

Climatology VWS forecast errors are weakly positive for all cases, indicating that the shear was greater than the 1979–1988 climatology during 1993. This is indicative of the westerly wind anomalies associated with that year's El Niño, which partially explains the fairly inactive 1993 hurricane season (Gray 1993). It is somewhat interesting that using climatology yields almost no forecast error for an initial easterly wind, since 200-mb westerlies exist in the climatology. Apparently, this procedure nudges the forecast back to a normal 200-mb westerly wind regime. This tendency is also apparent for the weak westerly stratification, since climatological winds are less than 10 m s^{-1} .

However, some caution is needed in interpreting the findings using a 10-year climatology. A longer-term climatology would possibly yield different results, since August–September wind flow patterns possibly were different in the 1950s and 1960s. Landsea and Gray (1992) note a reduction in major hurricanes (Saffir–Simpson categories 3, 4, and 5) in the last 20 years associated with a multidecadal drought in Africa's western Sahel. Teleconnection patterns related to this drought may have, in turn, altered the Atlantic's general circulation. According to Landsea and Gray, during these drought years anomalous westerly winds were observed in the Caribbean. Unfortunately, synoptic-

TABLE 4. Average relative forecast errors (in m s^{-1}) for the 48 h VWS of all wind stratifications at model initialization ($t = 0$) using the AVN prognostic field, persistence, and climatology. The number of cases are the same as Table 2.

Category	AVN	Persistence	Climatology
All cases ($t = 0$)	4.0	-0.1	1.3
West ($t = 0$)	4.3	-1.9	2.1
East ($t = 0$)	3.6	2.9	0.1
West < 10 m s^{-1} ($t = 0$)	4.3	-1.2	1.2
West \geq 10 m s^{-1} ($t = 0$)	4.2	-3.2	3.8

scale quantitative data over the whole basin for the long-term climatology is lacking.

It has now been established that using persistence and/or climatology introduces less VWS forecast bias, especially when compared to the rather large bias in the AVN model. But does using these alternate schemes actually *reduce* the overall forecast error? To answer this question, average absolute errors were calculated for the AVN model, persistence, and climatology and stratified by observed winds at model initialization (Table 5). Overall, persistence and climatology surpass the AVN in performance, but the 200-mb wind stratifications offer more insight. For an initial easterly wind regime, climatology has the smallest absolute error. For an initial weak west wind, climatology and persistence are equal in forecast performance. For an initially strong west wind, persistence contains the smallest absolute error.

In summary, it is recommended that the forecaster use persistence and/or climatology near the Caribbean Sea during the hurricane season to forecast 48-h VWS and 200-mb winds. For 200-mb east winds, climatology is the suggested predictor. For westerly winds less than 10 m s^{-1} , half climatology and half persistence is advised. For westerly winds greater than or equal to 10 m s^{-1} , persistence is suggested.

4. Discussion

Because TC genesis, intensity, and track models largely depend on the forecast fields of the AVN, a more complete understanding of the AVN model's systematic biases is necessary. For example, the latest statistical–dynamical model for TC track forecasting in the Atlantic basin, NHC90, as well as the latest baroclinic track forecasting model, the Quasi-Lagran-

TABLE 3. 1979–1988 Climatological VWS values (in m s^{-1}) for mid-August, late August, mid-September, and late September.

Date	15°N, 80°W	15°N, 70°W	20°N, 65°W	12.5°N, 60°W
Mid-August	14.6	14.7	10.5	8.3
Late August	12.6	14.1	9.9	9.1
Mid-September	10.7	13.5	9.3	9.9
Late September	11.1	14.0	10.6	13.4

TABLE 5. Average absolute forecast errors (in m s^{-1}) for the 48-h VWS of all wind stratifications at model initialization ($t = 0$) using the AVN prognostic field, persistence, and climatology. The number of cases are the same as Table 2.

Category	AVN	Persistence	Climatology
All cases ($t = 0$)	5.4	4.8	4.5
West ($t = 0$)	5.6	4.7	4.8
East ($t = 0$)	5.1	4.9	4.0
West $< 10 \text{ m s}^{-1}$ ($t = 0$)	5.3	4.1	4.0
West $\geq 10 \text{ m s}^{-1}$ ($t = 0$)	6.3	5.8	6.3

gian Model (QLM), use AVN forecast fields of the geopotential heights, including 200-mb heights (Neumann and McAdie 1991; Mathur and Ruess 1993). Note that once a bias (such as the one shown here) is identified, it is possible in a statistical model like NHC90 to account for it. Additionally, future plans for the only statistical-synoptic model available for TC intensity forecasting—the Statistical Hurricane Prediction Scheme—call for it to include AVN forecast fields of both VWS and 200-mb eddy angular momentum fluxes (DeMaria and Kaplan 1994).

What has been detailed here are systematic biases in the forecasted tropical upper-tropospheric flow patterns in the AVN that can seriously degrade the performance of models like NHC90 and the QLM, as well as misinform the forecaster as to the future evolution of the tropical circulation. We observed a strong tendency in the AVN's 48-h forecast of 200-mb flow to possess an easterly bias of 5 m s^{-1} for all cases and up to 10 m s^{-1} in cases where westerly winds were observed. This bias is most apparent near and south of the climatological position of the TUTT axis during August and September—the height of the Atlantic hurricane season.

There are a number of possible causes of such a systematic error. The bias might result from poor model resolution of the upper troposphere and lower stratosphere (Petersen and Stackpole 1989). In addition to the coarse-resolution problem, previous studies that identified the general tropical upper-tropospheric bias suggest that four other factors may be responsible. Bengtsson (1991) in his discussion of ECMWF model errors suggests that both convective parameterization and the treatment of momentum fluxes may be the cause of the excessive easterlies. Rosen et al. (1991) discuss the possibility that the parameterization of radiation may be the culprit in the AVN/MRF. In turn, a properly formulated radiation scheme will still suffer errors if the vertical moisture field is inaccurately portrayed in the model (Slingo and Webb 1992). However, the primary purpose of this paper is to simply document a systematic bias in the AVN model, not to specifically identify its cause.

Until this bias in the AVN is successfully reduced, it is desirable that the Atlantic basin TC forecaster be

aware of this systematic error and make subjective changes in his/her forecasts. In fact, it is recommended that the forecaster use persistence in cases where strong westerly winds are observed at 200 mb in the Caribbean Sea. For weak westerlies at 200 mb, half climatology and half persistence is the preferable predictor. If the TUTT is weak such that 200-mb easterly winds occur, climatology tends to be the best predictor as it nudges the forecast back to a normal westerly wind regime. However, should a forecaster surmise this to be improbable (as in the case of a far-displaced TUTT or a nonexistent TUTT), the AVN or persistence is probably best.

We would hope that these suggestions would be only a temporary fix and that the performance of the AVN itself can be improved. Accordingly, we would encourage research into the causes of this bias by members of the modeling research community.

Acknowledgments. We wish to thank Profs. William Gray, Roger Pielke, and Wayne Schubert for providing us with enlightening discussions regarding this problem. James Stricherz and The Florida State University provided some of the data used in the persistence calculations. The streamline figures were drafted by Judy Sorbie-Dunn. A special thanks is extended to George Forristall and Mike Vogal for the impetus to look closely at the AVN forecast fields. Lance Leslie and two anonymous reviewers made helpful comments on an earlier version of this paper. Partial support was given by NASA, who provided funding for J. Knaff and C. Landsea through the Global Change Fellowship Program under Contracts NGT 30147 and 30064. P. Fitzpatrick received partial funding through the Air Force Office of Scientific Research under Grant DEO102. This analysis was partially supported by the Office of Naval Research under Grant DEO306.

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