Comparisons of VAS and Omega Dropwindsonde Thermodynamic Data in the Environment of Hurricane Debby (1982)

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12 October 1987 and 28 January 1988

ABSTRACT

Synoptic-scale thermodynamic fields in the environment of Hurricane Debby (1982) determined from two sets of VAS soundings (VAS1, VAS2) are compared with those obtained from in-situ data (INS). VAS1 soundings were derived from an iterative solution of the radiative transfer equation with manual quality control. VAS2 soundings, which represent the present state-of-the-art, were derived from a simultaneous solution of the transfer equation with objective quality control. In situ data were obtained primarily from Omega dropwindsondes. Comparisons are made for 0000 UTC 16 September 1982 at the mandatory pressure levels up to 400 mb. The integrated effect of VAS–INS differences is estimated by comparing 400 mb geopotential height fields and their associated gradient winds.

The comparisons show that the VAS1–INS temperature differences are not spatially uniform at most levels, due largely to the influence of moisture. The quality of the VAS2 data is much improved over VAS1; the effect of moisture is not noticeable. However, the VAS2 analyses still show spatially nonuniform differences from INS at some levels. Thus, VAS gradient data may be of irregular quality on the synoptic scale. Geopotential height fields at 400 mb imply gradient wind differences from INS of up to 12 m s^{-1} for VAS1 and 6 m s^{-1} for VAS2. The VAS2 sounding set could be improved further by the use of manual data editing, and a more accurate first-guess of the surface temperature analysis.

1. Introduction

Recently compiled statistics on tropical cyclone track forecast errors in the Atlantic (Neumann 1985) and Pacific (Jarrell et al. 1978) have shown that the rate of improvement of track forecasts has decreased in recent years. Neumann (1981) has argued that this decrease is due to a decline in the quality of midtropospheric analyses in the hurricane environment. This decline has been caused by the closing of land and ship radiosonde stations, increasing prevalence of jet aircraft, and operational use of objective analyses, rather than carefully prepared hand analyses. Many believe that the potential of new dynamical and statistical tropical cyclone models probably will not be fully realized until the quantity and quality of observations over the tropical and subtropical oceans is increased (Burpee et al. 1984).

Two technologies are in use to improve the analysis of the hurricane environment: in-situ observations from Omega dropwindsondes (ODWs), and remotely sensed data from satellites. The Hurricane Research Division (HRD) of the NOAA/Atlantic Oceanographic and Meteorological Laboratory has deployed ODWs to gather mid- and lower tropospheric wind and thermodynamic data from the hurricane environment within about 1000 km of the storm center. The first such experiment was conducted in 1982 for Hurricane Debby and has been described by Burpee et al. (1984). In conjunction with the Debby experiment, HRD also collected data from rawinsondes, surface ships, U.S. Air Force reconnaissance aircraft, and the NOAA WP-3D aircraft that were involved in the ODW flights. These data wre analyzed by Lord and Franklin (1987), who reported a positive impact of the analyzed data on forecasts with the barotropic SANBAR model (Goldenberg et al. 1987).

Information from the VAS (Visible Infrared Spin Scan Radiometer Atmospheric Sounder) may play an increasingly important role in hurricane track forecasts. Although cloud-track winds from satellites have for years described tropical circulations in the lower and upper portions of the troposphere, hurricane motion is best correlated with wind and height patterns in the middle troposphere (George and Gray 1976; Neumann 1979). Velden and Goldenberg (1987) addressed this midlevel data void by computing gradient winds from thermodynamic data obtained from the the VAS and have produced some encouraging preliminary results in SANBAR model forecasts. About 40% of Velden and Goldenberg's midlevel dataset consisted of gradient winds. In addition to its application to hurricane track forecasts, oceanic VAS thermodynamic data have been,

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and will continue to be, a high priority dataset for major field experiments such as GALE (Genesis of Atlantic Lows Experiment) and ERICA (Experiment on Rapidly Intensifying Cyclones in the Atlantic). Therefore, the accuracy of VAS gradients over the ocean should be evaluated, and the consequences of using VAS data in numerical models should be determined.

O'Lenic (1986) has investigated the effect of VAS sounding data over the northeast Pacific Ocean on LFM (limited-area fine mesh) analyses and forecasts. Interpretation of his results, however, is complicated by the lack of corroborative information over the ocean, and incomplete documentation of VAS error characteristics. Velden et al. (1984) have presented results of "point" comparisons of VAS and ODW parameters for the Debby case, in the form of mean difference and standard deviation tabulations. It is difficult, however, to gauge the horizontal variability of VAS errors from point comparisons. Only modest point errors are required to render gradients meaningless, if the errors vary in space. As part of a case study, Mostek et al. (1986) compared analyses of VAS and rawinsonde 850 mb temperatures and dewpoints over the central United States. Their analyses of each data type, however, were based upon different horizontal scales, each compatible with the very different data densities of the VAS soundings and the rawinsondes. Assessment of VAS data accuracy is difficult from this type of analysis.

The HRD synoptic-flow experiments offer a rare opportunity for the assessment of oceanic VAS data and the consequences of its use. In this note, we take a first step in this direction by comparing mechanical analyses of thermodynamic fields determined from VAS and in-situ data.

2. Analysis procedures

a. Data

Two sets of VAS sounding data for 0048 UTC 16 September 1982 were obtained from the University of Wisconsin Space Science and Engineering Center (SSEC). The soundings consist of temperature and humidity estimates at the mandatory levels. Each VAS dataset is evaluated separately against in-situ data. The first set ("VAS1") was generated in 1982 using an iterative inversion of the radiative transfer equation (Smith 1983) involving the separate adjustment of temperature and moisture profile estimates. Editing was performed by a manual quality control procedure at SSEC. A second set of soundings ("VAS2") was generated in 1986 at SSEC, using a simultaneous adjustment of the temperature and moisture profile estimates (Smith et al. 1985). The goal of this approach is to minimize the dependence of the temperature profile error on the moisture distribution. In lieu of manual editing, the VAS2 dataset was edited by an objective quality control algorithm that examined the VAS thickness fields (Velden, personal communication). First-guess fields for VAS1 and VAS2 were from NMC's global spectral 12-h forecast.

The in-situ dataset (INS), against which VAS1 and VAS2 are compared, consists of data from the following sources: ODWs, rawinsondes, surface ships, U.S. Air Force reconaissance aircraft, and the NOAA WP-3D research aircraft. These data were collected in support of HRD research efforts to analyze the Hurricane Debby environment (Lord and Franklin 1987). The ODW data were subjected to rigorous quality control procedures during postprocessing at HRD (Franklin 1987). This postprocessing included a careful examination of each sounding's thermodynamic diagram, "buddy" checks against nearby ODWs, and checks against WP-3D flight-level data and surface ship observations. Identifiable errors were either edited or deleted from the ODW dataset. The postprocessed data were then run through a low-pass filter with a half-power wavelength of 100 mb, to eliminate aliasing due to the 50 mb vertical sampling interval used in Lord and Franklin's mechanical analyses.

Rawinsonde data at the mandatory and significant levels were obtained from the National Climatic Data Center (NCDC) in Asheville, North Carolina. Linear interpolation was used to obtain values of temperature and humidity at 10 mb resolution. Plots of the 10 mb data were made, and questionable values were edited or deleted. The 10 mb data were then filtered with the same low-pass filter used for the ODW data.

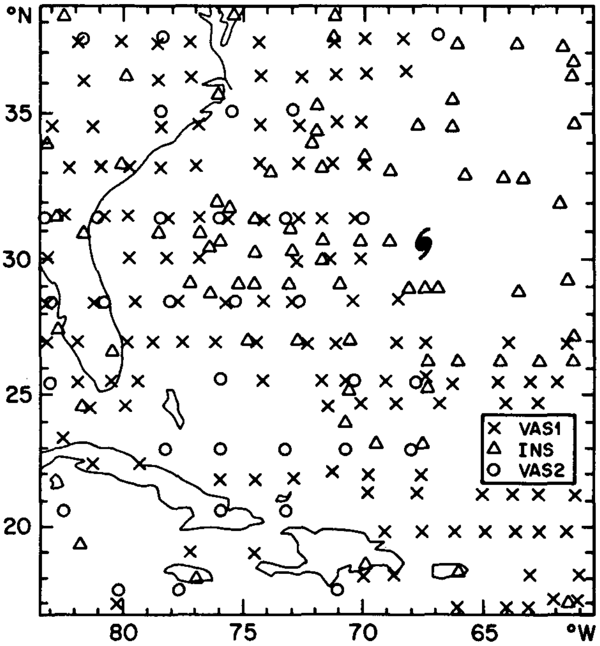

FIG. 1. Locations of observations used in the objective analyses of VAS1, INS, and VAS2 datasets. Hurricane Debby's location is represented by the hurricane symbol in this and subsequent figures.

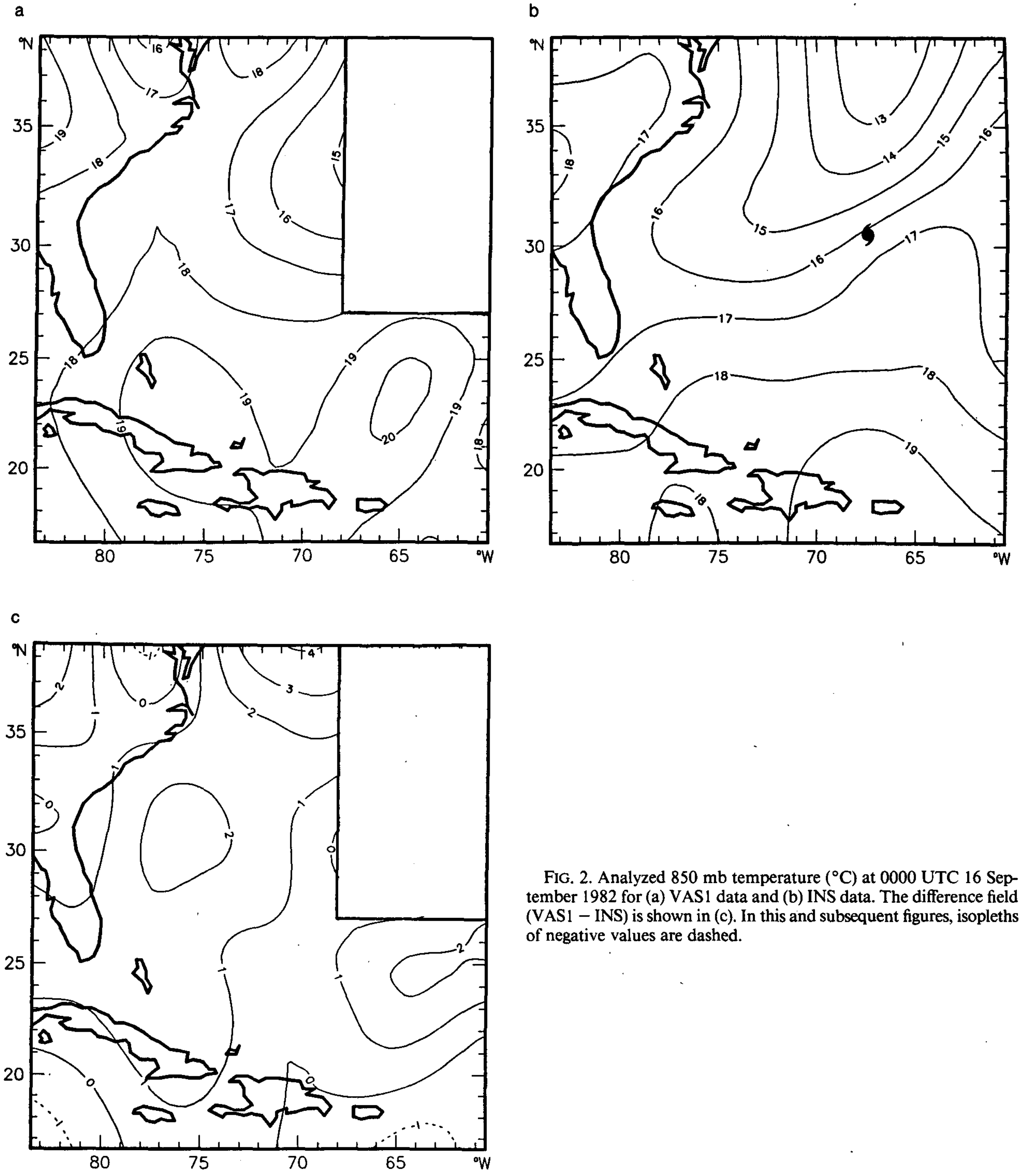

FIG. 2. Analyzed 850 mb temperature (°C) at 0000 UTC 16 September 1982 for (a) VAS1 data and (b) INS data. The difference field (VAS1 − INS) is shown in (c). In this and subsequent figures, isopleths of negative values are dashed.

The WP-3D flight-level temperature and humidity data at 1-min intervals were filtered using a one-dimensional version of the analysis scheme described in section 2b. The filter half-amplitude wavelength was 15 min, and smoothed data were picked off at 7.5-min intervals (~70 km horizontal spacing). Each data point was then assigned to the nearest 50 mb analysis level: relative humidity data were not changed, but temperatures were adjusted using a lapse rate determined from the top 50 mb of the two closest ODWs.

Marine surface observations at 0000 UTC 16 September 1982 were obtained from NCDC. These ob-

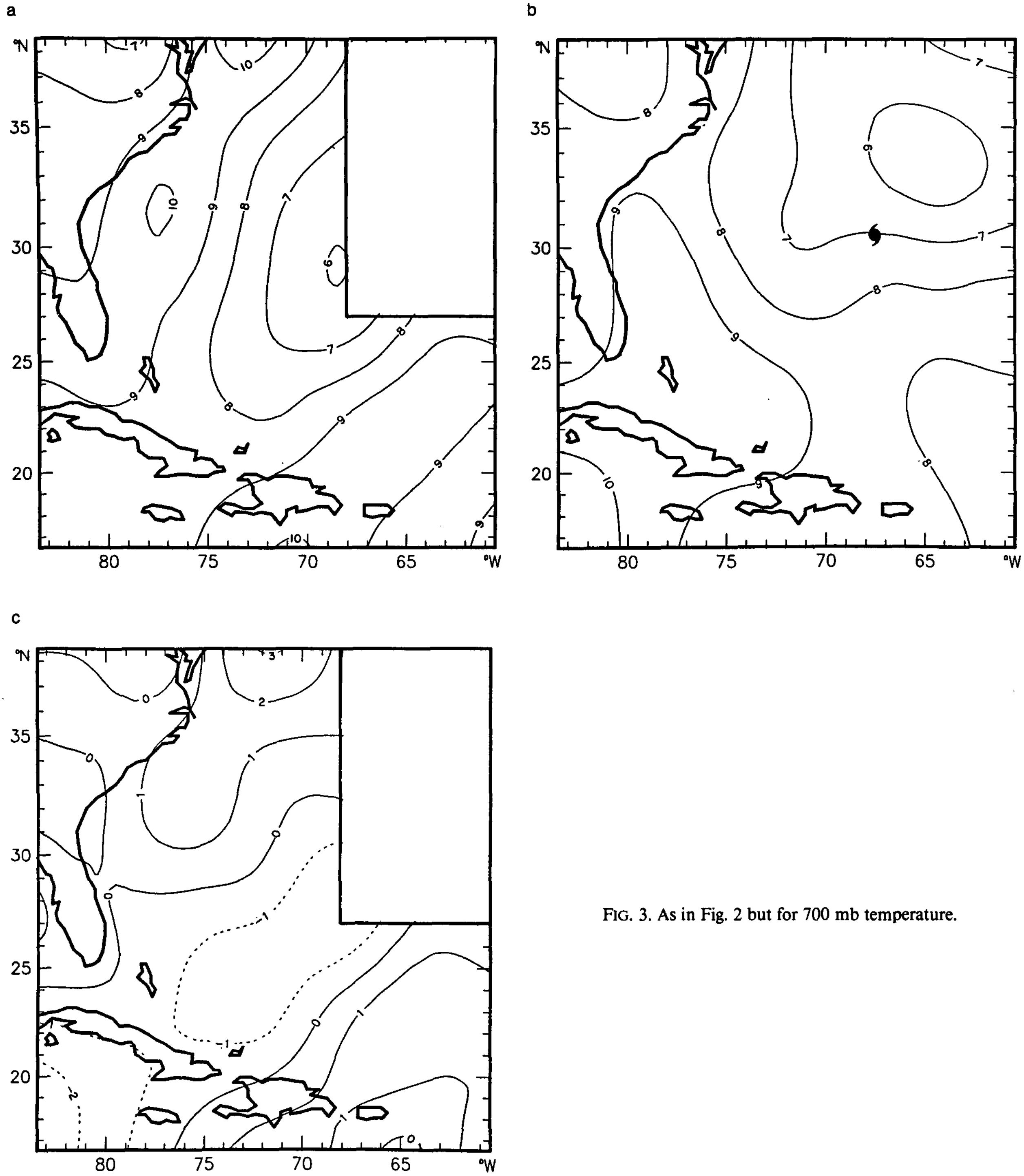

FIG. 3. As in Fig. 2 but for 700 mb temperature.

servations were plotted and examined for spurious reports, which were not used in the analysis.

U.S. Air Force reconnaissance observations (RECCOs) in the storm environment gave temperature and humidity data at levels generally close to a standard pressure surface (400, 500 or 700 mb). Temperatures were adjusted to the standard surfaces using Jordan's mean July–October lapse rate for the West Indies (1958). Humidity observations were not adjusted. In some cases, the adjusted data were inconsistent with nearby ODWs and were deleted from the INS dataset.

The data distribution for the VAS1, VAS2 and INS datasets is shown in Fig. 1. The particular distribution shown is for 400 mb, although the distribution at other levels is essentially similar. One notable exception is that the figure does not include the locations of 39 ship observations for the surface level. Another is the set of INS observations between 30°–32°N and 68°–75°W. These are Air Force RECCO's present only at 400 mb.

b. Analysis procedure

The mechanical analysis algorithm described by Lord and Franklin (1987) was used to analyze separately VAS1, VAS2 and INS data at the surface, and at the 850, 700, 500 and 400 mb levels. It employs a two-dimensional, least-squares fitting algorithm combined with a derivative constraint term, which acts as a low-pass filter on the analyzed field. This scheme allows observational noise to be removed by the filter, while information in the scales resolvable by the data is retained. Each analyzed field is represented continuously throughout the analysis domain as a bilinear combination of basis functions. These basis functions (local cubic splines) are centered at a two-dimensional array of nodal points. Since the basis functions are twice differentiable, derived meteorological quantities may be calculated directly without the finite differencing required by conventional grid point analyses. Homogeneous, analytically defined boundary conditions allow extrapolation of the analyses to the borders of a limited domain.

The temperature analyses shown below were generated with a filter cutoff wavelength of 6° latitude/longitude to produce analyses of only the large-scale features, as described by the VAS and INS data. This was the smallest filter compatible with the data distributions of the VAS1, VAS2 and INS datasets. Thus, we avoid the difficulty of interpreting comparisons of finely spaced (or analyzed) VAS data with widely separated rawinsondes. Since the ODW and aircraft data were taken over a 9 h period, all analyses employed a storm-relative coordinate system.

3. Results

a. VAS1 comparisons

Figure 2 shows the 850 mb temperature analyses for VAS1 and INS, and the difference field (VAS1 − INS). The upper right corners of the VAS1 and difference fields have been blanked out, since no VAS data were available due to cloudiness in this region. There are some similarities in the gross pattern; a cold trough between Debby and the U.S. eastern seaboard, and a warm ridge north of Puerto Rico and eastern Cuba are indicated by both VAS1 and INS. In detail, however, the analyses are sharply different. The difference field shows relative VAS1 differences >2°C off the U.S. east coast and southeast of Debby, although the latter region is not well sampled by INS. Smaller discrepancies are found southwest of the hurricane and over the continental U.S. *The spatial variability of the differences causes gradients in the difference field to be larger than the temperature gradients themselves over about one-third of the domain.* If VAS1 errors were relatively constant in space, one would expect temperature gradients in the difference field to be small compared with the actual temperature gradients.

The 700 mb VAS1, INS, and difference fields are shown in Fig. 3. There are again some gross similarities: a warm ridge along and just off the U.S. east coast, and a cool trough southwest of the hurricane. VAS1 temperature gradients, however, are stronger than INS gradients over most of the domain; in particular, the VAS1 diagnosis of a strong gradient extending from Haiti northeastward has no counterpart in INS. This region is particularly well sampled by both VAS1 and INS. Figure 3c shows that the VAS1 difference pattern is highly nonuniform spatially on scales of several hundred kilometers and that difference field gradients exceed INS gradients over more than half of the domain. Moreover, the sign of the difference at 700 mb is opposite to that at 850 mb over much of the domain.

The general pattern of differences shown in Figs. 2c and 3c may be associated with moisture. Figure 3c, in particular, bears a striking resemblance to the INS mixing ratio analysis shown in Fig. 4. Where 700 mb VAS1 temperatures are relatively warm (just off the U.S. coast, and southeast of Debby), the humidity is low, while the cooler VAS1 differences are largely coincident with a tongue of moisture that stretches

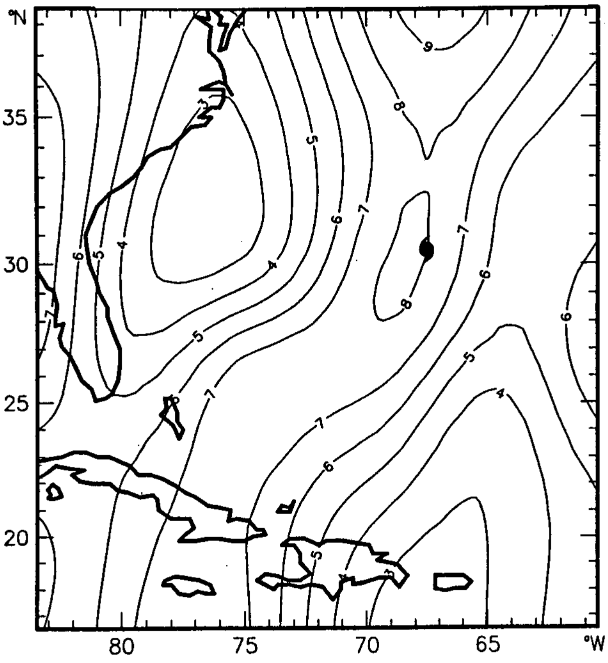

FIG. 4. Analyzed 700 mb mixing ratio (g kg^{-1}) at 0000 UTC 16 September 1982 for INS data.

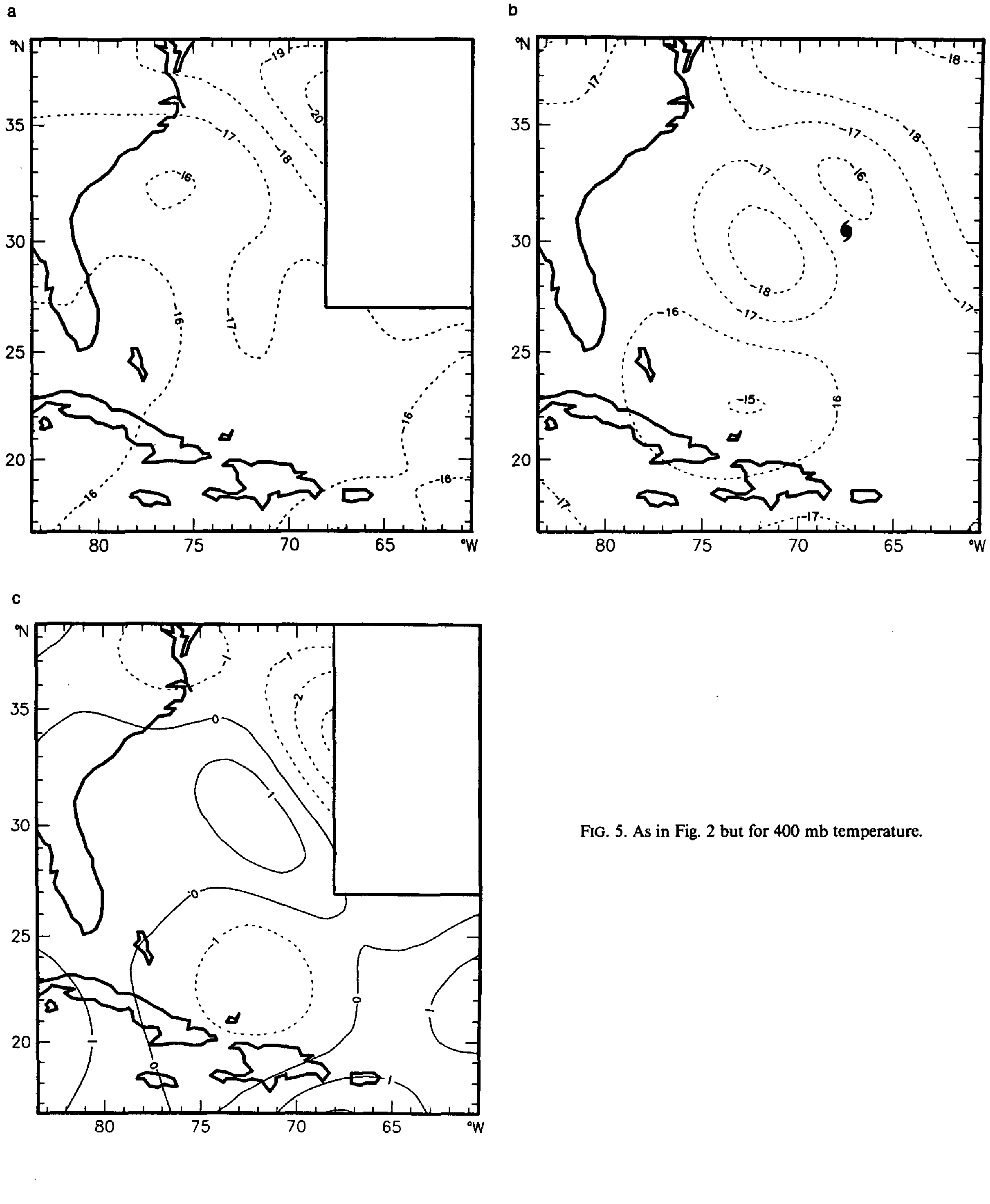

FIG. 5. As in Fig. 2 but for 400 mb temperature.

from the southwest to northeast corners of the analysis domain. At 500 and 400 mb, where the mixing ratio is low everywhere, no such relationship is observed.

Analyses for 400 mb are shown in Fig. 5. The INS analysis of the −15°C isotherm northeast of Cuba is an analysis error, due to a lack of data in this area (Fig. 1). Just west of Debby, however, the VAS1 data do not resolve a well-documented pocket of cold air; this results in significant horizontal gradient differences extending from Debby northwestward (Fig. 5c). INS analyses above and below 400 mb (not shown) indicate that the pool of cold air is probably too shallow to be

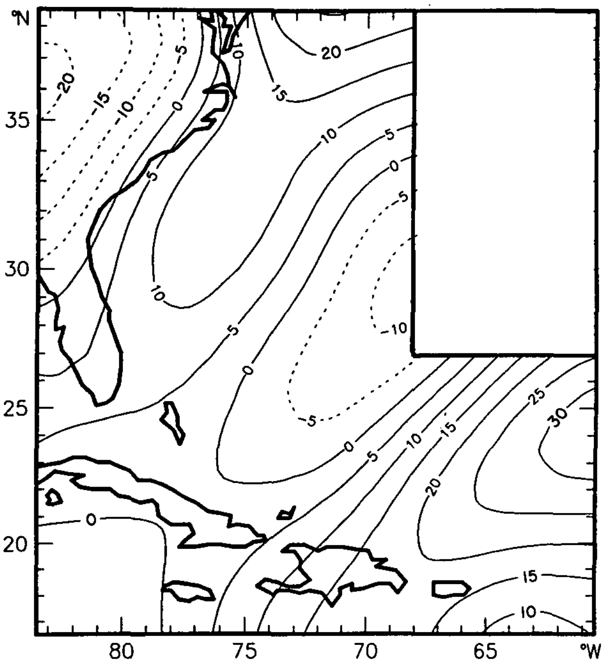

FIG. 6. Difference field (VAS1 − INS) of 400 mb geopotential height (m) at 0000 UTC 16 September 1982.

picked up by the VAS. These discrepancies illustrate a difficulty of using both VAS and in-situ data, which have different vertical resolutions, in a horizontal analysis.

The implications of these differences for midlevel VAS gradient winds can be gauged by using the VAS1 and INS temperature and moisture analyses to calculate 400 mb geopotential heights. For this study, all available surface data (ODWs, rawinsondes, and ships) were first analyzed to obtain a sea-level pressure field, to be used as the initial condition for both VAS1 and INS height integrations. Geopotential heights at 400 mb were calculated from the VAS1 and INS thermodynamic analysis values at the surface, 850, 700, 500 and 400 mb at each nodal point. *Differences between the VAS1 and INS 400 mb heights are thus due solely to the analyzed differences of the respective thermodynamic data.* Heights were calculated from thermodynamics analyzed with three filter cutoff wavelengths: 6°, 9° and 12° latitude/longitude. Of the three, the 9° height patterns are most consistent (geostrophically) with ODW and rawinsonde wind observations.

The 9° height difference field (VAS − INS) for 400 mb is shown in Fig. 6. The patterns of temperature difference shown in Figs. 2–5 are reflected in the height difference field, which has positive values off the U.S. coast and southeast of the hurricane. The height differences rarely exceed 20 m; nonetheless, the spatial variability of the differences produces significant height gradients. The height differences shown in Fig. 6 indicate that VAS1 gradient winds may significantly overestimate the strength of the large-scale trough circulation. Implied vector differences between VAS1 and INS gradient winds (not shown) are >5 m s^{-1} over about half of the domain and are >12 m s^{-1} south and southeast of the hurricane. Of particular importance is the fact that these differences are on the synoptic scale; there is no way to remove the "noise" from the "signal."

b. VAS2 comparisons

Figure 7 shows the VAS2, INS, and difference fields for surface temperature. These analyses are shown, because even though VAS surface data are not actual measurements from the VAS (they represent a first-guess field), accuracy at this level is as important to midlevel gradient wind calculations as accuracy at other levels. VAS2 surface temperatures exceed INS estimates by 3°C or more north of Hispaniola and off the Delaware coast, with negative differences over most of the eastern seaboard. Figure 8, which shows the VAS2, INS, and difference fields at 850 mb, suggests that the surface differences may have some small signature at 850 mb. South of 30°, VAS2 gives good estimates of the temperature gradients (Fig. 8c). However, VAS2 differences range from a maximum of +2°C near 30°N to slightly negative values north of 35°N. Between 30° and 35°N, the temperature gradients indicated by VAS2 are approximately normal to those of INS (Figs. 8a, b). It is not clear what is causing this discrepancy; possibly the retrieval first guess profiles may be a factor here (first-guess profiles were not part of the dataset provided by SSEC). Despite this, the VAS2 850 mb analysis represents a significant improvement over VAS1, which can be seen by comparing Figs. 2c and 8c.

At 700 mb, VAS2 estimates exceed INS estimates by about 1°C over most of the domain (Fig. 9). Due to the spatial homogeneity of this difference, however, VAS2 gradient estimates at this level represent a significant improvement over VAS1 (compare Fig. 3c). There is no longer any discernable correlation of the difference field with moisture. At 500 mb (Fig. 10), VAS2 temperatures agree with INS generally to within 1°C; although the sign of the difference at 500 mb is generally negative, while at lower levels it is largely positive. Gradient information is in good agreement where there is adequate data coverage. The −2°C difference contour near the hurricane is due to the analysis boundary condition and does not reflect any bad retrievals.

The 400 mb VAS2, INS, and difference fields are shown in Fig. 11. Like VAS1, VAS2 does not pick up the shallow cold pool west of Debby. Once again, the −15°C contour north of eastern Cuba in Fig. 11b is due to a lack of INS data. Excessively cold VAS2 temperatures over Haiti are probably due to cloud contamination associated with scattered convection in this

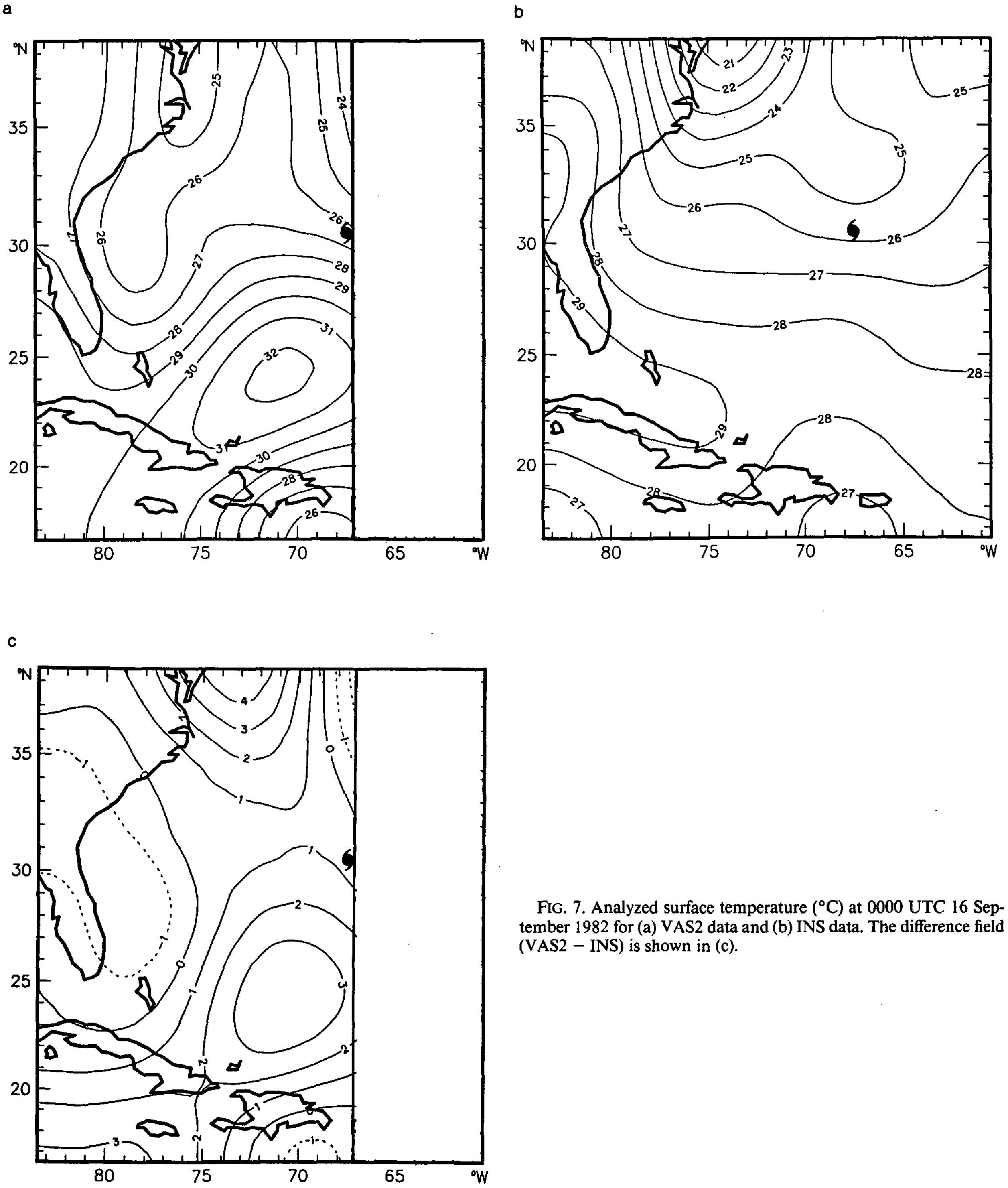

FIG. 7. Analyzed surface temperature (°C) at 0000 UTC 16 September 1982 for (a) VAS2 data and (b) INS data. The difference field (VAS2 − INS) is shown in (c).

area. Manual editing might have identified the two affected retrievals. The difference field (Fig. 11c) suggests that there is little real information in the VAS2 gradients at this level, even after the −2° contour east of Cuba is discounted as an analysis error.

VAS2–INS geopotential height differences were computed in the same manner as for VAS1. The 400 mb VAS2 − INS geopotential height difference field shows generally small (<20 m) differences (Fig. 12a). Despite the small differences, a large anticyclonic cir-

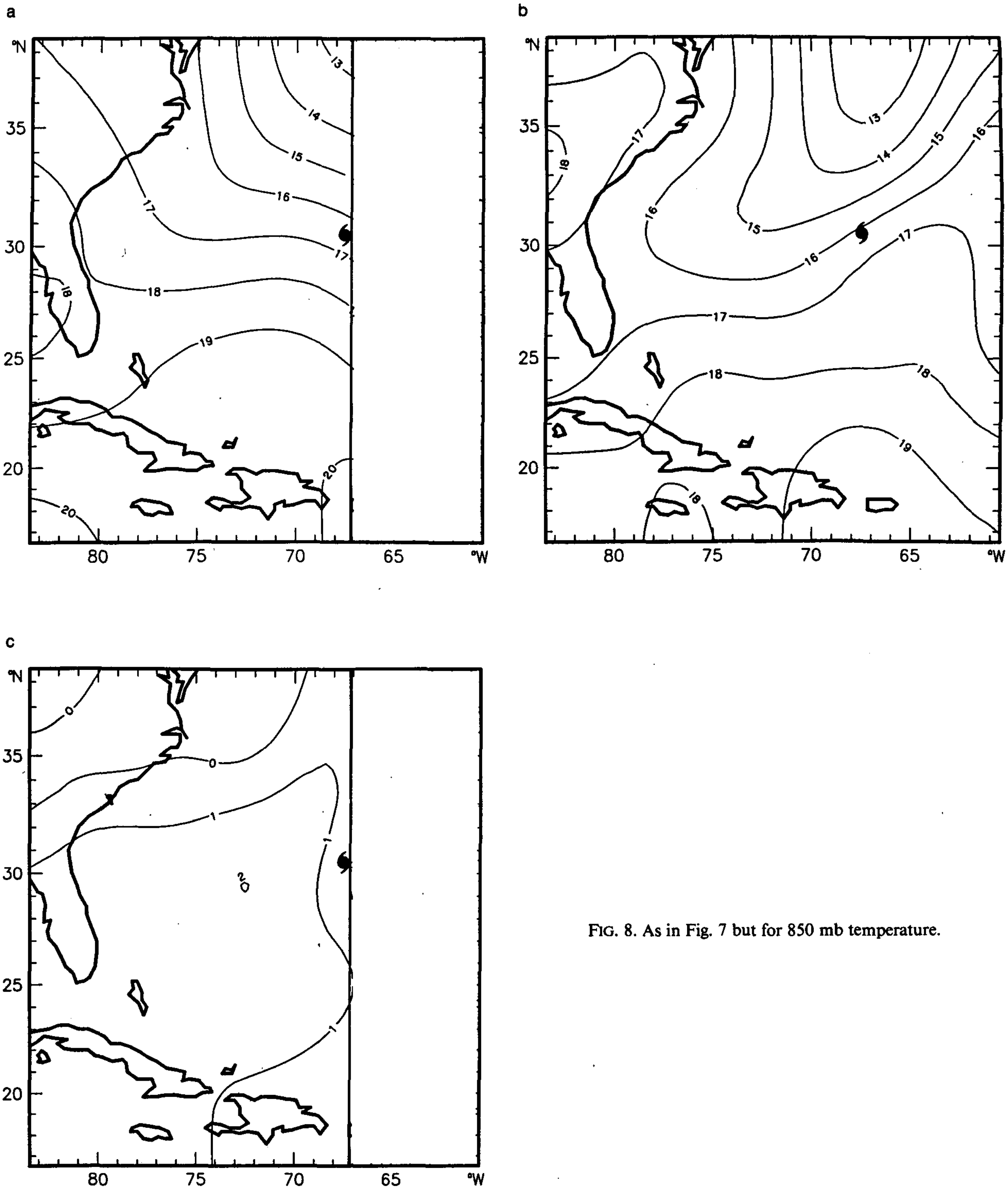

FIG. 8. As in Fig. 7 but for 850 mb temperature.

culation is indicated about the warm anomaly east of Florida. Implied gradient wind differences (VAS2 − INS) are shown in Fig. 12b, with the greatest differences of about 6 m s^{-1} just southwest of the hurricane and east of Cuba. The portion of the domain with gradient wind differences >5 m s^{-1} is about 10%, down from 50% for VAS1. The 850 mb height difference field (not shown) has a similar pattern to that of Fig. 12a. This suggests that additional improvements could be expected if a better surface temperature analysis had

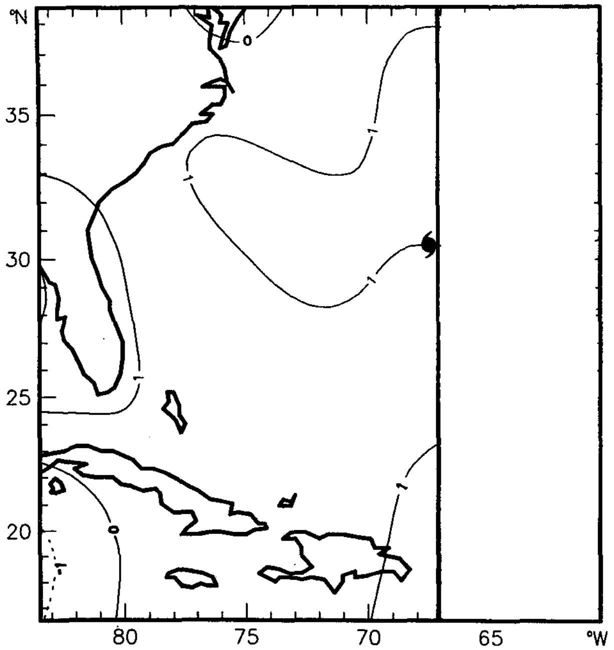

FIG. 9. Difference field (VAS2 − INS) of 700 mb temperature (°C) at 0000 UTC 16 September 1982.

been used to anchor the retrievals. It also indicates that the 850–400 mb *thermal* wind would be a useful product in this case.

Note that the difference field shown in Fig. 12b reflects only inconsistencies between the VAS retrievals and the in situ measurements. Substantial errors in gradient winds can also be introduced through the surface pressure analysis. The difference between the 6 m s^{-1} northeasterly apparent bias of the VAS1 gradient wind near 32°N, 72°W implied by Fig. 6, and the 5.0–7.5 m s^{-1} *southerly* VAS difference in the same location noted by Lord and Franklin (1987, see their Fig. 15a), is due to the use of different surface pressure fields.

4. Summary and discussion

This note compares two VAS retrieval temperature fields (VAS1, VAS2) with in-situ (INS) temperature data on the synoptic scale in the environment of Hurricane Debby (1982). The data density of the VAS2 sounding set precluded an examination of the mesoscale information content of VAS2. VAS1 data were derived from an iterative solution of the radiative transfer equation with manual quality control. VAS2 data were derived from a simultaneous solution and objective quality control. INS data were obtained primarily from ODWs.

Comparison of VAS1 and INS temperature analyses show clearly defined large-scale (several hundred kilometers) patterns in the difference fields at 850 and 700 mb. These patterns appear to be highly correlated with moisture. Temperature gradients in the difference fields are as large as, or larger than, the gradients indicated by INS about half the time. Geopotential heights at 400 mb were computed for both VAS1 and INS. Although differences in computed height between the two analyses are rarely >20 m, the spatial variability of the difference fields results in implied gradient wind differences of >5 m s^{-1} over half of the domain. The largest wind differences are 12 m s^{-1} and are aligned over the region of sharpest moisture gradient.

The VAS2 data compare much more favorably with INS. The correlation of VAS2 temperature differences with humidity is negligible. This is a particularly important result for the problem of tropical analysis. Nearly constant difference fields of 1.0°C or less at 700 and 500 mb indicate that the horizontal temperature gradients are being well estimated by VAS2 at these levels. However, in the northern part of the domain at 850 mb and over nearly the entire domain at 400 mb and the surface, analyzed VAS2 temperature gradients are quite different from those determined by INS data. Thus VAS2 and INS gradient estimates differ substantially over about 50% of the total area analyzed in this case study. The largest discrepancies at 400 mb are probably related to contamination by cloud and the poor vertical resolution of the VAS. Comparisons of the 400 mb geopotential heights show a large (1000 km) anticyclonic difference circulation of up to 6 m s^{-1} between Debby and the U.S. East Coast. Most of the 400 mb height differences are due to differences at and below 850 mb, which illustrates the importance of an accurate surface analysis to anchor the retrievals.

It is encouraging that the newer techniques used to

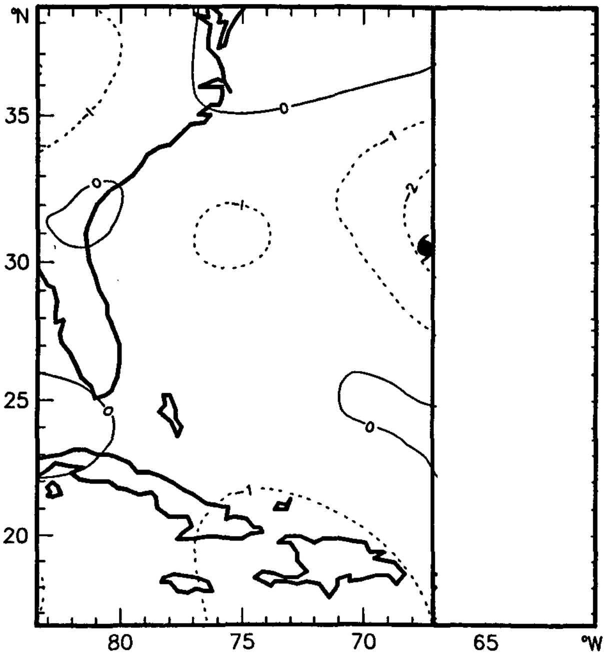

FIG. 10. As in Fig. 9 but for 500 mb temperature (°C).

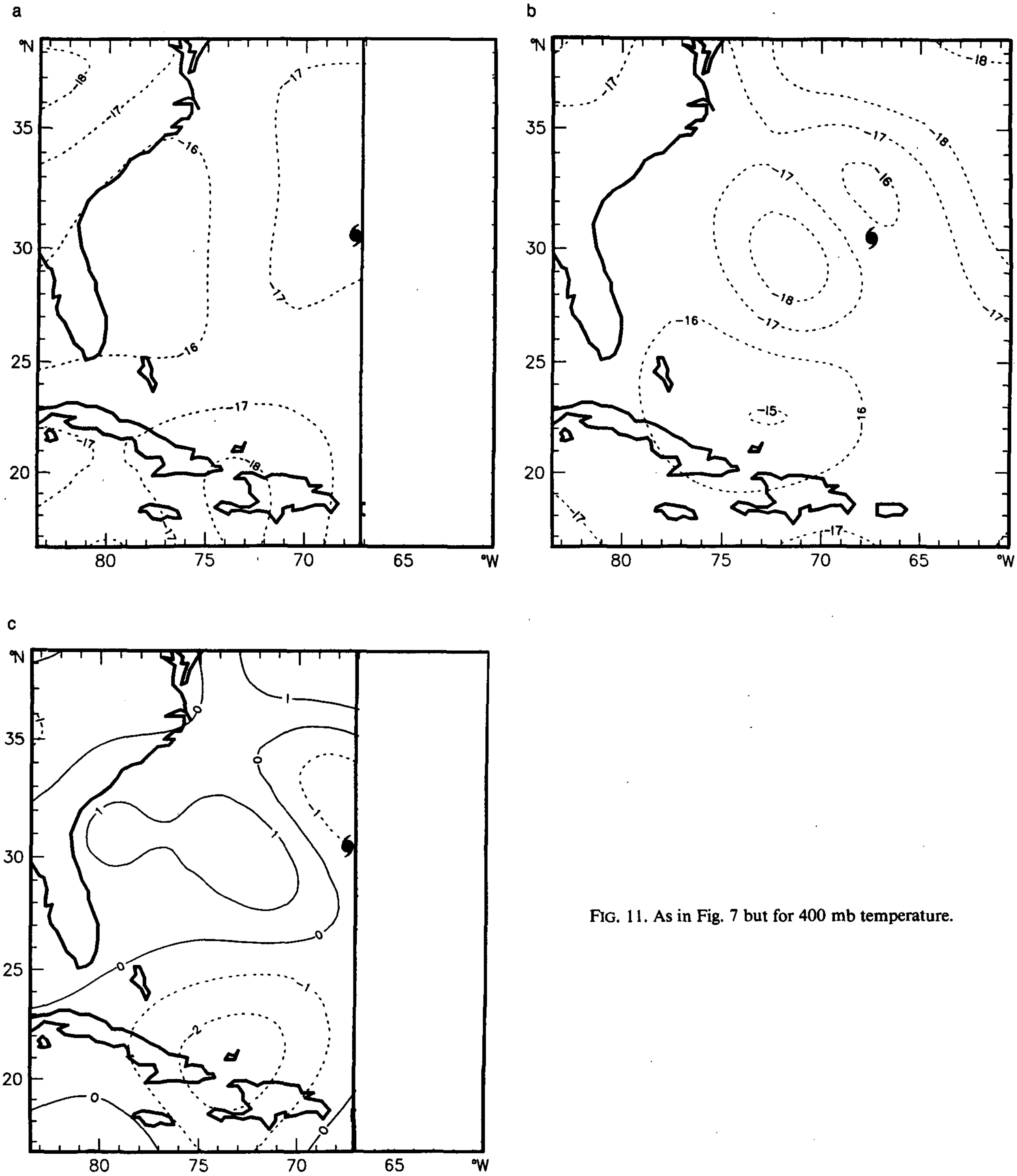

FIG. 11. As in Fig. 7 but for 400 mb temperature.

generate the VAS2 soundings have produced significantly better comparisons with the INS data. Studies at the National Hurricane Center suggest that a return to manual quality control procedures could result in additional improvements (Gerrish, personal communication). Despite the improvement associated with the simultaneous retrieval algorithm, VAS2 gradient information still is of irregular quality in this case study. This is an item of some concern, particularly as VAS-derived quantities begin to be used in hurricane forecasting applications. Those factors contributing to spurious large-scale circulations must be examined

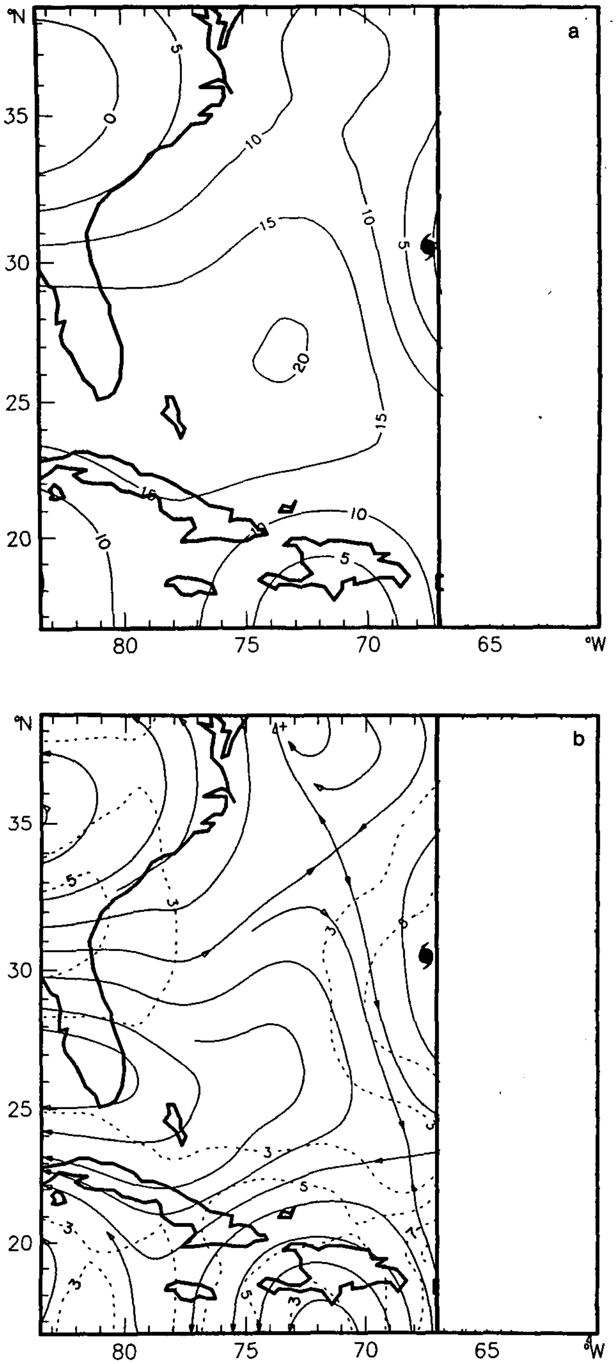

FIG. 12. Analyzed 400 mb difference fields (VAS2 − INS) at 0000 UTC 16 September 1982 for (a) geopotential height (m) and (b) gradient wind (m s^{-1}). In (b), streamlines are solid lines and isotachs are dashed.

further as opportunities arise. One such opportunity has already arisen. On 23–26 September 1987, three experiments involving ODWs were conducted for Hurricane Emily, as it moved from the western Bahamas northeastward past Bermuda. These ODW missions were coordinated with SSEC, and should produce valuable additional datasets for VAS/INS comparisons.

Acknowledgments. The authors thank Dr. Christopher Hayden (NOAA/NESDIS) and Mr. Chris Velden (SSEC) for the VAS data, as well as for many valuable consultations during the course of this work.

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