NOAA Technical Memorandum ERL AOML-65

REDUCTION OF ERRORS IN OMEGA DROPWINDSONDE DATA THROUGH POSTPROCESSING

James L. Franklin

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida
March 1987

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

NOAA Technical Memorandum ERL AOML-65

REDUCTION OF ERRORS IN OMEGA DROPWINDSONDE DATA THROUGH POSTPROCESSING

James L. Franklin

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida
March 1987

UNITED STATES DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Anthony J. Calio, Administrator

Environmental Research Laboratories
Vernon E. Derr, Director

NOTICE

CONTENTS

REDUCTION OF ERRORS IN OMEGA DROPWINDSONDE DATA THROUGH POSTPROCESSING

James L. Franklin

ABSTRACT. The postprocessing of Omega dropwindsonde (ODW) data at the NOAA Hurricane Research Division (HRD) is described. The errors common to ODW data are illustrated with examples, and the improvements to ODW data accuracy through postprocessing are estimated.

1. INTRODUCTION

Omega dropwindsondes (ODW's) are instruments released from aircraft to obtain vertical profiles of pressure, temperature, humidity, and wind over otherwise data-sparse oceanic regions. ODW's have been used in recent years in the Genesis of Atlantic Lows Experiment (GALE), by meteorologists studying the El Niño phenomenon, and by the Hurricane Research Division of the Atlantic Oceanographic and Meteorological Laboratory in its studies of the environmental flow of Atlantic hurricanes. These studies and others are using ODW's in hopes of computing diagnostic quantities that require precise wind and/or thermodynamic measurements (e.g., Lord and Franklin, 1987). To produce high-quality ODW data sets for such research, HRD has implemented a package of data processing and quality-control algorithms for the postprocessing of real-time ODW data.

The ODW data systems on the NOAA Office of Aircraft Operations (OAO) WP-3D research aircraft produce data hardcopy printouts in real-time as ODW's fall to the surface. Included are measurements of pressure, temperature, and relative humidity at 10-s (~5-mb) intervals, and winds computed at 30-s intervals from Omega navigational signals relayed from the ODW (Passi, 1974). Real-time ODW data can be used operationally; the HRD synoptic flow experiments provide ODW data to the National Hurricane Center (NHC) and National Meteorological Center (NMC) for use in numerical hurricane forecast models (Burpee et al., 1984).

The accuracy of ODW data can be greatly improved through various postprocessing techniques. In a technical memorandum by Franklin (1983), HRD postprocessing of ODW data was outlined; however, since that time, new processing algorithms have been implemented and many older ones revised. This revision of the memorandum describes the current postprocessing procedures at HRD and provides several examples of how errors in real-time ODW data are eliminated or reduced.

2. ODW POSTPROCESSING PROCEDURES

In addition to the hardcopy printouts ("slave printouts") produced in real time, the airborne ODW system also records raw ODW data digitally on magnetic cassette tapes. The raw data recorded include pressure, temperature, and humidity at 1-s (rather than 10-s) resolution, and the Omega navigational signals at 10-s resolution. The winds computed and displayed in the slave printouts are not stored on the cassette tapes. The cassette tapes are converted to 9-track magnetic tape at NOAA-OAO. All subsequent processing is done on HRD's Hewlett-Packard A-900 (HP A-900) computer and assorted graphics peripheral devices.

The 9-track magnetic tape is read and a disk data file for each ODW is created on the HP A-900. The 1-s thermodynamic (pressure, temperature, and relative humidity; henceforth "PTH") data initially are in a raw form (Hz) and must be converted into meteorological units through calibration and baselining constants stored for each ODW. After these conversions are done, plots are made of the 1-s PTH data (Fig. 1) and the 10-s Omega data (Fig. 2).

PTH Data are compared with flight-level data from the NOAA WP-3D aircraft, any available surface and upper air analyses, and other ODW'S to help identify any gross errors. Many types of errors have distinct "signatures" that can be identified from the 1-s plotted data; they are discussed in section 3. The desired subjective corrections (edits) to the PTH and Omega data are drawn on the plots, which are then placed on a digitizing tablet (a Summagraphics Bit Pad Two). An interactive editing program allows the ODW data file to be corrected by tracing over the desired edits on the tablet. The precision of the digitizing tablet for this purpose depends not only on the resolution of the tablet, but also on the steadiness of the hand of the human editor. Experience suggests that edits on the tablet have a precision of 1.5 mb, 0.25°C, and 1% for PTH data. ODW sensors have an advertised accuracy of 2 mb, 0.5°C, and 5% (Govind, 1975).

After the desired edits have been made, a marker is placed in the ODW data file at the point where the ODW splashed down. This point is easily determined from the 1-s PTH plot. The PTH data are then run through a low-pass Fourier filter. Generally, the half-power wavelength cutoff of this filter is 20 s (to be compatible with the 10-s [~5 mb] sampling interval of the final data set). If the data are particularly noisy, a longer filter is used (generally 40 s). Any PTH data judged unreliable are deleted from the ODW data file and replaced by a "missing data" code.

Geopotential heights (which are not part of the slave printouts) are then computed. This computation may be done in one of two ways. If reliable flight-level pressure and geopotential altitude data are available, the hydrostatic equation is integrated from flight-level to the surface. This produces a hydrostatic estimate of the surface pressure, which can be a more reliable estimate than the splash pressure measured by the ODW (section 3.1.3). In this case, the ODW pressure profile is adjusted to agree with both the flight-level pressure at launch, and the hydrostatic surface estimate at splashdown. Geopotential heights are then recalculated with the adjusted pressure data. If reliable flight-level data are unavailable, the surface pressure for the ODW is estimated from a carefully prepared surface analysis (taking into account the ODW splash pressures); the height integration in this case begins at the surface.

Since the wind data computed in real-time are not recorded, winds in the postprocessed data set must be recomputed from the recorded Omega navigation signals. Flight-level navigation (ground speed and track) data are used to remove the aircraft component of motion from the Omega signals. Removal of this component reduces the effect of aircraft accelerations (turns) on wind accuracy (Franklin et al., 1987). Omega signals from each of the eight Omega transmitters are examined and three or more are chosen for the wind

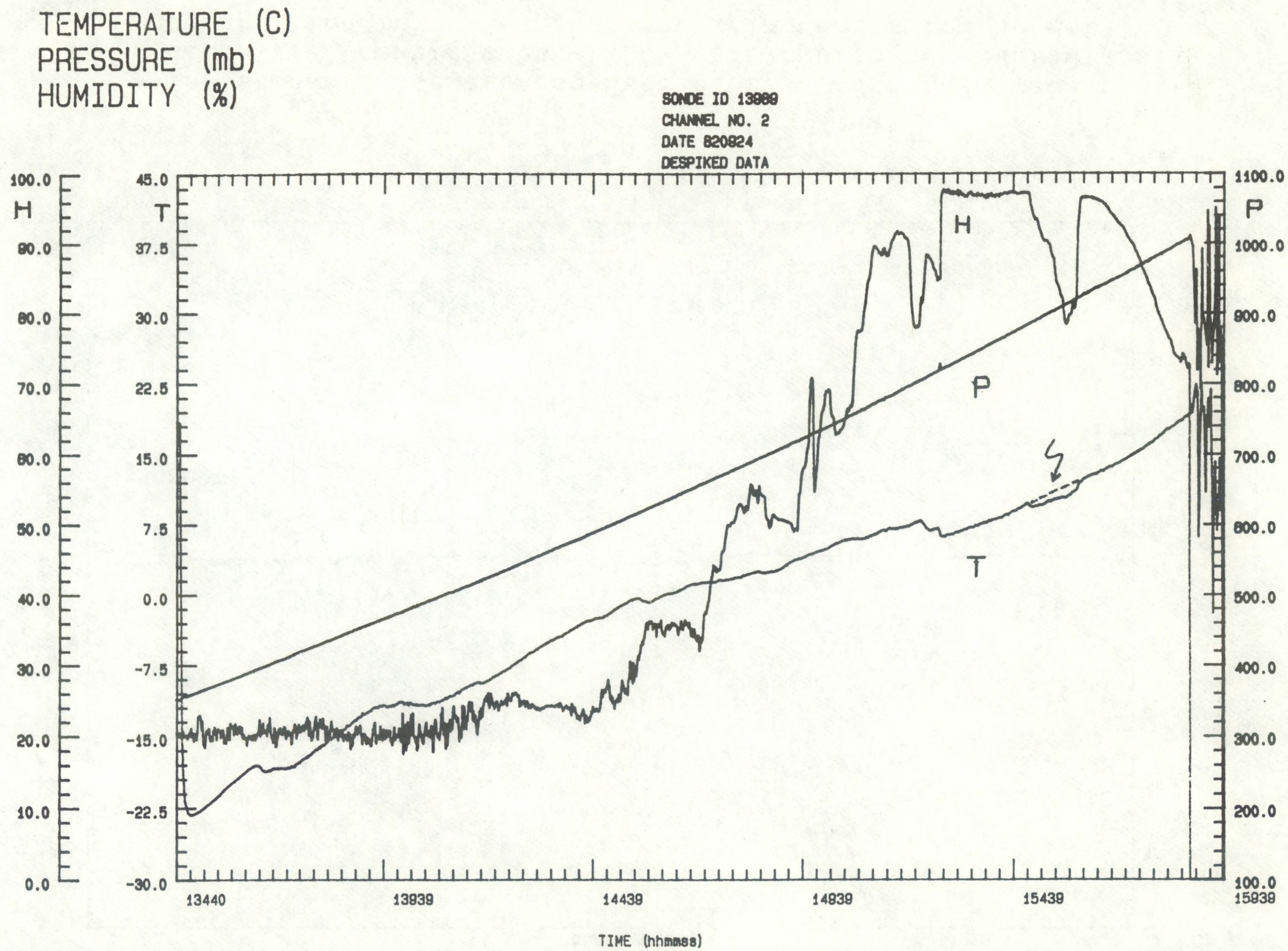

Fig. 1 The standard plot of 1-s resolution PTH data for postprocessing. An example of thermistor wet-bulbing (section 3.1.4) is indicated by the arrow. The dashed line indicates how this error would be edited.

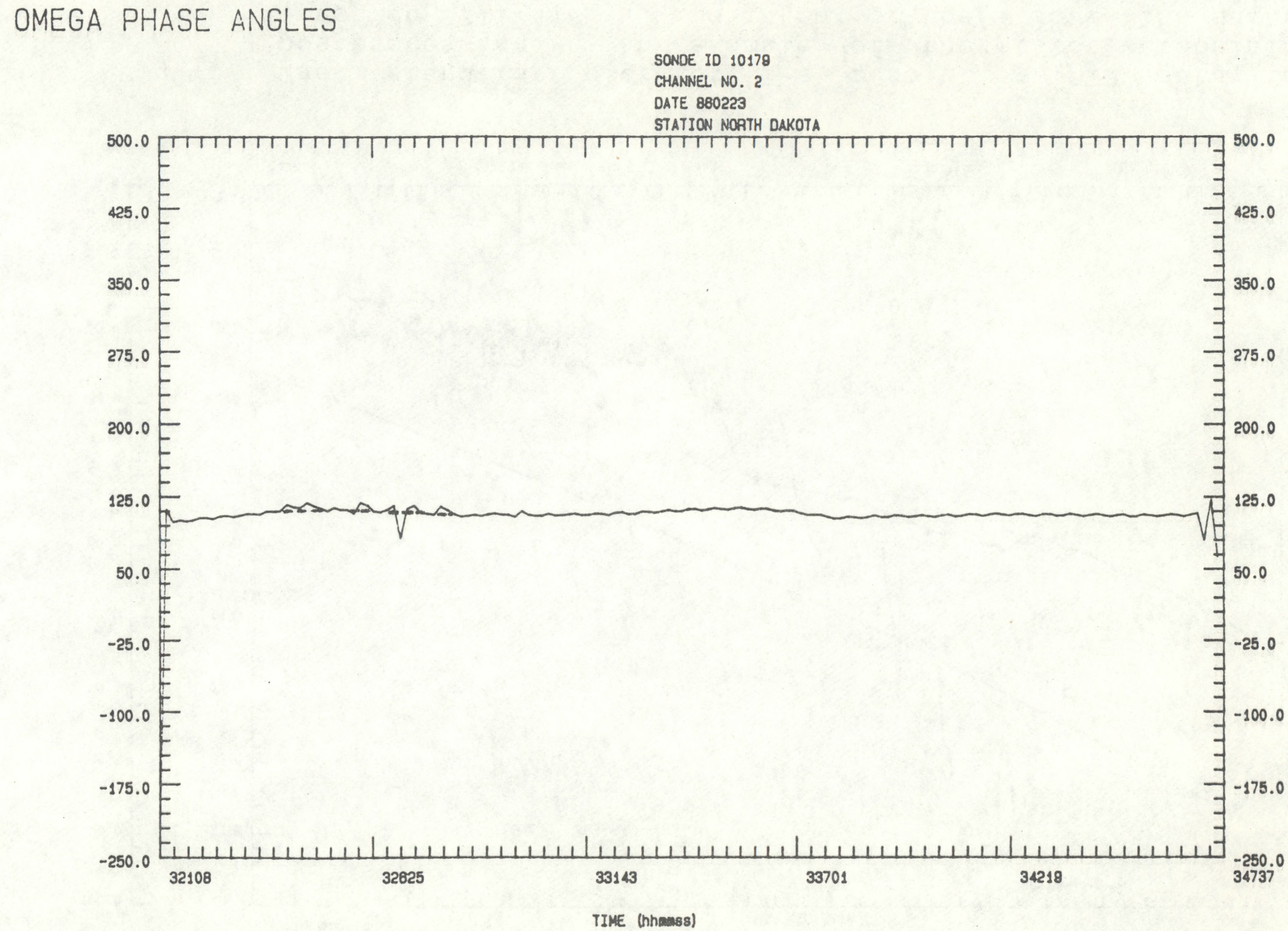

Fig. 2 The standard Omega phase data plot. Units for Omega phase data are centicycles (100 centicycles = 2π radians). Dashed line indicates postprocessing edits to the data.

computation. The stations chosen may or may not be the same as those used in real time. Objective smoothing of the Omega data before the windfinding equations are solved is done with a sophisticated scale-controlled cubic-spline smoothing algorithm (section 3.2.3).

After the wind profile has been obtained, a thermodynamic (skew-T log-P or pseudo-adiabatic) diagram for the ODW is plotted and checked to verify that the data are reasonable. Data for all ODW's from the experiment are plotted and synoptic analyses are performed to help identify remaining data problems. After this final check, the postprocessed ODW data are written to 9-track magnetic tape for distribution.

Many aspects of the postprocessing are subjective. However, subjective changes to ODW data are made only when the data are clearly in error and a likely cause can be identified. Questionable situations are generally left for interpretation by the user. Users are provided with documentation of the subjective edits to the data. Questionable data that have not been edited are also documented for the user.

3. COMMON PROBLEMS IN REAL-TIME ODW DATA

3.1 Thermodynamic Data

3.1.1 Equilibration of sensors

Comparisons of aircraft flight-level data with ODW data just after launch show that a short time period is needed for the ODW thermistor and carbon hygristor to reach ambient conditions. Although the thermistor equilibrates in just a few seconds, humidity estimates for about the first 30 s of fall (~20 mb) may be in error. Initial humidity data are generally edited with a subjective interpolation from flight-level values.

3.1.2 Baselining/calibration errors

Shortly before an ODW is launched, it is placed in a test chamber and ODW output is compared with the known chamber conditions. Offsets determined during this baselining procedure are used for a final calibration of the instrument. After baselining, however, roughly 5-10% of the ODW's still have a noticeable offset. Offsets in pressure are overwhelmingly the most common and are sometimes as large as 20 mb. Offsets are determined by comparisons of ODW data just after launch and before splash with flight-level data and surface synoptic analyses. Offsets in temperature data, which are nearly always <2°C, are most easily detected when geopotential heights are computed. Once identified, offsets are easily corrected for the postprocessed data set.

There have been cases where the manufacturer-supplied calibration constants for an ODW were deleted by the on-board ODW computer, producing spurious PTH data in the real-time slave printouts. Since the calibration conversions are redone as part of the postprocessing, real-time PTH data lost for this reason can be completely recovered in postprocessing.

3.1.3 Errors in ODW surface pressures

Whenever possible, ODW splash pressures are compared with surface synoptic analyses. These comparisons show that significant errors in ODW splash pressures occur frequently. Julian (1982) found a bias in ODW surface pressure estimates of -7 mb in a sample of 60 drops. An HRD investigation of Global Atmospheric Research Program Alpine Experiment (ALPEX) ODW's showed that 8% had surface pressure errors of 4 mb or more. A comparison of ODW's dropped by HRD during its synoptic flow experiments for Hurricane Debby (Burpee et al., 1984) with NHC analyses gave an rms difference of 6.5 mb. In all these cases, ODW pressures were in agreement with flight-level values at launch. If the nature of this error is a linear drift of pressure with time, computed geopotential height errors at 850 mb would be ~30 m, and at 1,000 mb would be ~50 m.

Hydrostatically computed surface pressures, using the ODW thermodynamic data and flight-level data, can give more reliable estimates of surface pressure than the ODW pressure aneroid. Data from one HRD flight in Debby showed a 60% reduction in rms pressure differences from NHC analyses when hydrostatic estimates replaced raw ODW splash pressures. This method of estimating surface pressure depends critically upon the accuracy of the aircraft's radar altimeter and static pressure instruments and, in fact, a problem with the static pressure instrumentation on the NOAA WP-3D aircraft was uncovered as a result of some of the pressure comparisons discussed above.

The accuracy of raw ODW pressure measurements, in particular the surface estimates, is probably not better than ~5 mb rms. In postprocessed data, for which hydrostatic calculations from flight level are made, pressures are probably good to within 2 mb rms.

3.1.4 Errors caused by moisture

Moisture on the ODW thermistor/hygristor assembly can severely compromise the accuracy of the thermodynamic data. The worst of these problems occurs when water droplets produce a short circuit in the thermistor, the effect of which can be seen in Fig. 3. In this case, temperature errors of up to 8°C develop in the two lower cloud layers. Many times the errors are not as obvious and may not be noticed in real time. There is no way to recover the missing data; if the vertical extent of the problem is small (<100 mb), linear interpolation is used for the postprocessed data. It is not known how much cloud or rain water around the sonde typically triggers this problem; however, a recent redesign of the thermistor/hygristor assembly should prevent or greatly reduce this problem in the future.

Another water-related problem can occur when an ODW falls out of cloud, and water on or near the thermistor evaporates into the drier air below. In this case the temperature measurement would be suppressed, falling between the true air temperature and the wet-bulb temperature. An example of this occurrence is shown in Fig. 1. When the evaporation stops, the temperature reported by the ODW jumps up quickly to the true air temperature. The indicated jump in temperature is usually highly superadiabatic. Linear interpolation is used to correct errors of this kind. Figure 4 shows skew-T log-P diagrams for an ODW before and after an episode of "wet-bulbing" was corrected.

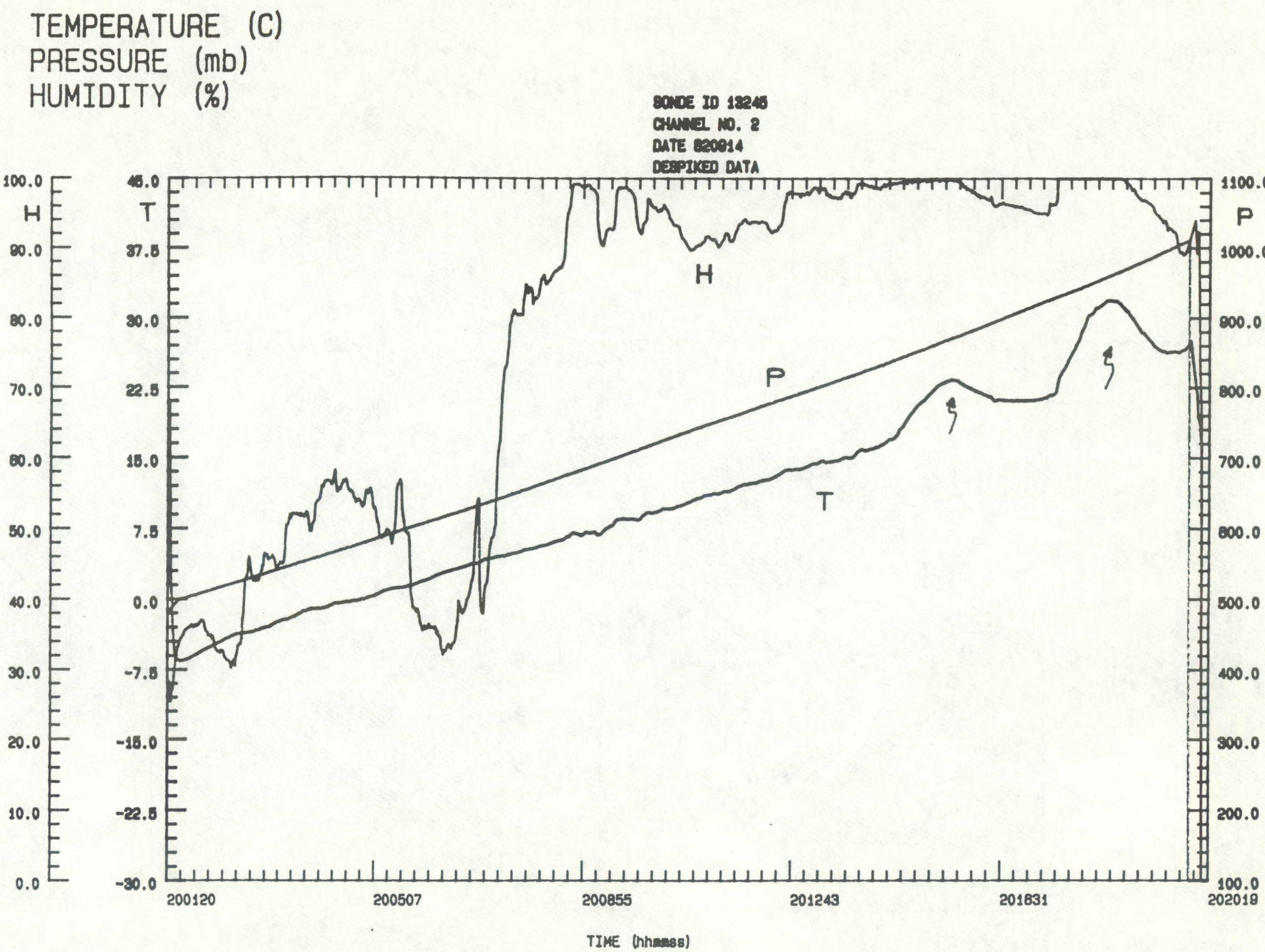

Fig. 3 Plot of unprocessed PTH data for Debby ODW #13245. Arrows indicate temperature "runaway" due to water droplets causing a short circuit in the ODW's thermistor.

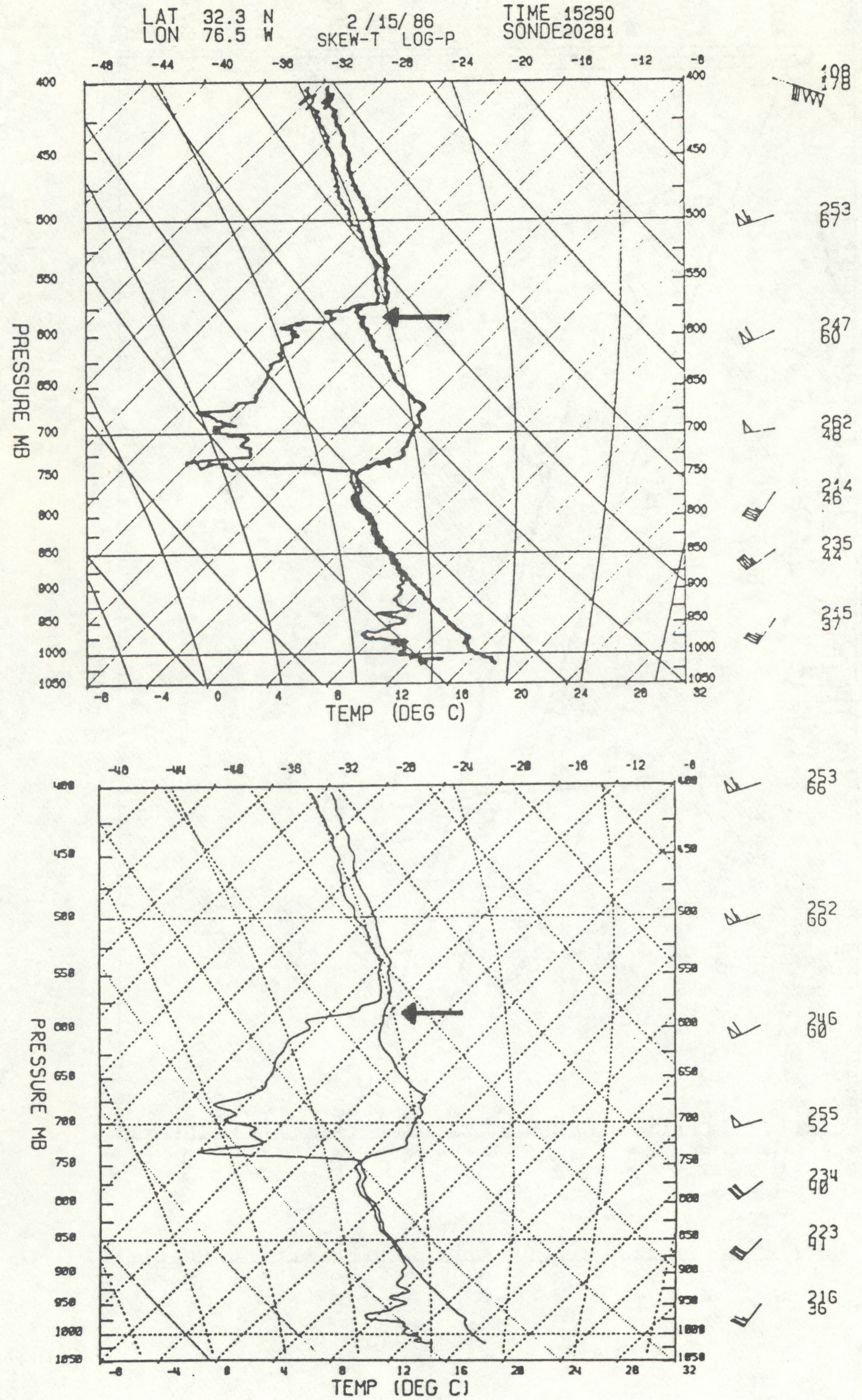

Fig. 4 Skew-T log-P thermodynamic diagrams for GALE ODW #20281 for unprocessed (real-time) data (top), and postprocessed data (bottom). Arrows indicate region of wet-bulbing. Winds at selected levels are plotted to the right of the diagram. Numbers to the right of the plotted wind barbs indicate direction (degrees) and speed (knots).

Water on or near the thermodynamic sensors may also cause errors in humidity measurements in or below saturated or rainy layers. The extent of this problem has not been carefully examined, however. Subjective humidity edits are often made if thermistor wet-bulbing appears to be occurring while the hygristor reports saturation. Proposed redesigns of the carbon hygristor call for the sensor to be heated to keep water from condensing on the element.

3.1.5 Noise and interference

Interference and noise can be a major problem in ODW data. There are many sources: multipath interference from the same ODW, interference from other ODW's or other sounding devices of the same frequency, interference from nearby machinery, or static discharges from the aircraft, itself, can cause multiple spikes or data dropouts. An example is shown in Fig. 5. These data can be extremely difficult to sort out from the real-time slave printouts, but by making plots of the 1-s raw data, one can often identify points that can provide the basis for reasonable interpolations.

3.2 Wind Data

Measurements of the signal phase from the eight worldwide Omega transmitters are made every 10 s, and from three or more of these signals the motion of the ODW (the wind) can be computed. Wind estimates every 30 s are computed in real-time and displayed as part of the slave printouts. Recomputing the winds from the Omega data as part of the postprocessing has significant advantages, however, for reasons outlined below.

3.2.1 Use of additional Omega stations

The ODW system on the NOAA WP-3D aircraft uses Omega signals from a maximum of four stations at a time. The windfinding programs that are part of the HRD postprocessing, however, can use as many as seven. The improvement associated with the addition of a fifth station will vary depending upon signal quality and geometry, but may typically be ~15% (Franklin and Julian, 1985). There are times, of course, when only three or four Omega signals are usable.

3.2.2 Editing noisy Omega data

Significant improvements in wind accuracy can be obtained by subjective editing of noise spikes in the Omega data. The amount of improvement will vary widely, depending upon the amount of noise in the Omega data. Figure 2 shows an Omega signal with a moderate amount of editing indicated. Similar edits of the other Omega signals for this ODW produced the changes in computed wind shown in Fig. 6. Differences between the two wind soundings (edited versus raw Omega) are seen to reach a peak of 8 m s^{-1} near 500 mb and 4 m s^{-1} near 900 mb. Tests with stationary ODW's (Franklin and Julian, 1985) show sounding-mean improvements in wind accuracy of ~20% as a result of moderate amounts of editing.

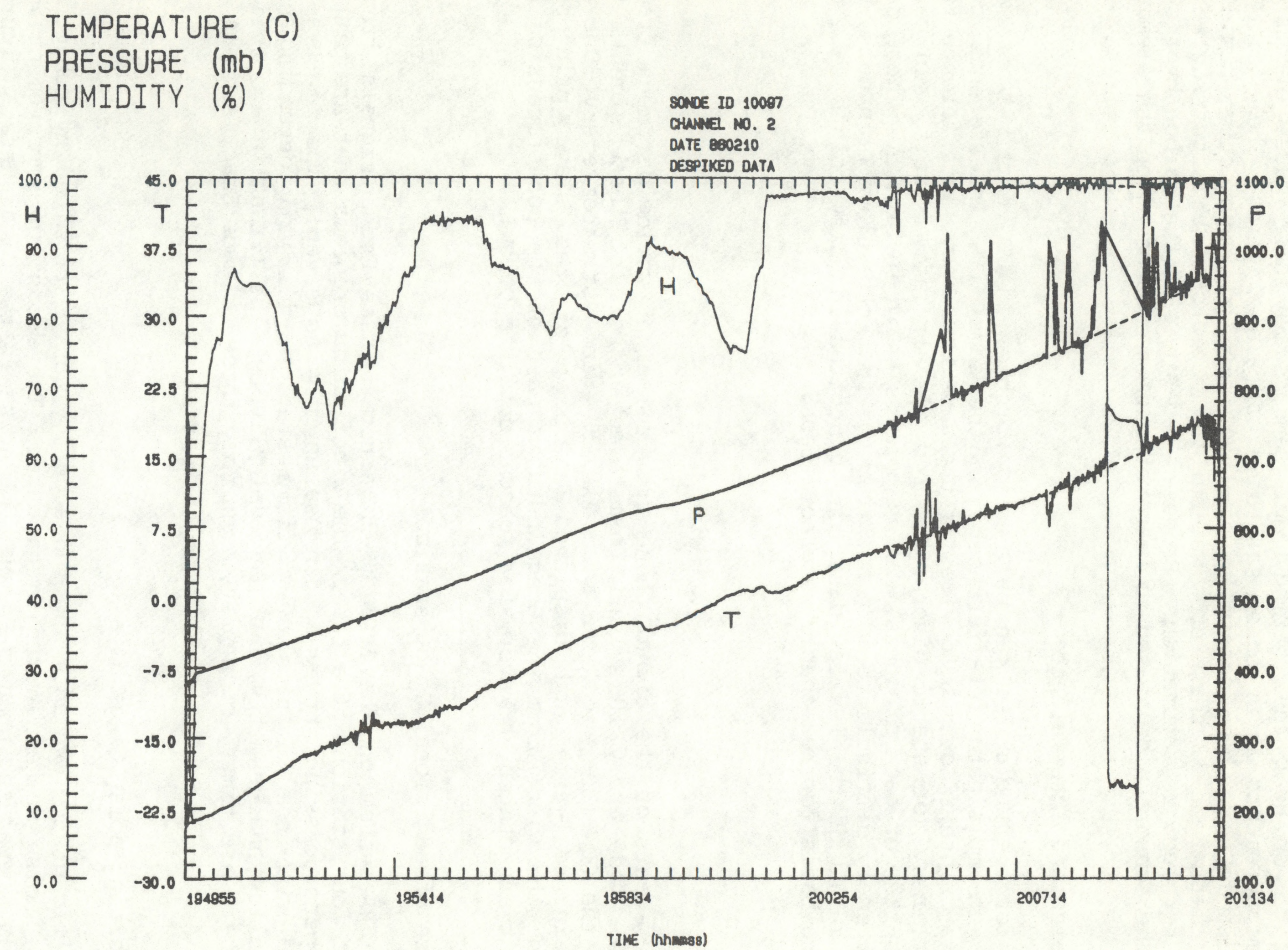

Fig. 5 Plot of unprocessed PTH data for GALE ODW #10097. Edits to data lost by interference are indicated by dashed lines.

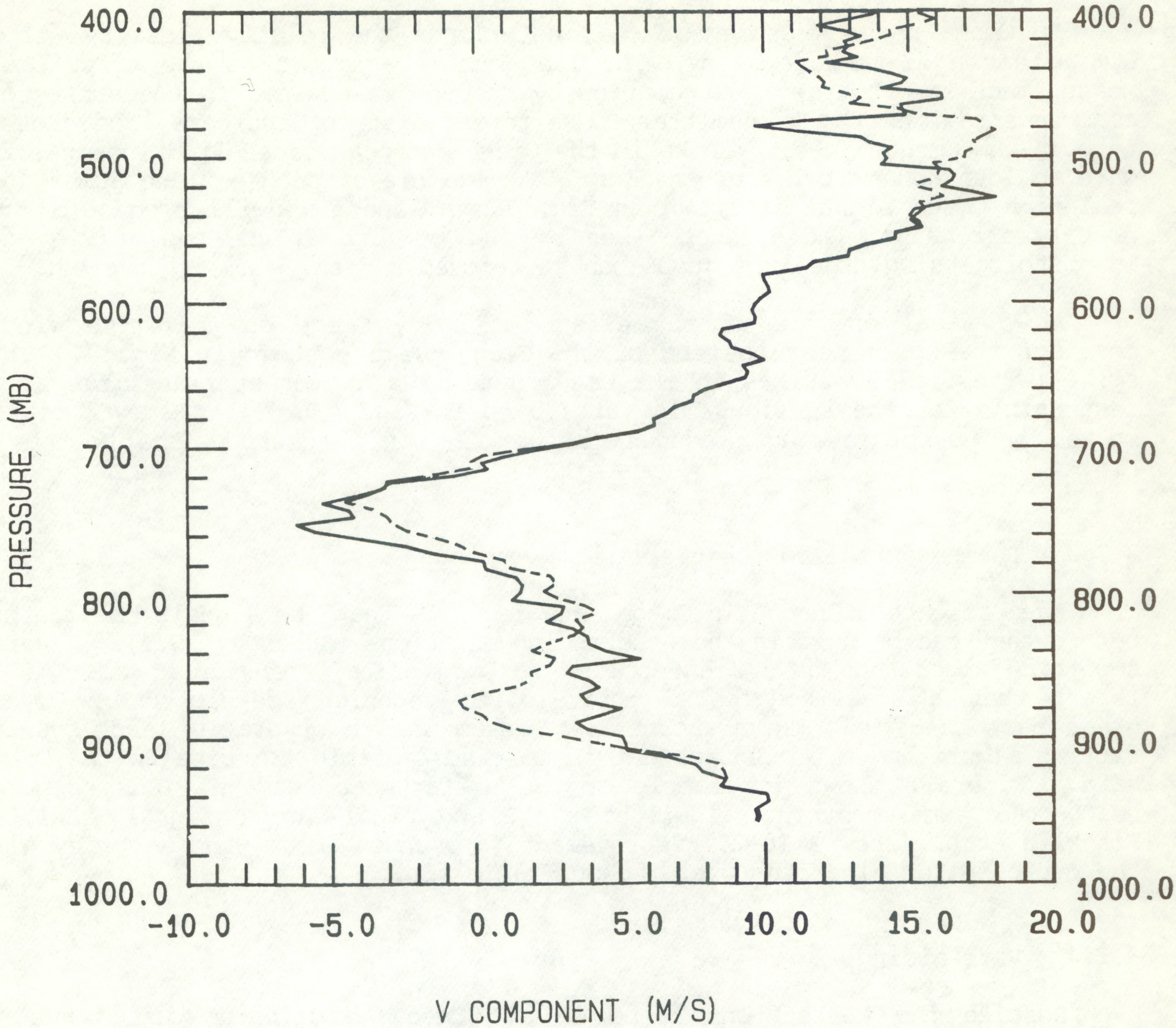

Fig. 6 V wind component of GALE ODW #10179. Solid line shows winds computed from real-time (unedited) Omega data; dashed line shows winds computed from postprocessed (edited) data.

An Omega phase measurement only determines the relative position of an ODW within a 22-km-wide lane. The lane number assigned to the first Omega measurement is arbitrary; but continuity must be maintained in the subsequent measurements. As the transmitter/ODW/aircraft distance increases and crosses through the Omega lanes, a spike in the Omega data can cause windfinding software to lose count of the proper lane. An example of such a "lane jump" in a real-time Omega signal is shown in Fig. 7. A lane jump will produce a completely erroneous wind estimate (see the 400-mb wind at the top of Fig. 4). In postprocessing, the lane jumps can be removed and the winds recovered.

As a final example of the effect of noisy Omega on real-time winds, consider the spike near the end of the Omega profile shown in Fig. 7. This spike (with similar spikes in the Omega data from the other transmitters) is responsible for the spurious wind at 775 mb in Fig. 4 (top). Removal of the spikes in postprocessing produces the smooth winds shown at the bottom of Fig. 4.

3.2.3 Scale-controlled cubic-spline smoothing

The presence of noise in Omega data requires that the signals be smoothed before they can be used in the windfinding equations (Acheson, 1974). Several smoothing algorithms have been applied to Omega data; Franklin et al. (1987) report that a scale-controlled cubic-spline technique developed by Ooyama gives best results. The airborne ODW system uses a quadratic least-squares fitting algorithm, a procedure that is more susceptible to noise in the Omega data. Figure 8 shows an example of the differences between winds computed using the two smoothing algorithms. For typical Omega signal quality, Franklin et al. show a 10-20% improvement in sounding-mean wind accuracy with the cubic-spline algorithm over the quadratic fit.

3.2.4 Rate-aiding

Despite the corrections found in all Omega windfinding algorithms to account for the sequential nature of the Omega transmissions, accelerations of the aircraft (turns) adversely affect ODW wind estimates. To reduce the effect of turns, HRD wind postprocessing includes a procedure known as "rate-aiding" (Cole et al., 1973). In this procedure, flight-level ground speed and track data are used to compute the component of the measured Omega signals arising from the motion of the aircraft. This component is then subtracted from the measured Omega signals. Franklin et al. report that rate-aiding improves real-time wind measurements in turns typically by 1-2 m s^{-1}. Figure 9 shows wind profiles computed with and without rate-aiding. Differences between the two in the region of the turn reach 3 m s^{-1}. Operational considerations frequently require changes in course while ODW's are in the air. The postprocessing of Omega data with the rate-aiding algorithm makes it possible to execute complicated flight patterns where necessary, without seriously compromising wind accuracy.

4. THE STANDARD LEVELS: REAL-TIME VERSUS POSTPROCESSED

Whether an ODW data set requires postprocessing depends upon the application involved. The preceding sections describe the ways in which errors in

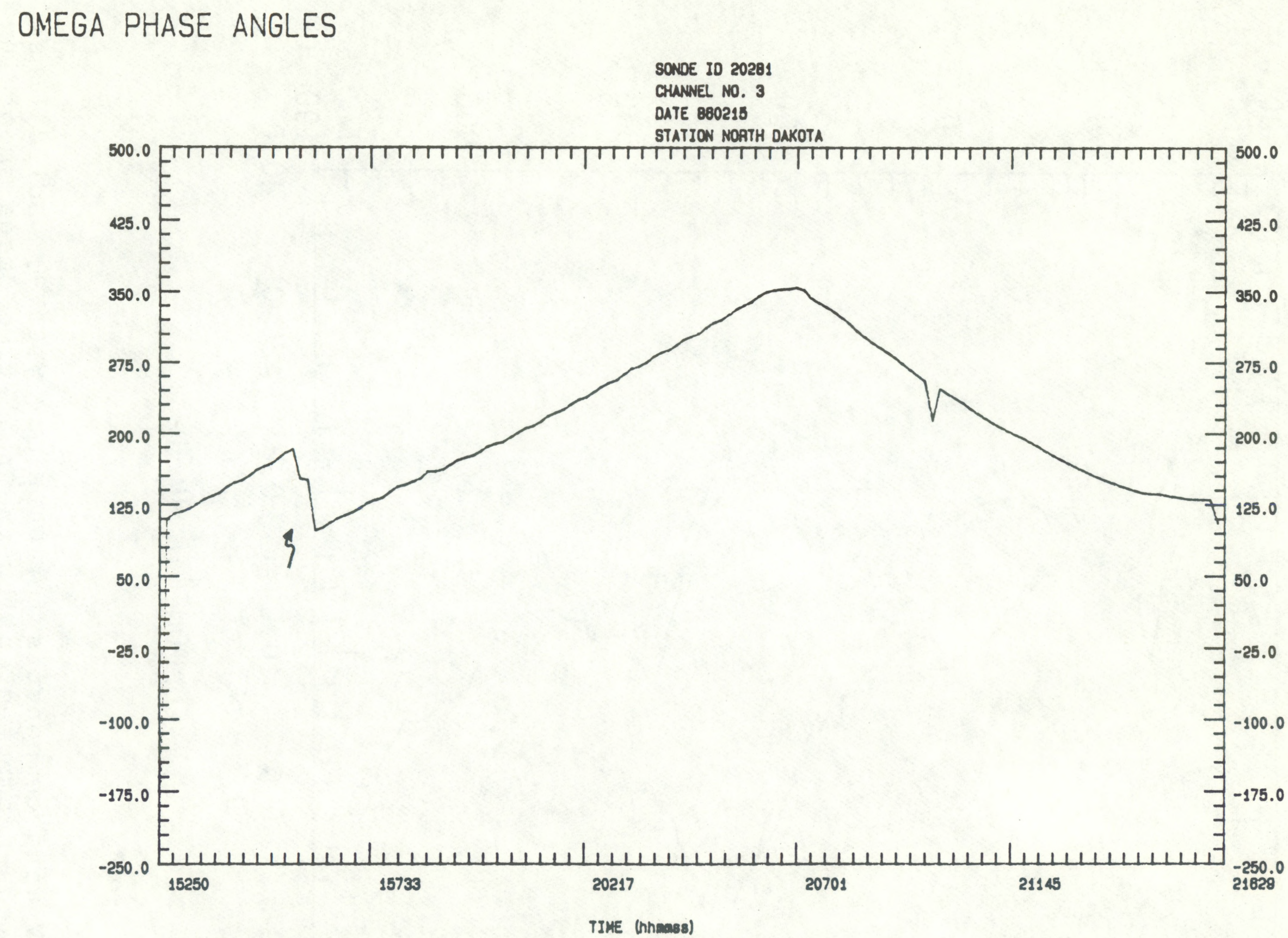

Fig. 7 Plot of unprocessed Omega data for GALE ODW #20281. Arrow indicates location of "lane jump".

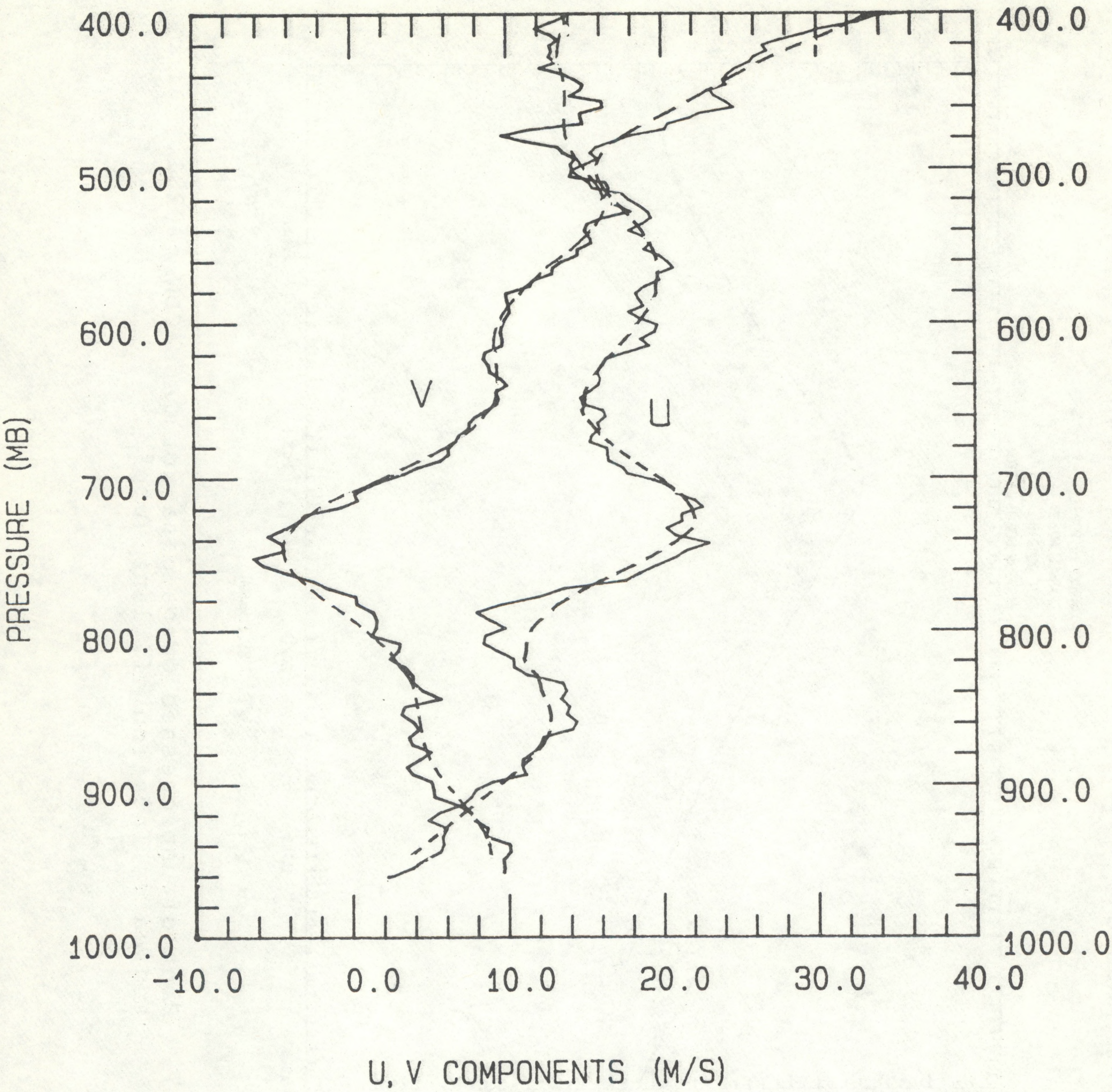

Fig. 8 U and V wind components for GALE ODW #10179. Solid lines show winds computed using the real-time Omega smoothing algorithm (quadratic fit); dashed lines show winds computed using postprocessing algorithm (scale-controlled cubic spline). Both sets computed using unedited Omega data.

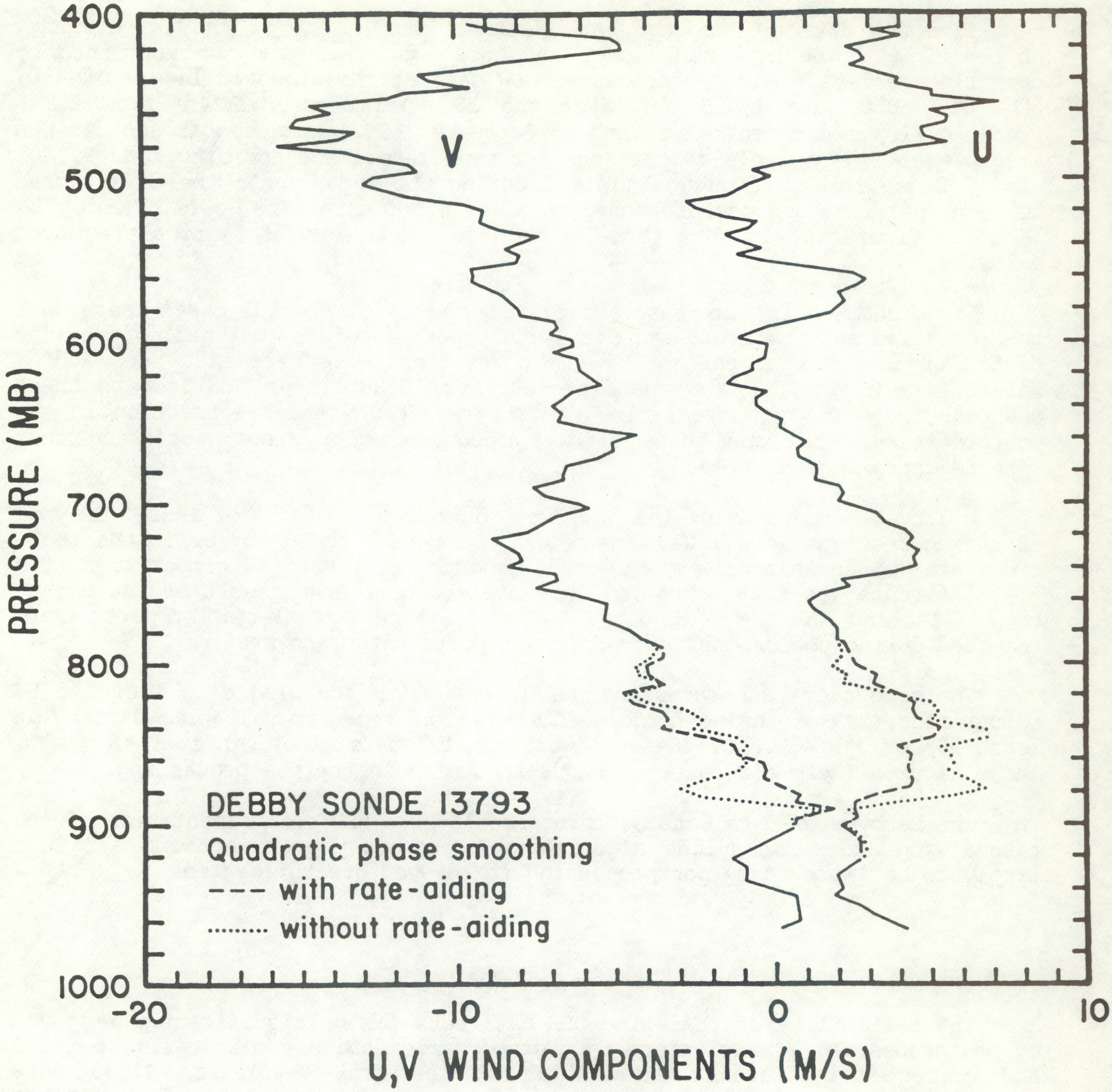

Fig. 9 U and V wind components for Debby ODW #13793. Dotted line shows winds computed without rate-aiding; dashed line shows winds computed with rate-aiding (after Franklin <u>et al.</u>, 1987).

real-time ODW data are reduced, and estimate the extent of the improvement. An overview of the combined impact of these improvements can be obtained by comparing real-time and postprocessed ODW data at the standard levels of 400, 500, 700, 850, and 1,000 mb. For the 26 postprocessed ODW's from HRD's synoptic flow experiment of 14 and 15 September 1982, this comparison defines a sample of 114 possible comparisons for temperature and humidity, and 99 for wind. Since interference was minimal during the experiment; the differences between real-time and postprocessed data for other data sets would probably be larger. Figures 10-14 show these comparisons, and some statistics are given below.

Large changes in temperature data were rare. Of the 101 cases where both the real-time and postprocessed data sets reported values, 93% had corrections of 1°C or less. Four percent of the corrections were between 1° and 2.5°C, while 3% were >2.5°C. The rms difference was 0.88°C. In addition to these changes, there were two real-time reports rejected without correction in the postprocessed data, and three reports recovered during postprocessing that were rejected in real time.

Eighty-nine percent of the humidity corrections were 5% or less. Only 5% of the corrections were >10%. There was one case of a 75% error in the real-time data. When this case was removed from the sample of 97 comparisons, the rms difference was 5.2%. Most of this difference is the result of the objective filtering of the PTH data. Six additional real-time reports were rejected during postprocessing, and two reports were recovered.

The effect of postprocessing was largest with the wind data. Of the 87 comparisons, 29% of the postprocessed winds differed from real-time data by at least 20° or 5 m s^{-1}. Of these, fewer than 1/3 were light winds of <5 m s^{-1}. These figures include 5 cases of winds recovered in the postprocessing.

The Debby wind data were postprocessed before HRD's implementation of the rate-aiding and cubic-spline algorithms. Consequently, newer wind data are likely to be improved by postprocessing to an even greater degree.

5. SUMMARY

The reliability of real-time ODW data sets can be significantly improved by postprocessing. Many errors in thermodynamic data are most easily noticed and corrected by careful examination of the full resolution (1-s) data unavailable in real time. Real-time surface pressure data typically have rms errors of ~5 mb. This can be reduced to ~2 mb in postprocessing. Significant changes in standard level data for one experiment in Hurricane Debby occurred in 7% of the temperature observations (>1°C), 5% of the relative humidity observations (>5%), and 29% of the wind data (>20° or 5 m s^{-1}). Improvements in wind data quality are particularly dramatic, because of the use of all available Omega data, the editing of noise from Omega signals, a more sophisticated phase-smoothing algorithm, and the use of rate-aiding to reduce the effects of turns. Investigators considering the use of ODW data for sensitive diagnostic computations are strongly cautioned against using real-time ODW data sets.

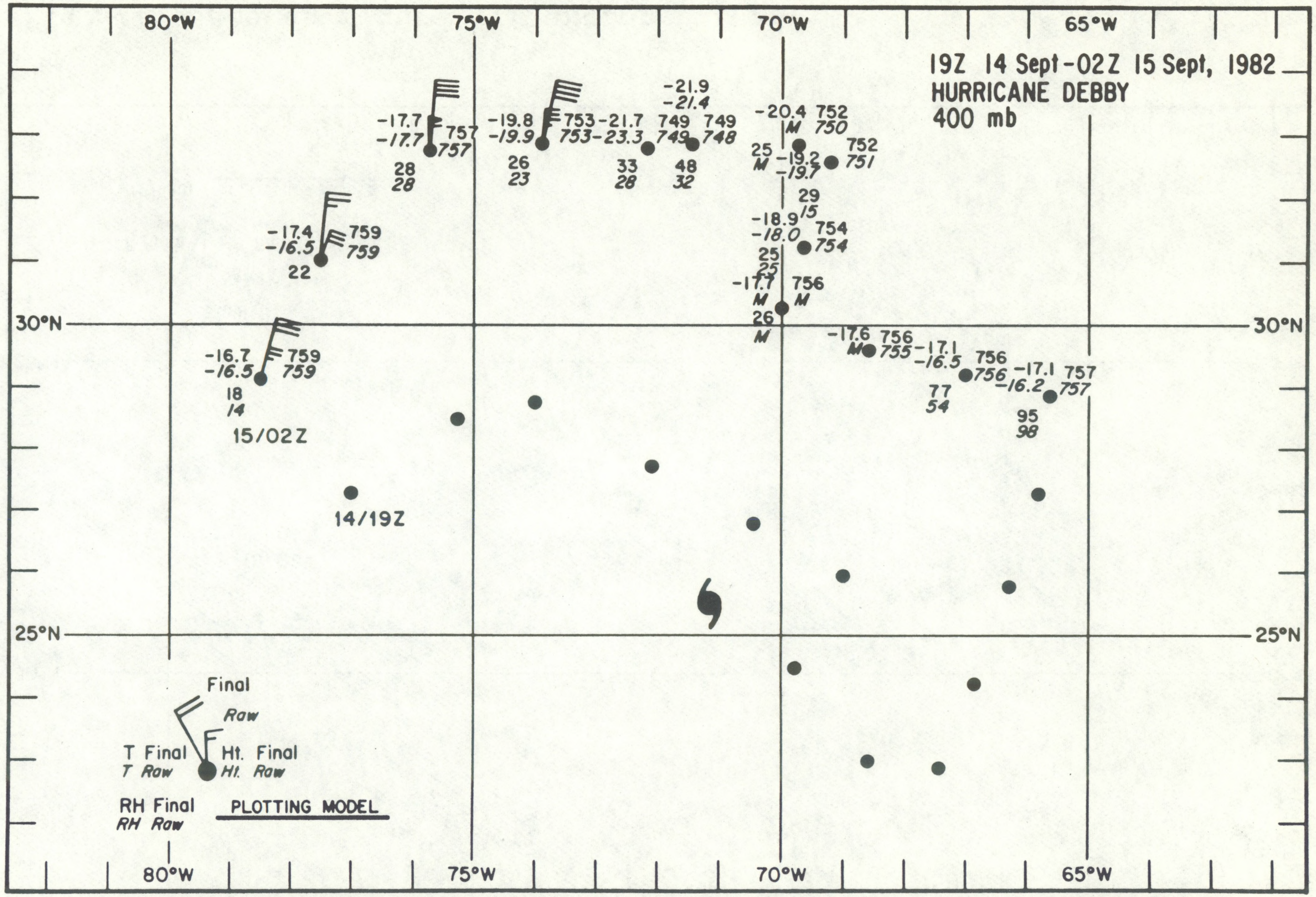

Fig. 10 Comparison of real-time and postprocessed data at 400 mb for HRD's Debby experiment of 14 September 1982. Hurricane symbol indicates mean location of Debby during the 7-h flight. Postprocessed values of temperature, humidity, and height are plotted above real-time values. (All heights were computed after the experiment, using both real-time and postprocessed PTH data.) Postprocessed winds are indicated by the longer wind barbs.

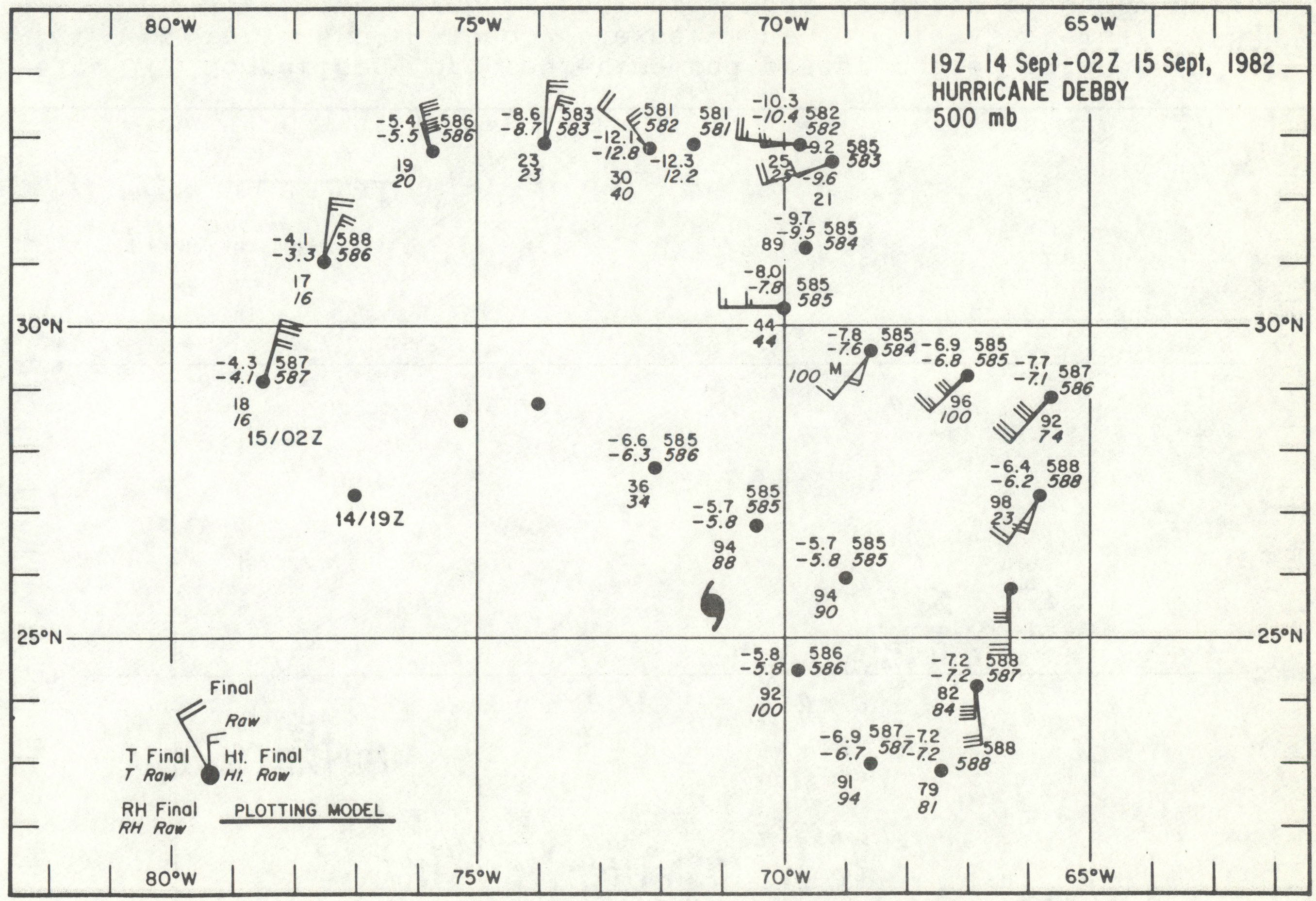

Fig. 11 Same as figure 10, except for 500 mb.

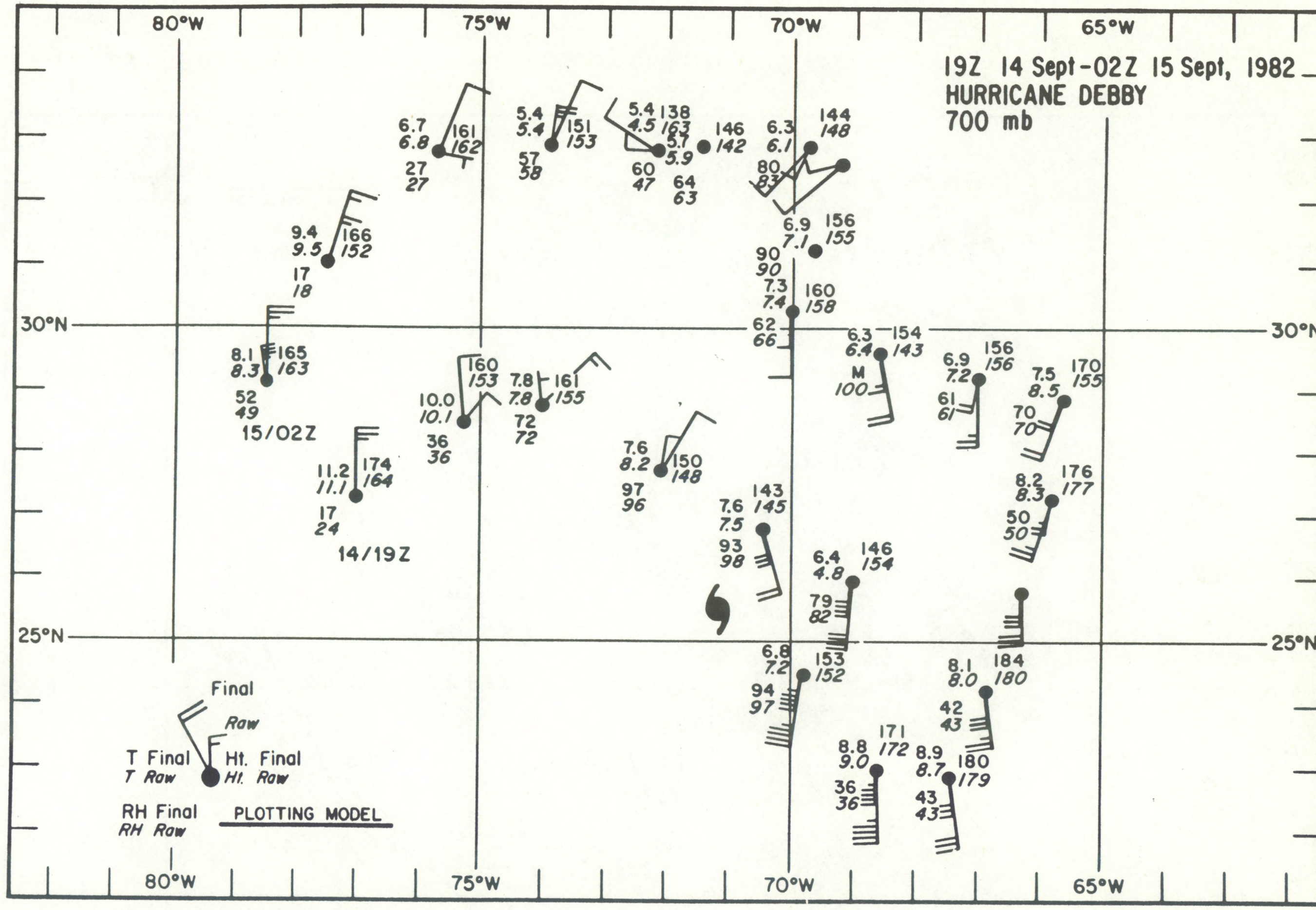

Fig. 12 Same as figure 10, except for 700 mb.

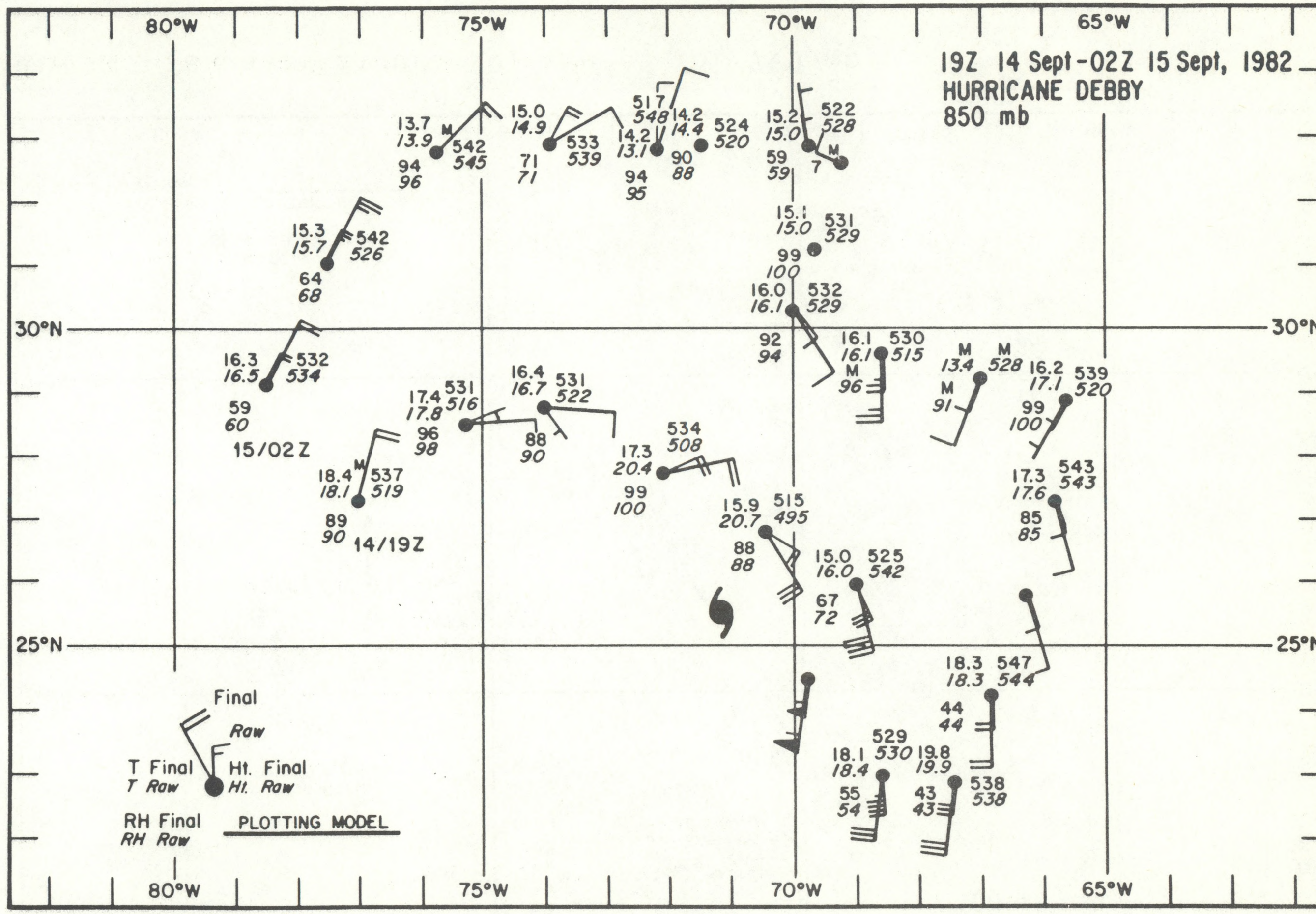

Fig. 13 Same as figure 10, except for 850 mb.

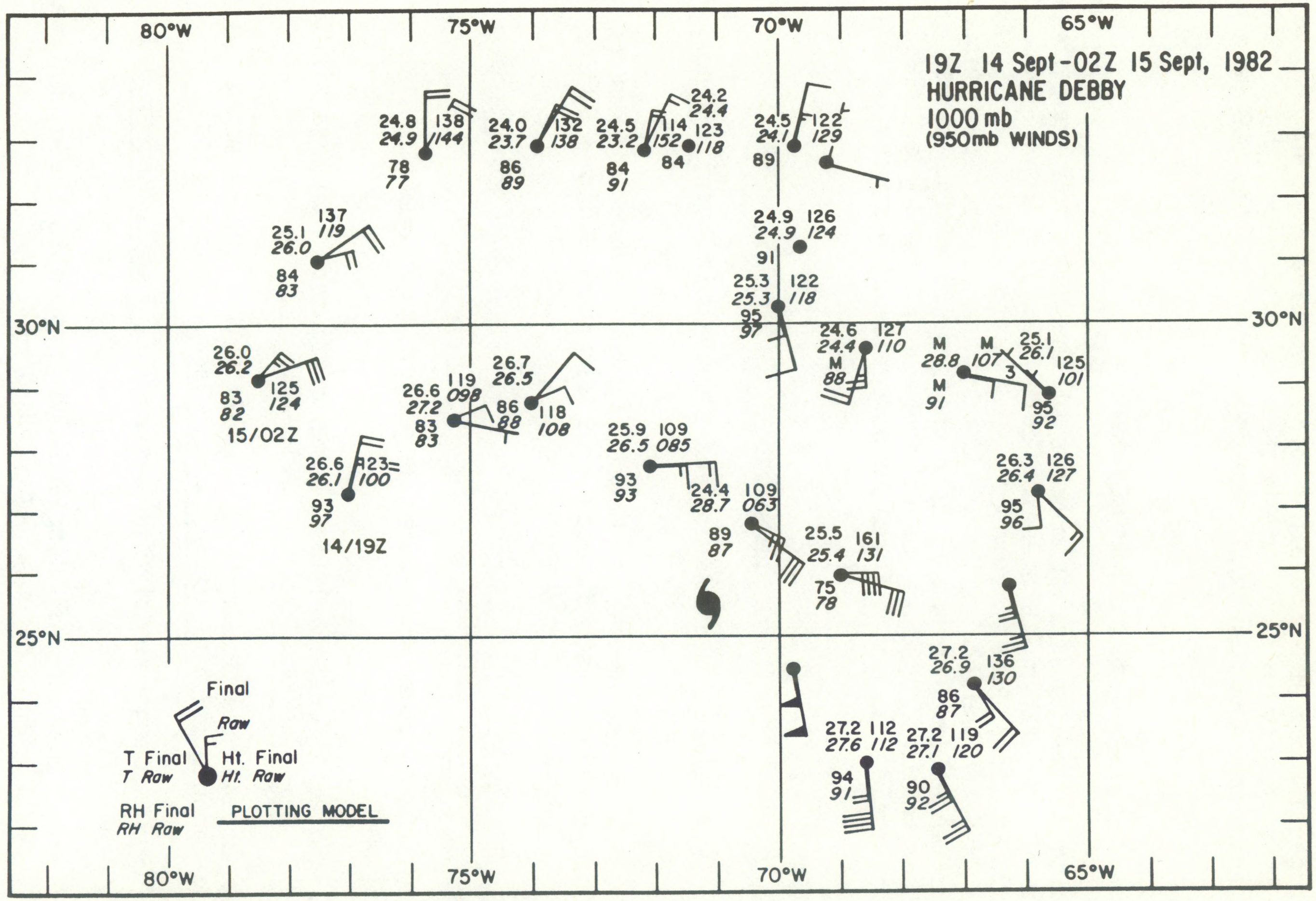

Fig. 14 Same as figure 10, except for 1000 mb. Plotted winds are for 950 mb.

ODW postprocessing at HRD contains both objective and subjective procedures. Only data clearly in error are edited subjectively. These edits, as well as questionable but unedited data, are documented for the ODW data user.

6. ACKNOWLEDGMENTS

The following current or former members of the HRD staff contributed to the development of the ODW postprocessing software: Jim Brown, Evan Darby, Neal Dorst, Seth Ehrlich, Robert Feinberg, Ray Glass, Joe Griffin, Stephen Lord, Katsuyuki Ooyama, and the author. Thanks are due to Paul Julian for sharing his experiences (and software) from the postprocessing of ODW data at NCAR. The author would also like to acknowledge HRD's Joyce Berkeley and Robert Wright for their diligent efforts in postprocessing scores of ODW's.

7. REFERENCES

Acheson, D. T., 1974: Omega windfinding and GATE. Bull. Amer. Meteor. Soc., 55:385-398.

Burpee, R. W., D. G. Marks and R. T. Merrill, 1984: An assessment of Omega dropwindsonde data in track forecasts of Hurricane Debby (1982). Bull. Amer. Meteor. Soc., 65:1050-1058.

Cole, H. L., S. Rossby and P. K. Govind, 1973: The NCAR windfinding dropsonde. Atmos. Tech., 2:19-24.

Franklin, J. L., 1983: Omega dropwindsonde processing. NOAA Tech. Memo. ERL AOML-54, 34 pp.

________, J. L. and P. R. Julian, 1985: An investigation of Omega windfinding accuracy. J. Atmos. Ocean. Tech., 2:212-231.

________, K. V. Ooyama and S. J. Lord, (1987): Two improvements in Omega windfinding techniques. J. Atmos. Ocean. Tech., 3 (in press).

Govind, P. K., 1975: Omega windfinding systems. J. Appl. Meteor., 14:1503-1511.

Julian, P. R., 1982: The aircraft dropwindsonde system in the global weather experiment. Bull. Amer. Meteor. Soc., 63:619-627.

Lord, S. J. and J. L. Franklin, 1987: The environment of Hurricane Debby (1982). Part I: Winds. (submitted to Mon. Wea. Rev.)

Passi, R. M., 1974: Wind determination using Omega signals. J. Appl. Meteor., 16:934-939.

 U.S. GOVERNMENT PRINTING OFFICE: 1987 - 754-126/40187