Surface Analysis Over the Oceans—Searching for Sea Truth

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ABSTRACT

For the Atlantic storms in ERICA IOP 1-5, NMC operational surface analyses, both manual and automated, were compared with two sets of research analyses prepared later. The positions of cyclone centers agreed within 100 km on average only between the two research sets. Root-mean-square deviations of the automated analysis positions from the research positions were 180 km. Central pressures were not deep enough, especially in the automated analyses. Comparison of reported pressures with the research analyses shows that those from the moored buoys and C-MAN stations were most accurate and reliable. The drifting buoys were nearly as good, as were the best ships.

Analyses are shown in detail for the IOP 2 storm, during its evolution from a complex multi-centered system to a single center of great intensity. Careful consideration of low-level aircraft data and of observations from ships (with detection and correction of their errors), was necessary for reconciliation of analyses differences. There were not enough observations to resolve all problems. The final great intensity of the center would not have been known without a low-level aircraft traverse.

A small sample of delayed ships' observations received after completion of the research suggested that the root-mean-square error of the pressure analysis was about 1.5 mb.

1. Introduction

Analysis over oceanic regions is much more difficult and uncertain than analysis over land because of the paucity and irregularity of observations; and because of their varying reliability. To give an idea of the sparsity of data, a count was made of the number of surface observations no more than 222 km from nine inland rawinsonde sites in the eastern United States. The average was 20, with a range from 11 to 40. Almost all of these are airways observations, available at least hourly.

For comparison, a similar count was made for a set of research analyses prepared by the author for the first five Intensive Observational Periods (IOPs) of the field phase of the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA), discussed by Hadlock and Kreitzberg (1988). Of the 46 analyses, only those 31 maps showing the main cyclone at sea, used as the reference point, were examined for this purpose. The average number of observations was four, with a range from zero to ten. Almost half of these were from ships, which report (with rare exception) only at 6-h intervals. The remaining majority were either from moored buoys close to the coast, or from special ERICA drifting buoys farther at sea. Most of these provided hourly observations. Oceanic analyses not favored by the special data collections of a field experiment are based on a probable data density of only one or two observations within 222 km of a given point.

Variable quality of the marine observations compounds their sparsity. Clearly erroneous pressures, for example, are relatively much more frequent at sea than on land. Occasional erroneous positions are among the litany of other errors and discrepancies in observations from ships which challenge the detective powers of the analyst.

This is not to denigrate observations from ships. They are the only source of complete observations of the weather. The reported winds do not suffer from the unrepresentativeness due to exposure at a particular land location, and the ERICA buoys reported no winds at all. The ships' crews are the witnesses to what is happening out there, and their testimony cannot be neglected.

For ERICA IOPs 1-5, December 1988-January 1989, various surface analyses were examined over the western North Atlantic. These included the automated initial analyses in the Medium-Range Forecast (MRF) runs of the National Meteorological Center's (NMC's) global spectral model (Kanamitsu 1989) and Nested Grid Model (NGM), as described by Hoke et al. (1989). Among the manual analyses considered were the operational ones prepared at NMC for North America and adjacent oceanic sectors (NA) (with data cut-off at 40 min after the nominal time of observations), and for the Northern Hemisphere (NH) (with data cut-off at 1 h 40 min after). These are described

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by Corfidi and Comba (1989). In addition, two sets of research analyses, manually prepared after the fact, were consulted. These were done by Professor Greg Forbes (GF), ERICA forecast coordinator, as taken from the Field Phase Summary (Hadlock et al. 1989), and by the author (FS). All manual analyses used satellite imagery, in addition to all available *in situ* observations. The Forbes analyses were preliminary. They were completed about six weeks after the end of the field period and therefore did not have complete sets of ship and aircraft data as were available to the author two months later.

These two sets of analyses are considered to be the closest approximation to the actual state of the atmosphere because of the use of a number of observations received too late for operational analysis (including those from ships, drifting buoys, and low-level ERICA aircraft flights), because of the possibility of establishing continuity both before and after a given time, and because of the relief from haste imposed by operational deadlines. The Sanders analyses were arbitrarily taken as ground (or sea) truth, owing to a slightly larger data base and a slightly later preparation time.

2. Cyclone position and central pressure

For the period of study, 35 Sanders analyses of cyclones could be compared with one or more of the others. The comparison is exclusively in terms of the analyzed positions and central pressures of low centers, reflecting the focus of the ERICA project. The Sanders maps were at intervals of 6 h, except for two instances of 3-h continuity during rapid intensification in IOPs 2 and 4. The Forbes and NA maps were at 3-h intervals, while the NH maps were at 6-h intervals. The NGM analyses were at 0000 and 1200 UTC, while the MRF analyses were available only at 0000 UTC. The results of the comparisons of the various analyses with the Sanders maps are summarized in Table 1.

The three sets of manual analyses agreed with the Sanders analyses more closely than did the automated analyses, with respect to both position and central pressure. The positive pressure deviations for all the series suggest a Sanders bias toward deep lows, which we acknowledge but hope is subliminal. Only the Forbes analyses showed a root-mean-square (rms) position deviation smaller than 100 km. Lack of numerous observations from ships during the first 40 min after observation time produced somewhat larger position and pressure deviations for the NA series than for the other manual ones.

Larger mean and rms position deviations for the NGM and MRF analyses attest to the difficulty of automated handling of ships' observations, with their rich and creative variety of errors. The sample of comparisons for the MRF is extremely small, but substantial southwestward position bias and insufficient pressure depth were found also in a study of a larger sample of cyclones over the western Atlantic, to be reported elsewhere. The shortfall in depth of central pressure may reflect coarser resolution in this analysis model than in the NGM.

These results confirm that verification of model predictions of the central pressure of cyclones against initial analyses produced by the models themselves may fail to show the systematic underestimate of deepening seen when verification is with respect to manual analyses. Extreme cases show discrepancies near 20 mb, in spectacular events on a relatively small scale. These would not be known to have occurred at all were the automated analyses to be considered as ground truth. The IOP 4 cyclone, in which low-level aircraft observations indicated a central pressure below 938 mb (unprecedented, in the author's experience, for an extratropical cyclone so far south) was such a case.

TABLE 1. Mean latitude and longitude (degrees) and mean central pressure (mb) for the FS maps. For the other map series, mean geographic bearing (degrees) and distance (km) from this position, and mean central-pressure deviation (mb). Values in parentheses are rms deviations from the means.

FS analyses: 37.6N (4.7) 65.7W (7.1) 987 (20) N = 35

Series	Bearing/distance	Pressure	N
GF	272/31 (69)	+0.5 (2.5)	35
NH	066/11 (107)	+0.6 (4.0)	29
NA	063/08 (131)	+2.1 (5.6)	34
NGM	152/34 (181)	+3.4 (3.5)	17
MRF	217/45 (179)	+7.5 (5.7)	8

3. An example of complex development

Bjerknes (1918) has noted that cyclones do not show circular symmetry of airflow, even at sea, and the ERICA storms were no exception. Troughs emanating from the cyclone centers, which were themselves often multiple, did not conform entirely to traditional frontal notions. The most difficult analyses were probably those for IOP 2, judging from the number of large discrepancies in the various analysis series (despite the relative abundance of data), and from the complexity of the cyclone development. The analyses for this storm will be discussed in some detail to illustrate the problems inherent in oceanic analysis.

The evolution of this storm is illustrated in Figs. 1–8. In these Sanders analyses, notations of pressure centers are omitted (except for the major cyclone) in order to minimize obscuration of data. Fronts are not shown for the same reason. Where fronts were strong and unambiguous, however, the isobars and isotherms leave little doubt where they were.

a. 1200 UTC 13 December

In Fig. 1a, two cyclones were evident: one to the south, along the edge of the relatively homogeneous

ing to an excessively low central pressure.

2) The "120" pressure report from KSYP was too high, somewhat more than the positive bias of 2–3 mb in other observations from this ship.

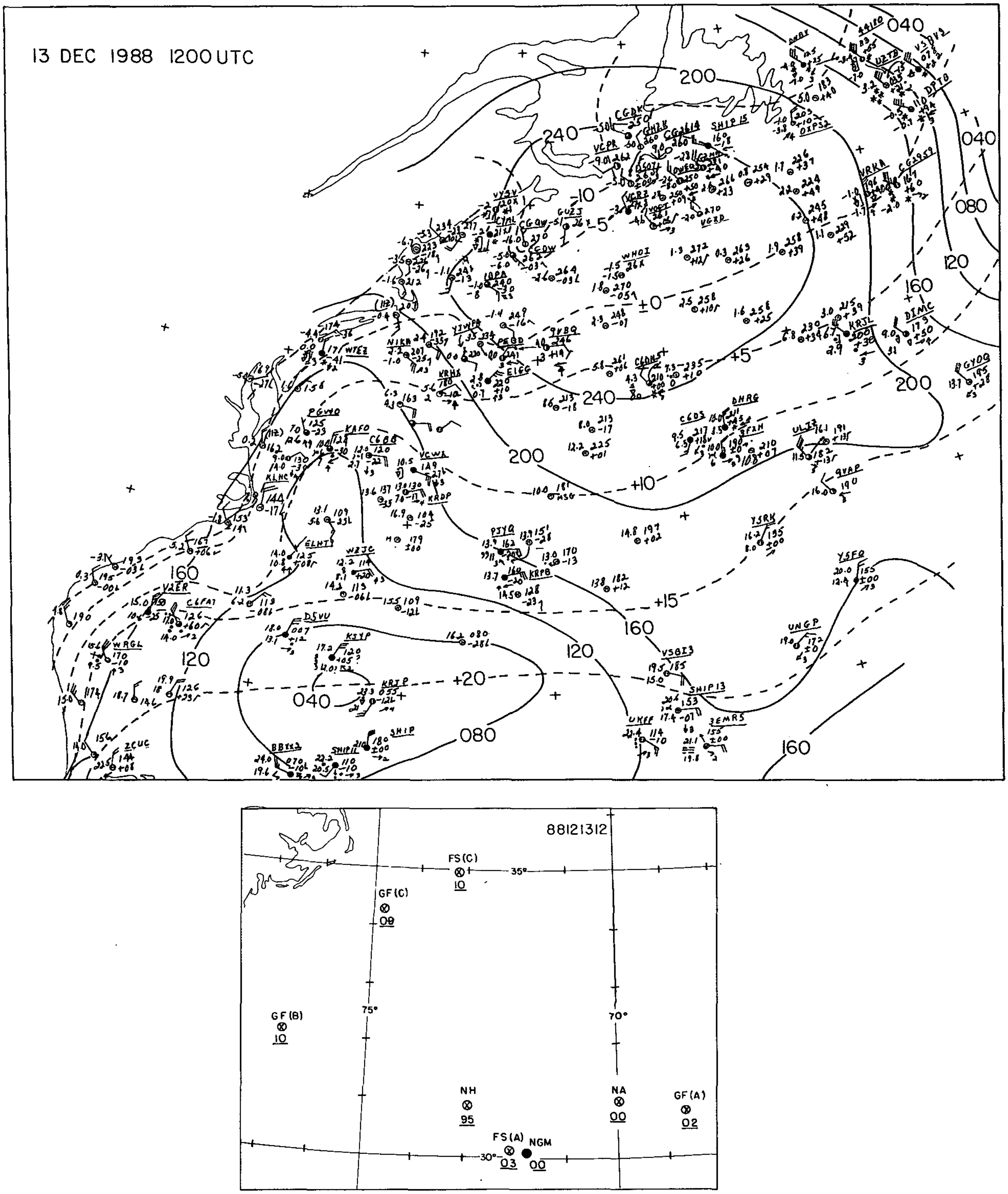


FIG. 1. (a) Analysis of sea-level isobars (solid), at intervals of 4 mb and of surface isotherms (dashed) at 5-C intervals, at 1200 UTC 13 December 1988. Observations are plotted with the conventional model. Those showing only temperature, pressure, and tendency are from drifting buoys. The underlined letter or number designator is the radio call sign of the ship, except for "WHOI," which is the moored buoy of the Woods Hole Oceanographic Institution. (b) Center positions and pressures (underlined) of each low in the various analyses for this time. Automated analyses are shown by filled circles.

warm air, and another, barely defined by the SE wind and low pressure at the buoy E of Cape Hatteras. It lay in cooler air, but at the warm edge of a band of strong contrast between the coast and the offshore waters. These two centers were denoted A and C, respectively, in the Forbes analyses. The former was the result of a complex development north of the Bahamas and had been in existence for more than 24 h, deepening markedly but not spectacularly. The northern center had not appeared before this time, but represented development in a trough extending northward from the earlier low center.

The position and central pressure of cyclone A varied widely among the various analyses (Fig. 1b). The 1008-mb isobar was zonally elongated as was the envelope of analysis positions. The four ships' observations nearest the center were suspect. A diagnosis follows:

1) If the "007" (1000.7 mb) reported by D5VU were taken to be "070" (1007.0 mb), then the observation would be consistent with others prior to this time, showing a low bias of 1–2 mb. This interpretation was made by the Sanders analysis, but the report was evidently taken at face value by the NH analysis, leading to an excessively low central pressure.

2) The "120" pressure report from KSYP was slightly larger than the +5-mb error characterizing this ship's observations during this period. (Five weeks later, during IOP 5, the observations from this ship showed no error, so the bias had evidently been corrected in port.) All analyses appear to have discounted this observation.

3) The pressure reported by KRJP was within the range 0 to +2 mb, characteristic of this ship at this time. The report appears to have been discounted by the NGM analysis.

4) The SHIP lacking call sign, reporting "180" pressure and a N wind of 30 kt, was obviously wrong. A position error is likely, but it was not possible to relocate or otherwise correct this observation. It has to be regarded as a stray bullet. All analyses dodged it.

Aside from this last, the reported winds appear to be correct and were used to locate the center in the Sanders analysis. Continuity helped with the central pressure.

There is a large distance between the centers as shown in the Sanders and Forbes analyses, because some of the relatively abundant data was available only to the former. Finally, the Forbes analysis shows a third center, B, to the SW of C in Fig. 1b. It also lay along the warm edge of the coastal temperature gradient. The pronounced cyclonic wind shift between the northwesterly at C6FA7 and the northeasterly at the buoy to the NE indicates a sharp trough in that region. A maximum of relative vorticity may be present, but there is no evidence of a closed circulation. The Sanders analysis regarded the pressure at C6FA7 as 2 mb low, whereas in other observations before and after it appeared to be correct on average. This analysis therefore appears to err by not having a sharp enough trough in the 1012-mb isobar. Even so, a pressure minimum seems unlikely at this time, given the complete data set available to the author.

b. 1800 UTC 13 December

Six hours later (Fig. 2a) there had been a general fall of pressure over the area, somewhat greater in the northwestern part of the disturbance than elsewhere. The disagreement among the analyses as to the location of cyclone A was somewhat reduced but still substantial (Fig. 2b). Few reporting ships were near the center.

1. KRJP had crossed a front in the path of the low, to judge from the wind shift and temperature drop since the preceding map (cf., Fig. 1a). The pressure appeared to be correct.
2. The 1009.0-mb pressure at SHIP 11 was taken as 3 mb too high, close to the bias in other observations from this vessel (identified by continuity of track and particular options in use of the synoptic code).
3. The 1010.3-mb pressure from VSBI3 was also too high, somewhat more than the positive bias of 2–3 mb in other observations from this ship.

From the wind directions at KRJP and SHIP 11, a position near 30N 70W seems likely, SW of any of the analysis positions. The NH and Forbes (A') positions are closest, with the Sanders (A) low too far E. The NA position and central pressure, both far off the mark, must have been the result of extrapolation of the preceding analysis, with no new data. The additional NH center near 32N 64W accommodated the observation from Bermuda (32.3N 64.7W, not shown) but displayed no continuity and does not seem necessary.

A low-level ERICA flight (Fig. 2c) guided the research analyses for lows C and B. The former was well covered by observations from ships and moored buoys of reasonable quality, but the flight confirmed the evidence. It showed at least one wind direction from each of the four main quadrants, and suggested a center of about 1002 mb near 37N 72W around 1830 UTC. This is consistent with the NH and Sanders (C) positions and central pressures. The Forbes (C) position appears to be too far SW.

The only major pressure error in the area was the 1010.7 value reported by WZJC. It is not consistent with its own 3-h pressure tendencies and observations 6 h earlier and later. It cannot be corrected by the often efficacious interchange of digits or alteration of the tens' digit. It's simply wrong.

The ill-defined low B was suggested rather than determined by the *in situ* data (Fig. 2a), and no unambiguous position was indicated by the satellite imagery (not shown). Note that the flight data (Fig. 2c) showed a sharp wind shift to a 35-kt northwesterly in this area, the strongest observed on the low-level traverse, but

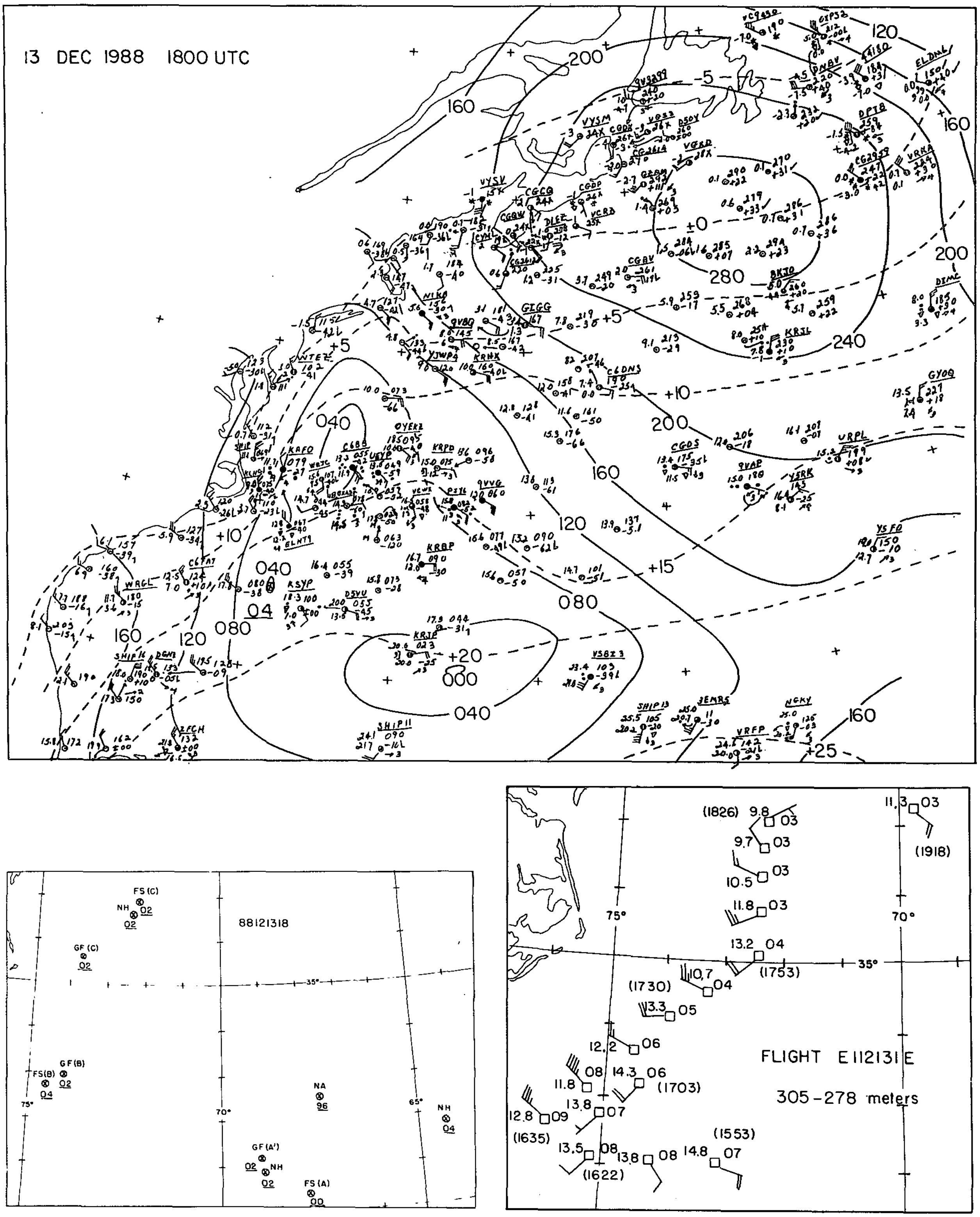


FIG. 2. (a) Same as Fig. 1a, but for 1800 UTC 13 December. (b) Same as Fig. 1b, but for the time of Fig. 2a. (c) Selected observations from the low-level traverse of ERICA flight E112131E, at the indicated range of elevations, showing flight-level wind and temperature, and extrapolated sea-level pressure. The plotting is conventional, but only the tens and units digits of pressure are given. Selected UTC times are shown in parenthesis.

no distinct circulation center. It is therefore surprising that the Sander (B) and Forbes (B) positions are so close. Luck is not always bad.

A remarkable aspect of the region of only slight horizontal pressure gradient over a substantial area centered near 34N 71W is the observations of Ely wind between 10–20 kt. These appear to represent a continuation of winds corresponding to the pressure gradient in the area 6 h earlier (Fig. 1b). At sea, unlike the situation over land, surface friction is evidently insufficient to reduce the winds promptly to calm as the gradient vanishes, and the residual flow may approximate an anomalous gradient-wind or cyclostrophic balance.

c. 0000 UTC 14 December

At the next synoptic time, the situation remained complex despite substantial overall deepening (Fig. 3a), but the Forbes and Sanders analyses had reached very close agreement. The centers in the NA and NH analyses, if they were shown at all, were not far off (Fig. 3b). Low A was defined by the observations from the nearby drifting buoys and the observation (not shown) from Bermuda. To the SW the two nearest ships reported pressures with opposing errors, each consistent with their own records of error, FNXS's being too low and SHIP 11's too high.

Low C was well defined by a combination of observations from ships and buoys, so it is surprising that neither the NA nor NH analyses detected the center. Presumably the ships' observations were received too late for operational use. The only large pressure error was in the "040" reported by OYEK2 (plotted in Fig. 3a away from its correct location). The +4-mb error at this time was consistent with errors in its other observations over a 24-h period, but larger than errors in earlier and later observations.

Low B was ill defined at first glance. Its presence was based primarily on a judgment that the 25-kt southeasterly wind reported by VCWX was correct and not the result of a 180-degree error, as happens from time to time. In fact such an error occurred in one of the observations from this ship in the Gulf of St. Lawrence during the following month. Its other observations during this IOP, however, appeared to be entirely reliable. Its report of continuous moderate rain, moreover, along with thunderstorm activity reported by KRPB and KSYP to the west, indicated that development was afoot. This conclusion was consistent with satellite imagery (Hadlock et al. 1989) showing rapid development of a large mass of deep high clouds extending from near 33 N 71 W to the SE coast of New England. Low C was well within this mass while B was near its southern extremity.

Only a single low center was present in the automated initial analyses from the NGM and the MRF run. They favored Low B. In fact, the 5-day forecast from the MRF (Fig. 3b) produced a low position closer to the Forbes (B) and Sanders (B) positions than any other output from this model, closer also than the NA and NGM analyzed positions. Considering that another storm (the IOP 1 cyclone) was successfully predicted earlier in this MRF run, and that the IOP 2 storm could be traced only to some weak cyclonic circulation in the NW Gulf of Mexico in the initial analysis, this was a remarkable forecast. Unusually so, unfortunately. At all ranges, the MRF forecast position is seen in Fig. 3b to have verified within about 250 km, with a central pressure error of no more than 8 mb. Since the model never predicted multiple centers, it is evident that this detail was not necessary in this instance for the model to get the right idea.

d. 0300 UTC 14 December

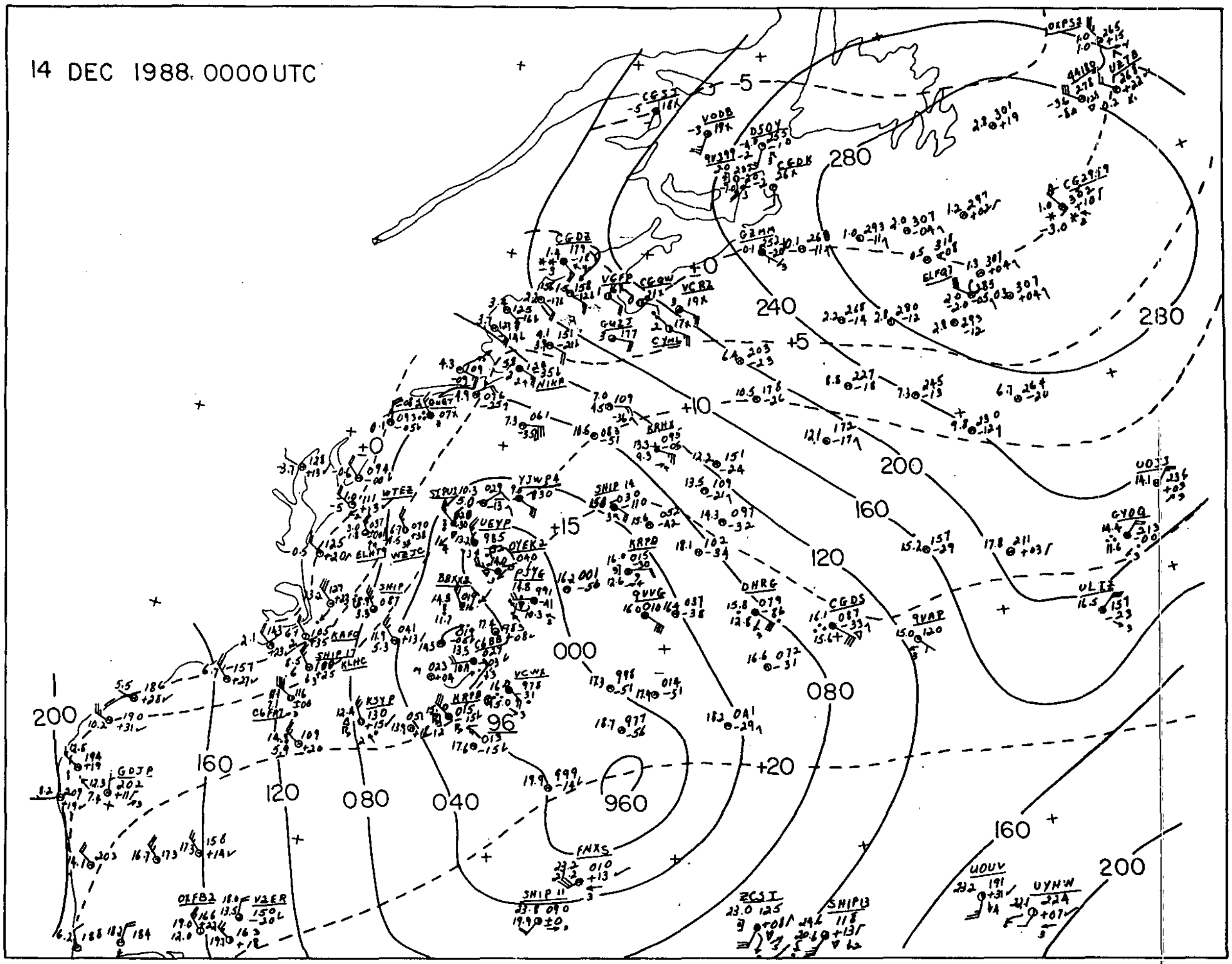
The extremely rapid deepening that now encompassed lows B and C prompted preparation of a Sanders analysis for the intermediate time of 0300 UTC. From Fig. 4a, it is apparent that such an effort would be fruitless were it not for the numerous ERICA drifting buoys. Seaward of the moored buoys within 350 km of the shore, only Bermuda and the faithful (if erroneous) FNXS provided other observations.

The complexity of the analysis was revealed only through use of the low-level ERICA flight data (Fig. 4c). The lowest pressures reported by the buoys, and the most rapid pressure falls, appeared to be associated with Low B, but the flight passed directly a small but intense Low C at 38.0 N 68.5 W at 0336 UTC. Note the wind shift from NE 35 knots through light SW to WNW 20 kt at consecutive 1-min intervals, with a minimum pressure of 989 mb. By linear interpolation from the nearly identical Forbes (C) and Sanders (C) positions and central pressures at 0000 UTC, the low would have had a central pressure of 990 mb at 37.9 N 68.7 W at 0300 UTC. Both of these analyses, done without benefit of the above exercise, show a central pressure 2 mb too deep (in anticipation of things to come) and a position slightly too far E. In addition, the Forbes analysis shows the center about 40 km too far S.

It was not possible to locate Low B with such precision, but the satellite imagery (not shown) indicated rapid development of the cloud structure toward a vortex configuration, with Low B near the southern edge of the deep high shield. The Sanders (B) and Forbes (B) analyses were in close agreement.

Low A had been absorbed in the Sanders analysis but still appeared in the Forbes version (Fig. 4b). The NA analysis also carried a low in the vicinity of Bermuda. What the basis was, other than continuity, is not clear; but a separate center appears difficult to maintain in the face of the strong deepening to the NW.

The pressure data from the drifting buoys were not without fault. Although none of them had a crucial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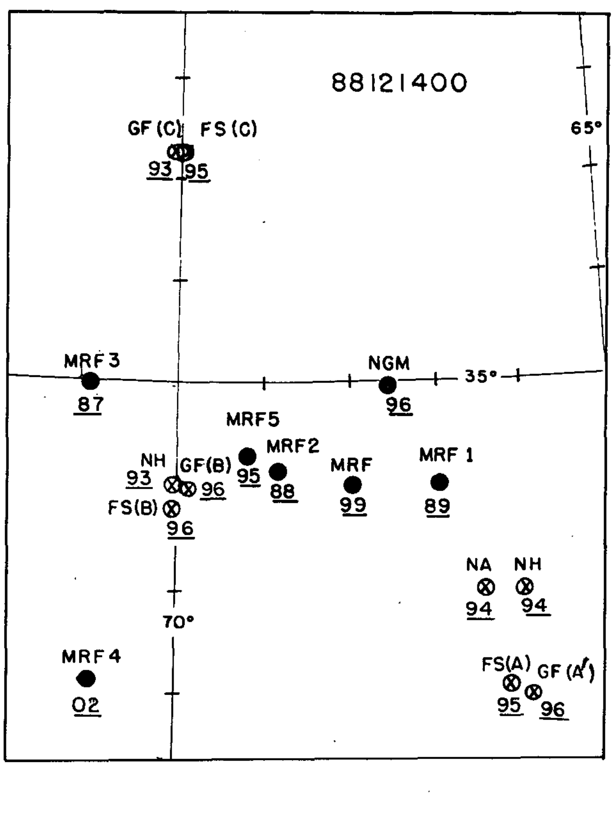
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effect on the analysis of the lows at 0300 on the 14th (Fig. 4a), we present some examples.

1. At 358, after many days of accurate measurements, the error grew on the 13th and 14th to +7 mb, after which nothing further was heard from this buoy.
2. At 368, again after many flawless days, the error was rapidly growing to +10 mb late on the 14th. By the 17th, accuracy had returned, but only for a day; after which a +5-mb error developed. The nature of this behavior is not known.
3. A growing positive error at 353 reached a peak of +4 mb on the 14th, but after the low went by (as we shall see), the pressure refused to rise appropriately. That is, it remained low until late on the 17th, when a large positive error again developed, with dramatic fluctuations not matching anything discernable on the maps.
4. Lest the impression be given that the errors were always positive, thereby raising a suspicion that the analyzed pressures were systematically low, 365 carried an error ranging between −1- and −4-mb for several days until it vanished early on the 15th. Good accuracy at 355 at this time was a temporal oasis in the middle of errors of either sign up to 5 mb from the 10th through the 14th. After this time the buoy performed nearly flawlessly.

On the whole, and despite these problems, the buoys were a valuable source of data during IOP 2 and other periods in which they were abundant. During IOPs 1–3, buoy 356 reported pressure values in perfect agreement with all Sanders analyses.

e. 0600 UTC 14 December

By 3 h later (Fig. 5a) enormous deepening had occurred, 10 mb in the GF (*C*) low and 12 mb in the single Sanders (*B*) low. The NA and NH analyses now placed single lows intermediate between the Sanders and Forbes positions (Fig. 5b) but with substantially higher central pressures. The agreement on position seems a stroke of luck and the failure to analyze a deep enough center is not surprising, since no ship observations and only limited buoy data were evidently available for the operational analyses.

The three ships closest to the center (or centers) in question were KRPD, 9VVG and DHRG. We consider each of them:

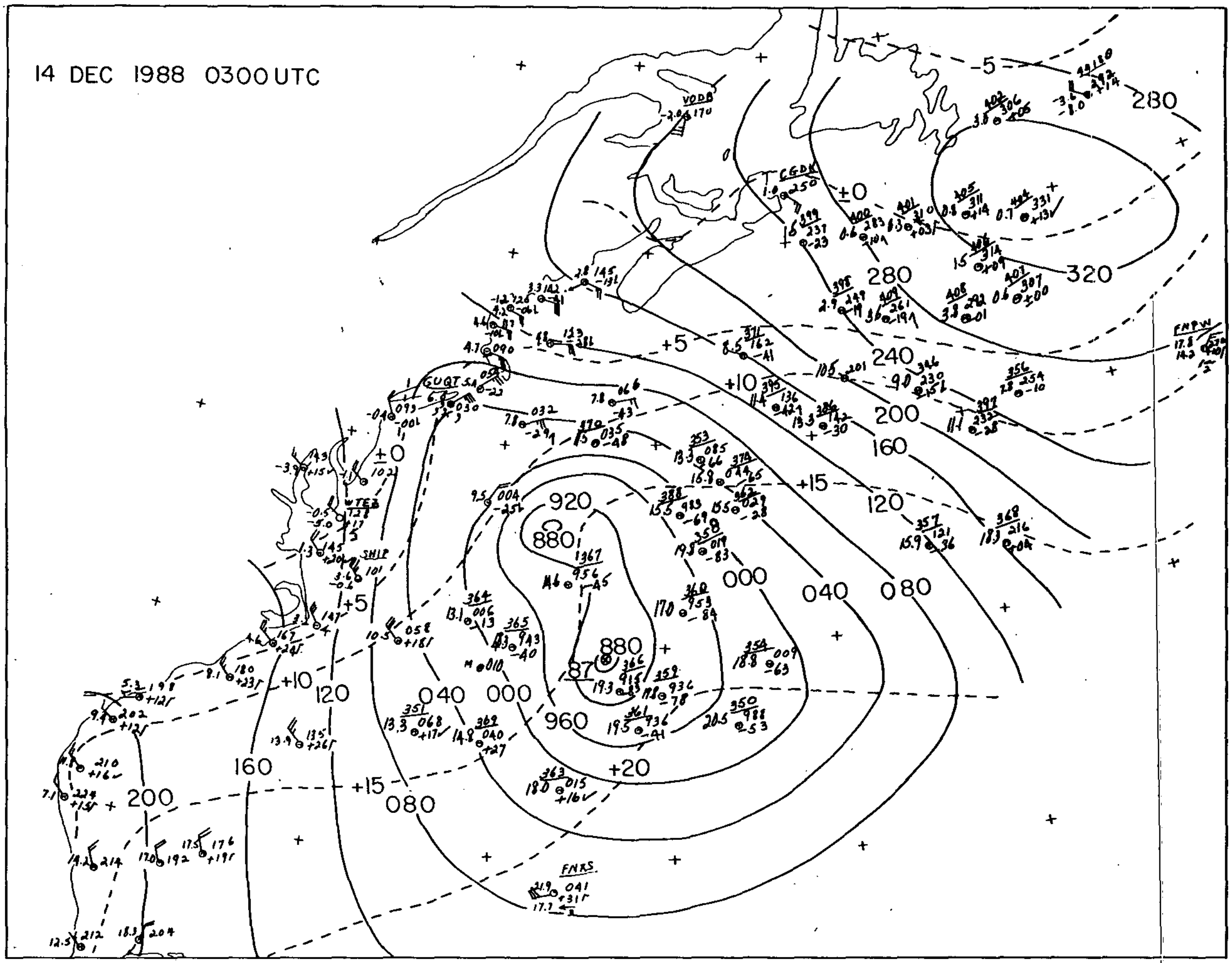
1. The first (KRPD) was plotted W of its actual location in Fig. 5a, owing to its proximity to buoy 358 (where the pressure was by this time 7 mb too high). It was not available for the Forbes analysis, but appeared to have a small negative pressure error at earlier times (cf., Figs. 1a, 2a, and 3a). Even its corrected pressure was lower than any other observed value, however, and its E wind at 45 kt indicated a main low center S of its latitude (37.0N). Low *B* fulfilled this requirement, but this low was not as deep as Low *C* in the Forbes analysis.
2. The pressure at 9VVG had also been slightly low at earlier times, but for some reason the 0600 UTC value was transmitted as identical to the value 6 h earlier (cf., Fig. 3a) despite obvious large falls which must have occurred. The 50-kt wind slightly W of S argues for a low N of its latitude (36.1N).
3. The observations from DHRG were entirely reliable and accurate, within 1 mb in pressure, during IOP 2. Its location, however, was too far from the center to have a strong influence on details.

The low-level flight that crossed Low *C* earlier continued until after 0600 UTC (Fig. 5c). At 0616–0619 UTC the aircraft flew south-southeastward across a short distance of very light winds with a cyclonic shift of 180 degrees at 37.8N 66.9W, but no verification of a closed circulation and no minimum of sea-level pressure. Continuing on and then turning to an east-northeastward track, the aircraft experienced at 0627 UTC and at 37.5 N 66.6 W a 1-min shift of wind from WNW 15 ms^{-1} to SE 20 ms^{-1}, with a minimum sea-level pressure of 978 mb. This value did not rise as the aircraft flew a bit farther on the same heading and then flew north-northwestward before ascending out of the boundary layer after 0640 UTC. After another half-hour of flight in the area at higher levels, fuel limitations required the aircraft to head back to the base at NAS Brunswick, Maine.

The interpretation of these observations in the Sanders analysis is that the light wind patch around 0617 UTC represented the remains of Low *C*, no longer a distinct center. The abrupt wind shift at 0627 UTC represented a trough of high vorticity extending northwestward from Low *C*, which was the dominant feature. The interpretation in the Forbes analysis was that the strong wind shift at 0627 UTC denoted the cyclone center itself, which was identified as Low *C*. Low *B* continued almost as deep, but about 200 km SE. Had the aircraft flown S in the boundary layer during the interval between 0627 UTC and the time at which a return to the base had to commence, it might have found the northern limit of southwesterlies and determined more accurately the position and central pressure of Low *B*. Hindsight is invaluable.

As it is, the difference in the Forbes and Sanders interpretations cannot be resolved. The Forbes interpretation requires Low *C* to take a brief jog to the ESE during extreme deepening, interrupting a track oth-

FIG. 3. (a) Same as Fig. 1a, but for 0000 UTC 14 December. (b) Same as Fig. 1b, but for the time of Fig. 3a. Additional filled circles denote the data for MRF-predicted lows verifying at this time, for the number of days range indicated by the digit for the right of "MRF."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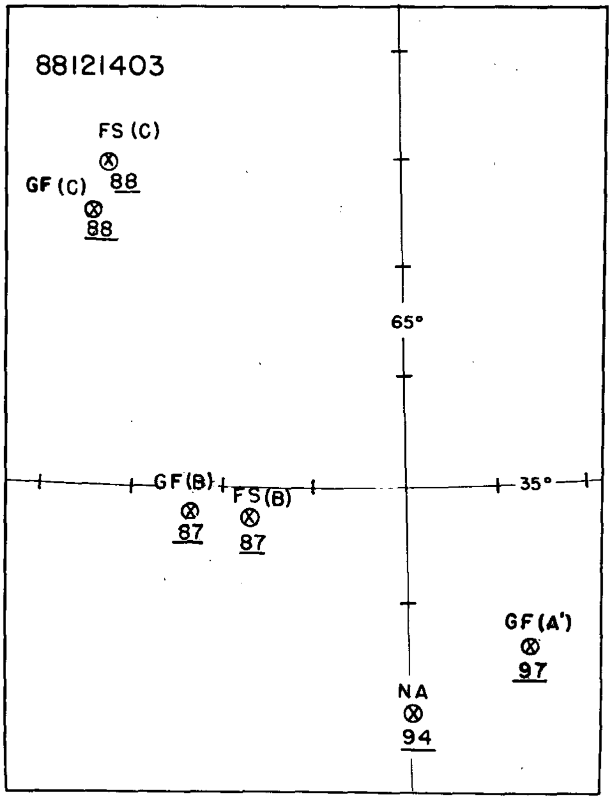
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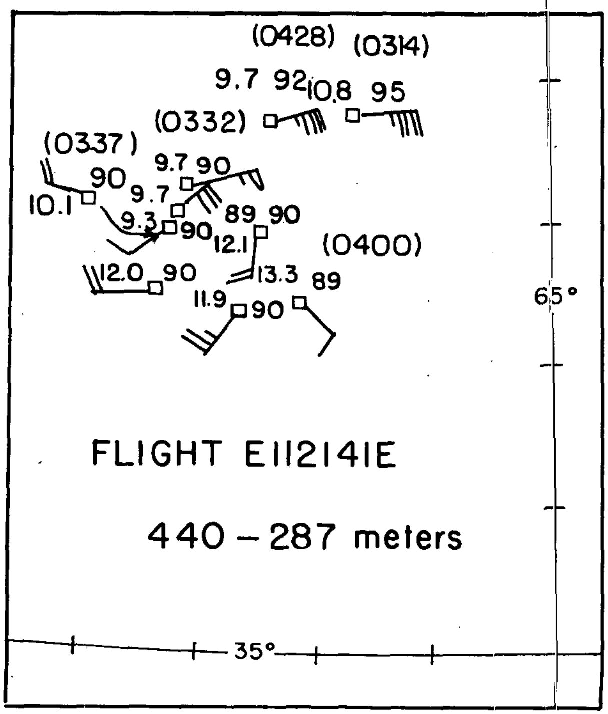
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erwise toward the ENE. The Sanders interpretation requires that during explosive deepening, Low *B* take a similarly brief jog (of somewhat larger amplitude) toward the NNE in a track likewise toward the ENE. The author's experience with rapidly deepening cyclones in dense data coverage over land is that the latter is a more likely scenario.

f. 1200 UTC 14 December

The next analysis (Fig. 6) leaves little doubt that only a single center existed. The ellipsoidal isobars, also evident in Fig. 5a, had rotated nearly 90 degrees counterclockwise in the preceding 6 h, with the major axis now oriented NE–SW. Among the numerous ships and buoys, the familiar players can be seen, with pressure errors similar to what had been estimated earlier.

All analyses agree that only a single center existed at this time (Fig. 5b). They are arranged in an elliptical envelope, matching the elliptical shape of the isobars. Central pressures ranged from the NGM's 974 mb (due presumably to the absence of the 968.5-mb value from buoy 388) to the 964 mb in the Sanders analysis (displaying perhaps a mb or two of over-enthusiasm). The Sanders position was the southwesternmost and was a reflection of the delay in minimum pressure in the hourly data from buoys 388 and 358 until after map time, even though the deepening had slowed considerably. Wind data from these drifting buoys would have reduced the uncertainty, of course.

g. 1800 UTC 14 December

The position and central pressure of the low were closely determined by a low-level aircraft traverse at 1800 UTC (Figs. 7a and b). Descending into the boundary layer and entering the storm from the W, the aircraft experienced from 1732–1744 UTC a substantial warming and moistening. This was due only in minor part to a slight descent, since the equivalent-potential temperature also rose markedly (as seen in Fig. 7c), and the boundary layer presumably was well mixed. The northerly wind of 45 ms^{-1} in the coldest air slowed to 10 ms^{-1} by 1750 UTC, with a slight veering. A rapid decrease of sea-level pressure changed to a much more gradual fall, qualitatively consistent with geostrophic requirements. This transition represented passage across a front which lay out in the peripheral flow surrounding the cyclone center, and might be described in traditional frontal terminology as a "warm bent-back occlusion"; or in more recent coinage, as part of a "T-Bone structure" (Shapiro and Keyser 1990).

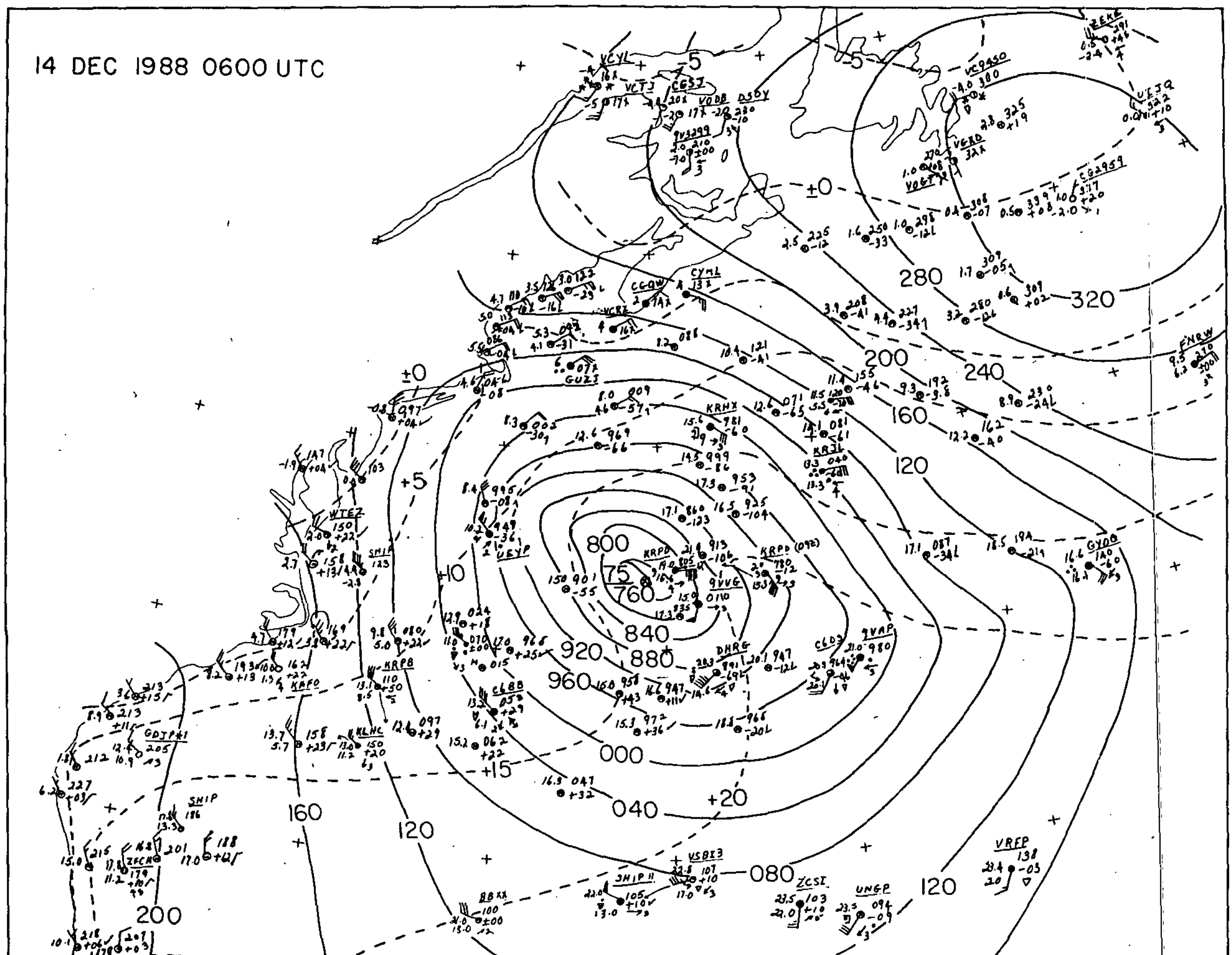
As the flight continued on toward the center, a second zone of stronger fall of pressure and rise of equivalent-potential temperature was experienced, with some increase of northwesterly wind. This occurred as the aircraft flew NNE-ward between 1805–1810 UTC (Fig. 7c), encountering the small intense center at the end, as marked by a minimum sea-level pressure and a shift to a light south-southeasterly wind. Continuing on north-northeastward for another 2 min, the aircraft immediately encountered a 25-ms^{-1} NE wind. On turning eastward, the aircraft experienced an immediate return to southerly winds, briefly light and then increasing to 25 ms^{-1} as the equivalent-potential temperature reached its peak values. This quantity then decreased markedly over the next 15 min with a slight decrease of southerly wind (after another interruption for a brief ascent), as the aircraft departed the warm, moist intense inner core of the system.

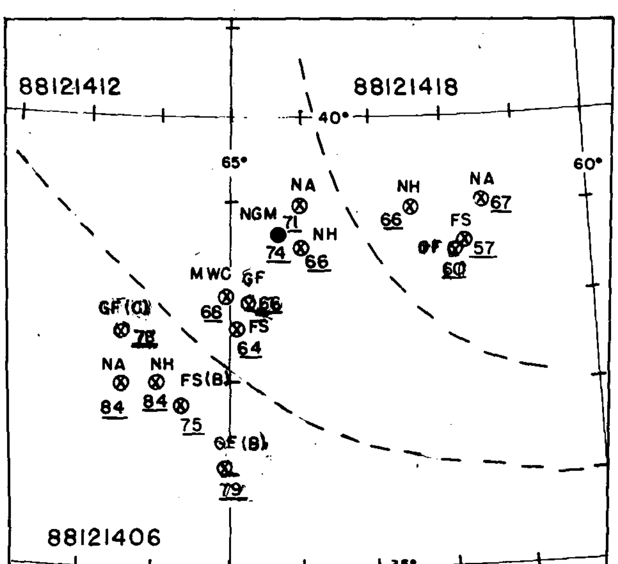
From the track of the system (Figs. 6 and 7a), it appears that this core passed between buoys 388 and 358, and must have passed almost directly over 362 (the numbers are given in Fig. 4a). Hourly reports from this last, highly accurate, buoy never showed a pressure lower than 966.1 mb. The sea-level pressure observed by the aircraft was less than this value for about 25 min during which it progressed E-ward over 1.75 degrees of longitude. Since the system was moving east-northeastward at this time at the rate of about 0.5 longitude degrees/h, with little change of shape, the zonal extent of the 966-mb isobar (had one been drawn) should have been about 1.5 degrees, and a fixed point on the earth's surface over which the center directly passed should have experienced lower pressures for 3 h. From these considerations, we must question both the reliability of the buoy data under these extreme conditions, and also the innermost isobars in the Sanders analysis (Fig. 7a). They are too large, and in fact were based on an operational version of the aircraft data, in which the innermost pressures were almost 4 mb lower.

So far as the various analyses are concerned (Fig. 5b), there was close agreement, especially between the Forbes and Sanders versions. The NA and NH analyses did not have the advantage of the aircraft data, and therefore had no ability to either detect the pressure deficit associated with the intense inner core, or to locate the center with more precision than that afforded by the ship and buoy observations.

The high values of equivalent-potential temperature in the inner core of the disturbance call for further study. Whether they were the result of horizontal transport, or whether they reflected largely the input of heat and moisture from the sea surface, as suggested by Davis and Emanuel (1988), is a question requiring

FIG. 4. (a) Same as Fig. 1a, but for 0300 UTC 14 December. The underlined 3-digit number above each drifting buoy is its identification number. (b) Same as Fig. 1b, but for the time of Fig. 4a. (c) Same as for Fig. 2c, but for flight E112141E.


14 DEC 1988 0600 UTC


88121412
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88121406
40°
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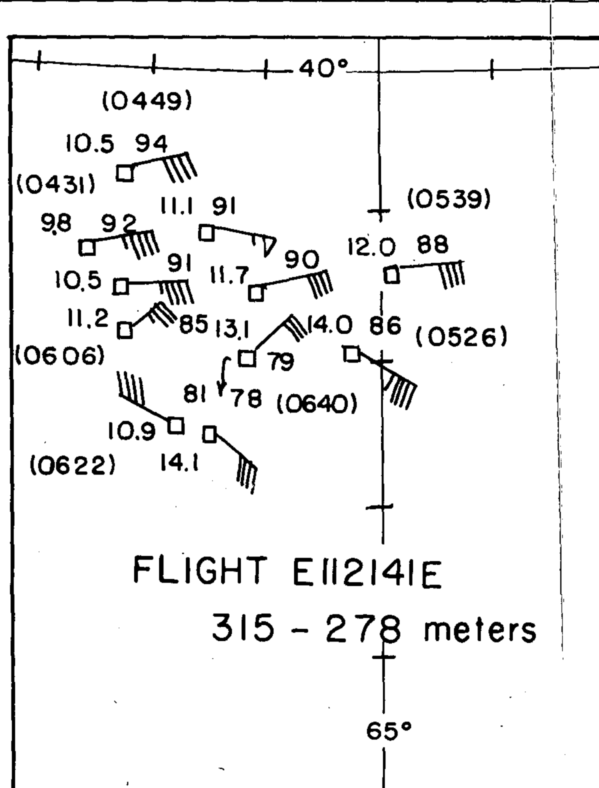
GF(B)


40°
65°
(0449)
(0431)
(0539)
(0526)
(0606)
(0640)
(0622)
FLIGHT E112141E
315 - 278 meters

a detailed analysis of the temperature and moisture fields at low levels. Such a study is beyond the scope of the present investigation.

h. 0000 UTC 15 December

The last Sanders analysis for this storm (Fig. 8a) shows a single center, somewhat less deep than previously and with a long trough extension toward the NE. The ship data, and especially the buoy observations, were well distributed about the center, but none was very close. All the analyzed positions of the low center, including the automated ones, were bunched within a circle of radius near 65 km. There was a large range of central pressures, however, from the FS 960 mb to the MRF 974 mb. The former implied the continuing existence of an intense inner core, for which there was some evidence in the satellite imagery (not shown), as there had been also at 1800 UTC. The latter is apparently incapable of showing such a feature in any case, as discussed above.

The MRF forecasts verifying at this time ranged from good to excellent. As was the case for 24 h earlier, the 5-day forecast was remarkably accurate, with a position error of 150 km and a central pressure as low as the MRF initial analysis. The worst was the updated 4-day forecast, with a position error of 425 km (still much better than average), but a disappointingly high central pressure. At shorter ranges, the forecasts improved, but only the 2-day forecast was an improvement over the oldest one. Since the model never showed any awareness of the complicated structures and evolution we have described, it is clear that the model in this instance was indifferent to them. We doubt that things always work out this way.

4. Evaluation of pressure observations

A by-product of the research analyses is careful documentation of the discrepancy between observed pressure values minus those indicated by the Sanders analysis at the point of observation. Several examples were discussed in the preceding section. These are taken to be errors in the observations. After removal of observations with obvious position errors, comparisons were made for 448 platforms, each providing 1–38 observations during the period of comparison. Of the 279 platforms contributing at least three observations, 161 (58%) produced pressure data at all times that could be fitted by the analysis with a discrepancy of no more than 1 mb. Of the remaining 169 platforms, providing one or two observations, 70% were in equally close agreement, reflecting no doubt the reduced opportunity for getting it wrong.

For each of the 279 platforms reporting at least three times, mean and rms errors were calculated. Distributions of these quantities appear in Table 2.

These data were stratified according to platform type. The special drifting buoys were considered apart from the regular moored buoys and the C-MAN platforms along the US coast. The ships were stratified according to the first letter or number of the radio call-sign. Results appear in Table 3. The moored buoys and C-MAN stations appeared to be most reliable, with the drifting buoys somewhat less so.

The group of most reliable ships was about on par with the drifting buoys, perhaps as a matter of chance since the individual samples were small. Among ship categories with a respectable sample size, those with call-signs beginning with *G* or *C* fared best, along with those for which none was provided. This indicates that the oversight did not imply a poor observation. The W- and K-ships did not do as well as we might have hoped (to say nothing of the N-ships!), while the U-ships, which the folklore holds in poor repute, did not do especially badly. Any conclusions must be tentative, owing to the generally small sample size. Errors in a given ship's observations were reasonably consistent in time, but examples of wild values, due to careless observation or communication error, could be found in any category.

Even within a call-sign group with relatively poor overall performance, examples of excellence could be found in individual ships. Plying between New York and Bermuda, PJYG reported especially faithfully and reliably, with a mean bias of +0.4 mb and an rms deviation of 0.5 mb. Its observations were exceptionally useful, as can be noted in Figs. 1–6. Stereotyping of individuals is an abhorrence.

5. Evaluation of the pressure analyses

An opportunity to test the Sanders analyses on independent data arose when groups of ships' observations for IOPs 2–5 were received from the ERICA Data Center after completion of the FS analyses. Some of these were for times for which there were no analyses; and others had, in fact, been received earlier through other channels and used in the analyses. Two purported to be in the ERICA regions at an analysis time, but were obviously from some other planet.

Of the remaining 37 new observations, 24 fitted the analyses with a discrepancy of no more than ±1 mb.

FIG. 5. (a) Same as Fig. 1a, but for 0600 UTC 14 December. (b) Same as Fig. 1b, but a combination showing comparative data for three times, those of Figs. 5a, 6a, and 7a. The center marked "MWC" denotes data from the Atmospheric Environment Service's Maritimes Weather Center in Halifax, NS. (c) Same as Fig. 4c.

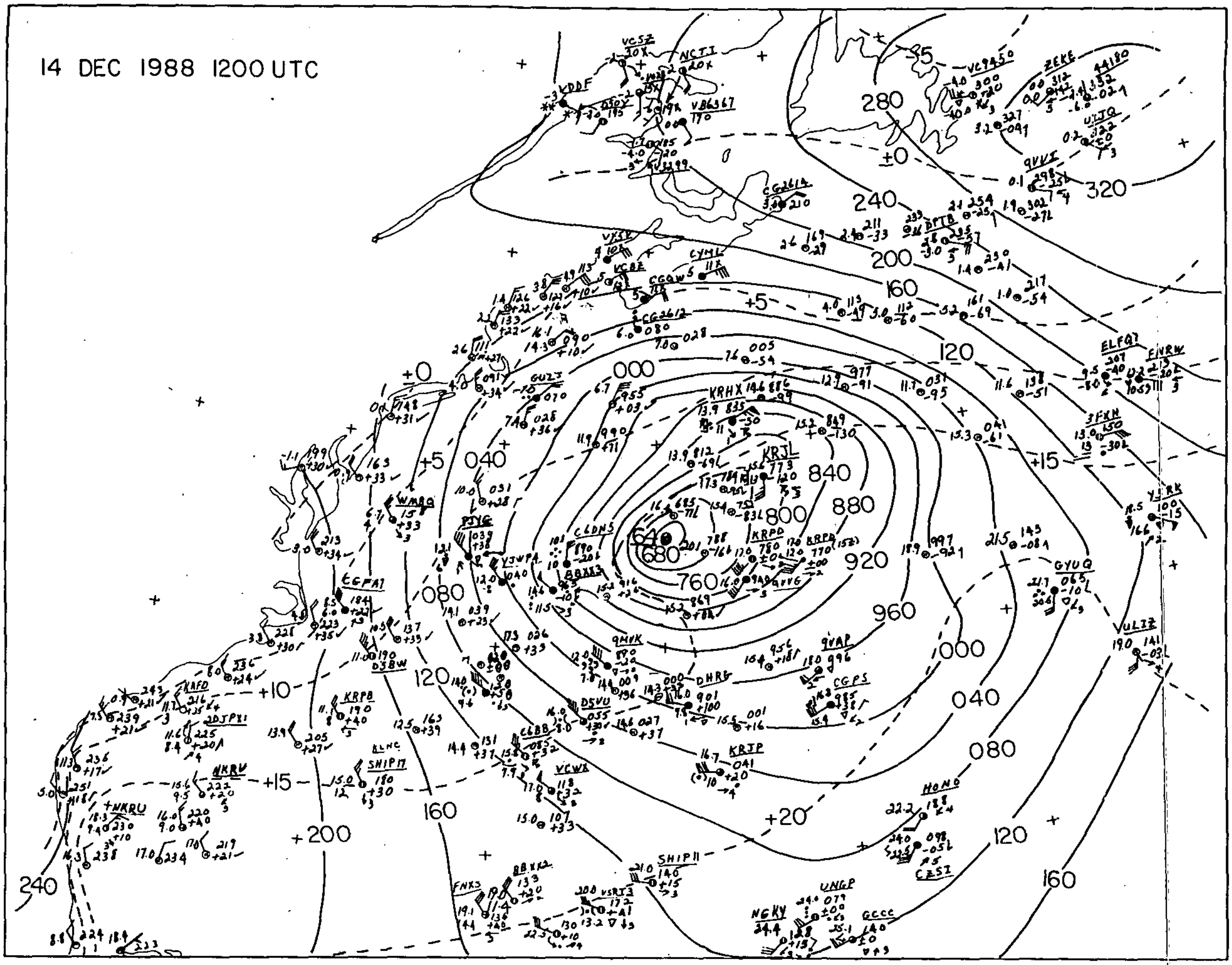


FIG. 6. Same as Fig. 1a, but for 1200 UTC 14 December.

There were two extreme deviations of +4 mb and 4 of −3 mb. One of the ships (VSBI3) showed positive discrepancies of 2 or 3 mb in three new observations, while others from the same ship used in the analyses showed a mean bias of +2.8 mb. Another, not previously heard from (NHNF), appeared to have a low bias of 2 or 3 mb in four observations close to the coast or to other ships and moored buoys. One of the extreme discrepancies of +4 mb was almost certainly an erroneous value from XCBR, since it was not consistent with other observations from that ship. With the rest, however, the discrepancies reflected errors in the analysis, or small errors in the reported pressures.

When the eight suspect observations had been culled, the remaining 29 showed a mean discrepancy of +0.1 mb, with an rms value of 1.5 mb. The large values were in regions of strong gradient. Generally, then, the overall reliability of the FS maps, in terms of rms analysis error, is probably not more than 1.5 mb.

6. Concluding summary

For times of interest during ERICA IOPs 1–5, we have compared central positions and sea-level pressures in lows as shown in a variety of analyses, made in both operational and research environments. The operational analyses were both automated and manual.

Agreement was closest between the two series of research analyses. The rms deviation was 69 km around a mean position difference whose magnitude was 31 km. The rms deviations for the automated analyses were about 180 km, around similar mean position differences. Central pressures in the automated analyses were several mb less deep, on average, than in the manual analyses based on substantial numbers of observations from ships. Extreme cases showed differences of about 20 mb.

A detailed study was undertaken of the analysis differences for the evolution of the IOP 2 storm from a

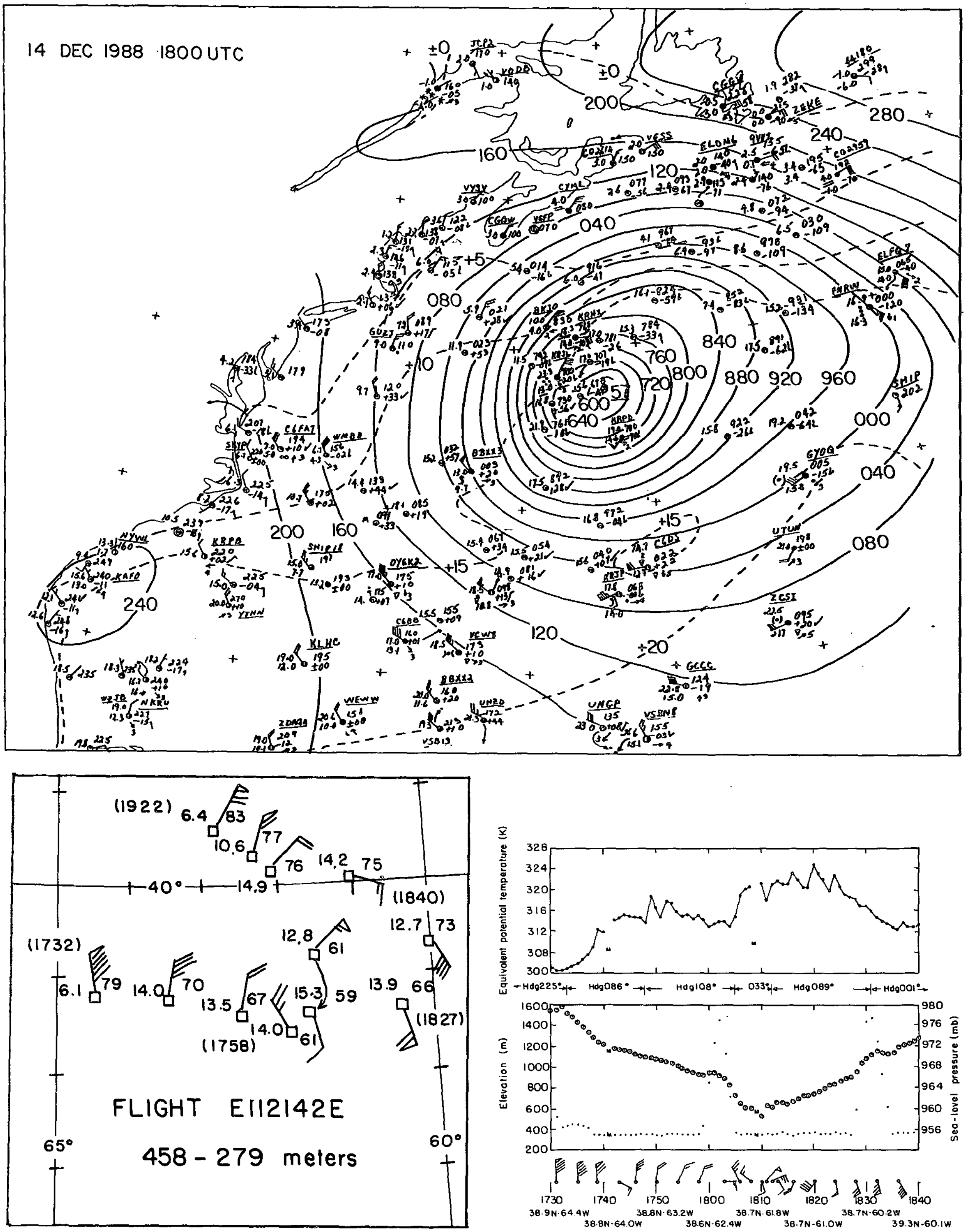


FIG. 7. Same as Fig. 1a, but for 1800 UTC 14 December. (b) Same as Fig. 2c, but for flight E112142E. (c) For the segment of the flight from 1730–1840 UTC, elevation and sea-level pressure (lower diagram), and equivalent-potential temperature (upper diagram). Selected winds are plotted in the conventional fashion. Those plotted at 1743 and 1803 UTC represent vector averages over several minutes, when winds were erratic and not credible. Even the averages are highly doubtful. Approximate headings of the aircraft are given between the upper and lower diagrams over the indicated time intervals.

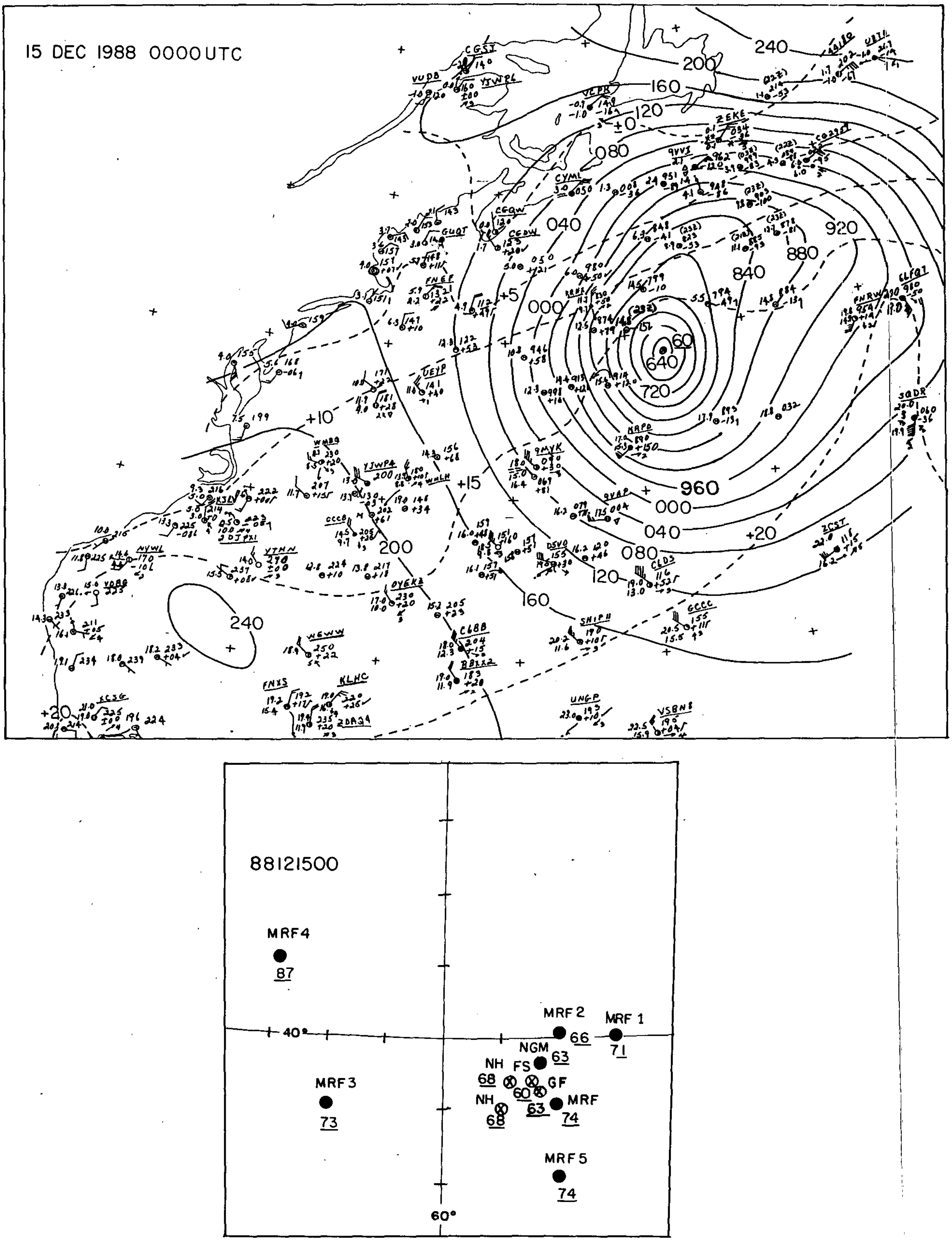


FIG. 8. (a) Same as Fig. 1a, but for 0000 UTC 15 December. (b) Same as Fig. 3b, but for the time of Fig. 8a.

TABLE 2. Mean and rms pressure errors (*halves* of mb) for platforms providing at least three observations.

Error	>+8	+8	+7	+6	+5	+4	+3	+2	+1	0	−1	−2	−3	−4	−5	−6	−7	−8	<−8
Mean	1	1	3	3	3	4	7	17	42	113	31	23	14	7	1	4	1	1	2
rms	3	5	3	6	5	8	16	55	130	48									

complex multiple beginning state to an intense single final state. Findings included the necessity for (1) following the recent history of pressure errors for individual ships, (2) detecting reversal of order of digits in the coded message, (3) recognizing gross errors in reported position, (4) using wind observations as a guide in placement of isobars, (5) making the analyses consistent with low-level aircraft traverses, (6) making the analyses consistent with major features of the satellite imagery, and (7) recognizing that the data from the special drifting buoys, although excellent in general, contained instances and episodes of highly erratic behavior. In particular, the small intense inner core of the final cyclone was not observed by a buoy very near its track, and would have been undetected but for a nicely-timed low-level aircraft traverse.

The MRF forecasts for the final state of the cyclone were extremely good (even five days in advance), despite the model's failure to predict the complex structure during the evolution of the storm. In this instance, then, the final major cyclogenesis was not sensitive to the details of the early history of the system.

A comparison was made of pressures from the author's research analyses with the observed pressures from a variety of platforms. Of the 279 platforms providing three or more observations, 58% showed a discrepancy of no more than 1 mb at all times. Mean errors exceeded 2 mb for only 7% of the platforms. RMS deviations of individual observations from the platform mean exceeded 2 mb in only 8% of the instances. Stratification by platform type showed that the moored buoys and C-MAN platforms produced the most accurate data, with the drifting buoys and the best categories of ship not far behind.

TABLE 3. Mean and rms pressure discrepancies between reported and FS-analyzed pressures.

Source category	N	% of platforms mean error >+1 mb	% of platforms rms error >1 mb
C-Man and moored buoys	30	0	0
Drifting buoys	55	4	11
ABDJST234-ships	31	10	6
G-ships	13	15	15
Unidentified ships	16	25	6
C-ships	30	13	20
W-ships	16	19	25
U-ships	10	40	20
V-ships	28	32	29
K-ships	13	38	31
EFILNOPZ9-ships	37	40	30

Comparison of the pressures in the research analyses, with a small sample of observations received after completion of the maps, suggested an upper limit of uncertainty for the analyses of 1.5 mb. Uncertainty appeared to be larger where pressure gradients were strong.

Comparison of manual with automated analyses shows serious deficiencies in the latter, owing in part to the great difficulty in dealing with the marine data base with its variable quality and multitude of error sources and characteristics. If accurate positions and central pressures are important, manual analyses over the oceans must continue until such time as algorithms for automation may improve substantially.

Of course, the less deep central pressures in automated analyses of cyclones will make the dynamical predictions (also insufficiently deep) look better. But is it not compelling to have our best estimate of what is actually out there?

We must concede that the closeness of the NH analyses to the manual ones prepared after the fact, as shown in Table 1, was due in part to the extra data available because of ERICA, and to the real-time consultation between the routine analysis operation and the special ERICA operations center. This level of accuracy cannot be expected to continue. In fact, with automated isobars over the oceans, the level of accuracy will drop significantly, to judge from Table 1.

We hope that this information is helpful to those who wish to undertake oceanic surface analysis in either manual or automated mode, or to those who wish to use the existing maps. We urge that features of these analyses be referred to as "analyzed" rather than "observed". Use of the latter term tends to conceal the uncertainty inherent in this challenging and fascinating enterprise.

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