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A systematic satellite approach for estimating central surface pressures of mid-latitude cold season oceanic cyclones

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ABSTRACT

During the past 5 years, the National Environmental Satellite, Data and Information Service (NESDIS) has undertaken a major operationally-focused study of mid-latitude ocean cyclones in support of various National Oceanic and Atmospheric Administration (NOAA) and Department of Defense (DoD) programs. The intent was to develop techniques for improving the accuracy of surface pressure analyses over ocean areas where conventional surface data is limited. The study focused on the North Atlantic Ocean initially. Current research has included North Pacific Ocean cyclones, as well. We examined more than 5 dozen storms and developed conceptual models which described their growth and decay. We then incorporated the work of Smigielski, Junker and Haller and Dvorak to develop a set of operationally-focused, user friendly, decision trees. The technique (referred to as the SMB technique, for its originators) has been applied operationally in the Atlantic for about 3 years, and in the Pacific for slightly more than 1 year. Results suggest that the technique provides very reliable estimates of central pressure for certain categories of storms. Errors are typically ±4mb from in-situ data (when such data is available).

1. History

Satellite data has been shown to be a valuable tool in detecting extratropical cyclones, monitoring their development, and estimating their central pressure. This is not a new concept. Early researchers noted the value of satellite observed cloud patterns in interpreting surface meteorological conditions, especially the positioning of surface fronts and lows, and the likelihood of cyclogenesis.

Using visible polar orbiter imagery, Smigielski (1973) introduced a series of satellite cloud patterns which showed both developmental and non-developmental cyclogenesis over 24-h time intervals. Smigielski noted that extratropical cyclones typically evolved from incipient wave to full maturity in approximately 72 h. The process is speeded up (i.e., about 48 h) for rapidly developing cyclones. After development ceases, slow dissipation usually occurs. Redevelopment, or reintensification is not likely, unless a reinforcing influence, such as positive vorticity advection (PVA) is introduced into the system. Even with this influence, cyclogenesis usually involves a newly developed cyclonic system.

In recent years, Junker and Haller (1980), Younker (1981), Smigielski and Ellrod (1985) and others described various ways to use satellite imagery in oceanic surface analysis. Satellite indicators of cyclogenesis, intensification rates, location and intensity of strongest surface winds, and estimates of central surface pressure were among the topics studied.

2. Developing the technique

We capitalized on the concepts put forth by Junker and Haller concerning middle latitude oceanic cyclones and merged them with the

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developmental technique for tropical cyclones originated by Dvorak (1984). The result is the Smigielski-Mogil-Burtt (SMB) technique, a decision-tree approach for estimating central surface pressures for mid-latitude storms in both the North Atlantic and West Pacific Oceans.

Junker and Haller (1980), recognizing the need for improved oceanic analysis in data poor areas, devised a technique for estimating surface pressures using a single satellite image. All cyclones that formed along strong baroclinic zones during the cold seasons of the year, October to April in the Northern Hemisphere, were studied. Using infrared imagery, cloud pattern recognition was used to identify various stages of storm development. The amount of cloud pattern circulation shown by satellite imagery within and around the storm was used to assign central surface pressures to the cyclone. Because surface pressures in the larger scale environment surrounding the cyclone were less uniform than those around tropical cyclones, we did not attempt to use the technique for directly estimating the wind field. We felt that this would evolve once the entire surface weather map was analyzed.

Dvorak's technique uses 24-h changes in cloud patterns within the main central overcast and corresponding cloud bands to determine maximum winds and associated surface pressures of tropical cyclones. The 24-h period helps to eliminate the strong diurnal influence in convection observed in the tropics.

In developing the SMB technique, we used the Dvorak technique as a model and applied it to the patterns described by Junker and Haller (1980). We studied a total of more than sixty cold season storm events from both the Atlantic and Pacific Oceans, and several summer season events in the North Atlantic. Most cases did not include research data sets. Nonetheless, we were able to develop a more systematic, empirically-based, procedure for using satellite imagery to determine minimum central pressures of mid-latitude, cold season oceanic cyclones.

In our studies, we discovered that a 12-h period for imagery comparison was better suited for the baroclinic forcing found in middle-latitudes. Using this shorter time interval, we studied more than 60 storms and found that increasing amounts of multi-layered clouds and increasing curvature of the storm system were both directly related to lower surface pressures. We used this information to develop conceptual graphs of cloud pattern-central pressure relationships (Fig. 1).

The cloud schematics and pressure graphs of Fig. 1 represent conceptual cloud patterns at 12-h intervals for fully developing mid-latitude cyclones, from incipient wave to the initial filling stages. This does not mean that all cyclones progress through this whole cycle, that they do at the same rate, or with exactly the same cloud patterns. Many storms will reach their minimum pressure before going through the entire cycle. Some develop slower or faster than the patterns shown. The observed developmental curve for slowly deepening storms will lie above the conceptual curves, while more rapidly developing storms will reach their minimum pressure earlier and will lie below the conceptual curves. The initial central pressure value of 1012 mb was chosen based on cases examined as part of our empirical study; it serves only as a starting frame of reference point. The cloud patterns seen throughout the life cycle of a oceanic cyclone, however, seem to faithfully represent the central surface pressure values of the cyclone within ± 4 mb.

Because surface data is so scarce, we used all plotted surface reports to maximum advantage. This included checking the consistency of ships, buoys, and land stations from map to map (Sienkiewicz, 1990), as well as using single station analysis for fixed observation sites (buoys and land stations). To avoid biasing our study, we estimated surface pressures first using the SMB technique; then we compared these to the analyses and observed data. Almost every storm we studied had enough nearby surface data at several times during its life cycle to provide a reasonable assessment of central pressure. We have just begun to examine ways of incorporating microwave data from polar orbiting weather satellites as another check on the structure and strength of these storms.

The SMB technique is based on the same premise as the Dvorak technique: "once a system begins to develop, it will usually develop (as seen on satellite imagery and surface pressure data) in a fairly uniform manner until it reaches maturity". Although there may be variations in antecedent conditions (e.g., split jet streams), our studies show that cloud and system evolution appears to proceed in a fairly similar manner for the storm types we studied. Additional studies involving

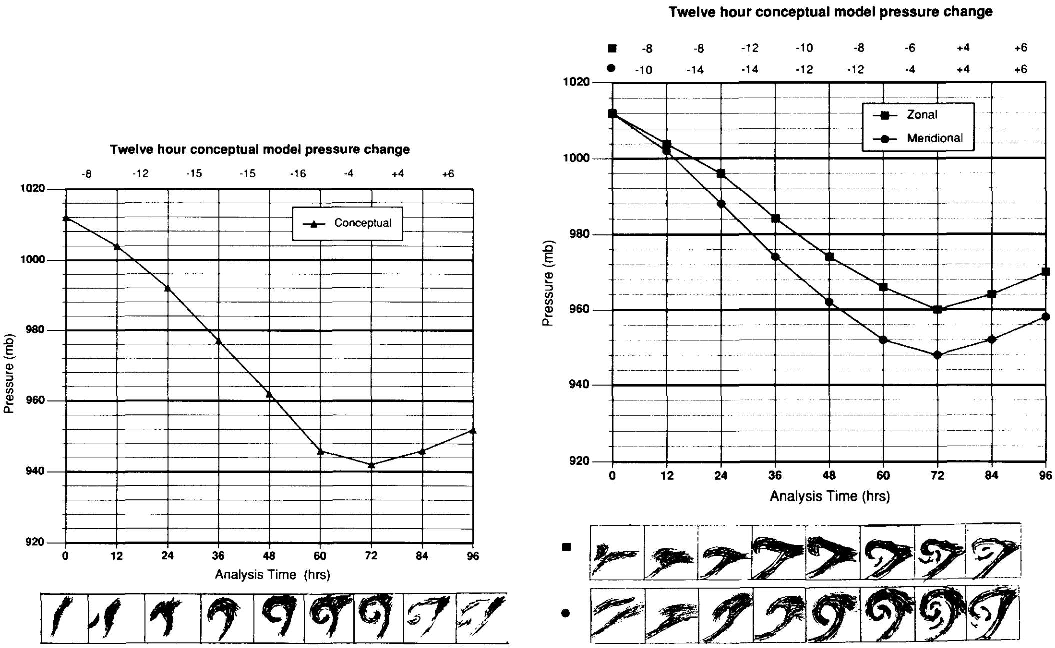


Fig. 1. (a) Conceptual SMB pressure curves and cloud schematics for meridional moving storms in the North Atlantic Ocean. (b) Conceptual SMB pressure curves and cloud schematics for meridional and zonal moving storms in the North Pacific Ocean.

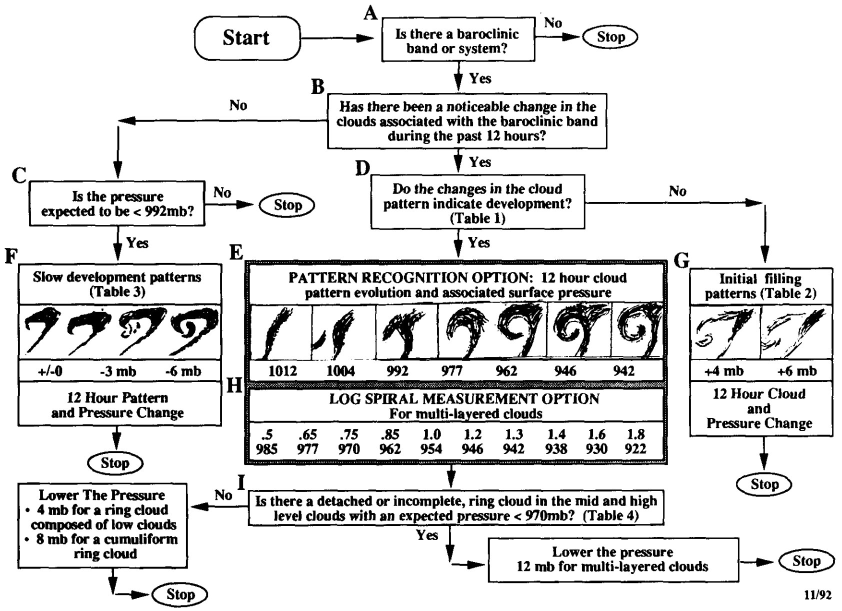
small-scale polar lows, "digging" systems, and lower latitude cut-off lows are underway.

One of the most important steps in analyzing mid-latitude storms, just as is the case for tropical systems, is determining time continuity of central pressures. Since all storms do not start and end with the same minimum central pressure, a complete history of central pressure plotted against a conceptual pressure-cloud pattern curve is necessary. This also helps to correct for variations in the large-scale pressure field surrounding each storm. Although a 12-h interval for image comparison is recommended, the technique can be used at more frequent intervals, especially when storms are developing rapidly. It is only necessary to remember that 12-h intervals were used to develop the technique.

Flow charts were developed to enable meteorologists to determine cloud pattern changes leading to development and subsequent decay of mid-latitude ocean cyclones. The conceptual graphs and schematics (Figs. 2a–b), along with Tables 1 to 5, are used in applying the SMB technique. The indicators in Tables 1–3 provide clues as to the type of development or filling which is occurring. We have found that, at times, indicators from more than one table are present. In these cases, we balance the conflicting indicators to see which table dominates. When two indicators suggest filling and two suggest deepening, the system is often at or near the end of its developmental cycle.

The specific decision boxes for the Atlantic technique are described in Section 3. Adjustments for storm size (baroclinic) and shape (barotropic) in Table 5 have only been developed for Pacific systems at this time. Fig. 3 shows the steps to follow at each synoptic time period to reach a decision on rate of development. The approach can then be extended to adjust 12-h numerical model predictions of cyclogenesis.

Different flow charts had to be devised for the North Atlantic and West Pacific Oceans because cloud patterns associated with developing cyclones differed in each ocean. This may well be linked to the stronger jet stream present in the western Pacific (i.e., the Himalayan effect). The North Atlantic flow chart was originally developed only



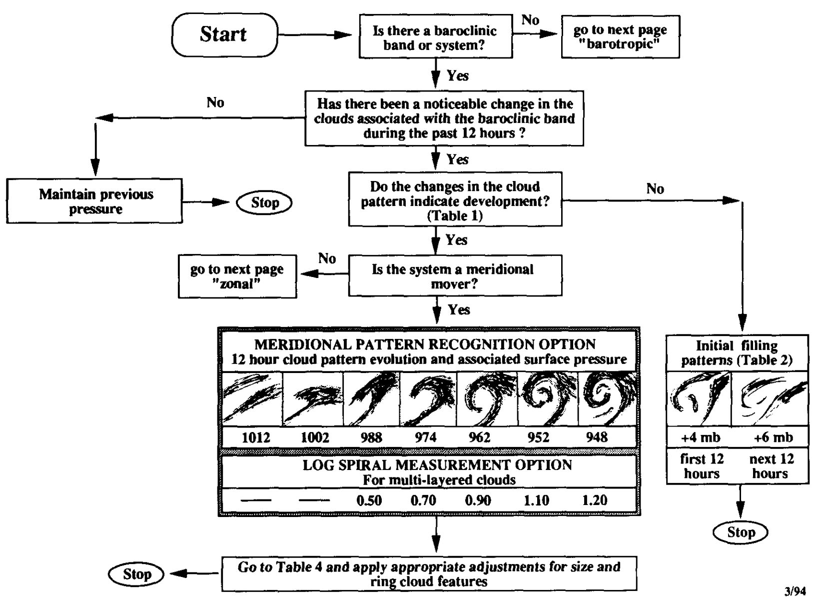


Fig. 2. (a) Flow chart (SMB technique) for estimating central pressures of mid-latitude, cold season North Atlantic Ocean cyclones. Letters assigned to various decision boxes are described in Section 3. (b) Flow chart (SMB technique) for estimating central pressures of meridionally moving, baroclinic, mid-latitude, cold season North Pacific Ocean cyclones.

Table 1. *Infrared imagery indications of extra-tropical cyclone development*

Expected pressure 1004 mb or less
(other than for initial classification)

- Baroclinic leaf cloud increases in area and brightness
- An "S" shape begins to develop and amplifies
- A PVA area is located within 10° latitude west or northwest of the baroclinic leaf and approaches the leaf with time
- A dry slot forms and expands behind the baroclinic leaf
- An anticyclonically curved polar jet streak approaches the bottom portion of the leaf from a west northwest direction

Table 2. *Infrared imagery indicators of cyclone filling*

- Comma cloud becomes detached from the baroclinic band
- Cloudiness in the comma cloud becomes thin and decreases
- The baroclinic frontal band becomes thin, or the cloud tops within it warm
- A ring cloud (composed of middle and high clouds) completely encircles the cyclone center; minimum central pressure is reached

Table 3. *Infrared imagery indicators of continued slow development*

Expected pressure <992 mb

- The north side (polar side) of the baroclinic leaf flattens along an east-west axis indicating blocking. Slow deepening of 6 mb/12 h can be expected if a PVA area is located in the cold air, either south or east of the cloud system center
- The presence of enhanced cumulus clusters in the cold air to the south, or east of the cloud system center in a mature cyclone indicates slow deepening of 3 mb/12 h
- If none of the above indications are present in a blocking situation, maintain the same pressure for the 12-h period

Table 4. *Rules for pressure adjustments with ring cloud features*

Expected pressure <970 mb

Measure the log spiral curvature of the solid middle and high level clouds to ascertain the minimum pressure of the cyclone. Then apply the following adjustment criteria (using the primary cloud type observed) for ring cloud features:

- If a ring cloud formation is evident or suspected in the low level clouds, lower the central pressure 4 mb
- If enhanced cumulus give evidence of a ring cloud feature, lower the pressure 8 mb
- If the ring cloud is distinct and detached in the middle and high clouds, lower the pressure 12 mb

for meridional storms, and for rapidly developing zonal storms north of 45° N latitude. Pacific storms were divided into meridional and zonal classes, each with its own distinct cloud patterns and surface pressures. After we completed our initial work on Atlantic systems, we recognized the need for introducing barotropic systems in the technique. These systems form north of the main baroclinic band (polar front) in the cold unstable air. They may, or may not, eventually interact with a baroclinic band. If they do become "instant occlusions," they can be treated as regular baroclinic systems according to the SMB techni-

Table 5. *Pressure adjustments for size and shape pacific ocean storms*

Baroclinic (meridional)		
Size (degrees latitude) of multi-layered clouds		Adjustment
5–9		+8 mb
10–14		+4 mb
15+		none
Barotropic (pressure <1000 mb)		
Size (degrees latitude) of multi-layered clouds	Shape	Adjustment
<15	circular	+4 mb
15+	circular	none
<15	elongated	+8 mb
15+	elongated	+4 mb

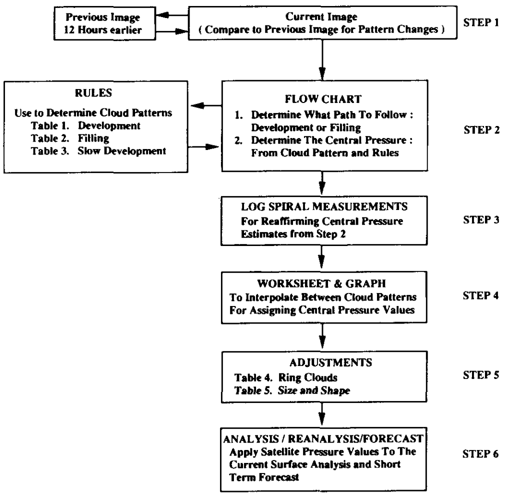


Fig. 3. SMB technique procedures.

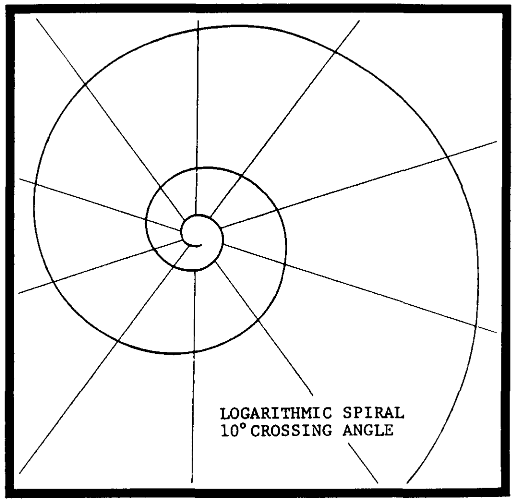


Fig. 4. 10-degree logarithmic spiral. "10 degree" refers to the crossing angle or the angle of inflow. This is the same spiral used to evaluate the curved band axis of tropical cyclones (Dvorak, 1984).

que. We have included them in the Pacific technique, but still urge caution when assigning central pressures to these systems when they are in the barotropic stage of development. This is because our research on their classification and evolution is incomplete.

Although cloud patterns for some stages of development appear similar for Pacific Ocean zonal and meridional movers, it is fairly easy to recognize which system type is present. In the West Pacific Ocean, due to stronger westerly winds at upper levels, developing zonal systems become elongated in an east-west direction and are more wedge-shaped than their meridional counterparts. Our research has also shown that developing zonal storms actually have brighter clouds than weakening meridional storms. The historical system track can help determine which type of storm is present, as well; but the best clue involves how much (if at all) clouds are building northward ahead of the system. When clouds do not build northward, or build northward only slightly, the system is most likely to be a zonal mover.

The SMB technique, just as the Dvorak technique for tropical cyclones (Dvorak, 1984), makes use of the 10 degree logarithmic spiral (Fig. 4) for measuring cloud curvature of main cloud features associated with the cyclone. Our studies have shown that the amount of cloud system curvature around the storm is related to the central pressure of the cyclone. Analysts place the log spiral onto a satellite picture (hard copy or computer display) and rotate the spiral until they obtain a "best fit" around and near the comma head and adjacent frontal (baroclinic) band. Then they count the number of tenths of a spiral (tick marks) from the tip of the comma head to where the spiral curvature of the log spiral becomes parallel to the back edge of the baroclinic band (Fig. 5).

In cyclones that have a wedge-shaped "dry slot" (i.e., those that are developing and zonally-moving, and those that are starting to fill as they move meridionally), the spiral measurement is taken only in the comma cloud portion of the system (Fig. 6e).

In addition to log spiral measurements of cloud curvature around the storm, adjustments to central pressure are made due to the presence of "ring cloud" features within the central portion or curl of the cyclone. "Ring clouds" are similar in appearance to the eye wall of a tropical cyclone, but typically lack an intense convective character. They sometimes develop as the central pressure in the cyclone drops below 970 mb (although we have seen cases of "ring clouds" with pressures around 990 mb). Examination of nearly a dozen cyclones with "ring clouds" showed that these systems often have hurricane or near-hurricane

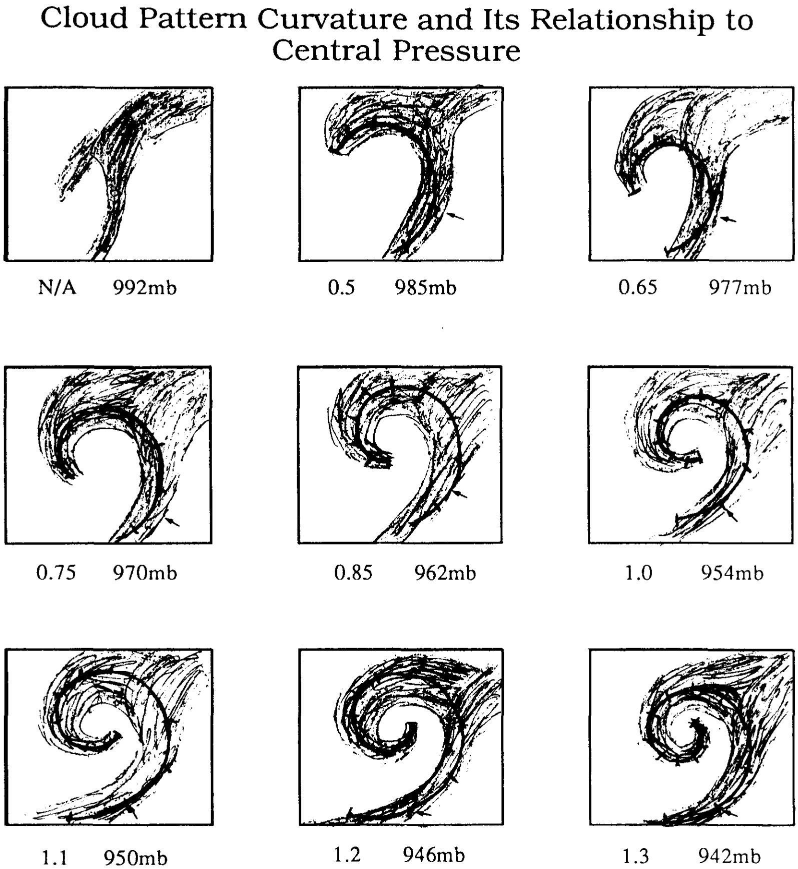


Fig. 5. Cloud measurement in tenths of a ten degree log spiral (tick marks) and associated central pressures for North Atlantic Ocean cyclones. Shading indicates middle and high clouds only.

force winds within or near the ring cloud, with weaker winds associated with the "eye" of the system.

Based on our empirical studies, we assigned adjustments for three types of ring clouds (Table 4). Fig. 6 shows schematically how ring cloud features are used to make adjustments to the central pressure. In Figs. 6d, e, no adjustments are necessary, since the cloud spiral remains unbroken and is continuous around the cloud vortex center. Ring cloud adjustments are made only for detached and incomplete ring clouds (i.e., those not directly connected to the comma cloud). A complete ring cloud usually means the cyclone has reached its lowest pressure.

It is important to note that ring cloud adjustments only apply when the ring cloud is developing. Once the cyclone begins to lose high and middle cloudiness or becomes elongated, or the ring cloud elongates and becomes detached from the main baroclinic system, ring cloud adjustments no longer apply.

In filling storms (Fig. 7), the baroclinic band shows signs of eroding, the baroclinic band moves away from the cloud system center and/or a wedge shaped clear zone appears between the cloud system center and the baroclinic band. Overall, the system takes on a more elongated appearance.

Some systems may become blocked by a high- or low-pressure system to their north. When this occurs, the poleward cloud edge typically becomes straightened and the cloud pattern appears to suggest filling of the system. The comma cloud-baroclinic portion of the system will remain intact,

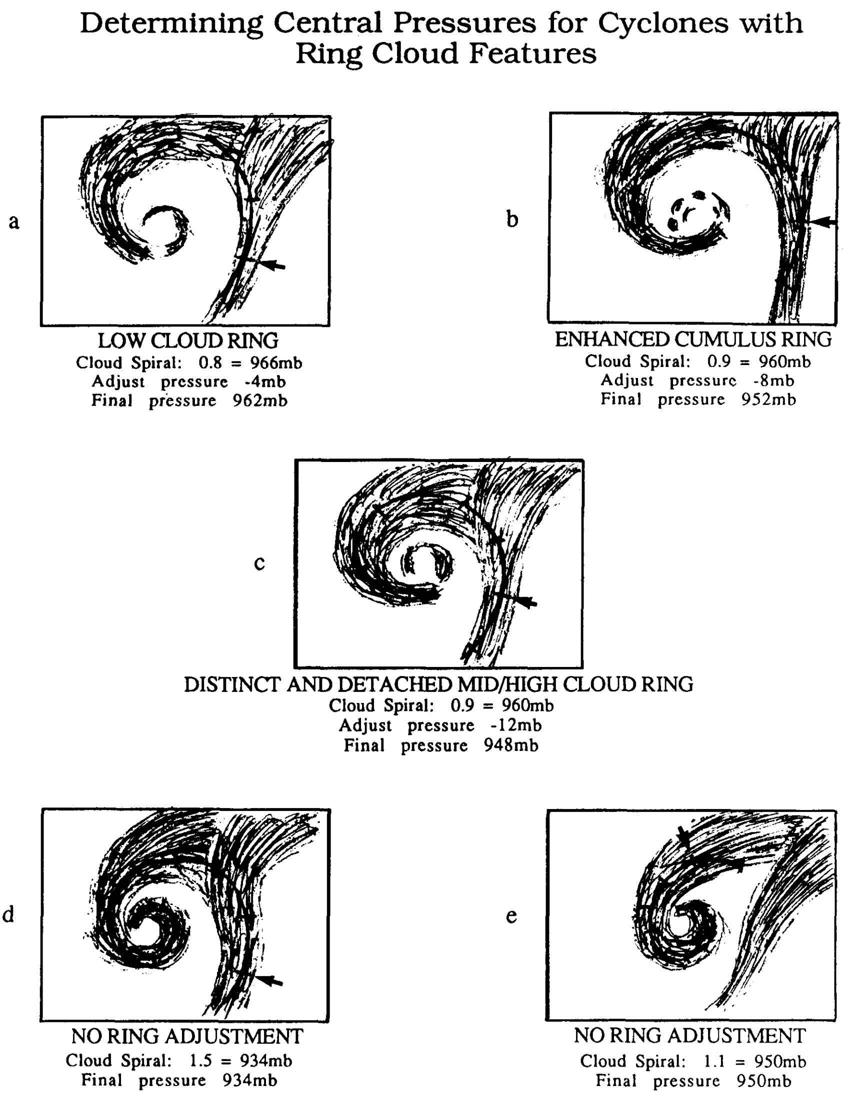


Fig. 6. Schematics showing examples of central pressure estimates for Atlantic Ocean cyclones with ring cloud features. For schematics (d) and (e), ring cloud adjustment was NOT applied because the ring cloud is attached to the main spiral band. For schematic e, spiral measurement is for comma head portion only due to the presence of a wedge-shaped "dry slot", separating the head and tail portions of the comma cloud.

however, with little erosion of high and middle clouds. Also, the cloud edge associated with the dry slot will remain rounded, rather than wedge shaped. An example of such a slow developing system is shown in Fig. 8. Compare Figs. 7 and 8 to see the differences between cloud patterns associated with filling and slowly developing storms.

3. The flow chart, atlantic ocean

The key to estimating surface pressures of cyclones based on satellite image interpretation is the flow chart (Figs. 2a, b). Since the SMB technique can only be used with certain types of cyclones, it is important that a systematic approach be followed in analyzing satellite cloud

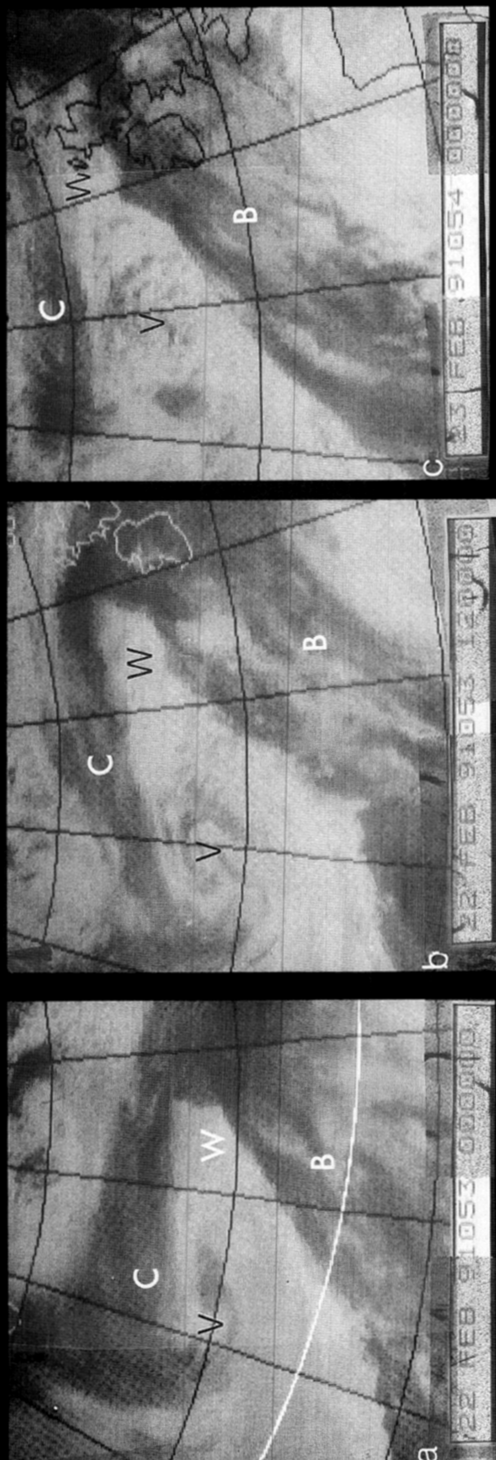


Fig. 7. An example of a filling baroclinic system in the North Atlantic Ocean (refer to box G of Fig. 2a).

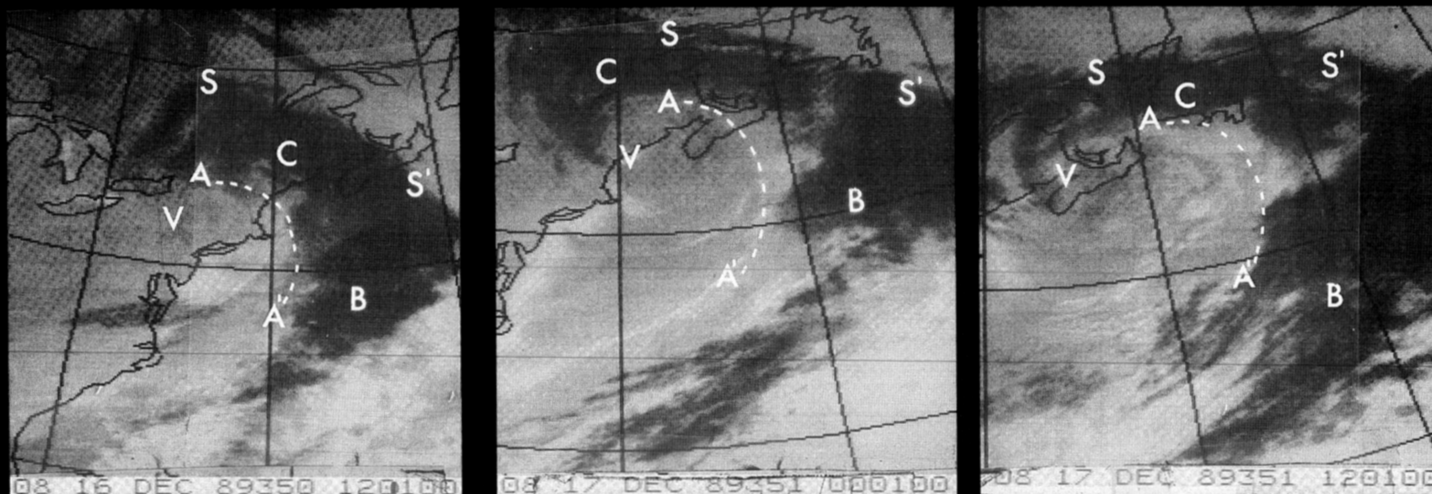


Fig. 8. An example of a slowly deepening system in the North Atlantic Ocean. During the 24-h period shown, cloud pattern evolution continues with increasing curvature around the storm system vortex "V". Clouds associated with both the baroclinic band "B" and the comma cloud "C" remain bright. The back edge of the cloud system (A-A′) remains rounded, while the northern or leading edge (S-S′) is straighter. Development should proceed slowly, with lower pressures than cloud curvature would indicate, due to the presence of a blocking high or low to the north of the system. In the last image, the boundary S-S′ is becoming rounder, indicating an end to blocking and a return to more typical storm development.

pattern changes and their relationship to central pressures. The following describes the steps in using the flow chart for the North Atlantic Ocean. Due to space constraints, the explanation of the West Pacific flow chart has been omitted. Once you understand the Atlantic Ocean chart (Fig. 2a), it should become easy to understand the one for Pacific Ocean (Fig. 2b).

The first question asked is in Box A. *Is there a baroclinic band*? To proceed, a "yes" response is needed, since the technique requires the presence of such a feature (Table 1). One exception involves a barotropic, cold air development that does not acquire baroclinic tendencies until the system becomes more mature. The flow chart can be used at any time the barotropic system takes on baroclinic characteristics (i.e., cold air cloud circulation merges with the baroclinic frontal band and becomes an "instant occlusion"). This type of development was introduced for Pacific storms and is being examined for Atlantic systems at this time.

Once it has been established that a baroclinic band exists, the next consideration is *whether a noticeable change has occurred during the past 12 h*, (Box B). In initial and subsequent developments, noticeable changes could include an increase in the amplitude of the typical "S" shape associated with cyclogenesis and/or and increase in the bright cloudiness within the baroclinic leaf.

If the answer to the question in Box B was "yes", proceed to Box D to determine *if the changes are associated with development or filling*. If the answer to *do the changes in the cloud pattern indicate development*? (Box D) is *yes*, the 12-h cloud pattern (Box E) should be used to estimate the central pressure.

Box E lists the conceptual 12-h cloud patterns associated with cyclogenesis. Below the cloud patterns are the corresponding central pressure values. Central pressure values estimated from satellite imagery can vary ± 4 mb from those analyzed on a surface chart.

In addition, development can be slower or faster than the conceptual cloud patterns and associated pressure values shown. It is possible for a 1012 mb cloud pattern to become a 992 mb cloud pattern in 12 h under rapidly developing conditions. When development is slow, a 1012 mb pattern may take up to 24 h to become a 1004 mb pattern.

If a well-organized storm system is present, with a central pressure less than 992 mb (Box C), and little change in cloud pattern is discernible in a 12-h period, slow development may still be taking place, (Box F). Table 3 gives the criteria for slow development, and Fig. 8 shows a sequence of images illustrating this situation.

The main feature that typifies slowly developing cyclones is the presence of a well defined east-west band which extends from the cloud vortex center to the main baroclinic band. This east-west band typically remains bright, with a flat poleward edge. The region near the cyclone center often becomes oval shaped, also with an east-west orientation. The poleward edge moves slowly toward the block, while the north-south baroclinic band moves more rapidly eastward away from the cloud system center. This situation is normally associated with a blocking high or low poleward of the advancing cyclone.

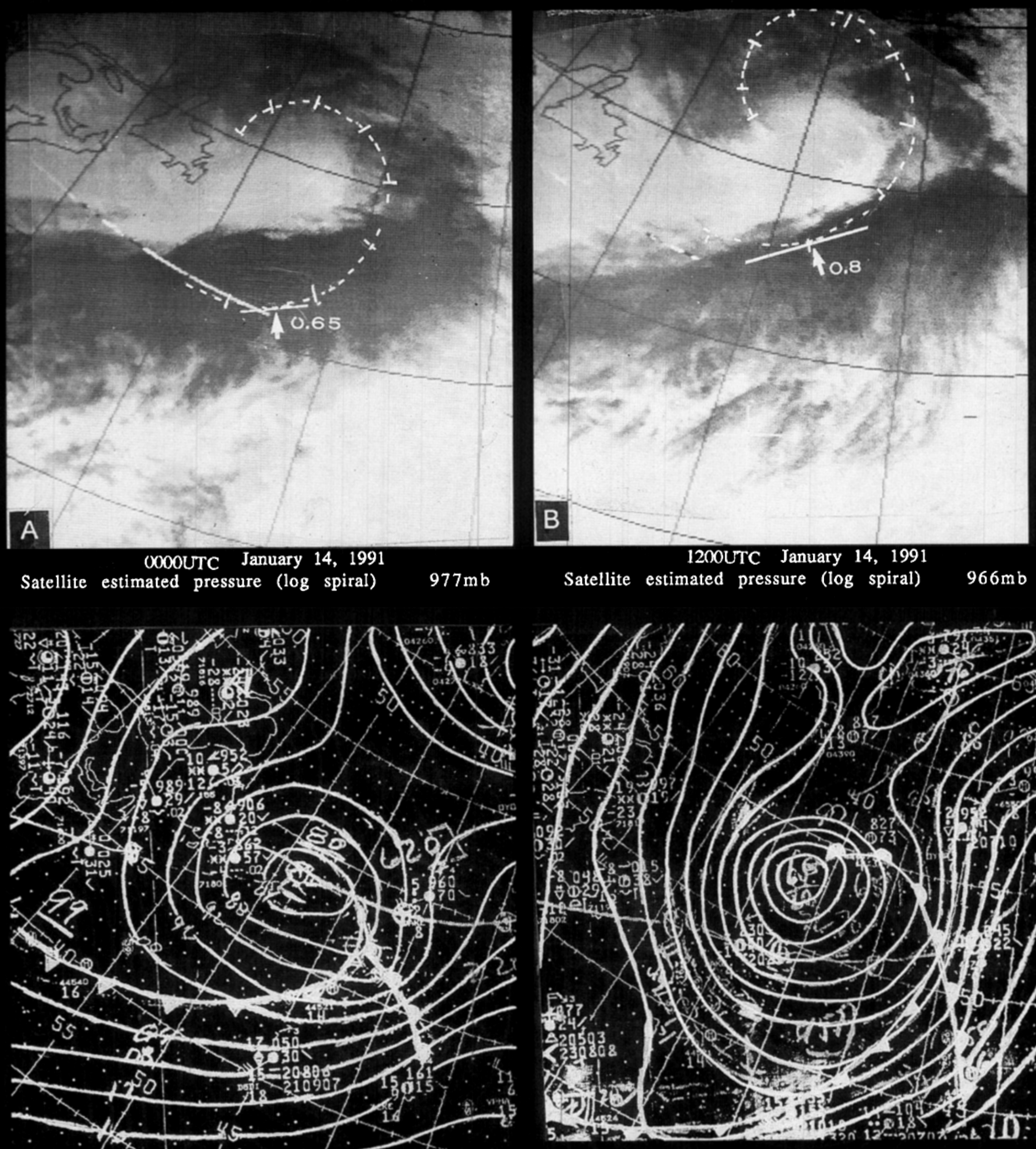
In the schematic drawing, (Box F), the evolution from the first to the second pattern indicates no substantive change in cloud structure within, or around the cloud circulation center. Thus, the 12-h pressure change would be zero. The presence of enhanced cumulus adds energy into the system and the pressure would lower about 3 mb from the previous 12-h pressure value. If a PVA area is observed south or east of the vortex center, stronger energy is being introduced and a pressure fall of about 6 mb during the 12 h period can be expected.

Another option under Box D involves filling. The criteria for filling are given in Table 2. It is possible to estimate the amount of initial filling by using the conceptual cloud patterns listed in Box G.

Each schematic in Box G represents a conceptual 12 h cloud pattern during the first 24 h of filling. The storm would fill 4 mb during the first 12 h and an additional 6 mb during the next 12-h period. After this, pressures can fill more rapidly. Small-scale, rapidly deepening, systems typically fill more rapidly than the values suggest here.

To add objectivity to the technique, we introduced a 10 degree log spiral distance measurement (Box H). This is the same approach used in analyzing tropical cyclones (Dvorak, 1984). The length of the comma cloud spiral composed of middle and high clouds is measured from the tip of the comma head where it shows the greatest amount of curvature to a point within the baroclinic band where the spiral becomes parallel to the back edge of the frontal or baroclinic band. Although different analysts may align the spiral slightly differently, our experience through scores of training workshops shows differences are only about 0.05 of a spiral measurement.

To further refine our estimates, we explored measuring the curvature of the dry intrusion (or



0000UTC January 14, 1991
Satellite estimated pressure (log spiral) 977mb

1200UTC January 14, 1991
Satellite estimated pressure (log spiral) 966mb

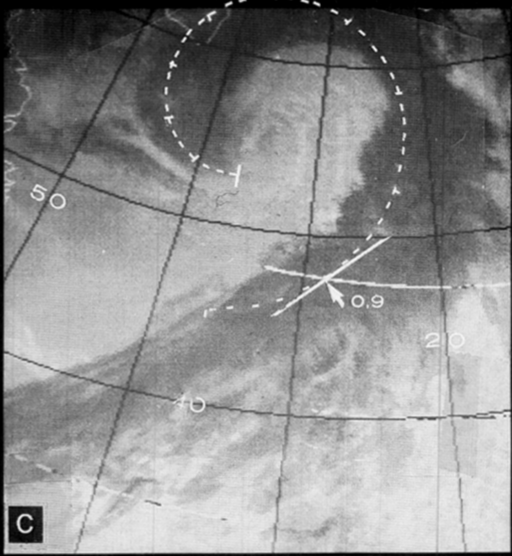
0000UTC January 14, 1991
NMC analyzed pressure 980mb

1200UTC January 14, 1991
NMC analyzed pressure 964mb

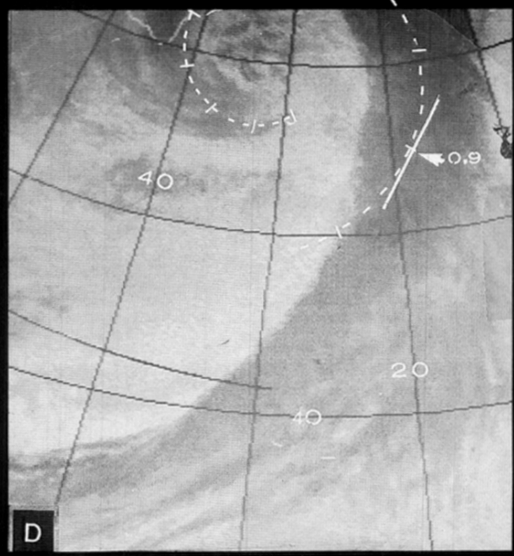
Fig. 9. 36-h sequence of storm evolution over the North Atlantic Ocean for the period 0000UTC, 14 January to 1200UTC, 15 January, 1991. Satellite pressure estimates determined from the SMB technique; surface pressures taken from NMC operational analyses.

"dry slot"). Because this approach provided very little additional information, we dropped it from the technique. We may try this approach again when we examine water vapor and microwave data.

Adjustments to central pressure are made when a ring cloud is present near the center of the cloud vortex (Box I). Depending on the amount and type of clouds comprising the ring, adjustments to pressure range from 4 to 12 mb. Whenever a complete ring cloud composed of middle and high clouds is observed, ring cloud adjustments are not made. Spiral measurements (Box H) and pattern recognition (Box E) are then combined to deter-



0000UTC January 15, 1991
Satellite estimated pressure (log spiral) 956mb



1200UTC January 15, 1991
Satellite estimated pressure (log spiral) 952mb

0000UTC January 15, 1991
NMC analyzed pressure 960mb

1200UTC January 15, 1991
NMC analyzed pressure 948mb

Fig. 9 (cont'd).

mine the central pressure. An explanation of the rules for applying ring cloud measurements is given in Table 4.

The cloud band can become stretched and show signs of deterioration in a filling situation, even though the ring cloud may still be associated with the system. However, ring cloud adjustments are not applied during filling stages.

4. Applying the technique: Atlantic Ocean

Figs. 9a through 9d show a 36-h sequence of storm evolution over the North Atlantic Ocean for the period 0000UTC, 14 January to 1200UTC, 15 January 1991. Satellite estimates of central pressure were obtained through pattern recognition procedures, log spiral measurements, and ring cloud adjustments. These are compared to the operational surface analyses of the National Meteorological Center (NMC) of the National Weather Service. Fig. 10 shows the graphical comparison between NMC analyses and SMB estimates.

14 January 0000UTC (Fig. 9a). This image shows the mid-stages of a developing storm. This system has developed since the previous observa-

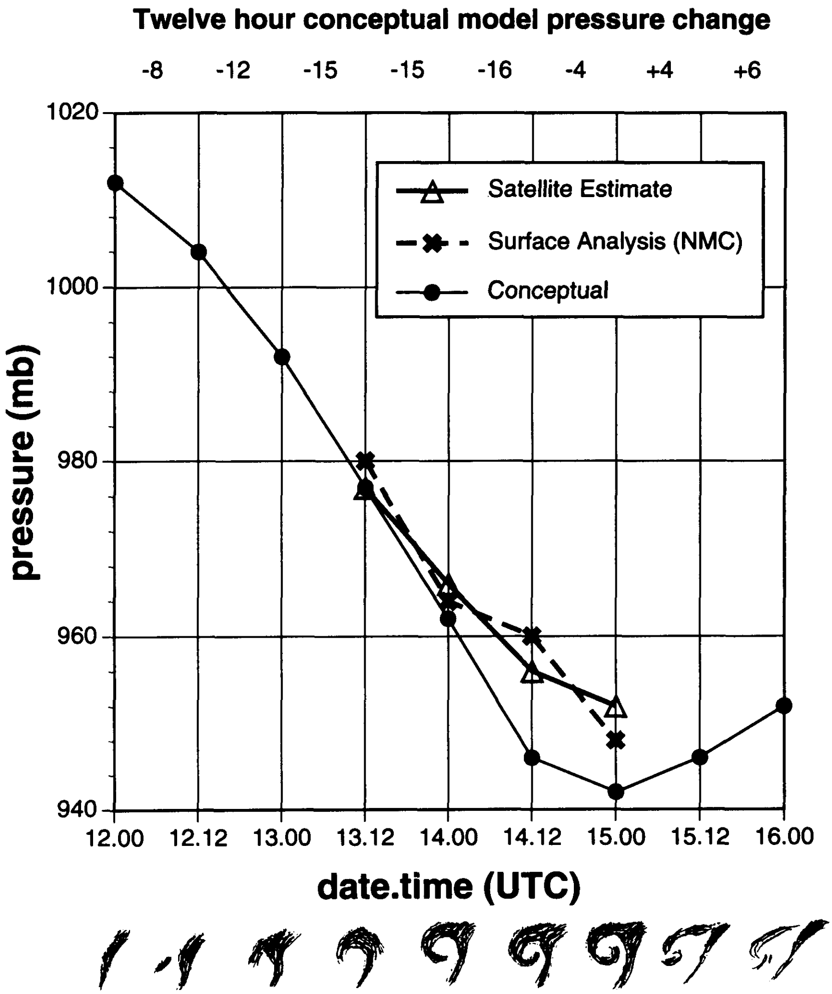


Fig. 10. Comparison between NMC analyses and SMB estimates of central pressure for the period 14–15 January 1991.

tion 12 h ago. There has been an increase in the curvature of the comma cloud, and there is expanding dry slot region. If the image were rotated counter-clockwise 90°, it would replicate the 977 mb pattern. The spiral distance measurement is 0.65, which corresponds to a pressure of 977 mb:

satellite estimate	977 mb (0.65 spiral)
NMC analysis	980 mb

The surface report from St. Johns/Torbay (near 47.5° N 52.5° W) has a pressure of 986.2 mb, with a "check" tendency showing a rise of 5.7 mb. This indicates that the low was at least 980.5 mb when it passed near the station. Since the low is still developing, the pressure should be below 980 mb at this time.

14 January 1200UTC (Fig. 9b). The cloud pattern shown in the satellite image shows a dramatic change during the 12 h period. The back edge of the cloud around the comma head and the dry slot have become more rounded. The amount of curvature in the middle and high clouds has increased. The log spiral distance is now 0.80, which corresponds to a central pressure of 966 mb. Again, it is easier to visualize the pattern by turning the image counter-clockwise about 90°:

satellite estimate	966 mb (0.80 spiral)
NMC analysis	964 mb

15 January 0000UTC (Fig. 9c). This image shows continuing development. The amount of curvature in the cloud band is slightly greater than in the previous image and the back edge of the cloudiness associated with the comma head was become more rounded. There is a hint that a ring cloud has formed, although only low and indistinct cloudiness is associated with it.

The cloud spiral measurement of 0.90 gives a central pressure of 960 mb. Subtracting 4 mb for the indistinct low cloud ring yields a final satellite pressure estimate of 956 mb.

A data buoy near 56.0° N 38.0° W with a pressure of 964.3 mb supports both the satellite and NMC pressure analyses.

satellite estimate	956 mb (0.90 spiral, −4 mb ring)
NMC analysis	960 mb

15 January 1200UTC (Fig. 9d). The low has nearly reached its lowest pressure at this time. The cloud spiral measurement is still 0.90, which yields a pressure of 960 mb. The ring cloud is now more distinct and is composed of cumuliform clouds. An adjustment of 8 mb for the cumuliform ring yields a final pressure of 952 mb.

satellite estimate	952 mb (0.90 spiral, −8 mb ring)
NMC analysis	948 mb

5. Conclusions

For the case study of Atlantic Ocean cyclogenesis that was presented here, we showed how satellite imagery cloud pattern changes and log spiral measurements could be used to estimate central surface pressures of mid-latitude oceanic cyclones. However, in comparing surface analyses with the satellite estimates of central pressure for dozens of storms (in both Atlantic and Pacific Oceans), we concluded that the satellite estimates of central pressure are reliable to ±4 mb of what we believe is the actual central pressure of the storm. We also found that satellite-based estimates of central pressure gave a more realistic trace of pressure change versus time over data sparse oceanic areas.

The technique has been used operationally by both NOAA and Navy national forecasting centers in the United States, and by forecast offices in the northeast United States, Hawaii, and Alaska. We have received favorable reports from these users about the value of using the technique on a day-to-day basis. For example, during the major storm that struck the British Isles in early January 1993, the technique was used by NESDIS' Synoptic Analysis Branch to estimate central pressures as low as 911 mb (Prosise and Schwartz, 1994). Observed surface data for this extreme event included reports as low as 895 mb. For a major storm event off the northwest United States coast in March 1995, the technique provided estimates only a few mb below the values analyzed on operational NOAA surface charts and which were reported at NOAA data buoys (Gilhousen, 1995). We also assessed central pressures for a North Atlantic storm described by Breivik et al. (1992). Our estimates of central pressure (using only a limited satellite data set) were also within ±4 mb.

However, we have purposely avoided developing a formalized set of statistics concerning the accuracy of the technique because of the lack of ground truth information.

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