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Investigation of Eddy Population and Motion in the Southern International Ice Patrol Operations Area (40Â°-47Â°N by 40Â°-55Â°W)

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INVESTIGATION OF EDDY POPULATION AND MOTION IN THE SOUTHERN

INTERNATIONAL ICE PATROL OPERATIONS AREA

(40°-47°N BY 40°-55°W)

by

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ABSTRACT

A study of the eddy population in the Newfoundland Basin region over the period from November 1981 to December 1984 was conducted. The study was undertaken to demonstrate the importance and basic character of eddy motion in the area patrolled by the International Ice Patrol. This is a descriptive study and no rigorous mathematical solutions are attempted. Data was collected on the number of eddies in the area, their average duration and size, formation, migration and deterioration patterns and rotational velocity. Satellite infrared imagery maintained by National Weather Service and Naval Eastern Oceanographic Center, Canadian Forces METOC Center sea surface temperature data and Tiros Ocean Drifter buoys and Side Looking Airborne Radar imagery maintained by the International Ice Patrol formed the basis for the investigation. This study indicates that eddies are ubiquitous in the area and that they are concentrated in the areas around the Newfoundland Ridge and the Seamounts. They drift to the west after formation. The Labrador Current generates eddies as well as the North Atlantic Current. The characteristics of the average eddy found in the area are presented.

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this information, because if an iceberg is trapped in an eddy it may be traveling in a direction opposite to that predicted by the model. It is a zone extending from 40°N to 47°N and from 40°W to 55°W and is the confluence of the Labrador Current, the Gulf Stream, the North Atlantic Current and the Slope Water flow and it includes the Newfoundland Sea Mounts, Newfoundland Ridge and the Grand Banks of Newfoundland. Figure (1) shows the topography of the area and the approximate positions of the major currents as they enter it.

Research has been conducted on the hydrography of the area, and on the general population and motion of eddies in other areas of the ocean, but no one has yet performed a study of eddy population and activity in this particular area of IIP interest. We do not know where we can expect to find eddies in the region, how often we can expect to see them or what the average size of the eddy may be. We do not know where or when we can expect an iceberg to be trapped in eddy motion or if there are areas where eddy circulation can be safely ignored for iceberg analysis. These questions are important if the watch officer is to make an educated decision in regard to input into the model.

One hypothesis is the eddy formation will be mainly associated with the seamount and ridge area, and the eddies will migrate west after formation. Seasonal variation should have no effect on eddy formation or distribution. The purpose of this study is to conduct an eddy population study for the southern IIP area in an attempt to demonstrate this hypothesis and provide the watch stander with additional guidelines he can use in his data analysis. The goal is to relate the eddy density to the topography of the area and to seasonal variations in an attempt to limit the occasions in which eddies must be considered. The results

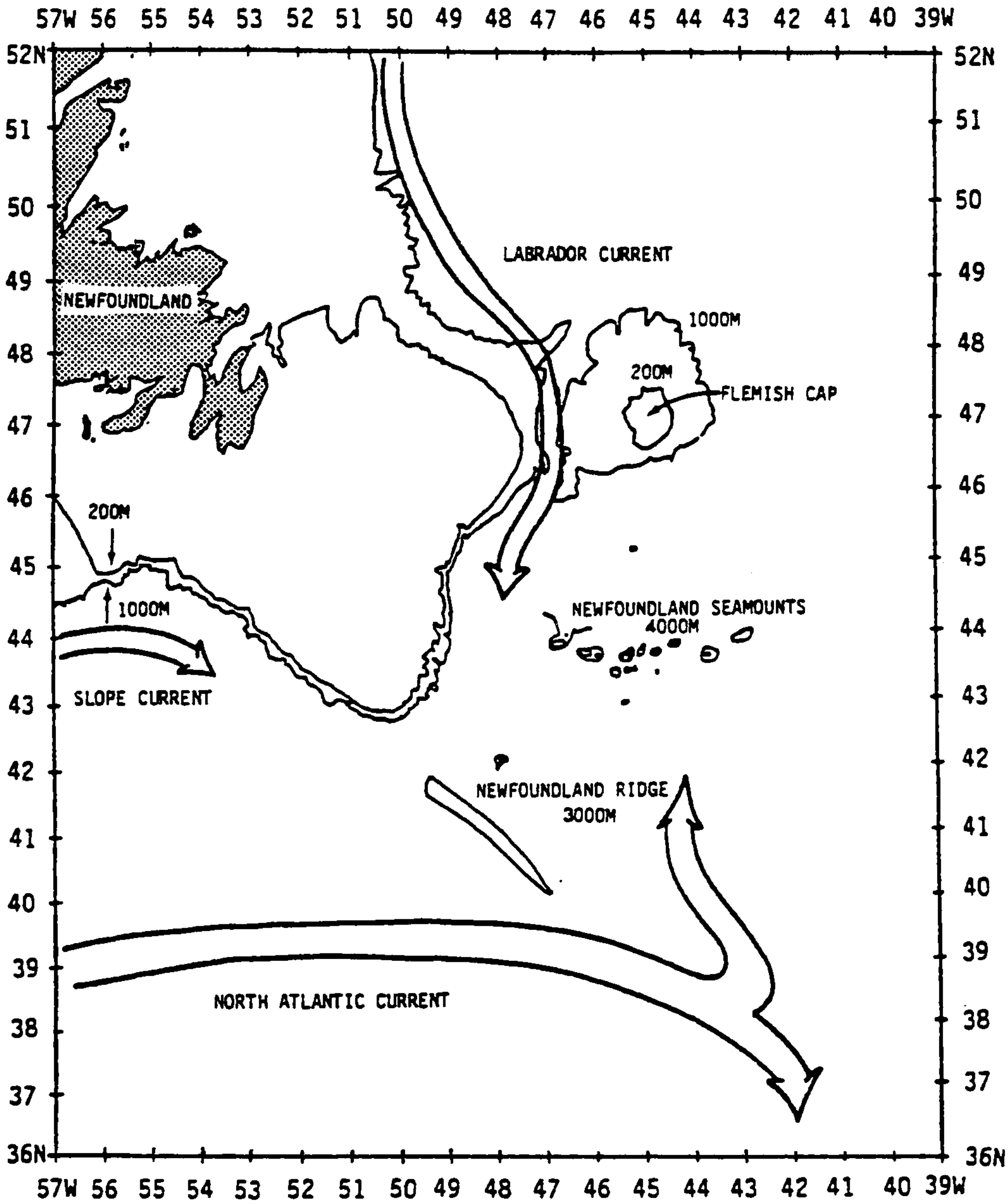

Figure 1 MAP OF RESEARCH AREA SHOWING

TOPOGRAPHY AND MAJOR CURRENTS

will be useful not only to the theoretical understanding of the oceanography of the area but also to the practical application of the drift model to icebergs in the area.

This study will constitute an initial survey of the overall eddy population of the region and report the findings. This will be a descriptive report and no attempt will be made to create a mathematical model at this time.

The study will cover the 38 month period from November 1981 to December 1984. This is the time frame for which the most complete data sets are available from the widest variety of sources.

REVIEW OF LITERATURE

Currents

To understand the motion in the Newfoundland Basin area it is important to have a basic knowledge of the currents flowing into and affecting the area.

The currents discussed in this paper are geostrophic currents driven by differences in dynamic height. Dynamic height is defined as the quantity in work needed to move a parcel of water from one level of the ocean to another. It is a function of water density and therefore of temperature and salinity. Currents flow along the contours from dynamic ridges into dynamic troughs curving as dictated by the effects of coriolis. The major ocean currents of the world are geostrophic and they form the main circulation gyres of the open seas.

A. Labrador Current. Much of the research in the Labrador Sea area has been conducted by the U.S. Coast Guard in support of the IIP. The Labrador Current is a cold, narrow, relatively fresh, southward flowing current with a high velocity core located on the eastern continental slope of the Grand Banks between the 200 and 2000 meter isobath (Kollmeyer, 1966 and Kollmeyer, O'Hagan and Morse, 1965). Cheyney and Soule (1951) defined the Current by an eight year mean T-S curve from data taken on the east slope of the Grand Banks. Their mean ranged from -1°C and 33.3‰ at the surface to 4°C and 34.9‰ at depth.

Hayes and Robe (1978) indicate that the Current splits into three distinct branches. Two branches flow south, one on the slope and one on the shelf. The third flows east on the north slope of the Grand Banks and then north of Flemish Cap. Current meter measurements made by Hayes and Robe (1978) indicate that the Current extends the entire depth of the water column to the bottom in the area of the continental shelf and slope.

B. Slope Water Flow. The Slope Water is the water mass lying just off the continental shelf of Nova Scotia and Southern Newfoundland, over the Continental Slope. It is a water mass having lower salinity at all temperatures than Gulf Stream water (Moynihan and Andersen, 1971). This water flows eastward along the slope in the Tail of the Banks area to join in the general circulation of the area (Moynihan and Andersen, 1971 and Mann, 1967)

C. North Atlantic Current. The North Atlantic Current is the common name for all easterly and northerly flowing water from the Tail of the Banks across the North Atlantic. It forms the northern boundary of the Sargasso Sea and the northern branch of the main North Atlantic Ocean current gyre. It is not a static flow, but is marked by meanders and cast off eddies (Fuglister, 1963, and Clark, Hill, Reininger and Warren, 1980). Fuglister (1963) and Warren (1969) state that the current extends, at least in some places, through the water column to the bottom. Fofonof (1980) and Clark, et al. (1981) believe that if the current does extend to depths it is masked by eddies and visible only in long term averaging.

The North Atlantic Current enters the area as the eastern most branch of the Gulf Stream System as defined by Iselin (1936). The entire System, like the North Atlantic Current, is marked by meanders and eddies. These upstream meanders may have an effect on the latitude at which the North Atlantic Current enters the study area, and how it affects the circulation of the area.

Eddies

Eddies exist almost everywhere in the oceans but their distribution is spatially heterogeneous and they are intermittent. These eddies contain more energy than the mean currents and are thought to be significant in driving the mean flow (Richardson, 1983). Rhines (1976) has described the general flow system of the ocean as a combination of two parts: eddy energy, the variable part and the mean flow (Eularian), the time averaged part. Various types of variability have been studied including meanders, semi-attached and cast off ring currents, advective vortices extending through the entire water column, linear vorticity, planetary waves and topographic waves. All of these variable flows are commonly referred to as "eddies" (Robinson, 1983).

Rhines has identified five types of eddy motion:

A. Simple linear Rossby waves

B. Two dimensional turbulent flow: In real oceans, eddy motion often combines the properties of both species A and B. Individual eddies have no particular identity and energy passes by jostling freely from cell to cell.

C. Lone eddies or rings: Many of these species retain their energy and identity for a year or more.

D. Meander motion of a jet current: In this case the flow is the sum of the time averaged (mean) flow plus the time varying part (eddy).

E. The simple tendency of a rough sea floor to break currents up into eddies. Currents flow along contours easily but waves result if currents try to cross contours.

We do not know which of these types are important in our area.

Eddies are themselves a dominant dynamic phenomenon which can influence the general circulation directly through eddy-mean field interactions and eddy-eddy interactions in the mean field. (Robinson, 1983) Rhines believes that on occasion eddies, if fast enough, can gang up to drive the mean flow.

Eddies can produce upwelling and eddy momentum flux can contribute to the momentum of long-shore pressure gradients (Robinson, 1983). Onshore-offshore eddy exchange of heat, salt and nutrients can contribute significantly to shelf balances of these properties. Eddies interact with mean flows to induce mixing of two or more currents or water masses.

Eddies are also important in determining the direction of drift of any object caught in their circulation field. This includes the subject of interest to the Coast Guard: icebergs. It is important to us to know how the eddies will move the ice through our operations area.

Although eddies exist almost everywhere, the most vigorous variabilities are associated with intense flow regions such as the Gulf Stream System. Eddies are produced there by eddy-mean field interactions which are large amplitude processes related to simple baroclinic instabilities or a strongly horizontally sheared current or a combination of both processes. The baroclinic process converts energy which would otherwise be stored in the mean field potential energy to eddy energy. The barotropic process converts mean field kinetic energy to eddy energy (Robinson, 1983).

Wyrtki (1976), Dantzler (1977) and Emory (1983) conducted studies of the potential energy distribution in the oceans as related to eddies. They all found that the highest concentration of potential energy was in the area of the high speed currents. Richardson (1983a) used over one hundred satellite-tracked drift-buoys to conduct a kinetic energy survey of the oceans. His highest readings were in the area of the Gulf Stream (2000 cm^2/sec^2) while the Newfoundland Basin area had readings of $1000 cm^2/sec^2$.

Eddy populations and movement have been studied in many areas of the Gulf Stream. Lai and Richardson (1977) used hydrographic data to plot the distribution of 163 cyclonic (cold core) rings and their mean trajectories. They indicate that the rings move west or southwest as a result of Coriolis and mean current flow in the Sargasso Sea. Richardson, Cheyney and Worthington (1978) studied twelve rings in a four month period in an area from 30°N to 45°N and 55°W to 75°W again using hydrographic data. They indicated that the nine cyclonic and three anticyclonic (warm core) rings represented a large eddy density. Again, the mean translation was southwesterly. Richardson (1983b) noted that up to ten rings may coexist in the area at any one time. Richardson (1980) used satellite-tracked free drifting buoys to track fourteen rings over a three year period. He found that rings that were not attached to the Gulf Stream translated to the west while attached rings were carried downstream or to the east. This study demonstrated the use of satellite drift buoys in locating and following eddy circulations. Joyce (1984) used hydrographic and infrared data to conduct a population and movement study of rings in an area from 40°N to 45°N and 55°W to 75°W. He verified westsouthwesterly translation in thirty six eddies. This area is immediately to the west of the IIP area that is the subject of this investigation. Shaw and Rossby (1984) also used SOFAR buoys to track Gulf Stream meanders, again demonstrating their usefulness as tools for studying current motion.

Several investigators have examined the role of bottom topography in the formation of eddies. Garzoli, Pouri and Paschini (1982) used a numerical model to show that two eddies in the Straits of Sicily were of topographic origin. Eide (1979) and Menke (1971) both studied ocean vortices trapped by topographic features on the Norwegian shelf and the Great Meteor Seamount respectively. Huppert and Bryan (1975) and Vasatov and Warren (1976) studied the Atlantis II Seamounts as an area of eddy generation. Closer to the study area, Smith, Morison, Johannessen and Untersteiner (1984) showed that the interaction of the currents with the topography around the eastern coast of Greenland could generate eddy activity. These areas have topography similar to the ridges and seamounts found in the Newfoundland Basin area where it is likely that topography will be important to eddy activity also.

Interactions within the research area

The Newfoundland Basin/Grand Banks area is one of the most dynamically complex areas in the ocean. Not only do three currents converge here, but Schmitz (1981) and Fu and Holt (1983) used hydrographic data and infrared satellite imagery respectively to show that eddies exist in the area. Many hydrographic surveys have been done in this area including many conducted by the U.S. Coast Guard in support of the IIP. Almost all have indicated the same general mean flow pattern with some temporal and spatial variations. This general pattern is shown in Figure (2).

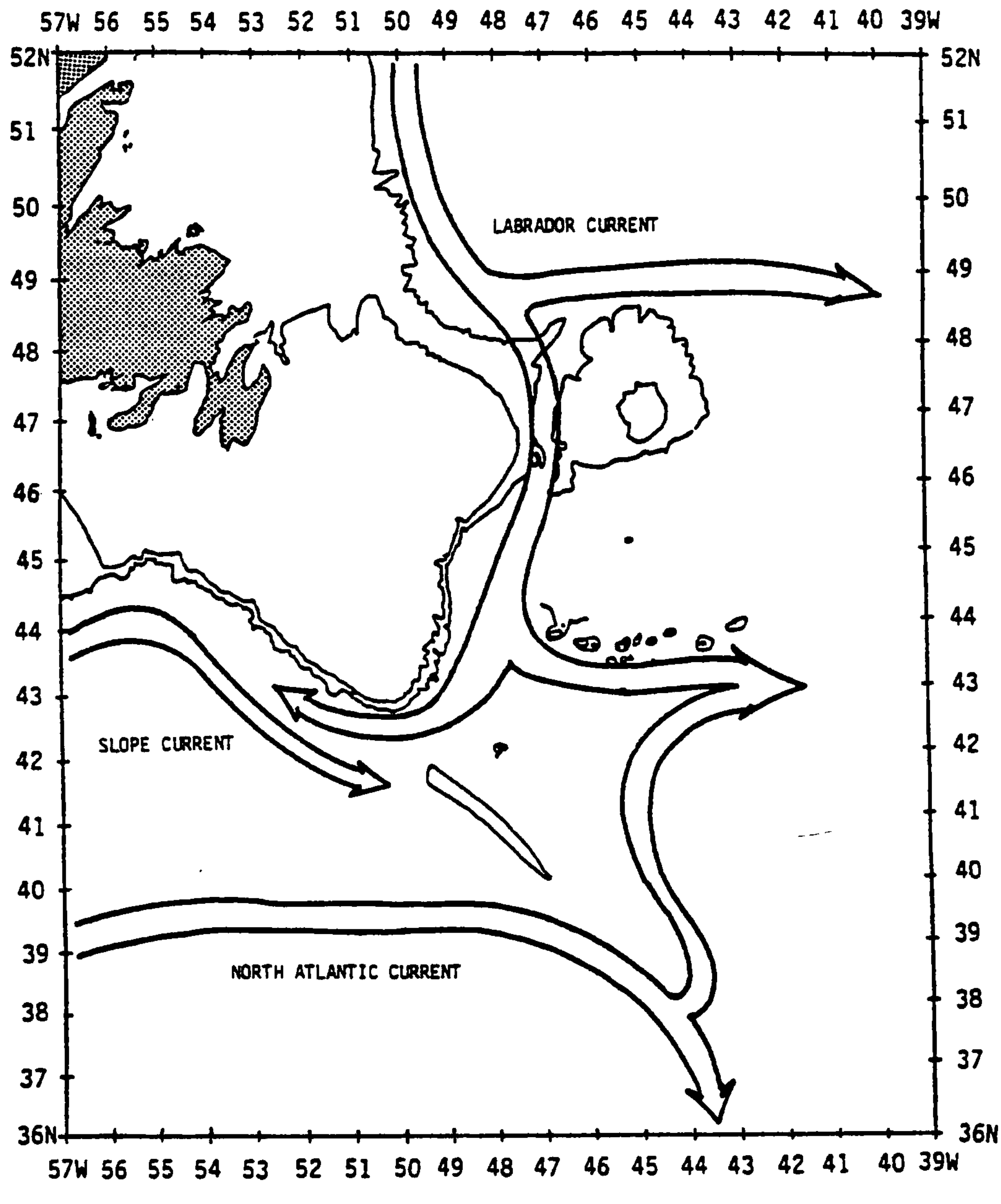

Figure 2 MEAN CURRENT INTERACTIONS IN THE RESEARCH AREA

The "normal" Gulf Stream circulation for the area may be taken from Mann (1967) as supported by Fuglister (1963) and Clark and Reininger (1973). In Figure (2) the Slope Water enters the area at 50°W north of 41°N. The Gulf Stream crosses 50°W south of 40°N and flows southeast to about 38°30'N 44°W where it divides. The major portion continues southeast along the south side of the Newfoundland Ridge. A portion crosses the Ridge and flows north to join the Slope Water and form the North Atlantic Current. Mann noted a counter current flowing westward between the Slope Water and the Gulf Stream in many of his stations. Based on several hydrographic surveys, both he and Fuglister (1963) believe this may be formed by an S-shaped meander departing from the Gulf Stream. Mann also believes a permanent anticyclonic eddy exists centered at 41°N 42°W based on hydrography.

Ettle and Wolford (1972), based on hydrographic studies, showed that the Labrador Current, flowing south along the Grand Banks, was separated from the northward flowing North Atlantic Current by a dynamic trough. Kollmeyer, et al. (1965) used hydrography to follow the Labrador Current south along the 200 meter curve to the Tail of the Banks and in 1966 Kollmeyer, et al. noted that it bifurcated at the Tail: one current flowing west around the Tail and one continuing east. Clark, et al. (1980) followed the east flow until it joined the North Atlantic Current. In observations of 1968 hydrographic data Andersen and Moynihan (1971) noted that the western flow was intermittent and could only be seen about half of the time. In a series of hydrographic surveys done in 1969, Moynihan and Andersen (1971) noted that the westward flow was prominent in the first cruise. South of it was a wide dynamic trough, south of which was an easterly flow, south of which was another westerly flow. In later cruises the trough narrowed until it and the westward flow around the Tail were no longer seen. The authors interpreted this regime as Labrador Current, trough, Slope Current, counter current. They believe the counter current is a meander of the Gulf Stream, after Mann and Fuglister. They believe that as the meander grows and spreads northward, it blocks the Labrador flow around the Tail of the Banks.

The idea that the Labrador current flow is dominated by the Gulf Stream is echoed by Kollmeyer, et al. (1965). On his first cruise, the Gulf Stream was north of 42°N and the Labrador Current flowed westward around the Tail of the Banks. On his second cruise the Gulf Stream had meandered as far north as 45°N. This meander forced the Labrador Current onto the Grand Banks and no western flow was seen (Figure 3). Scobie (1976) also noted that meanders of the Gulf Stream and North Atlantic Current could block the flow of the Labrador Current. Hayes and Robe (1978) noted that the North Atlantic Current forces the Labrador Current onto the Banks when it meanders, but that when it is in its normal position (between 40° and 41°N) the Labrador flows to the Tail of the Banks and divides as per Kollmeyer (1966).

Using hydrographic data from the Newfoundland Basin area Mountain and Shuhy (1980) found that the Gulf Stream either branches around or crosses over the Newfoundland Ridge depending on the latitude at which it encounters the Ridge, which further depends on its meander pattern at the time. They suggest that if the Gulf Stream enters the area at 39°N as per Mann (1967) it flows along the Ridge and branches south if it. If it enters at 41° or 42°N it more directly encounters the Ridge topography and flows over it (Figure 4). Mountain and Shuhy (1980) also believe that the topography has an influence on the actions of the currents. They assume, after Warren (1969) and Fuglister (1963), that

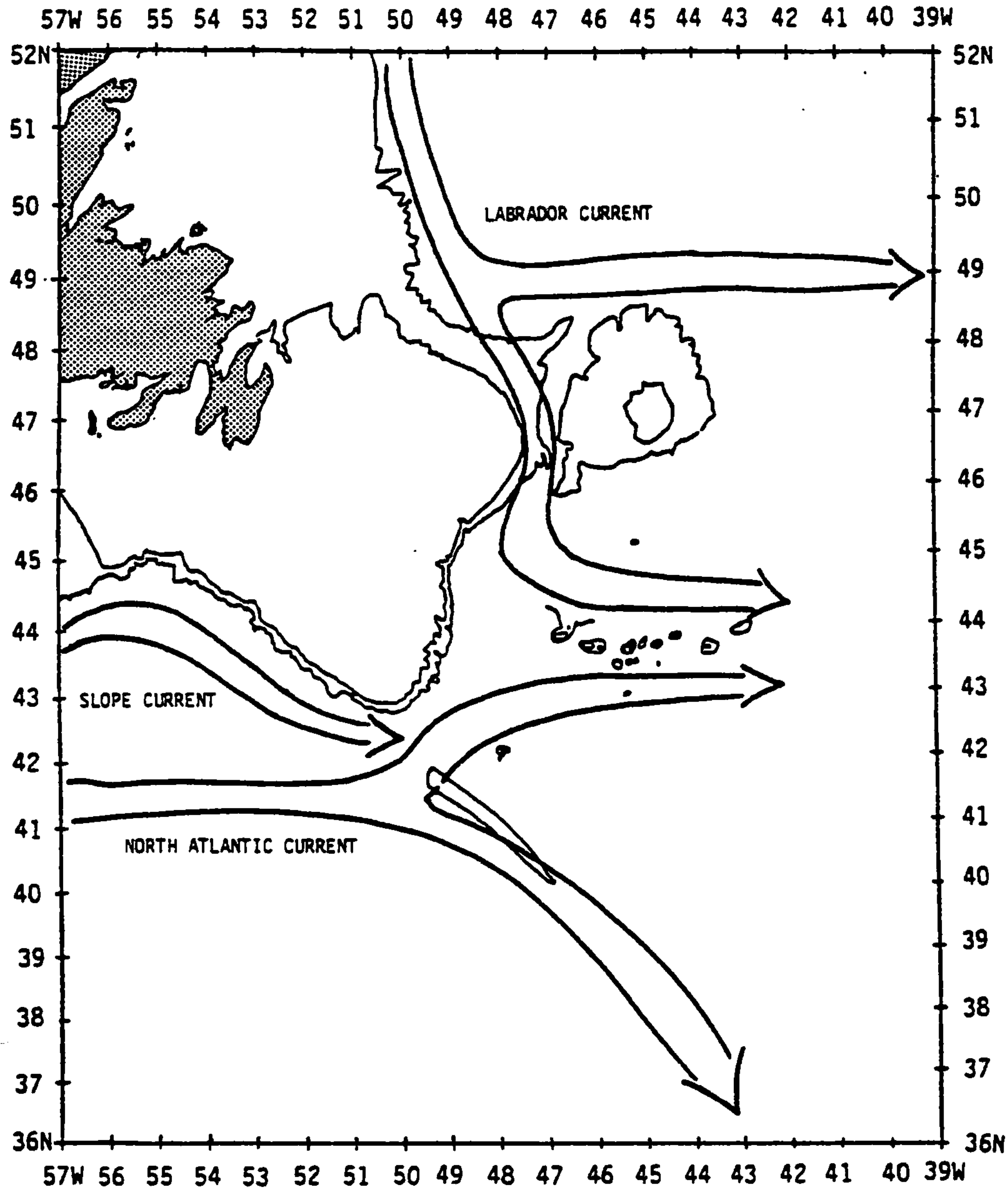

Figure 3 RADICAL MEANDER OF THE NORTH ATLANTIC CURRENT AS REPORTED BY KOLLMEYER (1965)

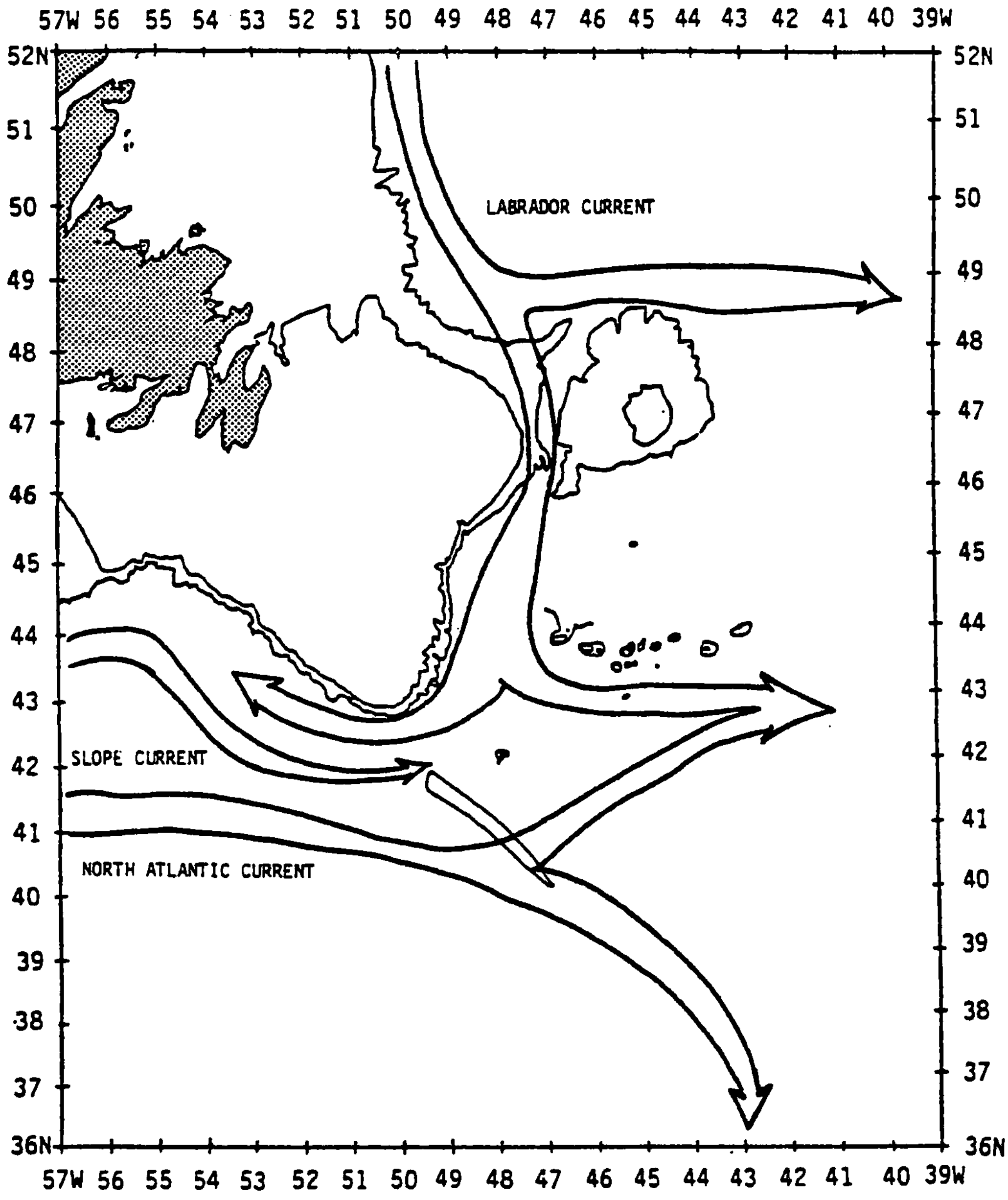

Figure 4 ALTERNATIVE FLOW OF CURRENTS AS

PROPOSED BY MOUNTAIN AND SHUHY (1980)

the Gulf Stream reaches the bottom of the Newfoundland Basin. They note that the easterly flow around the Tail of the Banks and along the south side of the Ridge follows relatively flat topography and no eddies are seen. Eddies are observed over the Ridge crest where topography is more complex. Richardson (1983a) confirmed flow over the Ridge by the use of SOFAR buoys. He also confirmed that eddies do play a part in the circulation of the area.

A thorough search of the published literature showed the only articles dealing specifically with the eddy population of the Newfoundland Basin were those by Schmitz (1981) and Voorheis, Aagaard and Coachman (1973). Voorheis, et al. (1973) studied historical dynamic height data in an attempt to define some characteristics of eddy motion in the Grand Banks area. They determined size and speed characteristics for 58 cases over the period 1922-1965. Schmitz's (1981) survey confirmed the existence of eddies in the area, and gave some details on overall characteristics of the eddies, but provided no population information. Many other authors alluded to eddy motion in their papers, but none focused on the topic.

DATA AND PROCEDURE

Data

The main sources of data for this thesis were the ocean frontal analysis charts published by Naval Eastern Oceanographic Center (NEOC) and the National Weather Service (NWS). The charts are based on infrared satellite imagery that shows warmer water darker than colder water. Navy and NOAA oceanographers and meteorologists interpret the color shading to locate water masses of varying temperatures and hand draw the charts to represent the images.

The two main types of satellites used to gather the images are a polar orbiter that passes over a given area in a variety of flight patterns at an altitude of 725 km and a geostationary that remains in a geosynchronous orbit 35400 km over a fixed position on the earth. Mainly because of the altitude difference the polar orbiter provides a higher resolution image and more accurate positioning. A comparison of the images is shown in Figures 5 and 6. In Figure 5 the research area is in the upper central part of the image. The very light areas are clouds and the subtle shading in the sea surface colors can be noted. In Figure 6 The research area is in the center of the image. Again the very light areas are clouds. The darker sea surface shades indicate warmer water.

The main disadvantage of the polar orbiter is that it is strongly dependent on land features for positioning. If no land appears in the

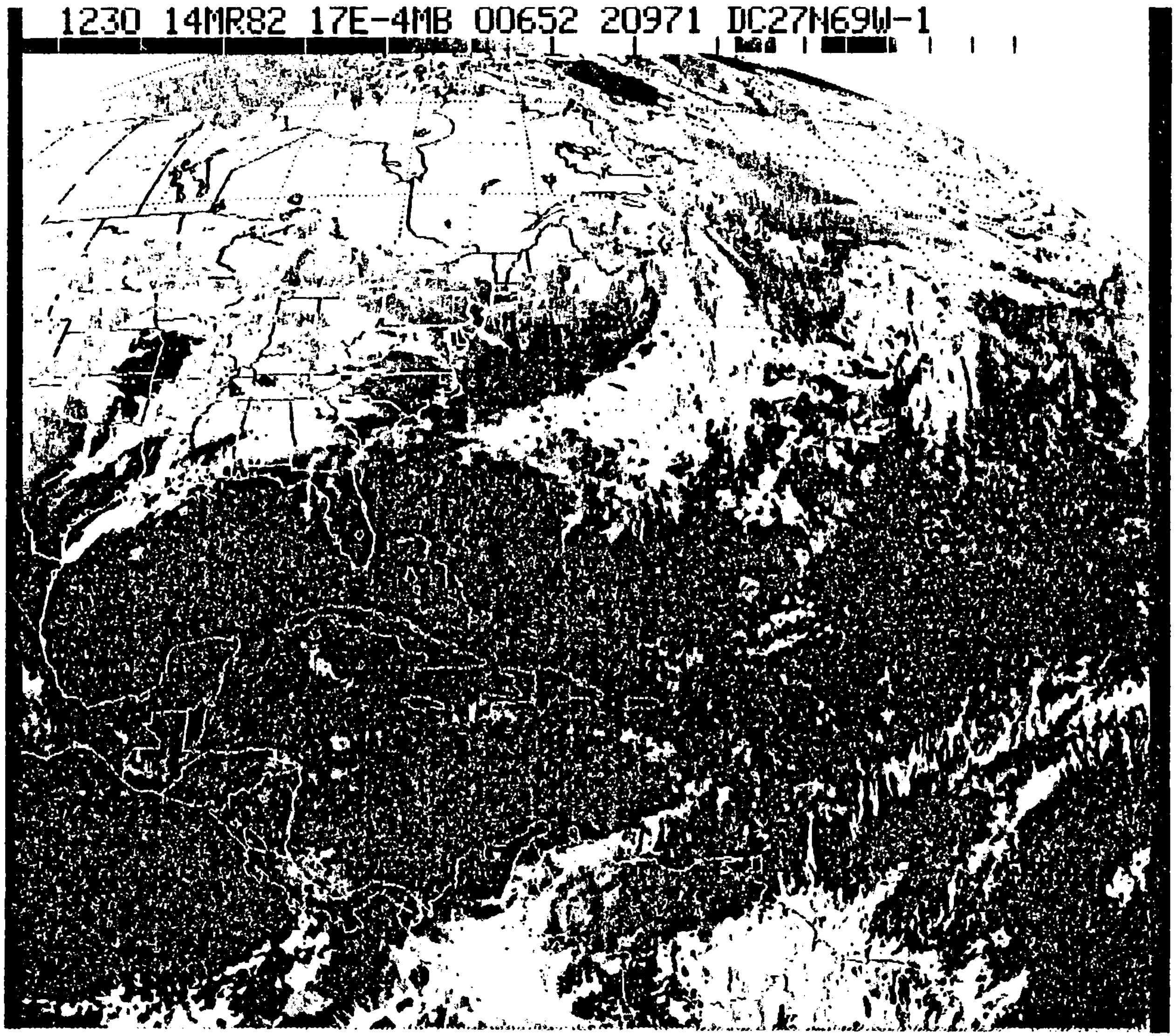

Figure 5 SAMPLE OF GOES SATELLITE IMAGERY USED BY NAVAL EASTERN OCEANOGRAPHIC CENTER

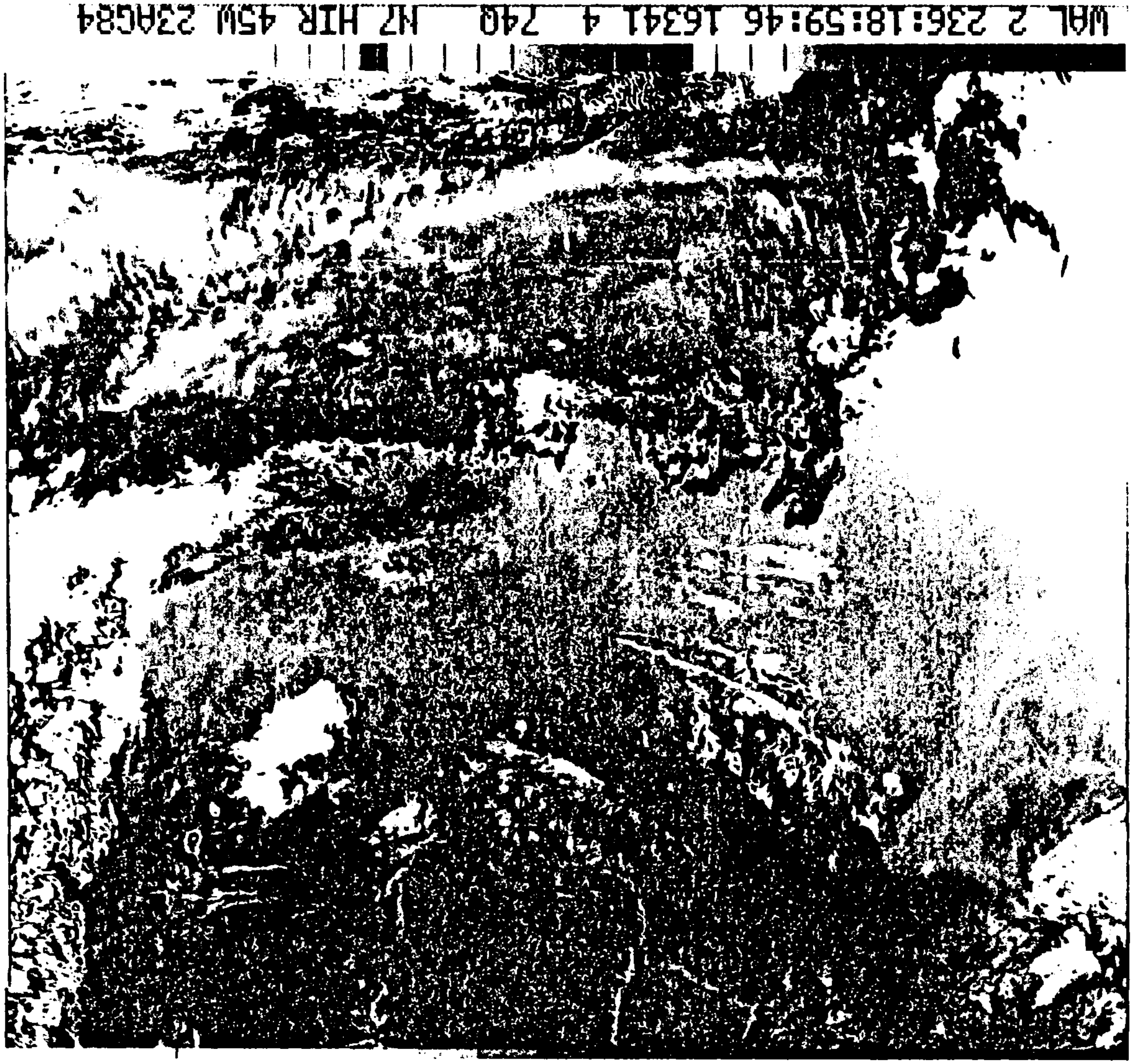

Figure 6 SAMPLE OF NOAA 6 SATELLITE IMAGERY USED BY NATIONAL WEATHER SERVICE

image it is difficult to accurately locate the feature depicted. Estimates of the accuracy of positioning of features shown without land vary widely with the most optimistic being about 16 km. It also produces the image of a given area at the same location and angle only once every several days. The geostationary satellite produces images of the same area and angle every thirty minutes, thus producing a time lapse history of the region.

Infrared satellite imagery works well for the majority of the ocean, but in the Grand Banks area it is hampered by heavy fog banks that often dominate the weather patterns. Both polar orbiting and geostationary type data are adversely affected by this condition. If the area is cloud covered the analysts must rely on past trends to drift eddies they have on plot. This process of extrapolation is inaccurate at best and, when coupled with possibly questionable initial positions, can lead to poor positioning. They can not see the formation of new eddies or verify loss of existing ones. These conditions lead to a good deal of inaccuracies in eddy forecasting in the study area.

The analysts have developed a simple code to explain to the users whether or not clouds interferred with the analysis on given days. If the satellite imagery was clear and readable the ocean features are presented as solid lines on the charts. If the imagery was obscured for any reason the features appear as dashed lines. In this study all eddies are counted as equal, whether they were solid or dashed lines.

NWS uses the NOAA 6 and 9 polar orbiting satellites for the majority of their analyses. They receive data continuously but produce charts of the Grand Banks area only on Monday, Wednesday and Friday. The analysts plot an eddy whenever they note a core of water surrounded by warmer or colder water, especially if circular motion is evidenced.

They carry an eddy on plot as long as it appears on the imagery. If fog dominates the area for an extended period their policy is to eliminate an eddy if it is not observed for a thirty day period. Because of the volume of data that they receive and process they are able to plot a number of features. They plot not only the Gulf Stream features but also Labrabor Current features and slope/shelf interface phenomena. An example of their chart is shown in Figure 7. The research area can be seen on the right side of this chart. Newfoundland is in the upper center of the chart. The Grand Banks are indicated by the dashed line and the Labrador Current is identified.

Because NEOC is mainly interested in meteorological data they receive the majority of their data from the GOES geostationary satellite. They receive only limited NOAA imagery and so they rely heavily on the NWS product to produce their chart. This means that the two data sets are not entirely independent and that one may heavily influence the other. Because the GOES imagery that makes up the bulk of their data has less resolution than NOAA imagery, the Navy analysts may miss several of the smaller eddies and frontal features seen by NWS. For this reason the NEOC charts are more sparse than those of NWS. The criteria used by Navy analysts for plotting features is similar to those of NWS. NEOC has no set time limit for carrying an eddy obscured by weather conditions. A sample NEOC chart is shown in Figure 8. Newfoundland can be seen in the upper left corner and the research area is on the left side of the chart. The Grand Banks and Flemish Cap are identified by the dashed lines.

A third source of sea surface temperature charts is the Canadian Forces Meteorological and Oceanographic (METOC) Center. Until 1984 these charts were based on vessel reports. This method eliminated the

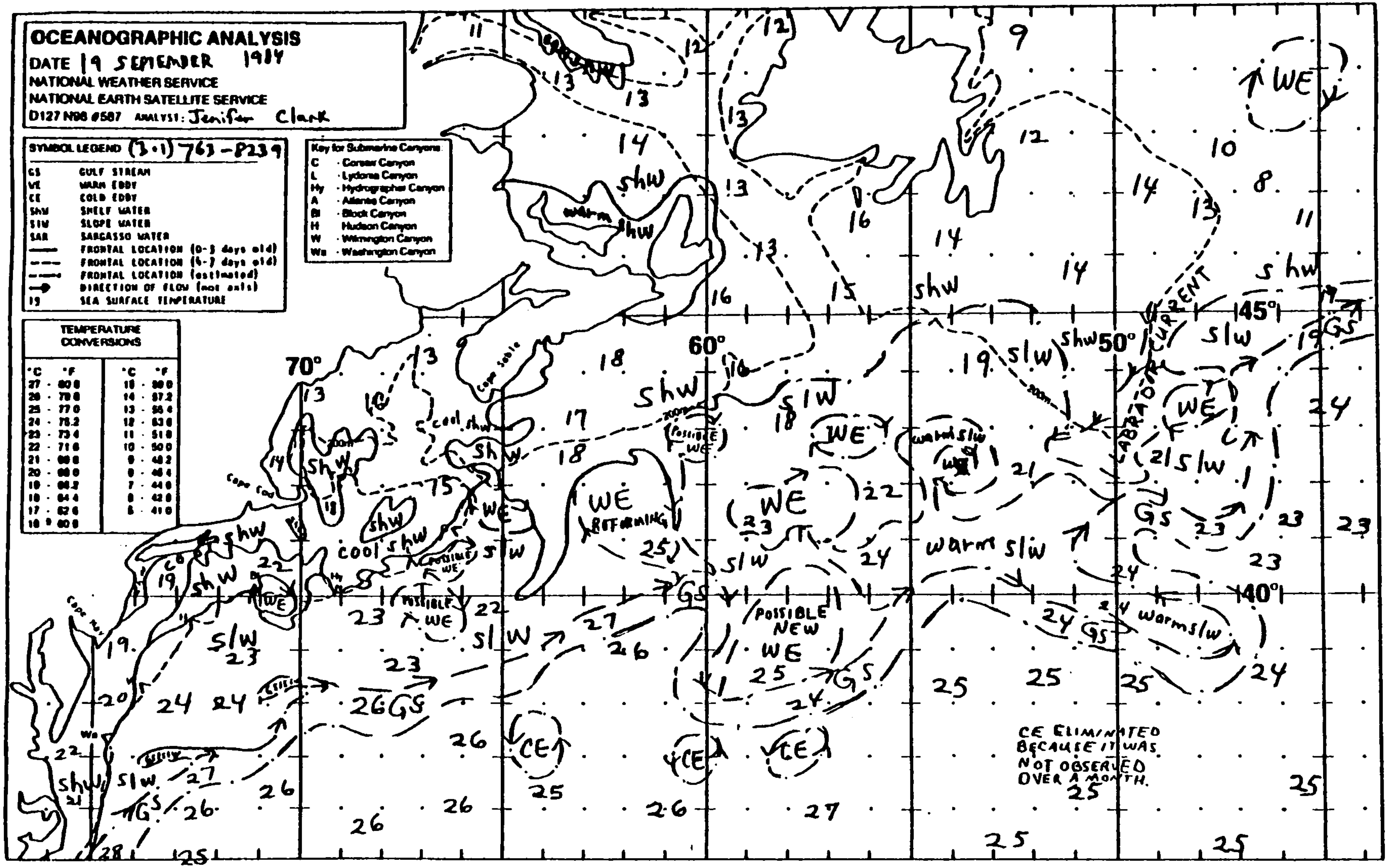

Figure 7 SAMPLE OF NATIONAL WEATHER SERVICE OCEAN FRONTAL ANALYSIS CHART

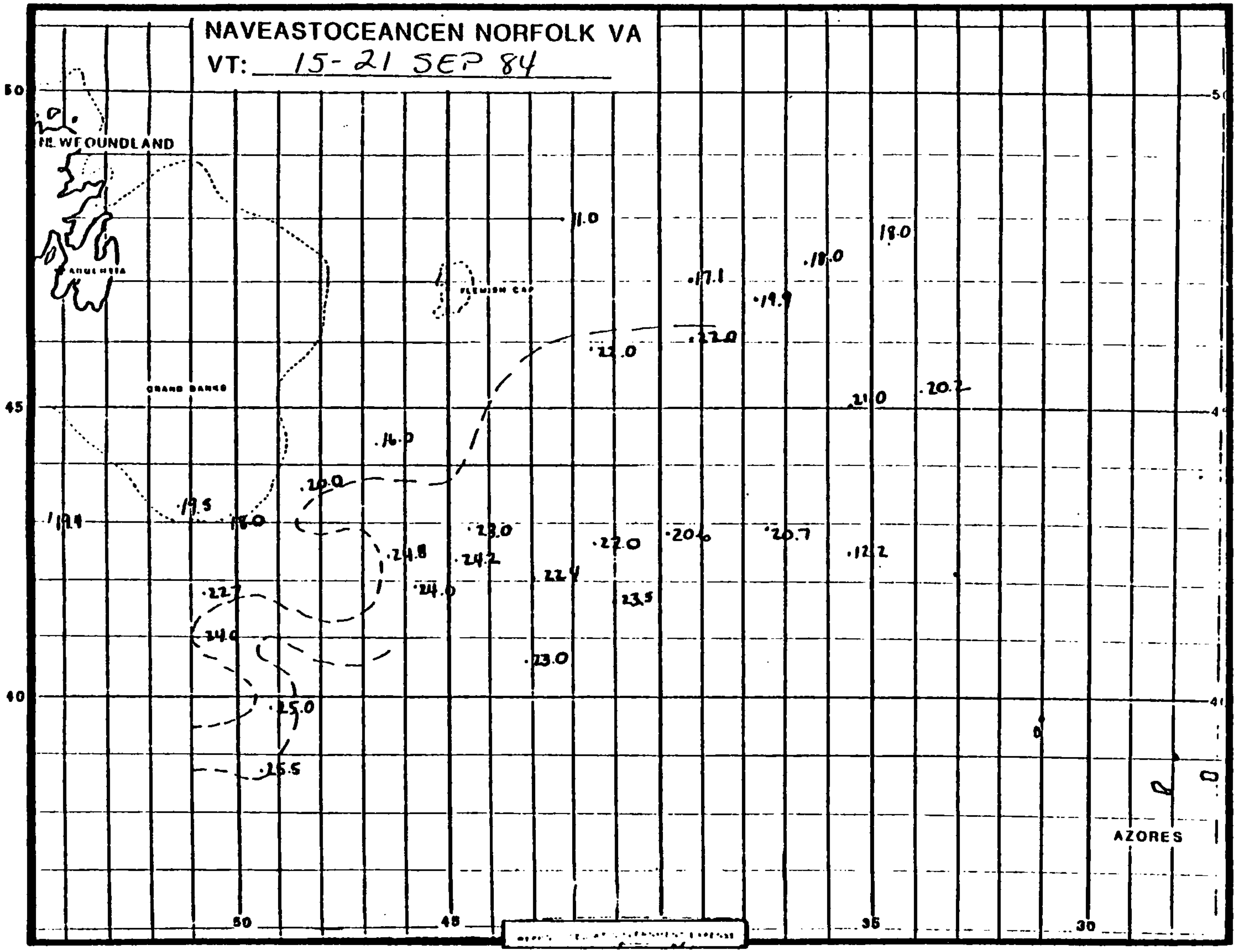

Figure 8 SAMPLE OF NAVAL EASTERN OCEANOGRAPHIC CENTER GULF STREAM ANALYSIS CHART

problem with cloud cover, but introduced its own inherent difficulties, notably that vessels are not consistent in where they record temperatures. Some record intake temperatures, others output temperatures. This may create anomalous temperature readings that in turn can distort contours producing artificial warm and cold spots that will be incorrectly labeled as eddies. In 1984 the Canadians started relying more on NOAA imagery and their recent products agree very closely with NWS.

Based on the criteria used by the organizations to plot an eddy it appears reasonable to assume that those plotted by NEOC probably exist, but that they may not plot others that are in the area. On the other hand, NWS and the Canadians plot eddies that probably exist, but may also add some that are spurious. Because the METOC data relies so much on vessel reports, the analysis in this study is based on the NWS and NEOC and use the METOC data only as an additional confirmation measure.

The second main source of data came from the satellite tracked Tiros Ocean Drifter (TOD) buoys monitored by the IIP. These buoys are launched from C-130 aircraft or from vessels every year during the ice season to provide real time current information used in our iceberg drift model. They provide position and sea surface temperature information through the Service Argos system. The position accuracy of these buoys is estimated at 150 meters (Besis 1981).

The tracks of these buoys will indicate eddy activity in the area by displaying circular motion. These tracks can be useful to verify the location and size of an eddy shown on either of the satellite prepared charts and to provide data on speed of circulation and possibly on duration of eddy activity. We started deploying TOD's in March 1980, and since have deployed over thirty buoys. All of the tracks are archived in our files and published in the annual end of season bulletins.

The final source of data is Side-Looking Airborne Radar (SLAR) imagery of the area. In 1983 IIP introduced the use of SLAR to the tracking of icebergs. SLAR is an x-band radar with antennae mounted on each side of a C-130 aircraft with the active faces at approximately right angles to the axis of flight. The radar then scans outward from the flight path of the airplane. Because the antennae are mounted along the side of the aircraft, they can be made 5.5 meters long, thus providing superior along track resolution. This high resolution makes the radar useful in terrain mapping. The SLAR imagery is displayed on a length of photographic film exposed by a cathode ray tube. The IIP aircraft flies a SLAR search pattern in a given part of our operation area mapping a 100 km swath on each leg of the flight.

Just as the SLAR maps surface terrains it can also map surface frontal features on the ocean surface. These features are clearly visible through highly discernible light and dark areas on the films, corresponding to areas of low and high radar backscatter. It has been suggested that these differences in radar return from the sea surface are due to temperature related roughness variations across frontal and eddy boundaries (LaViolette, 1983).

Some advantages SLAR data has over the other data sources for the location and identification of eddies and other frontal features are the high resolution of the radar and its ability to operate despite the prevailing cloud cover and weather in the area. The position data obtained from the SLAR is more accurate than some of the other data sources and the data is retrieved real-time while the airplane is in the air. The C-130 aircraft relies on an Inertial Navigation System for navigation. The design accuracy of this unit is 1.6 km per hour of flight and this error is correctable in flight using Loran C input. This accuracy would lead to an error over an average flight of no more than eight km.

There are some disadvantages in using the SLAR data. The SLAR coverage is dependent on the iceberg distribution, so the search patterns flown by the aircraft cover only very small squares of the total research area at any given time as shown in Figure 9. Patterns are only flown every other week during the iceberg season (usually March through about August), so the temporal spacing of SLAR data is also a disadvantage. This coverage not only limits the area in which features will be seen by the SLAR, but may result in the SLAR film plotting only small parts of features making it difficult to compare to a given feature plotted on the NWS or NEOC charts.

The features displayed on the SLAR films will assist in verifying the location and size of eddies shown on the NWS and NEOC charts and to compare the positions of the SLAR features versus the satellite plotted features. This comparison will show how accurate the predictions of the analysts are in the size and positioning of various features. The SLAR imagery is the standard with which to compare the satellite imagery.

Procedure

Complete sets of frontal analysis charts were available for only three years. This length of time is sufficient to determine the population density of eddies in the area and to describe the average

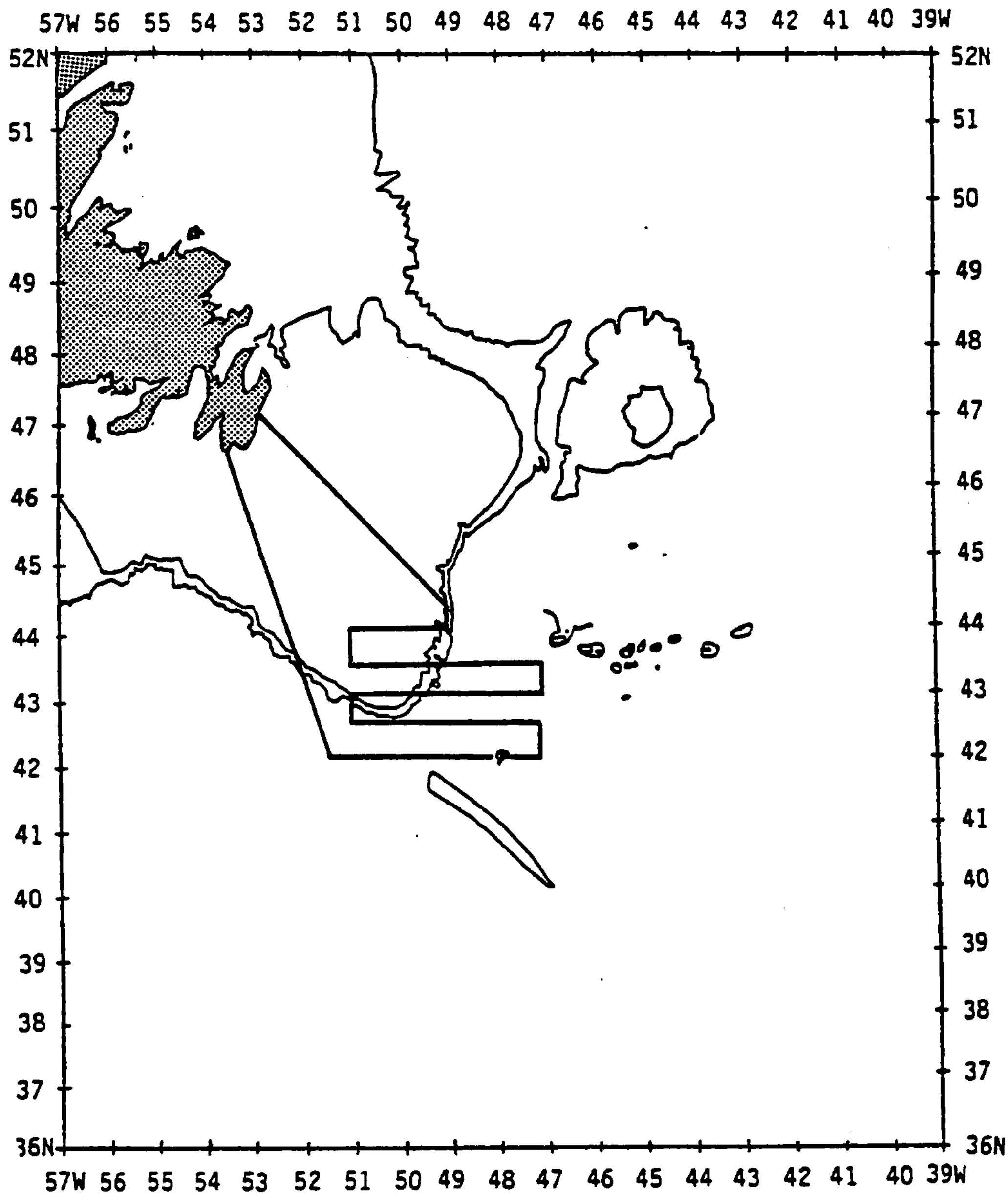

Figure 9 TYPICAL AREA COVERED DURING A SLAR PATTERN SEARCH BY AN IIP AIRCRAFT

eddy encountered. Based on this information, the time frame for the study was 38 months: from November 1981 to December 1984.

In determining the total number of eddies included in the study, the NWS charts contained the highest number of eddies, and they became the starting point for cataloguing eddies. Analysis involved sequentially numbering all eddies on the NWS charts noting the date and position of initial report, the size, core and whether it was interacting with the parent current, and comparing those on the NEOC charts with them to determine which were duplicated on both charts. Eliminating the duplicates and merging the remaining sightings yielded a comprehensive list of 46 eddies sighted in the research area during the time of my study. Comparing the eddies on the METOC charts with this list allowed for additional confirmation of certain features.

Because the data came from three different sources, each with inherent difficulties associated with methods, and in many cases dependent on each other, a problem of credibility arises. All of the eddy data can not be accepted at face value. Based on the reliability of the source, as previously discussed, the credibility levels were designed that show the probability that a given eddy exists. There are four levels of credibility:

1. Appeared on all three charts
2. Appeared on NWS and NEOC
3. Appeared either on NEOC or on both NWS and METOC
4. Appeared on NWS only

Other than the number of eddies present in the area, the important parameters in this study are area and method of formation, direction and speed of translation, method of deterioration and the relation of these characteristics to the topography and dynamics of the research area.

The only measure of area of formation is the position of the initial report. This may be an inaccurate measure in that, due to cloud cover, the first reported position may not be the actual location of formation. The eddy may have been present, hidden by cloud cover, for several days and have migrated several kilometers before it was first seen and reported. This is one area where the average translation characteristics may assist in determining the correct area of formation.

Determining the area of first report was a matter of plotting the position on a topographic chart of the area. Determining the translation involved plotting the longitudinal migration on graph paper. A computer program provided the entire trackline of the three longest lived eddies in the data set. This information established the relationship between formation and topography and to establish the average translation pattern in the research area.

In a review of formation and deterioration processes three methods were used to catagorize the formation of eddies: pinched off meander, interaction of two water masses and unknown origin, and three of deterioration: assimilated by parent current, moved out of area and lost surface expression. Eddies may form as a meander of the Gulf Stream pinches off and migrates independently. However, it may still associate with the Stream and mixing of water masses may occur for part or all of the eddies life. Eddies may also form as a result of the interactions of the warm water of the Gulf Stream mixing with the cold water of the Labrador Current. This mixing may cause pockets of water to be enclosed by warmer or colder water and form an eddy. The location of the eddy and the dynamic features in the area shortly before it formed provide the basis for determining its mechanism of formation. The eddy may ultimately be assimilated back into the Stream by another meander or it may dissipate or lose its surface expression. The same factors that formed the basis for formation determine the basis for deterioration.

In reviewing the TOD tracks in the IIP library, the position and dates of any circular motions indicated in the record were recorded and compared with the list of eddies extracted from the charts to see if the TOD's further confirmed the existence of any of them. The TOD tracklines also yielded information pertaining to the size and shape, position, translation and rotational velocity of the eddy. This information was useful in describing the profile of the average eddy.

Analyzing the SLAR film involved looking at each film in the library and marking the position of features that may have assisted in identifying eddies and plotting them on a topographic chart of the research area and then directly onto the NWS and NEOC charts to compare them directly with the features plotted by the analysts. The study of the SLAR film would confirm or deny eddy activity and provide an accurate indication of position, size, shape and translation.

Unfortunately no cross-sectional study of an eddy was available. The reader is referred to Joyce (1983) for a study of eddy dynamics.

RESULTS

Eddy Population

During the 38 months of the experiment the NWS and NEOC charts indicated 46 eddies in the area. Appendix A gives a full description of them. The credibility level distribution of the 46 was as follows:

Credibility Level 1	9	20%
Credibility Level 2	8	17%
Credibility level 3	12	26%
Credibility level 4	17	37%

The liberal policy of NWS resulted in more than one third of the total number of observed eddies being unsupported by any other organization.

Of the 38 months time span, only 175 days showed no sign of eddy motion. Eighty five percent of the time at least one eddy was active in the research area and on several occasions two or more were present. The life of the eddies ranged from two to 218 days with an average duration of 42.1 days.

Areas of Formation

The initial reported positions of the eddies are shown in Figure 10. Of the 46 observed eddies 12 (26%) were first sighted directly over the Newfoundland Seamount Range, in an area centered around 44N 46W.

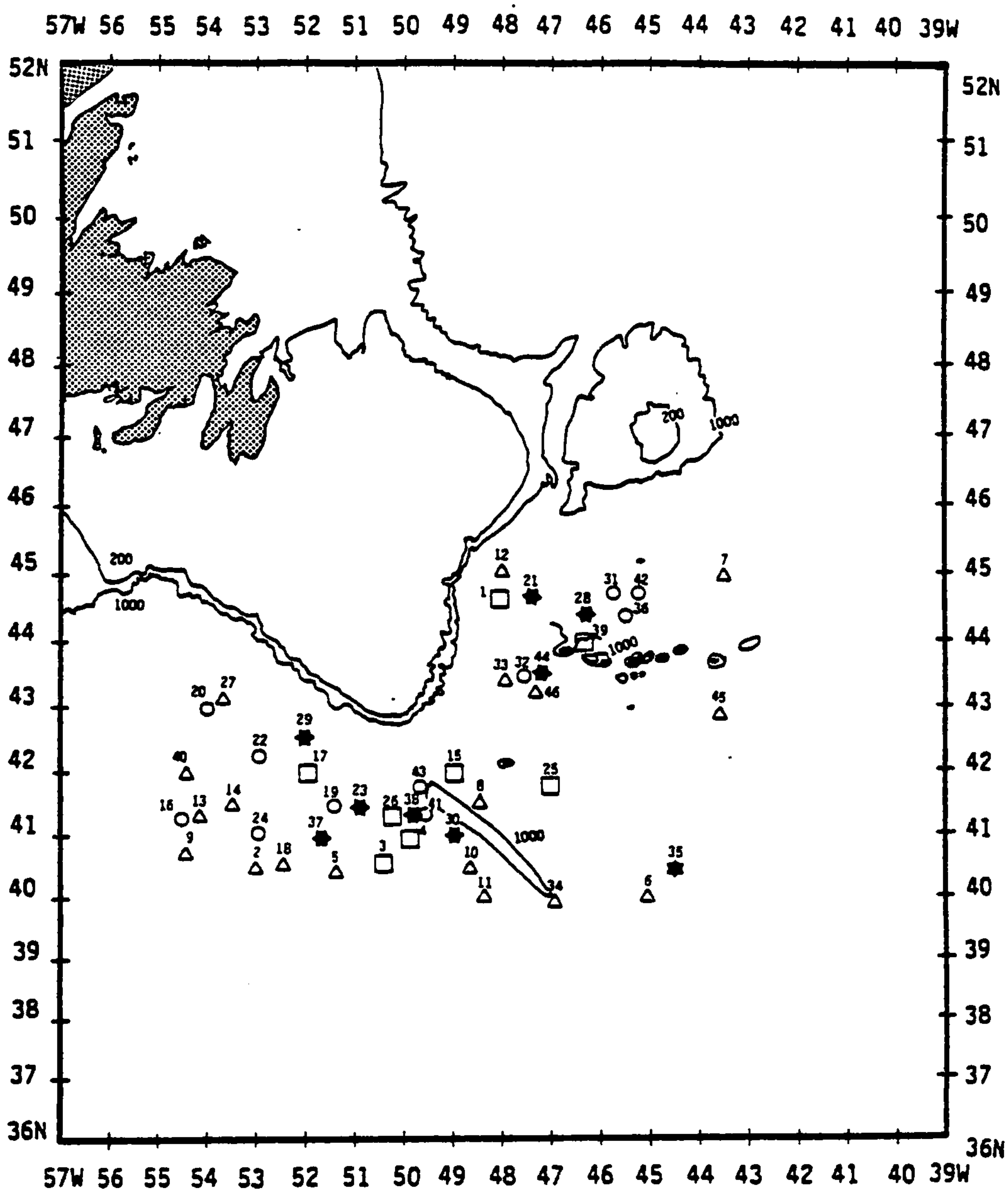

Figure 10 PLOT OF THE INITIAL REPORTED POSITIONS

OF THE EDDIES INCLUDED IN THIS STUDY

Although the origin of these eddies is uncertain, they may have formed as a result of interaction with the topography in the area of the Seamounts. Thirty-four (74%) were first sighted west of the Newfoundland Ridge. As with those over the Seamounts, these eddies may have formed as a result of interaction with the topography of the Ridge and migrated west until they were first seen west of the Ridge. Figure 10 shows these two clusters of eddies.

The literature review demonstrated that the North Atlantic Current meanders as it enters the oparea in the area just west of the Ridge and that these meanders influence the interaction of the Current with the Ridge (Mountain and Shuhy, 1980). Evidence of strong eddy formation in the area supports the belief not only that the North Atlantic Current feels the bottom in this area (Fuglister, 1963 and Warren, 1969), but also that this connection with the topography influences and increases eddy formation. This hypothesis is strongly supported by the cluster of eddies centered on the Seamounts. It is known that the Atlantis II Seamounts are an area of strong eddy activity (Vasatov and Warren, 1976); results presented here suggest that the Newfoundland Seamounts are also a favorable source area for them.

These results indicate that the main portion of the research area affected by eddy activity is the area centered around 44N 46W and the area to the west of the Ridge. The remainder of the area should be well represented by the historical currents, updated by real-time TOD data.

Generation and Deterioration

Twenty-one of the eddies (46%) formed from pinched off meanders, eight (17%) from interactions between the currents. Seventeen eddies

(37%) had no readily identifiable source, they just appeared on the chart. Of these, nine were credibility level four, unsupported NWS eddies and four were credibility level three, unsupported NEOC eddies. The other four were high credibility level eddies. Many of the former two categories may be explained by saying that they did not exist at all, but a different explanation must be given for the last four. It is possible that the cloud cover hid the meander from which the eddy formed and that by the time visibility improved, the eddy was in place and the analysts missed the generation process. Seven of these eddies were in the Seamount area and eight were near the Ridge.

Placing the eddies into the catagories discussed in the procedure section yielded the following information:

Meander to Assimilated	10	22%
Meander to Dissipated	8	17%
Interaction to Assimilated	4	9%
Meander to out of area	3	6%
Interaction to dissipated	4	9%
Unknown to assimilated	7	15%
Unknown to dissipated	10	22%

Translation Through the Area

Figure 11 displays the longitudinal drift of the eddies through the research area and Table 1 summarizes the drift statistics. Twenty one of them showed a net westward drift throughout their lives. Only three displayed an eastward net drift. The remaining 22 showed no net drift.

Of the 22 showing no net drift, 18 had a fully observed life span of fifteen days or less and so may not have had the opportunity to drift

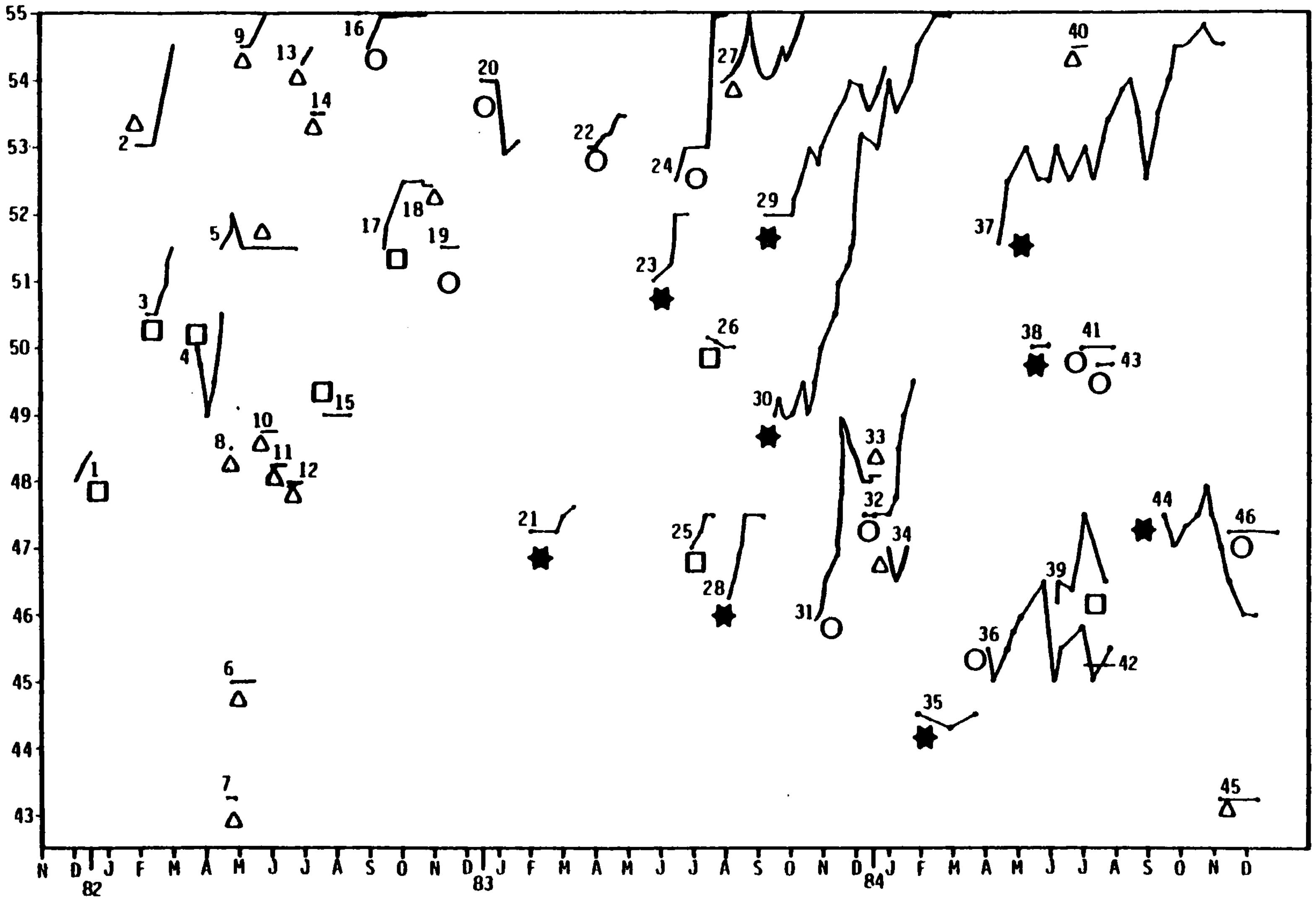

Figure 11   LONGITUDINAL DRIFT OF THE EDDIES INCLUDED IN THIS STUDY

TABLE 1

SUMMARY OF DIRECTION OF DRIFT OF

EDDIES IN THIS STUDY

Net West Drift	Net East Drift	Net No Drift
1	20	5*
2	26	34*
3	44	35*
4		36*
9		6**
13		7**
16		8**
17		10**
21		11**
22		12**
23		14**
24		15**
25		18**
27		19**
28		33**
29		38**
30		40**
31		41**
32		42**
37		43**
39		45**
		46**

* Demonstrated an oscillatory drift pattern.

** Not on plot long enough to establish a drift pattern.

at all. Numbers 42,45 and 46 were seen in periods of heavy clouds and so were carried in the original reported position for a month and deleted from the NWS charts. The other four showing no net drift display an oscillatory drift; both east and west alternately. This motion is also displayed by many of the longer lived eddies that show definite westward net drift. The motion may be explained by navigational and positioning errors on the satellite, and it can be assumed that these four eddies would have had a net west drift had they had a longer life span.

These same factors may have influenced the three eddies that displayed a net east drift. It was shown in the literature review that eddies interacting with the Gulf Stream in other areas display a predominantly westward drift (Richardson, et al., 1978). This study agrees because of the 21 eddies showing westward drift, 12 showed considerably interacting with the NAC during their life spans. Of the three that drifted east, one showed no interaction with the parent current at all. Interactions with the Gulf Stream then could not have caused the net east drift of the eddies.

The full tracklines of the three longest lived eddies are shown in Figure 12. The tracks display circular motion that is probably attributable to navigational and positioning errors by the satellite, but they display an overall net drift to the west. As most of the tracklines in Figure 11 display trajectories similar to these three, it is feasible to assume that these represent the typical paths of long-lived eddies in the IIP oparea.

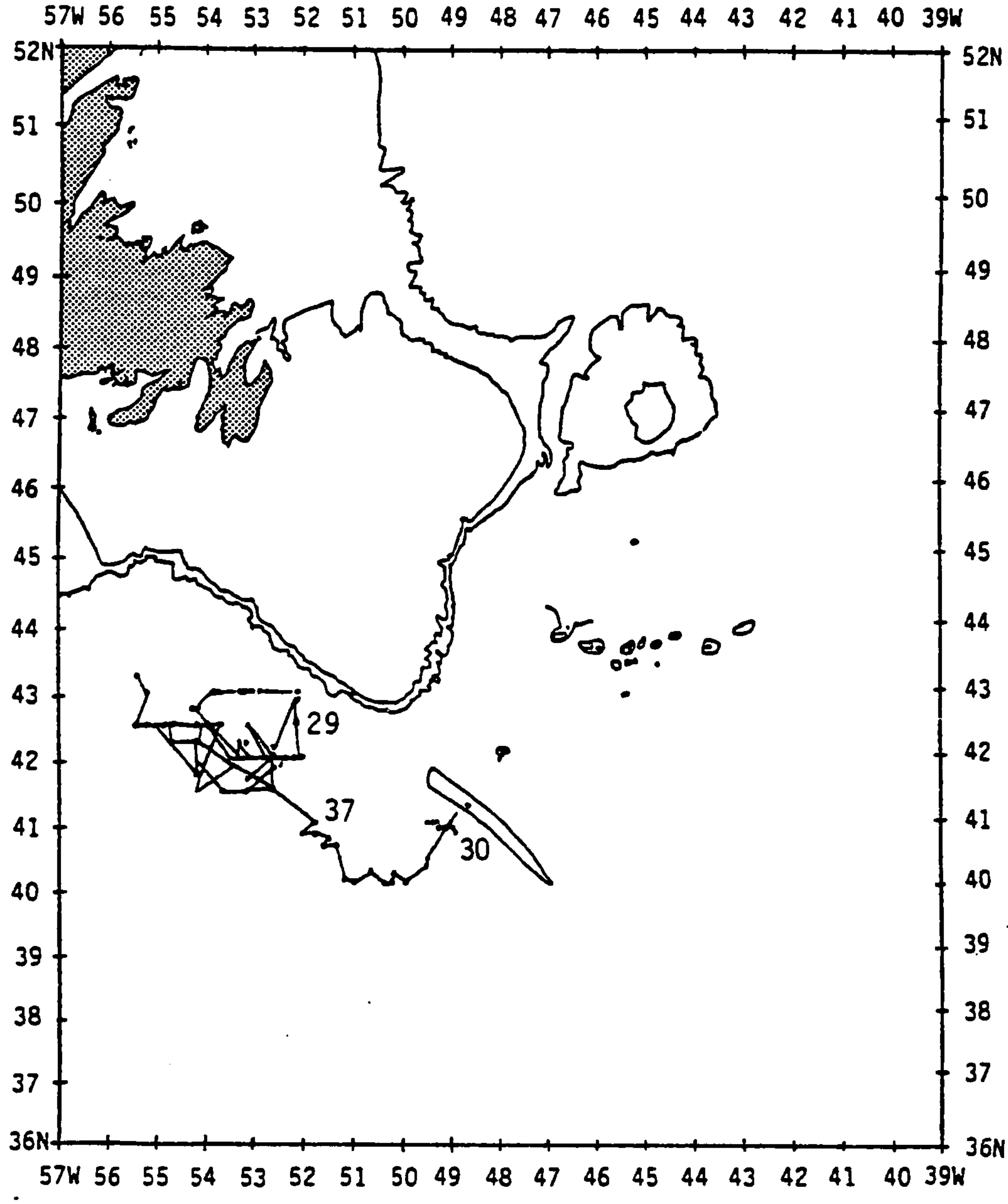

Figure 12 PLOT OF THE TRACKS OF THE THREE LONGEST LIVED EDDIES IN THE STUDY

Eddy Size

The eddies varied in shape from roughly circular to elongated ellipses and many had irregular circumferences. The average size is the average of the axes of each eddy and assumed all were assumed to be of circular form of this dimension. The mean of all eddies in the study was 71.4 km. The standard deviation was 23.27 and the variance was 530. The average of cold core eddies was 58.7 km with a standard deviation of 15.52 and a variance of 211 and of warm core eddies 74.1 km with a standard deviation of 74.08 and variance of 556. The warm eddies are slightly larger than cold core.

Comparison of Eddy Characteristics in two Areas

The characteristics of the eddies formed in connection with the Seamounts and the Ridge are shown in Table 2 and Table 3. A review of these tables show that the duration of eddies over the Seamounts ranged from six to 115 days with an average duration of 46.5 days. The same statistics for the 34 eddies formed near the Ridge show a range of two to 218 days with an average of 41.8 days. These figures indicate that the area of formation has little or no effect on the life span of the eddy.

The area of the Seamounts showed eddy activity existed 63% of the time; the Ridge, 69% of the time. Both areas are of equal potential as eddy generating areas.

The eddies that formed over the Seamounts showed a westward migration in six of twelve eddies while five showed no significant migration. The last eddy showed eastward migration. Those formed in

TABLE 2

CHARACTERISTICS OF EDDIES FIRST REPORTED IN THE

VICINITY OF THE NEWFOUNDLAND SEAMOUNTS

EDDY NO	DATES ON PLOT		LIFE	CLEV	CORE	FORMATION	DETERIORATION
7	04/23/82	04/28/82	6	4	C	Unknown	Absorb (GS)
12	06/14/82	06/25/82	12	4	W	Unknown	Dissipated
21	01/31/83	03/14/83	43	1	W	Meander	Dissipated
28	08/05/83	09/07/83	34	1	W	Meander	Dissipated
31	10/21/83	01/04/84	76	3	W	Interact	Dissipated
32	12/10/83	02/03/84	56	3	W	Unknown	Dissipated
33	12/14/83	01/04/84	22	4	W	Unknown	Dissipated
36	04/04/84	07/27/84	115	3	W	Unknown	Dissipated
39	06/04/84	08/04/84	66	2	W	Unknown	Dissipated
42	07/02/84	07/09/84	8	3	W	Unknown	Dissipated
44	09/12/84	12/05/84	85	1	W	Meander	Dissipated
46	11/10/84	12/14/84	36	3	W	Meander	Dissipated
			559				

559/12=46.6 average eddy life

TABLE 3

CHARACTERISTICS OF EDDIES FIRST REPORTED IN THE

VICINITY OF THE NEWFOUNDLAND RIDGE

EDDY NO	DATES ON PLOT		LIFE	CLEV	CORE	FORMATION	DETERIORATION
1	12/02/81	12/18/81	17	2	W	Unknown	Absorb (Lab)
2	01/27/82	03/03/82	36	4	W	Unknown	Dissipated
3	02/08/82	03/03/82	24	2	W	Meander	Dissipated
4	03/24/82	04/14/82	22	2	W	Unknown	Absorb (GS)
5	04/05/82	06/21/82	78	4	W	Meander	Dissipated
6	04/23/82	05/12/82	20	4	C	Unknown	Absorb (GS)
8	04/26/82	04/08/82	3	4	C	Unknown	Absorb (GS)
9	05/05/82	05/26/82	22	4	W	Meander	Out of Area
10	04/23/82	06/02/82	41	4	W	Meander	Absorb (GS)
11	06/02/82	06/18/82	7	4	C	Interact	Absorb (GS)
13	06/28/82	07/07/82	11	4	C	Interact	Absorb (GS)
14	07/07/82	07/21/82	15	4	W	Meander	Absorb (GS)
15	07/19/82	08/16/82	27	2	W	Meander	Absorb (Lab)
16	09/03/82	10/25/82	53	3	W	Meander	Absorb (GS)
17	09/13/82	10/18/82	36	2	C	Meander	Dissipated
18	10/22/82	10/29/82	8	4	W	Meander	Absorb (Lab)
19	11/08/82	11/24/82	17	3	W	Meander	Absorb (GS)
20	12/17/82	01/24/83	39	3	W	Unknown	Dissipated
22	03/25/83	05/02/83	39	3	W	Unknown	Absorb (GS)
23	05/25/83	06/27/83	36	1	W	Meander	Absorb (GS)
24	06/13/83	08/22/83	70	3	W	Meander	Out of Area
25	06/27/83	07/13/83	17	2	W	Meander	Absorb (GS)
26	07/13/83	08/08/83	26	2	W	Meander	Absorb (GS)

EDDY NO	DATES ON PLOT		LIFE	CLEV	CORE	FORMATION	DETERIORATION
27	08/01/83	10/17/83	78	4	W	Interact	Dissipated
29	09/07/83	01/04/84	120	1	W	Interact	Dissipated
30	10/16/83	03/14/84	181	1	W	Meander	Out of Area
34	01/04/84	01/25/84	22	4	C	Interact	Dissipated
35	02/01/84	03/21/84	49	1	C	Unknown	Dissipated
37	04/18/84	11/21/84	218	1	W	Meander	Dissipated
38	05/16/84	05/30/84	15	1	W	Meander	Absorb (GS)
40	06/20/84	07/04/84	15	4	W	Interact	Absorb (GS)
41	07/26/84	08/01/84	7	3	W	Unknown	Dissipated
43	07/14/84	07/21/84	8	3	W	Unknown	Dissipated
45	11/07/84	12/10/84	34	4	C	Interact	Dissipated
			1420				

1420/34=41.8 average eddy life

conjunction with the Ridge topography showed westward migration in 16 of 34 eddies and no migration in another 16. Two showed eastward migration. The area of formation shows no apparent affect on the migration of the eddy through the area.

The eddies formed over the Ridge had an mean size of 74.2 km, and ranged from 30 km to 130 km with a standard deviation was 24.41 and variance was 578. The mean for those over the Seamounts was 63.3 km, with a range of 35 to 100 km, a standard deviation of 24.16 and variance 534. There is very little difference in the physical size of the eddies in the two areas.

Only one of the eddies that formed over the Seamounts was cold core. Eight cold core eddies formed in the area of the Ridge. There are two possible explanations for this: either the Labrador eddies form more as a reaction with the North Atlantic Current in the Newfoundland Ridge/Tail of the Bank area, or the Labrador eddies drifted south out of the Seamount area hidden by cloud cover before they were reported.

A much higher percentage of Seamount eddies had an unidentifiable origin. Seven out of twelve or 58% had an unknown source of origin (Table 2) as compared with eight out of 34 or 23% of the Ridge eddies.

Labrador Current Eddies

Perhaps one of the most interesting results of this study is the location of five cold core eddies in the area north of the Gulf Stream. Eddies number 8, 11, 13, 34 and 45 were identified by NWS analysts and plotted in the normal domain of warm core North Atlantic Current eddies. The most likely explanation for the presence of these eddies is the Labrador Current. No studies have been conducted on the generation of eddies by this current, but the literature search showed that the Labrador Current extends to the bottom and that the flow is variable and quite often dominated by the North Atlantic Current. The bottom features may cause the bifurcation noted in the Current's flow. Given the variablility of the flow, it is reasonable to assume that the Labrador Current is as capable as the North Atlantic Current in generating meanders and eddies. Research dedicated to the generation of eddies by the Labrador Current should be planned.

TOD Tracklines

During the time frame of my study IIP released 21 TOD's, all drogued at thirty meters. Of these only six were active in the research area. The tracklines for these are presented in Figures 13 (a,b and c). The tracklines of all of the buoys provide an accurate presentation of the general current regime in the area. It can be seen that the buoys follow the Labrador Current along the slope of the Grand Banks to a point between the middle and the tail of the bank. They then enter the North Atlantic Current and flow west beyond Flemish Cap and out of the area. In addition, the tracklines of five of the six buoys exhibit circular motion suggestive of meander activity.

Circular motion in buoy #2610, released in May 1983, appears to confirm eddy #25, a credibility level 2 warm core eddy that appeared on the NEOC charts for 6 and 7 July 1983 at 4200N 4730W. However, the motion of the buoy is counterclockwise, indicating the presence of a cold core eddy. TOD #2610 enters a circular pattern on 4 July 1983 and makes two complete orbits before exiting on 12 July. The TOD travelled 250 km in eight days, giving the eddy a rotational speed of .8 kts. The

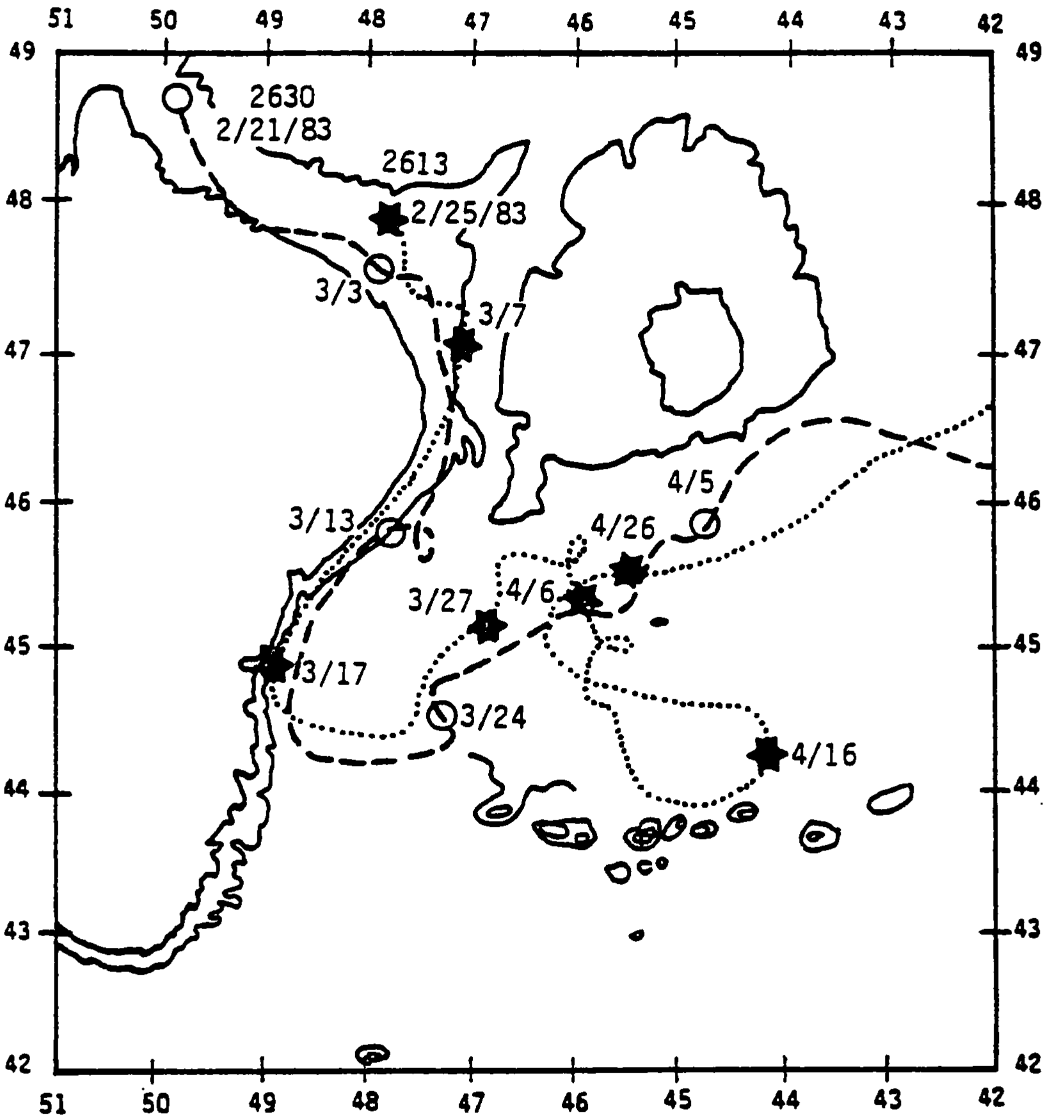

Figure 13a PLOT OF THE TIROS OCEAN DRIFTER TRACKS THAT DEMONSTRATED EDDY-LIKE MOTION

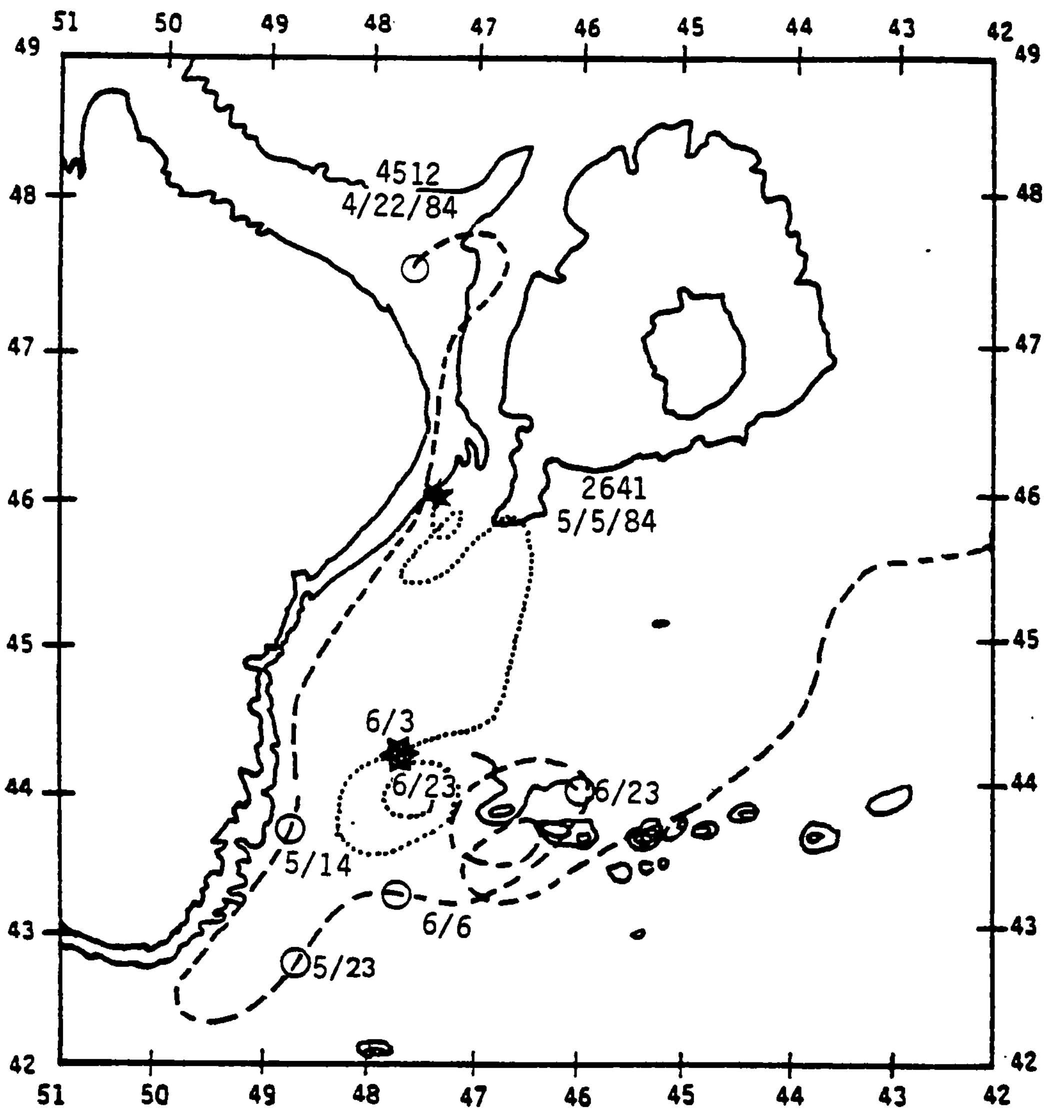

Figure 13b PLOT OF THE TIROS OCEAN DRIFTER TRACKS THAT DEMONSTRATED EDDY-LIKE MOTION

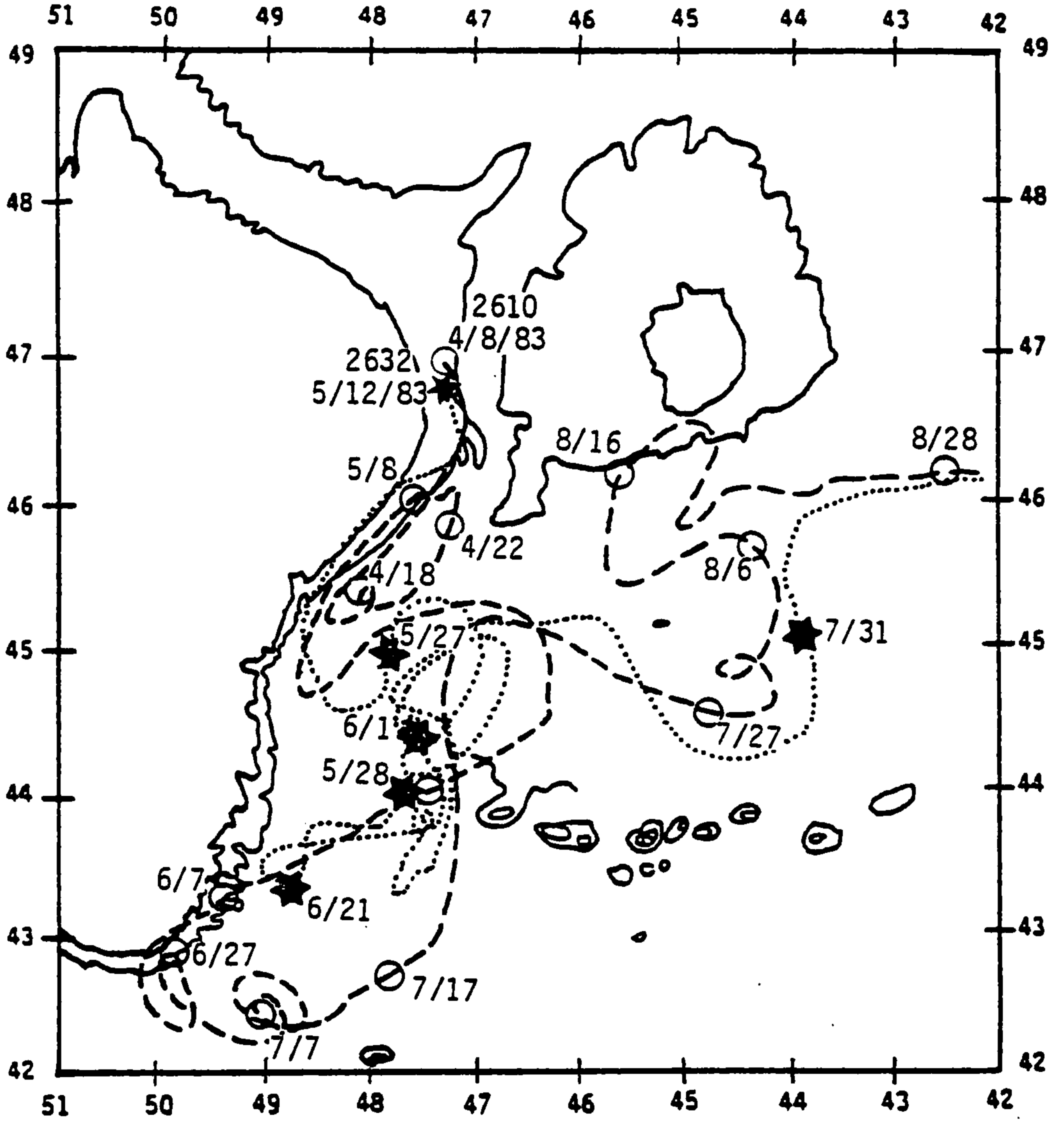

Figure 13c PLOT OF THE TIROS OCEAN DRIFTER TRACKS

THAT DEMONSTRATED EDDY-LIKE MOTION

diameter of the TOD rotation is about 80 km. The diameter of the plotted eddy is about 160 km. Discrepancies in the size of the eddy and in the positions may be explained as navigational error in the satellite imagery and extrapolation of the size necessitated by cloud cover. The chart showed the eddy in an approximate position.

Circular motion in the trackline of buoy #4512, released in April 1984, coincide with eddy #39, a credibility level one warm core eddy that appeared on the NWS and NEOC charts in position 4400N 4630W for about twenty days starting on 7 June. Again, as in buoy #2610 above, TOD #4512 indicates the motion of a cold core eddy: counterclockwise motion. In all other aspects the TOD trackline approximates the plotted eddy well. Both have diameters of about 45 nm and both occur during the same time frame. The TOD moved 770 km in 20 days indicating a rotational speed of .7 kts. The plotted center of the two TOD loops indicates southwestward migration through the area. The center of rotation moved about 40 km in the 20 days yielding a translation speed of about .04 kts.

One possible explanation for the apparent contradiction in direction of flow is that the buoy was caught in a more complex circulation and was moving between the eddy and the parent current while the two water masses were interacting with each other. The study showed that the eddies interact with the parent currents and that water is interchanged during these times. In this instance, the TOD would have been moved south by the Labrador Current, entrained into the eddy and moved north, resulting in counterclockwise rotation.

Another possibility is that the NWS analyst misinterpreted the infrared image and called a warm core eddy cold. Though this may be a remote possibility, it must still be considered as possible.

None of the other three buoys are in the vicinity of plotted eddies. The fact that they show eddy type motion may indicate that the satellite IR sensors are not picking up everything in the area.

An interesting point can be seen by comparing the tracks of eddy number #2630 and #2613 of 1983. Both buoys were released in the same area at about the same time and both followed similar paths for 40 days. In the first week of April, buoy #2613 went into a circular orbit at 4515N 4600W, while #2630 continued in a straight line. If an eddy existed in the area and the buoys were on the periphery of it, the southernmost buoy may have been entrapped while the northernmost escaped, but in this case the northernmost buoy was entrapped. This is indicative of the spatial and temporal variability of the dynamics in the area. Buoy #2630 was about two days ahead of #2613 in passing the position. In that short time an eddy formed or moved into the area and entrapped #2613 while #2630 was not affected.

SLAR Evaluation

Given the inherent difficulties with the satellite imagery, the SLAR coverage provided a means to confirm the existence of some eddies. The study was not designed to be an exhaustive treatment of the uses of SLAR in identifying ocean features. That is the subject of an ongoing IIP study.

The SLAR film contained 129 features in the research area that indicated the presence of frontal or eddy activity. Many of these corresponded well with features plotted on the NWS and NEOC charts. Many more did not correspond with any plotted feature and some showed that features were present in the area but were plotted up to 60 nm from the SLAR position. Figures 14 through 20 present examples of the SLAR features compared to plotted features. In all of these figures the SLAR image is plotted and defined by a solid arrow. The corresponding infrared feature, as plotted by the analyst, is indicated by a dashed arrow.

Figures (14a and b) represent the correlation between a feature on the SLAR film from 17 May 1983 and eddy #22 and #23 as plotted on the NEOC and NWS charts. The historical sequence as presented in the plots is that eddy #22, a credibility level 3 warm core eddy appearing in the NWS and Canadian charts in position 4230N 5300W, is assimilated into the Gulf Stream by a meander in position 4100N 5100W on 2 May 1983. The meander remained on plot until 23 May when it generated eddy #23, a credibility level 1 warm core eddy. The SLAR film on 17 May shows a 190 km long feature at 4200N 5200W. As shown in Figures (14a and b), the SLAR feature falls exactly on the charted feature shown on the NEOC chart of 14-20 May and about 25 km north of the feature plotted on the NWS chart of 18 May.

Another 25 km long feature on a SLAR film on 7 June coincides with a small portion of eddy #23 at 4130N 5000W. The SLAR feature falls exactly on the feature plotted on the NWS chart and is about 16 km west of the feature plotted in the NEOC chart of 4-10 June (Figure 15a and b).

These two samples of SLAR imagery combine to confirm the existence of these two eddies and the meander that interacted with them. The difference in the positioning in both of these SLAR features can be explained by the difference in the navigational accuracy of the two platforms.

Eddy #37, a credibility level 1 warm core eddy seen at 4100N 5140W on 18 April 1984, is well documented in the SLAR film. The eddy had no

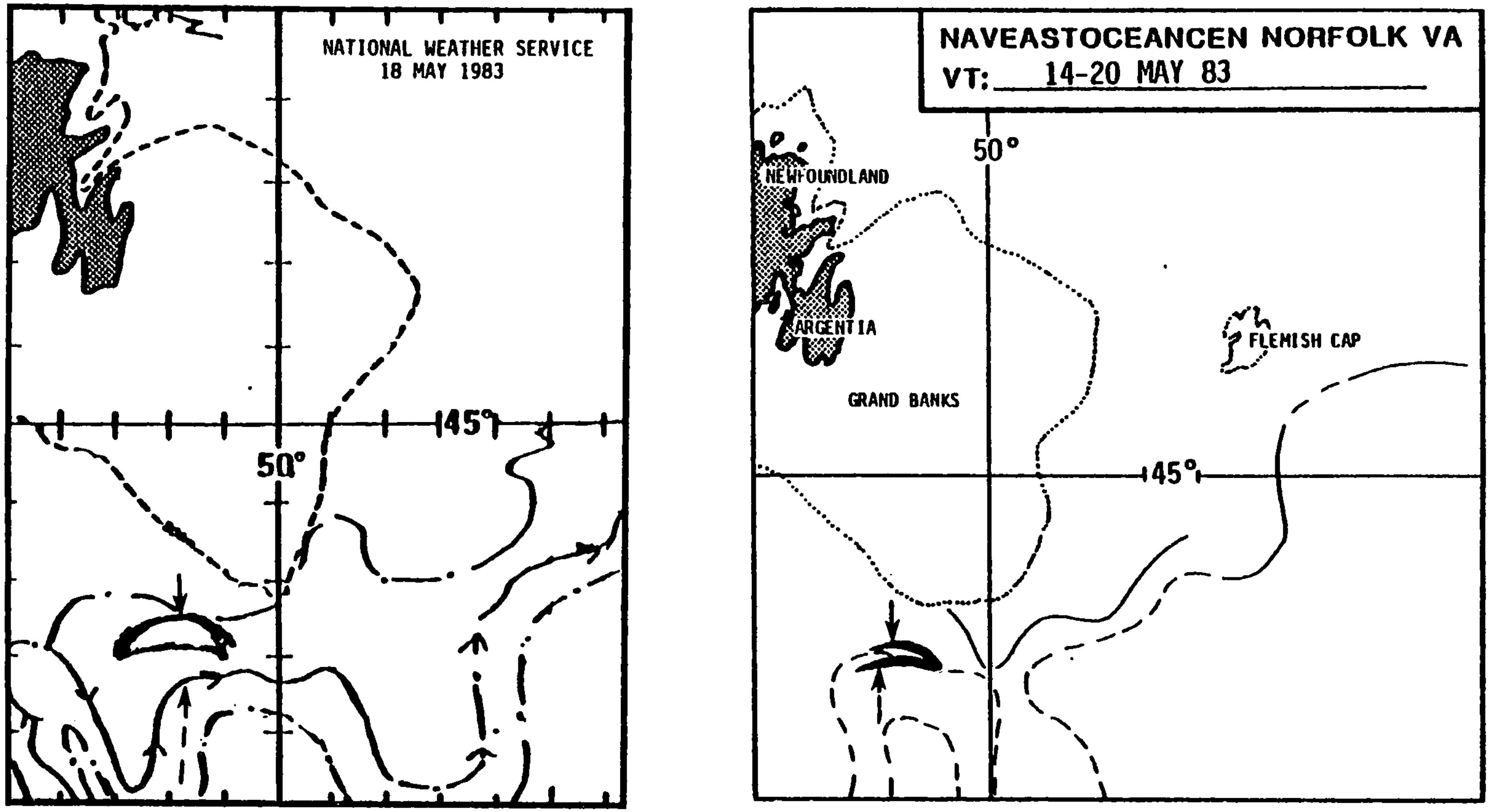

Figure 14 EDDY NUMBER 22 and 23 AS VERIFIED BY

SIDE-LOOKING AIRBORNE RADAR FILM

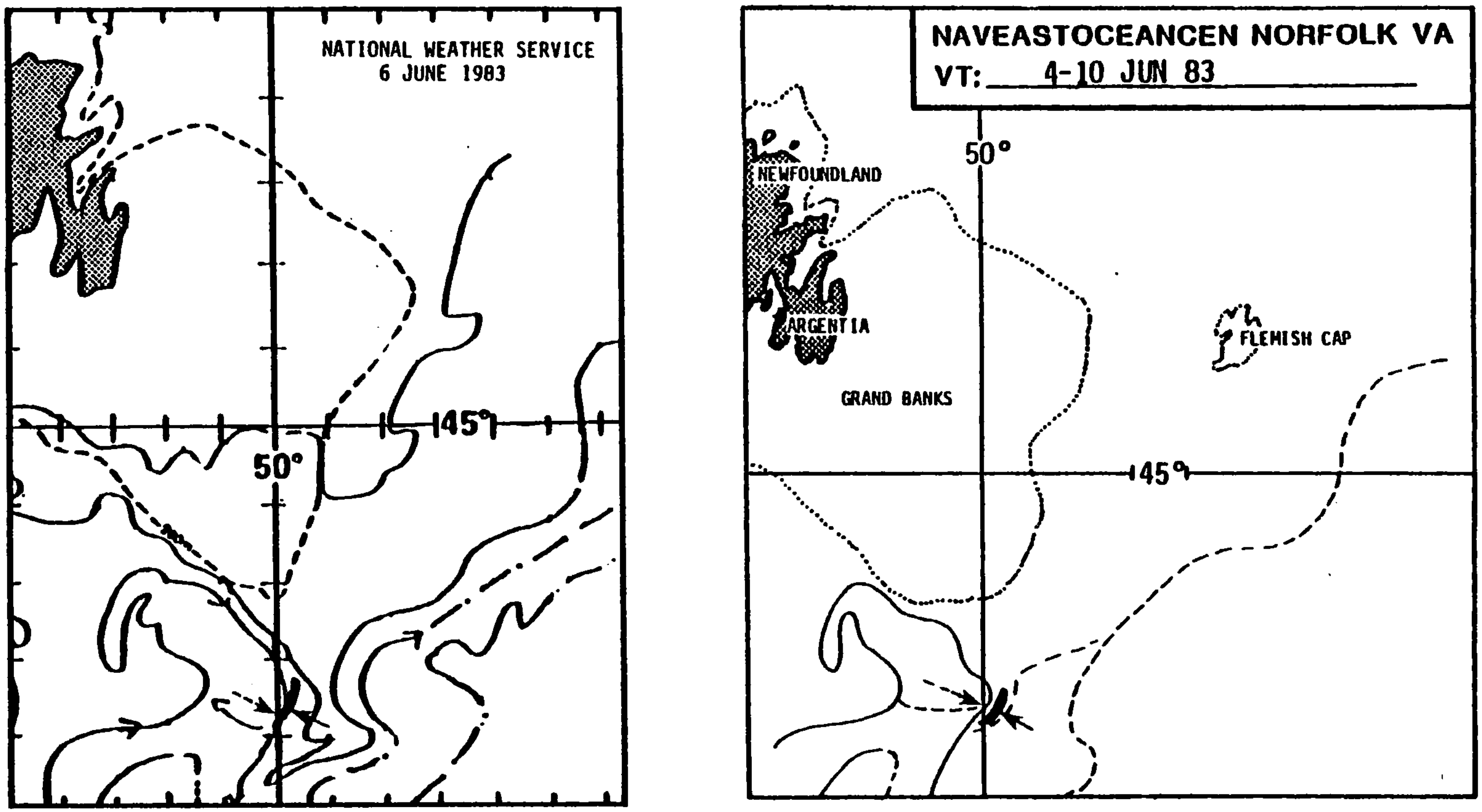

Figure 15 EDDY NUMBER 23 AS VERIFIED BY

SIDE-LOOKING AIRBORNE RADAR FILM

apparent source, but it remained on plot until 21 Nov 1984 when it lost its surface expression.

A SLAR film on 21 May shows a 70 km long feature at 4230N 5130W and a second feature at 4215N 5330W. Figures (16a and b) present the correlation between these features and the plotted eddy position on the NWS and NEOC charts for the week. As seen in Figure (16a), the SLAR film shows the eddy to be in about the same position but indicates a larger diameter and a different shape than shown on the NWS chart. The NEOC chart does not show a feature at this time (Figure 16b).

Another SLAR feature on 28 May at 4245N 5200W provides a second look at the eddy #37. Figures (17a and b) show the SLAR feature to be in the same position as the plotted eddy, but again indicate a different size and shape.

A third SLAR film on 30 May shows three parallel features about 160 km long in position 4100N 4200W. This position corresponds with the position of eddy #37 on both NWS and NEOC charts (Figures 18a and b), but the SLAR features are straight lines that do not show the curvature that would be expected if they were part of an eddy system. These features indicate that some frontal activity exists in the area, but not necessarily eddy #37. This would indicate that the eddy may be getting weaker and more difficult for the analysts to plot, but that frontal activity is still strong in the area.

Finally on 31 May a number of small SLAR features in the same general area indicates the existence of a complex frontal system. This still correlates well with the plotted position of eddy #37 on both NWS and NEOC charts (Figures 19a and b), but the size of the features makes it difficult to determine with any accuracy which SLAR feature would relate to given charted features.

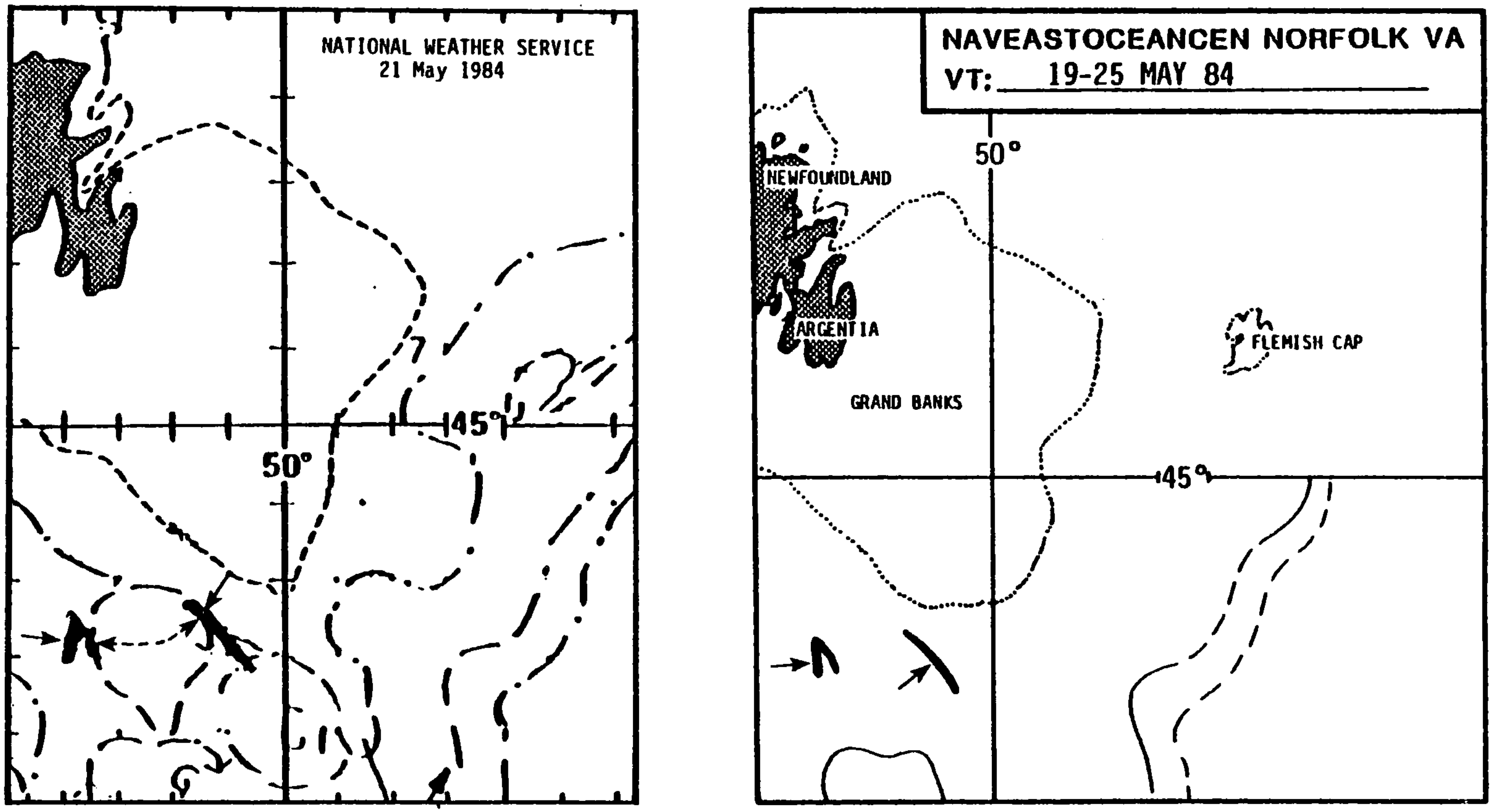

Figure 16 EDDY NUMBER 37 AS VERIFIED BY

SIDE-LOOKING AIRBORNE RADAR FILM

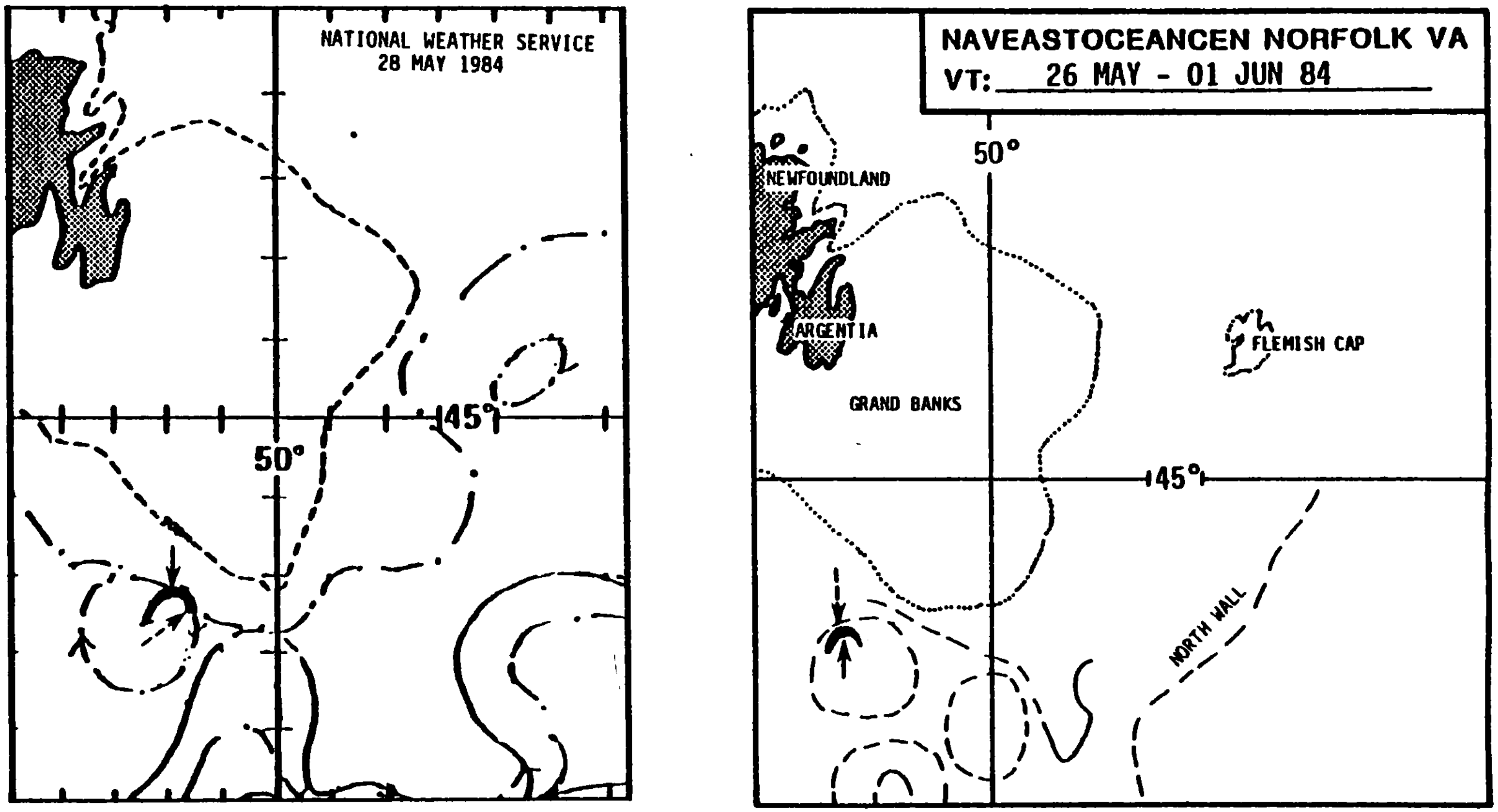

Figure 17 EDDY NUMBER 37 AS VERIFIED BY

SIDE-LOOKING AIRBORNE RADAR FILM

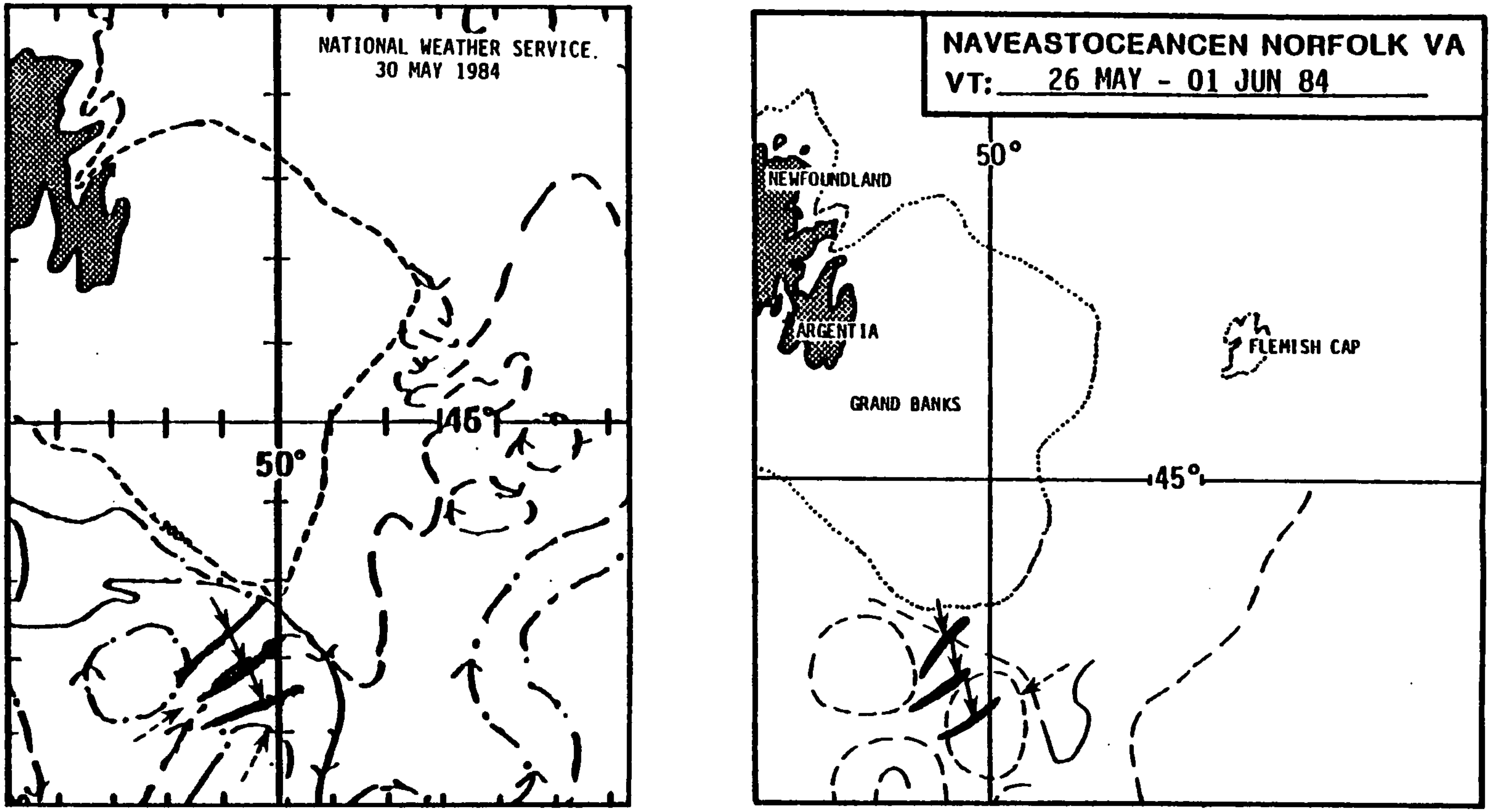

Figure 18 EDDY NUMBER 37 AS VERIFIED BY

SIDE-LOOKING AIRBORNE RADAR FILM

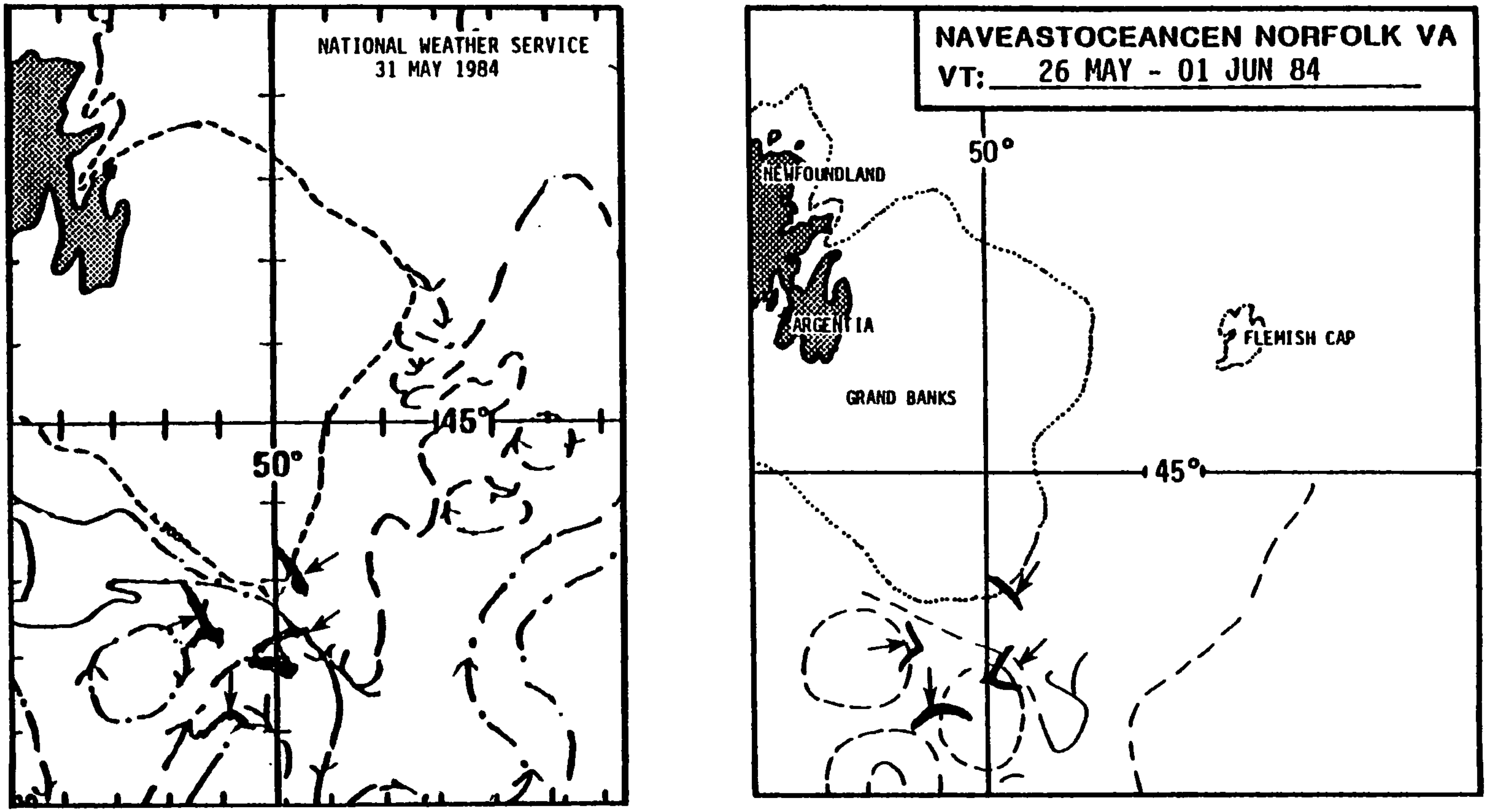

Figure 19 EDDY NUMBER 37 AS VERIFIED BY

SIDE-LOOKING AIRBORNE RADAR FILM

The sequence of SLAR films in the case of eddy #37 confirm the existence of the eddy but also indicate that on some occasions the analysts plots are their "best guess" of what is occurring. Cloud cover and navigational inaccuracies combine to confuse the true picture of the circulation. SLAR is also subject to the interpretation of the analyst, but is not hampered by weather or positioning.

The final SLAR case in this study relates to eddy #38, a credibility level 1 warm core eddy that was spawned by a meander in position 4115N 5000W on 16 May 1984 and was absorbed by a meander on 30 May 1984. A film from 26 May 1984 shows a 95 km long feature that is shown plotted on the appropriate charts in Figures (20a and b).

Figure (20a) shows that the SLAR feature plots exactly on the northwest curve of the meander on the NWS chart for 30 May 1984. The SLAR feature has the same radius of curvature as the meander. Figure (20b) shows that the NEOC chart for 26 May - 1 June 1983 shows the eddy has not been assimilated and that the SLAR feature lies approximately 50 km northwest of the plotted eddy. The radius of curvature for the SLAR feature is the same as the plotted eddy and indicates a radius of about 145 km.

The close agreement between these SLAR features and the plotted meander indicates that the analysts presentation represents an accurate picture of the motion of this particular meander. Attention must be given to a second feature on this same film. It is a 95 km curve in position 4200N 4815W and as shown in both Figures (20a and b) it does not correspond with any plotted feature.

Several other examples exist where SLAR film has confirmed the presence of dynamic features other than eddies and other than in my research area. Still other examples show that SLAR either shows a front

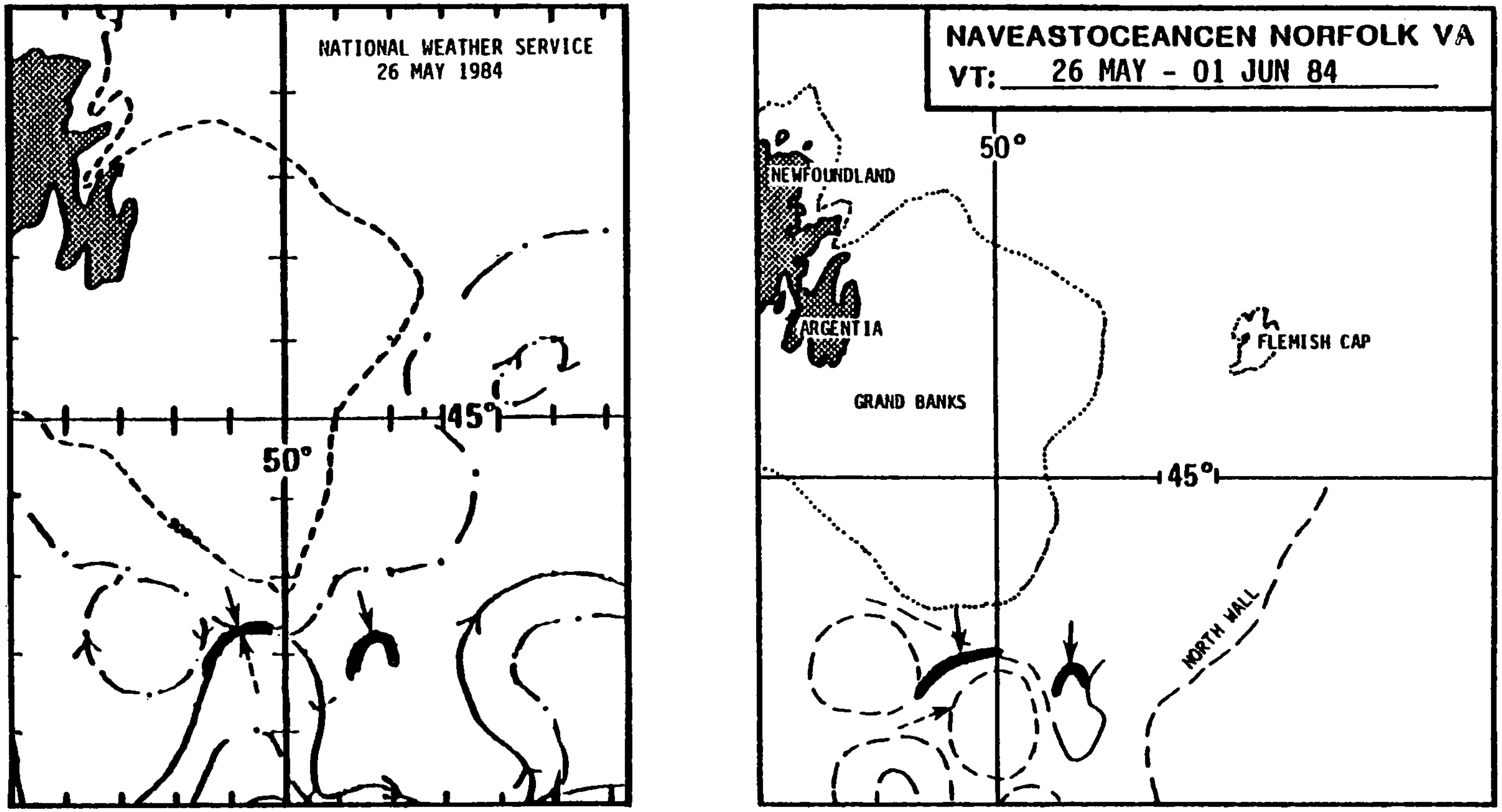

Figure 20 EDDY NUMBER 38 AS VERIFIED BY

SIDE-LOOKING AIRBORNE RADAR FILM

where none is plotted or shows no frontal action where analysts have plotted eddies. The final impression is that even though the analysis often produce an accurate picture of dynamics, the problems inherent in their craft lead to missed or mislocated features. The SLAR demonstrated that the charts give a good general indication of eddy activity in the area, though the plotted features may only be accurate to within about 95 km.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

For the three year period of the study this study evaluated data from five different sources and identified a total of 46 eddies in the research area. The research area was eddy free only 20% of the study period. This clearly indicates that eddies are ubiquitous in the area and that they are important to the dynamics of the area. The eddies were concentrated over the Newfoundland Seamount Range and the Newfoundland Ridge. Except for these two areas, the research area showed no sign of eddy activity. This distribution suggests that the bottom features had an influence in the formation of the eddies. This indicates that, at least in some areas, the North Atlantic Current is influenced by the bottom in the Newfoundland Basin area and is affected by the topography there.

The study also indicates that the Labrador Current is capable of generating eddies. Five cold core eddies were found in an area where they could not have been if they had been generated by the North Atlantic Current. The literature reveals no other mention of Labrador Current eddy activity. This is an area that will require further investigation.

The eddies followed the pattern predicted by Joyce (1983) and drifted predominantly to the west. This was true even for those eddies that showed a considerable interaction with the eastward flowing North

Atlantic Current. The eddies formed mostly from pinched off meanders and were absorbed back into the parent current by similar meanders.

The area of formation had no apparent effect on the characteristics of the eddies. Those formed over the Seamounts displayed similar features as those formed over the Ridge. All were of equivalent size, duration and translation.

The study indicates what the average eddy in the southern IIP oparea will be. It will be a warm core eddy approximately 74.1 km in diameter. It will form over the Seamounts or over the Ridge, normally from a pinched off meander, and will migrate to the west after formation. The speed of translation will be about .06 knots and the rotational speed will be about .7 knots. It will remain on plot for about 71.5 days and will normally be absorbed back into the parent current by a meander. We can expect to see an eddy similar to the one described here in our area about 80% of the time.

The TOD data was inconclusive in this study. Though the buoys showed meander motion, they did not support the other data sources in some eddy characteristics.

The SLAR data agreed closely with the frontal features charts and was useful in this study for supporting the existence and location of eddies. When the IIP SLAR aircraft is flying, the imagery provides updated information on the ocean frontal systems. It is more timely and more accurate than the data received from either NWS or NAVEASTOCEANO in the analysis of fronts and related features. The SLAR will be useful in future studies of ocean frontal features.

Recommendations

The watch officers must be aware of the affects that eddies may have on iceberg drift before they evaluate iceberg sightings to determine resights and predictions. They must review the most recent frontal analysis charts as a routine part of their analysis process. If SLAR data is available on a real time basis and the watch officer must be aware of features reflected on it.

The Senior Ice Observer must observe the SLAR film visually for oceanographic features as a clue to real-time surface currents. If he sees these features the location and extent should be passed to the watch stander along with the other iceberg information.

Additional research should be conducted in remote sensing of ocean fronts to accurately position their dynamic features in real time. Ice Patrol has scheduled two cruises in the coming year that will concentrate on locating and surveying eddies in the research area. Particular emphasis will be placed on locating and documenting a cold core Labrador Current eddy. The cruises will be coordinated with SLAR aircraft overflights of the eddy in an attempt to fully map and define the feature. TOD's will be released in the eddy and monitored closely so that dynamic characteristics can be recorded. Results of these cruises will be published in future IIP journals.

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APPENDIX A

CHARACTERISTICS OF ALL EDDIES

IN THIS STUDY

EDDY NO	INITIAL REPORT DATE	INITIAL REPORT POSITION	SIZE (KM)	CORE	CLEV	FORMATION	DETERIORATION	ACT
1	12/02/81	4445N 4800W	95	W	2	Unknown	Absorb (Lab)	Yes
2	01/27/82	4030N 5300W	95	W	4	Unknown	Dissipated	Yes
3	02/08/82	4045N 5030W	145	W	2	Meander	Dissipated	Yes
4	03/24/82	4100N 5000W	145	W	2	Unknown	Absorb (GS)	No
5	04/05/82	4030N 5130W	145	W	4	Meander	Dissipated	Yes
6	04/23/82	4000N 4500W	120	C	4	Unknown	Absorb (GS)	No
7	04/23/82	4500N 4330W	55	C	4	Unknown	Absorb (GS)	Yes
8	04/26/82	4130N 4830W	130	C	4	Unknown	Absorb (GS)	Yes
9	05/05/82	4045N 5430W	120	W	4	Meander	Out of Area	Yes
10	05/26/82	4030N 4845W	80	W	4	Meander	Absorb (GS)	Yes
11	06/02/82	4000N 4815W	65	C	4	Interact	Absorb (GS)	Yes
12	06/14/82	4500N 4800W	120	W	4	Unknown	Dissipated	No
13	06/28/82	4115N 5415W	95	C	4	Interact	Absorb (GS)	No
14	07/07/82	4130N 5330W	80	W	4	Meander	Absorb (GS)	No
15	07/19/82	4200N 4900W	120	W	2	Meander	Absorb (Lab)	Yes
16	09/03/82	4115N 5430W	120	W	3	Meander	Absorb (GS)	Yes
17	09/17/82	4200N 5200W	130	W	2	Meander	Dissipated	No
18	10/22/82	4030N 5230W	135	W	4	Meander	Absorb (Lab)	Yes
19	11/19/82	4130N 5130W	95	W	3	Meander	Absorb (GS)	Yes

	INITIAL REPORT		SIZE					
EDDY NO	DATE	POSITION	(KM)	CORE	CLEV	FORMATION	DETERIORATION	ACT
20	12/17/82	4300N 5400W	105	W	3	Unknown	Dissipated	No
21	01/31/83	4445N 4715W	105	W	1	Meander	Dissipate	Yes
22	03/25/83	4220N 5300W	50	W	3	Unknown	Absorb (GS)	Yes
23	05/23/83	4130N 5100W	195	W	1	Meander	Absorb (GS)	Yes
24	06/24/83	4100N 5300W	195	W	3	Meander	Out of Area	Yes
25	06/27/83	4150N 4700W	130	W	2	Meander	Absorb (GS)	No
26	07/13/83	4120N 5010W	130	W	2	Meander	Absorb (GS)	Yes
27	08/01/83	4315N 5355W	190	W	4	Interact	Dissipated	No
28	08/05/83	4420N 4610W	160	W	1	Meander	Dissipated	Yes
29	09/07/83	4235N 5200W	105	W	1	Interact	Dissipated	No
30	09/16/83	4100N 4900W	210	W	1	Meander	Out of Area	Yes
31	10/21/83	4450N 4550W	95	W	3	Interact	Dissipated	No
32	12/10/83	4330N 4730W	120	W	3	Unknown	Dissipated	Yes
33	12/14/83	4330N 4750W	95	W	4	Unknown	Dissipated	No
34	01/04/84	4000N 4700W	105	C	4	Interact	Absorb (GS)	Yes
35	02/01/84	4030N 4430W	90	C	1	Unknown	Dissipated	No
36	04/04/84	4430N 4530W	95	W	3	Unknown	Dissipated	No
37	04/18/84	4100N 5140W	130	W	1	Meander	Dissipated	Yes
38	05/16/84	4115N 5000W	210	W	1	Meander	Absorb (GS)	Yes
39	06/04/84	4400N 4610W	50	W	2	Unknown	Dissipated	No
40	06/20/84	4200N 5430W	65	W	4	Interact	Absorb (GS)	No
41	06/26/84	4115N 5000W	145	W	3	Unknown	Dissipated	No
42	07/02/84	4445N 4515W	110	W	3	Unknown	Dissipated	No
43	07/14/84	4145N 4945W	70	W	3	Unknown	Dissipated	No
44	09/12/84	4330N 4730W	110	W	1	Meander	Dissipated	Yes
45	11/07/84	4300N 4330W	95	C	4	Interact	Dissipated	No
46	11/10/84	4330N 4715W	95	W	3	Meander	Dissipated	No