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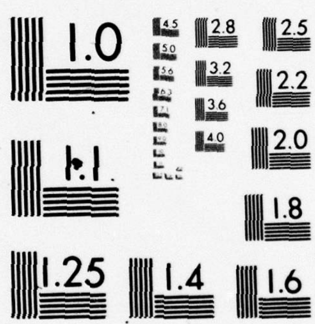

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SYNOPTIC OBSERVATIONS OF THE OCEANIC
FRONTAL SYSTEM EAST OF JAPAN

by

Robert E. Cheney

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WASHINGTON, D. C. 20373

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Seven flights were made east of Japan in October 1976. The Kuroshio and Oyashio fronts and nine eddies generated by them were studied from continuous measurements of surface temperature by airborne radiation thermometer. AXBT's, XBT's and STD's provided subsurface temperature profiles.

ABSTRACT

A series of seven flights was conducted in October 1976 to study the system of oceanic fronts east of Japan. Sea surface temperature was measured continuously with an airborne radiation thermometer and AXBT's provided sub-surface temperature profiles. These data were supplemented with shipboard XBT and STD measurements of selected features.

The Kuroshio was tracked from the coast of Japan eastward to 158°E. It had a width at the surface of approximately 75 km and exhibited two large anticyclonic meanders. Maximum horizontal temperature difference across the front was 12°C at 300 m; the maximum horizontal gradient at this depth was 0.3°C per km. STD stations showed the Kuroshio to extend to a depth of 2500 m. The Oyashio Front was tracked out to 154°E and, at depths less than 100 m, it displayed horizontal temperature gradients equal to those of the Kuroshio. The Oyashio is a much shallower feature, however, and was observed to weaken rapidly with depth.

A total of nine eddies generated by both fronts was found: three Kuroshio cold eddies, three Kuroshio warm eddies, two Oyashio warm eddies, and one Oyashio cold eddy. They were of varying ages and ranged in size from 100 to 240 km. Eddies formed by the Oyashio were observed to have distinctly different structures than Kuroshio eddies. However, Kuroshio eddies were found to have many characteristics common to Gulf Stream eddies. Satellite infrared imagery provided accurate location of the Kuroshio and Oyashio Fronts but, for the most part, the eddies lacked surface temperature gradients and consequently could not be detected by satellite.

CONTENTS

SYNOPTIC OBSERVATIONS OF THE OCEANIC FRONTAL SYSTEM EAST OF JAPAN

INTRODUCTION

Large-scale oceanic circulation in the North Pacific is composed of two major gyres which enclose waters of the subtropical and subarctic regions. The subtropical gyre maintains an anticyclonic (clockwise) circulation and occupies the Pacific basin between approximately 10°N and 40°N. As with all oceanic gyres, its most intense currents are found along the western edge; much of the eastern half of the gyre is composed of a broad equatorward flow. The western boundary current of the subtropical gyre is the Kuroshio, which flows north from the Philippines to Japan, then eastward into deeper water of the North Pacific. The subarctic region, north of the subtropical gyre, maintains a cyclonic (counter-clockwise) circulation. The western boundary current of the subarctic gyre is the Oyashio, which flows south along Kamchatka and the Kuril Islands. Both gyres contribute to a broad eastward flow between Japan and the west coast of North America in the form of the Subarctic and the North Pacific Currents.

Dominant currents of the North Pacific are thus the warm, northward flowing Kuroshio and the cold, southward flowing Oyashio (Fig. 1). These currents encounter each other east of Japan and result in a system of intense oceanic fronts. The frontal zone is further complicated by eddies derived from both currents and by the introduction of water from the Sea of Japan through the Tsugaru Strait.

In an attempt to determine the impact of this system of oceanic fronts on underwater sound transmission, the U.S. Naval Oceanographic Office conducted a study in the region east of Japan in October 1976. The project consisted of an initial thermal survey of the frontal area by aircraft, detailed measurements of selected features by ship, and a series of acoustic experiments performed by two aircraft. This report describes the distribution and thermal characteristics of the fronts and eddies studied during this project. Subsequent reports will deal with deep STD data gathered by ship, remote tracking of a cold Kuroshio eddy with a satellite-tracked buoy, and results of the acoustic measurements.

GENERAL CHARACTERISTICS OF THE STUDY AREA

The North Pacific is generally analagous to the North Atlantic although there are some basic differences. Average water temperature of the Pacific is less than that of the Atlantic and the main thermocline in the Pacific subtropical gyre, represented by the temperature range 6°C-16°C, is 300 m shallower than in the Atlantic. Masuzawa (1972) has suggested that this is due to a different rate of heat exchange through the sea surface and differences in the intensitities of the gyres. The Pacific is also less saline than the Atlantic, a factor which will be shown to have significant influence in determining the strength (transport) of the western boundary current.

A similarity between the two oceans is the presence of Subtropical Mode Water, the thick layer of cold, nearly isothermal water which forms above the main thermocline during winter. Average temperature of this water is 18°C in both the North Atlantic and Pacific (Worthington and Kawai, 1972). Other factors which influence the deep circulation are the North Pacific's lack of a highly saline estuary, such as the Mediterranean and Red Seas, and the absence of original Bottom Water, which is generated primarily in the Greenland and Weddell Seas (Neumann and Pierson, 1966).

The Kuroshio is the Pacific counterpart of the Gulf Stream. Both are swift (3-5 kt) western boundary currents which hug their respective continental slopes northward to 35°N, where they flow eastward into depths of approximately 5000 m. Of the two currents, the Gulf Stream has the greater crosscurrent temperature gradient, normally an indication of the stronger current in terms of current speed and transport. However, the Gulf Stream also exhibits a significantly larger crosscurrent salinity gradient which works in the opposite sense and tends to decrease current strength. This is because of the relatively higher salinity of the subtropical North Atlantic, compared to the North Pacific, whereas salinities of the corresponding subarctic regions are approximately equal. Other factors which influence volume transport are width and depth of the current. The Kuroshio and Gulf Stream have similar widths (about 100 km) but the Kuroshio extends to depths of only 2000-3000 m (Masuzawa, 1964) in the open ocean while the Gulf Stream can be detected to at least 4000 m (Warren and Wolkmann, 1968). The net result is that the Kuroshio has the larger volume transport along the coast, where both currents extend to the bottom, but in deep water the Gulf Stream and Kuroshio have approximately equal transports, on the order of $80 \times 10^6 \, m^3 \, s^{-1}$ (Worthington and Kawai, 1972).

Another similarity in the structure of the two currents is the presence of a warm core. This feature, found in the upper 100-200 m of both the Kuroshio and Gulf Stream, is created by warm water advected from southern seas. It is most prominent at the end of winter when the surface layer of the subtropical region reaches its minimum temperature.

When the Kuroshio leaves the coast it follows a meandering path which often results in the formation of eddies on either side. This process is well documented for both the Kuroshio and the Gulf Stream (Fuglister and Worthington, 1951; Masuzawa, 1957a; Saunders, 1971). Kuroshio warm eddies, especially, have received attention because of their role in the Japanese fishing industry. Most warm eddies separate from the first ridge of the Kuroshio in the vicinity of 145°E, although they are also generated further downstream. They are generally about 150 km in diameter, elliptical in shape, and have average lifetimes of 2-10 months (Kitano, 1975).

Hata (1969) presented a remarkable time series of observations over a period of 22 months which describes the life cycle of a warm eddy east of Honshu. A schematic representation over a slightly shorter time period is reproduced in Fig. 2a. The warm eddy observed in May 1960 was captured by an exceedingly large Kuroshio meander in July. In August this meander formed a new warm eddy with a diameter of 275 km. The eddy was surveyed repeatedly during the following year and was found to remain in approximately the same location while gradually shrinking to half its original size. Other warm eddies have been observed to move persistently to the northeast, apparently passing through the Oyashio Front as shown in Fig. 2b (Hata, 1974).

There have been relatively fewer observations of eddy genesis south of the Kuroshio and information on the subsequent life cycle of cold eddies is for the most part lacking. The most thorough cold eddy study was reported by Masuzawa (1957b) who was able to follow a Kuroshio cold eddy for 10 months from its formation in August 1955. This series of observations is illustrated schematically in Fig. 3. The eddy was observed as a separate mass of cold water in November 1955 and February, May, and June 1956. During this period it moved generally westward at 2 to 3 km per day while gradually decreasing in size and strength.

The Oyashio's counterpart in the North Atlantic is the Labrador Current. Both of these currents carry cold, subarctic water southward into lower latitudes and are instrumental in the formation of the Gulf Stream and Kuroshio frontal systems. The Oyashio is a much weaker current than the Kuroshio and has a transport of only $4\text{-}10 \times 10^6\ m^3\ s^{-1}$ (Hata, 1969). When the Oyashio meets the Kuroshio it abruptly changes direction from southward to eastward and in the process degenerates into a weak, fragmented flow. The feature which parallels the Kuroshio (Fig. 1) is more correctly known as the Oyashio Front*; it is a boundary between waters of vastly different temperature and salinity, but because these gradients have nearly an equal and opposite effect on density, it does not represent a coherent current (Kawai, 1972). The Oyashio Front is roughly equivalent to the Slope Front north of the Gulf Stream. However, while the Slope Front runs along the edge of the Continental Shelf in only 100-200 m of water, the Oyashio Front extends eastward across the slope where it encounters depths of 5000-7000 m. Like the Kuroshio, the Oyashio Front also forms eddies, although perhaps by different processes.

*Because the Kuroshio represents a region of large density gradient, it is both a front and a current. The terms Kuroshio and Kuroshio Front are therefore interchangeable.

The region between the Oyashio Front and the Kuroshio has been alternately called the "confluence zone" or the "perturbed region". It is the recipient of Kuroshio warm eddies, Oyashio cold eddies, shear eddies, and overrunning across both fronts. It also receives water from the Tsugaru Warm Current entering from the Sea of Japan (Fig. 1). The Tsugaru Current flows south, close to the east coast of Honshu, then turns east into the confluence zone where it mixes and ceases to exist as a distinct current. Its transport through the Tsugaru Strait is 1-4 x 10^6 m^3 s^{-1} (Hata, 1969). Water in the confluence zone is referred to as modified subtropical water.

METHODS

The initial survey was conducted during 9-22 October 1976 from a NAVOCEANO P-3C aircraft. Figure 4 presents tracks and AXBT (airborne expendable bathythermograph) drop positions for each of the seven flights. Two hundred seventy-nine AXBT's were obtained and sea surface temperature was measured continuously with an airborne radiation thermometer, which was calibrated at the beginning and end of each track. The AXBT probes provide a temperature profile to approximately 350 m. Information on the distribution of various fronts and eddies surveyed during these flights was relayed to USNS SILAS BENT, which conducted detailed XBT and STD (salinity/temperature/depth) measurements of selected features during 18-31 October.

SYNOPTIC MAPS

Contours of temperature at the surface and at depths of 100 and 300 m are presented in Figs. 5-7. Surface temperatures are those obtained using the radiation thermometer; values agree with AXBT surface temperatures to within less than 1°C. The analyses show a complicated system of intense oceanic fronts extending eastward from Japan. Numerous eddies in various stages of formation and decay are apparent. Comparison of the three levels shows that some frontal features are shallow while other are stronger at depth.

The Kuroshio flows eastward along 36°N but at 152°E exhibits an unusually large anticyclonic meander with an amplitude of 450 km. Further to the east it again veers northward and appears to be in the process of forming a warm eddy at 157°E. Temperature difference across the front is approximately 11°C at both 100 and 300 m; the difference at the surface is somewhat smaller due to the lingering effect of summer heating, which tends to diminish the strength of the front above 100 m. Although the average gradient across the Kuroshio at depths of 100-300 m is about 0.1°C per km the continuous record obtained with the radiation thermometer indicates that at the surface the front actually consists of a series of step-like changes with magnitudes of 1-3°C and gradients of 0.2-0.6°C per km.

The Kuroshio warm core is least apparent in late summer and early fall and does not show up clearly in these analyses. More closely spaced XBT sections taken by SILAS BENT, presented later in this report, do reveal the presence of a narrow warm core with a maximum temperature of 24°C.

The Oyashio Front runs along 40°N and can be seen to be quite a complicated feature. It is a much shallower front than the Kuroshio, as evidenced by temperature difference at 300 m of only 5°C, but in the upper 100 m it is as strong a discontinuity as the Kuroshio. The Oyashio also exhibits step-like temperature changes at the surface similar in magnitude to those of the Kuroshio. An Oyashio warm eddy is partially attached to the front at 146°E. The eddy has a diameter (defined by the intersection of 5°C with 100 m) of 185 km and from its appearance has formed quite recently. Further to the east two small warm and cold eddies with diameters of about 100 km seem to be imbedded within the front.

Between the two fronts in the confluence zone surface temperature gradients are weak. At deeper levels, however, sub-surface eddies begin to appear. The strongest of these is the warm Kuroshio eddy located just east of Honshu at 37°50'N, 143°20'E. It has an average diameter (6°C at 300 m) of 165 km and is similar to the warm eddies discussed by Hata (1969) and Masuzawa (1957) and would seem to be almost a permanent feature. Other globs of cold and warm water further to the east may be very old eddies or merely reflections of the turbulent conditions in the confluence zone.

South of the Kuroshio three cold eddies are apparent in the 300 m analysis although, like the warm Kuroshio eddy, they can not be detected at the surface. This suggests that they have been subjected to considerable mixing and seasonal effects and are therefore many months old. One way to estimate the ages of these rings is to assume decay rates similar to those measured for Gulf Stream rings. As a cyclonic ring spins down, the uplifted thermocline at its center sinks about 0.5 m per day (Parker, 1971; Cheney and Richardson, 1976). Applying this criterion to the three Kuroshio cold eddies and assuming reasonable initial conditions (15°C at 75 m) for water at the eddy core yields estimated ages of 4, 12, and 9 months for the eddies at 143°E, 149°E, and 157°E, respectively.

The newest of the cold eddies is located 350 km southeast of the Boso Peninsula at 33°N, 143°E and has a diameter (16°C at 300 m) of 240 km. This is slightly larger than most Gulf Stream eddies. It was thought at first that the glob of cold water attached to the northeast edge of the eddy was a result of the eddy splitting into two parts, as has been observed for Gulf Stream eddies (Cheney, et al., 1976). Shipboard XBT's indicate, however, that this region of colder water is confined to depths of 200-300 m and does not appear when temperatures at any other depth are contoured (Cheney and Richardson, 1977). The existence of this lens of colder water remains unexplained.

SATELLITE INFRARED IMAGERY

During October, direct read-out infrared data from the NOAA-5 satellite were being obtained through the Japanese Meteorological Agency and recorded VHRR (very high resolution radiometer) NOAA-5 imagery was being collected by NOAA-NESS (National Oceanic and Atmospheric Administration - National Environmental Satellite Service). An interpretation of a particularly cloud-free VHRR image on 17 October 1976 is presented in Fig. 8. This analysis presents a clear view of the Oyashio Front, the confluence zone, and a short segment of the Kuroshio during the time of the aircraft surveys. The Kuril Front, which might be considered the northern front of the Oyashio frontal zone (Uda, 1970; Sugiura, 1958), can also be detected. Infrared imagery shows a clear distinction between the four near-surface water masses of the region: subtropical water south of the Kuroshio, modified subtropical water in the confluence zone, modified subarctic water north of the Oyashio Front, and subarctic water, which originates further to the north. In Fig. 8 subarctic water has intruded southward along 147°E all the way to the Oyashio Front.

The NOAA-5 satellite analysis has been drawn to the same scale as the surface temperature map (Fig. 5) to facilitate comparison, although in some cases there is a difference of 5-6 days between the two types of data. There is reasonably good agreement on location of the Kuroshio and, in the confluence zone, the lack of significant sea surface temperature gradient is confirmed. Satellite location of the Oyashio Front corresponds closely to the 18°C isotherm in Fig. 5, which marks the southern edge of the front. The Oyashio warm eddy at 146°E does not appear in the satellite analysis, however. Surface temperature gradients across the northwestern half of the eddy are apparently not sharp enough to appear as a distinct feature in the infrared imagery. The intrusion of cold, subarctic water seen in the satellite analysis corresponds to sea surface temperature in the range 9-12°C in Fig. 5. The separate mass of cold water centered at 39.5°N, 149.5°E appears to be a cold Oyashio eddy, but was not surveyed by aircraft.

SONIC LAYER DEPTH

Sonic layer depth (depth of maximum sound velocity in the upper several hundred meters) was determined for each AXBT by assuming constant salinity and converting temperature profiles to sound velocity profiles. Results are presented in Fig. 9. The dominant feature of the SLD map is the sharp gradient associated with the Kuroshio; SLD changes abruptly from 40 m to 80 m as the front is crossed from north to south. The 90 m contour represents a maximum in the Kuroshio and corresponds to the warm core. During October, when these data were obtained, sea surface cooling and convective overturning have begun to extend the mixed layer downward through the seasonal thermocline, a process which continues through the end of winter when maximum SLD is achieved. However, this downward mixing process generally cannot penetrate the main thermocline. Because the top of the main thermocline is significantly deeper south of the Kuroshio than in the confluence zone (350 m versus 50 m) a corresponding discrepancy in mixed layer depth develops as the mixing process continues. Thus the SLD gradient across the Kuroshio shown in Fig. 9 will become much more pronounced as the fall and winter seasons progress.

The remainder of the survey area does not display as distinct a pattern in terms of SLD. The Oyashio is associated with a gradual increase from 30 to 50 m and portions of the subarctic intrusion exhibit zero layer depth. In general, cold eddies, with their raised thermolines, produce shallow layers while warm eddies are associated with deep layers. This effect is confirmed for most of the eddies located during the survey but for eddies that are relatively old, the effect is minimal.

TEMPERATURE SECTIONS

USNS SILAS BENT obtained detailed XBT and STD data for the large cold eddy south of the Kuroshio, the warm eddy in the confluence zone off Honshu, and the Kuroshio. Only selected XBT sections are presented here; more complete analyses of these data will appear in a separate report.

Figure 10 is a temperature section through the cold Kuroshio eddy at 33°N, 143°E. The main thermocline at the center of the eddy is 300 m shallower than in the surrounding Pacific subtropical water. Maximum horizontal gradient is found at 400 m; temperature at this depth is 6°C inside the eddy compared to 15°C outside and the average horizontal gradient is about 0.05°C per km. The STD's taken in the eddy indicate that the cold core extends to 3000 m, although temperatures in the eddy are only 0.05°C colder than the surrounding water at this depth.

Temperatures through the Kuroshio along 147°E are displayed in Fig. 11. Depth of the main thermocline, approximated by the 10°C isotherm, changes from 150 m in the cold water of the confluence zone to 600 m south of the Kuroshio. The largest horizontal difference in temperature occurs at 300 m where a change of 12°C is seen. Maximum gradient at this depth is 0.3°C per km. The warm core, defined by 24°C, reaches to a depth of 75 m. STD's show that at 2500 m temperature difference across the Kuroshio is only 0.1°C.

The section through the warm Kuroshio eddy (Fig. 12a) centered at 37°50'N, 143°20'E shows that its core is composed of an isothermal layer of 11.5°C water between depths of 100 m and 400 m. This type of structure is also a common characteristic of warm eddies formed by the Gulf Stream. The isothermal core is created during winter when water is mixed downward to the level of the main thermocline, about 400 m deeper at the center of a Kuroshio warm eddy than in surrounding water. Temperatures at the eddy center are 6°-7°C greater at a depth of 400 m than outside. Seven STD's taken in the warm eddy show that at 1500 m this difference is reduced to 0.3°C. The seasonal thermocline, represented by the 12°-18°C isotherms in Fig. 12a, forms a "cap" over the eddy's isothermal core.

The seasonal cycle of a warm eddy has been well documented by Hata (1974). Selected temperature sections from a 2-year time series of observations in a Kuroshio warm eddy are shown in Fig. 12b (movement of this eddy was illustrated in Fig. 2b). The eddy formed in October 1969 and during winter its isothermal core was established. During summer, development of the seasonal thermocline created the "cap". The same process was repeated during the following year: surface cooling, mixing, and reinforcement of the isothermal core in winter followed by surface warming, stratification, and formation of the "cap" in summer. These processes resulted in the eventual destruction of the eddy's structure, as indicated by the October 1971 section.

Two sections through the Oyashio Front, constructed from AXBT data, are shown in Figs. 13 and 14. The first is a north-south section through the front along 147°30'E. The Oyashio Front is at the left of the section and is seen to be largely a near-surface feature. As was shown previously, the front has its maximum strength at 100 but is more difficult to detect below 200 m. At the center of the section is what appears to be an old Kuroshio warm eddy, located at about 39°N, 148°E. An indication of this eddy's age is provided by the shallowness of its thermocline.

The section in Fig. 14 is through the Oyashio warm eddy. Like the Oyashio Front, it is a relatively shallow feature, and has its strongest horizontal gradient at about 100 m. Comparison with the Kuroshio eddy in Fig. 12 suggests that the two types of warm eddies are entirely different. This difference is to be expected since the eddies, although both anti-cyclonic, are generated by vastly different fronts. Oyashio warm eddies have a much shallower thermocline and apparently do not develop the isothermal core characteristic of Kuroshio warm eddies.

TEMPERATURE PROFILES

Temperature profiles of the various water masses encountered in the frontal system east of Japan during the October survey are presented in Fig. 15. They are separated into those associated with the Oyashio Front and those representative of the Kuroshio features. Numbers indicate the various oceanic regions.

Modified subarctic water north of the Oyashio (profile 1) is characterized by a shallow thermocline at 50 m and uniformly cold 2°C water below. This is in contrast with modified subtropical water south of the Oyashio (profile 4); this profile is representative of the confluence zone and displays a more gradual temperature decrease through the thermocline.

The difference between profiles 1 and 4 is greatest at 100 m; below this depth the traces gradually converge as the Oyashio weakens. Profiles 2 and 3 are from the warm Oyashio eddy at 146°E and the cold Oyashio eddy at 152°E, respectively. The relative newness of these eddies is reflected by the similarity of these traces to the original core waters (profiles 1 and 4).

Modified subtropical water is repeated in the Kuroshio group since it is also representative of water just north of the Kuroshio. South of the Kuroshio is warmer subtropical water (profile 7) with its slightly deeper mixed layer and significantly deeper main thermocline (temperature range 6-16°C). As noted previously, a maximum horizontal temperature difference of 12°C occurs across the Kuroshio at 300 m; this difference is reduced to 3°C at 800 m. Temperatures at the centers of the cold and warm Kuroshio eddies at 143°E are represented by profiles 5 and 6. Temperatures in the cold eddy, similar to those of profile 4 when the eddy was first formed, have warmed about 4°C during the eddy's estimated lifetime of 4 months. The warm eddy profile displays a 300 m thick layer of isothermal, 11.5°C water beneath the strong seasonal thermocline.

SUMMARY AND CONCLUSIONS

In the survey described here the Kuroshio was tracked from the coast of Japan eastward to 158°E. At 152°E it displayed a large anticyclonic meander with an amplitude of 450 km and a second meander at 157°E appeared to be forming a warm eddy. Width of the front at the surface was about 75 km. Maximum horizontal temperature difference across the Kuroshio was 12°C at a depth of 300 m and the maximum horizontal temperature gradient at this depth was about 0.3° per km. However, continuous data from the airborne radiation thermometer showed that at the surface the front consisted of several step-like changes with magnitudes of 1-3°C and gradients of 0.2-0.6°C per km. Depth of the main thermocline increased 450 m from north to south across the Kuroshio. This difference in thermocline depth resulted in a corresponding change in SLD, which increased from 40 m to 80 m across the front. STD stations indicated that the Kuroshio extended to at least 2500 m, where the total horizontal temperature difference was 0.1°C.

During three flights south of the Kuroshio, three detached Kuroshio cold eddies were found. The youngest of these was estimated to be 4 months old and the oldest, approximately 1 year. This suggests that many such eddies exist at any one time and that some have lifetimes in excess of a year. This conclusion is in agreement with studies south of the Gulf Stream where as many as 10 distinctly different cold eddies have been located during a period of a few months and lifetimes of 2 years are common (Cheney, 1976). The youngest of the cold Kuroshio eddies had a diameter of 240 km, was 9°C colder than the surrounding water, and extended to a depth of 3000 m.

In the confluence zone two warm Kuroshio eddies were found and a third was believed to be forming. This is also comparable to the Gulf Stream where 3 to 4 warm eddies can usually be found (Cheney, 1976). The warm eddy off Honshu was 165 km in diameter and extended to at least 1500 m. The core contained an isothermal layer between 100-400 m which was 6°C warmer than the surrounding water.

The Oyashio Front was tracked from the coast of Japan eastward to 154°E. In the upper 100 m the front maintained a horizontal temperature difference of 12°C and had gradients similar in magnitude to those of the Kuroshio. Temperature change at the surface also occurred as a series of sharp steps as observed in the Kuroshio. The Oyashio Front is relatively shallow, however, and at 350 m had a temperature difference of only 3°C. The change in SLD across the Oyashio Front was not nearly as distinct as that of the Kuroshio, although there was a gradual increase of about 20 m from north to south.

A newly formed Oyashio eddy, attached to the front at 146°E, had a diameter of 185 km and was 10°C warmer than surrounding water. Oyashio warm eddies are distinctly different from warm Kuroshio eddies as revealed by their cross-sectional temperature structures. The other Oyashio eddies, one warm and one cold, were imbedded in the front further to the east.

Satellite infrared imagery provided accurate locations of the Kuroshio, the Oyashio Front, and the Kuril Front, further to the north. Most of the eddies could not be detected at the surface by satellite, however; because of their age their surface expression had been erased by mixing and seasonal effects.

The system of oceanic fronts east of Japan is seen to be analagous to that of the western North Atlantic. The Kuroshio and the Gulf Stream are remarkably similar in many respects: they leave the coast and enter deep water at the same latitude, they both maintain maximum current speeds of 3-5 kts, they have similar crosscurrent structures, and both exhibit meanders which generate eddies. Fronts north of the Kuroshio appear to be stronger and more complex than those of the Gulf Stream system. The Oyashio Front is situated in deep water while the Slope Front remains near the continental shelf. Furthermore, the Oyashio generates eddies while the Slope Front apparently does not.

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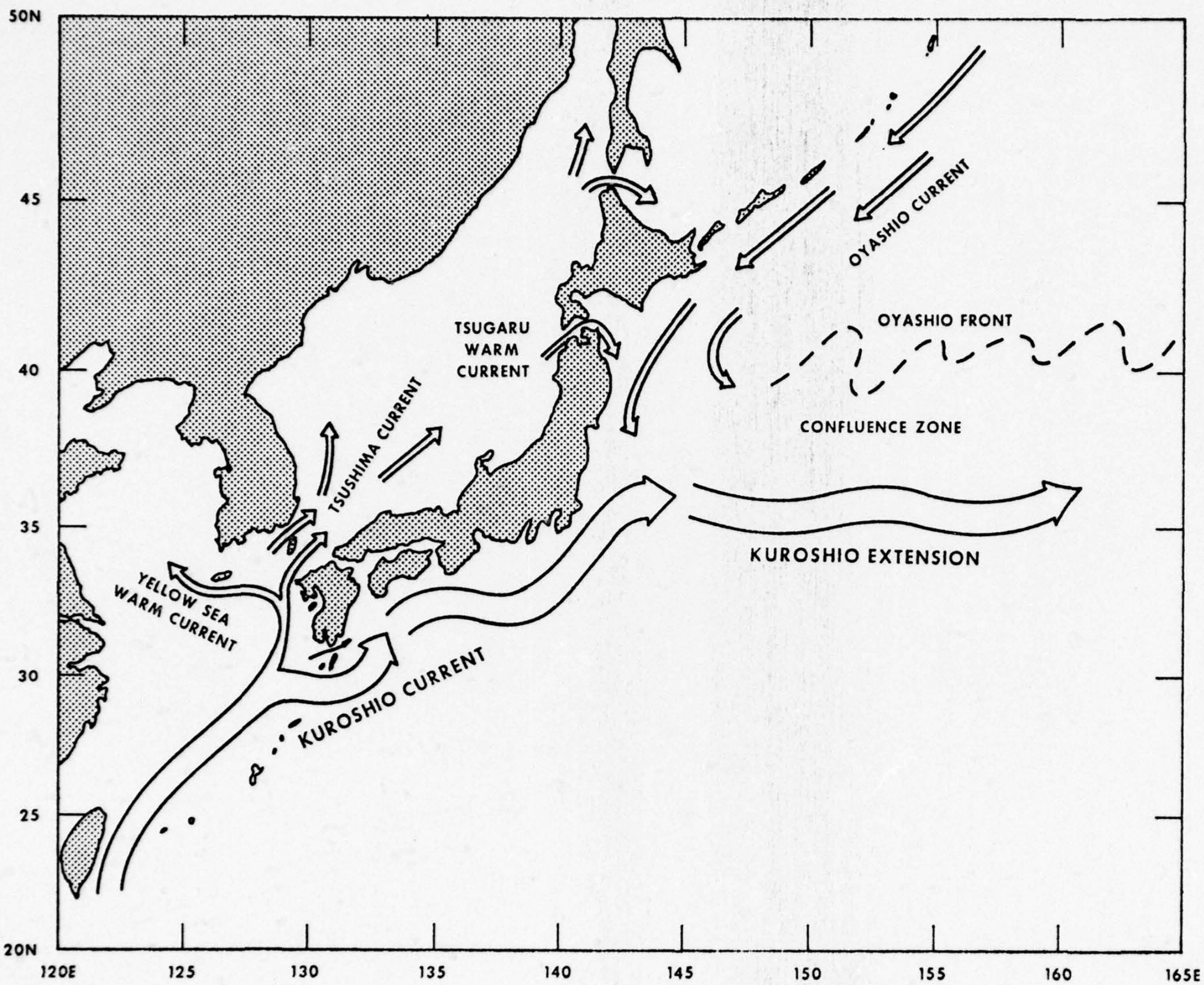


Fig. 1 - Oceanic circulation around Japan. The northward flowing Kuroshio encounters the cold Oyashio Current east of Japan and creates a region of intense oceanic fronts.

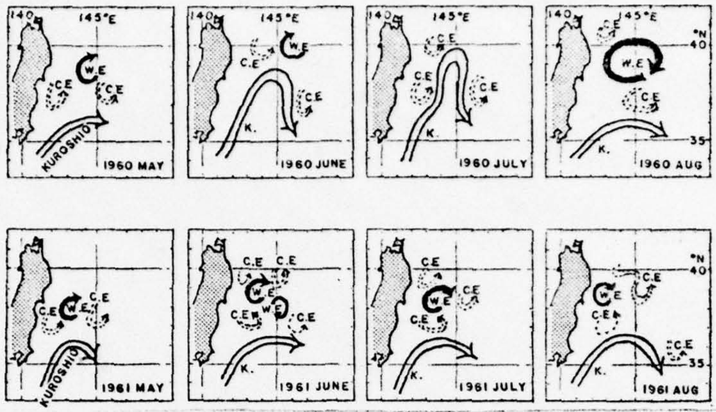
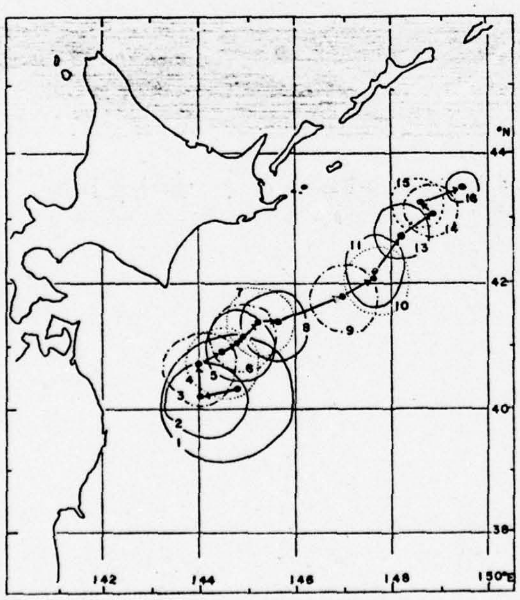


Fig. 2a - Observed life cycle of the warm Kuroshio eddy off Honshu. The eddy, indicated by the solid arrow, was captured by the Kuroshio in July 1960. Another warm eddy subsequently formed in August and remained nearly stationary for the next 13 months while gradually weakening. (From Hata, 1969)



NO.	DATE		(VESSEL)
1	FEB. 11-19,	1970	(KŌFŪ-MARU)
2	APR. 18-29,	"	(")
3	MAY 14-22,	"	(")
4	JUN. 10-16,	"	(WAKATAKA)
5	JUL. 18-27,	"	(RYŌFŪ-MARU)
6	AUG. 18-20,	"	(KŌFŪ-MARU)
7	AUG. 26-28,	"	(")
8	SEP. 6-12,	"	(WAKATAKA)
9	NOV. 9-11,	"	(RYŌFŪ-MARU)
10	DEC. 5- 8,	"	(KŌFŪ-MARU)
11	FEB. 2-10,	1971	(")
(12)	APR. 7-11,	"	(DAITŌ)
13	APR. 28-MAY 3,	"	(KŌFŪ MARU)
14	AUG. 8-10,	"	(")
15	AUG. 20-27,	"	(")
16	OCT. 18,	"	(")

Fig. 2b - Movement of a Kuroshio warm eddy during the period February 1970 through October 1971. The eddy was observed forming in October 1969. (From Hata, 1974)

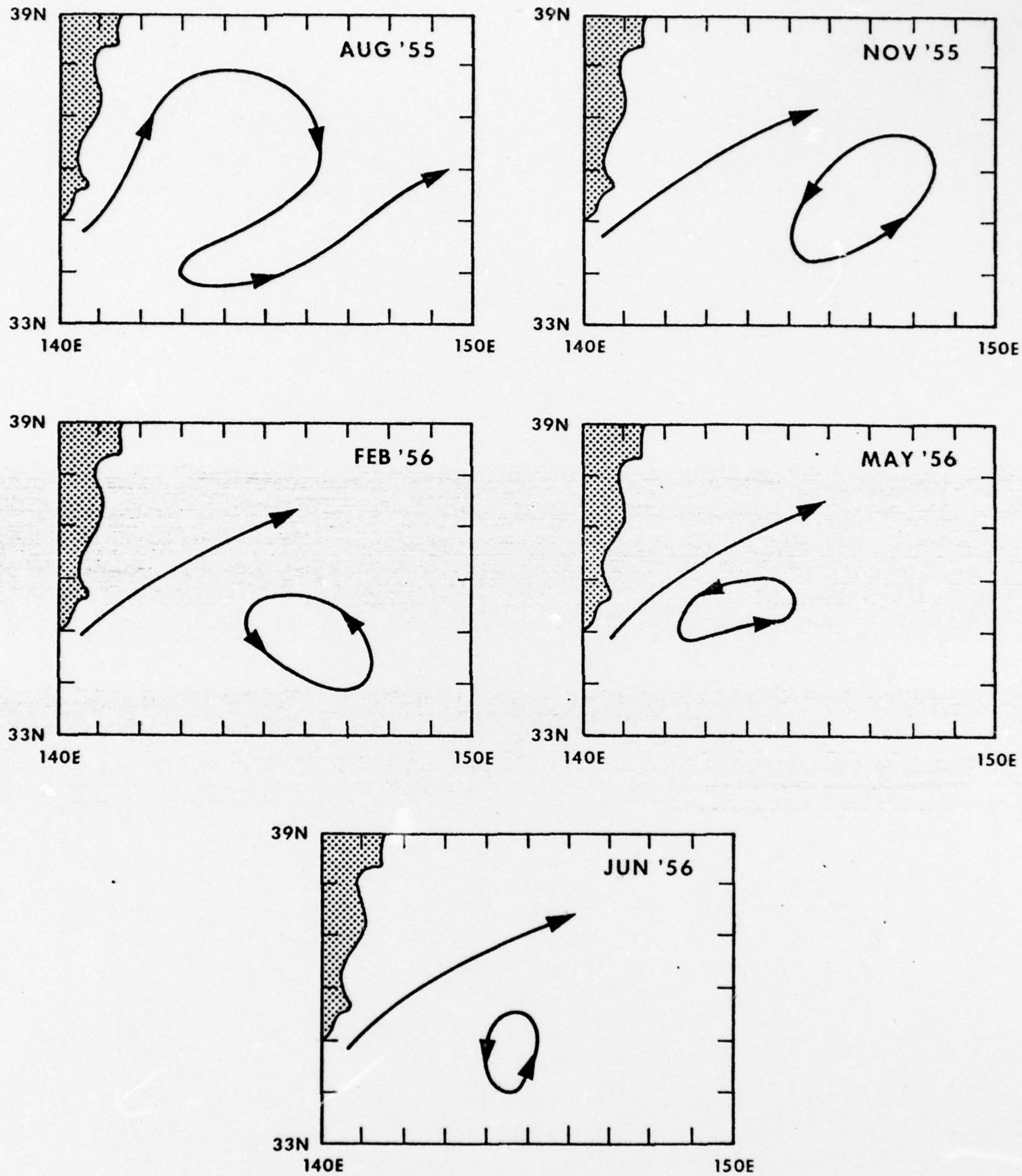


Fig. 3 - Observed life cycle of a cold Kuroshio eddy. The eddy broke off from the Kuroshio in August 1955 and was repeatedly observed through June 1956. Its movement was to the west at 2-3 km per day. (After Masuzawa, 1957b)

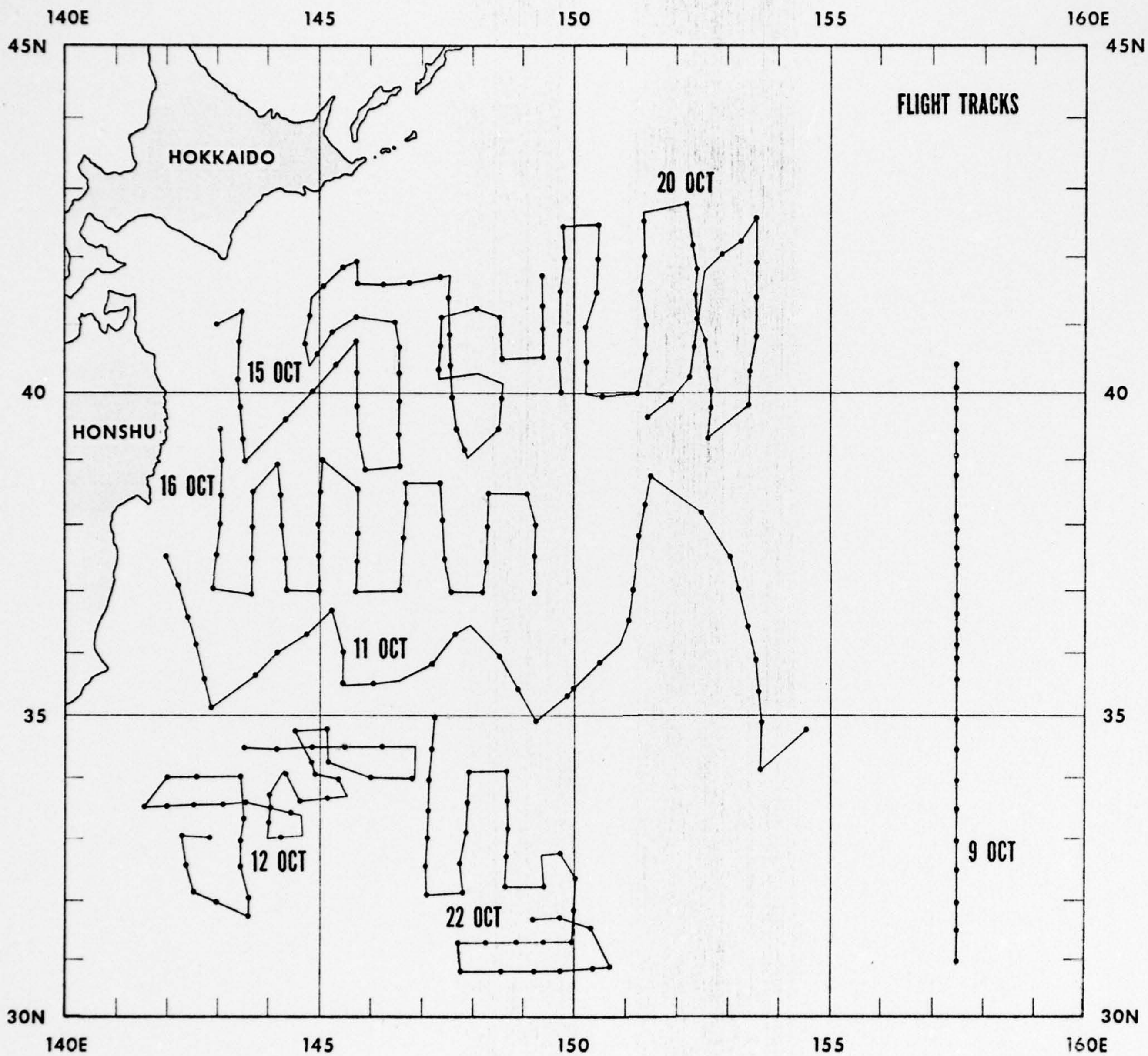
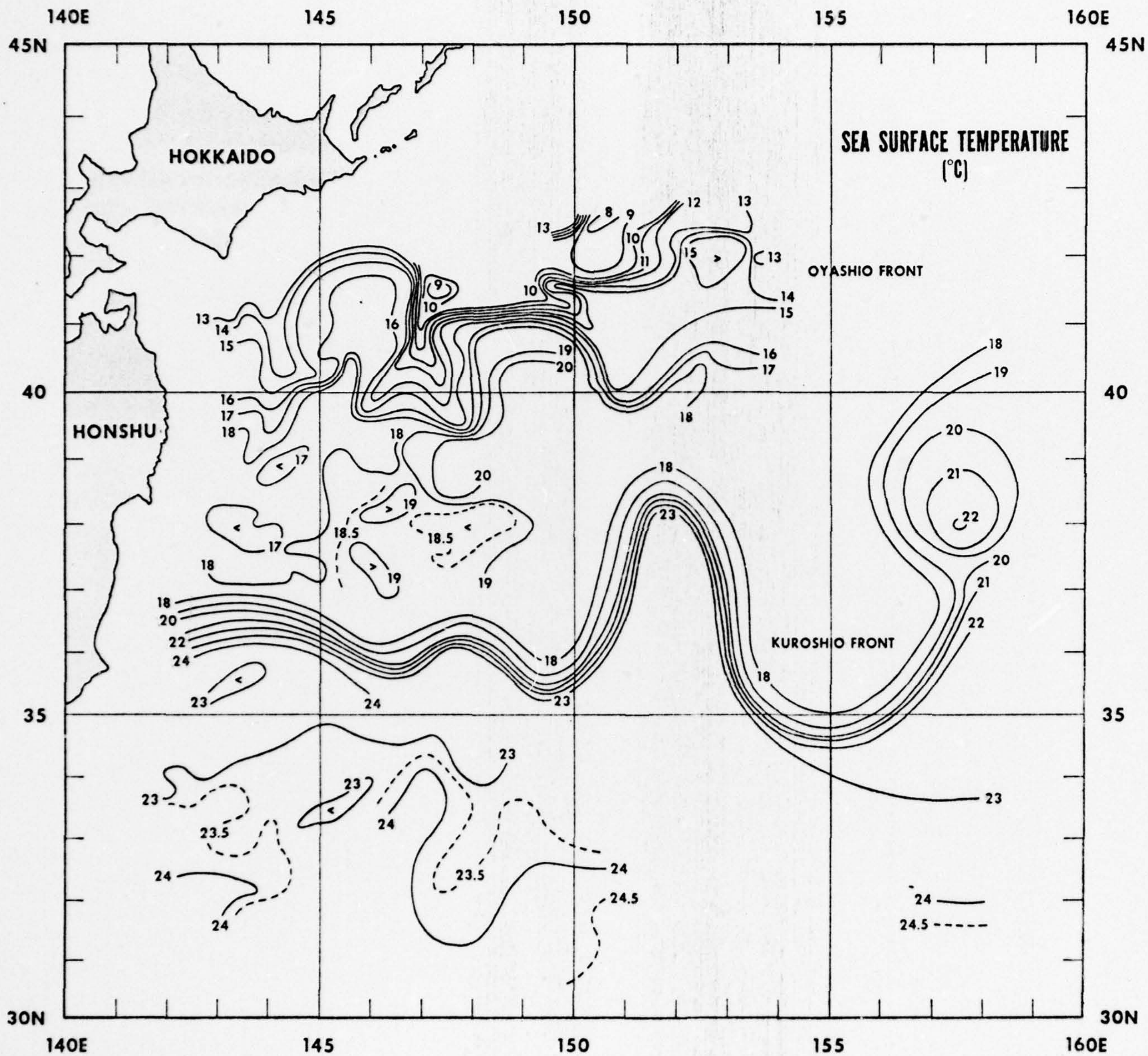
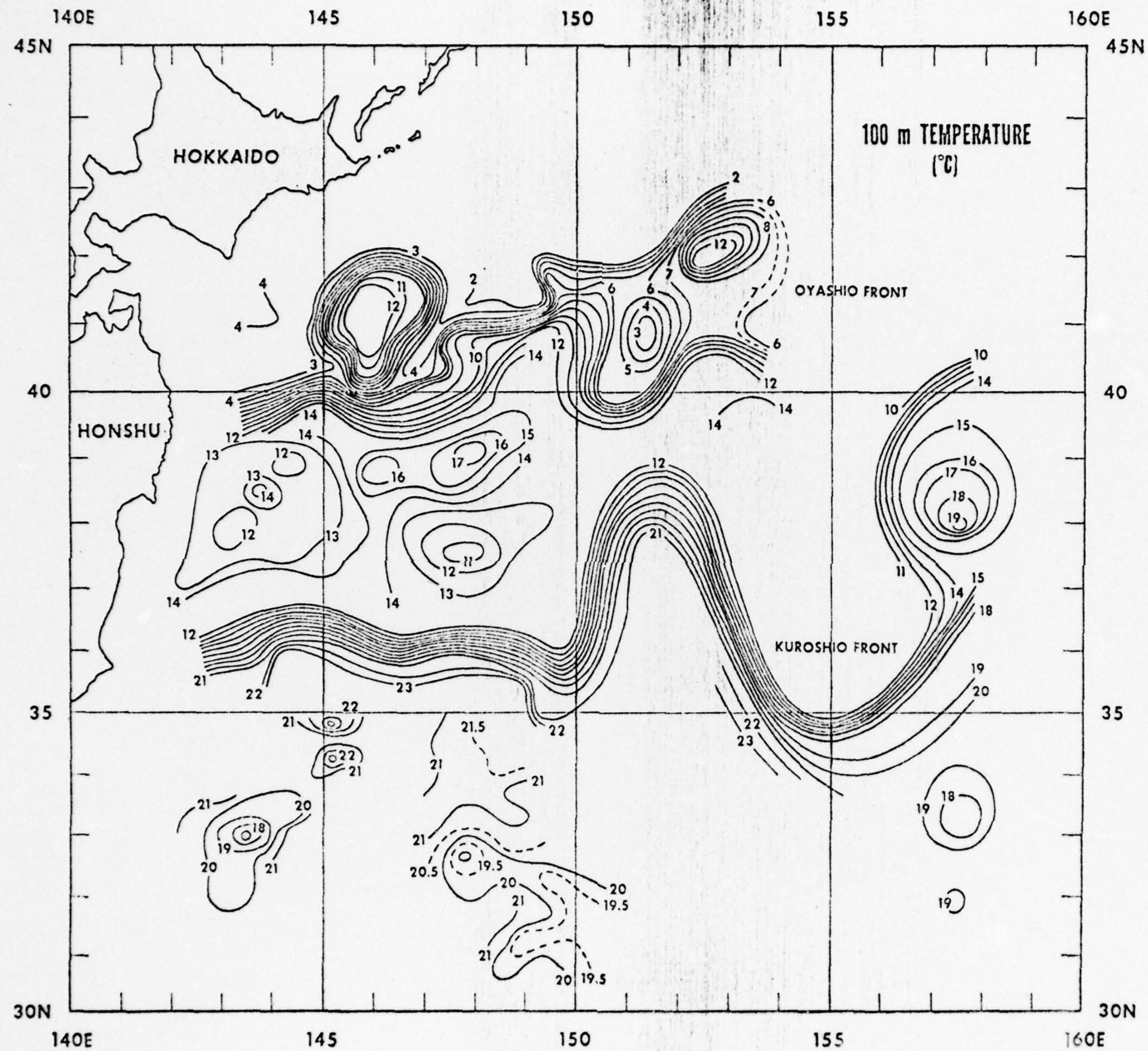


Fig. 4 - Flight tracks and AXBT drop positions east of Japan.



<u>Fig. 5</u> - Contours of sea surface temperature during 9-22 October 1976.



<u>Fig. 6</u> - Contours of temperature at 100 m during 9-22 October 1976.

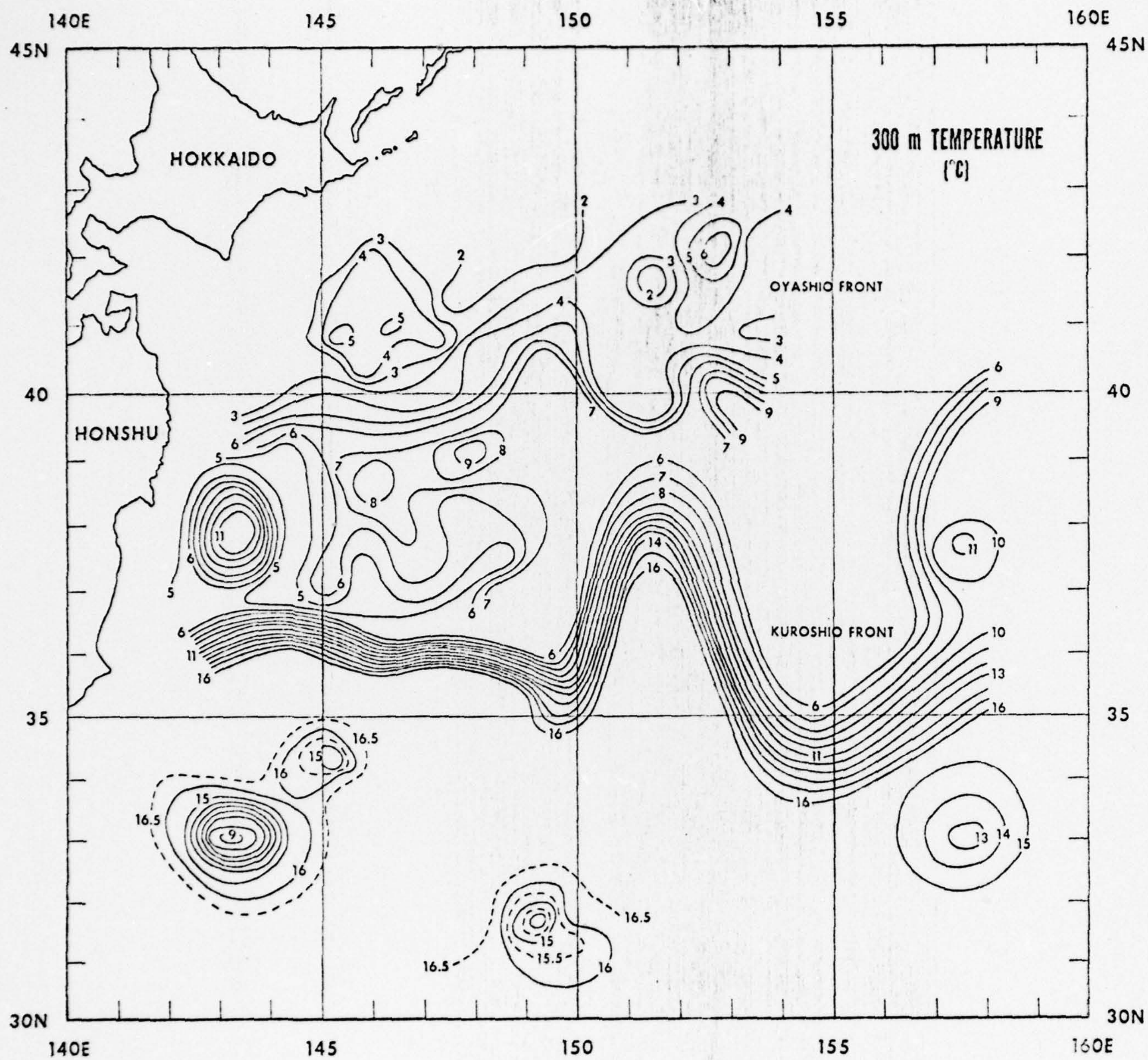
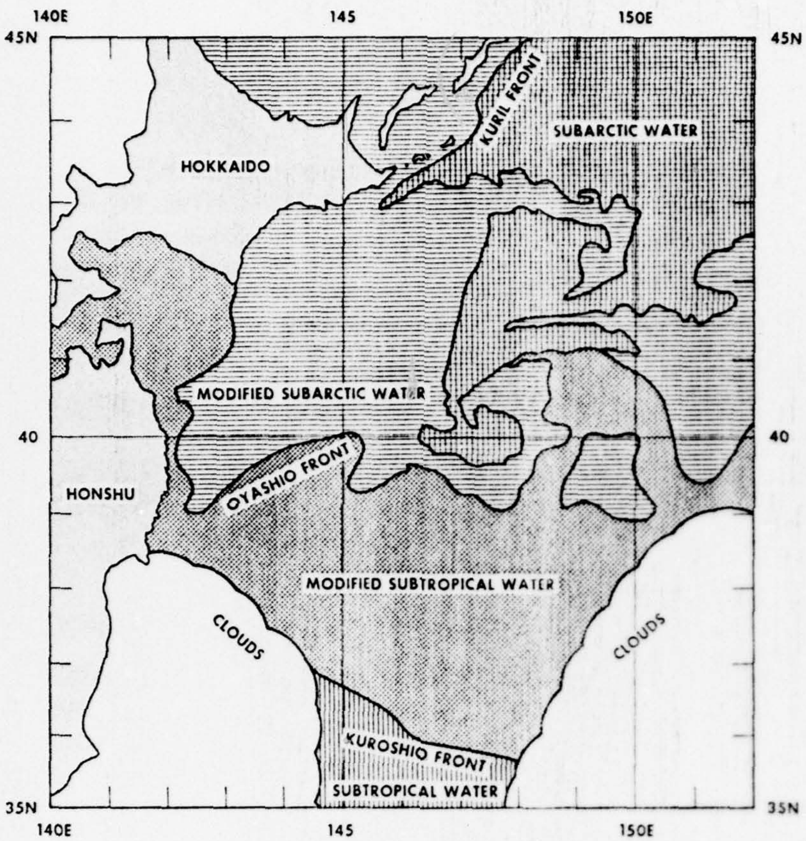


Fig. 7 - Contours of temperature at 300 m during 9-22 October 1976.



<u>Fig. 8</u> - Interpretation of NOAA-5 satellite image, 17 October 1976. Distinct boundaries between the four water masses (subarctic, modified subarctic, modified subtropical, subtropical) were apparent. The Kuril, Oyashio, and Kuroshio Fronts are shown.

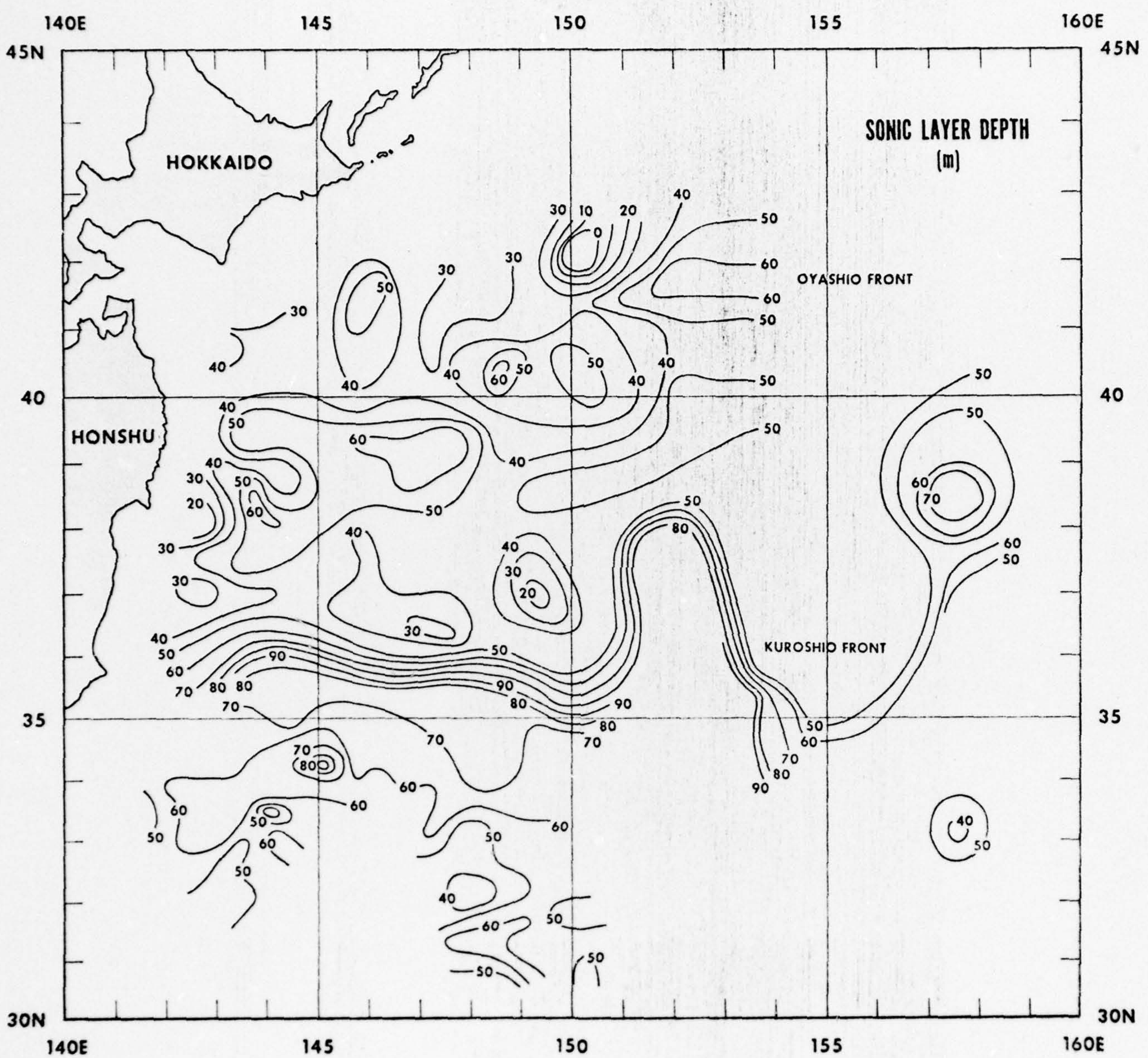


Fig. 9 - Contours of sonic layer depth during 9-22 October 1976.

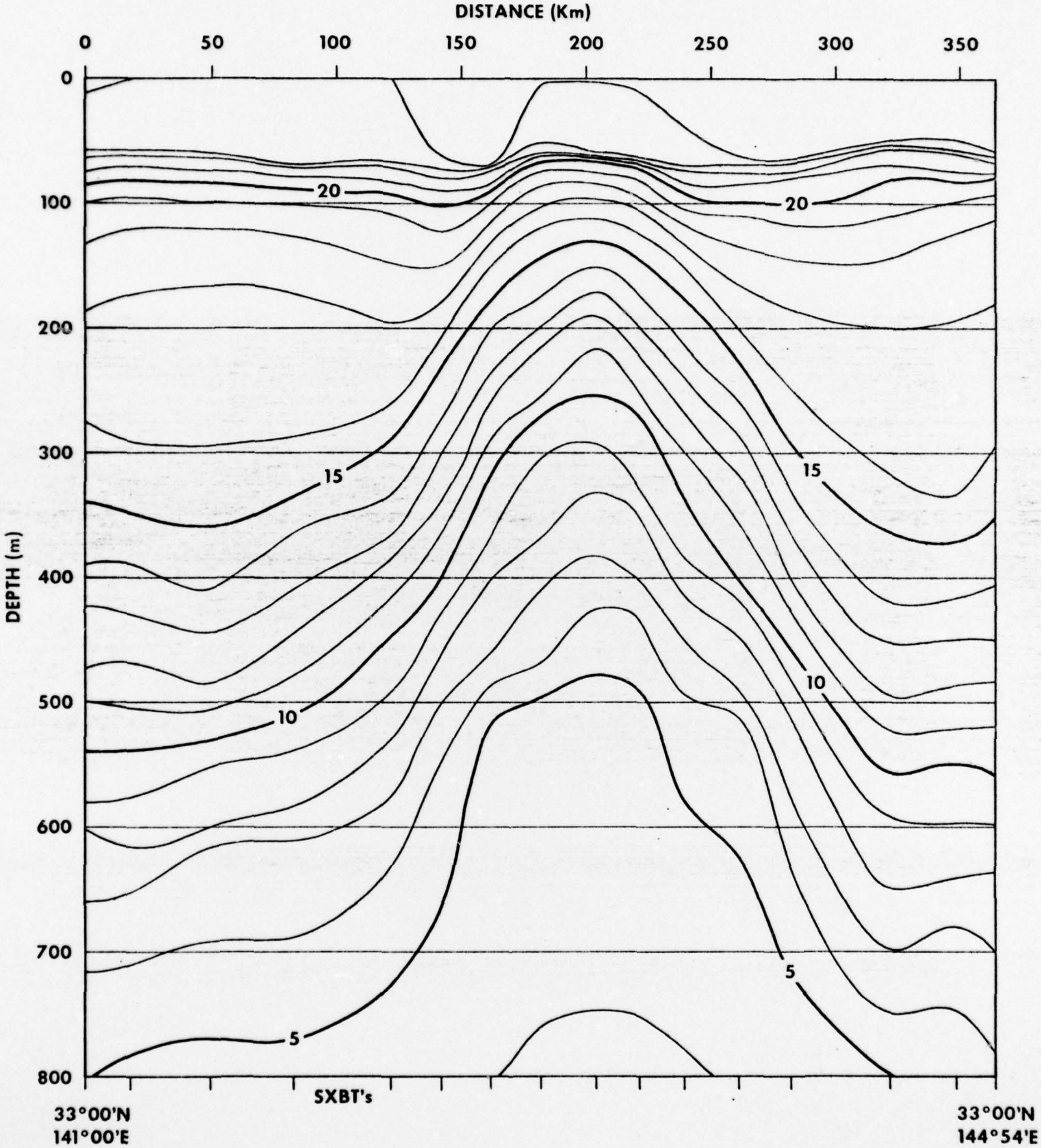


Fig. 10 - Temperature section through the cold Kuroshio eddy, 22-23 October 1976. Locations of XBT's are indicated. The main thermocline is 300 m shallower at the center of the eddy than in surrounding waters.

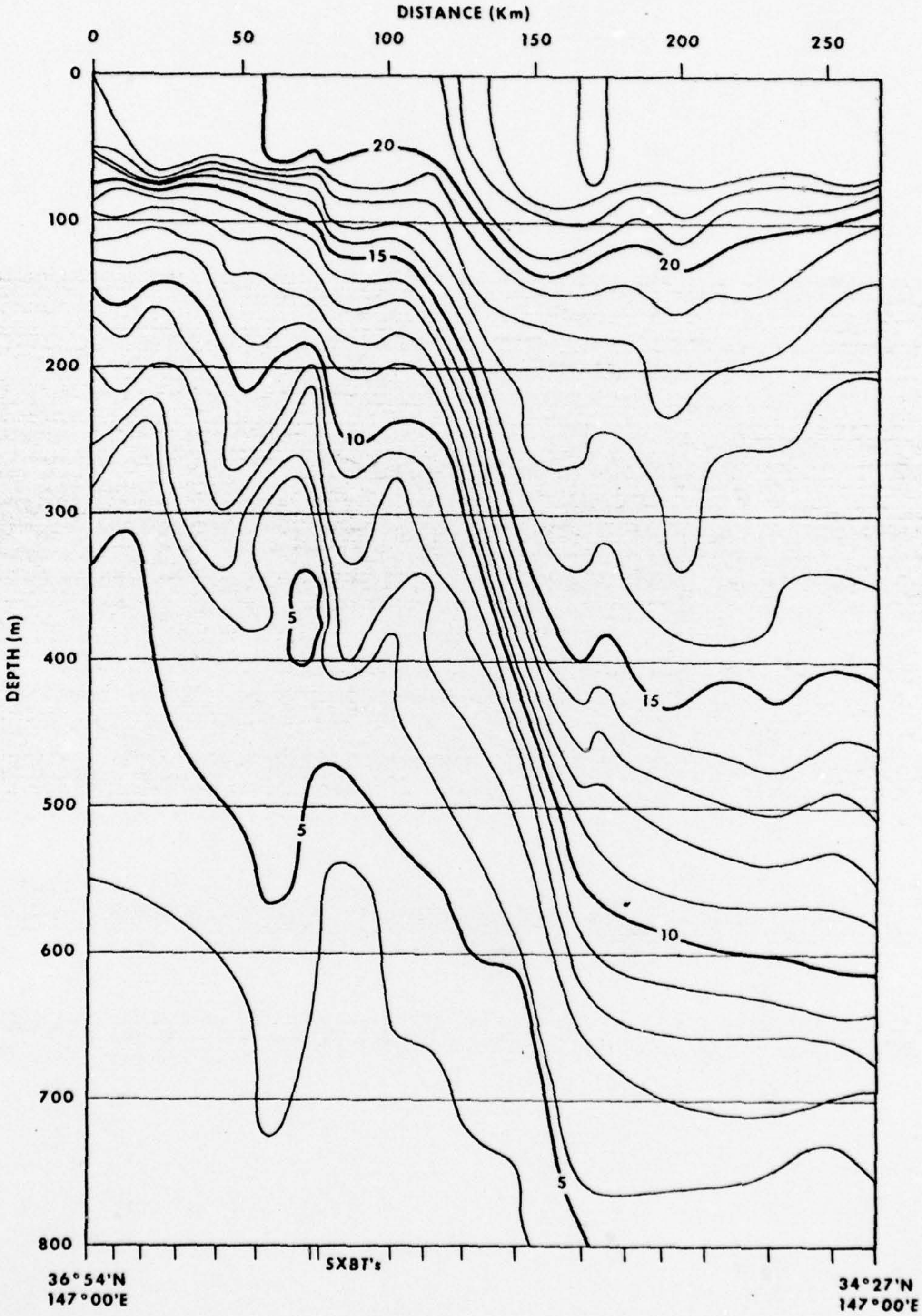


Fig. 11 - Temperature section through the Kuroshio, 25-26 October 1976. Isotherms slope steeply downward into the warmer subtropical water south of the front.

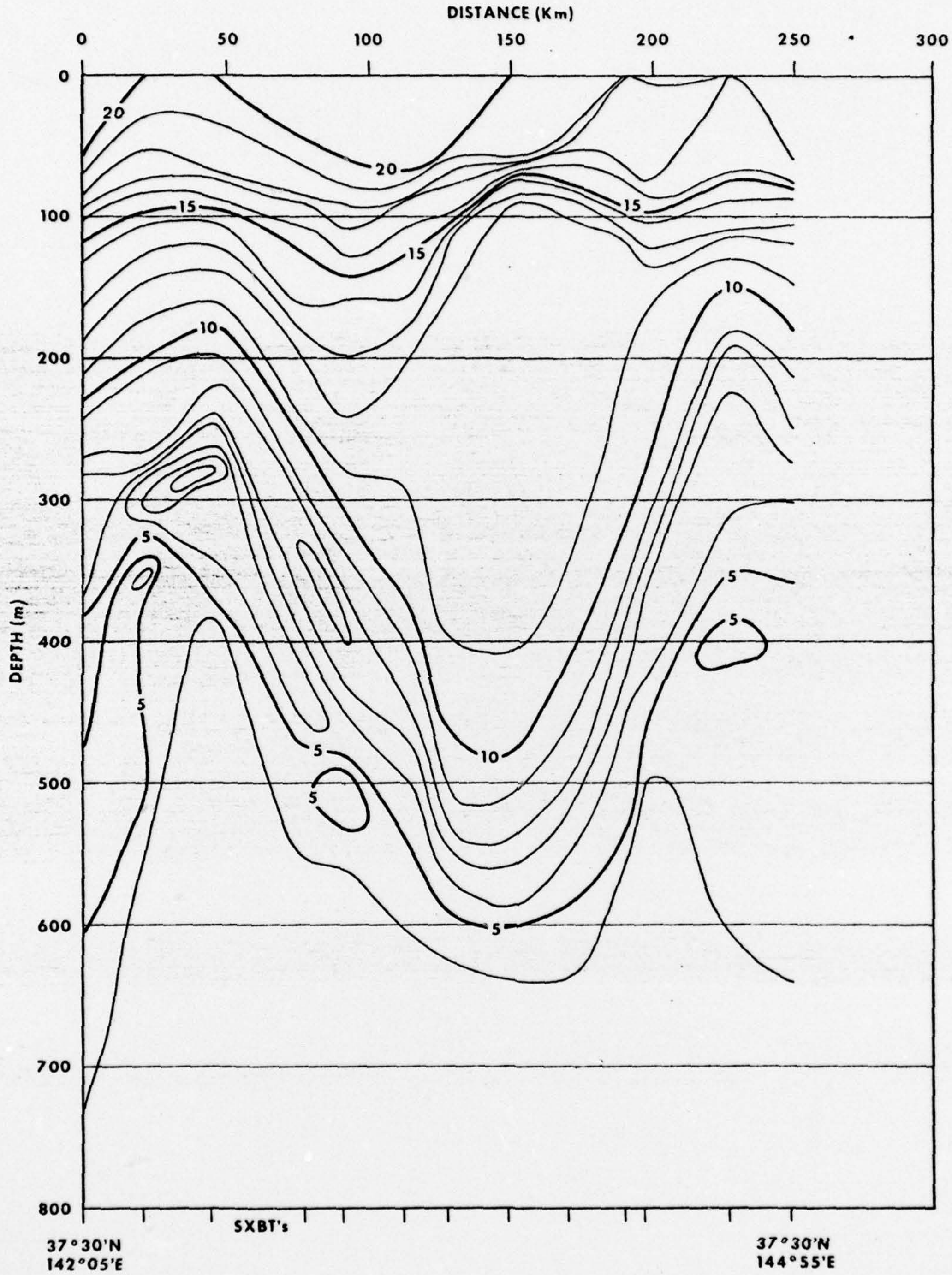
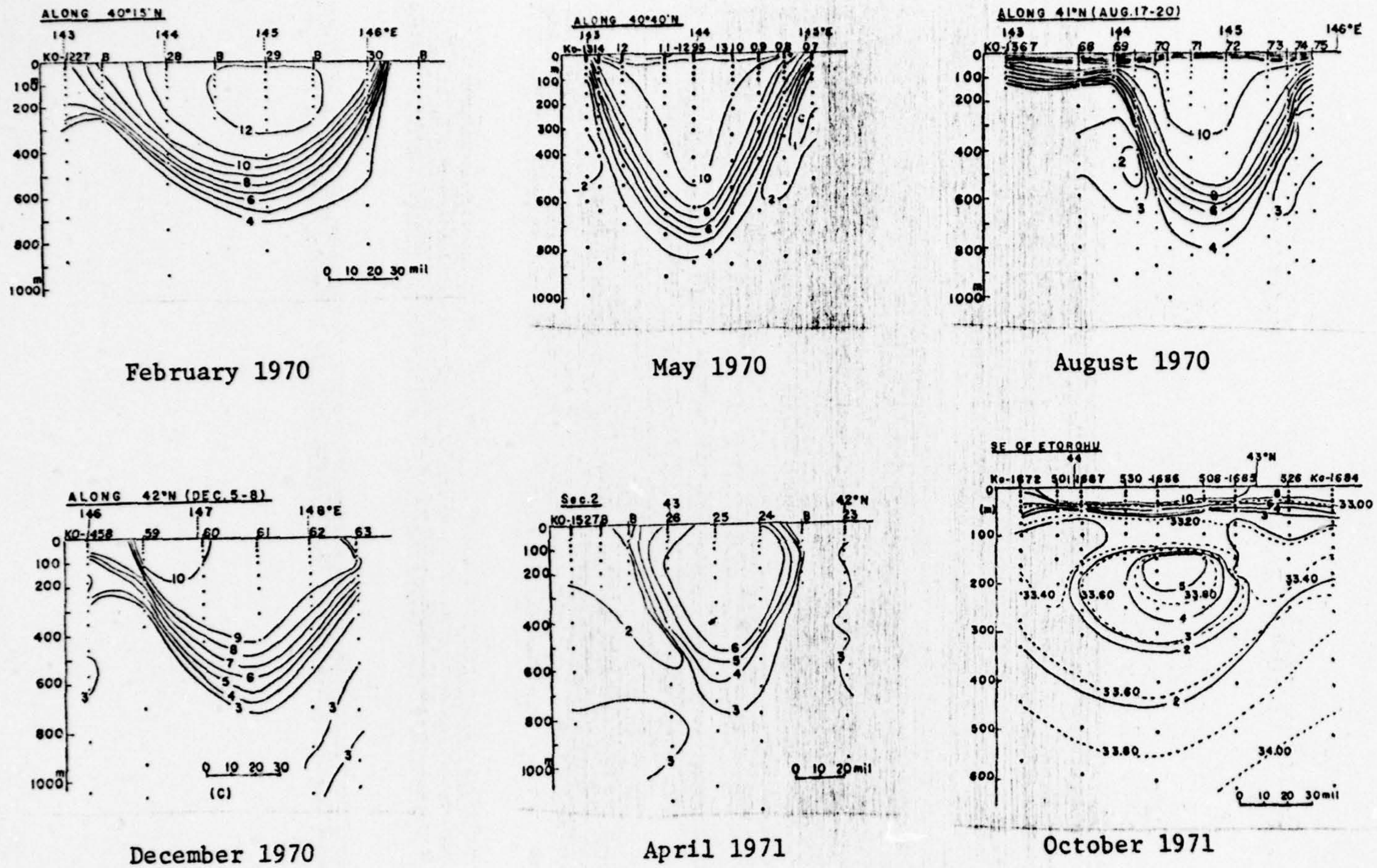


Fig. 12a - Temperature section through the warm Kuroshio eddy, 29-30 October 1976. An isothermal layer of 11.5°C water forms the eddy core between 100-400 m.



<u>Fig. 12b</u> - Seasonal cycles of a Kuroshio warm eddy over a period of 21 months. The eddy formed in October 1969. The isothermal core is reinforced during winter while during summer a "cap" is formed by the seasonal thermocline. (From Hata, 1974)

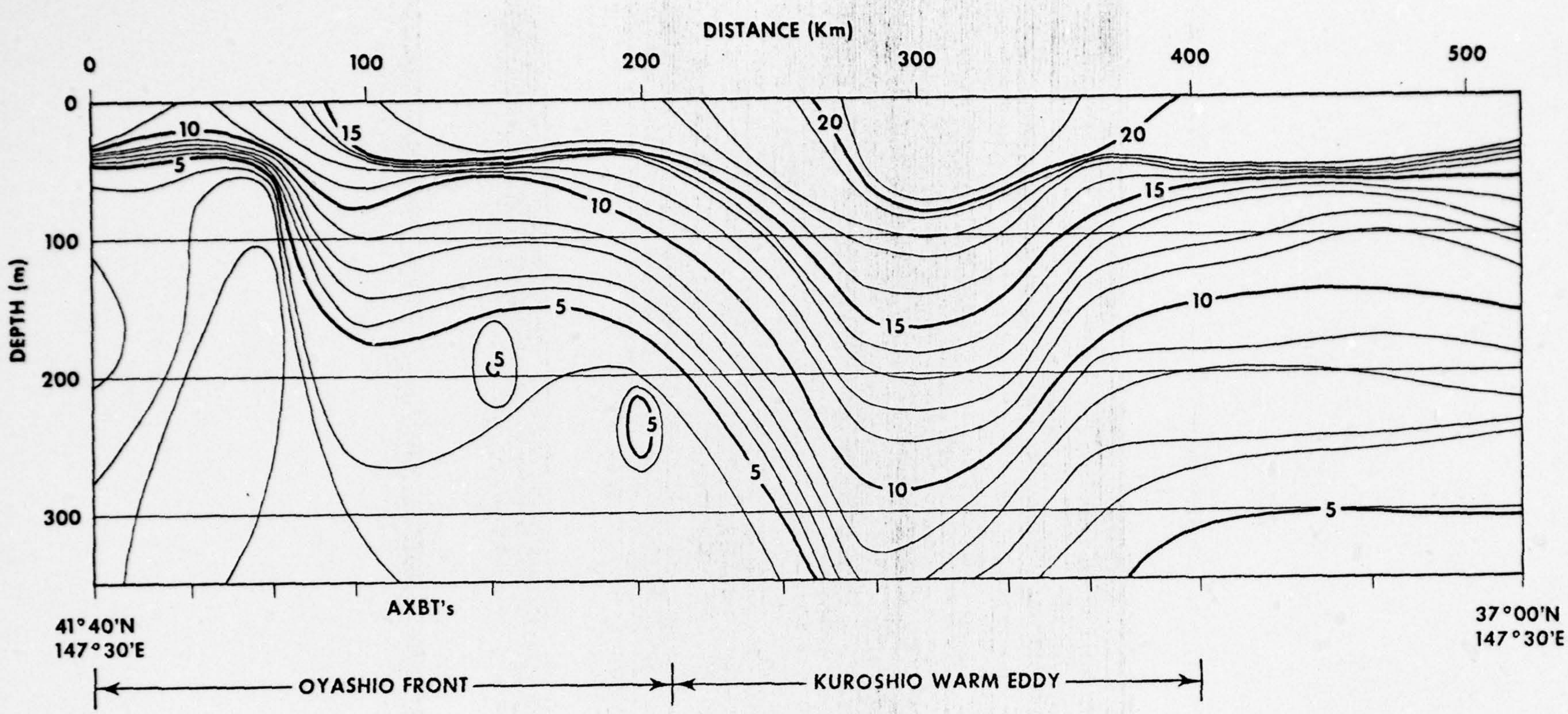


Fig. 13 - Temperature section through the Oyashio Front, 15 October 1976. The front is the shallow feature at the north end of the section where isotherms experience a sudden 100 m change in depth. Near the center of the section is an old Kuroshio warm eddy.

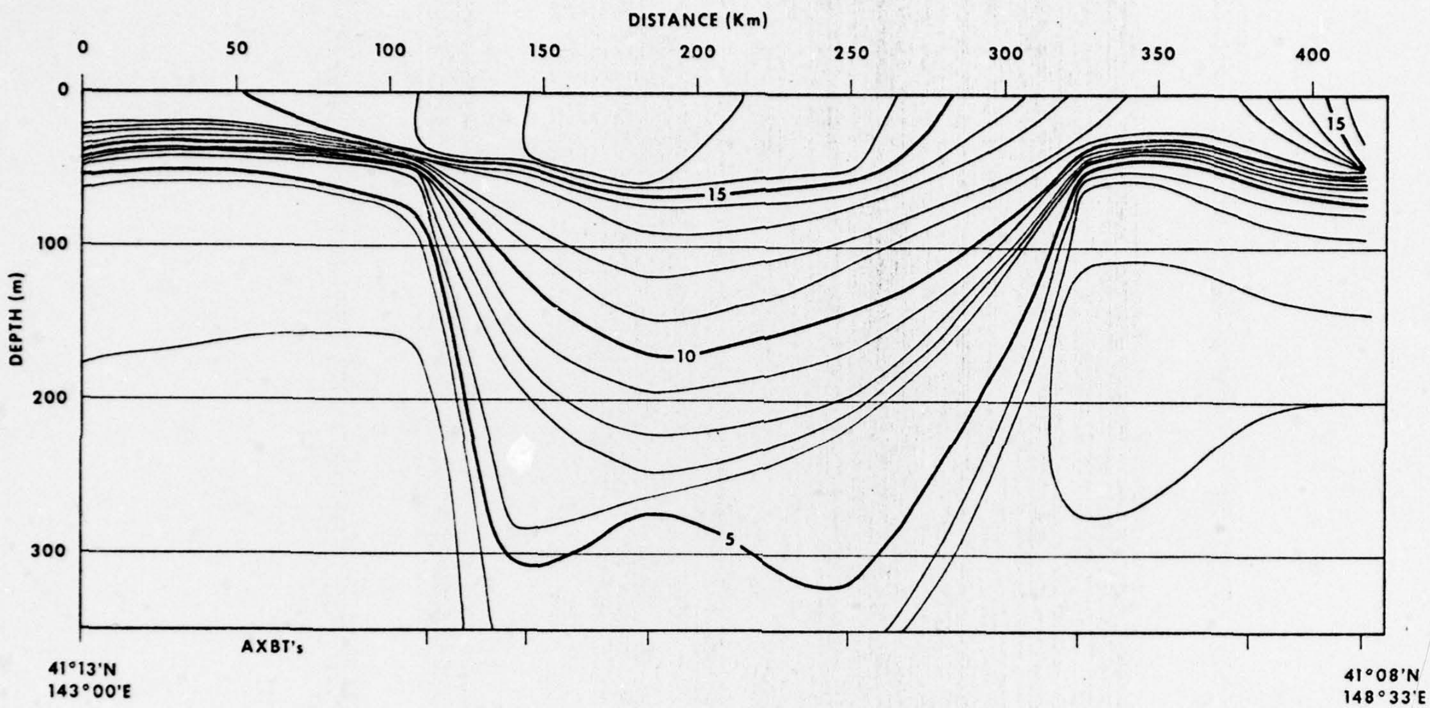


Fig. 14 - Temperature section through the warm Oyashio eddy, 15 October 1976.

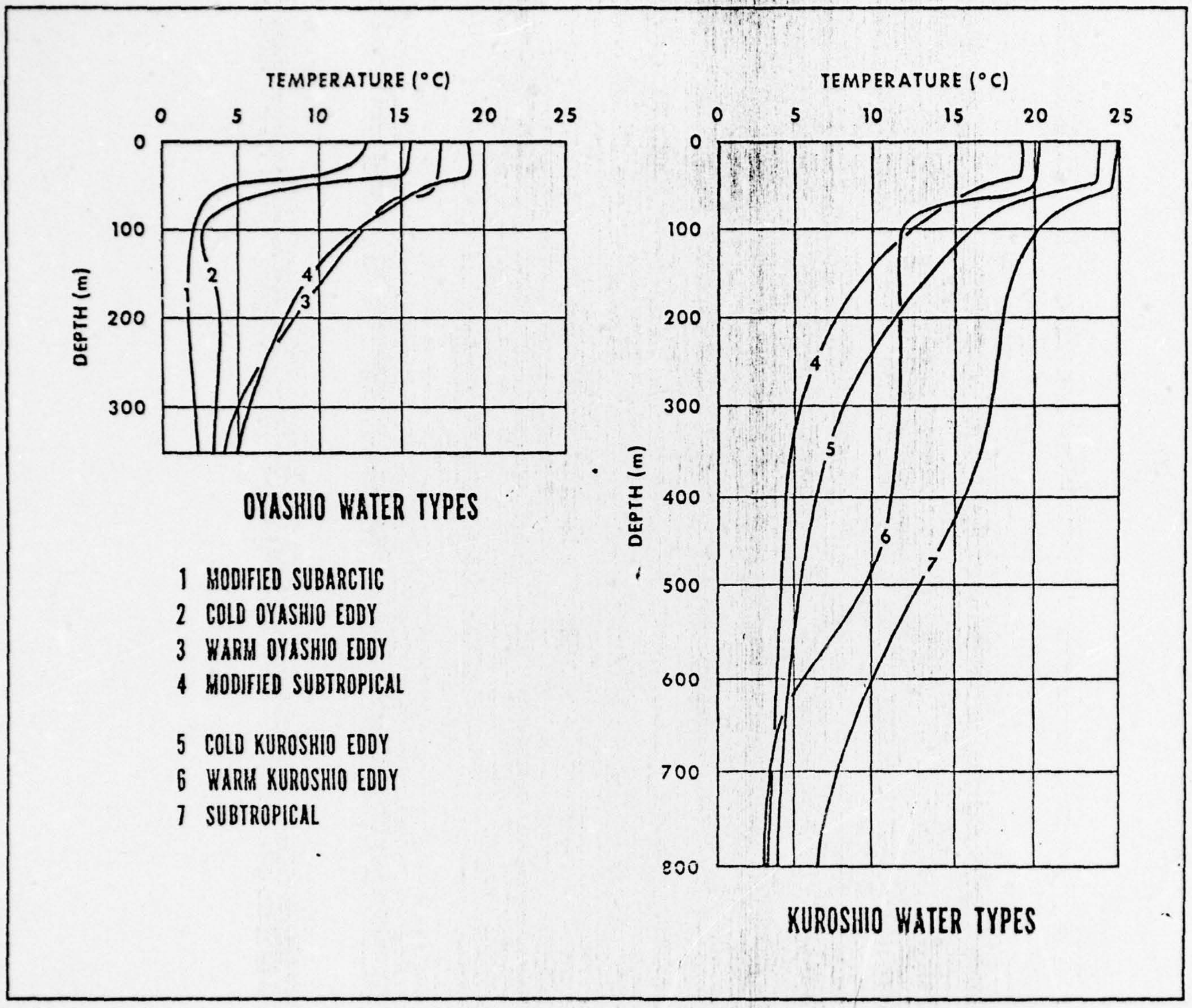


Fig. 15 - Temperature profiles representative of the various Oyashio and Kuroshio water types.