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R. A. Barkley

The Kuroshio current

The Kuroshio is one of the world's major ocean currents, equal in volume to some 6000 large rivers. Its sudden variations can have disastrous effects on Japanese fisheries, but as oceanographers develop routine monitoring methods fish catches could increase threefold

EVERY second the Kuroshio current carries some 50 million tonnes of sea water past Japan's southeast coast—a flow equal in volume to about 6000 rivers the size of the Danube or Volga. But even this massive current would take some 250 years to equal the total volume of the north Pacific. Thus, although the Kuroshio is one of the major currents in the world's oceans, and plays a vital role in the circulation of the north Pacific, it occupies only a small fraction (less than 0.1 per cent) of that ocean: a thin narrow band less than 100km in width and about 1km at maximum depth running for 3000km along the western edge of the Pacific between the Philippines and the east coast of Japan.

Asia's seamen have known the Kuroshio since ancient times. They named it Kuro-shio (which means 'black stream' in the Japanese language) because of the deep ultramarine colour of the warm, high salinity water which is found flowing north on the right hand side (looking downstream) of the current's axis. The heat which is carried north by this flow influences the weather throughout the northern hemisphere. The Kuroshio therefore plays an indirect but important part in the everyday life of the fishermen and farmers of eastern Asia and also, to a lesser extent, in the lives of most of the rest of mankind as well.

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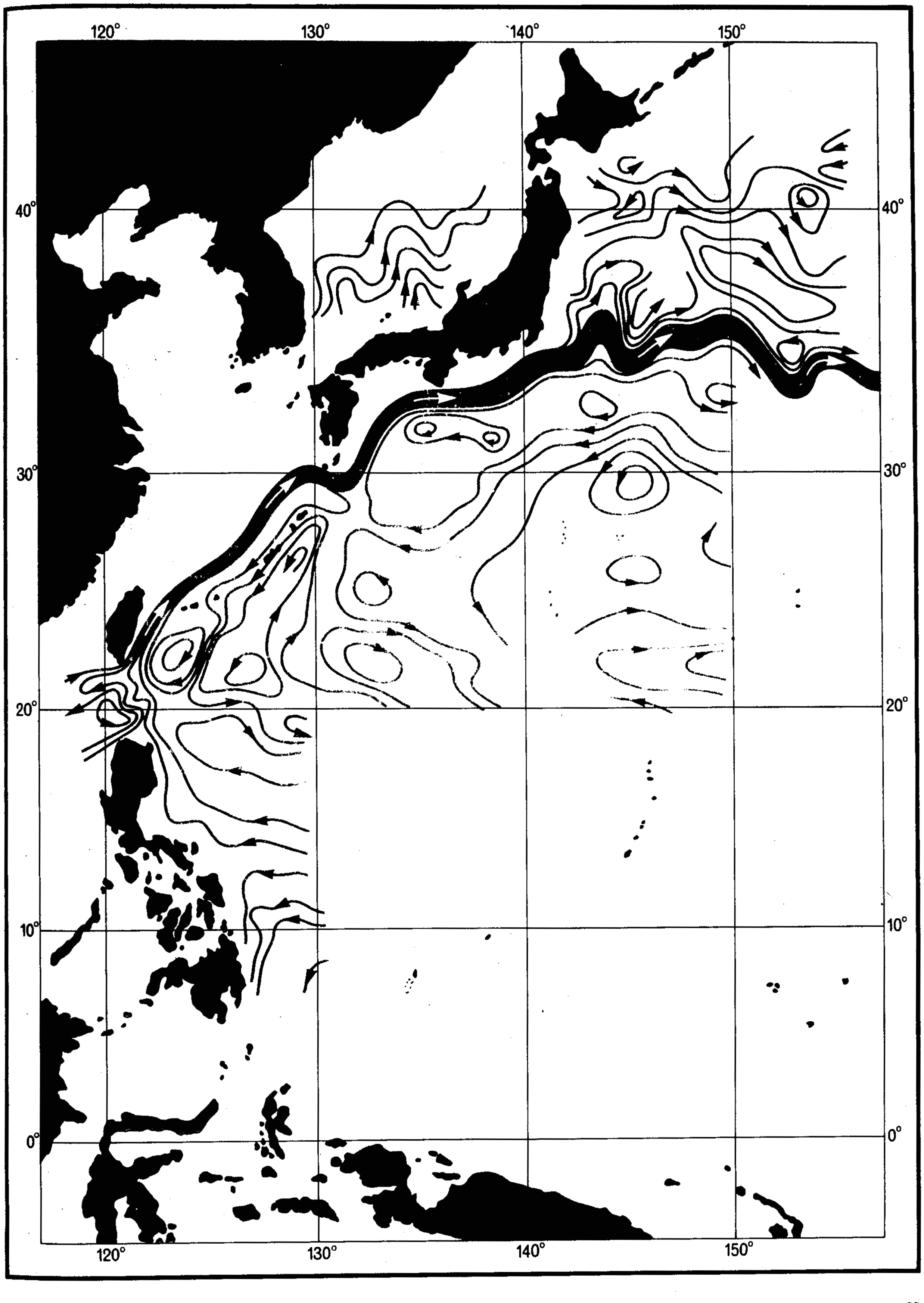
The first European chart to show the Kuroshio was Varenius' "Geographia Generalis" of 1650. Later, expeditions headed by Captains James Cook (1776-80) and Krusenstern (1804) added to western knowledge about the Kuroshio. Although Japanese scientists began to study the biology of the Kuroshio in 1880, it was not until 1893, when Wade started a series of drift bottle experiments, that systematic examination of its currents first began.

Today, in an attempt to learn more about the Kuroshio, scientists from China, Indonesia, Japan, Korea, Philippines, Singapore, Thailand, Hong Kong, United States, the Soviet Union and Vietnam are engaged in a major international project called the Co-operative Study of the Kuroshio (CSK). By keeping a figurative finger on this pulse of the north Pacific, they hope to learn more about western boundary currents in general, the Kuroshio in particular, and the whole north Pacific Ocean as well. In the process, they should also learn more about the way in which both weather and climate respond to changes in conditions at sea, and the ways in which marine animals and plants are affected by their environment.

THE INFLUENCE exerted on ocean currents by the Earth's rotation was not generally appreciated until 1835, when G. de Coriolis, while studying equations of motion in a rotating frame of reference, discovered what is now called coriolis force. Coriolis showed how the effects of the Earth's rotation could be incorporated into the Newtonian equations of motion by adding two additional terms. One, the centrifugal force of the Earth's rotation, is usually absorbed into a redefined term for 'gravitation', which includes gravity and centrifugal forces together and acts along a vertical defined by the direction of a plumb bob. By this definition there is no horizontal component of either force. The other term, the coriolis force, makes

PATH OF THE KUROSHIO is shown in heavy shading on this streamline chart prepared from geostrophic current measurements. The region of narrow intense flow east of Japan is the Kuroshio extension, which differs from the Kuroshio in that it has no land boundary to generate frictional flow. Convergence and divergence is shown by streamlines terminating and beginning


120°
130°
140°
150°
40°
30°
20°
10°
0°

allowance for the effects of conservation of angular momentum on a particle which moves relative to the Earth's surface. Coriolis force acts at right angles to such motion and also at right angles to the Earth's axis of rotation, and thus has no effect on the energy of motion but only modifies its direction.

The vertical component of coriolis force is so small when compared to the force of gravitation that it can always be neglected in ocean current theory. In the sea, however, forces which act along the horizontal are generally weak. Indeed, frictional and inertial forces are far smaller than those we are accustomed to on land—by at least five orders of magnitude—and they have little or no effect on any but the fastest moving ocean currents. The forces exerted by wind stress are often even weaker. Thus the horizontal component of the weak coriolis force becomes an important factor when considering ocean currents.

In most ocean currents the horizontal pressure gradient is found to be in balance with coriolis force. Such currents are called geostrophic or 'Earth-balanced' currents. Thus it is possible to obtain a useful approximation (to within 15 per cent) to actual currents by making measurements of horizontal pressure gradients. To do this, a series of temperature and salinity measurements is made to depths of 1km or more at several locations (called 'stations') across a current. These observations define the field of density (which depends on temperature, salinity and pressure, or depth), from which horizontal pressure gradients can be computed. A chart showing this field of pressure gradients is equivalent to a chart showing streamlines of geostrophic flow. This procedure is referred to as the dynamic method, and was first used by J. W. Sandstrom and B. Helland-Hansen in 1903. Unlike direct current measurements, which are more expensive and time consuming to make and more difficult to interpret, the dynamic method is little affected by transient motion due to surface waves, tides and winds, which are often much stronger than the movements of water in the permanent current system.

Geostrophic current calculations have one major drawback—they only give information on the flow relative to some reference surface which is presumed to be nearly motionless. The problem arises because the dynamic method depends upon an integration, and the constant of integration—the absolute pressure at some level surface common to all the oceanographic stations used in the calculations—is not normally known, and cannot be measured directly with the required accuracy. In practice it is common to use the 1000 decibar surface (at very nearly 1000 metres depth) as a reference surface for measurements used in dynamic calculations.

The theory of wind driven ocean currents concerns itself primarily with the forces which generate, control and finally dissipate energy in the sea. Most of this energy appears in two forms: kinetic energy of motion—the currents *per se*—and potential energy of position—the 'pressure head' due to slopes in the sea's surface and the internal density structure. There are also others, primarily thermal energy, which affect the distribution of density and thereby influence currents.

Those forces which carried Kuroshio water through nets set by Japanese fishermen this morning were generated weeks, months, or even years earlier by winds blowing over the entire north Pacific Ocean. Even a small gust of wind rippling the quiet waters off Baja, California, for example, contributes to the oceanwide accumulation of energy which drives the inexorable flow of millions of tonnes of water past Asia's coasts. A major problem in ocean theory is to determine the way in which energy is transferred from the winds to the shallow wind driven upper layers of the ocean; from there, into the geostrophic currents; and, finally, into the narrow sheer zone on the left hand side of the Kuroshio, where energy is dissipated.

When V. W. Ekman provided, in 1905, a theoretical explanation for Nansen's observation that Arctic icebergs tend to drift to the right of the wind, he laid a major cornerstone for all subsequent studies of wind driven flow. Ekman showed that a steady wind produces transport of water at right angles to the wind's direction (toward the right in the northern hemisphere, and to the left in the southern hemisphere). This movement of water is usually called Ekman transport. A balance is reached between coriolis force and wind stress at the sea surface, which is a precise analogy to the balance existing between coriolis force and the horizontal pressure gradient in geostrophic flow.

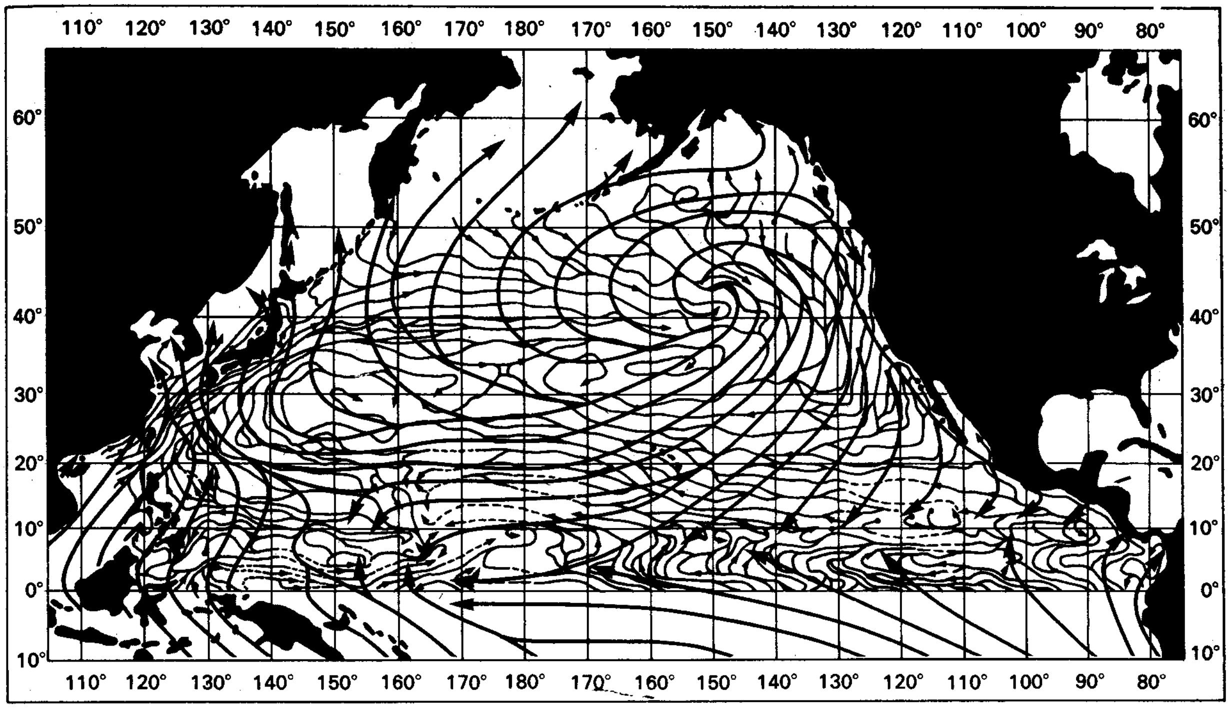
In 1947, H. U. Sverdrup, the Norwegian oceanographer and meteorologist, used Ekman's concepts to calculate the wind driven transport in equatorial currents of the Pacific Ocean. The following year H. Stommel showed that changes in the coriolis effect with latitude (the horizontal component of coriolis force varies as the sine of the latitude, so that it reaches a maximum value at the pole, and vanishes at the equator), were responsible for the narrow swift currents along the western boundaries.

A major advance in the theory of wind driven circulation was made by W. H. Munk in his pioneer study of oceanwide transports. He pointed out the fundamental importance of wind sheer, or torque, which transmits angular momentum to the sea surface and thus generates the major circulation systems. Munk's study was based on a linear steady state mathematical model in which friction played a large part. K. Hidaka has explored such theoretical models extensively since 1949.

In more recent years the importance of large scale friction in currents such as the Kuroshio and Gulf Stream has been questioned by a number of theoreticians, who regard it as characteristic of the climatic-mean flow, but not of the instantaneous current. That is, meanders and eddies formed from time to time by the current could be considered as a form of turbulent friction of the magnitude required in Munk's and Hidaka's theories, if their effects were averaged over large areas over long periods of time. On a shorter time scale, and over smaller distances, such meanders and eddies must be treated individually, which requires the use of nonlinear time dependent mathematical models. Such models present formidable mathematical difficulties which in some cases can only be overcome by the use of numerical computer methods.

PREVAILING SURFACE WINDS over the north Pacific in summer describe a clockwise circulation around the mid-latitude high pressure cell, from which the air spirals outward, away from the high, towards the low pressure regions over Asia and Alaska, and towards the climatic Equator, the doldrums, near 5°N. Initially, this is cool, dry air which descends towards the sea surface and speeds up, removing both heat and moisture from the surface water layers as it goes. It then slows down as it reaches the convergent lows, where the air rises and much of the moisture returns to the sea as rain. In winter, the high pressure band moves south some 20° of latitude and splits into eastern and western cells, with a low pressure band, the Aleutian low, all across the Pacific farther north.

On streamline charts (such as the map on page 55), constant amounts of water flow between any two streamlines (within the accuracy of the methods used), so velocity of flow is inversely proportional to the distance between adjacent streamlines. In addition, such charts show convergences and divergences, flow of water downward out of the layer in question, or upward from below, by showing streamlines terminating (convergence) or beginning



EKMAN TRANSPORT in the north Pacific is shown in the map above, where the prevailing winds in July are shown in colour, and the surface current streamlines in black. Off the coast of California, and the northeast coasts of China and Japan, the wind blows along the coast, inducing offshore transport of water. The opposite situation, where Ekman transport carries surface water towards the coast can be seen on the eastern side of the Gulf of Alaska

(divergence) at a coast or in midocean. In the following discussion it will be convenient to use the term 'Sverdrup unit' to indicate a flow of one million cubic metres per second.

According to the map on this page Ekman transport removes water from the equatorial currents and the northern gyre and transports it into the central gyre. Some 45 streamlines enter the gyre at its perimeter (from the coasts, between islands and across 10° and 50°N). What happens to this massive flow? Most of it—about 40 Sverdrup units—evaporates into the cool, dry air flowing out of the atmospheric high. But Ekman transport more than makes up for this loss; the excess 'piles up' in the Subtropical Convergence and sinks to depths of 100 to 200 metres. From there, much of this water spreads radially outward but some of it is mixed downward, warming the underlying water. Over long periods of time, a 'lens' of lower density water about one kilometre thick has accumulated in the centre of the gyre. The low density layer is only one quarter to one-tenth as thick at the perimeters of the gyre, and cold dense, deep water is found much closer to the surface there.

Density gradients due to convergence and divergence of the Ekman transport cause horizontal pressure gradients which generate the geostrophic flow shown on the map on page 59. Such gradients are largest in the upper 100 to 200 metres and diminish to negligible values at 1 to 2km depth, due to compensating displacements of denser, deep water.

The effectiveness of coriolis force in limiting the flow of water out of the thick, warm water lens at the convergence can be understood by comparing currents and horizontal pressure gradients in the central gyre with those at the Equator, where coriolis force vanishes. At the Equator a pressure gradient only one per cent as strong as that across the Kuroshio produces comparable current velocities. Why? Because flow at the Equator is not geostrophic and is therefore free to speed up until friction and inertia forces are large enough to balance the pressure gradient. At higher latitudes coriolis force allows much larger horizontal pressure gradients to build up before the flow reaches speeds where friction and inertia forces become important limiting factor.

The potential energy stored in the mid-latitude gyre is many hundreds of times greater than the kinetic energy of its currents, and represents an accumulation of energy five to ten times larger than the energy added by winds in a year. It is not surprising, then, that the ocean's density structure is remarkably constant, and that currents such as the Kuroshio hardly respond to changes in the local winds. Currents near the Equator, on the other hand, represent much smaller accumulations of energy and respond much more readily to changes in the wind.

AFTER DECADES of effort by Japanese oceanographers, supplemented by studies made during international expeditions and by individuals from many countries, it is now possible to piece together a reasonably satisfactory description of the Kuroshio proper. Water enters the Kuroshio over a broad front 1000km in width (13°N to about 23°N at longitude 125°E) then accelerates and narrows. Some water leaves the right hand side of the Kuroshio as soon as it begins to turn towards the east, but narrow, intense flow persists for 1500 to 2000km after the current leaves Japan's east coast, after which there is a marked drop in velocity. This region of narrow intense flow east of Japan is called the Kuroshio extension, and it differs from the Kuroshio in that there is no land boundary on the left hand side to generate a frictional boundary layer.

Comparison of velocity profiles (plots of velocity across the surface current) of the Kuroshio and the Kuroshio extension shows that, although both have essentially identical velocity profiles on their right hand sides, the velocity gradient on the left hand side of the

Kuroshio is at least six times greater (a change of 2m/s in 8km) than that in the Kuroshio extension (2m/s in 50km). Other things being equal, this would result in six times greater frictional stress on the left side of the Kuroshio. Such velocity profiles support the theoretical view that the Kuroshio and Kuroshio extension are the major nongeostrophic portions of the flow in the central and northern gyres, where important adjustments in the distribution of energy take place.

In the Kuroshio energy is dissipated through friction (on a small scale, since the frictional boundary layer is only about ten kilometres wide). On average, the dissipation rate must be in balance with the mean rate at which wind adds energy to the central gyre.

However, friction not only dissipates energy, it also generates counter-clockwise angular momentum at a rate which more than compensates for the decrease in the Earth's (counter-clockwise) angular momentum as the current flows north. To balance this excess, clockwise angular momentum is generated on the right hand side of the current, where the velocity decreases towards the right in what is sometimes termed an inertial boundary layer. As H. Stommel pointed out in 1948, this balance of angular momentum can only be attained on the western boundary, which accounts for the westward intensification in the current systems of the world oceans.

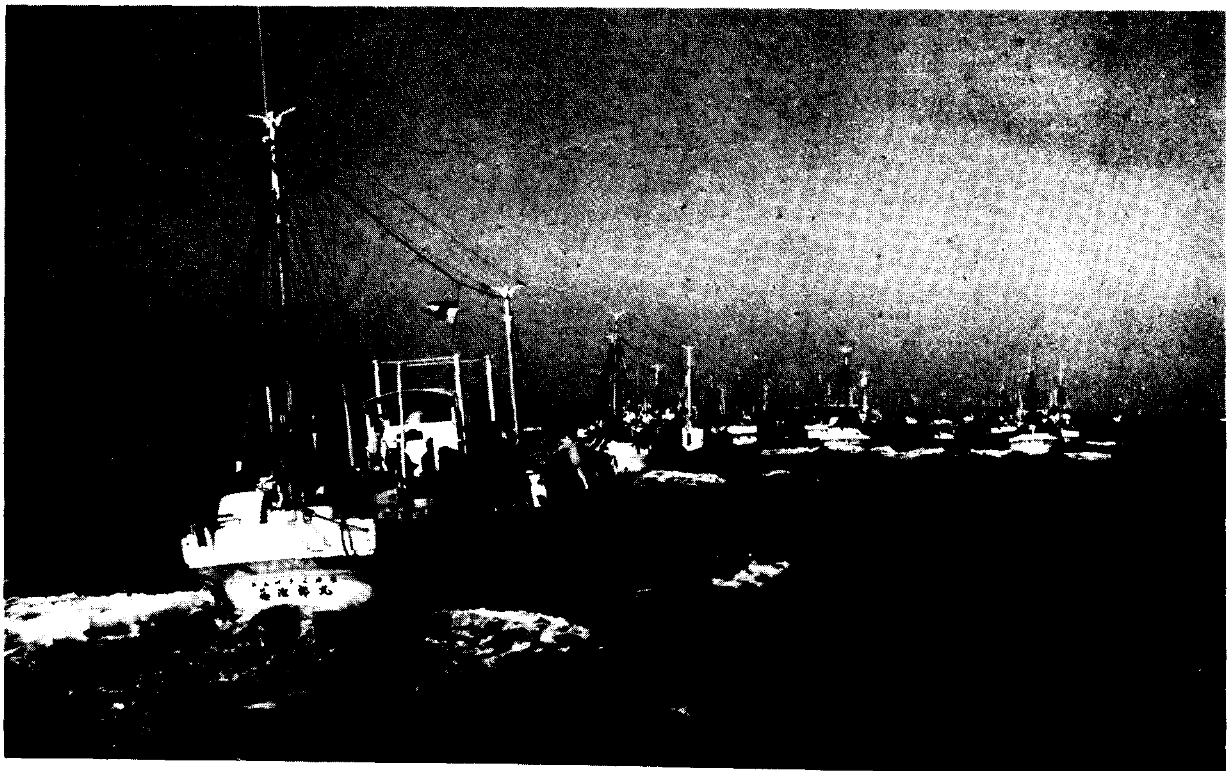
In the Kuroshio extension the flow adjusts to conditions in the ocean's interior, where large velocity gradients, and the angular momentum associated with such gradients, cannot persist. Friction is no longer concentrated at the boundary, nor are inertial forces restricted to the right hand side of the stream. Instead, large eddies and meanders dissipate kinetic energy throughout the path of the flow, and redistribute angular momentum at the same time. The transport decreases downstream as the flow fans out and becomes the broad, slow West Wind Drift between 155° and 160°E.

Fifty Sverdrup units of flow approach the east coast of Mindanao in the Philippines and half of this volume turns north into the Kuroshio. Most of this flow consists of warm (20°-28°C) water in the upper 200 metres; there is a layer with relatively high salinity (near 35 parts per thousand) between 100 and 200 metres with slightly more dilute water (34.5 parts per thousand) above that.

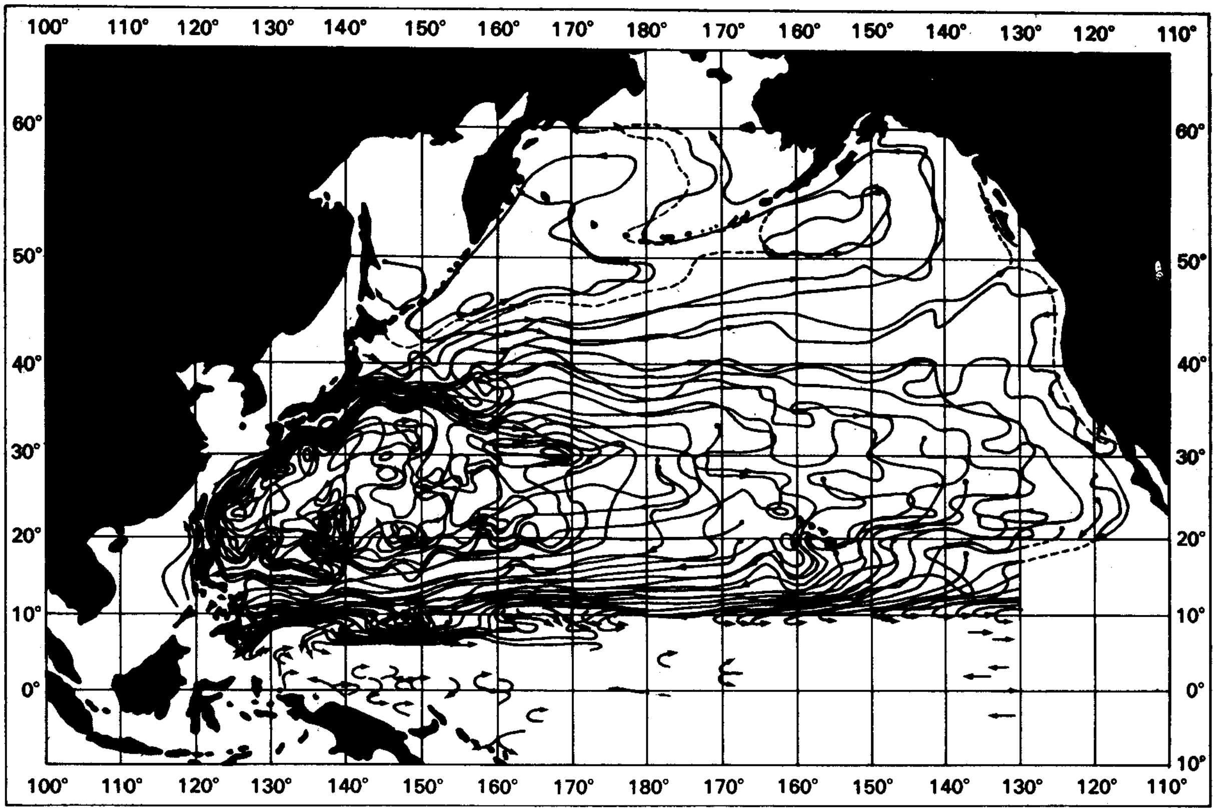
The depth of the high velocity flow increases from 200 to 400 metres, and the velocity goes up from a few tens of centimetres per second to one metre per second as the current narrows east of Taiwan. From Taiwan to Japan some dilute water from the Asian shelf, on the left of the current, is entrained by the flow, which speeds up even more, to velocities of 1.5 to 3m/s. Transport just off Japan's south coast amounts to 35 Sverdrup units, but there may be significant flow below 1000 metres since the current extends to considerable depths at that point, and so the total transport may be as high as 45 to 50 Sverdrup units.

Just as the current reaches Japan's southeast tip, it flows over the shallow Izu-Bonin Ridge which extends due south from Honshu, Japan's main island. The Kuroshio undergoes complex and little understood fluctuations near this ridge.

Once past the Izu-Bonin Ridge, the Kuroshio may turn north along Japan's east coast for a short distance, or it may continue to flow almost due east. In either case, it joins the Oyashio current, which flows southward from the Kamchatka Peninsula. Together these two currents leave the coast and form the Kuroshio extension. Transports here amount to about 45 Sverdrup units (up to 60 on occasion) though only 25 to 35 Sverdrup units are within the high



MACKEREL FISHING FLEET from Choshi heading for the rich fishing grounds of the Kuroshio extension. Some boats spend 80 per cent of their time scouting for fish, but improved knowledge of the current could reduce this time, and so increase their catch



TOTAL TRANSPORT by geostrophic currents in the north Pacific. Transport in the upper 1000 metres is shown in colour (each line represents 5 Sverdrup units), and in the upper 100 metres in black (each line represents 1 Sverdrup unit). The map shows the intense narrow flow at the western boundary, the change to broad slow moving flow downstream, near longitude 160°E, and the even broader slower moving water transport which occurs toward the south

velocity core of the Kuroshio extension, where speeds of two metres per second or more are often observed.

By the time the current has reached 160°E, towards the end of the Kuroshio extension, it consists of a mosaic of water types: warm saline water from the original source off the Philippines, coastal and shelf water of lower salinity, and cold dilute water from the Oyashio, with summer temperatures of 3° to 10°C, and salinities sometimes as low as 33.8 parts per thousand.

Some mixing occurs in the core of the Kuroshio extension, but on the whole there are two distinct types of water in the current: warm saline water on the right, and cold dilute water on the left. The convoluted front separating these two types of water is often very sharp and active, with strong velocity gradients and shape contrasts in the properties of the water on the two sides. Rich fishing grounds are located on both sides of the frontal zone in the Kuroshio extension, so this complex feature of the western north Pacific is of particular interest to Japan's fishing fleet. A pioneer in fisheries oceanography, Professor Michitaka Uda, has studied such fronts and the fisheries associated with them since 1930. He and his colleagues in Japan's unique system of fisheries universities have contributed much to our knowledge of the sea as an environment. They have taken particular interest in variability in the occurrence of various kinds of fish, and changes in the environment which cause much of this variability.

The path of the Kuroshio as shown in the map on page 55 is very nearly its average position, but the current can undergo marked and fairly rapid changes in speed and in the location of its axis. Apart from changes due to tides, short term changes due to major shifts in the axis of the Kuroshio can occur as it flows past southern Japan. Meanders develop in the current which occasionally bring high velocity flow unusually close to the coastline, and part of the Kuroshio's flow may be diverted into nearby bays, where it can flush out much of the coastal water within a matter of days. These sudden and as yet unpredictable events cause widespread damage to boats and fishing gear anchored in the normally quiet waters, as offshore currents move inshore at speeds of 1-2m/s, or more.

Meanders in the Kuroshio south of Japan have been studied intensively. The axis of the current may shift onshore or offshore 100km or more in a matter of weeks. For example, in 1959 the Kuroshio off Japan's south coast (at 133°E) began to move offshore in March or April, shifting from its initial position 20km offshore to a distance of 140km in about one month. This meander also drifted rather slowly downstream, reaching the central portion of the south coast (136°E) by the end of May and the eastern portion (139°E) by early August, at which time the Kuroshio's axis was back within 25 Km of the coast farther upstream (133°E), where the disturbance was first observed. Such meanders may appear and disappear within a few months, but they may also remain more or less stationary for more than a decade. When the meander develops, cold water is brought up toward the surface between the Kuroshio and the coast and temperatures drop to as much as 10°C below normal. This change has profound effects on coastal and offshore fisheries, since the area involved is fairly large—about the size of the Bay of Biscay. Familiar species of fish move away and are replaced by others, and so fishermen must either move to new grounds or market what they can catch on the old grounds.

The only nontidal changes in the Kuroshio which appear to be at all regular are annual changes in velocity and transport, which are easily obscured by the irregular variations discussed above. Japanese scientists generally agree that the speed is greatest from May until August, with a second maximum in January and February. But an analysis by Y. V. Pavlova has shown that the annual cycle is rather more complex, at least for geostrophic currents. Speed and transport not only vary with season, they vary in different ways from place to place along the Kuroshio. Off the southern tip of Japan, for example, maximum transport within the Kuroshio occurs in September and again in March or April, while maximum velocities are observed in July and January. Just east of Japan, according to Pavlova, maxima in transport occur during June and December, with velocity maxima in August and February.

WHAT NOW REMAINS to be learned about currents such as the Kuroshio? Perhaps most valuable would be information on fine structure and on fluctuations over periods of a month or less. To determine how fluctuations propagate from place to place, measurements must be made simultaneously at several points along the current, and at least a few direct measurements must be made of the currents at all depths. Many developments in ocean current theory await the results of such observations, which will also be needed for forecasts of conditions in and near the Kuroshio to serve the needs of fishermen and meteorologists. But the effort required, for a complete survey of the Kuroshio, in terms of ships, time and operating costs, is staggering and detailed rapid surveys of the Kuroshio must wait until more efficient tools, such as instrumented buoys, become commonly available.

Once routine monitoring of the marine environment becomes commonplace, we can expect marked improvements in long range weather forecasts and in catch rates of commercial fisheries, which will rapidly repay the original investment of effort and funds. Even rather minor improvements in weather forecasts can bring significant savings to farmers, public utilities, cargo ships, airlines and others who use forecasts in scheduling operations or planning routes.

Farmers in northern Japan may have good or poor harvests depending on the extent to which the Kuroshio flows north along Japan's east coast, before joining the cold Oyashio water, since water temperatures offshore strongly influence cloud cover and rainfall. Similarly, cold air from Siberia flows out over the Pacific in winter, to encounter warm water carried north by the Kuroshio; these temperature contrasts trigger formation of numerous cyclonic lows in the atmosphere over the Kuroshio. The lows carry stormy weather east to northeast across the northern Pacific Ocean towards the coasts of Alaska, Canada and the United States.

Improved knowledge of the ocean as an environment can help fishermen locate and catch protein to feed an increasingly hungry world. Fishermen could make direct use of forecasts of the Kuroshio's flow, because the entire current system is a series of fishing grounds which move about with changes in the flow. Various species of tuna, sardine and anchovy, mackerel, squid and many other commercially important species are each found in specific zones in and near the Kuroshio. For example, fronts where coastal and offshore waters meet are often good fishing grounds. Species such as sardines are caught on the coastal side of these fronts, while mackerel and tuna occur in abundance in the warmer offshore waters. Changes in the marine environment appear to influence both the timing and the paths of fish migrations.

For more than 50 years, Kitahara, Uda and their fellow fisheries oceanographers in Japan have studied the response of fish to their environment. They have set up an extensive network for collecting and reporting temperatures at the sea surface and at various depths, movements of schools of fish near various fishing grounds, catch rates, and ocean current information for making fishing condition forecasts.

Six regional fisheries research laboratories and 38 prefectual fisheries experiment stations are responsible for collecting, analysing and distributing information on individual fisheries, such as the salmon, sardine or albacore. Ships at sea send information on their catches and the environment to the appropriate laboratory by radio. There these reports are compiled and analysed to produce charts of fishing conditions, conditions in the ocean, and forecasts of various kinds, which are sent to the fishing fleet by mail, radio and facsimile. Some charts and forecasts are prepared at 10 day intervals, and others are sent out once a month. Research and cargo ships also provide information on temperature, salinity, currents and other factors in the environment for use in the fishing condition broadcasts.

Forecasts are based on long term trends, the time when fishing begins or ends on various grounds, data on age and size composition of the catch, and on experience with changes in the ocean in various fishing areas and the consequences of such changes in the past. It is still too early to evaluate the system's effectiveness, except to note that the information provided to the fishermen is very much in demand.

The potential value of fishery forecasting systems can be judged from the fact that boats in some fisheries must spend 80 per cent or more of their time scouting for fish. If this time could be reduced by half, each ship in such a fishery could increase its catch as much as threefold.

We have seen that there are many reasons for undertakings such as the Co-operative Study of the Kuroshio. They range from the most abstract, through the coldly practical to the mundane—improvements in ocean current theory, better weather predictions, more efficient ways to catch fish, and improved charts of the oceans. All these and more will result from studies of the Kuroshio and other parts of the world ocean. But regardless of motive, form or content, the goal of these studies can be summarized in much simpler terms: the search for man's ultimate tool, knowledge.

FURTHER READING

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