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Co-operative study of the Kuroshio
and adjacent regions

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Preface

Presented during the ninth session of the Assembly of the Intergovernmental Oceanographic Commission, this series of lectures is dedicated to the memory of the noted Danish oceanographer and first Chairman of the Commission, Dr. Anton Frederick Bruun. The "Bruun Memorial Lectures" were established in accordance with IOC resolution VI-19 in which the Commission proposed that important inter-sessional developments be summarized by speakers in the fields of solid earth studies; physical and chemical oceanography and meteorology; and marine biology. The Commission further requested Unesco to arrange for publication of the lectures and it was subsequently decided to include them in the "IOC Technical Series".

Anton Bruun was born on 14 December 1901, the first son of a farmer; however, a severe attack of polio in his childhood led him to follow an academic, rather than agrarian, career.

In 1926 Bruun received a Ph. D. in zoology, having several years earlier already started working for the Danish Fishery Research Institute. This association took him on cruises in the North Atlantic where he learned from such distinguished scientists as Johannes Schmidt, C. G. Johannes Petersen and Thomas Mortensen.

Of even more importance to his later activities was his participation in the Dana Expedition's circumnavigation of the world in 1928-1930, during which time he acquired further knowledge of animal life of the sea, general oceanography and techniques in oceanic research.

In the following years Bruun devoted most of his time to studies of animals from the rich Dana collections and to the publication of his treatise on the flying fishes of the Atlantic. In 1938 he was named curator at the Zoological Museum of the University of Copenhagen and later also acted as lecturer in oceanology.

From 1945-1946 he was the leader of the Atlantide Expedition to the shelf areas of West Africa. This was followed by his eminent leadership of the Galathea Expedition in 1950-1952, which concentrated on the benthic fauna below 3,000 m. and undertook the first exploration of the deep-sea trenches, revealing a special fauna to which he gave the name "hadal".

The last decade of Bruun's life was devoted to international oceanography. He was actively involved in the establishment of bodies such as the Scientific Committee on Oceanic Research (SCOR), the International Advisory Committee on Marine Sciences (IACOMS), the International Association for Biological Oceanography (IABO) and the Intergovernmental Oceanographic Commission (IOC); he was elected first Chairman of the Commission in 1961.

His untimely death a few months later, on 13 December 1961, put an end to many hopes and aspirations, but Anton Bruun will be remembered for his inspiring influence on fellow oceanographers and his scientific contribution to the knowledge of the sea which he loved so much.

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Opening statement

Professor H. U. Roll

First Vice-Chairman

I have great pleasure in opening this plenary session devoted to the Anton Bruun Memorial Lectures. I extend a particular welcome to our speakers, who have come here to lecture on the scientific results of the co-operative investigations of IOC.

These lectures are dedicated to the memory of the first Chairman of the Commission, the late Professor Anton Bruun from Denmark, who died in December 1961 during his term of office.

The first Anton Bruun Memorial Lecture, which was devoted to the earth's mantle, was delivered by Dr. Roger Revelle of the United States of America during the second session of the Commission in 1962.

The Commission continued the series of lectures until 1969. Eminent scientists spoke on important topics, as for instance: "Variability in the Ocean", a lecture given by Dr. Bob Stewart from Canada; "Air-sea Interaction", a lecture presented by Professor Henry Charnock from the United Kingdom; and "Sea Floor Spreading", a lecture given by Dr. Art. Maxwell from the United States.

In 1969, the Commission, desiring to increase the scientific content of its sessions, decided to intensify the Anton Bruun Memorial lectures and to schedule three such lectures during plenary meetings of each future Assembly. Further, the practice was started of reporting on the scientific results of the co-operative investigations co-ordinated by the IOC.

In 1971, we had four lectures on the scientific results of the International Indian Ocean Expedition. In 1973, we enjoyed five lectures on the International Co-operative Investigations of the Tropical Atlantic (ICITA), four lectures on the Co-operative Investigations in the Mediterranean (CIM), and six lectures on the Global Atmospheric Research Programme (GARP) and its sub-projects GATE(1) and FGGE(2). Altogether in 1973 we had fifteen lectures which was a climax.

For this session of the Assembly, it was decided to reduce the number of lectures to four but we have continued the well-tried practice of reporting the scientific results of our co-operative investigations. This time we have selected the Co-operative Study of the Kuroshio and adjacent regions (CSK) as the central topic and invited scientists from the Member States that have actively participated in CSK to lecture on particular aspects of physical and chemical oceanography. I regret that we did not succeed in obtaining a fourth speaker, for the field of marine biology, but I am happy to announce that, in International Women's Year, we have the first lady to present a paper in the Anton Bruun Memorial Lectures. This is Dr. Mitsuko Ambe from Japan.

It gives me particular pleasure to announce that one of the initiators of CSK, who is also one of its most active sponsors, has come here to introduce this subject to the audience. I refer to Professor Ken Sugawara who, as a marine chemist of world-wide reputation, and as Vice-Chairman of our Commission for several terms of office, has rendered extraordinary service to international oceanography. It is in recognition of his great achievements that I ask him to open the Anton Bruun Memorial Lectures on CSK with an introductory speech.

(1) GARP Atlantic Tropical Experiment.
(2) First GARP Global Experiment.

The co-operative study of the Kuroshio and adjacent regions (CSK)

Professor Ken Sugawara

Ladies and gentlemen: this introduction to the Anton Bruun Memorial Lectures on CSK will be devoted to three topics, namely: the outcome of CSK; its accomplishments; and its future prospects.

1. Outcome of CSK

Thirteen years ago the idea of a co-operative investigation in the Kuroshio was first presented by Dr. Kazuhiko Terada of Japan who is attending the present IOC Assembly, on the occasion of the Regional Meeting of Marine Science Institutions in East and South-East Asia in Manila, March 1962. Discussion there reached agreement on the need for a "Co-operative Investigation of the Kuroshio including studies of the South China Sea and exchange through the Luzon Strait"; this was transferred to IOC for its consideration. After the preparatory meeting of experts of the Kuroshio region, co-sponsored by Japan in Tokyo, October 1963, the Commission adopted the "Co-operative Study of the Kuroshio and adjacent regions" as an official project at its third session in 1964.

In February 1965 the first session of the International Co-ordination Group for CSK was held in Manila to discuss the fundamental objectives and programmes, with the participation of representatives from Hong Kong, Japan, Republic of Korea, Philippines, Taiwan, USSR, United States and Socialist Republic of Viet Nam. Dr. K. Wadati of Japan and Mr. J. C. Marr of the United States were nominated as International Co-ordinator and Assistant International Co-ordinator respectively. Since then, the International Co-ordination Group has met ten ~~times~~s to examine CSK activities and to orient its future work. During the past ten years, some countries have withdrawn and others have joined. Thus the present composition of member countries is: France, Indonesia, Japan, Republic of Korea, Philippines, Singapore, Thailand, USSR, United Kingdom (Hong Kong) and the Socialist Republic of Viet Nam.

The Assistant International Co-ordinator for Fisheries, Mr. J. C. Marr, was later replaced by Dr. I. A. Ronquillo of the Philippines.

2. Activities and accomplishments of CSK

I venture to say that the activities of CSK in the past ten years have contributed much to the increase of knowledge of oceanography and fisheries in the regions concerned. At the same time, CSK focused the attention of participating countries on oceanography and assisted them in laying down a scientific basis for oceanic research. For this we must extend our gratitude to other international organizations such as FAO and its IPFC(1) and SEAFDEC(2) which have co-operated with our project.

I will now give a brief account of some concrete aspects of CSK activity.

The results of CSK have been published by participating organizations and individual scientists, in professional journals and by other means.

The three CSK symposia held in Hawaii (1968), Tokyo (1970) and Bangkok (1973), were another way of publicizing and discussing the results of the research. Proceedings of the three symposia have been published under the titles "Kuroshio 1, 2 and 3". The Oceanographic Data Centre of Japan, designated as the "Kuroshio Data Centre" has received data from 16,727 oceanographic stations from 435 cruises. The data have been computed, processed and published as "Data Reports of CSK"; up to now 328 volumes have been issued. The Centre is also compiling the "CSK Atlases"; to date, 6 volumes have been completed. The "CSK Newsletter" from the same Centre has been distributing miscellaneous information on CSK activities, and has reached issue No. 47.

For preserving and sorting CSK biological, and particularly zooplankton, samples, a Regional Biological Centre was established in Singapore University in 1968. Samples collected from 1965 to March 1967 were sorted by Dr. Isamu Yamaji of the National Science Museum, Ueno, Tokyo and the results were published as the "Data Report and Distribution Maps of the CSK Standard Zooplankton Samples", in 1971.

"Kuroshio - Its Physical Aspects" was published by Dr. H. Stommel and Dr. K. Yoshida in 1972 through the University of Tokyo Press and the University of Washington Press. The book embodies the results and summarizes the author's examination of observations conducted over the

(1) Indo-Pacific Fisheries Council.
(2) South-East Asia Fisheries Development Centre.

past 50 years on the Kuroshio, and ideas involved in them.

The preparation and distribution of CSK standards for marine nutrient analysis may also be counted as a contribution of CSK.

3. Prospects for the future development of CSK

As a consequence of the great progress of the world ocean study, there is a strongly felt need to work out a new pattern of approach to the study. In fact, the Long-term and Expanded Programme of Ocean Exploration and Research and the International Decade of Ocean Exploration can be said to crystallize the response of our IOC colleagues to this urgent need. On the other hand, the ocean cannot escape from the threat of global environmental pollution, and marine pollution has become an important additional item of our research. Naturally the future activity of CSK must be planned and developed so as to take accout of these circumstances. Thus, at the tenth session of its International Co-ordination Group held in Tokyo last March, CSK concluded that a new structure was needed for the Western Pacific, aiming at: (i) promoting the oceanic research of Member States on a national and international basis; and (ii) promoting training, education and mutual assistance, by entrusting the definition of future scientific projects in the area and specification of existing needs in the field of training, education and mutual assistance to a new body, as reported in recommendations CSK-X.1 and X.4 (document IOC/CSK-X/3, Paris, 26 May 1975).

Professor Roll

On behalf of the audience, I wish to thank you, Professor Sugawara, for introducing us to the subject of CSK. You have given us a comprehensive account of the history, activities, achievements and even the future development of CSK. We thank you again and wish you, Professor Sugawara, a long and active life for the benefit of CSK, which will certainly grow and prosper as an instrument of sound research carried out in the Western Pacific.

Our next speaker will be Dr. Mitsuko Ambe. Dr. Ambe is a lady who obtained her doctor's degree with a study on the geochemistry of deuterium abundance in Antarctic water masses. As you will realize from this, she is a marine chemist. She joined Professor Sugawara in the Sagami Chemical Research Centre, close to Tokyo, and took part in Professor Sugawara's studies on CSK standard solutions for the determination of nutrients in sea-water. She is now engaged in the preparation of standard solutions for heavy metals in sea-water. Her paper will be on the accuracy of the determination of nutrient elements in sea-water by using CSK standard solutions.

Accuracy of the determination of nutrient elements in sea water by using CSK standard solutions

Dr. Mitsuko Ambe

Sagami Chemical Research Centre,
Japan

Ladies and gentlemen: I am honoured by your invitation to speak on this occasion and I wish to express my appreciation to Professor Roll for his suggestion that I should take up the subject of our CSK standard solutions for nutrient elements.

I will speak on three topics: (1) CSK standards themselves; (2) examination of the results of the International Intercalibration Experiment carried out during 1969-1970; and (3) examination of data from the direct application of the standards to actual measurements in the ocean.

1. CSK standards for marine nutrient analysis

When the "Co-operative Study of the Kuroshio and Adjacent Regions" was initiated, it was recommended at its first International Co-ordination Group session in Manila, February 1965, that Japan prepare and distribute standards for phosphate-P, silicate-Si, nitrite-N, nitrate-N, KIO_3 solutions for dissolved oxygen etc., among the participants, in order to permit intercalibration of the various methods of chemical analysis used and to ensure the compatibility of the resulting data.

Responding to this recommendation, the Sagami Chemical Research Centre started to check widely-used methods of analysis of these elements and to prepare a series of standard solutions satisfying the conditions: (i) they must be of the highest accuracy attainable in today's state of technical advancement; (ii) the concentrations should cover the whole range of concentration of several elements in sea-water and it should be possible to use them without dilution to draw a standard curve; and (iii) at least one year stability after preparation must be ensured.

Thus in addition to the KIO_3 standard solution for dissolved oxygen, series of standards for PO_4-P, SiO_2-Si, NO_2-N and NO_3-N were prepared, as listed in Table 1 (page 12).

Details of the background studies of existing methods of analysis, the established procedures for the preparation of the standards and the accuracy of the prepared standards, are given in references 1 and 2.

I am happy to report that we are receiving orders for thousands of bottles yearly from various countries such as the United States, Canada and Germany (Federal Republic of) reflecting the evaluation of the standards and their usefulness to concerned experts.

2. Examination of the results of the ICES-SCOR International Intercalibration Experiment of Nutrient Analytical Methods (1969-1970)

Recognizing the need for exactness and reliability, SCOR Working Group 25 on Nutrient Chemistry recommended an international intercalibration experiment as an ICES-SCOR programme by using sets of unknown synthetic solutions which could be offered by the Sagami Chemical Research Centre, instead of natural sea-water samples. The recommendation was implemented as the ICES-SCOR International Intercalibration Experiment, 1969-1970, by the participation of 56 world institutions and constituted the first example of international intercalibration by using common synthetic solutions.

The programme consisted of two parts: Part I - Test of single solutions; and Part II - Test of P-Si binary mixtures.

The Sagami Chemical Research Centre was responsible for preparing test solutions and distributing them. For Part I, four series of samples of PO_4-P, SiO_2-Si, NO_2-N and NO_3-N were prepared, each consisting of 4 bottles with O, low, medium and high content of several elements.

The participants in the programme who received the test samples were told only the approximate concentration ranges and were requested to analyse the samples by any method they thought appropriate, using their own standards.

In the progress report, September 1970, Dr. F. Koroleff (Helsinki) calculated the deviations, expressed in μg-at/l, of the data for the single solutions given by 36 laboratories from the correct values of concentrations which were known only to him and to Dr. K. Sugawara. Dr. Koroleff added a remark that "In my opinion the results are reasonably good, however this intercalibration trial has its greatest value in that I most certainly am able to examine the analytical techniques and can forward my conclusions to the participants".

At that time when I started work on the CSK standards, I felt it important to touch on this Intercalibration Programme and I wanted to reach an understanding with Dr. Koroleff, to use his calculated data and to discuss further the line which he indicated in his above remark.

My approach was further to examine the deviation data from the angle of the analytical methods employed by different laboratories.

Thus in the case of Si, the methods employed are categorized into two, namely the molybdenum yellow method and molybdenum blue method. The deviation range of the data from the correct values, deviation average, standard deviation and coefficient of variance in % (CV%) are listed in Table 2 (page 12).

Fairly uniform values of CV % were obtained, ranging from 3.3 to 5.8 for different methods and concentrations.

In the case of NO_2-N, for which only the Bendschneider-Robinson method was used, a small CV % was obtained as with Si, with the exception of a rather high value of 9.0 for low NO_2-N.

In the case of NO_3-N, the procedure of the determination is divided into two parts. The final determination of NO_2-N by the Bendschneider-Robinson method is preceded by a reduction process of NO_3-N to nitrite by using Cd-Cu, Cd-Hg or hydrazine. With the exception of the case for medium NO_3-N where Cd-Cu was used for reduction and cases for high NO_3-N using Cd-Cu or Cd-Hg for reduction, high values of CV % were obtained, in the range of 11.4-29.6 (see Table 3, page 13).

In the case of P, three different methods were used, two ascorbic acid methods (MRM and MRC) and a stannous chloride method. As compared with the rather low value CV % with high and medium P for which MRC or the stannous chloride method was used, the values of other CV % were found to be rather high (see Table 4, page 13).

In completing the present analysis, it is appropriate to examine these variances in the light of the values of CV % of the distributed test solutions which were provided by the Sagami Chemical Research Centre.

In Table 5, the CV % of the ICES-SCOR Experiment is compared with those of corresponding test samples given by the Sagami Chemical Research Centre, as well as the methods employed. It is evident that the CV % obtained by the International Intercalibration Experiment are 3.4 to 22 times larger than the corresponding values provided by the Sagami Chemical Research Centre. These large values of the ICES-SCOR Experiment were possibly caused by differences in the methods employed, perhaps the way in which they were applied, including insufficient care for handling the processes and differences in the standards referred to (see Table 5, page 14).

In conclusion, I venture to say that it is certain that the observed CV % could be greatly reduced if our expert colleagues were to pay attention to the points I have mentioned above. Further, I believe that if a similar experiment were to be repeated now, a better result would be obtained, because of the efforts which have been made by those experts over the past few years.

3. Examination of data from the direct application of the standards to the actual measurements in the Pacific by the Hakuho-Maru, Ocean Research Institute, University of Tokyo

Turning to the accuracy of the determination of nutrient elements at sea, I will refer to the result of the Hakuho-Maru duplicate analysis experiment at stations 11 and 19 of cruise KH-71-3, primarily planned to check the reliability of data obtained through the methods and procedures the ship had been using in reference to CSK standards.

One hundred and eighty samples were collected at each station, at 45 different levels from the surface down to 5,000 m deep, on two occasions with an interval of five days. Each sample was then divided into two aliquots to be subjected to the analysis of SiO_2-Si, NO_3-N and PO_4-P. The difference between the results from each aliquot pair was taken to indicate the error from the method, procedure and instruments used.

The 360 values thus obtained were used to calculate their CV % for SiO_2-Si, NO_3-N and PO_4-P by using:

$$CV\ \% = \frac{\sqrt{\frac{1}{2n} \quad \Sigma (D_1 - D_2)^2}}{\frac{1}{n} \quad \Sigma (D_1 + D_2)} \times 100$$

where D_1 and D_2 are the results for each aliquot pair, and n is the total amount of data used.

Thus CV % of 1.1, 1.3 and 4.4 were obtained respectively for Si (ranging from 1.5 to 159 with the average 100μg-at/l) for P (ranging from 0.08 to 3.35 with an average 2.16μg-at/l), and for NO_3-N (ranging from 1.0 to 45.0 with an average 27.9μg-at/l), in contrast to CV % of 1.0, 1.3 and 0.4 respectively for our standards: SiO_2-Si 100 μg-at/l, PO_4-P 1.0μ g-at/l and NO_3-N 30μ g-at/l.

A similar experiment conducted by a team from our Centre aboard R.V. Bosei Maru of Tokai University gave CV % 4.6 for SiO_2-Si with an average 24μ g-at/l and 5.6 for PO_4-P with an average 1.0μg-at/l (see Table 6, page 14).

Turning to the vertical distribution data of nutrient elements in rather deep layers obtained by three Hakuho-Maru cruises KH-68-4, KH-70-2 and KH-71-5 in the Pacific, giving particular attention to the data at two stations, here named A and B, located at about 17°N, 145°W and 30°N, 146°W respectively, where observations were repeated two to three times during a one- to three-year period (see Figure 1), Figures 2-4 show that three fundamental oceanic parameters - temperature, salinity and dissolved oxygen - remained unchanged, particularly at levels from 2,000 m downward where their distribution curves for each parameter practically coincide.

The situation, however, is somewhat different for nutrient elements. The distribution curves are given in Figures 5-7 in which the individual values are plotted as a circle, point or cross, with a bar showing the possible range of analytical error as determined by the duplicate analysis experiment referred to above.

As for NO_3-N, the distribution curves in Figure 5 are in fairly good coincidence at Stations A and B. This chemical component is concluded to have remained unchanged during the period of observation, as have the three fundamental oceanic parameters above. SiO_2-Si distribution curves in Figure 6 are in good coincidence at Station A, while at Station B some differences are seen among three observations in the three-year period. The difference between the PO_4-P distribution curves is however more marked, as shown in Figure 7. Let us look at these discrepancies and try to examine the possible factors determining them.

At Station B, among three distribution curves, two of them - for KH-70-2 and KH-71-5 - practically coincide where the data are reported to have been obtained by the ascorbic acid method using a Hitachi spectrophotometer, while for cruise KH-68-4, on which measurements were made by the stannous chloride method using a filter photometer, the curve obtained runs in a zigzag and away from the other two curves. We are tempted to take the view that the PO_4-P concentrations remained unchanged during the period of three years, and the run-away of the KH-68-4 curve is to be ascribed to some defect inherent in the method or instrument employed, or in handling.

On the other hand it is not easy to explain the distinct discrepancy as observed between the two distribution curves at Station A.

All the PO_4-P data are reported as obtained by the same analytical method and instrument, the ascorbic acid method and Hitachi spectrophotometer. The only difference is that during cruise KH-70-2, measurement was made in reference to standard absorption curves newly constructed at intervals during the cruise using CSK standards, while during cruise KH-71-5 it was made in reference to the standard curve which was constructed at the shore station before the ship left port and checked at intervals at sea by using solutions prepared by diluting a stock standard solution which the analyst prepared himself.

Considering such a situation with the measurement process, the discrepancy between the two curves appears to reflect an actual decrease in PO_4-P concentration on the spot. The questions are: Can such a decrease occur in situ through the transformation of phosphate into another form of the element? Could any chemical or biochemical reaction be imagined at such a low temperature and in darkness, as met with on the spot? Or was the decrease caused by replacement of the preexistent water with water containing less PO_4-P? If so, we must imagine some source which supplied the water with a low rate of flow on the spot within a short period of one year. We have no likely answer to these questions.

Now let us approach the problem from two other angles:

1. When the values of PO_4-P obtained on cruises KH-70-2 and KH-71-5 are plotted on the same diagram as given in Figure 7, all the values at Stations Nos. 16-10 of KH-70-2 and Nos. 3-6 of KH-71-5, covering a stretch of more than 4,000 km from the north (43°N to the south, 5°N, along 146°W), fall in the concentration range bordered by the two distribution curves at Station 9 of KH-70-2 and at Station 2 of KH-71-5. This means that the PO_4-P values represented by these two curves are the highest and lowest among values distributed over a north-south stretch exceeding 4,000 km. As a result we are compelled to doubt the reliability of these lowest and highest series of values.

2. Another approach is the calculation of the abundance ratios SiO_2-Si/PO_4-P, NO_3-N/PO_4-P and SiO_2-Si/NO_3-N. Table 7 gives averages of atomic ratios Si/P, N/P and Si/N for values ranging from 2,400 m depth downward at four successive stations starting from Station A each for KH-70-2 and KH-71-5. The ratio Si/P, 54 at Station 9 of KH-70-2 (Station A) is considerably lower than the values at other stations ranging 56-58 and especially the value 58 at Station 2 of KH-71-5, the same Station A. Is it reasonable to assume that the PO_4-P values at Station 9 of KH-70-2 were too high, thus accounting for the low Si/P? Another question is: What could be the cause of the higher values? As stated above, the two sets of measurements during the two Hakuho-Maru cruises are believed to have been carefully conducted by experienced analysts, using the same method, the same instrument and the same CSK standard solutions. Thus we cannot identify any possible accidental failure during the whole procedure of analytical processes.

I must leave the final solution of the problem to future studies and approaches. But I believe that my primary aim has been partly achieved; namely that of bringing out the difficulty and complexity of acquiring correct and exact data of nutrients in actual sea-water by mentioning examples of those data which are believed to have been obtained by experienced analysts according to a procedure using proper methods, instruments and reliable standards, and further the difficulty and complexity of understanding the true and exact meanings which the obtained data imply.

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Table 1. CSK standard solutions

Components	Concentrations
PO_4-P	0.0, 0.5, 1.0, 2.0 & 3.0 μg-at/l
SiO_2-Si	0.0, 5.0, 10, 25, 50, 100, 150 & 200 μg-at/l
NO_2-N	0.0, 0.25, 0.5, 1.0 & 2.0 μg-at/l
NO_3-N	0.0, 5.0, 10, 15, 20, 30, 40 & 50 μg-at/l
KIO_3	0.0100 N

Table 2. Variance of the data from the ICES-SCOR International Intercalibration Experiment (1)

Element	Method	Number	Deviation			CV %
			Range (μg-at/l)	Av.	St. Dev.	
Si-low	Blue*	26	+ 0.4 — - 0.5	+0.02	0.21	4.2
	Yellow**	6	+ 0.2 — - 0.3	-0.12	0.29	5.8
	All methods	32	+ 0.4 — - 0.5	-0.005	0.22	4.4
Si-medium	Blue	28	+ 5.0 — - 5.2	+0.45	2.23	4.5
	Yellow	6	+ 1.4 — - 3.0	-0.77	1.64	3.3
	All methods	34	+ 5.0 — - 5.2	+0.23	2.06	4.1
Si-high	Blue	26	+14 — -11	-1.0	6.25	4.2
	Yellow	6	+ 9.0 — - 2.8	+1.2	4.94	3.3
	All methods	32	+14 — -11	-0.53	5.83	3.9

* Molybdenum blue method.
** Molybdenum yellow method.

Table 3. Variance of the data from the ICES-SCOR International Intercalibration Experiment (2)

Element	Method	Number	Deviation Range (µg-at/1)	Av.	St. Dev.	CV %
NO_2-low	B & R*	32	+0.03 – -0.05	+0.001	0.018	9.0
-medium		34	+0.1 – -0.1	+0.008	0.048	4.8
-high		34	+0.2 – -0.2	-0.0007	0.082	4.1
NO_3-low	Cd-Cu**	17	+0.22 – -0.2	+0.009	0.103	20.6
	Cd-Hg**	8	+0.2 – -0.19	+0.03	0.15	29.6
	Hydrazine**	5	+0.11 – 0	+0.03	0.057	11.4
	All methods	30	+0.22 – -0.2	+0.025	0.120	24.0
NO_3-medium	Cd-Cu	16	+0.4 – -1.2	-0.16	0.57	5.7
	Cd-Hg	8	+1.8 – -2.0	-0.03	1.22	12.2
	Hydrazine	5	+1.7 – +0.7	+1.26	1.5	15.0
	All methods	29	+1.8 – -2.0	+0.052	0.920	9.2
NO_3-high	Cd-Cu	15	+0.6 – -4.0	-0.69	1.73	5.8
	Cd-Hg	7	+1.9 – -2.0	-0.25	1.22	4.1
	Hydrazine	5	+6.4 – -0.4	+3.14	4.65	15.5
	All methods	27	+6.4 – -4.0	-0.058	2.21	7.4

* Bendschneider and Robinson method.
** Reduction methods of nitrate to nitrite.

Table 4. Variance of the data from the ICES-SCOR International Intercalibration Experiment (3)

Element	Method	Number	Deviation Range (µg-at/1)	Av.	St. Dev.	CV %
P-low	MRM*	22	+0.06 – -0.03	-0.0045	0.025	10.0
	MRC**	6	+0.01 – -0.05	-0.02	0.029	11.6
	$SnCl_2$	4	+0.05 – -0.02	+0.0018	0.035	14.0
	All methods	32	+0.06 – -0.05	-0.005	0.034	13.6
P-medium	MRM	22	+0.15 – -0.11	-0.031	0.112	11.2
	MRC	7	+0.025 – -0.1	-0.04	0.057	5.7
	$SnCl_2$	4	+0.08 – -0.05	-0.013	0.056	5.6
	All methods	33	+0.15 – -0.11	-0.025	0.090	9.0
P-high	MRM	23	+0.14 – -0.22	-0.03	0.138	4.6
	MRC	7	0 – -0.18	-0.07	0.103	3.4
	$SnCl_2$	4	+0.07 – -0.2	-0.025	0.123	4.1
	All methods	34	+0.14 – -0.22	-0.035	0.120	4.0

* Murphy and Riley mixed reagent method.
** Murphy and Riley method with ascorbic acid added separately.

Table 5. CV % between the ICES-SCOR Intercalibration Experiment and CSK standards

	ICES-SCOR Experiment		CSK Standards		
	Conc.	St. Dev.	Conc.	St. Dev.	Method
P	Low	13.6	0.25	5.1	Murphy-Riley (MRC)
	Medium	9.0	1.0	1.3	
	High	4.0	3.0	0.4	
Si	Low	4.4	5.0	1.2	Blue
	Medium	4.1	50	1.2	
	High	3.9	150	1.0	Yellow
NO_2	Low	9.0	0.25	2.4	B & R
	Medium	4.8	1.0	0.4	
	High	4.1	2.0	0.4	
NO_3	Low	24.0	0.5	1.6	Cd-Cu
	Medium	9.2	10	0.8	
	High	7.4	30	0.4	

Table 6. CV % of the values obtained by determination of sea-water

	KH-71-3 Sea-water			Sagami Chem. Res. Ctr.			
				Std. Soln.		Sea-water	
	Conc. (μ g-at/l) Range	Aver.	CV %	Conc.	CV %	Conc. Aver.	CV %
SiO_2-Si	1.5-159	100	1.1	100	1.0	24	46
PO_4-P	0.08-3.35	2.16	1.3	1.0	1.3	1.0	5.6
NO_3-N	1.0-45.0	27.9	4.4	30	0.4	12.2	10.4

Table 7. Si, P, NO_3 ratio 2,400 m deep downward - cruises KH-70-2 and 71-5

	St.	Si/P	NO_3/P	Si/NO_3
KH-70-2	12	58	13.3	4.4
	11	59	13.2	4.4
	10	56	12.8	4.2
	9*	54	12.3	4.3
KH-71-5	2*	58	12.9	4.4
	3	58	13.1	4.2
	4	57	13.6	4.1
	5	58	13.8	4.1

* St. A.

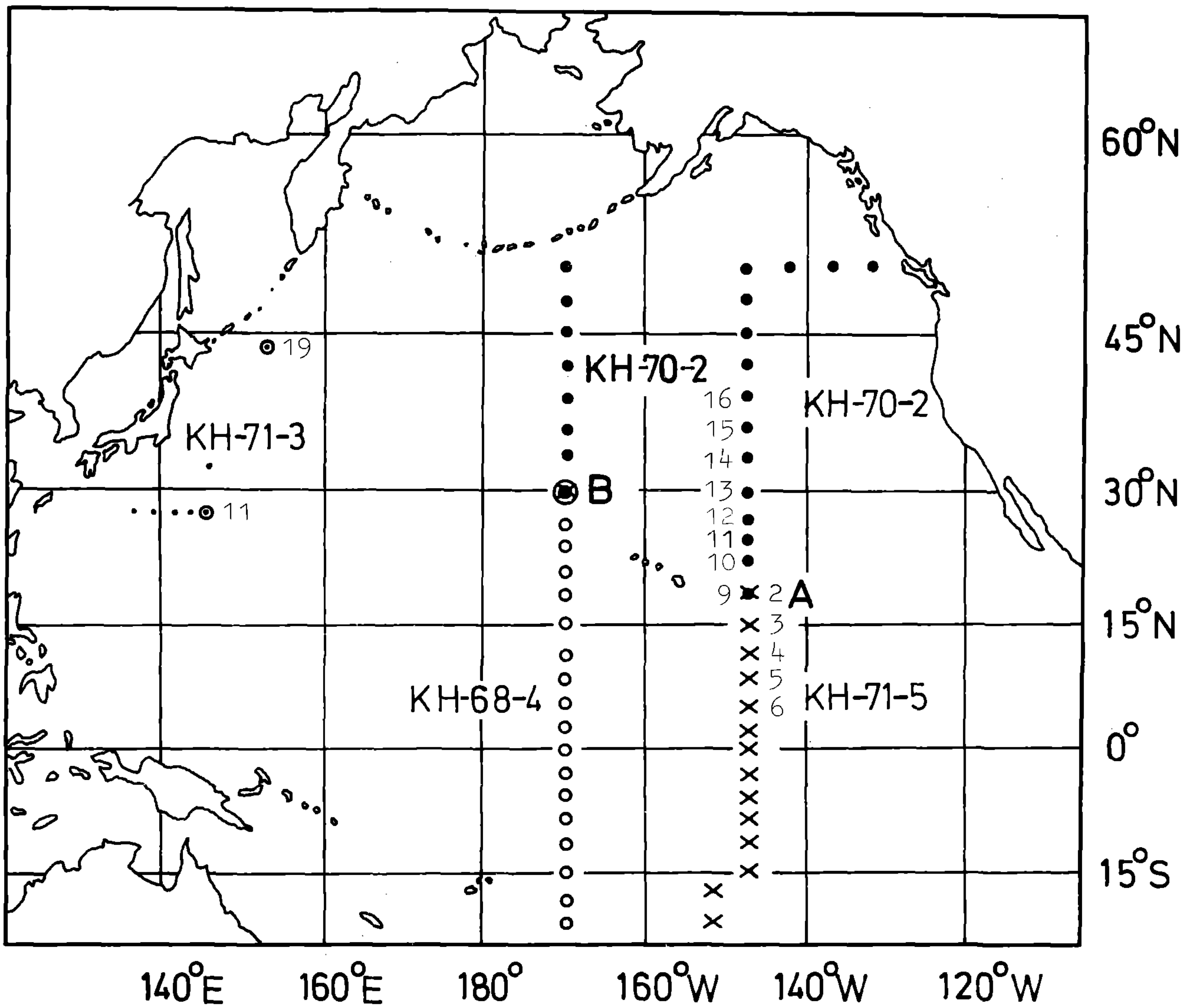

Fig. 1.   Sampling Stations of the Hakuho Maru

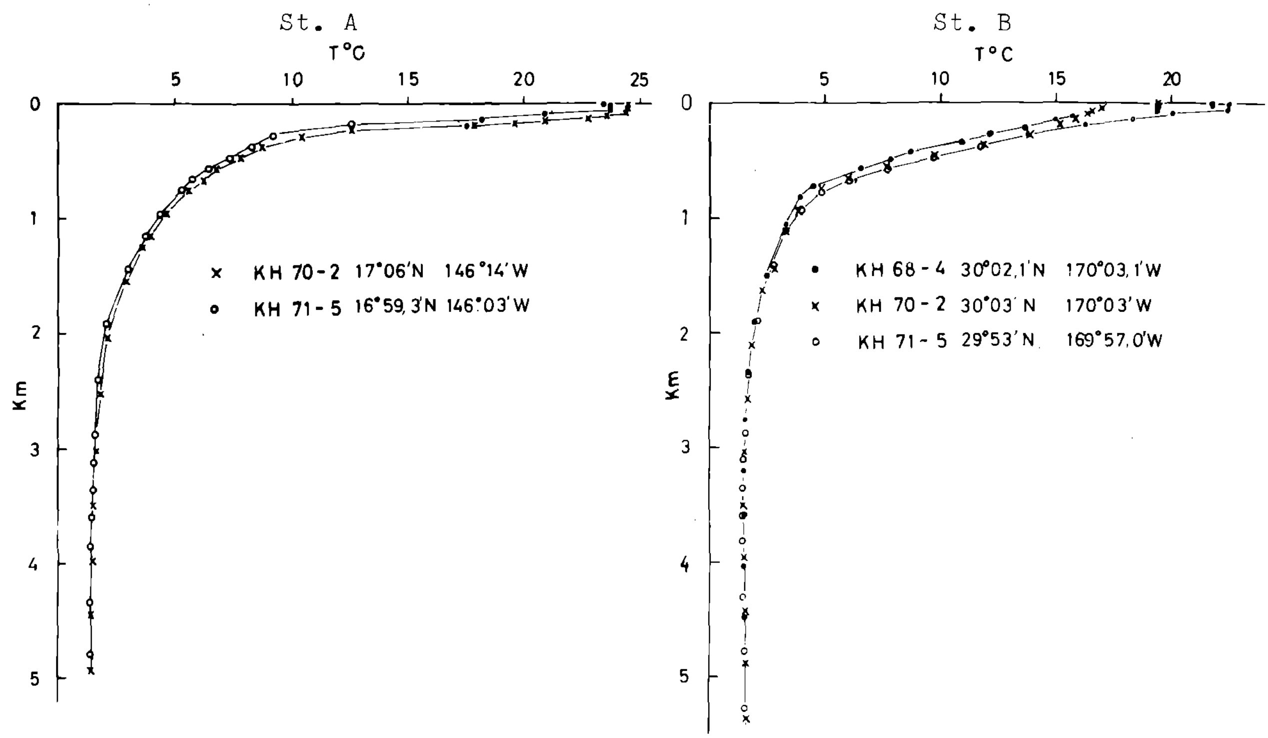

Fig.2. Vertical distribution of temperature at Stations A and B

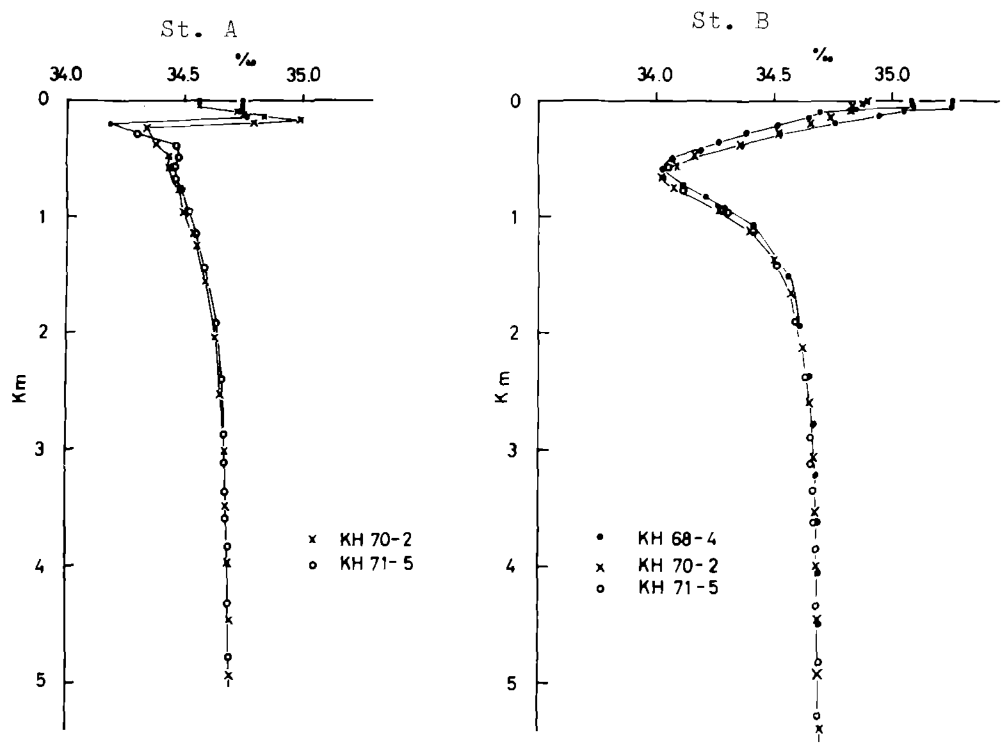

Fig.3. Vertical distribution of salinity at Stations A and B

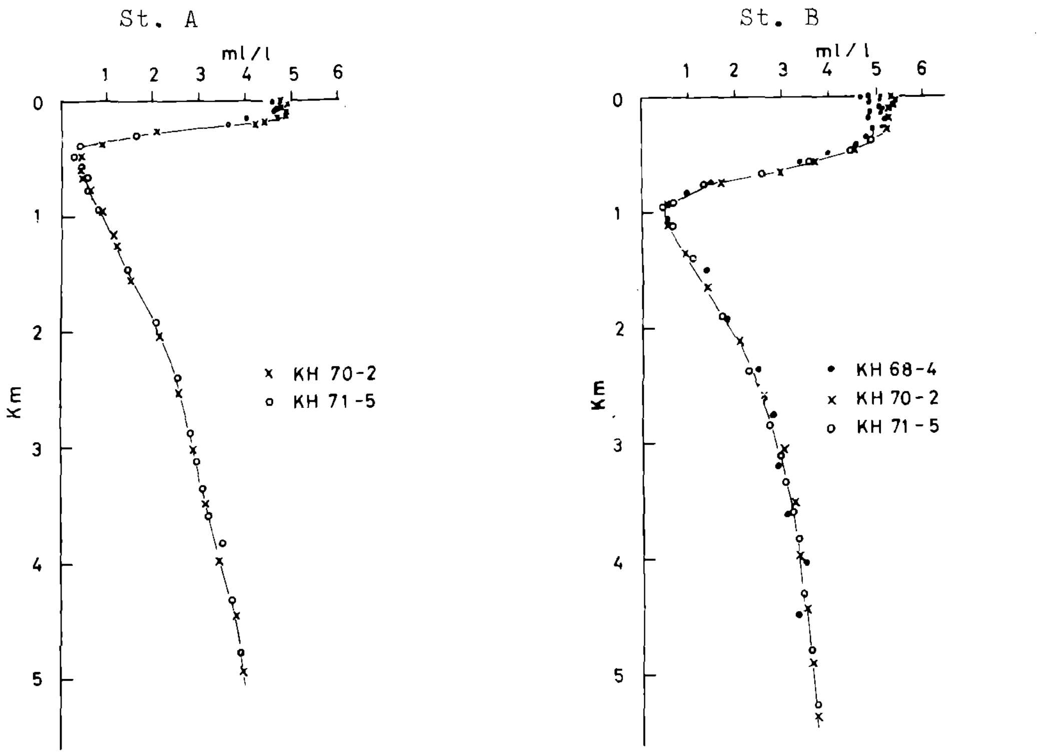

Fig.4. Vertical distribution of dissolved oxygen at Stations A and B

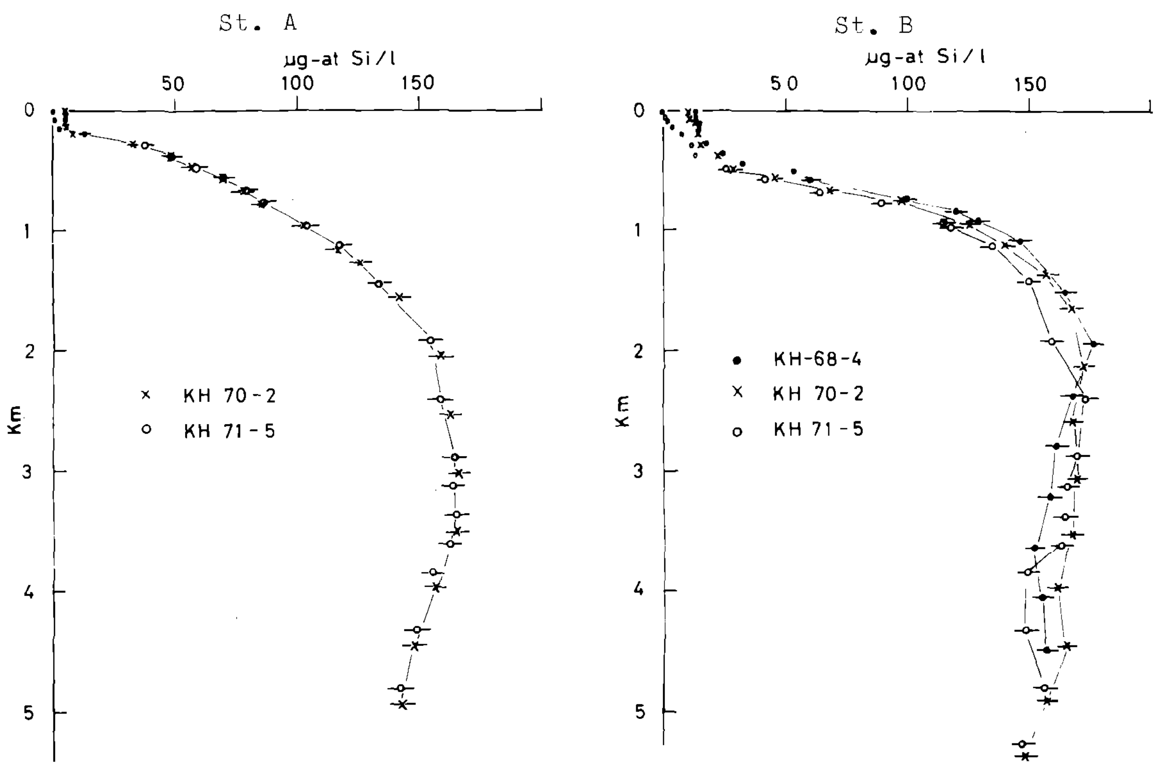

Fig.5. Vertical distribution of SiO_2-Si at Stations A and B.

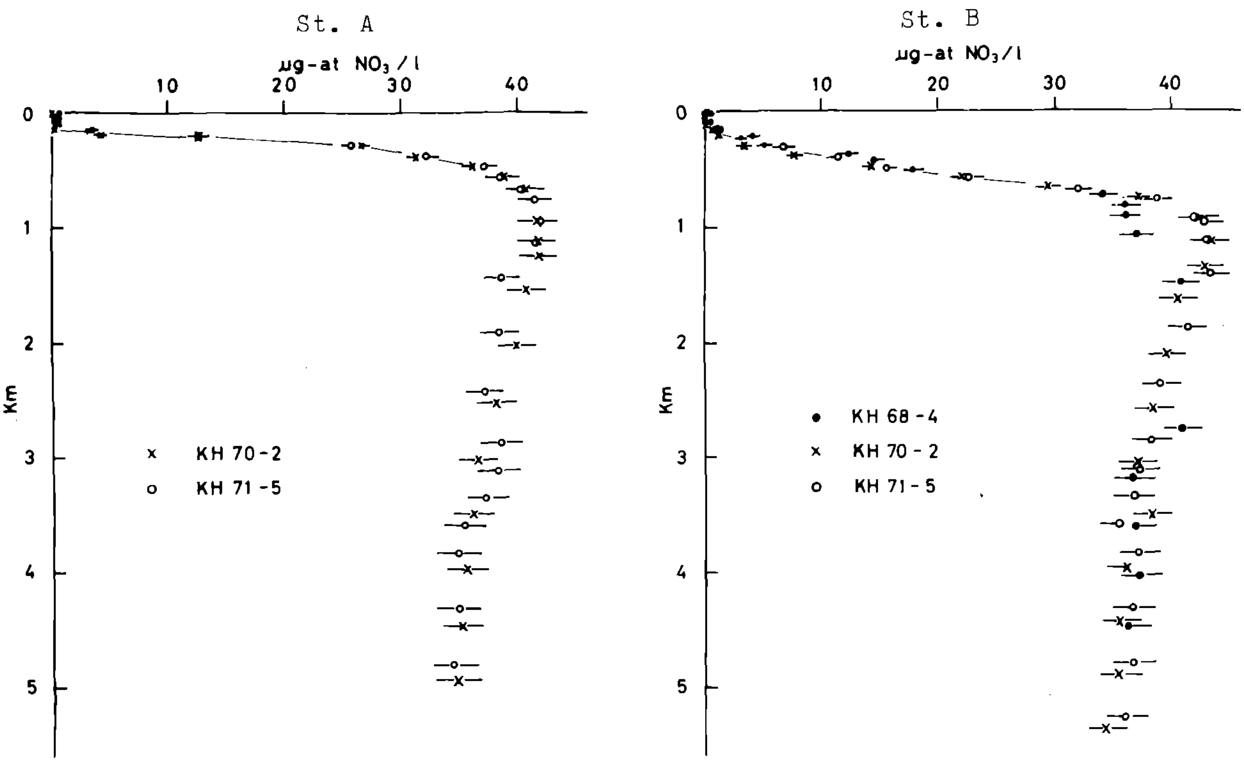

Fig.6. Vertical distribution of NO_3-N at Stations A and B.

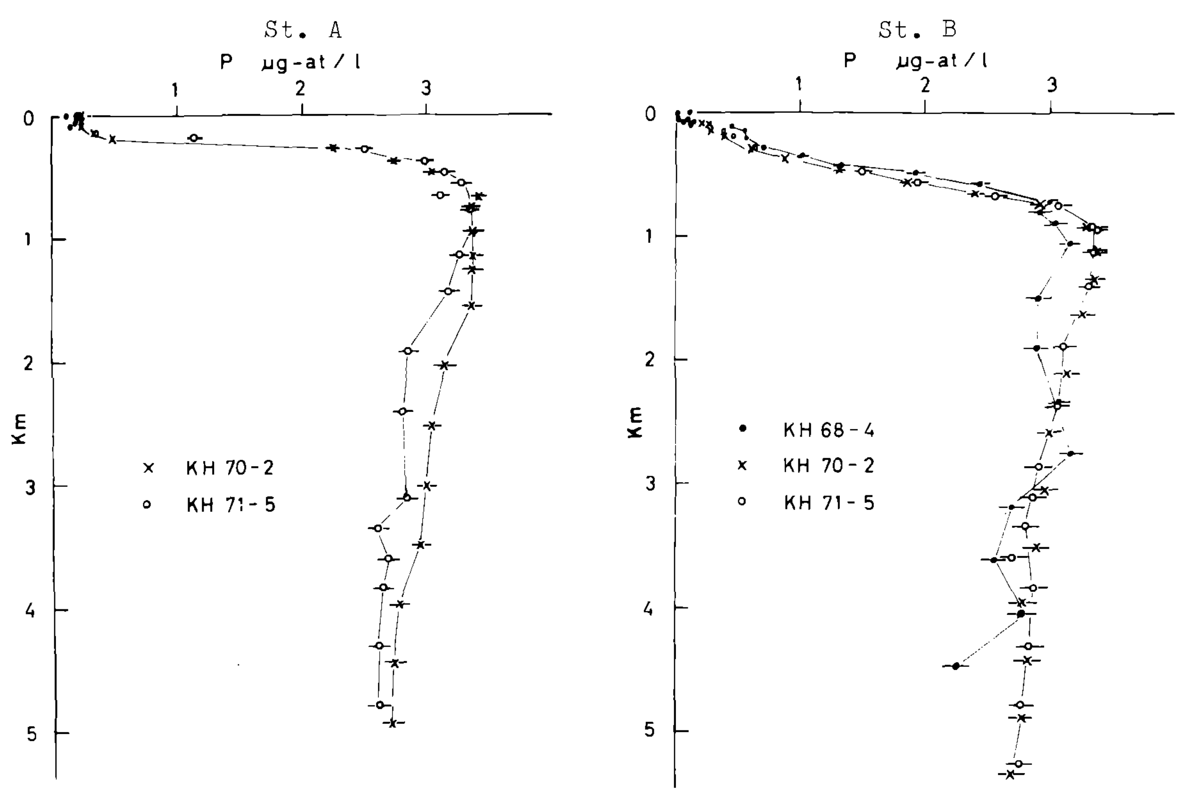

Fig.7. Vertical distribution of PO_4-P at Stations A and B.

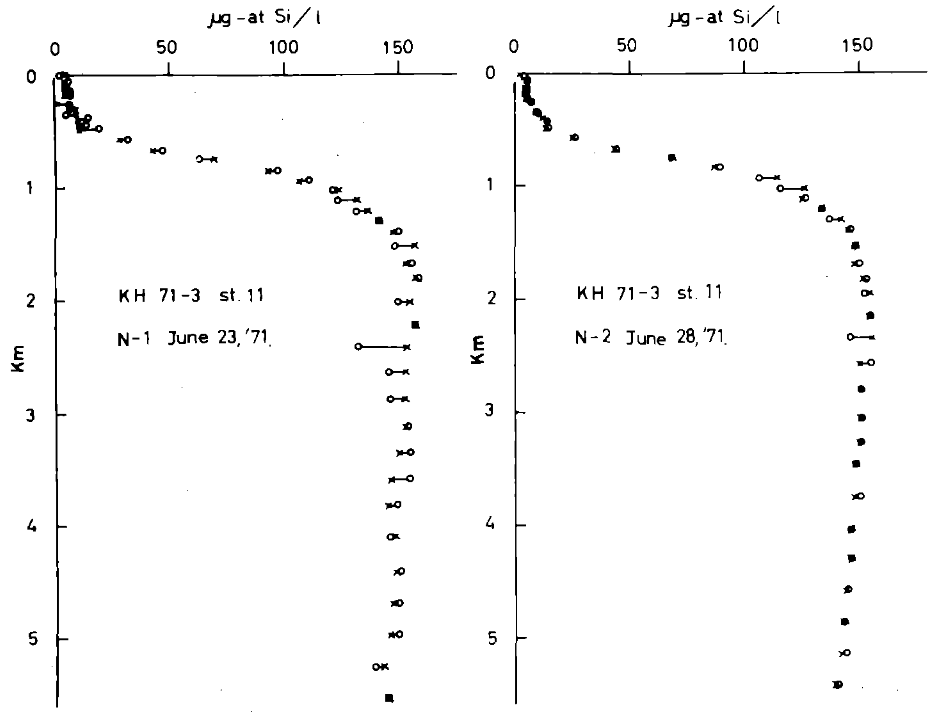

Fig.8. Duplicate determination of SiO_2-Si with an interval of 5 days at the same station.

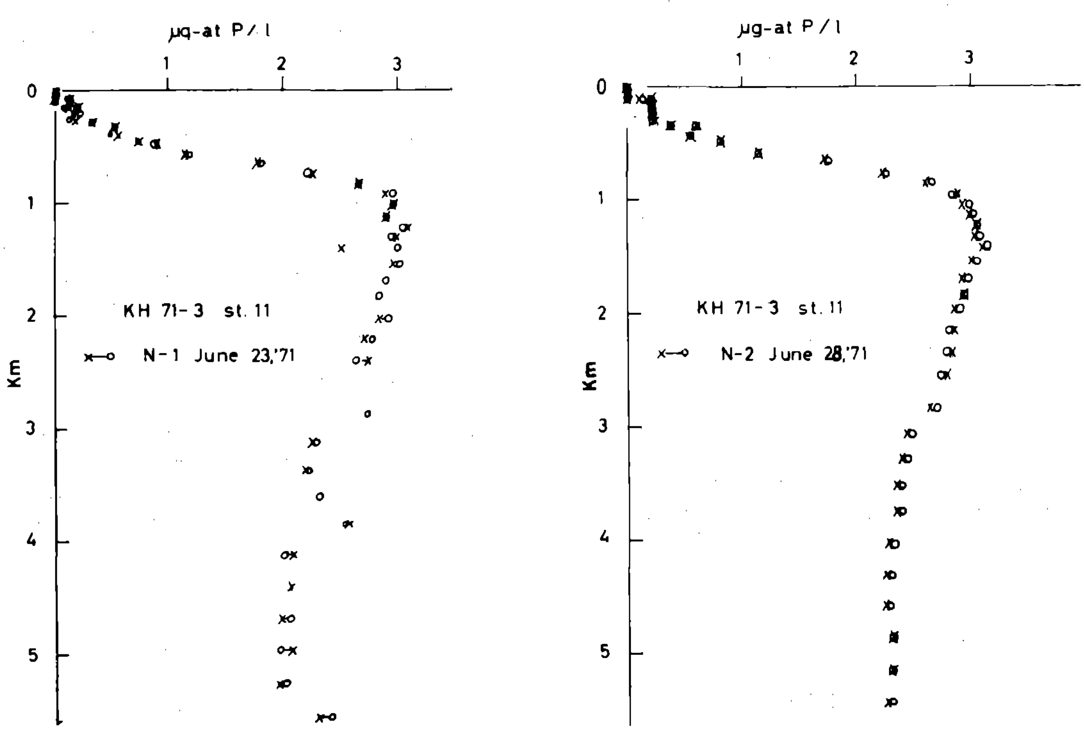

Fig.9. Duplicate determination of PO_4-P with an interval of 5 days at the same station.

DISCUSSION[1]

PROFESSOR ROLL

Thank you Dr. Ambe for your lecture. You have given us an insight into the laboratory of a marine chemist and it is clear that a new dimension in accuracy has been achieved through your work on the determination of nutrients in sea-water. Now, as we know, you have started similar work on heavy metals and this of course is of very great interest at a time when we are looking for exact determination of marine pollution. Thank you very much for coming here, for speaking to us, and in particular, I must praise your perfect pronunciation of the English language.

DR. QASIM

I am very happy to learn about the CSK standard solutions. I would like to know what, apart from accuracy, are the advantages of this method over the more conventional methods, in particular in relation to auto-analysis.

DR. AMBE

Dr. Sugawara, please.

DR. SUGAWARA

I would like to say something about our experiments with the auto-analyser. It was generally thought that, in comparison with standard methods of analysis, the auto-analyser would produce less reliable results. However, recently, we conducted very careful tests with an auto-analyser which proved most successful. We found that the auto-analyser will achieve as high a standard of accuracy for a number of elements. I believe many experts in other parts of the world have had the same experience. However, in order to achieve these high standards, great care has to be taken in the handling of the instrument and in the methodology used.

PROFESSOR MACCHI

First, allow me to congratulate Mme Ambe for the work she has done. It provides us with a very important result as part of the universal attempt in modern chemistry to improve the precision and reliability of methods of analysis. This work may one day allow the judicious use of nutrients as an indicator of water masses in the problem of the study of circulation, chiefly I think, of the deep circulation.

DR. PALOMO

First of all I would like to congratulate Dr. Ambe for her excellent exposé and for the interesting results she has achieved.

I would like to ask Dr. Ambe, since I am a specialist in geology and therefore I understand very little of her statement, if this lack of some elements like phosphorus and some others to which she referred, indicates that they could have been transported to another place with the same mass of water or they could have been diluted, and consequently an answer to the problem could be found in the sediments.

Logically, it would be a statement in favour of this idea if the concentration of these problematic elements were to increase with depth at each station.

On the other hand, I would like to know what would be the value of extending this important research into the recent superficial layer of marine sediments.

PROFESSOR ROLL

May I ask you, Dr. Ambe, whether you have done some work on sediments or whether you intend to do any?

DR. AMBE

For each set of data given in Figures 2-9 of my paper, the datum at the deepest level was for samples collected from 10 m above the sea bottom. So, the data can be accepted as showing the concentration of the element in bottom water samples.

Turning to the question whether the apparent decrease in P might have been caused by precipitation, part of the P existed as particulates or a component of particulates, and tended to gradually move downwards through the stagnant water strata. However, I think that it is impossible to imagine that the velocity of sedimentation is large enough to remove particulates through a thickness of thousands of metres. On the other hand, the apparent total loss of P in question is calculated as 1,200 μg-at/cm^2, y. If this total is assumed to have been removed to be settled on the sea floor, the sedimentation amount is exceedingly large, nearly 4,000 times larger than the amount estimated in other ways in the Pacific, one example of which is 0.03 μg-at/cm^2, y given by Professor Miyake.[2]

PROFESSOR ROLL

Now I wish to thank Dr. Ambe again for coming here and giving us this talk and I am happy that there are at least a few marine chemists here in order to give her the recognition she has earned.

(1) Names and titles of speakers are found at the end of the publication.

(2) Y. Miyake and K. Saruhashi. Papers in Meteorology and Geophysics, 18, 89-94 (1967).

PROFESSOR ROLL

We now come to our second lecture given by Professor Allan Robinson from the United States. He will be lecturing on the dynamics of the Kuroshio current, in particular on theoretical and experimental studies from South of Kyushu to the Izu-ogasawara Ridge.

Professor Robinson is Gordon McKay Professor of Geophysical Fluid Dynamics at Harvard University and he has greatly contributed to our theoretical understanding of large-scale ocean circulation and, in the past few years, he has also penetrated into experimental oceanography. He included in his studies both thermohaline as well as wind-driven circulations. He developed a general theory of major ocean currents and included in these modelling studies, the equatorial under-current, as well as the Gulf Stream and also the Kuroshio, and he later developed critical experimental field work in those areas. I think he has given us a very important contribution to the on-going development from descriptive oceanography into a field where the tools provided by mathematical and physical sciences are applied to ocean circulation. A few days ago you saw a film on the MODE[(1)] experiment and you will not be surprised that one of the scientists who was seen in the film is now here in this room giving us his lecture. This is Professor Robinson who was a leading scientist of the MODE and POLYMODE experiments and I think we should be very happy that he could come here and give us an account of his work.

(1) Mid-Ocean Dynamics Experiment.

Dynamics of the Kuroshio current: experimental and theoretical studies from south of Kyushu to the Izu-Ogasawara ridge

Professor Allan R. Robinson

Harvard University

Ladies and gentlemen: It is a pleasure for me to be able to deliver an Anton Bruun Memorial Lecture, because it gives me an opportunity to share with you some of my ideas and some of the ideas of my scientific colleagues about the Kuroshio Current and about its role in the general ocean circulation. I hope that through my presentation I can tell you something about what we know about the Kuroshio, something about what we don't know about the Kuroshio, and something about how we go about thinking about scientific problems that we consider to be interesting.

The general circulation of the ocean consists of an interlocking system of many scales of motion. It includes regions of intense, swift currents and turbulent eddies, vast reaches of the open ocean through which on the average the water is drifting horizontally while masses of cold deep water slowly rise, as well as regions of violent overturning and downwelling. Different scales of motion represent different phenomena or physical processes. We must understand both how the basic processes work, and also how they fit together into the general circulation system. Thus, to understand the general circulation of the world ocean we must isolate and study the basic physical and dynamical processes which play critical roles. The ocean is a vastly complex and complicated physical system. Many scales of motion occur: time scales from seconds to decades and even longer, and space scales from millimetres up to the size of the earth itself.

Processes which occur on a certain scale in a particular region of the ocean represent special physical problems. However, when they are studied in isolation (either scale isolation or geographical isolation) the interconnections and feedback mechanisms with other scales and/or with other regions must be modelled in theoretical studies or measured when possible in experimental studies. For example, small- and medium-scale turbulent fluctuations of velocity occur in the ocean. Even though they themselves *vanish* on the average, they have a profound residual effect on the average circulation (the general circulation). This is because these fluctuations transport on the average important physical quantities (momentum, heat, and energy) from one place to another in the ocean. Another example is that the internal dynamics which occur in a certain geographical region may have profound effects of primary importance outside that region, and thereby influence the general circulation. This may occur by the requirement of fluxes of mass or heat across the boundary of the region or by the radiation of various types of waves into the external region, or by the expulsion (or throwing off) of turbulent eddies or large vortices into the surrounding water.

The Kuroshio is one of the world's strongest currents, and as such is a major element in the general circulation. I shall tell you today about some special studies of its dynamics in the region south of Japan, which include studies of "medium-scale" fluctuations of the current. These studies are of interest for several reasons. The special dynamical phenomena are interesting scientifically in their own right. Moreover, understanding those dynamics of the Kuroshio may shed light on similar or analagous dynamical processes that occur in other ocean currents, or in other flows in the ocean, or even in the atmosphere. Another reason is that the behaviour of the Kuroshio in this region may be of significance in a practical sense, by influencing fisheries and local climate (and thereby affecting agriculture). Finally, the local dynamics of the Kuroshio may indeed have an important feedback effect on the general circulation of the North Pacific. If so, there is an implied chain of possible extended influence on the circulation of the entire world ocean. Now, if this turns out to be the case, the influence of these medium-scale dynamical processes would have to be represented in large-scale general circulation models. There is growing evidence that this is the case (Holland and Lin, 1975). Hopefully, in the long run, there need not be an explicit representation of the exact medium-scale wiggles of the current, but rather some appropriate representation of their overall large-scale effect maybe devised. Adequate representation requires first of all a physical understanding of the local dynamics.

Although we do not as yet basically understand the dynamics of the general ocean circulation, we are at a stage of rapid scientific progress. This is brought about by new measurements and novel instrumentation, as well as by sophisticated hydrodynamical theories and large computer or numerical models. Understanding the dynamics of the circulation, which will result ultimately in the construction of a physically correct large-scale computer model ocean, will be useful in many ways. Numerical calculations can then be made of the rate of dispersal of particles that are moved about by currents. The circulation models can be coupled to geochemical models to estimate the global distribution of chemicals on various time scales, and to biological models for productivity studies. Perhaps the most important application will be the coupling together of an ocean model with an atmospheric model to study large-scale air-sea interaction and the dynamics of climate. Over long periods of time the enormous thermal and mechanical inertia of the ocean may be the mechanism that controls the coupled system and thus the evolution of climate.

We will look at the Kuroshio first with coarse resolution observational data, and then with finer resolution data. Correspondingly, we will model it with rough resolution and finer resolution, keeping in mind the idea of scales and interactions mentioned above. So I will first show you the Kuroshio current as it is revealed in classical oceanographic observations and then describe the classical ideas as to why it exists and illustrate its appearance in large-scale coarse resolution numerical models. Next, I will introduce some recent finer resolution data which will help further to refine and define the phenomenon, and to serve as a more critical test of models. Data for the region south of Japan exhibits the phenomenon of the large meander or loop in the current which may be present or may be absent for a period of several years. It has been speculated that this phenomenon has substantial practical significance, e.g., affecting local climate (Uda, 1964). Theories put forward to account for the specific location of the current and the existence or not of the meander will be presented and illustrated by the results of high resolution local numerical model experiments. I will then set the problem into the context of contemporary high resolution numerical models of the general circulation of the North Pacific subtropical gyre, and relate these models to larger scale models of interest for global climate dynamics.

The Kuroshio as an element of the world's general circulation is shown schematically on the map of Figure 1, which is based on the classical data base of ship drift observations over many years. The deep flow mirrors many of the features of the surface circulation. Looking with an "idealizing" eye, one can observe a degree of symmetry about the equator, and similar flows in the major ocean basins. For example, the North Pacific and the North Atlantic each have two major gyres (or large vortices) of circulation (a subtropical gyre between about ~ 15°N - 50°N and a subpolar gyre between ~50°N - 60°N). The Kuroshio and the Gulf Stream are the major currents of their respective subtropical gyres. Their importance can be characterized by the fact that, over depth, across their narrow width they transport to the north as much water as flows to the south across the rest of the ocean basin. The major subtropical gyres are much intensified to the west.

Classically, ocean currents have been difficult to measure directly and physical oceanographers have learned to detect their presence indirectly, e.g., by examination of the temperature distribution. Figure 2 is a constant level map of the distribution of temperature which reveals the Kuroshio current by the bunching together of the isotherms (contours of constant temperature), e.g., south of Japan. This map represents all the available data pre-CSK. To prepare this map, 43,000 hydrographic stations have been averaged over time and 1° squares of latitude and longitude. The lack of smoothness of the isotherms may be real, or may be due to inadequate data to achieve true averages, even with this coarse resolution. The existence of gyres and strong western boundary currents like the Gulf Stream and Kuroshio was rationalized in the theoretical models of the early 1950s (Robinson, 1976). An analogue Kuroshio can be seen in Figure 6(a); it is the tightly packed streamline pattern along the western boundary (consider that boundary in part to be an idealized Japan).

Recent data of much finer resolution (Figure 3) shows that the current is narrow and time variable. It moves about from week to week and month to month, but does have remarkably stable boundaries to its movement over several years. This is illustrated in Figure 4. Each general configuration remains for a few years; it takes a few months only to move from one general configuration to another.

Why the current has a particular path, why it varies, and why the slope and meander path boundaries remain stable for so long are important questions - addressed by contemporary theory and observational experiments, but not as yet reliably answered. Many physical factors govern the path a current takes. A general theory of current movement has been developed (Robinson and Niiler, 1967) and applied to the Kuroshio by numerical computer experimentation (Taft and Robinson, 1972). Various factors which influence the path are studied in isolation and then in combination. Such factors include the earth's sphericity, its diurnal rotation, the shape of the ocean bottom, and the shape of the current profiles. Figure 5 (a) illustrates the different paths a simple current will follow, depending upon the angle at which it impinges upon a bottom slope. Applying these general theoretical ideas to the Kuroshio presents a plausible explanation of the existence and stability of the bimodal path structure. Figure 5(b) shows a "shadow" zone where theoretically the current cannot flow. This exists because the shadow region could be occupied only by shallow meanders. These cannot exist because the tendency towards such behaviour leads to a capture of the current by a strong bottom topographic interaction which then leads it northward into a slope path behaviour. An alternative local dynamical theory, based more strongly on suggested transport changes in the Kuroshio current has recently been proposed (White and McCreary, 1976).

The present state of the art of modelling the ocean circulation and its intense currents has advanced rapidly and involves using data and computer models of higher resolution. Medium-scale phenomena and variability occur not only in intense current regions, but over the vast open ocean regions as well (Ocean Eddies, 1976). In Figure 6 the two different versions of the model computer ocean are driven by identical smooth and steady forcing functions of wind and surface heating. The difference lies only in the explicit resolution of the currents, and in the viscous damping of the flow by very small scales of motion, which is necessarily larger in case (a) than in cases (b) and (c). The intense variability and eddying shown in 6 (b) is important on the average; compare 6(a) and 6(c). Notice the permanent "Kuroshio" meander. In these model results the eddies on the average are important because of associated transports of heat and momentum. In addition, the strong current region and the open ocean are dynamically coupled.

In order to construct an ocean model to couple directly to an atmospheric numerical model for the study of global climate, it is still necessary to use coarse grid resolution. Notice in Figure 7 how the Kuroshio and Gulf Stream are barely discernible in the coarse description of the temperature field. For this to be a usefully applicable type of model, the heat transport by these simulated currents must be on the longtime average representative of that in the real oceans. In order to construct a world ocean climate model, we must continue to develop models of various resolutions and to understand the influence of the local medium-scale dynamical processes upon the general circulation at large.

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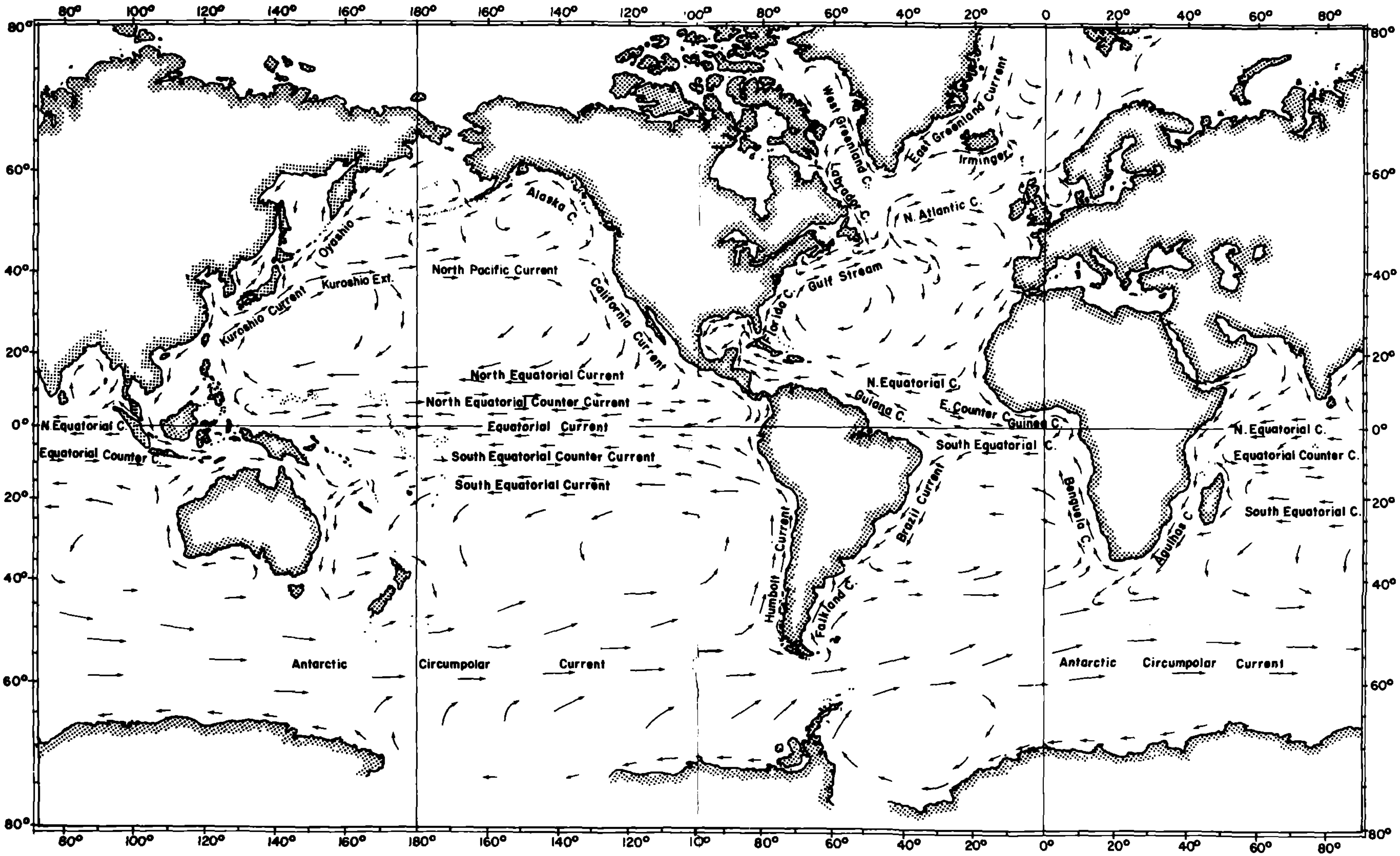
Figure 1. Major features of the surface general circulation of the world oceans (after McLellan, 1965).



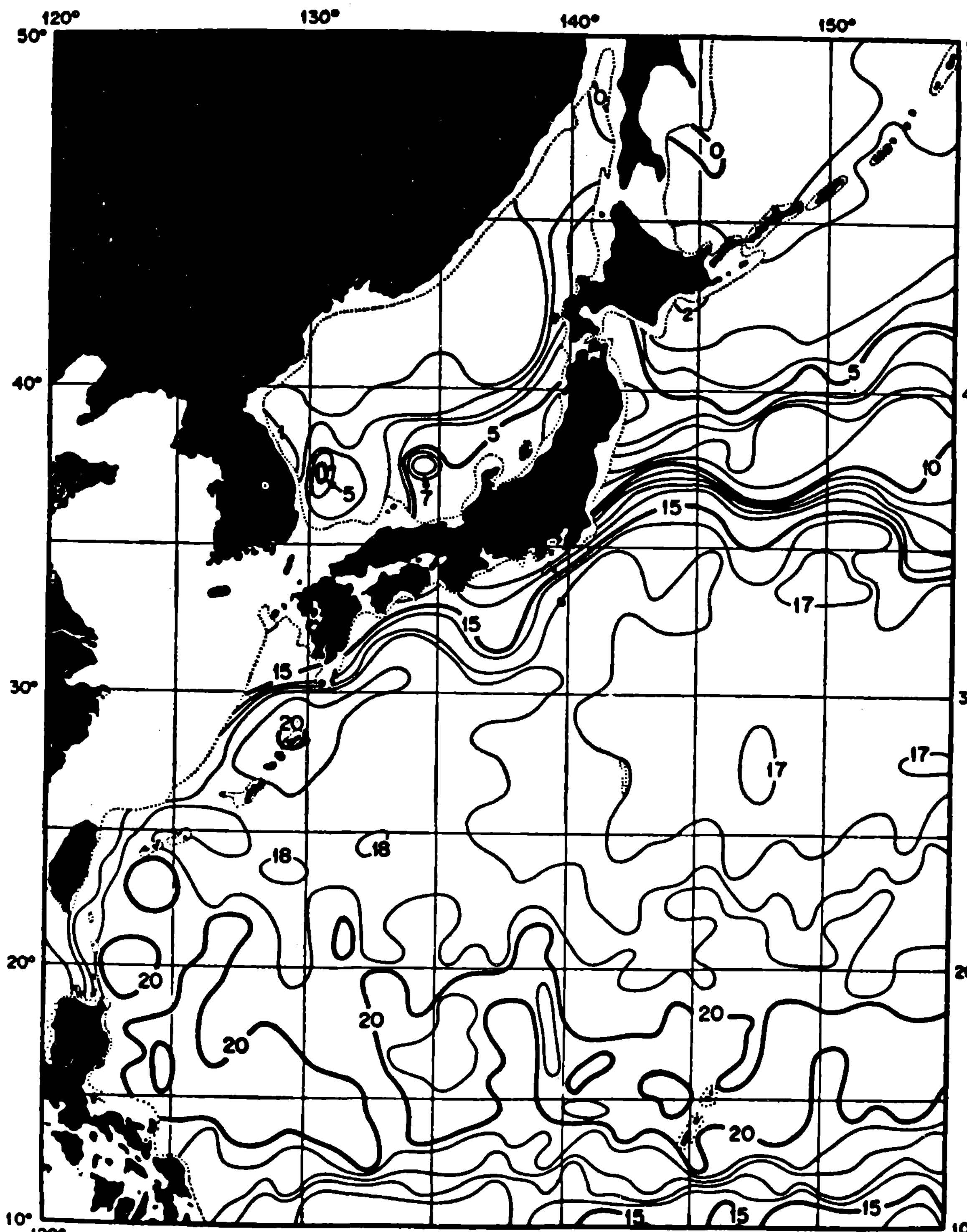
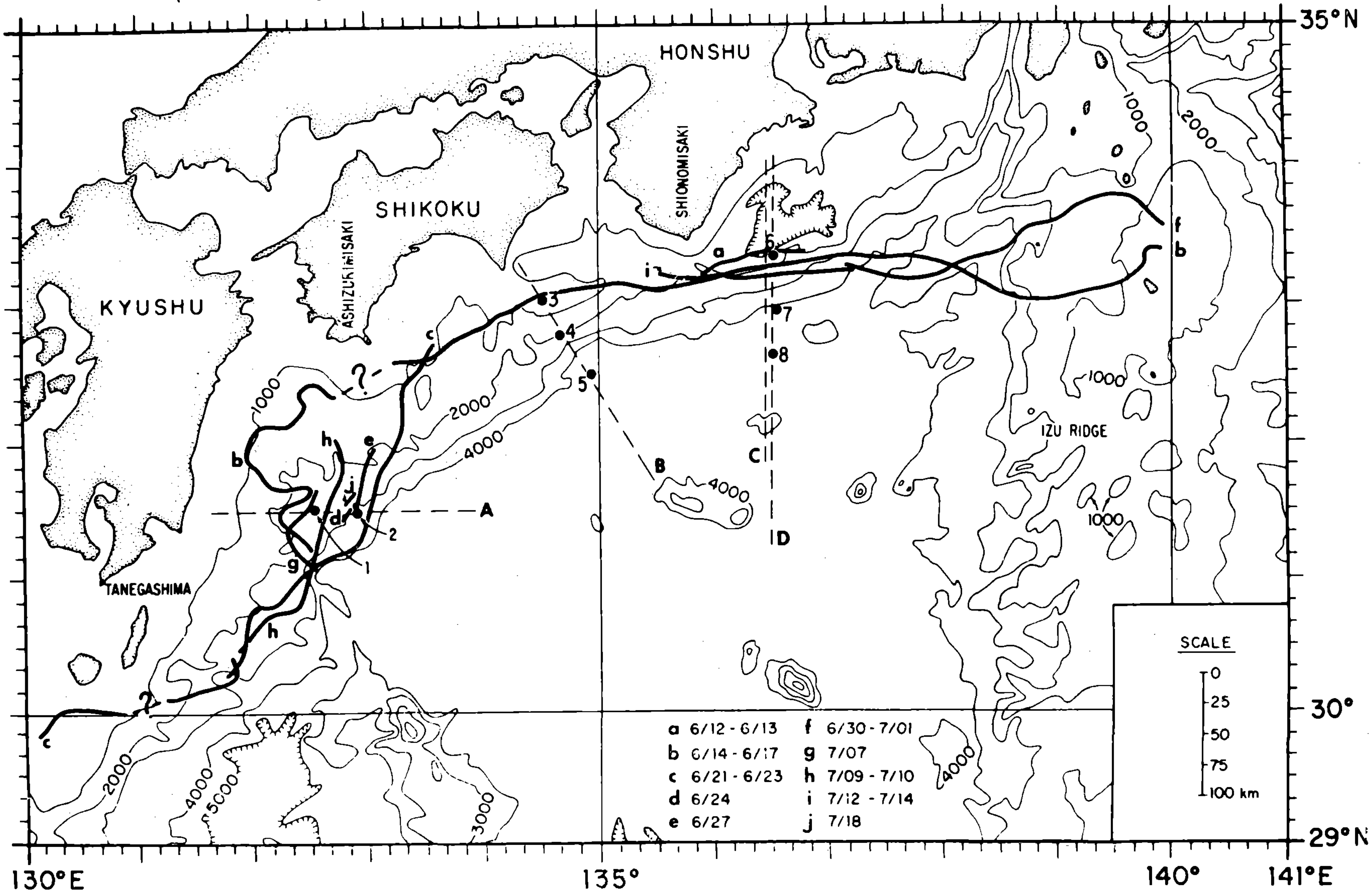
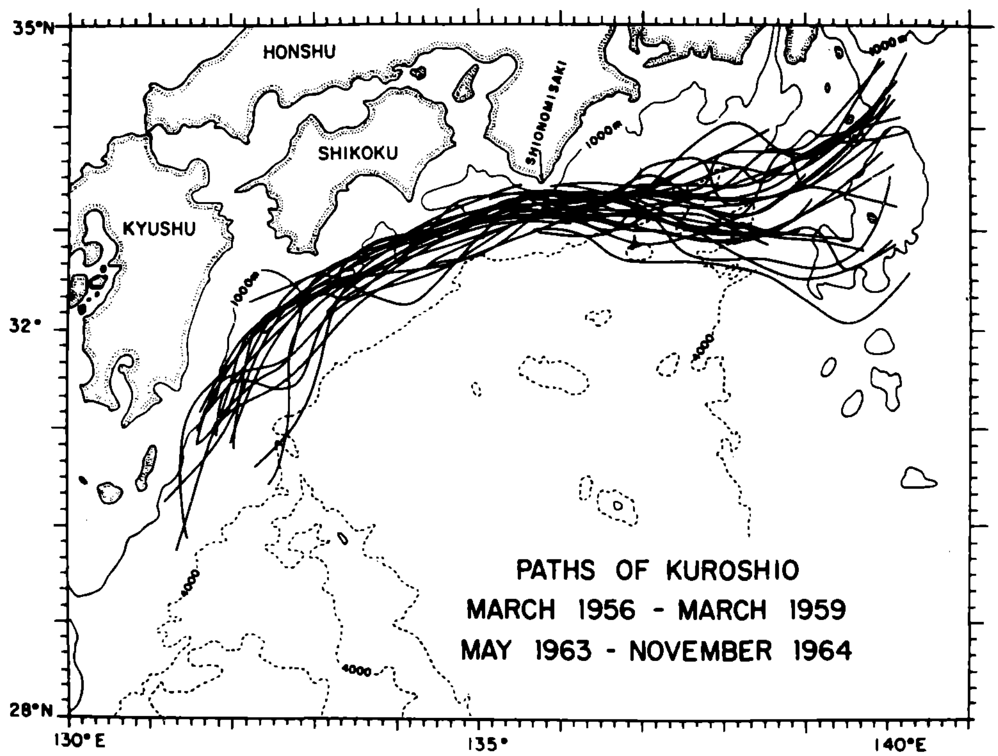


Figure 2.

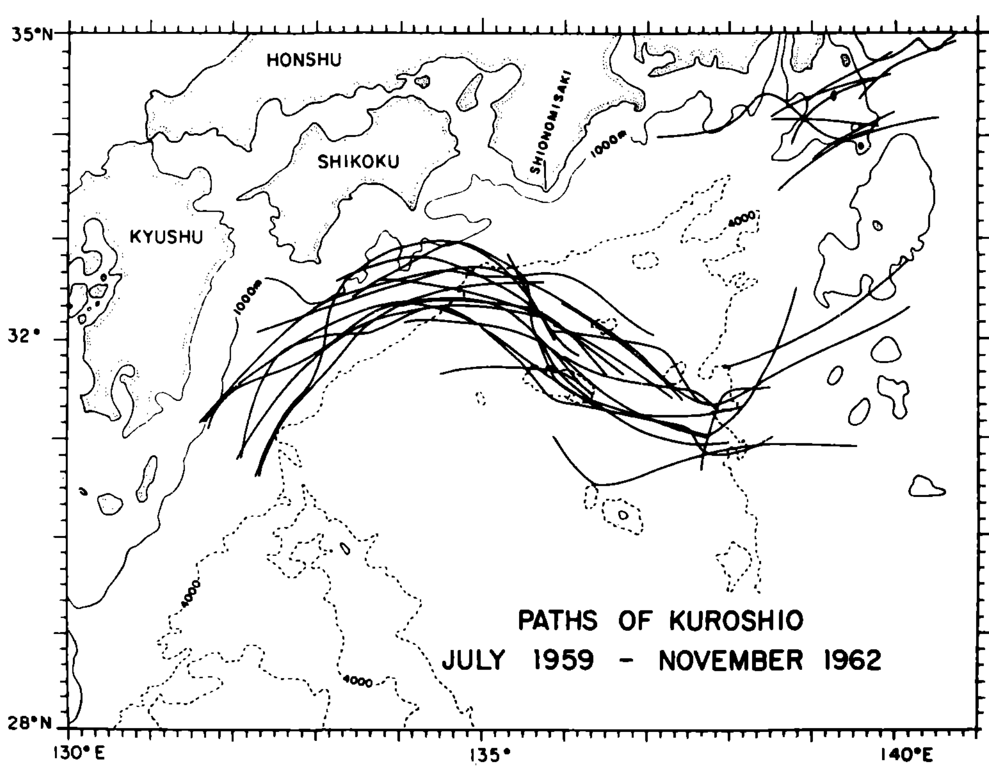
Map of the temperature distribution of the northwestern Pacific Ocean at a depth 200 m below the ocean surface from historical data. The lines drawn are contours of constant temperature, labeled in degrees Celçius (Winterfield and Stommel, 1972).

Figure 3. Synoptic picture of the axis or path of the Kuroshio current as defined by position tracks of the 15°C isotherm at a depth of 200 m. The number of days required to obtain each track is indicated on the figure (Taft et al., 1973).





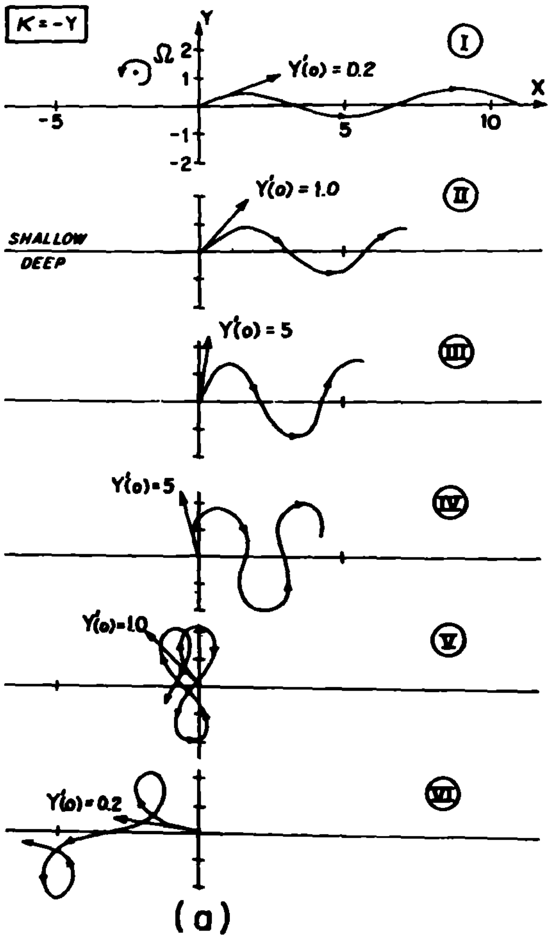
(a)

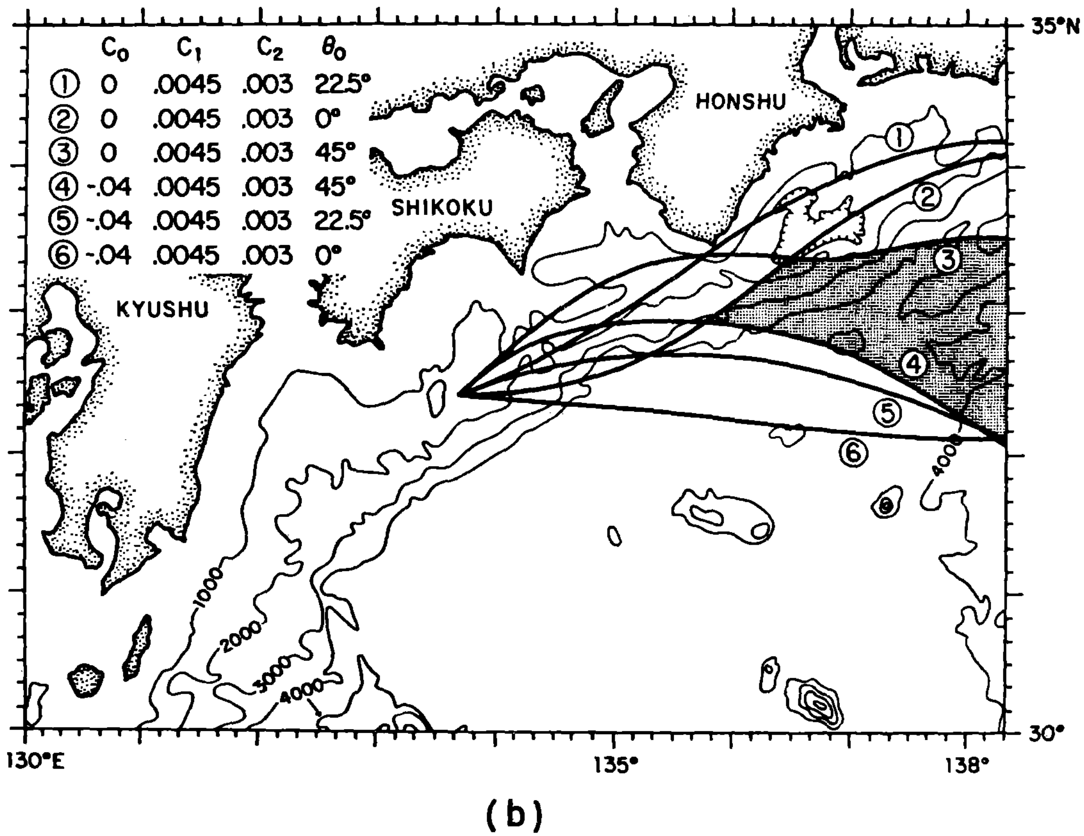


(b)

Figure 4. Composite of Kuroshio path data for the period 1956-1964. (a) Slope (normal) paths. (b) Meander (abnormal) paths (Robinson and Taft, 1972).

Figure 5. Theoretical current paths as obtained from an inertial current model. (a) The meandering flows of an idealized current model over a uniformly sloping bottom (Robinson and Niiler, 1967). (b) Theoretical slope and meander flow patterns obtained by application of the inertial model to an idealized Kuroshio (Robinson and Taft, 1972).





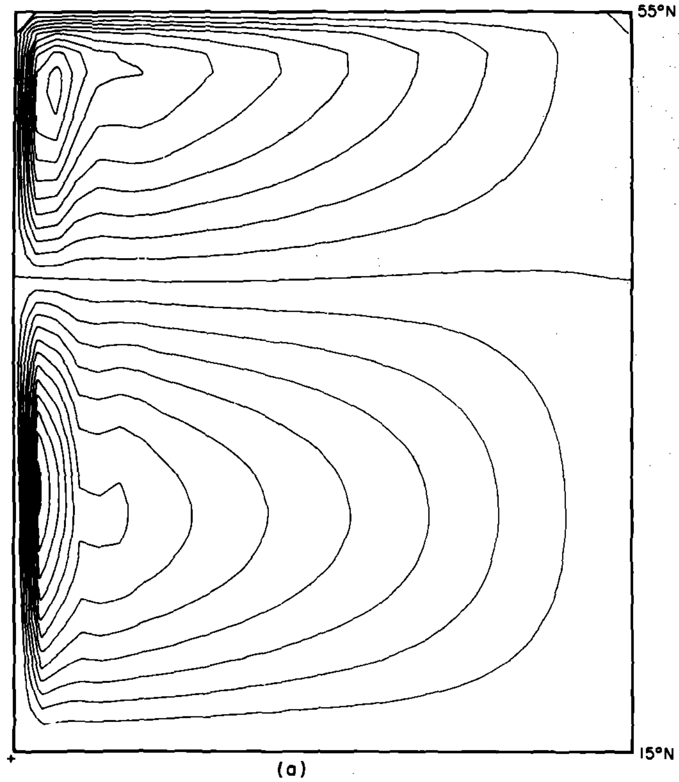
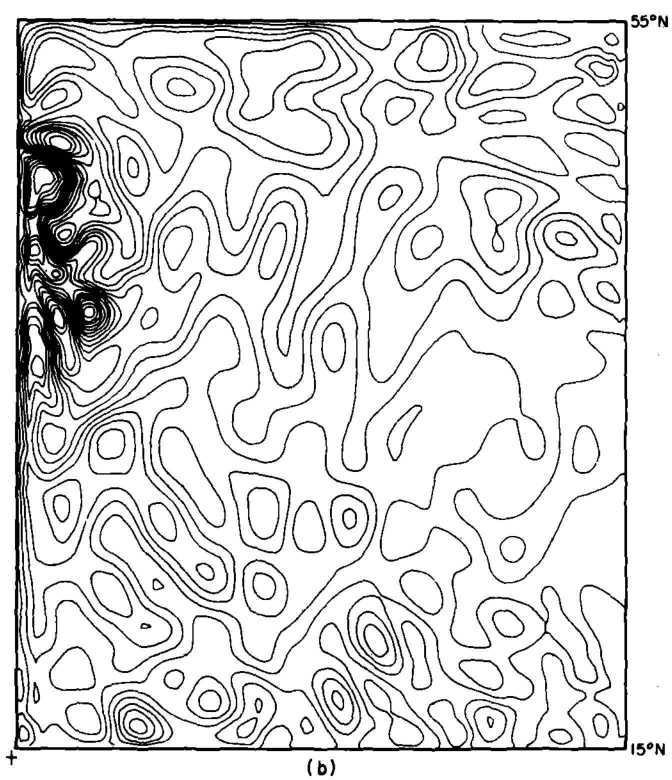


Figure 6
Numerical computer model results for an idealized subtropical and subpolar gyre. Streamlines of the flow are shown. (a) Horizontal grid resolution of 120 km. (b) 40 km resolution - a typical instantaneous flow pattern. (c) 40 km resolution flow averaged over a period of 3 years (adapted from Han, 1975).



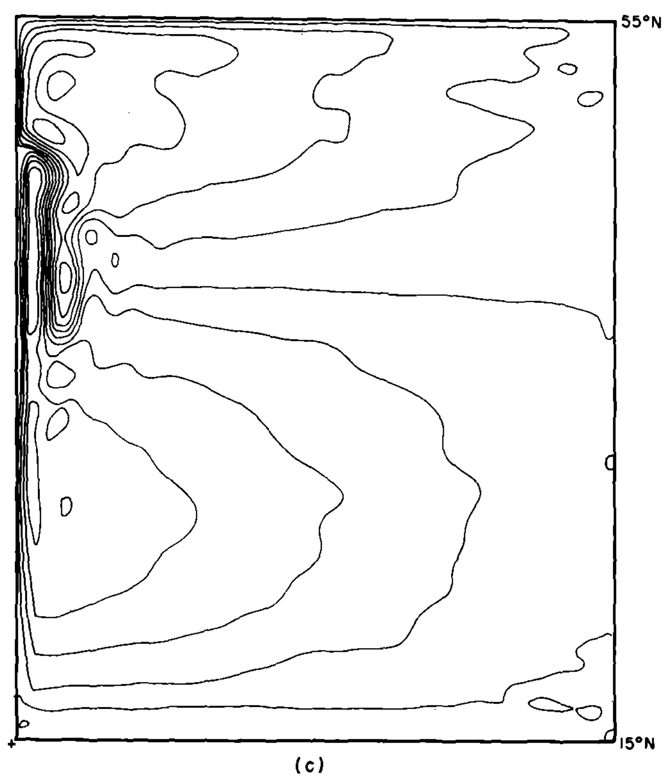
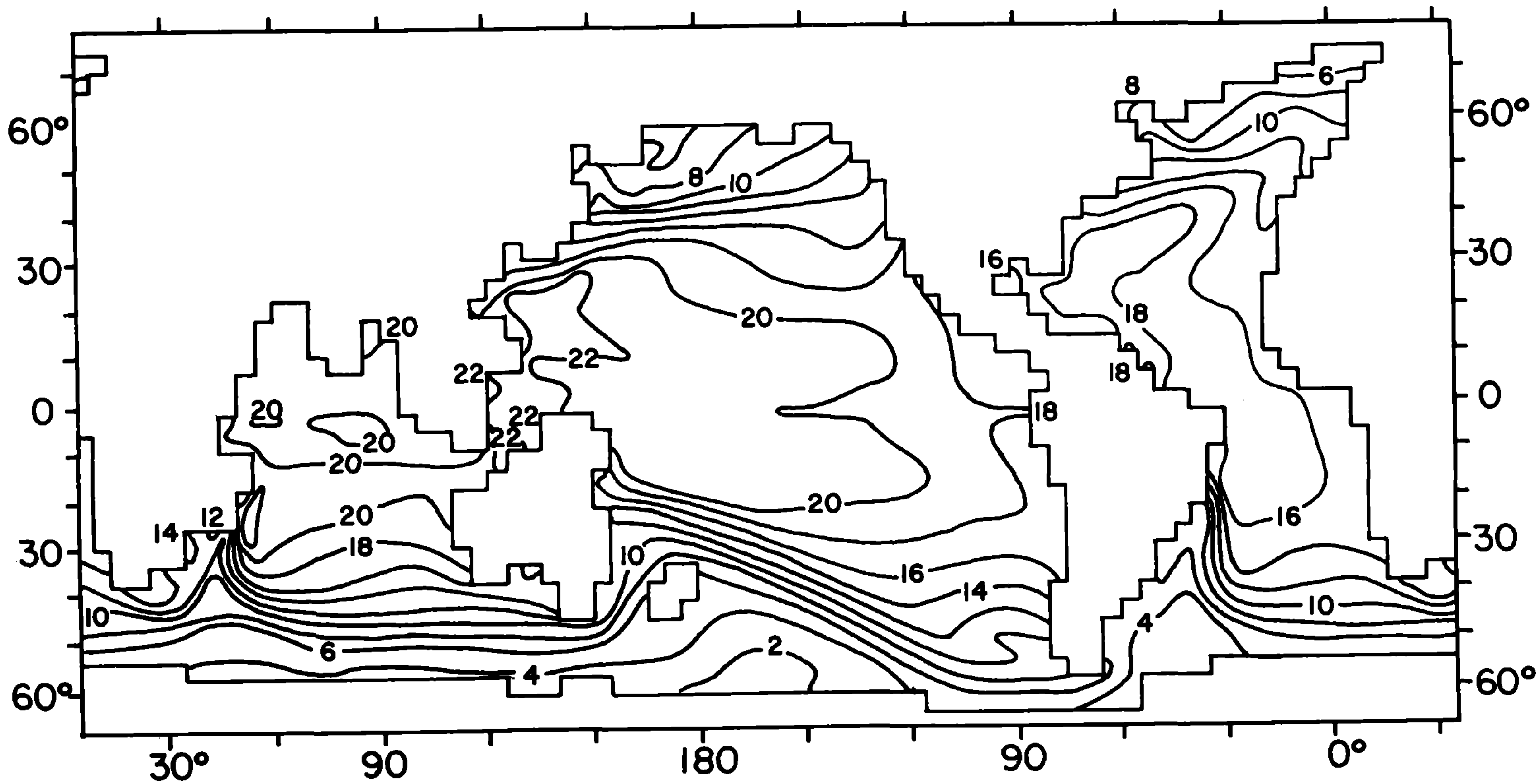


Figure 7. Numerical computer model results for temperature distribution at 120 m for an idealized world ocean model. The horizontal resolution is coarse, approximately a 300 km grid spacing (Takano, 1975).



DISCUSSION[1]

PROFESSOR ROLL

We are all very grateful to Professor Robinson for giving us this introduction to oceanic modelling. We have seen what a powerful tool these mathematical physical models can be. At the present stage, when we are considering co-operation with the meteorologists in the field of GARP[2] and FGGE[3], it is extremely informative for us to know the scale effects both in ocean and atmosphere, since it is essential to know what dimension and density of an observational network are necessary for the understanding of the circulation in the ocean as well as in the atmosphere. If we are to work together with the meteorologists, we may have to accept their scales, which are perhaps not always very useful for us in the ocean. We all are very grateful to Professor Robinson for giving us this very informative and interesting introduction into oceanic modelling, in particular with regard to the Kuroshio.

DR. QASIM

Mr. Chairman, I am fascinated by this talk by Professor Robinson. In fact it shows how a mathematician can prove his theory by using the right type of data which have been collected over a period of years and this has happened in the case of the Kuroshio. I would like to ask him if he has tested his theory in other regions of the ocean?

PROFESSOR ROBINSON

Yes. I think that these theoretical ideas which I mentioned here take somewhat different form in different circumstances, although the underlying ideas such as the conservation of potential vorticity would be the same. For example, there are considerable data and considerable work has been carried out on the meandering of the Gulf Stream. Many other scientists are attacking medium-scale phenomena now because it is emerging as a very energetic and possibly physically dominant factor.

PROFESSOR ROLL

Am I right in my assumption that in your modelling you did not take atmospheric interaction into account?

PROFESSOR ROBINSON

That is correct - not locally. This is because we regard the strength of the current as being the accumulated effect of the wind over the whole rest of the gyre because of its comparable transport.

DR. VOIGT

I think we really ought to congratulate ourselves on having Professor Robinson here in the IOC Assembly at a time when we need to understand more about the processes in the ocean by approaching these aims with a very strong regional contact. In his introductory remarks as well as in his results, he showed that at present the application of theoretical and experimental results of modern geophysical fluid dynamics makes it necessary to draft or work our research programmes for our Commission on more up-to-date lines, taking into account the real processes, the various scales, responsible for the variability, as well as the physical, chemical, biological and geological parameters. And therefore we should be very grateful for this lecture.

DR. WALDEN

I think it is not necessary for me to repeat how highly this lecture impressed me but I have a specific question. You were showing, Professor Robinson, a world chart of temperatures in 200 m steps and I saw there that the temperatures south of the Kuroshio were higher than 22°C, whereas in the corresponding area south of the Gulf Stream they were only 18°C. Could you perhaps tell me the origin of, or the reason for, this?

PROFESSOR ROBINSON

Thank you for asking me a very difficult question. Perhaps someone else in the room would like to attempt to answer it.

PROFESSOR ROLL

Professor Robinson, you rightly mentioned the interaction and transport of energy from one scale to the other from the micro- and meso-scales to the larger scales and you also mentioned that, as far as we know, the only way of dealing with such things is parameterization, but this depends on measurement in order to ensure that the coefficients therein are right. Could you give us an indication whether you did consider this transport of energy and how you did it and in which form you did the parameterization?

PROFESSOR ROBINSON

I think that the most important point is that to understand the transfer between scales, or the transport from one place to another of energy by smaller fluctuating scales, depends very much on a measurement or experimental programme, one which is designed to get the sampling frequencies and types of measurements which are actually needed. In many cases, especially in the medium-scale phenomena, one needs a lot of measurements in order to proceed as rapidly as possible we have to use a combination of experimental programmes, together with theoretical and modelling programmes, so that we can interpret as deeply physical as

(1) Names and titles of speakers are found at the end of the publication.
(2) Global Atmospheric Research Programme.
(3) First GARP Global Experiment.

possible the measurements that we are capable of getting from well-designed experiments. So right now I think we need a combined programme of well-designed experiments coupled with models so that we can understand what is happening on the medium and smaller scales because what is happening may very well be special and peculiar to the ocean and to various regions of the ocean. Once we have the understanding of one or two events, we may be able to devise special schemes of parameterization.

PROFESSOR ROLL

The third and last of the Anton Bruun Memorial Lectures this year will be given by Professor V.G. Kort of the Institute of Oceanology of the Academy of Sciences of the USSR. Professor Kort needs no introduction, for he has been with us for many years and has contributed much to our discussions, to our results, to our resolutions, and I am sure that everybody knows him very well. For me he represents the seagoing oceanographer, a very important type of oceanographer, and every time I meet him he is coming from the sea or he is going on another marine expedition. He has a very great sea experience and even at his present age he still likes to be at sea and take an active part in scientific investigations at sea. This must be fully recognized.

Dynamics and thermohaline structure of the waters of the Kuroshio current and adjacent regions

Professor V.A. Kort

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Ladies and gentlemen: The Soviet Union has played an active part in the implementation of the CSK programme. Between 1965 and 1973, its research ships carried out 40 specialized expeditions, occupying 3, 230 hydrographic stations along the standard sections allotted to the Soviet Union (Figure 1); this represents about 25 per cent of the stations occupied by countries participating in the CSK programme.

Until 1969, surveys were usually taken at approximately tri-monthly intervals, but since then, observations have been carried out only in the spring and summer, thereby reducing the programme. Data accumulated by Soviet and foreign expeditions have augmented previous knowledge of the biological productivity of the waters of the area, and have provided a basis for the study of seasonal and year-to-year variability in oceanographic conditions. The purpose of this report is to communicate some of the results obtained by Soviet scientists through scientific analysis of CSK material dealing with variability in water circulation, thermohaline and thermal structure, and with the position and structure of the sub-Arctic front. The area under investigation is bounded to the north and south by parallels 43°N and 20°N respectively, to the west by the Pacific shores of the islands of Honshu and Hokkaido, and to the east by meridian 155°E.

I. Water circulation as shown by CSK material

In areas where the waters show marked baroclinicity, a fairly close approximation to the actual circulation pattern may be obtained by dynamic computation, in which observations of the temperature and salinity fields provide the basis for drawing up diagnostic representations of the velocity fields. On the dynamic topography charts for specific seasons of different years (Figures 2 and 3), the main part of the Kuroshio was distinctly indicated by the concentration of the horizontal dynamic isopleths into a narrow, powerful stream. In the section lying between longitudes 135° and 145°E, this stream flows at velocities in excess of 1 knot, and is 35 to 40 nautical miles across. Maximum velocities of 2.5 and 2.8 knots were observed in all seasons along the southern coast of the island of Honshu, and also 300 miles southeast of the Boso Peninsula (longitude 145° to 146°E).

Areas of nearly stationary meanders were noted in all seasons, especially in summer. Cyclonic meanders developed in the 33° to 36°N latitude belt between longitudes 137° and 140°E, and between longitudes 145° and 148°E; anticyclonic meanders occurred between longitudes 141° and 145°E and between 150° and 155°E. From the vertices of the meanders, currents branched off and diffused southward and north-eastward. It is, of course, from the southward-spreading branch currents that the Kuroshio countercurrent is formed, beginning east of longitude 155°E, and completing the anticyclonic gyre to the south. In certain seasons, the countercurrent is weak. In the summer of 1965 and winter of 1966, for instance, it degenerated into minor cyclonic eddies.

A more complex dynamic structure is formed in the areas of interaction between the Kuroshio and Oyashio currents. The intensity with which the branches of the Oyashio develop fluctuates sharply from season to season. As a rule, when the continental branch of the Oyashio is weakly developed, as in 1966 and 1967, there is more vigorous transport of cold sub-Arctic waters by its oceanic branch. In the zone of contact between the Kuroshio and the Oyashio, a large number of local eddies make their appearance, arising from frictional forces, developing out of meanders, or generated by typhoons. The major dynamic formations are the anticyclonic eddies that develop out of meanders of the Kuroshio and travel in a northerly direction. These have a diameter of 60 to 200 miles, extend vertically to a depth of 500 to 600 metres, and have a surface velocity (according to data obtained from facsimile charts) of 0.5 to 2.0 nautical miles per day. They appear most frequently in winter in the zone lying between longitudes 141° and 145°E and latitudes 33° and 38°N. Between 1965 and 1973, three cycles could be discerned in the development of major anticyclonic eddies: 1965-1967, 1968-1969 and 1970-1972. Over certain periods of time, the major eddies appear on the charts as localized vortices, with life-spans of about one year.

In the sub-Arctic Ocean zone north of 40°N, the current velocity does not exceed 0.2 to 0.3 knots, whereas along the south coast of the island of Hokaido it frequently reaches 1 knot. The intensification of the current in this area is due to the confluence of the continental branch of the Oyashio with the Sangara current flowing south-east into the inner regions of the frontal zone.

The characteristics described above relating to the horizontal surface circulation of the waters of the Kuroshio are maintained to depths of 150 to 200 metres. At lower levels (Figure 5 shows depths of 500 to 800 metres during the summer of 1965), the nature of the geostrophic circulation changes to some extent. Some of the eddies disappear (or disperse), the currents become weaker and are displaced to the right, and in areas of convergence (or divergence) a sign change occurs. As an illustration of the vertical flow structure, Figure 4 shows a dynamic section along the 138°12'E meridian for the spring of 1972. It can be seen from the diagram that the maximum velocity (of up to 100 cm/sec) is observed in the upper 50-metre layer of the ocean, the current measuring some 70 nautical miles across on the surface and broadening out at sub-surface depths to 120 miles.

The overall pattern of horizontal circulation studied, both as a whole and in its individual parts, is subject to considerable seasonal and annual variations (especially in the meanders) that can be clearly traced from the CSK data. To show the nature of the Kuroshio's seasonal variability, we shall use the results of geostrophic circulation computations for a section along the 138°12'E longitude. Some dynamic indicators of the Kuroshio's intensity - surface speed of the main stream, depth of the 20 cm/sec isotach, transport in the 0 to 1,000 metre layer, and breadth of stream or distance between the 20 cm/sec isotachs - in the selected section off the south coast of the island of Honshu for the period between 1965 and 1973 are given in Table 1. This table indicates that the surface velocity of the main stream ranges from 70 to 22 cm/sec, the breadth of the main stream from 50 to 120 miles, and its depth from 570 to 760 metres. The 10 cm/sec isotach runs at a depth of approximately 800 to 900 metres in the Kuroshio's main stream.

To obtain an overall indication of current intensity, it is convenient to use water volume transport, which, other factors being equal, is less subject to short-term fluctuations than, for example, current velocity at different levels. The difference between the maximum volume transport (73.8 million m^3/sec in the spring of 1967) and the minimum (38.5 million m^3/sec in the summer of 1970) comes to 35.3 million m^3/sec (Table 2), i.e., the intensity of the Kuroshio altered by a factor of almost 2 between those years.

It will be seen (Figures 9 and 12) that there is greater year-to-year than seasonal fluctuation, not only in velocity and transport but in individual circulation characteristics. As an indirect indicator of year-to-year variation in the Kuroshio, we shall examine changes in the position of its dynamic axis off the south and east coasts of Honshu during the summer period. The curves representing these changes (Figure 6), plotted from CSK data and published sources, show that shifts in the axis of the Kuroshio off the eastern coast of Honshu over the past 40 years (lower curve) follow a cyclic pattern recurring every 4 to 5 years. The results of spectral analysis (Figures 6 and 13) reveal cyclic patterns also in the changes of position of the axis of the current over periods of 1-2 and 17-19 years.

One of the important results of the research carried out under the CSK programme was the discovery by Japanese and Soviet scientists of the subtropical countercurrent, flowing from west to east at speeds ranging from 0.2 to 1.3 knots. This current can be traced against a background of irregular eddies in the zone lying between latitudes 20° and 25°N; i.e., it can be matched against the subtropical convergence - the axis of the subtropical gyre.

The subtropical countercurrent is usually distinguished from the surrounding waters by a slightly lower salinity level, by the presence of a warm core in the 0 to 200 metre layer, and by the fact that, within it, the subtropical front drops to a depth of 300 to 500 metres.

Table 3 gives some of the dynamic characteristics of the subtropical countercurrent within sections of it taken along the 138°12'E and 149°E meridians (Figure 11). It shows that the countercurrent can be observed during practically all seasons of the year, and that its axis undergoes considerable shifts (2 to 3 degrees latitude), apparently because of localized vortices at the left and right boundaries of the stream.

The maximum velocities are observed in the upper layer and vary from season to season between 5-10 and 40-50 cm/sec. At greater depths (particularly in excess of 300 m) the geostrophic velocity decreases noticeably, and transport of the bulk of the water therefore takes place in the 0-300 m layer.

In individual years during the 1965-1970 period, the maximum transports in the subtropical countercurrent along the 138°12'E and 149°E longitudinal sections occurred during different seasons. The maximum transport between 1965 and 1970 was observed on the 138°12'E section in the spring of 1967 and came to 37.2 million m^3/sec, and the largest seasonal variation in any one year amounted to 31.5 million m^3/sec (in 1967).

Downstream seasonal fluctuations in transport diminish (except in 1968), as may be expected from the general slackening of the stream as it proceeds eastwards. It is also noticeable (Figures 9 and 11) that there is a direct relationship between the intensity of the subtropical countercurrent and the number of tropical cyclones occurring over this region; a decrease in their number corresponds to a drop in the intensity of the countercurrent. This relationship is frequently disturbed in winter and spring, however, when there are scarcely any typhoons and when the winter monsoon exerts a considerable influence on the circulation regime. It can be demonstrated (Figures 4, 5 and 8) that the presence of such an important factor in the water circulation of the western half of the Pacific

Ocean as the subtropical countercurrent plays a significant part in determining the distribution of the various kinds of plankton and fishery resources in the subtropical latitudes.

II. Some characteristics of the thermohaline and thermal structure based on CSK data

One of the major characteristics of the thermohaline structure consists of temperature and salinity anomalies relative to their long-term average values.

The most complex year-to-year temperature (Figure 7) and salinity (Figure 8) variations are observed in the Kuroshio frontal zone. This is where the anomalies and their gradients have the largest values. Surface temperature anomalies, for example, reach 4-8°, with horizontal gradients of 2-3° over a distance of 60 nautical miles; salinity anomalies reach 0.6-1.0°/oo, with horizontal gradients of up to 0.4-0.8°/oo over 60 miles.

The greatest year-to-year fluctuations in temperature anomalies are noted in winter in the surface layer, where they reach 16.4°; the highest salinity fluctuations are found in the 0-200 m layer with a range of 1.4-1.6°/oo. The highest values for year-to-year fluctuations in seasonal temperature anomalies are found down to depths of 500-800 m, with fluctuations of 10 per cent at the 500 m level.

Between 1965 and 1969 the year-to-year fluctuations in summer and winter water temperature anomalies at the surface ranged in different places from 0.1 to 16.4° and salinity anomalies from 0.1 to 1.5°/oo.

Within the main thermocline layer (0-800 m), certain concentrations of anomalies appear at various depths (Figure 12).

The most significant feature that emerges from an analysis of the thermodynamic state of ocean waters is the heat content of the various layers.

The bulk of the heat of the Kuroshio is in the upper layer (Figure 9), which is therefore the layer of maximum horizontal heat transport.

The ratio between the amount of heat advected in the 0-500 m layer and in the 0-1,500 m layer fluctuates between 38 and 100 per cent, according to longitude.

III. Water masses and fronts

The fundamental features of the Kuroshio front (the subarctic front) and of its variations, as revealed by the CSK data, were examined with respect to temperature and salinity. The position of the front at various depths was determined from the intersection of the frontal surface with the corresponding horizontal level (Figures 7, 8 and 13). For this purpose temperature readings of vertical sections were taken, thus establishing the depths of the maximum gradient within the ocean thermocline layer, with the maximum salinity gradient providing an additional indication.

Figure 9 shows some observed positions of the southern and northern fronts; these diagrams are similar to charts of the long-term average position of the front for the corresponding seasons. The southern subarctic front represents the northern boundary of the subtropical water mass, whereas the northern front refers to the boundary of the area to which the subarctic water mass extends (corresponding respectively to the terms "Kuroshio front" and "Oyashio front" used by Japanese scientists). The two-stage frontal structure persisted throughout the entire period except in certain winter seasons (Figures 3 and 13). This feature of the front can also be seen in the fact that the northern front is most developed in the surface layers while the southern front is most developed in the subsurface layers. The inclination of the frontal surface at a depth of 100 m did not exceed an angle of 10' (Figures 3, 7 and 10).

A characteristic feature is that, as the Kuroshio intensifies, the frontal zone narrows, and conversely, when the current becomes weaker, it broadens. This rule holds good both on the seasonal and on the annual scale. Judged on the basis of the extent of fluctuations in the position of the front, the northern front is more stable than the southern, with a mean annual displacement of 22 miles as against 61 miles.

It has been established (Figures 3, 8 and 13) that the northern front occupies its most southerly position in the autumn, whereas for the southern front this occurs in the winter. The most northerly positions are occupied by the two fronts in the summer and autumn, respectively. When, in a given season, the northern front is displaced towards the south, the southern front moves towards the north during the same period. Conversely, when the northern front shifts in a northerly direction, the southern front simultaneously moves south. This serves to confirm the conclusion already arrived at by Japanese oceanographers concerning the connection existing between changes in the positions of the northern and southern branches of the subarctic front. The result of this interrelationship is that the frontal zone is at its broadest in winter, narrows somewhat in the spring, widens again in the summer and is at its narrowest in the autumn.

IV. Large-scale air-sea interaction (in the CSK region)

As already demonstrated (Figure 15), changes in the heat content of the ocean's baroclinic layer (down to the depth of the lower boundary of the Kuroshio current; i.e., approximately the 1,000 m level) show seasonal fluctuations that are nevertheless considerably smaller in range than the longer-term changes, which occur over a period evaluated at 7-8 years (Figure 10).

Comparison of the curves illustrating changes in the mean annual values of the heat content in the 10, 200- and 1,000-metre layers, with the curves showing variations in mean annual values for total solar radiation and the temperature of the air above the region in question, reveals a significant correlation between the incidence of solar radiation and the heat content fluctuations within the ocean's active layer (0-200 m), while changes in heat content in the baroclinic layer correlate more closely with air temperature, allowing for a 2-3 year time lag (Figure 11).

These correlations are entirely to be expected, since the heat content of the ocean's active layer is determined basically by the seasonal nature of the external heat exchange of this ocean layer, which depends entirely on the radiation balance. In other words, the atmosphere has a decisive effect on the thermal regime of the ocean's active layer. This also explains the simultaneous changes that occur in the temperature of the surface water and even of the active layer, over vast ocean basins, as recently observed by a number of research workers (Ivanov, Shishkov, Bjerknes, Khandzava, Namias and others).

It would appear, however, that over a period of years variations in the temperature of the air above the ocean are caused to a greater extent by fluctuations in heat advection by currents; i.e., by heat content changes in the ocean's baroclinic layer.

Although these variations are not large (3-4°C for the entire layer), the large difference in heat capacity between water and air, together with the significantly large area of the current surface, exerts a substantial influence on the thermal regime of the atmosphere over a period of years. Hence, as far as long-term thermal air-sea interaction is concerned, the major role is played by the ocean in regions where there are powerful ocean currents.

An analysis of quantitative changes in heat content in the baroclinic layer of the ocean outside the Kuroshio current did not reveal such clearly defined annual fluctuations. It may be assumed that the zones where the most active large-scale air-sea interaction takes place are those through which the main streams of currents flow.

Even more marked interaction occurs in the neighbourhood of physical oceanic fronts. This can be seen, for example, in the northerly shift in the axis of the westerly winds in the northern part of the Pacific in the polar front region, which takes place some 3-5 months after a shift to the north has occurred in the 15° water-surface isotherm (Figure 12).

As early as the 1960s, Japanese research workers (Fukuoka, Ichiye, Uda and Takenouti) demonstrated that a shift to the north in the subarctic front (or main stream of the Kuroshio) was connected with an increase in the Kuroshio's intensity and therefore with an increase in heat advection by these currents.

Comparison of data relating to variations in the heat content of the Kuroshio and California currents shows that extreme values for the heat content of the Kuroshio off the Japanese coasts occur, on average, 4-6 years after those for the California current (Figure 13).

The time lag is almost two years longer than the time taken for the water to travel through the southern branch of the north Pacific circulation system. It would appear that this two-year period represents the time necessary for a temperature anomaly to build up in the ocean's baroclinic layer in the neighbourhood of the Californian coast. Taking into account the generative influence of the subarctic oceanic front on the intensification of the westerly atmospheric movement over the northern regions of the Pacific, it is possible to devise a physical model, as illustrated in Figure 14, to show large-scale air-sea interaction in the CSK region. This model is based on the fact that an increase in the westerly atmospheric movement over the northern part of the Pacific leads to an intensification of the cold California current, with the result that cold water masses begin to accumulate in the eastern part of the tropical zone of the Pacific, giving rise to a negative anomaly in the heat content of the north Pacific anticyclonic circulation.

The cooling of the surface waters of the eastern part of the tropical zone of the ocean produces conditions giving predominantly dry weather with little cloud in this region; this in turn leads to more intensive heating of the water by the increased flow of solar radiation, so that a new positive anomaly in the heat content of the north Pacific circulation begins to form, renewing the cycle of large-scale air-sea interaction.

The system follows a cyclic pattern taking, on average, something like 6 years, the length of the cycle being governed mainly by the rate at which temperature anomalies develop in the ocean's baroclinic layer. Long-term fluctuations in the system are of course complicated by seasonal fluctuations in the heat regime of the ocean's active layer, the incidence of monsoons and the general pattern of the circumpolar atmospheric vortex.

Rationally organized observations of changes in the heat content of the California current and of the Kuroshio provide a solution to the problem of long-term (3-5 years) ocean and climate forecasting. The intensification noted in the thermodynamic processes of the air-sea interaction system in the area of the polar ocean fronts places these regions of the Pacific among those which should be given priority for study.

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Table 1

SOME DYNAMIC CHARACTERISTICS OF THE KUROSHIO
AT 138°12' E

Year	Season	Velocity in the core (cm/sec.)	Width (miles) on the surface between lines of equal velocity (20 cm/sec. isotach)	Vertical extent of the 20 cm/sec isotach	Transport ($10^6 m^3$/sec.) in the layer between 0 - 1000 m.
1965	Summer	131	94	730	56.6
1966	Winter	148	112	740	61.0
	Summer	119	86	760	63.5
1967	Winter	105	112	580	43.7
	Spring	109	120	730	73.8
	Summer	95	114	580	64.5
	Autumn	127	86	620	50.1
1968	Winter	71	80	650	40.0
	Spring	126	96	680	51.4
	Summer	148	112	730	68.4
	Autumn	101	80	630	41.5
1969	Winter	117	88	600	48.9
	Spring	111	110	570	47.8
	Summer	219	50	740	44.8
	Autumn	130	100	570	48.7
1970	Winter	104	72	590	48.3
	Spring	117	100	610	53.3
	Summer	86	60	560	38.5
	Autumn	157	90	690	57.0
1971	Spring	93	100	620	47.9
	Summer	128	106	640	53.3
1972	Spring	103	60	570	45.3
	Summer	116	100	620	48.0
1973	Summer	118	110	560	53.0
1974	Summer	88	90	820	58.8

Table 2

YEAR-TO-YEAR VARIATIONS IN VOLUME TRANSPORT (10^6 m^3/sec.) IN THE KUROSHIO

A.

Seasons	Winter	Spring	Summer	Autumn
Maximum	61.0(1966)	73.8(1967)	68.4(1968)	57.0(1970)
Minimum	40.0(1968)	45.3(1972)	38.5(1970)	41.5(1968)
Range	21.0	28.5	29.9	15.5

AVERAGE SEASONAL VARIATIONS IN VOLUME TRANSPORT (10^6 m^3/sec.) IN THE KUROSHIO (Averaged for the period 1965 - 1972)

B.

Seasons	Winter	Spring	Summer	Autumn
Volume transport ($10^6 m^3$/sec)	48.4	53.2	54.5	49.3

DEVIATIONS OF VOLUME TRANSPORT (10^6 m^3/sec) FROM THE 1965-1973 AVERAGE FOR SUMMER IN THE KUROSHIO

C.

Year	1965	1966	1967	1968	1969	1970	1971	1972	1973
Deviation	2.1	9.0	10.0	13.9	-9.7	-16.0	-1.2	-6.5	-1.5

VOLUME TRANSPORT (10^6 m^3/sec) AT VARIOUS LONGITUDES IN THE KUROSHIO REGION

D.

Season and Year \ Longitudes	138°15'	138°12'	145°00'	152°00'	Average
Summer 1965	62.3	56.6	55.2	31.5	51.4
Winter 1966	57.1	61.0	55.9	50.2	56.0
Summer 1966	65.4	63.5	56.2	40.8	56.5
Winter 1967	37.8	43.7	41.4	44.0	41.7
Summer 1967	66.1	64.5	56.6	45.2	58.1

Table 3

SOME DYNAMICAL CHARACTERISTICS OF THE SUB-TROPICAL COUNTERCURRENT FOR THE PERIOD 1965 - 1970.

Season	Year	Volume transport 10^6 m^3/sec.		Velocity in the core (cm/sec)		Depth of the 10cm/sec isotach	
	Longitude	138°12' E	149°00' E	138°12' E	149°00' E	138°12' E	149°00' E
Summer	1965	16.1	6.3	24.6	15.7	220	120
Winter	1966	12.6	7.9	24.1	30.7	460	190
Summer	1966	5.8	21.6	18.4	36.0	110	660
Winter	1967	5.7	22.0	10.6	49.6	20	720
Spring	1967	37.2	13.0	44.6	25.7	840	280
Summer	1967	19.8	15.8	35.0	36.5	470	190
Autumn	1967	8.1	-	27.5	-	190	-
Winter	1968	23.2	-	41.3	-	680	-
Spring	1968	8.7	10.1	48.0	20.2	260	110
Summer	1968	26.7	25.8	46.4	33.0	640	550
Autumn	1968	3.7	4.8	12.8	22.0	40	120
Winter	1969	23.1	5.6	22.9	14.7	650	130
Spring	1969	17.6	7.8	37.4	26.2	320	180
Summer	1969	1.2	4.8	5.1	16.0	10	120
Autumn	1969	3.7	1.2	27.8	9.5	160	-
Winter	1970	5.6	8.4	24.3	25.0	110	220
Spring	1970	9.1	10.6	41.4	30.6	210	190
Summer	1970	20.8	8.7	36.0	25.0	540	300
Autumn	1970	4.6	4.0	25.2	12.0	160	70

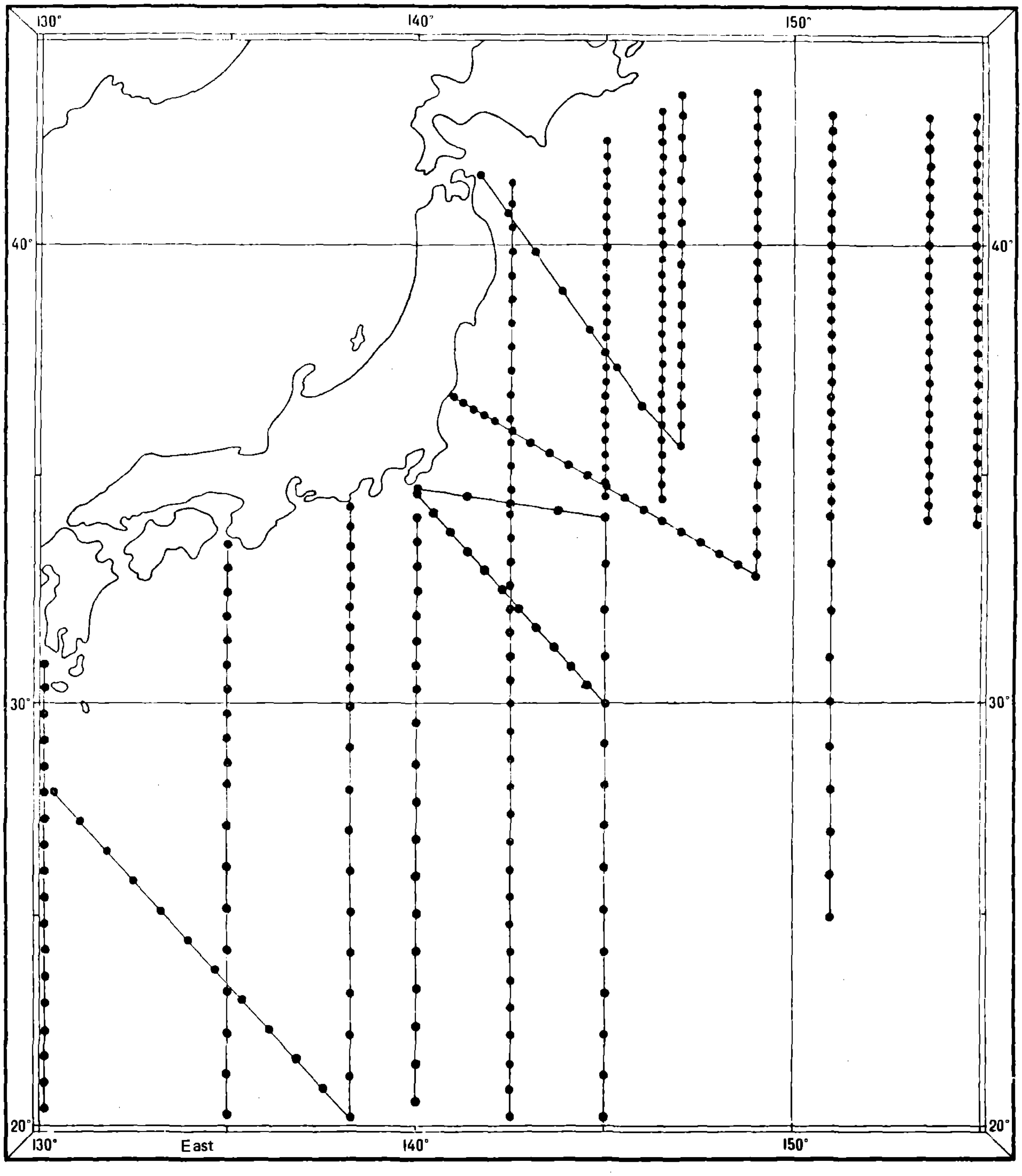


Fig. 1 Diagram of hydrological sections.

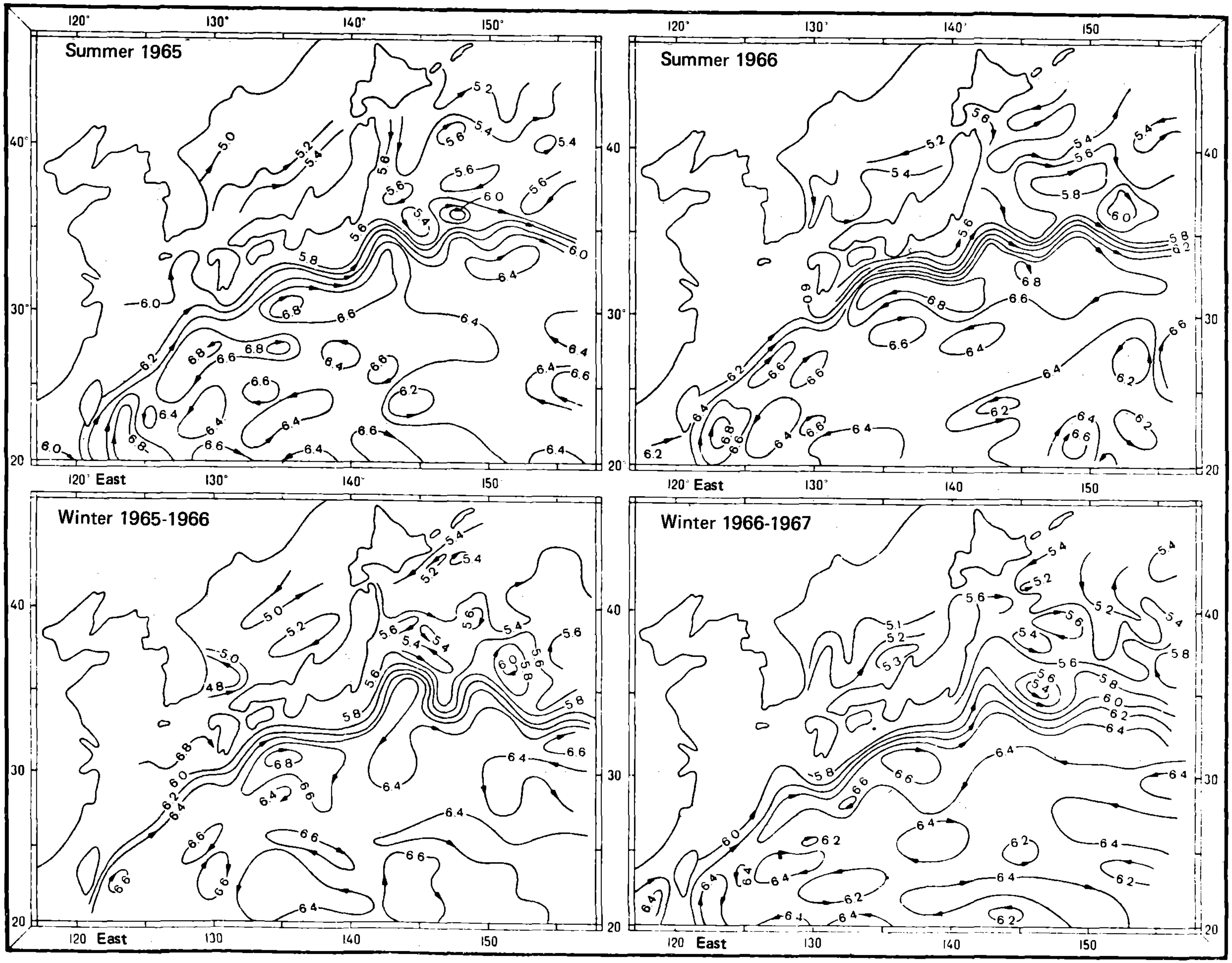


Fig. 2 Dynamic topography of the surface currents of the north-western Pacific ocean. Top left-hand figure - summer, 1965; top right- hand figure - summer, 1966; bottom left-hand figure - winter, 1966; bottom right-hand figure - winter, 1966-67.

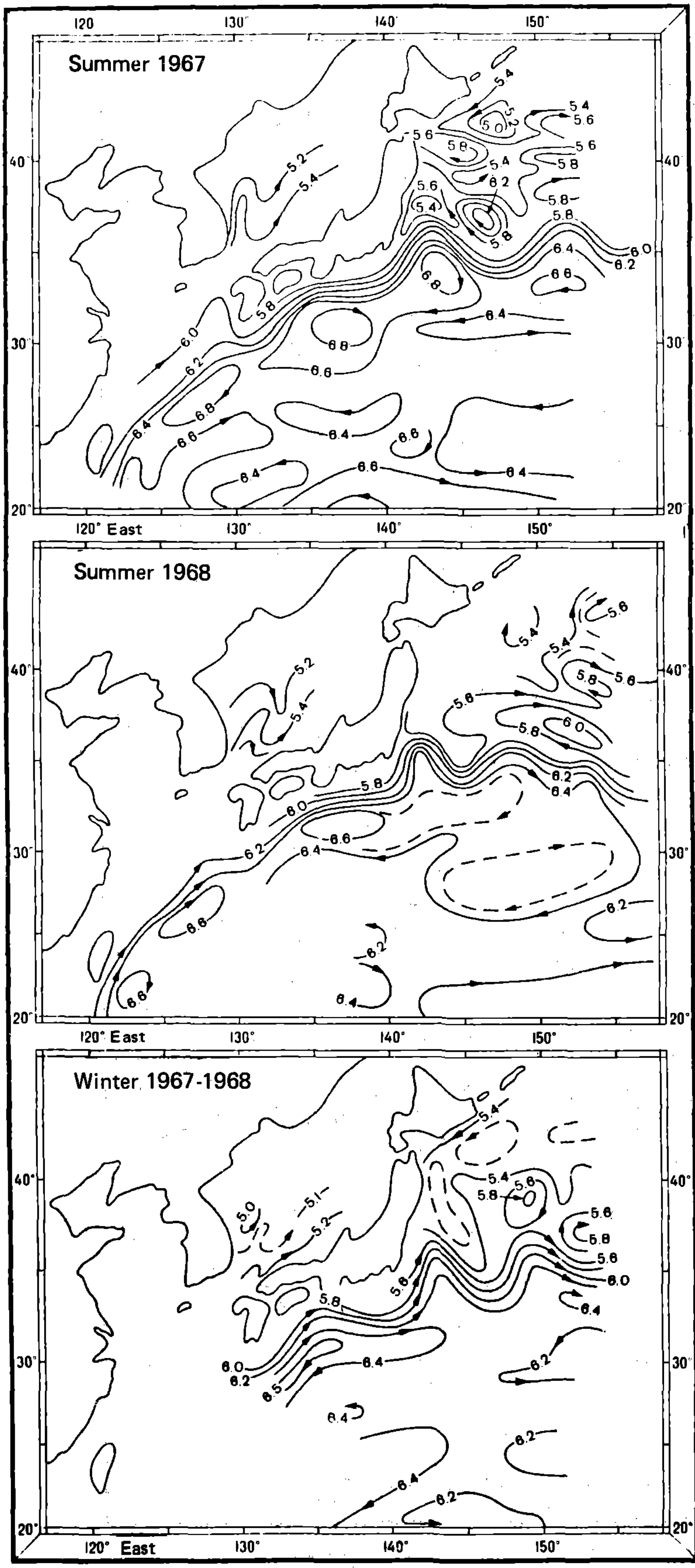
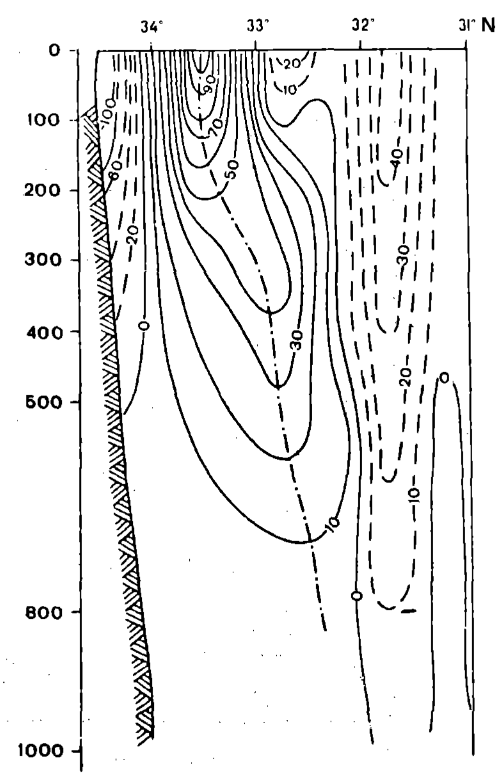


Fig. 3

Dynamic topography of the surface currents of the north-western Pacific ocean. From top to bottom: summer, 1967; summer, 1968; winter, 1967-68.

Fig. 4 Velocity (cm/sec) of the geostrophic currents in a section taken along the 138°12'E longitude - spring, 1972. Current flowing eastwards ——10——— ; current flowing westwards ----10----; Vertical position of the main stream of the Kuroshio -·-·-·-·-



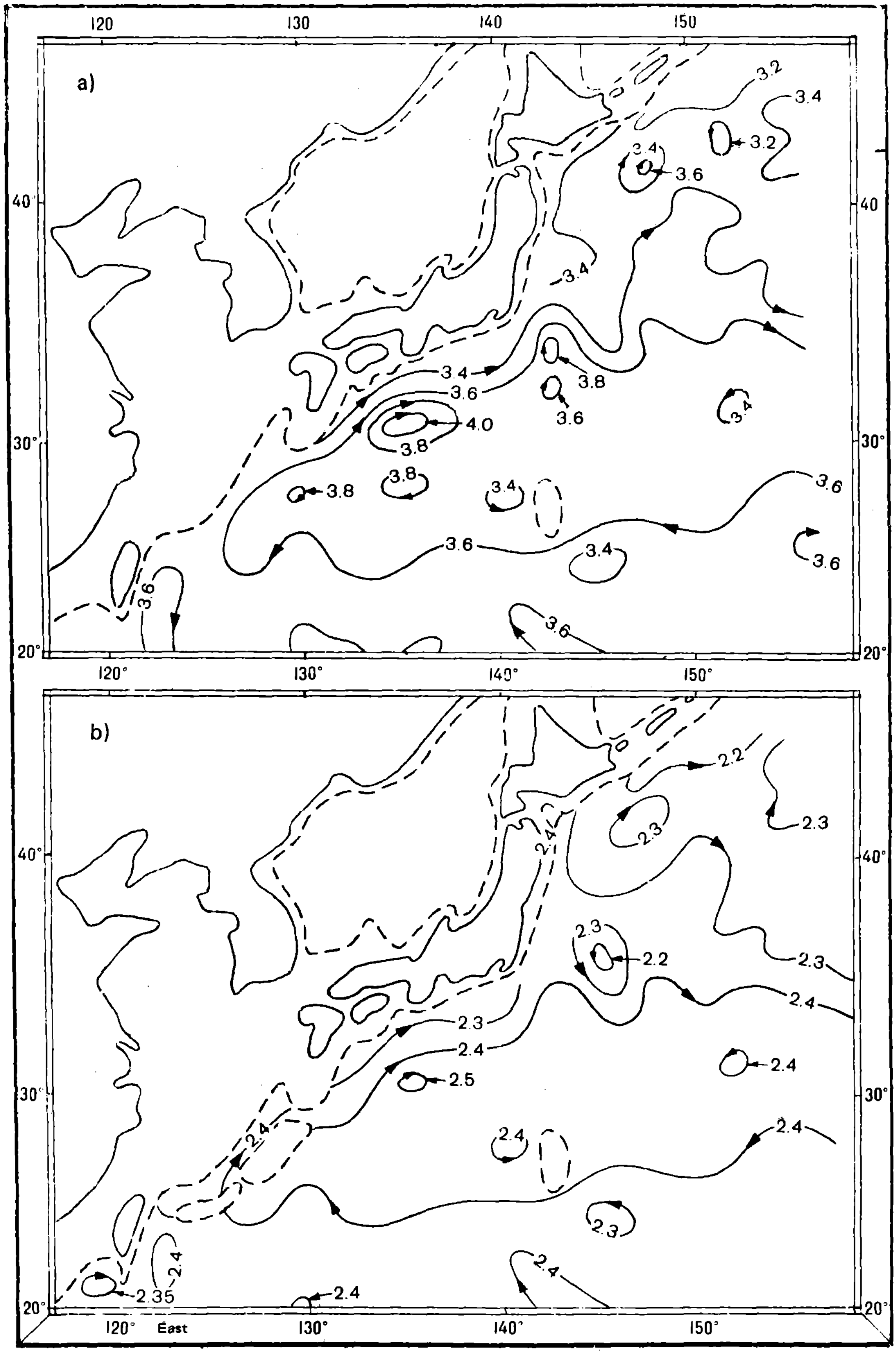


Fig. 5 Geostrophic circulation at the 500m (top figure) and 800m (bottom figure) levels in the summer of 1965.

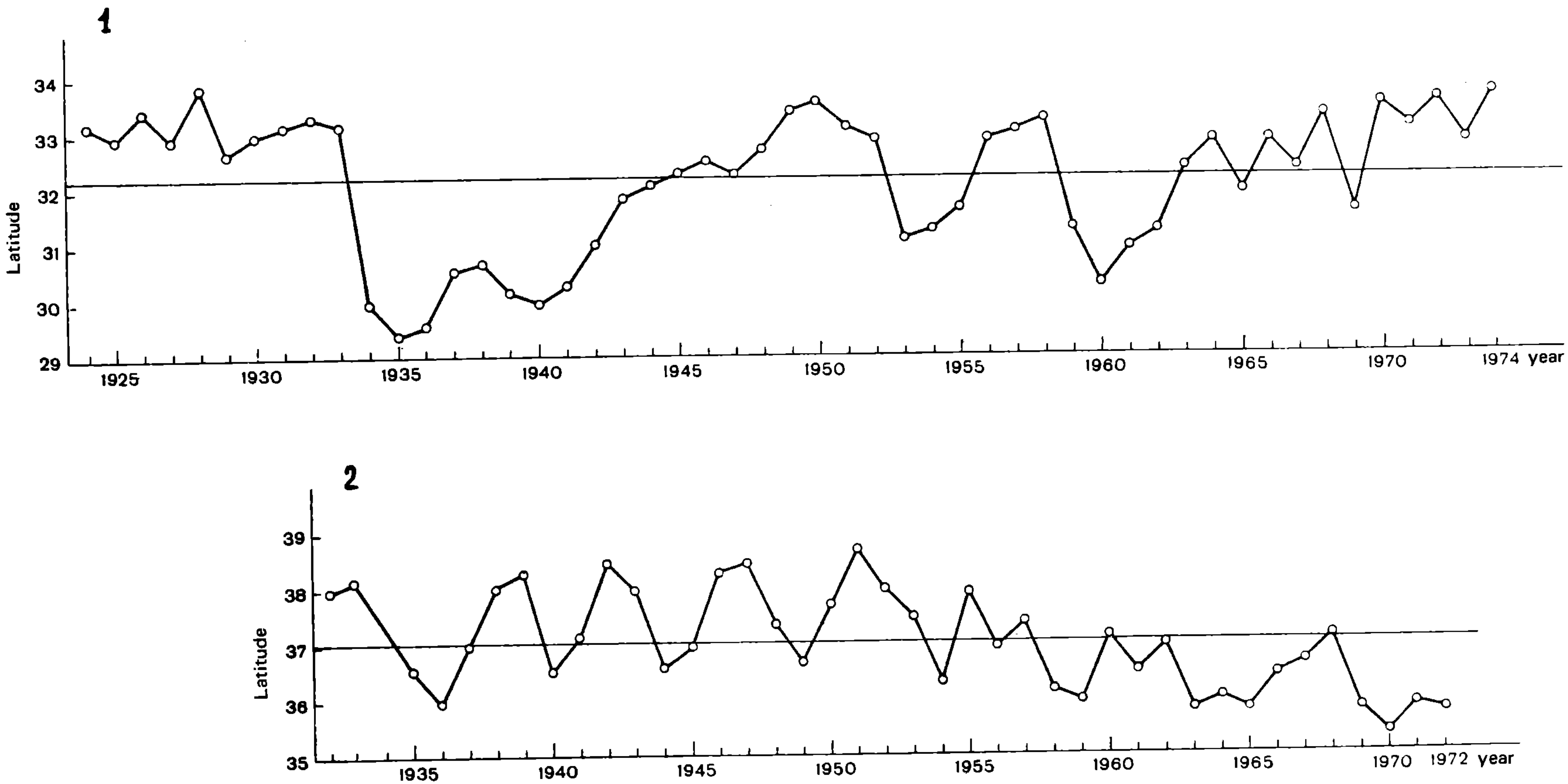


Fig. 6 Position (latitude North) of the axis of the Kuroshio in summer off the south (1) and east (2) coasts of the island of Honshu.

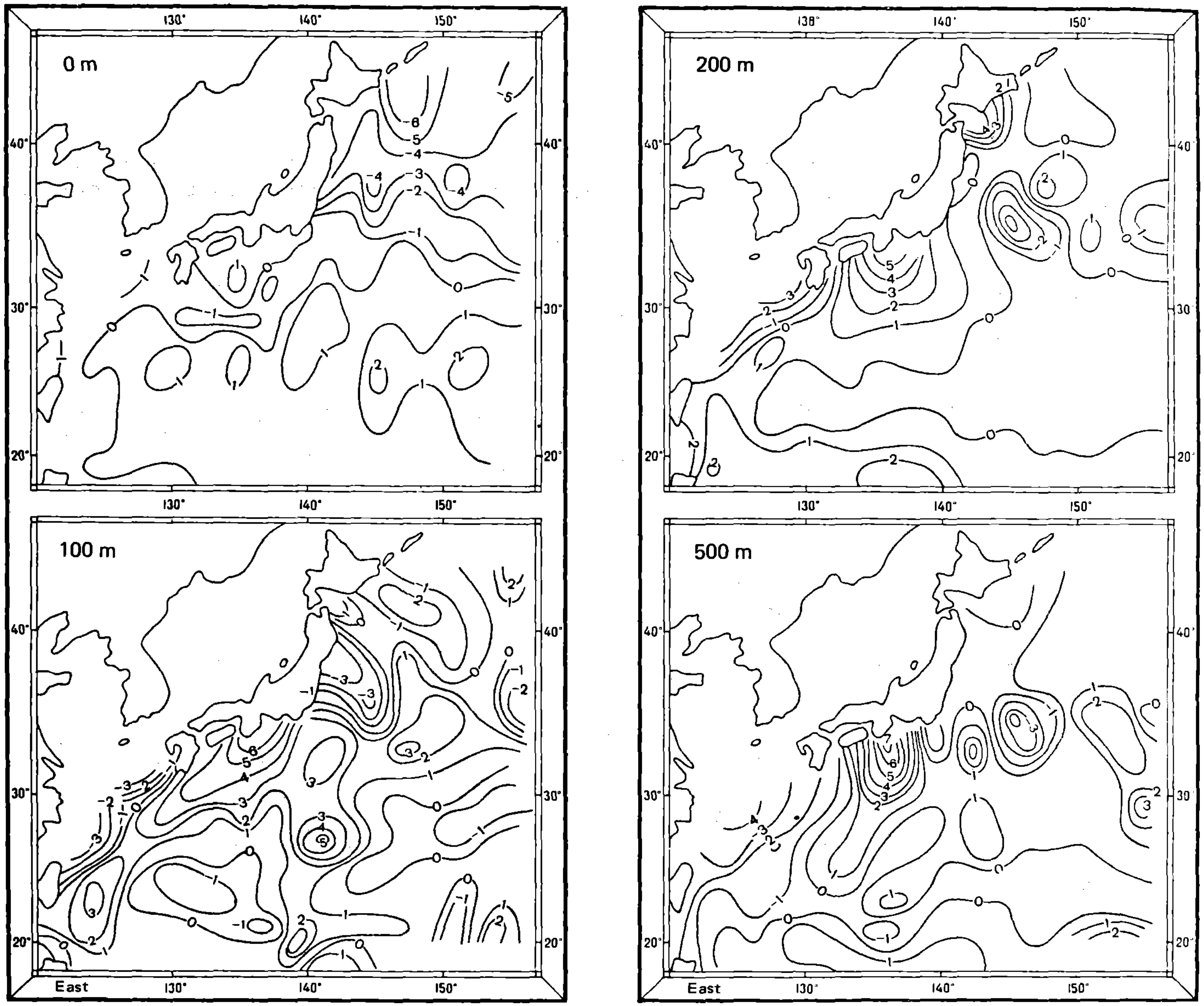


Fig. 7 Year-to-year anomalies in water temperature (in degrees C).
Positive deviations ——1—— ; negative deviations —— -1——

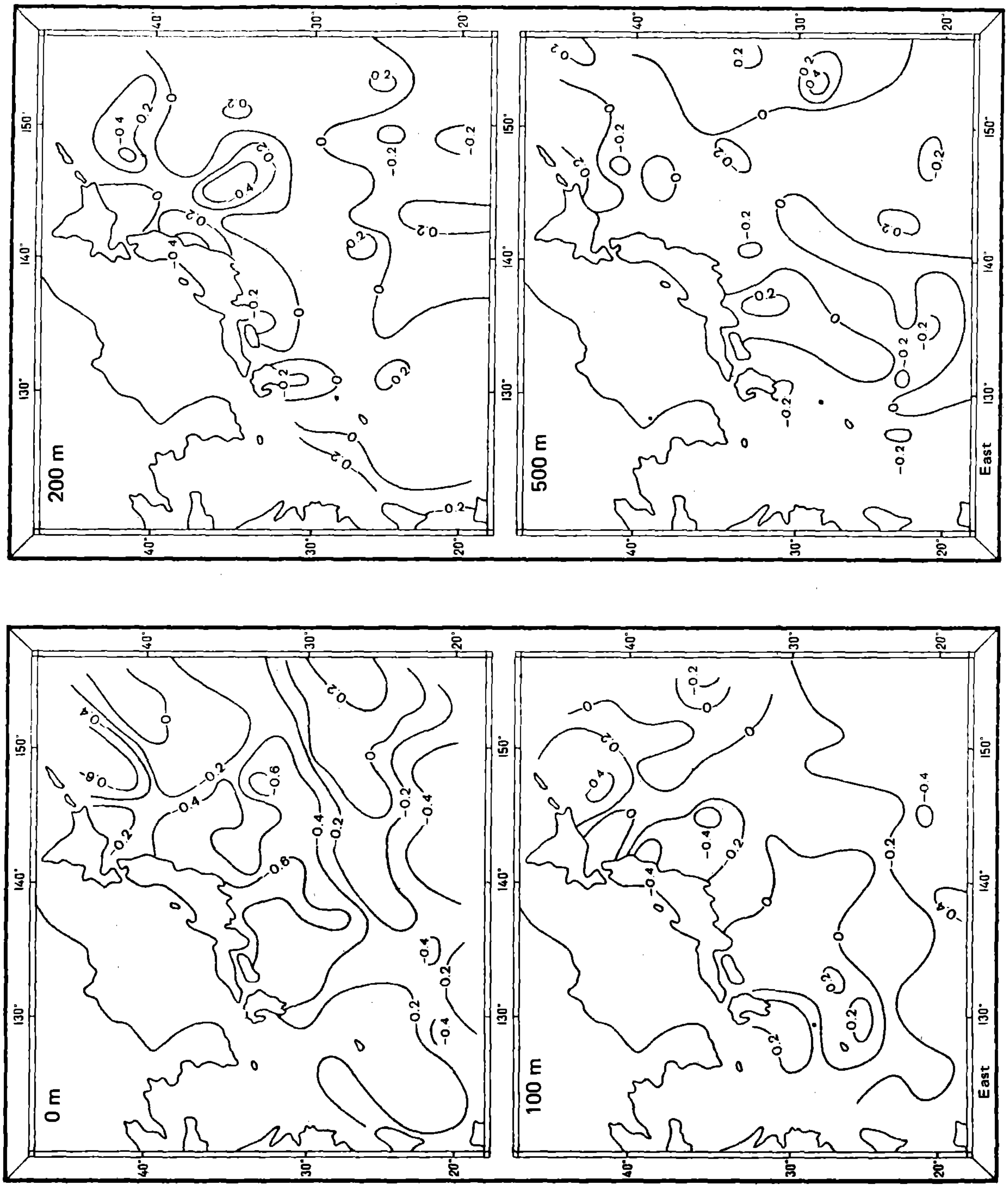


Fig. 8 Year-to-year anomalies in salinity (in parts per thousand).
Positive deviations - 1 -; negative deviations - -1 -.

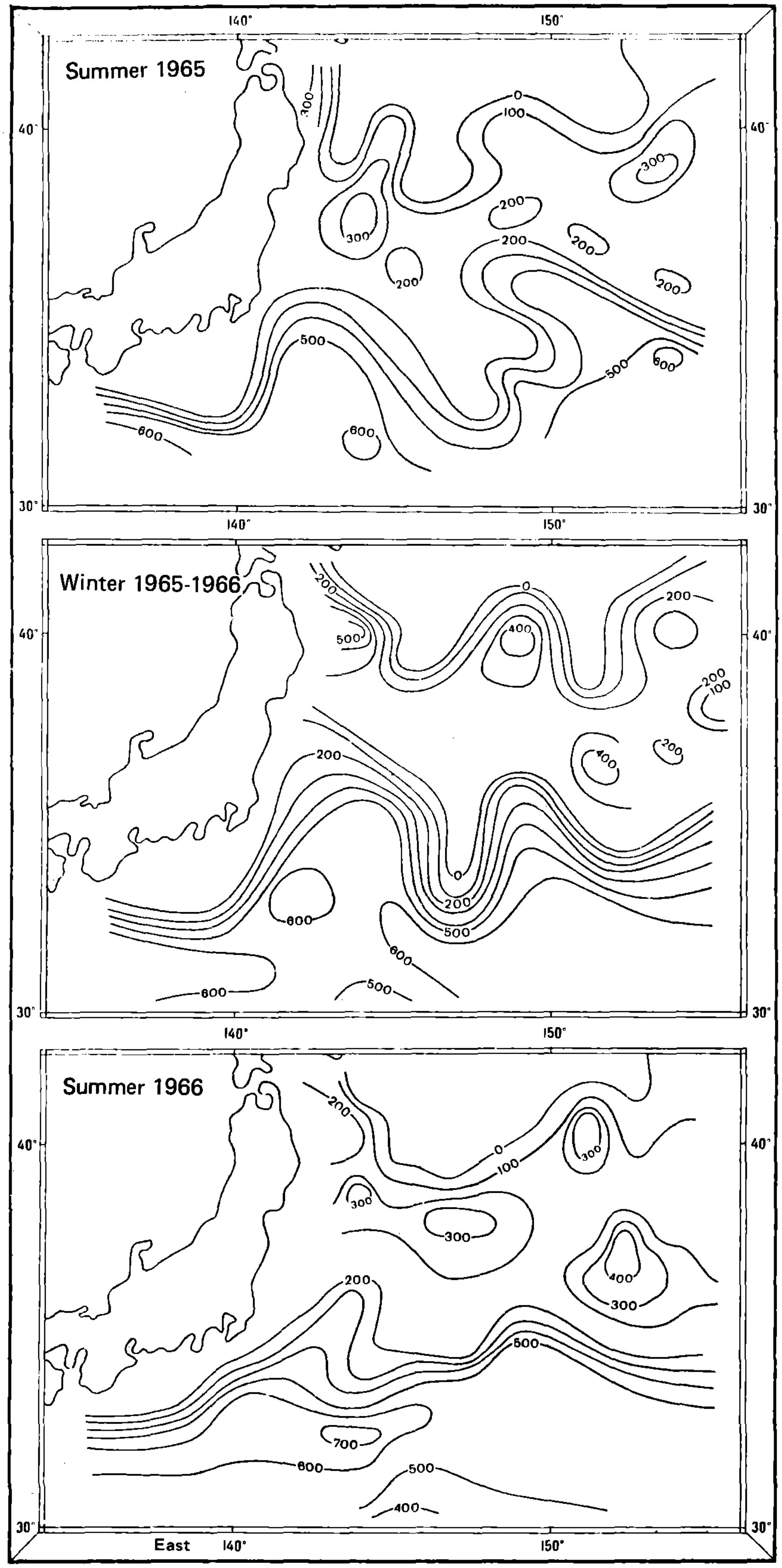


Fig. 9 Diagram showing position of subarctic front. Contours show depth (metres) of ocean thermocline.
Top figure - summer, 1965; middle figure - winter, 1965-66; bottom figure - summer, 1966.

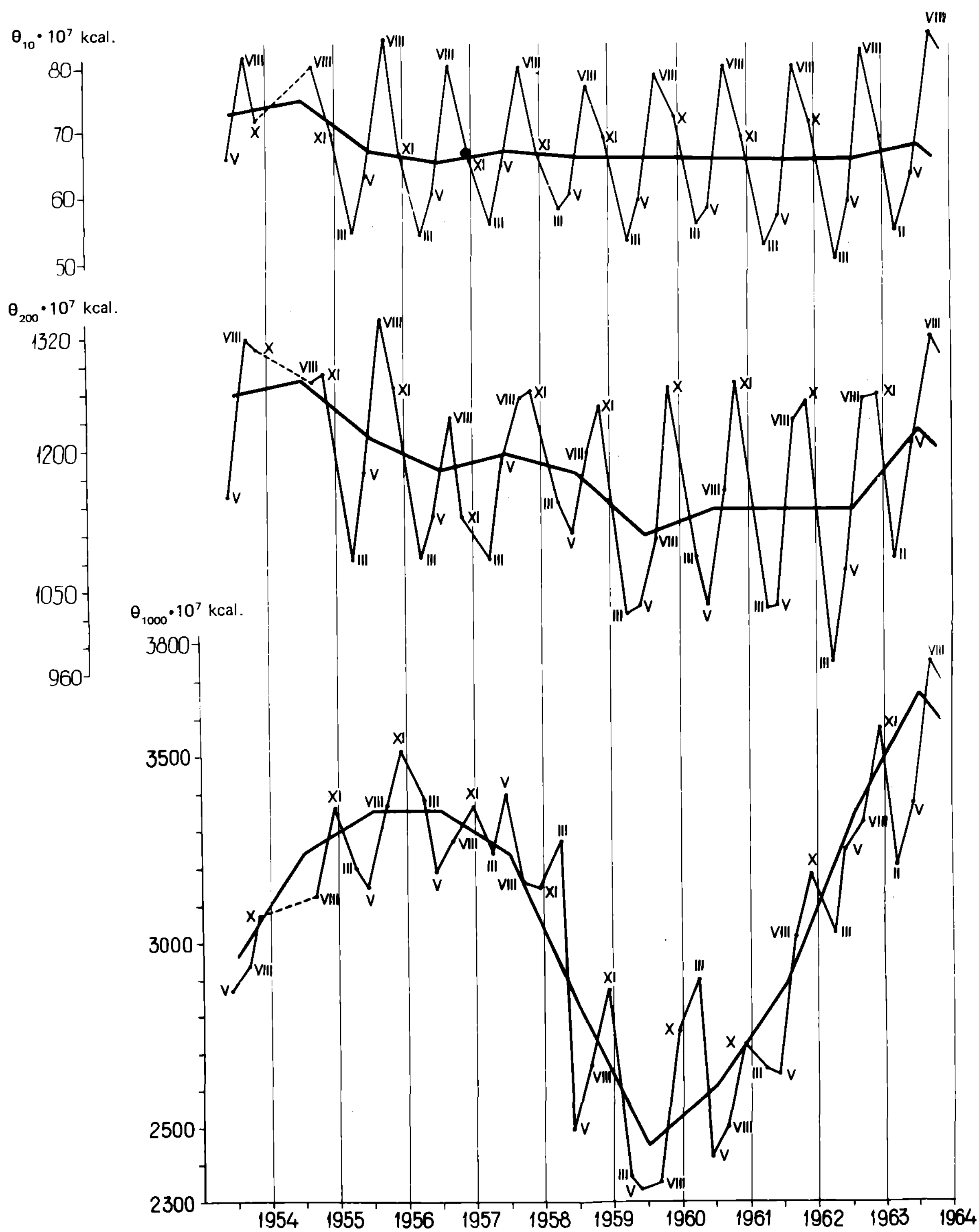


Fig. 10 Heat content (θ, in 10^7 kcal.) of the Kuroshio.
Top graph - 0-10 m. layer; middle graph - 0-200 m. layer; bottom graph - 0-1000 m. layer. Each plot shows seasonal deviation (fine lines; month in roman numerals) and annual average (thick line).

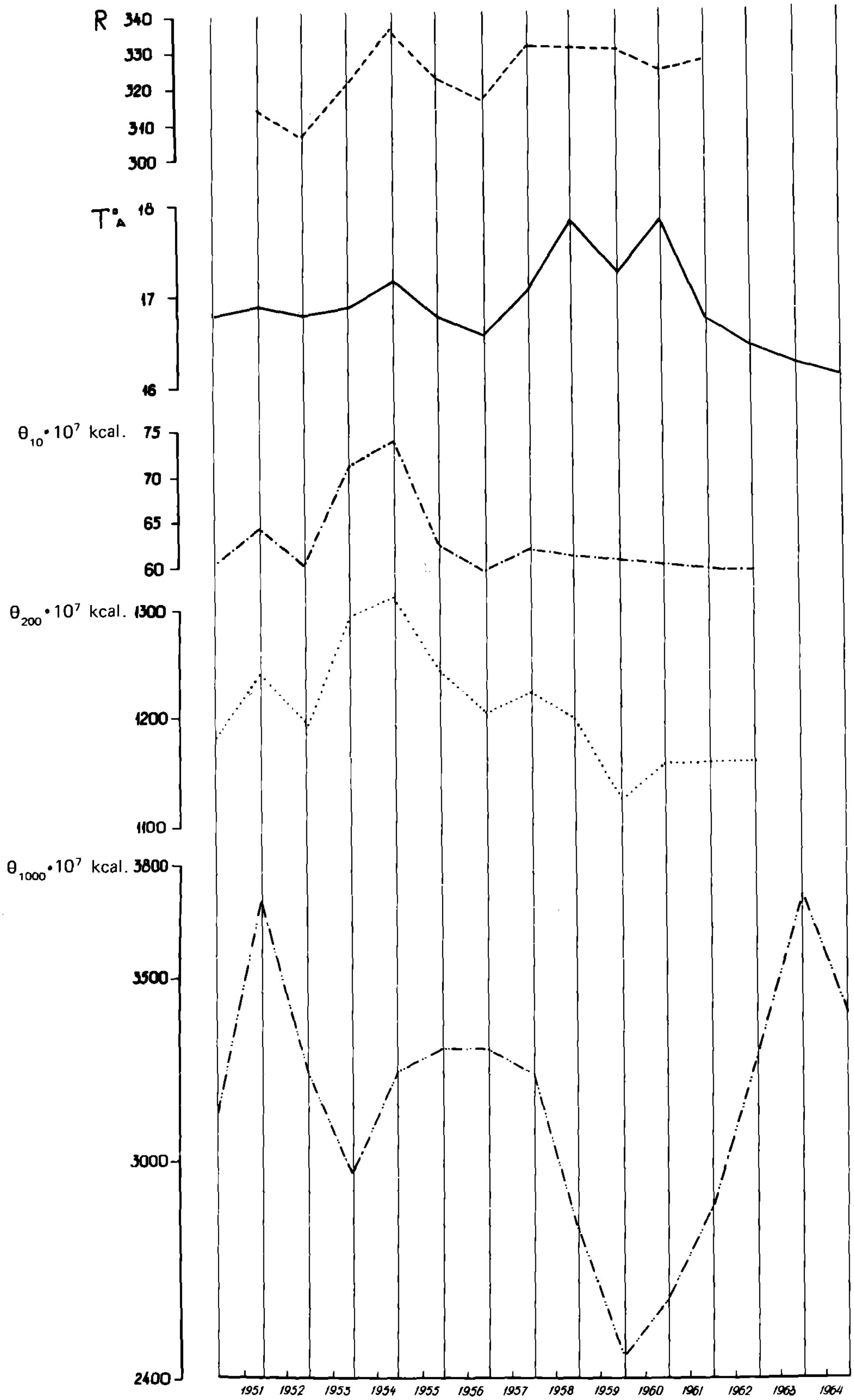


Fig. 11 Annual values of solar radiation (R, ---) in kcal/cm^2 per 24-hr. period; mean annual air temperature (T,——) in °C (at the Shiono Misati station); mean annual heat content (in 10^7 kcal.) (-.-.-.-), in the 0-200 m. layer (·····), and in the 0-1000 m. layer (-··-··-)

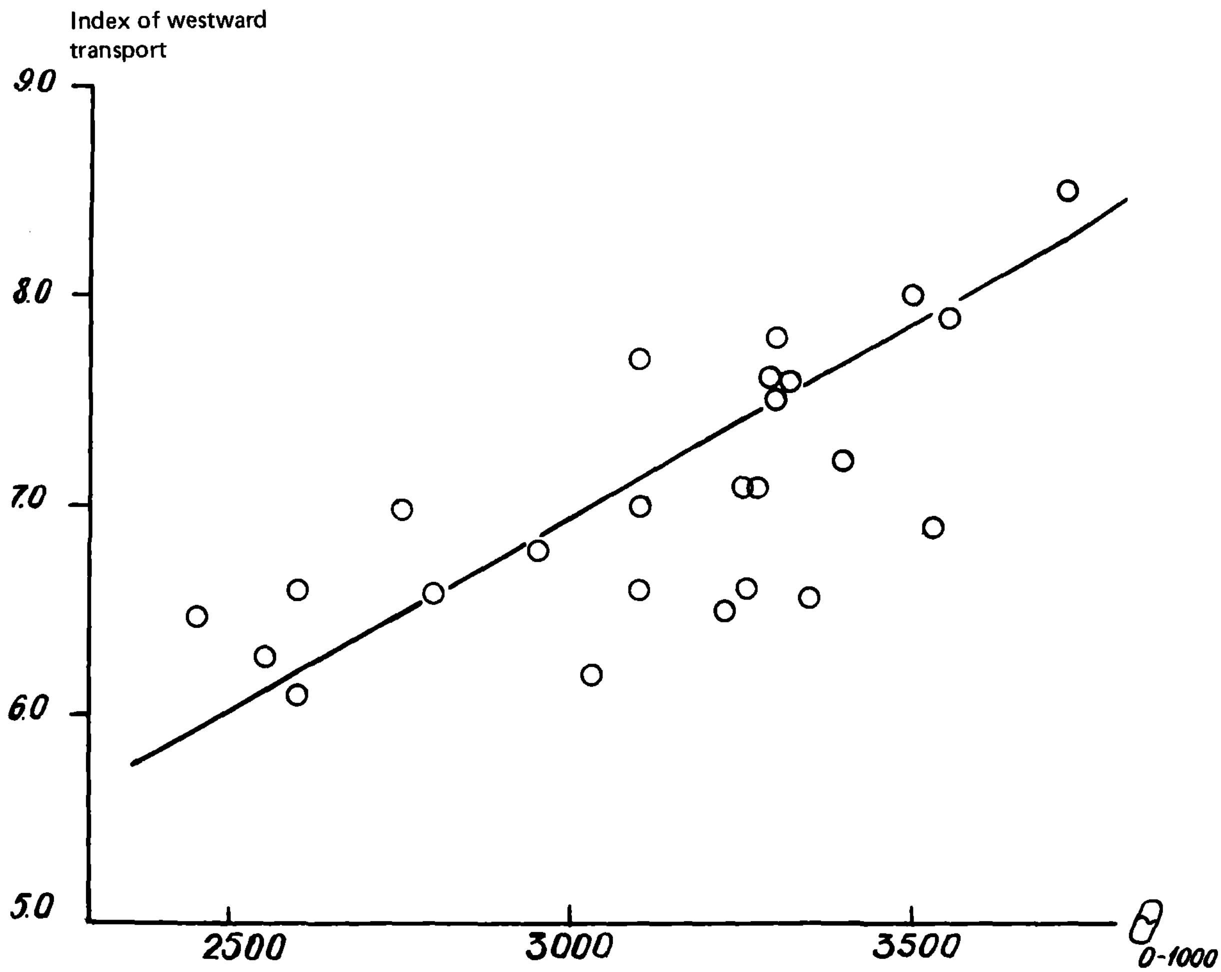


Fig. 12 Plot of index of westward transport (J) against heat content (θ) in the upper 1000 m. of the Kuroshio current.

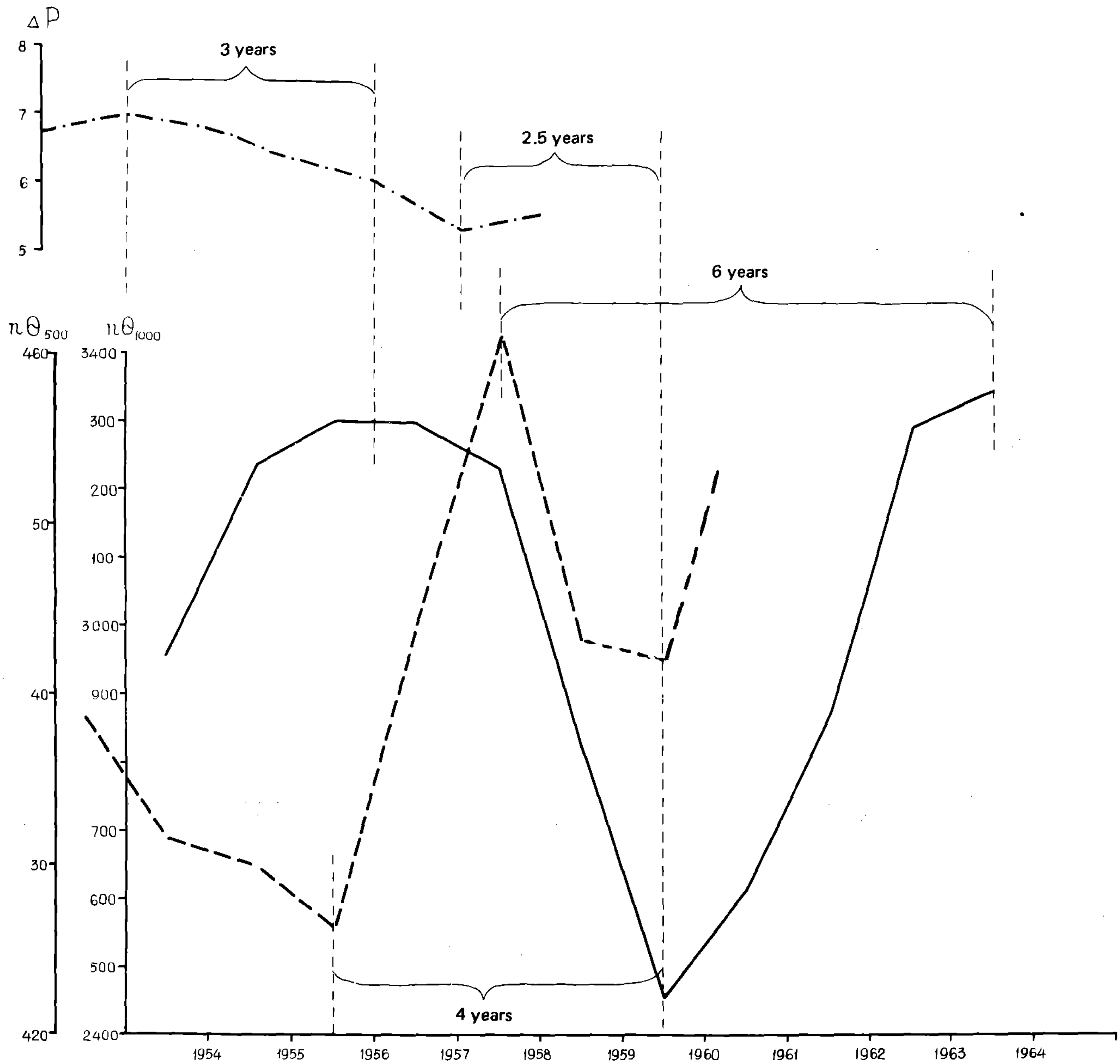


Fig. 13 Plots of: mean atmospheric pressure gradient (ΔP) along 6 sections from longitudes 125°W to 160°E for the northern trade-wind zone (— · — · — ·); heat content (θ, 0-500 m. and 0-1000 m. layers) of the Kuroshio (——), the California Current at station 8090 (— — — —). The vertical dashed lines mark off several intervals (from top to bottom: 3 years, 2.5 years, 6 years and 4 years, as indicated by the horizontal brackets).

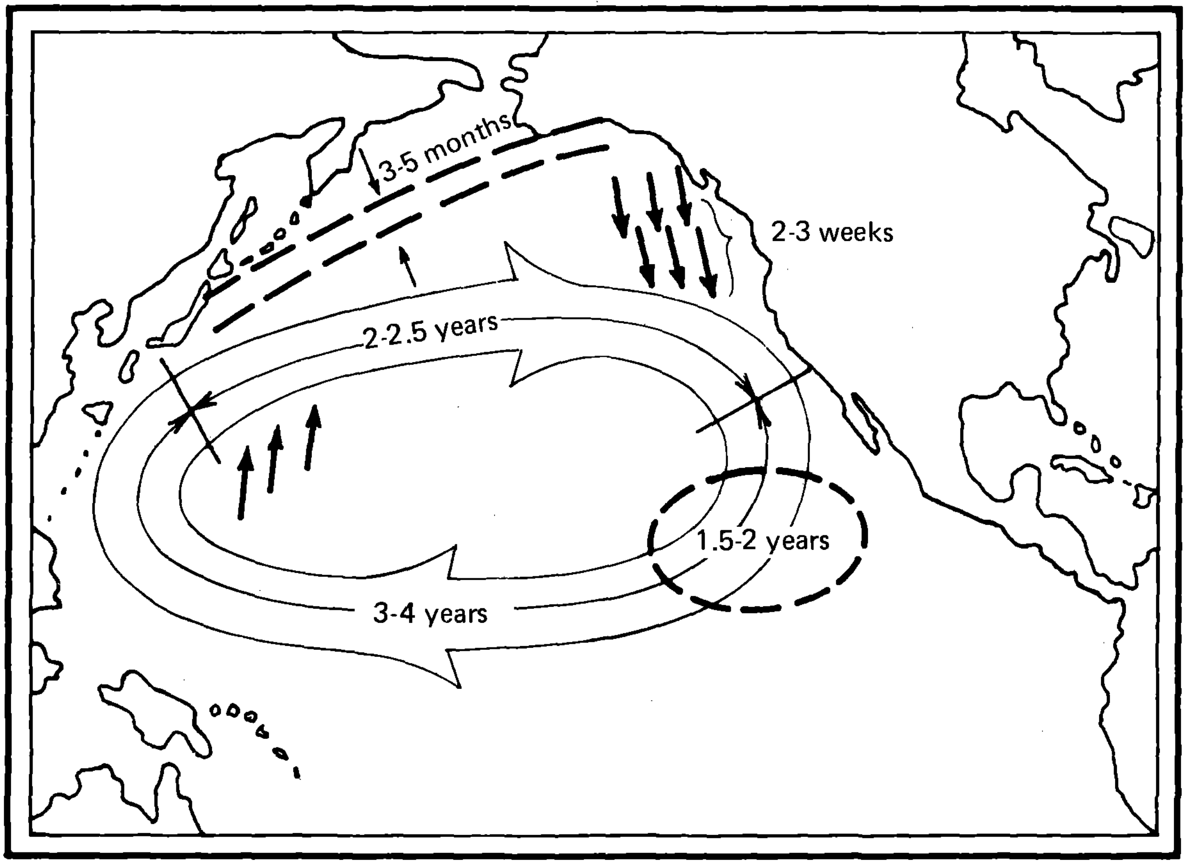


Fig. 14 A proposed model of large-scale air-sea interaction in the North Pacific Ocean.

DISCUSSION[1]

PROFESSOR ROLL

I think we should be very grateful to Professor Kort for giving us this very informative lecture. I expected that Professor Robinson would give us a lecture on modelling the ocean circulation, in order to understand why meanders occur, and I had hoped that Professor Kort's lecture would be an analysis of the results of observational material. And so it turned out exactly as I had hoped.

DR. TERADA

May I say a few words of congratulation for the lectures in connection with CSK which have been arranged by Professor Roll. As Professor Sugawara said, I proposed the research of the Kuroshio current in 1962. At that time I was the Chief of the Marine Division of the Japan Meteorological Agency.

In Japan, the Japan Meteorological Agency, the Hydrographic Office and the Fisheries Agency had been carrying out a systematic study of the Kuroshio only in the southern part of Japan and we had decided that it was extremely important to expand the region of the Kuroshio study to the eastern part of the Philippines. Therefore on the occasion of the third session of the Commission, I proposed this idea and the CSK was officially adopted as a co-operative investigation of the Commission. The CSK research has been carried out very actively and successfully with the collaboration of the enthusiastic oceanographers of various countries which joined the CSK project. The voluminous data of the CSK have been analysed by the Kuroshio Data Centre where Dr. Shoji, who is now sitting next to me, was in charge at the time and already many CSK atlases, newsletters and publications have been published. It was my great pleasure and also surprise that the CSK extended so rapidly; this was due to the international co-ordination system carried out under the IOC. Again I would like to congratulate all concerned on the very fruitful results achieved in the CSK.

PROFESSOR ROLL

Thank you, Dr. Terada, for this information on the historical background of CSK.

This then is the end of our Anton Bruun Memorial Lectures of this Assembly which, I think, has provided us with a good report on the present state of the results of this very important co-operative investigation carried out under the auspices of IOC. I thank the speakers again and am grateful to you for your continuous attention.

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(1) Names and titles of speakers are found at the end of the publication.

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