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Water Circulation Patterns on Flemish Cap from Observations in 1977–82

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Abstract

Analysis of geostrophic circulation charts, based on oceanographic data from 26 surveys of Flemish Cap by USSR research vessels from December 1977 to April 1982 and a Canadian survey in January 1979, confirmed that the anticyclonic gyre is the prevailing form of water circulation, which favor the retention of ichthyoplankton, mainly eggs and larvae of cod and redfish, on the bank. Destruction of the gyre by the passage of frequent storms results in a meandering flow across the bank, providing conditions which favor the transport of eggs and larvae away from the bank and their loss from the Flemish Cap ecosystem. Therefore, the relative stability of the anticyclonic gyre during the period from spawning until the larvae are able to avoid massive transport by currents is an important element in determining the success or failure of year-classes of Atlantic cod and Atlantic redfish in the area.

Introduction

A coordinated international research program for Flemish Cap was developed by the Environmental Working Group of the International Commission for the Northwest Atlantic Fisheries (ICNAF) in May 1977 and approved for execution at the 1977 Annual Meeting (ICNAF, 1977). With the termination of ICNAF in 1979, the program was continued under the aegis of the NAFO Scientific Council (NAFO, 1980). The main objectives of the program involved studying the effects of biotic and abiotic factors on reproduction and year-class success of the major commercial fish stocks on Flemish Cap (NAFO Div. 3M) by frequent hydrobiological and ichthyological observations.

The results of previous studies of water circulation on Flemish Cap (Buzdalin and Elizarov, 1962; Kudlo and Burmakin, 1972; Kudlo and Borovkov, MS 1975; Kudlo *et al.*, MS 1976; Kudlo and Boytsov, MS 1977) indicated the existence of an anticyclonic gyre over the central part of the bank. Further studies (Kudlo and Borovkov, 1977, Kudlo and Boytsov, 1979) showed that year-class strength of Atlantic cod (*Gadus morhua*) on Flemish Cap depended mainly on the dynamic state of the anticyclonic water circulation during early ontogenic stages, good and poor year-classes appearing in years of intensified and weakened water circulation respectively.

This paper presents the main results of USSR oceanographic investigations on Flemish Cap during 1977–82, which were aimed at studying environmental variability and its probable effect on distribution of ichthyoplankton in the area.

Materials and Methods

The materials used for analysis of water circulation on Flemish Cap were temperature and salinity observations from more than 1,000 hydrographic stations during 26 surveys of the region from December 1977 to April 1982 by USSR research vessels and a survey by the Canadian research vessel *Hudson* in January 1979 (Gagnon, 1980). Measurements of oxygen, phosphorus and silicon were obtained during several of these surveys (Table 1).

The majority of the surveys (16) covered the area bounded by latitude lines 46° 20′ and 48° 20′N and longitude lines 43° 30′ and 46° 30′W, consisting of a grid of stations at intervals of 20′ latitude and 30′ longitude, as established by the Environmental Working Group. Observations for the remaining surveys were made at trawling stations and at stations on two perpendicular sections across the bank, one at 47° N and the other at 45° W.

Data from the hydrographic surveys were used to construct a series of charts of dynamic sea surface topography relative to the 200 db level, taking account of long-term experience which showed that this level was reasonable to use in studying currents over shallow bank areas. The data were treated by the dynamic methods interpreted by Zubov and Mamaev (1956). It is known that the results of calculations of marine current elements obtained by the dynamic method depend greatly on the observance of some conditions of its application (Zubov and Mamaev, 1956; Fomin, 1961), and it is rather difficult to determine these conditions in each concrete case.

TABLE 1. List of 26 oceanographic surveys carried out by USSR research vessels on Flemish Cap during 1977-82, and a survey by the Canadian research vessel *Hudson* in 1979.

	Vessel (cruise No.)	Year	Survey dates	No. of stations T,S	O_2	P	Si
1.	*Protsion* (16)	1977	06-26 Dec	28	—	—	—
2.	*Protsion* (16)	1978	12-22 Jan	31	—	—	—
3.	*Protsion* (16)	1978	03-12 Feb	39	—	—	—
4.	*Protsion* (16)	1978	20-27 Feb	42	—	—	—
5.	*Protsion* (17)	1978	24 May-02 Jun	43	39	38	38
6.	*Protsion* (17)	1978	17-29 Jul	51	30	31	30
7.	*Persey III* (20)	1978	26 Jul-01 Aug	36	—	—	—
8.	*Hudson*	1979	15-22 Jan	52	—	—	—
9.	*Suloy* (2)	1979	20 Mar-07 Apr	34	17	17	—
10.	*Gemma* (17)	1979	07-20 Apr	42	21	42	42
11.	*Gemma* (17)	1979	03-10 May	42	42	—	—
12.	*Suloy* (2)	1979	05-18 Jun	34	8	8	—
13.	*Suloy* (3)	1979	01-10 Sep	43	31	31	—
14.	*Protsion* (20)	1980	19 Mar-01 Apr	56	56	56	47
15.	*N. Kononov* (2)	1980	23 Apr-03 May	33	18	18	17
16.	*Protsion* (20)	1980	02-12 May	56	56	56	55
17.	*Protsion* (20)	1980	01-11 Jun	56	56	56	56
18.	*N. Kononov* (2)	1980	24 Jul-01 Aug	36	25	11	11
19.	*Protsion* (21)	1980	03-15 Aug	47	40	20	20
20.	*Gemma* (23)	1981	22 Mar-05 Apr	48	—	—	—
21.	*Gemma* (23)	1981	06-16 Apr	33	—	—	—
22.	*Gemma* (23)	1981	23-30 Apr	47	—	—	—
23.	*Gemma* (23)	1981	21-30 May	48	—	—	—
24.	*N. Kononov* (4)	1981	01-08 Jun	26	16	16	14
25.	*Protsion* (24)	1981	27 Oct-05 Nov	46	—	—	—
26.	*Persey III* (26)	1981	02-08 Dec	29	18	18	18
27.	*Suloy* (25)	1982	17-30 Apr	31	—	—	—

The recent deployment and satellite-tracking of drifting buoys on Flemish Cap by Canadian scientists (Ross, 1981) appears to be useful in studying the reliability of geostrophic circulation patterns determined by the dynamic method. The dynamic charts indicate the existence of a quasi-stationary anticyclonic gyre over the bank. Resemblance between the tracks of drifting buoys in 1979-80 with current lines on charts of geostrophic circulation for the same period from observations by the Canadian research vessel *Hudson* (Gagnon, 1980) and by USSR research vesels (Kudlo and Borovkov, MS 1980) tends to support the usefulness of the dynamic method in depicting the water circulation system on Flemish Cap, at least relative to the direction of water movement.

Results and Discussion

The charts of geostrophic water circulation on Flemish Cap, based on USSR surveys from December 1977 to June 1981 (Table 1) were previously documented (Borovkov and Kudlo, 1980, MS 1981, MS 1982; Kudlo and Borovkov, MS 1980). These together with charts from surveys in late 1981 and early 1982, are brought together as a continuous series in the Appendix to this paper.

The qualitative analysis and comparison of the whole series of dynamic charts show that the anticyclonic gyre was the prevailing form of water circulation on Flemish Cap, but other forms of water motion were observed at different times (Table 2). In general, it was possible to distinguish four types of circulation, the first two (V and V_L) being representative of anticyclonic movement with slightly different patterns of circulation. Dynamic situations corresponding to these types (Fig. 1 and 2) were observed during 67% of the surveys in 1977–82. The third type (T_M), indicative of a transient meandering flow eastward across the bank (Fig. 3A), was evident only during 7% of the surveys. The fourth type (M), showing the simultaneous indication of local gyres and transient flow across the bank (Fig. 3B), was observed during 26% of the surveys. The prevalence of a quasi-stationary anticyclonic gyre on Flemish Cap during most of the 1977–82 surveys is consistent with the analysis of mean water circulation in the region from observations during 1962–78 (Kudlo *et al.*, 1980).

TABLE 2. Types of geostrophic water circulation on Flemish Cap and their frequency from surveys in 1977-82.

Characteristics of circulation types	Water circulation type	Surveys showing specific types No.	%
Vastly pronounced anticyclonic gyre	V	12	44.5
General anticyclonic circulation with local centers of rotation	V_L	6	22.2
Transient meandering flow across the bank	T_M	2	7.4
Mixed circulation with some indication of types V, V_L and T_M	M	7	25.9

TABLE 3. Monthly distribution of types of geostrophic water circulation on Flemish Cap from surveys in 1977-82.

Month	No. of surveys by circulation type V	V_L	T_M	M	Total
Jan	2	—	—	—	2[a]
Feb	—	—	1	1	2
Mar	1	—	1	1	3
Apr	—	4	—	1	5
May	3	—	—	1	4
Jun	2	1	—	—	3
Jul	1	—	—	2	3
Aug	—	—	—	1	1
Sep	—	1	—	—	1
Oct	—	—	—	—	—
Nov	1	—	—	—	1
Dec	2	—	—	—	2
Total	12	6	2	7	27

[a] Includes survey by Canadian research vessel *Hudson* in January 1979.

The available data are inadequate for determining reliable statistical characteristics of water circulation processes. However, the seasonal nature of circulation types is given in Table 3. Prevailing types (V and V_L) were observed during most months of the year, and the mixed type (M) occurred in winter, spring and summer,

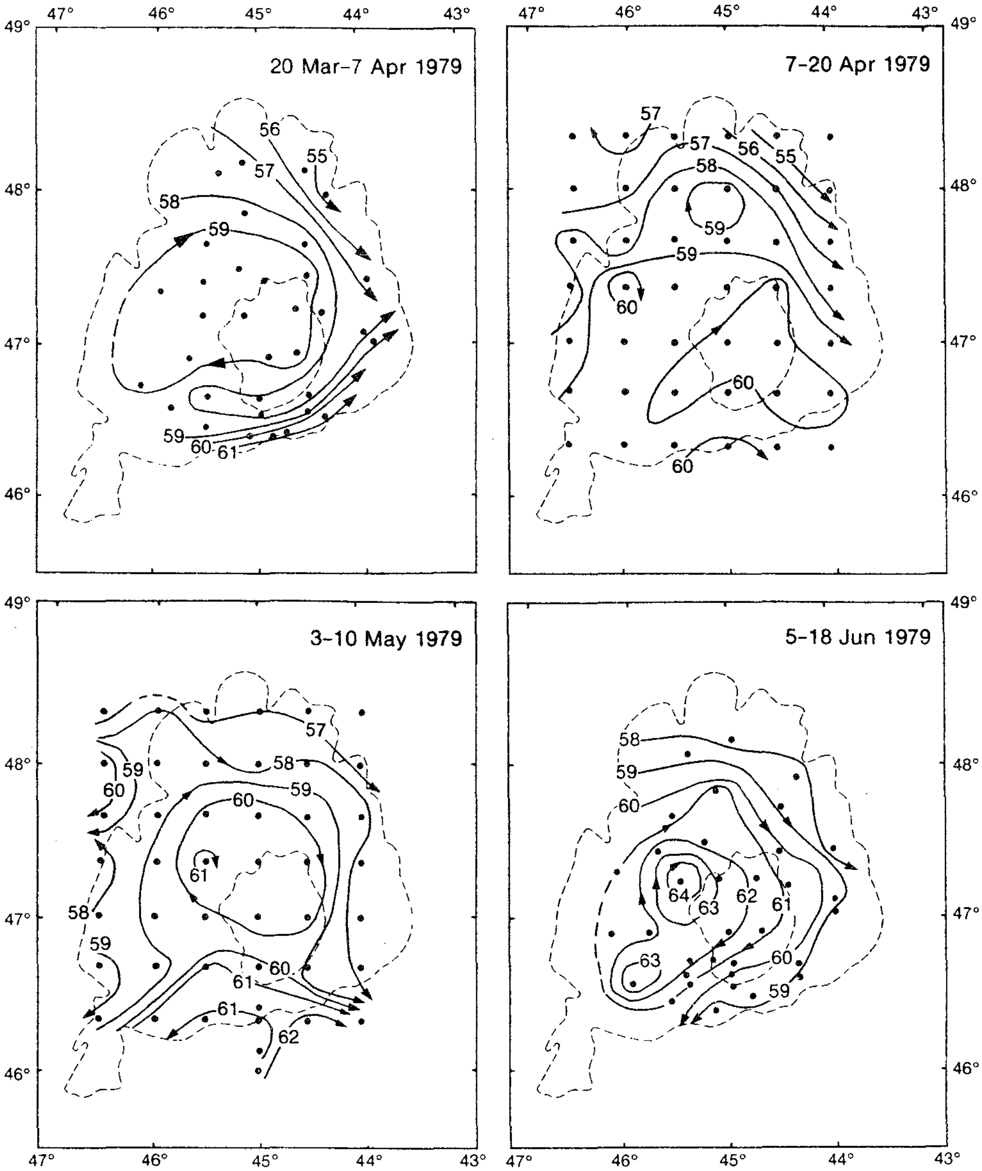

Fig. 1. Geostrophic water circulation on Flemish Cap, relative to the 200 db level, from four surveys in the spring of 1979.

whereas the transient type (T_M) was evident only in winter.

The analyses of hydrochemical data, obtained during certain surveys (Table 1), indicate the association of different concentrations of dissolved oxygen and other substances with circulation types (Fig. 4 and 5). When the anticyclonic gyre was present over the bank (types V and V_L), the relative and absolute content of dissolved oxygen was minimum in the surface layer of the central part of the gyre (Fig. 4A and 4B). At 100 m, the oxygen content of the water tended to be maximum (Fig. 4C), whereas the concentration of silicon was minimum (Fig. 4D). Changes in the concentration of phosphorus tended to follow the same pattern as silicon. These changes in concentration of hydrochemical substances may be explained by downwelling in the central part of the gyre and upwelling around its periphery. Due to convergence, the oxygenated surface water flows from the periphery toward the center of the vortex, with some oxygen being expended during the process. Nevertheless, more oxygen is left in the surface water than in the deeper layers, and downwelling in the center of the vortex results in increased oxygenation of water at intermediate depths. On the other hand, the concentration of biogenous substances decreases considerably (due to biological processes) during the flow of surface water from the periphery to the center of the vortex. The concentration of these substances increases rapidly during the downwelling process from the photic to the intermediate layer, and replenishment of their deficiency in the surface layer occurs during upwelling of intermediate water to the surface at the periphery of the gyre.

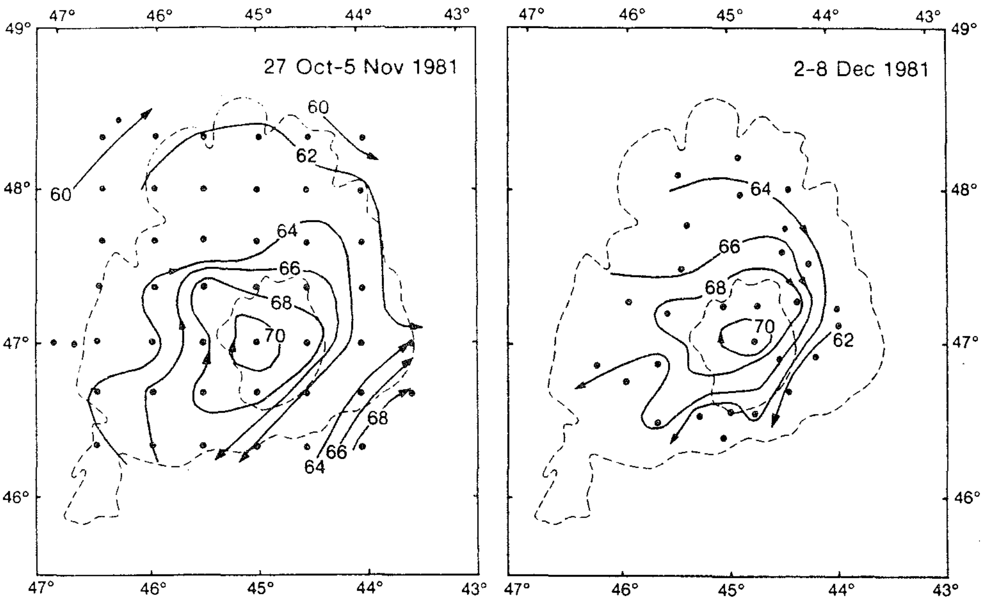

Fig. 2. Geostrophic water circulation on Flemish Cap, relative to the 200 db level, from two surveys in late autumn of 1981.

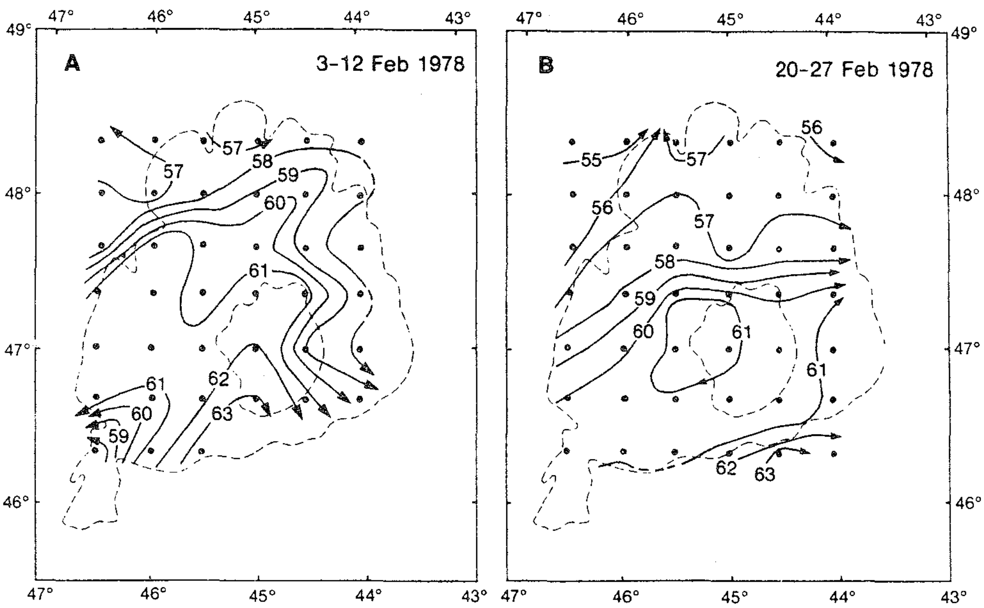

Fig. 3. Geostrophic water circulation on Flemish Cap, relative to the 200 db level, from two surveys in February 1978.

During periods when water circulation on Flemish Cap was in the form of a meandering flow (types T_M and M), the distributions of hydrochemical substances were different from those associated with the anticyclonic gyre. The distributions of oxygen and silicon in the near-surface layer (approximately 0–50 m) show little evidence of local extremes in concentration over the center of the bank (Fig. 5A and 5C), whereas the distributions of phosphorus and silicon at 100 m (Fig. 5B and 5D) do show the formation of local maxima in the region where the meander over the northern half of the bank (Appendix Chart 14) is greatest.

A comparative analysis of atmospheric processes preceding the formation of each dynamic situation was made in an effort to determine the reasons for the variability in water circulation on Flemish Cap. For this purpose, many daily weather maps for the northern hemisphere, constructed by the USSR Hydrometeorological Centre, were analyzed concurrently with a series of charts of surface dynamic topography. From the qualitative comparisons, it was found that the change in type of geostrophic water circulation was connected with storm activity in the Flemish Cap area. In the absence of storms for extended periods, the water cir-

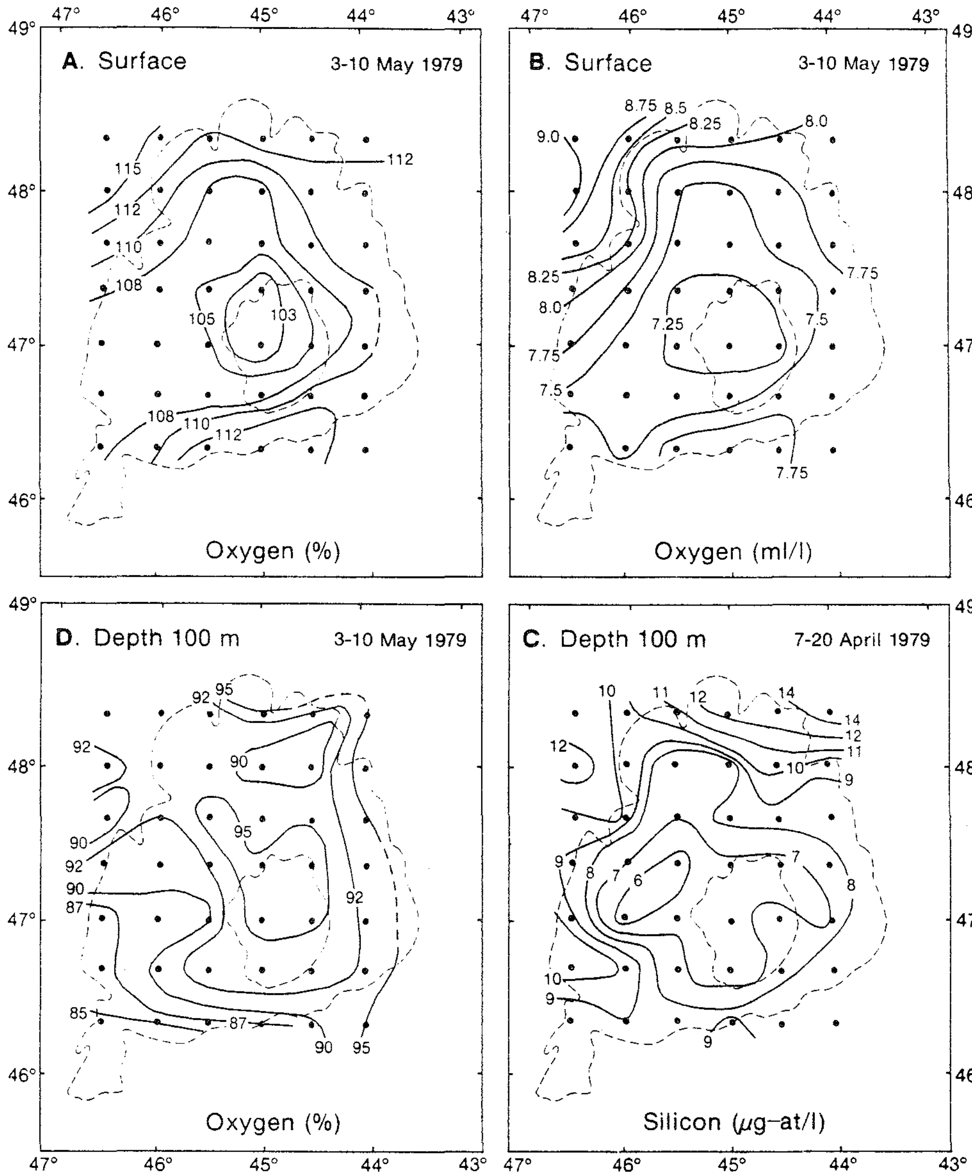

Fig. 4. Distribution of hydrochemical elements in Flemish Cap water for circulation types V and V_L: **A**, relative content of oxygen at the surface in May 1979; **B**, absolute content of oxygen at the surface in May 1979; **C**, relative content of oxygen at 100 m in May 1979; **D**, concentration of silicon at 100 m in April 1979.

culation pattern was in the form of an anticyclonic gyre (types V and V_L). The periodic destruction of the gyre occurred following the passage of one or more successive atmospheric disturbances (cyclones) over the shallow part of the bank or severe storms passing in the vicinity of Flemish Cap. Characteristic effects of the storms are rapid changes in the water circulation pattern under the influence of strong winds and the comparatively long life of the disturbances. Similar conclusions were drawn from investigations of tropical disturbances (hurricanes and typhoons) in the open areas of the ocean (Leipper, 1967; Tunegolovets, 1976; Pudov *et al.*, 1978; Fedorov, 1979).

When analyzing the variability of water circulation on Flemish Cap, one questions why the most frequent dynamic water formations are anticyclonic in nature. The answer lies in Taylor's theory of columns which has as its basis the principle of potential vortex formation. This has been shown theoretically (Huppert, 1975; Huppert and Bryan, 1976; McCartney, 1975) and experimentally (Taylor, 1923; Davis, 1972) to lead to anticyclonic dynamic disturbances (vortex, meander, and their combination) over topographical features such as mountains and banks. According to Huppert and Bryan (1976), the form of the topographically-generated disturbance is dependent on the following

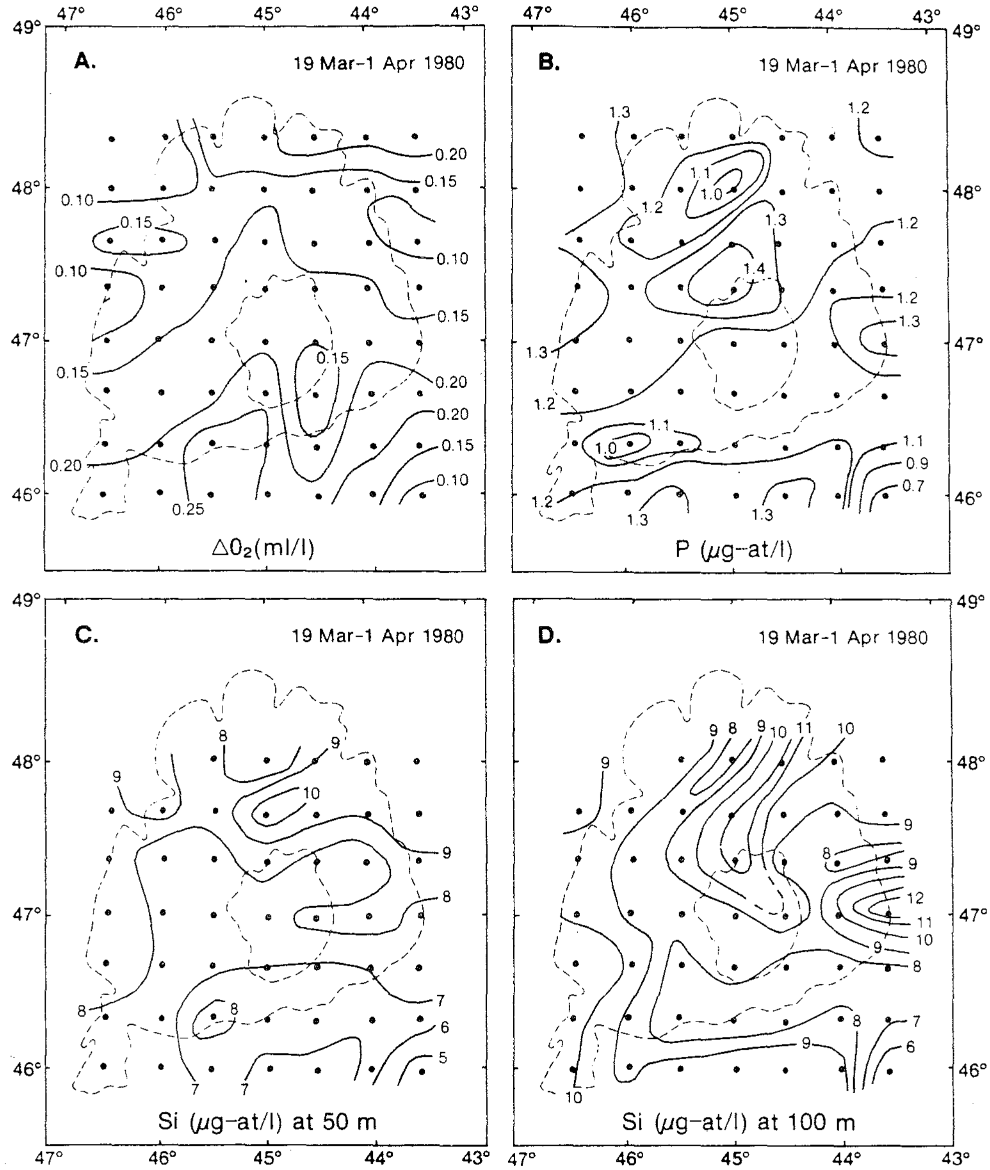

Fig. 5. Distribution of hydrochemical elements in Flemish Cap water for circulation type T_M in March 1980: **A**, mean oxygen content in the layer from the surface to compensation depth; **B**, concentration of phosphorus at 100 m; **C**, concentration of silicon at 50 m; **D**, concentration of silicon at 100 m.

three parameters: degree of fluid stratification, height of the feature, and velocity of oncoming flow. Under conditions of kinematically-homogeneous current and uniformly-stratified medium, for a weak flow and/or strong stratification when there is insufficient energy available to lift the fluid through a vertical displacement comparable to the height of the feature, part of the fluid is forced to move laterally around the feature, forming an anticyclonic vortex. In the case of a strong flow and/or weak stratification, the circulation is in the form of an anticyclonic meander. On this basis, if the changes in velocity of the current flowing towards Flemish Cap is caused by winds, meandering currents would be expected after the passage of severe storms and an anticyclonic vortex in periods of weak storm activity.

To obtain a clearer view of the variability in water circulation on Flemish Cap and the underlying causes, special investigations should be undertaken with realistic analytical or numerical hydrodynamic models. However, regularities in temporal variability of water circulation may be determined from the available data without elucidation of the underlying mechanism. In particular, it is possible to define the pattern of seasonal variability in circulation in greater detail than was done by Borovkov and Kudlo (1980), from an analysis of storm activity in the area. Climatic data from the Atlas of Oceans (Anon., 1977) were used as the basis of the trends illustrated in Fig. 6. Annual variations in wind frequency and mean velocity are very pronounced and show a similar trend, with maximum in winter (February) and minimum in summer (July). On

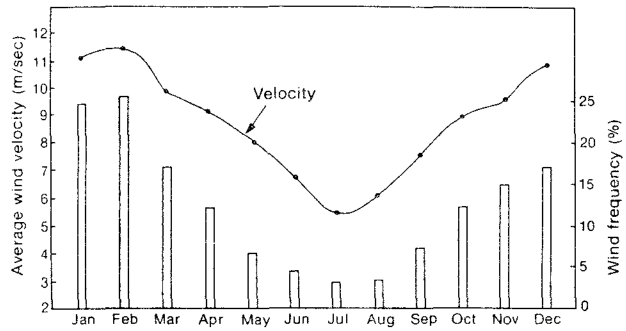

Fig. 6. Monthly variation in wind frequency at speed ⩾16 m/sec (bars) and in mean wind velocity (curve) in the Flemish Cap area (47° N, 45° W).

this basis, it would be expected that the frequency of T_M and M circulation types will, on the average, be maximum in late winter and minimum in late summer. Despite the scantiness of the information on circulation types (Table 3), it is interesting to note that meandering types (T_M and M) were observed during four of the five surveys in February–March.

Variability in ichthyoplankton abundance is one of the most important biological effects of spatial-temporal variation in horizontal water circulation on Flemish Cap, as indicated by observations on distribution of cod eggs and larvae in the area (Serebryakov, 1967). Retention of ichthyoplankton on the bank is likely to occur during periods when the anticyclonic gyre is the prevailing feature of water circulation in the area. The destruction of the gyre and formation of a meandering flow across the bank results in mass transport of eggs and larvae away from the bank. Therefore, the stability of the gyre is one of the main factors regulating the retention of ichthyoplankton within the Flemish Cap ecosystem. In view of the foregoing observations on meteorological conditions in relation to water circulation patterns, it is reasonable to suppose that the probability of ichthyoplankton retention on the bank also varies during the year, with the maximum occurring in summer. Hence, conditions are generally favorable for fish species (e.g. cod and redfish) in which spawning and early development of larvae occur in spring and summer and unfavorable for species whose larvae are subject to drift by surface currents in winter.

Year-to-year variation in retention of ichthyoplankton is undoubtedly one of the reasons for variability in year-class strength of major species. In particular, good year-classes of cod and redfish would be expected to occur in years when a high frequency of V and V_L circulation types prevailed during the period from spawning until the larvae have acquired the ability to avoid considerable transport by currents. Validation of this hypothesis would require very detailed information on distribution of eggs and larvae during the early stages of development coincident with reliable information on variation in water movements over the bank. The development of remote-sensing technology via satellites has added a new dimension to the study of oceanography in permitting the continuous monitoring of sea-surface temperatures and water movements, but standard oceanographic surveys are still needed to obtain information on ichthyoplankton distribution and abundance.

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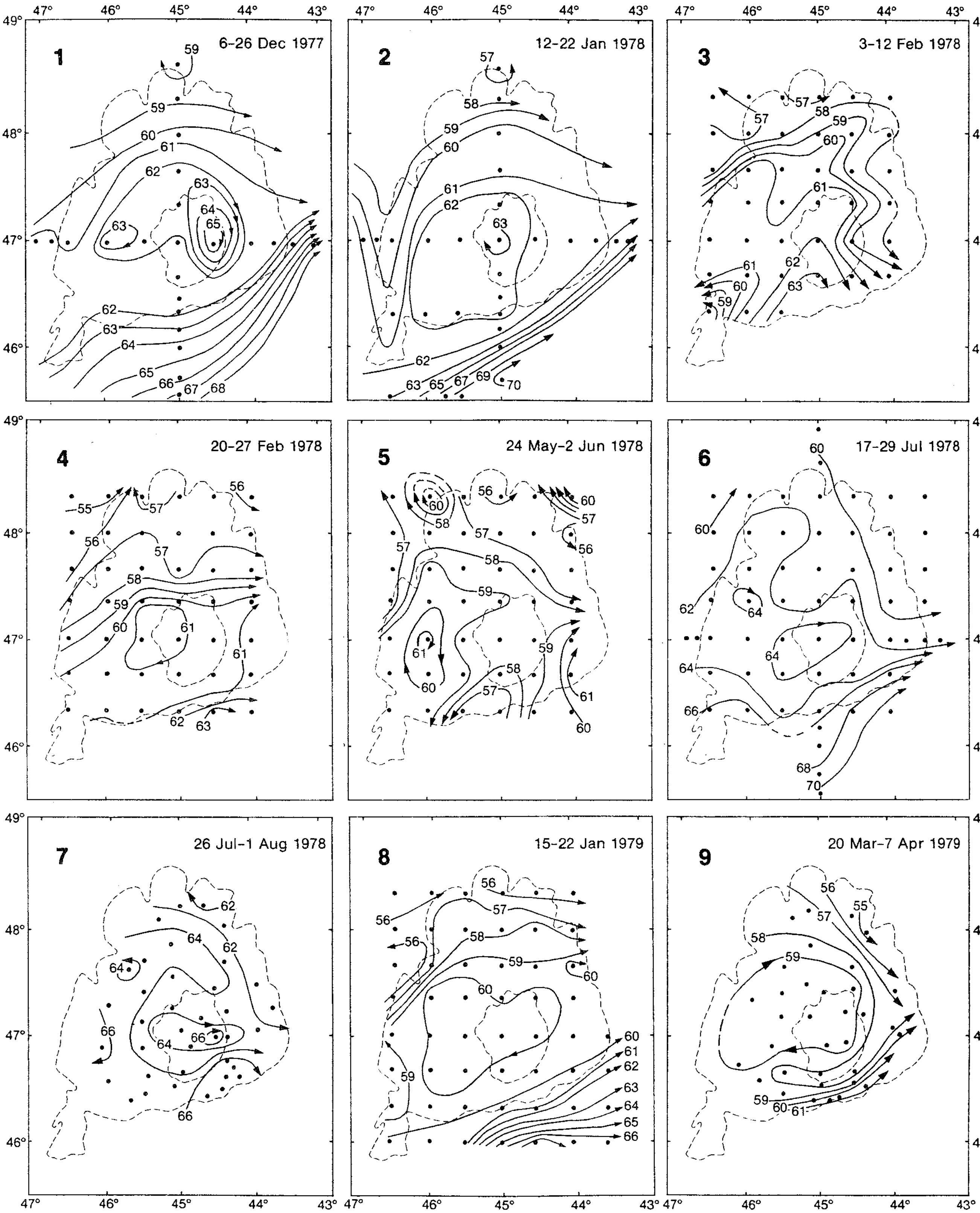
Appendix

Geostrophic Water Circulation Charts for Flemish Cap, Numbered as Listed in Text Table 1.



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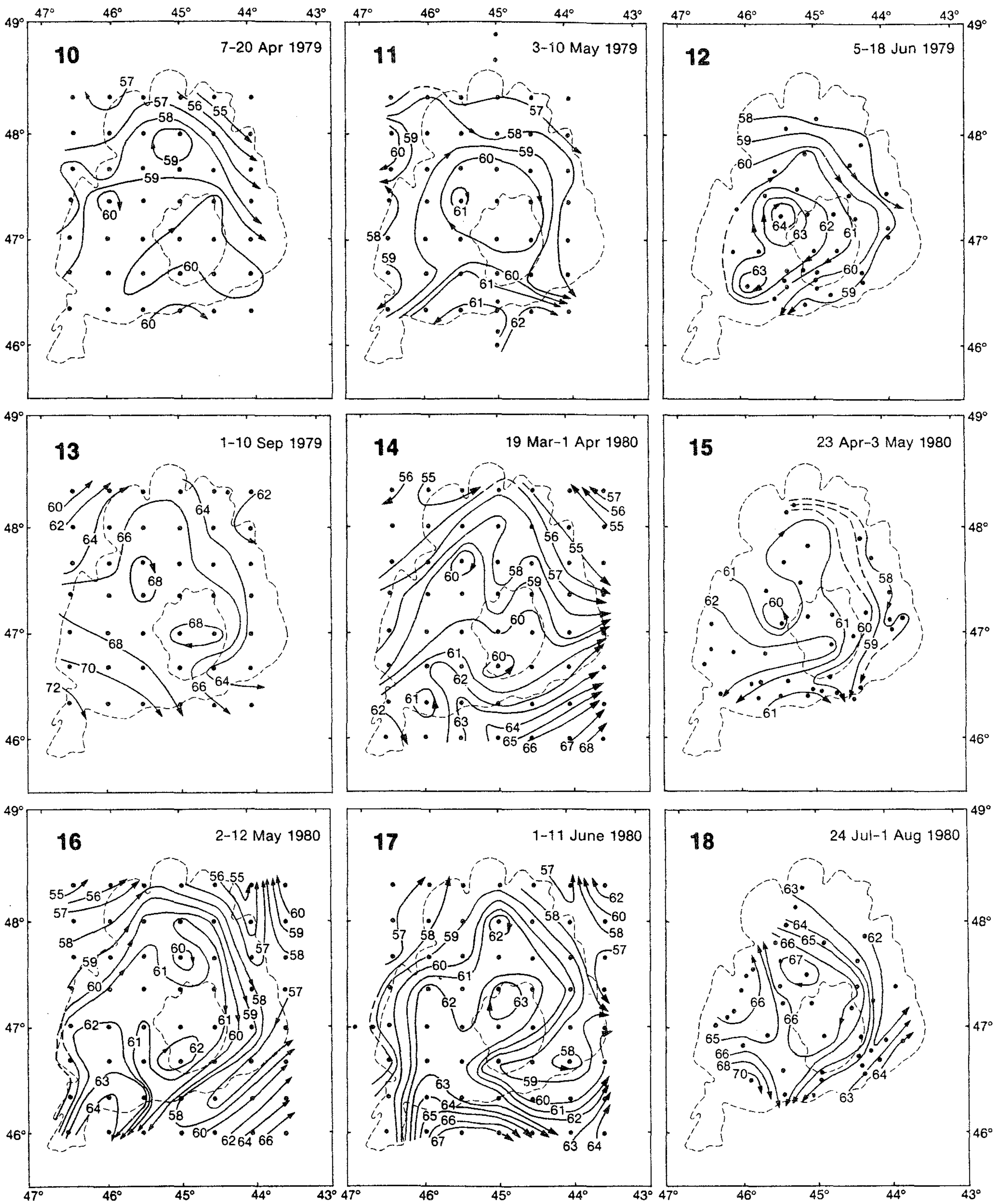

Appendix (continued)