Nutrients and fertility of Icelandic waters

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ABSTRACT

Nutrient distribution in the waters around Iceland is described and examined for different regions in relation to vertical mixing and oxygen saturation. Mean concentrations at standard depths down to 1000 m of phosphate, nitrate, silicate and percentage oxygen saturation for stations on 6 sections across the the continental shelf are presented. The deep water concentrations of phosphate and nitrate in the southern and western areas are found to be significantly higher than those in the area north of Iceland. The effect of fresh water runoff on the nutrient content of the near-surface layers is found to be insignificant with respect to phosphate and nitrate except close inshore but appreciable with regard to silica. The fresh water afflux is important, however, for the development of stratification. In the Faxaflói region nutrient uptake in spring begins about two months earlier at near-shore stations than in the deep region west of the bay and at the edge of the continental shelf south of Iceland. Generally, the uptake starts earlier in the region north of Iceland than at offshore stations in the south and west, but in warm years the uptake is delayed. There are large year to year variations in nutrient concentrations as well as vertical mixing, especially in the area north of Iceland. Normally, there is a markedly stronger stratification and smaller nutrient concentrations in the North Icelandic shelf area than in the regions of Atlantic water south and west of the country. The main reason for this difference is the admixture of low-salinity polar water in the northern region. Influx of Atlantic water provides an important nutrient source to the North Icelandic area. The $\Delta N/\Delta P$ ratio is between 14/1 and 15/1. In the Atlantic water south of Iceland the two nutrients become simultaneously depleted, whereas in the mixed arctic waters north of Iceland nitrate becomes practically exhausted while significant phosphate concentrations are still present. Silicate / nitrate data from some years fall within well defined limits and can be fitted by an exponential function. Anomalies from this normal relationship may provide a useful indicator of phytoplankton species, e. g. *Phaeocystis,* which do not utilize silicon. Primary productivity compares favourably with vertical mixing and nutrient availability except where mixing is very intense or grazing by zooplankton is substantial. The oxygen saturation and computed evasion rates of oxygen may in connection with productivity, mixing conditions and nutrient concentrations afford helpful information on the biological history of the water.

Keywords: North Atlantic; water masses; vertical mixing; nutrients; dissolved oxygen; primary productivity; *Phaeocystis.*

INTRODUCTION

The stated goal of the Joint Global Ocean Flux Study (JGOFS) is "to determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, the sea floor and continental boundaries" (SCOR 1987). The achievement of this objective calls for *inter alia* detailed information on nutrient cycles and nutrient distributions in connection with physical and biological processes. Thus, there is now a renewed interest in nutrient data from as many areas as possible.

Compilations of primary production rates in the world oceans (e. g. Koblentz-Mishke *et al.*

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1970), as well as satellite-derived phytoplankton pigment distribution for the North Atlantic (Brewer *et al.* 1986; Anon. 1989), have indicated relatively productive areas in large parts of the northern North Atlantic including the waters around Iceland. However, the extensive studies carried out by Thórdardóttir (1976, 1977, 1984, 1986) over the last two decades have revealed marked variations in plant production of Icelandic waters, not only seasonal and regional, but also from year to year. Since growth conditions in the sea are largely dependant upon supply of nutrients to the surface layer as governed by vertical and horizontal mixing, it should be of interest to examine available information on nutrient distributions and physical processes in this area and to analyze these data in relation to biological processes.

On a global scale, considerable nutrient and oxygen data which exist in the various national and international Oceanographic Data Centres have been used to compile standard sections and atlases of oxygen, nutrient concentrations and derived quantities in the Atlantic (e. g. Worthington and Wright 1970; Miller *et al.* 1970; Bainbridge 1976; Broecker and Peng 1982; Kamykowsky and Zentara 1986; Glover and Brewer 1988). These data relate mostly to the area south of the Scotland-Greenland Ridge, and include only few observations from the Icelandic shelf or the deep waters north of Iceland. Considerable oxygen and nutrient data, however, have been collected for several decades from the shelf area surrounding Iceland and beyond the continental slope. Only specific results of these observations, mainly from the Irminger Sea, have been reported (Stefánsson 1968a, 1968b; Thórdardóttir and Stefánsson 1977; Takahashi *et al.* 1985; Stefánsson *et al.* 1987) but no overall analysis has been made. In this contribution, some of the historical nutrient and oxygen data obtained from Icelandic waters will be presented in the form of horizontal and vertical distributions, and it will be attempted to analyze how the observed variations relate to physical and biological processes, both with respect to space and time.

MATERIAL AND METHODS

Most of the nutrient and oxygen data have been collected over the last 25–35 years during the routine Icelandic late spring/early summer cruises, normally conducted in the period May 20 – June 10 (Fig. 1). The surveys have always started at the southwest or west coast and proceeded clockwise around Iceland. Due to this time difference of roughly 3 weeks, the observational data can of course not be considered as synoptic, and the values found off the southwest or west coasts are not strictly comparable to those found off the east or southeast coasts. We will return to this discrepancy later on.

Considerable data are also available since 1964 for the period July–August from the Selvogsgrunn and Reykjanes sections as well as from the region north of Iceland, mainly the Siglunes and the Langanes sections (see Fig. 1). Only limited data are available for the deep offshore regions from the winter season except for observations made in February/March 1982 on two sections between North Iceland and Jan Mayen, a survey of all the main sections around Iceland in February–March 1991, and some observations south and west of Iceland from year to year.

In addition to these annual surveys in May/June and occasional August and winter observations, seasonal changes of dissolved oxygen at various depths at stations 1–4 on the Siglunes section (Fig. 1) were studied during 1953–1955, and of nutrients as well as oxygen near the continental edge off the south coast in the Selvogsgrunn region (station S in Fig. 1) in 1964–1965 and at 23 stations in the Faxaflói region in 1966–1967. The locations of Faxaflói stations, nos. 1, 8 and 14, considered in this paper, are also shown in Figure 1. Furthermore, in the period February 1987 to February 1988 nutrients were measured in connection with seasonal plankton studies in the Ísafjardardjúp, northwest Iceland (Ástthórsson and Jónsson 1988). All of these data are kept on file at the Marine Research Institute, Reykjavík.

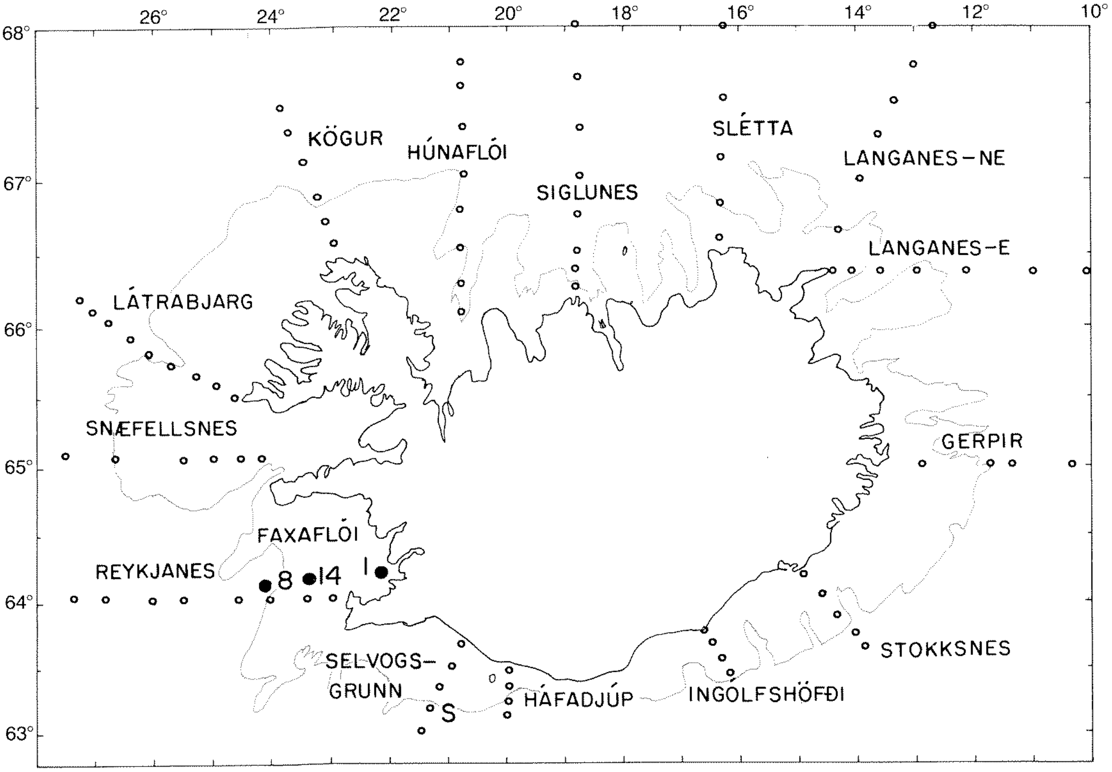

Fig. 1. Sections and stations occupied during spring cruises in the years 1972–1982. In 1983 and and the following years the Reykjanes section was replaced by a section due west from Reykjavík. Location of stations where seasonal studies were made in 1964–1965 (S) and in 1966–1967 (1, 14 and 8) are also shown. In 1953–1955 seasonal studies were made at stations 1–4 (counted from land) on the Siglunes section.

The nutrient concentrations of 34 Icelandic rivers were compiled from published data (Ármannsson 1970, 1971; Anon. 1974; Ólafsson 1979; Stefánsson and Jóhannesson 1978, 1982, 1983; Stefánsson and Thorsteinsson 1980) as well as unpublished observations, mainly from south coast rivers, made in the period 1964–1979, but also from the Faxaflói region in 1966–1977 and from the Kaldbaksvík River, Strandir, northwest Iceland in 1987. The sampling locations of these rivers are shown in Figure 2. The names of the rivers in question and information as to when they were sampled are given in Table 1.

The analytical methods used were standard techniques (Strickland and Parsons 1968; Grasshoff *et al.* (eds.) 1983). Oxygen was always measured at sea. During the first part of the observational period the nutrient samples were quick-frozen in polyethylene bottles and stored in a deep-freezer until thawed and analyzed ashore. In the last 10–15 years most of the nutrient samples were analyzed at sea, using automated methods for nitrate and silicate and manual spectrophotometry for phosphate.

Mean monthly wind data from the following meteorological observation stations (Anon. 1979, 1980) were used in this paper: For the western part of the south coast region: Vík, Vestmannaeyjar, Eyrarbakki, Reykjanes; for the west coast region: Reykjanes, Arnarstapi, Gufuskálar, Hvallátur; for the western part of the North Icelandic area: Hornbjargsviti, Grímsey; for the northeastern area: Grímsey, Raufarhöfn. The locations of the meteorologi-

TABLE 1
Inventory of nutrient data from Icelandic rivers. Summer observations include the months May – September, winter observations October – April.

River		*Years*	
No.	*Name*	*Summer observations*	*Winter observations*
1.	Elliðaár	1967, 1969, 1970, 1979	1969, 1970, 1971
2.	Laxá í Kjós	1967, 1979	
3.	Brynjudalsá	1967, 1979	
4.	Botnsá	1967, 1979	
5.	Laxá í Leirvogssveit	1967, 1979	
6.	Andakílsá	1967, 1979	1966
7.	Hvítá í Borgarfirði	1967, 1979	1966, 1979
8.	Dunká	1979	
9.	Skrauma	1979	
10.	Hörðudalsá	1979	
11.	Miðfjarðará	1979	
12.	Haukadalsá	1979	
13.	Laxá í Dölum	1979	
14.	Fáskrúð	1979	
15.	Fljótaá	1977	
16.	Ólafsfjarðará	1978, 1979	1979
17.	Laxá í Aðaldal	1971, 1972	1971, 1972
18.	Vesturdalsá í Vopnafirði	1981	1982
19.	Skeiðará	1979	1976
20.	Sandgígjukvísl	1979	1976
21.	Núpsvötn	1979	1976
22.	Hverfisfljót	1976	
23.	Skaftá við Kirkjubæjarkl.		1976
24.	Eldvatn		1976
25.	Skaftá í Skaptárdal		1976
26.	Hólmsá		1976
27.	Skálm		1976
28.	Múlakvísl	1979	1976
29.	Jökulsá á Sólheimasandi	1979	1976
30.	Markarfljót	1979	1976
31.	Ytri Rangá	1979	1976
32.	Þjórsá	1964, 1973, 1979	1965, 1972, 1973, 1976
33.	Ölfusá	1964, 1973, 1979	1965, 1973
34.	Kaldbaksá á Ströndum	1987	

cal observation stations as well as most of the regions and places referred to in the text, are shown in Figure 2.

HYDROGRAPHY

Iceland is located on the Greenland-Scotland Ridge where strong, permanent boundaries are formed between the relatively warm waters of the Northeastern Atlantic and the arctic waters of the Nordic Seas. The circulation patterns of different parts of the ocean areas surrounding Iceland have been investigated since the beginning of this century (e. g. Helland-Hansen and Nansen 1909; Hermann and Thomsen 1946; Alekseev and Istoshin 1956; Stefánsson 1961,1962; Malmberg *et al.* 1972; Swift 1980; Hansen 1985).

As illustrated in Figure 3, the south coast of Iceland is bathed by relatively warm and saline Atlantic water carried by a branch of the Gulf Stream. This water flows clockwise along the south and west coasts. At the Iceland-Greenland Ridge the mean residual cur-

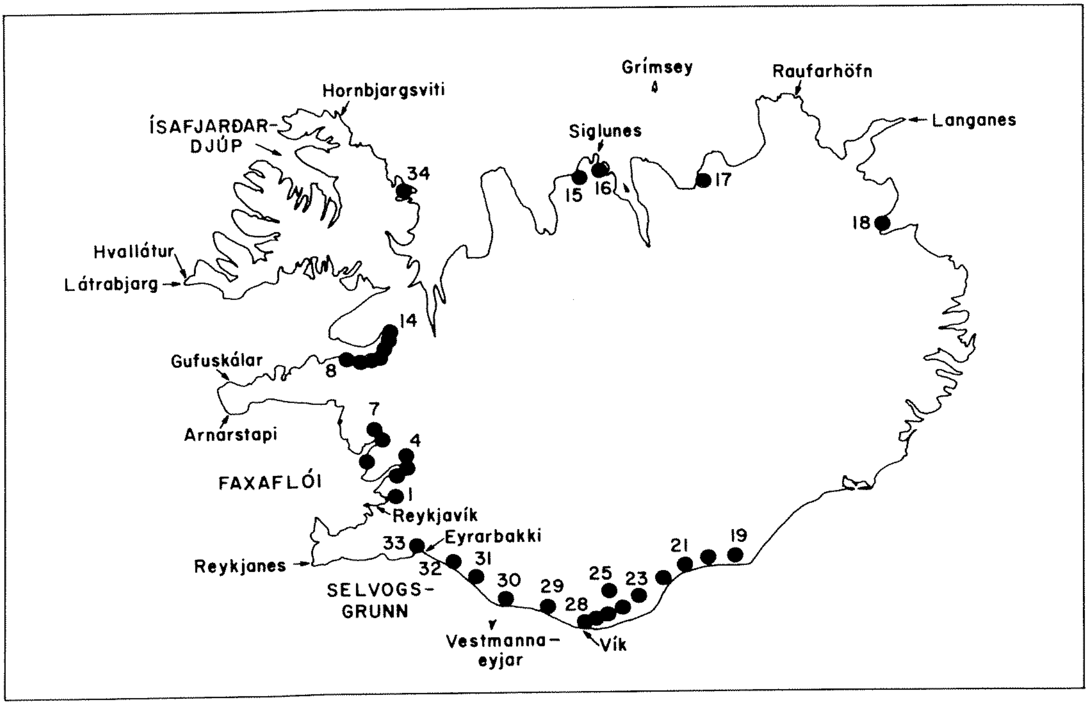

Fig. 2. Sampling localities of 34 Icelandic rivers (see numbers and corresponding names in Table 1) where nutrient samples were taken and locations of meteorological observation stations mentioned in the text. Locations of most of the other places and regions referred to are also shown.

rent splits into two parts: one swinging to the west and southwest and forming a cyclonic eddy in the Irminger Sea, the other, the North Icelandic Irminger Current, following the Icelandic shelf area and continuing eastwards along the north coast. This Atlantic influx to the North Icelandic area appears as a tongue of relatively warm and saline water, where the Atlantic component decreases in the direction of flow. In the northwestern part of the Iceland Sea the strong East Greenland Current transports cold, low-salinity water along the Greenland coast to the south and crosses the Iceland-Greenland Ridge, while in the area south and southeast of Jan Mayen an appreciable current is directed to the north or northwest, carrying relatively warm and saline water from the Norwegian Sea. In the central part of the region between Iceland and Jan Mayen there is a weak cyclonic circulation. This eddy feeds water to the East Icelandic Current which flows southeast along the Icelandic continental slope. Another contribution to the East Icelandic Current is water from the North Icelandic Irminger Current, and furthermore, to a variable degree, polar water from the East Greenland Current.

Because of its location near the boundary between warm and cold currents, conditions in the area north of Iceland are highly sensitive to meteorological changes (Stefánsson 1962; Stefánsson and Gudmundsson 1969). Consequently, variable influx of Atlantic water and/or variable admixture of polar water in the surface layers north of Iceland, may lead to large temperature and salinity fluctuations, both in space and time. Off the south coast, however, where Atlantic water predominates, year to year variations are normally much less conspicuous (Stefánsson 1970). In warm years a strong influx of Atlantic water from the southwest enters the shelf

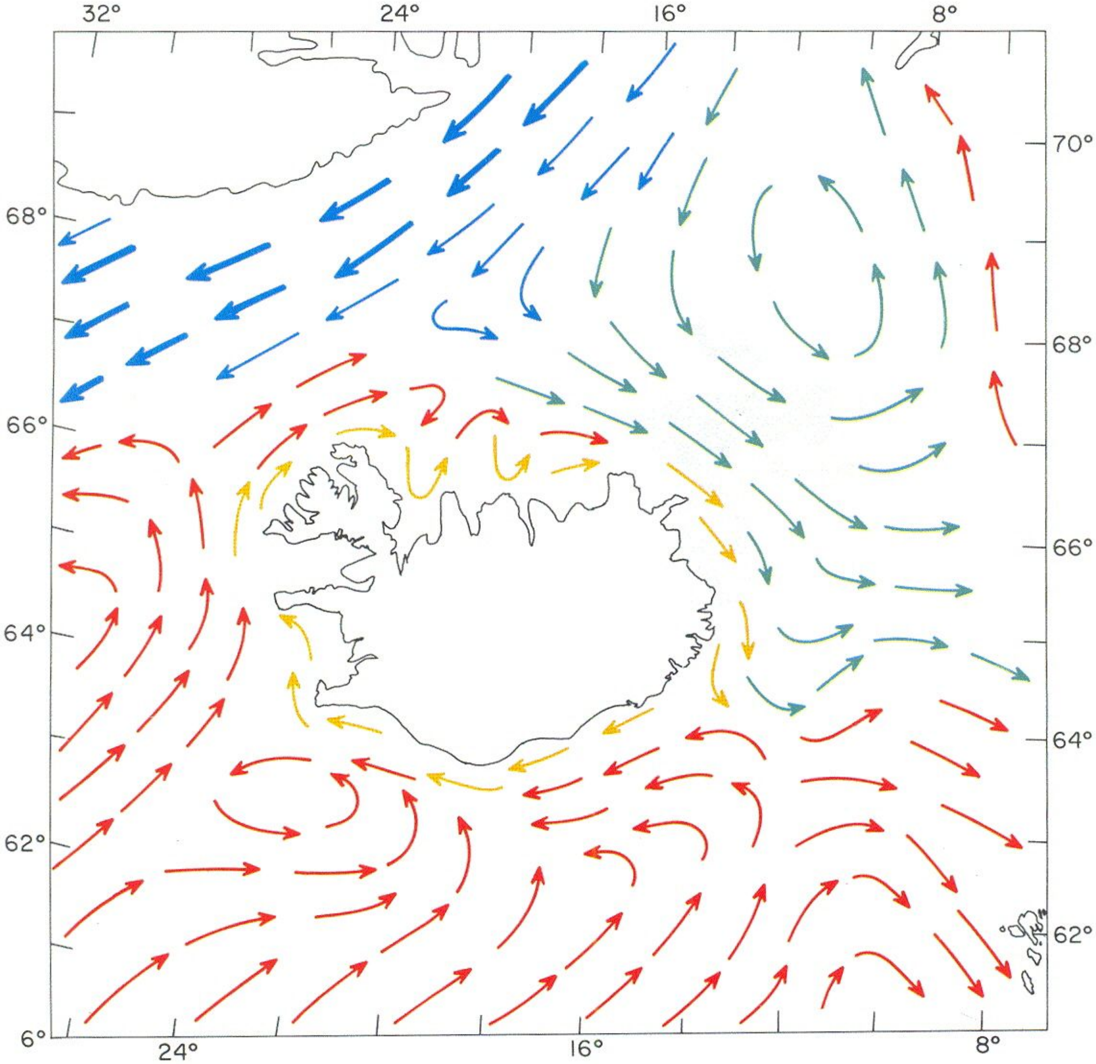

Fig. 3. Ocean currents around Iceland. Red colour: relatively warm and saline Atlantic water. Blue: Cold and low-salinity polar water. Green: Arctic water. Yellow: Icelandic coastal water (Based on Stefánsson 1961).

area north of Iceland in late spring and can be traced all along the north coast and even south of Langanes. An example of this was found in May–June 1980 (Fig. 4). Conversely, in very cold years, such as in late May–June 1979 (Fig. 4), only a weak influx of Atlantic water had reached the Kögur section, whereas no Atlantic influence was observed farther east in the North Icelandic area (Malmberg 1983). At this time an appreciable proportion of cold, low-salinity polar water was found in the surface layers of the whole region from Húnaflói to the east coast. An example of near average conditions is shown in Figure 4, from May–June 1986.

Extensive studies have been made during the last half a century on temperature and salinity variations in the Icelandic coastal region and adjacent deep sea areas (Dickson *et al.* 1975; Malmberg 1972, 1984; Malmberg and

Svansson 1982; Stefánsson 1954, 1962, 1969a, 1985; Stefánsson and Jakobsson 1989). As an index of the variability in the volume of Atlantic water flowing into the region north of Iceland, Ólafsson (1985) computed the deviations from the mean temperature and salinity of the uppermost 200 meters for 5 stations between 2 and 46 naut. miles offshore on the Siglunes section. His results, reproduced in Figure 5, clearly show marked inter-annual variations, which may be summarized as follows: a) in the period prior to 1965 (starting in the 20's as judged by older data) the temperature was comparatively high and the Atlantic influx large; b) the period 1965–1971 was characterized by negligible inflow of Atlantic

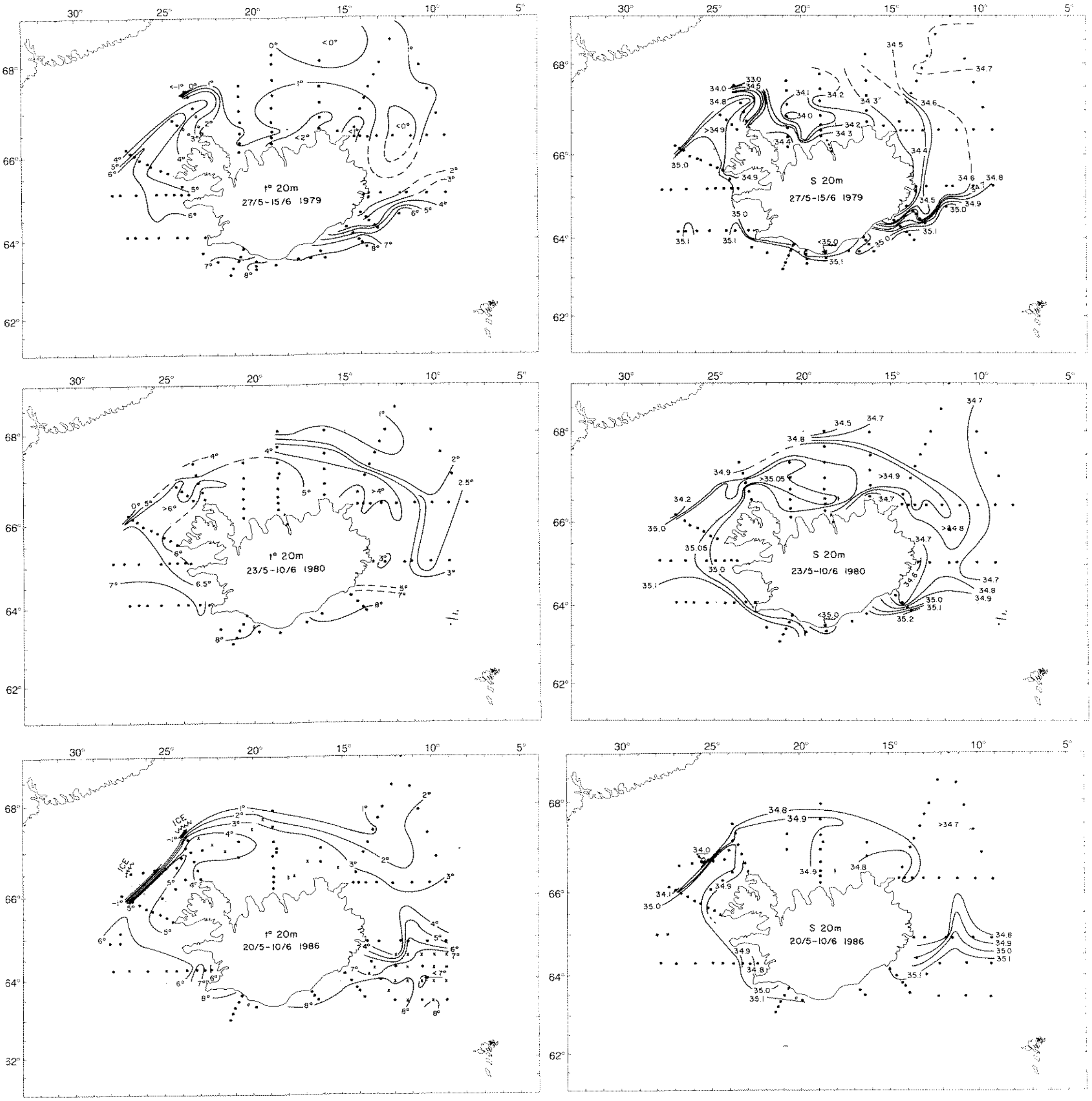

Fig. 4. Temperature and salinity at 20 m around Iceland during May 27 – June 15, 1979, May 23 – June 10, 1980 and during May 20 – June 10, 1986. (After Malmberg 1983, Anon. 1986).

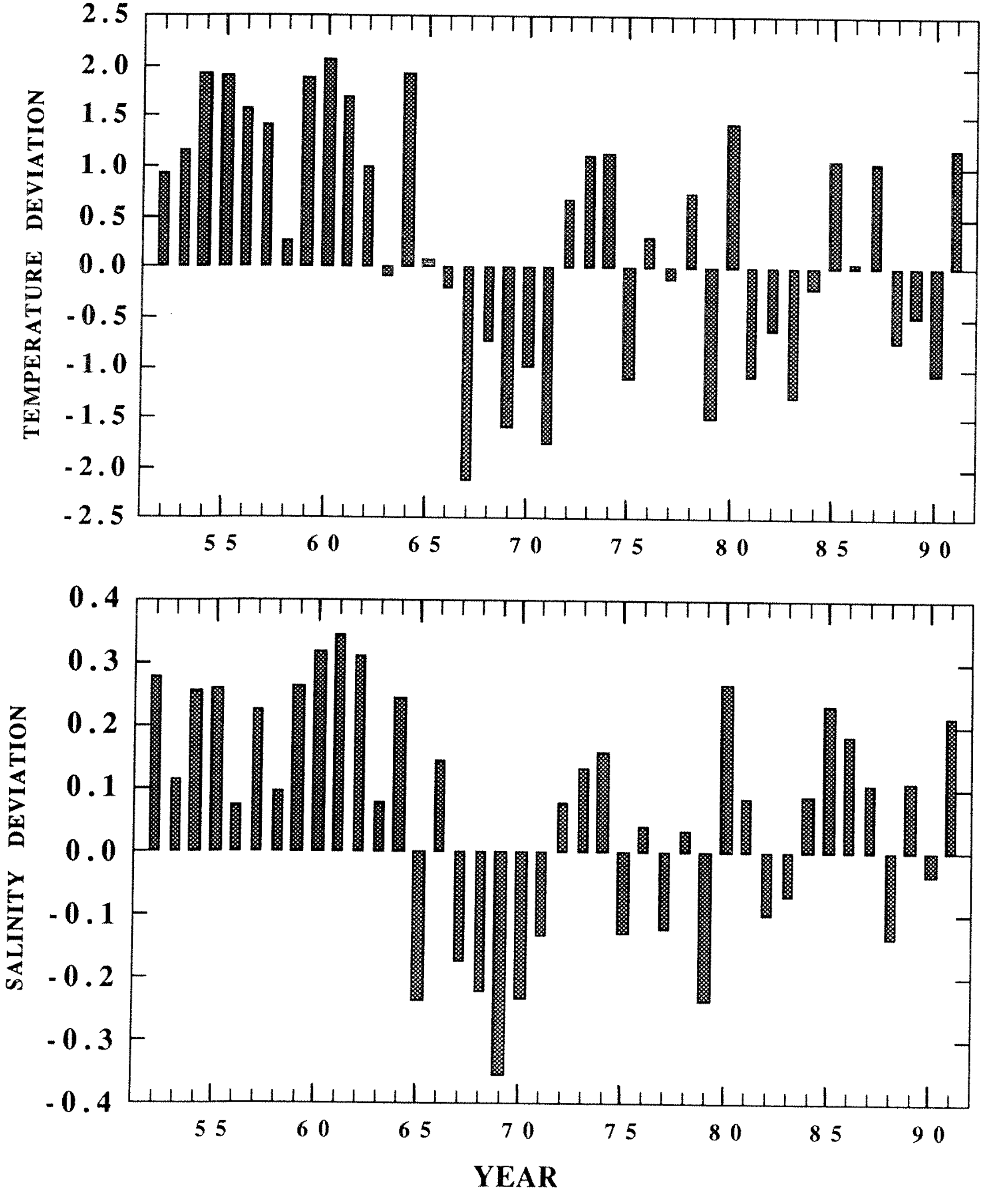

Fig. 5. Temperature and salinity deviations in late spring from the 1961–1980 mean for stations 1–5 on the Siglunes section. The deviations were computed as mean values for 0–200 m at the 5 stations between 2 and 46 naut. miles offshore. (Based on Ólafsson 1985, with values added for 1986–1991).

TABLE 2

Nutrient sources of Icelandic coastal waters (inside 200 m): Mean concentrations of Icelandic rivers and sea water (0–200 m). P: phosphate, N: nitrate, Si: silicate, S.D.: Standard deviation; n: number of seasonal means. As in Table 1, Winter includes the months October–April, summer the months May–September.

	Winter values (μM)			*Summer values (μM)*			*Annual means (μM)*		
	PO_4-P	*NO_3-N*	*Si*	*PO_4-P*	*NO_3-N*	*Si*	*PO_4-P*	*NO_3-N*	*Si*
Rivers									
South coast	*0.99*	*5.5*	*216*	*0.71*	*1.0*	*169*	*0.85*	*3.3*	*193*
S.D.	±0.51	±2.1	±52	±0.49	–	±76			
n	18	17	18	13	2	13			
West coast	*0.60*	*3.9*	*197*	*0.19*	*0.26*	*151*	*0.20*	*2.1*	*174*
S.D.	±0.24	–	±16	±0.15	±0.26	±32			
n	4	2	6	15	9	16			
North coast	*0.52*	*2.3*	*240*	*0.29*	*0.8*	*146*	*0.41*	*1.6*	*193*
S.D.	±0.18	±1.3	±98	±0.15	±1.0	±37			
n	4	5	4	7	7	7			
East coast	*0.21*	*5.0*	*288*	*0.23*	*0.40*	*269*	*0.22*	*2.7*	*279*
n	1	1	1	1	1	1			
Weighted average	*0.73*	*4.5*	*227*	*0.48*	*0.8*	*174*	*0.61*	*2.7*	*201*
Ocean	*0.85*	*12*	*6*	*0.55*	*7*	*3.5*	*0.70*	*9.5*	*5*

water but by pronounced polar influence over the whole North Icelandic area; c) in the years since 1972 warm and cold years have alternated, but the average influx for this period has been appreciably smaller than for the years 1952–1964.

Variations in hydrographical conditions, in particular salinity, greatly effect vertical mixing in the North Icelandic area. Thus in cold years with appreciable admixture of polar water, a strong pycnocline is formed in the surface layers, preventing renewal by mixing from below. On the other hand, in years with strong Atlantic influx, and consequently relatively high near-surface salinities, vertical mixing is favoured. As we shall see, such variations in stratification explain the large differences between years in near-surface concentrations of dissolved nutrients in spring and summer.

NUTRIENT SOURCES

The nutrient content of Icelandic shelf waters will depend mainly on the concentrations found in the oceanic water masses entering the region, but near-shore they will be modified by the admixture of fresh water which may have an entirely different nutrient composition.

A summary of the nutrient concentrations of Icelandic rivers (Fig. 2) is presented in Table 2, with average values for the winter and summer seasons respectively for the different parts of the coast. These average values are grand means, obtained by averaging the mean seasonal (summer or winter) values for each year for the various rivers discharging within a given part of the coast. The weighted averages were obtained by taking into account the total river discharge from the respective regions using the data compiled by Rist (1956) on drainage areas and runoff per unit area for different regions of the country.

The results in Table 2 indicate relatively large standard deviations of the fresh water concentrations with respect to all three nutrients. The standard error, however, and the uncertainty of the weighted averages, will clearly be much smaller. Another uncertainty, possibly more serious, is the lack of data from some of the major rivers, in particular from the regions of northern and eastern Iceland. Nevertheless, it is believed that the weighted averages here presented will provide a reasonably good estimate of the nutrient concentrations of the river water discharged into the Icelandic coastal area.

It will be noted that the summer values are markedly lower than the winter values with respect to all three nutrients, but this applies in particular to nitrate. These differences can no doubt be largely attributed to photosynthetic uptake, but also to the fact that for many rivers the fresh water in spring and summer is „diluted“ by the meltwater from snow and ice. Table 2 also includes the average sea water concentrations for 0–200 m. The ocean values were estimated on the basis of seasonal studies at offshore stations for the regions south and west of Iceland (see Fig.1), the yearly late-spring surveys, occasional summer studies as well as winter observations north of Iceland in 1982 and a winter survey of some 60 stations around Iceland in 1991. The average winter values here presented are quite similar to the average concentrations estimated by Glover and Brewer (1988) for the region south and west of Iceland by interpolation to the base of the winter time mixed layer (extrapolation method). The results in Table 2 show that the phosphate concentrations of the river water are only slightly lower than those of the sea water, whereas the nitrate concentrations of the rivers are lower by a factor of at least 3. On the other hand, silicate concentrations of the river water are on the average 40–50 times greater than those of sea water.

SEASONAL VARIATIONS

Maps of mixed-layer depth (Levitus 1982; Glover and Brewer 1988) indicate that in the deep areas south and west of Iceland seasonal variations may be detected down to depths between 250 and 500 m, except in a limited region southwest from Reykjanes where they exceed 500 m. Icelandic winter observations have shown that at the deepest station on the Selvogsgrunn section (for location see Fig. 1) the mixed layer depth is about 500 m as a maximum. At station 8, the deepest station sampled during seasonal studies in the region west of Faxaflói (Fig. 1), the water column was found to be isopycnal down to the bottom (320 m) on one occasion (middle of March 1967). Farther to the west and southwest in the Irminger Sea, the mixed layer depth is somewhat greater (about 600 m) as indicated by Glover and Brewer (1988) and confirmed by Icelandic observations in late February 1991 (cf. Fig. 16). Our seasonal studies have shown, however, that at a depth of 200 m and deeper off the south and west coasts, seasonal variations in nutrients and oxygen are only very slight, although detectable.

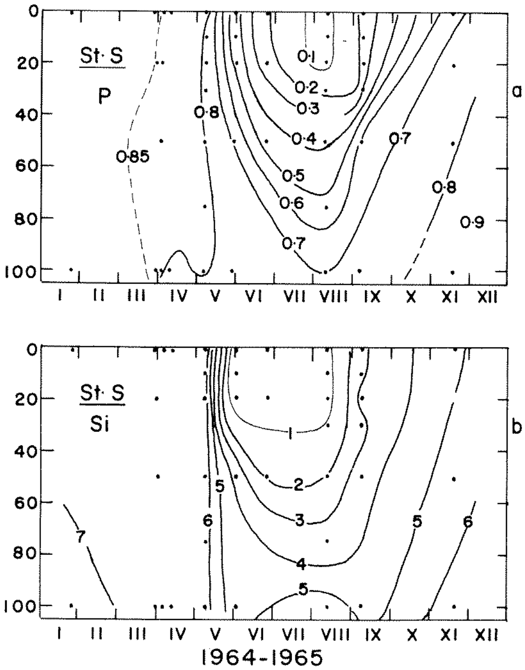

Fig. 6. Seasonal variations of a) phosphate (μM) and b) silicate (μM) at station S in 1964–1965.

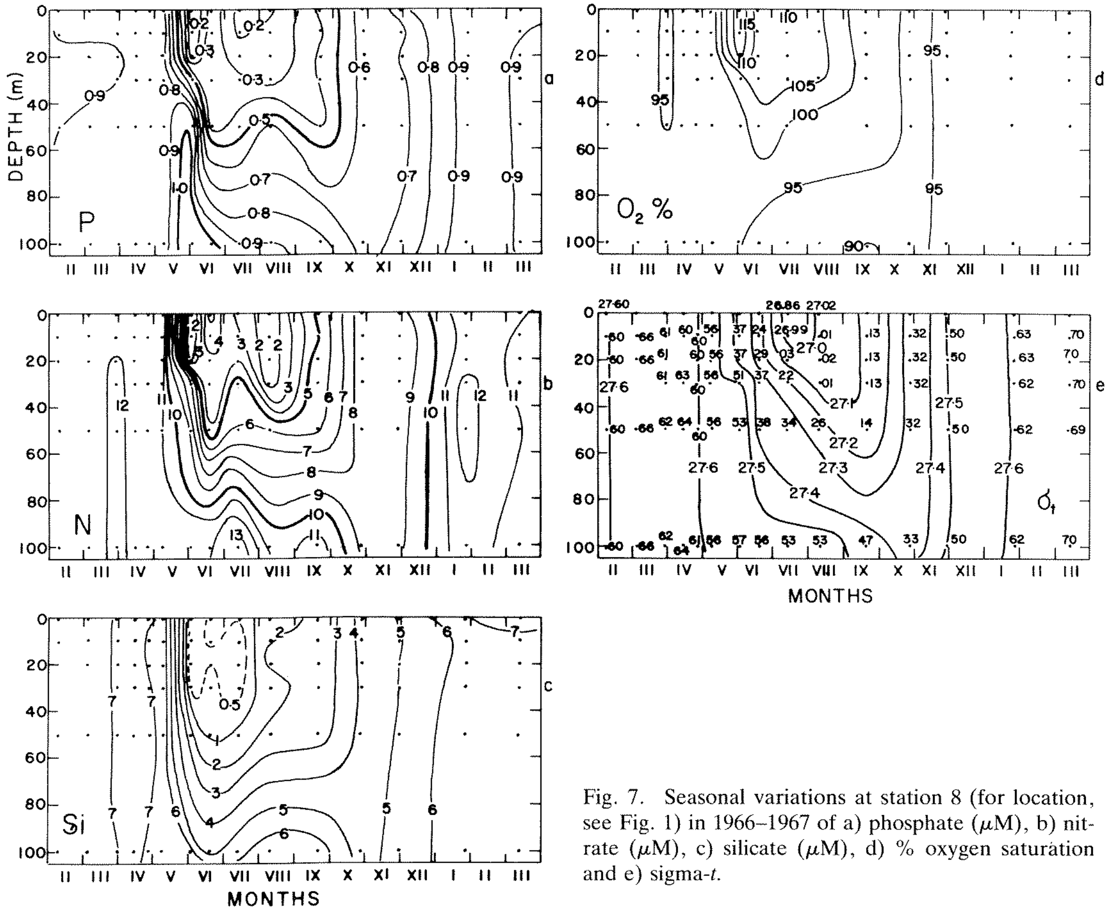

Fig. 7. Seasonal variations at station 8 (for location, see Fig. 1) in 1966–1967 of a) phosphate (μM), b) nitrate (μM), c) silicate (μM), d) % oxygen saturation and e) sigma-*t*.

Variations in phosphate and silicate concentrations with depth in the period 1964–1965 were studied at station S (Fig. 6; for location see Fig. 1), at the outer edge of the Selvogsgrunn region (depth: 250–290 m). It will be seen that winter conditions, with relatively high concentrations from the surface down to 100 m, persisted throughout April. The decrease in nutrient concentrations due to uptake by plants was slow at this station until the beginning of May. Very low phosphate and silicate concentrations were observed in the surface layers in July–August. Following the cooling and mixing in autumn, the near-surface concentrations increased, approaching typical winter values by the middle of November.

The seasonal distributions of phosphate, nitrate, silicate, oxygen saturation and density at 3 stations in Faxaflói (Stations 8, 14 and 1, see Fig. 1) during the period 1966–1967 are shown in Figures 7, 8 and 9. At the deep station west of Faxaflói (depth: 320 m) the seasonal nutrient variations closely resembled those found at station S south of Iceland. Thus the spring uptake did not start until after the first week of May, when a slight stratification had begun to develop (Fig. 7). It will be noted that the rate of nutrient removal was rapid during the following 2–3 weeks. There was a slight increase in phosphate and nitrate in mid-summer followed by a secondary minimum in July–August. The nitrate concentration, however, never went below 1.5

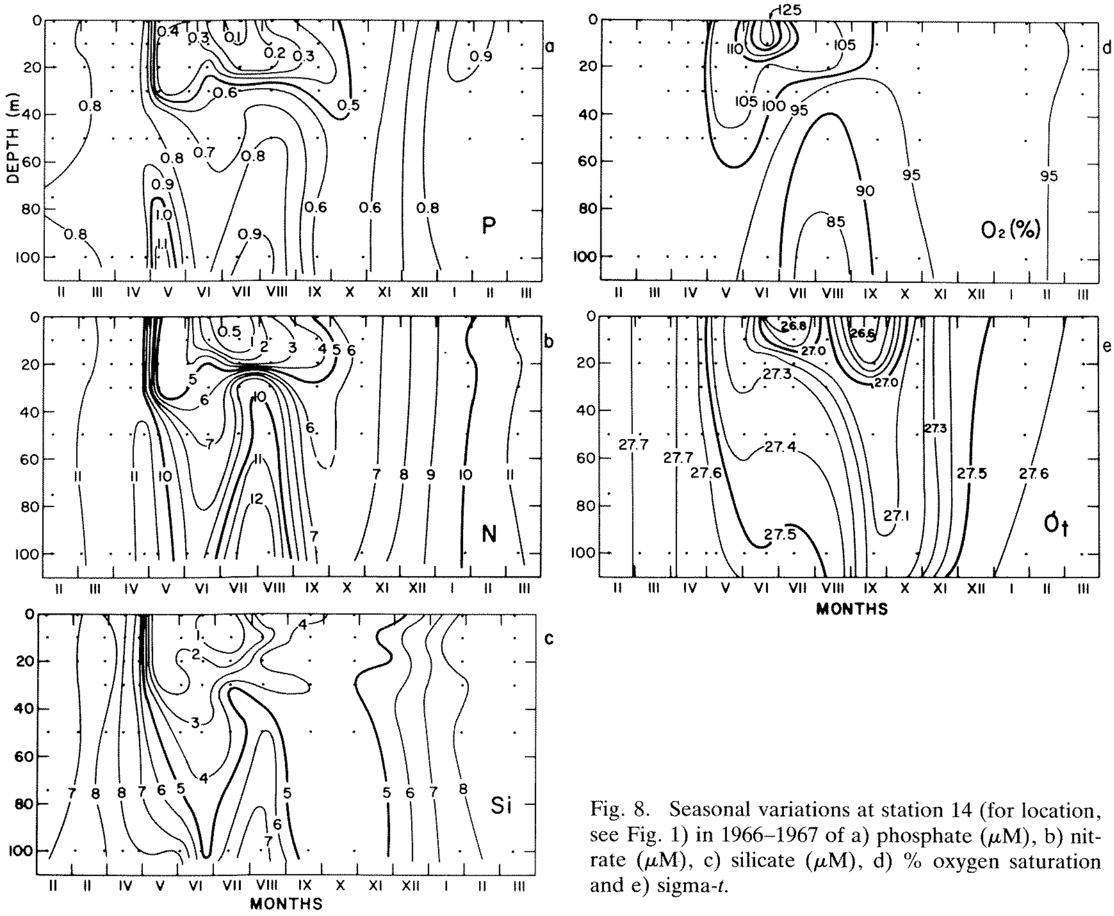

Fig. 8. Seasonal variations at station 14 (for location, see Fig. 1) in 1966–1967 of a) phosphate (μM), b) nitrate (μM), c) silicate (μM), d) % oxygen saturation and e) sigma-*t*.

μM. Also at this station, the water had become thoroughly mixed down to 100 m at the end of November, and at the beginning of January the concentrations had increased to typical winter values. The silicate concentration showed similar changes as observed for phosphate and nitrate, but reached very low summer values (< 0.5 μM) in the near-surface layer.

As typically found in this region, the oxygen saturation at station 8 was between 95 and 98% during the late autumn, winter and spring months until around the middle of May. These undersaturations were presumably due to a) the gradual *in situ* cooling of the water beginning in autumn and continuing throughout winter, leading to an increase in oxygen solubility, while equilibrium with the atmosphere is not attained, and b) the mixing with undersaturated water resulting from the oxidation of biogenic matter below the photic zone (Stefánsson *et al.* 1987). On the other hand, after the water becomes stratified in spring, the photosynthetic oxygen production causes an increase in the oxygen saturation to more than 100%. *In situ* warming may also contribute to this. At station 8 a maximum value of almost 115% was measured in early June. Saturation of slightly less than 90% observed at 100 m in September, must have resulted from the oxidation of organic matter.

At station 14 (depth: 114 m) the stratification began only slightly earlier than at station 8, but became more developed in the near-surface layer (Fig. 8). The nutrient uptake started during the second half of April and the rate of nutrient decrease was quite rapid in the period from April 20 to May 10. In the beginning of July phosphate had decreased to < 0.1 μM, nitrate to < 0.5 μM, and silicate to < 1.0 <M. Thus, in July nitrate was appreciably lower at this station than it was at station 8. At 100 m the nutrient concentrations were quite similar at both stations throughout the year. The oxygen saturation in the surface layers reached very high values (> 125%) at this station in June, whereas in the layers below the photic zone undersaturation was much more marked than at station 8.

At station 1, (Fig. 9, depth: 38 m) where near-surface salinity is lowered by fresh water admixture, stratification was more pronounced during the summer months than at stations 8 and 14. Due to more intensive winter cooling , however, in the near-shore region, winter densities were similar at all 3 stations. Clearly, the uptake of nutrients started much earlier at station 1 than at stations 14 and 8, or already during the latter half of March, but the most intensive nutrient removal took place in early April. Considerably lower phosphate and nitrate values were observed during the growing season at this station than farther off-shore. In the winter time, phosphate values at station 1 were similar to those at stations 14 and 8, while the nitrate concentrations were slightly lower. Silicate concentrations, presumably due to fresh water mixing, were slightly higher at this station than at stations 14 and 8. As was the case for station 14, the near-surface oxygen saturation reached high values in the beginning of June, while conspicuously low saturation values, even just below 80%, occurred during summer in the near-bottom layer. These low saturation values at the shallow stations 1 and 14 must be attributed to the oxidation of organic matter of a relatively large standing crop at these stations where primary production was found to be particularly high during the spring months (Stefánsson *et al.* 1987).

The highest nutrient concentrations in the surface layers of Faxaflói, 1966–1967 were found in February–March, when phosphate ranged from 0.80–0,90 μM and nitrate from 11–12 μM. These values were, however, somewhat lower than those found in February 1991, when phosphate ranged from 0.90–1.00 μM and nitrate from 13–14 μM.

Farther to the north off the west coast of Iceland, viz. at the station observed in 1987–1988 in the Ísafjörður Deep (Ástthórsson and Jónsson 1988), seasonal nutrient changes were similar to those found in the Faxaflói region in 1966–1967, while the winter values were slightly higher.

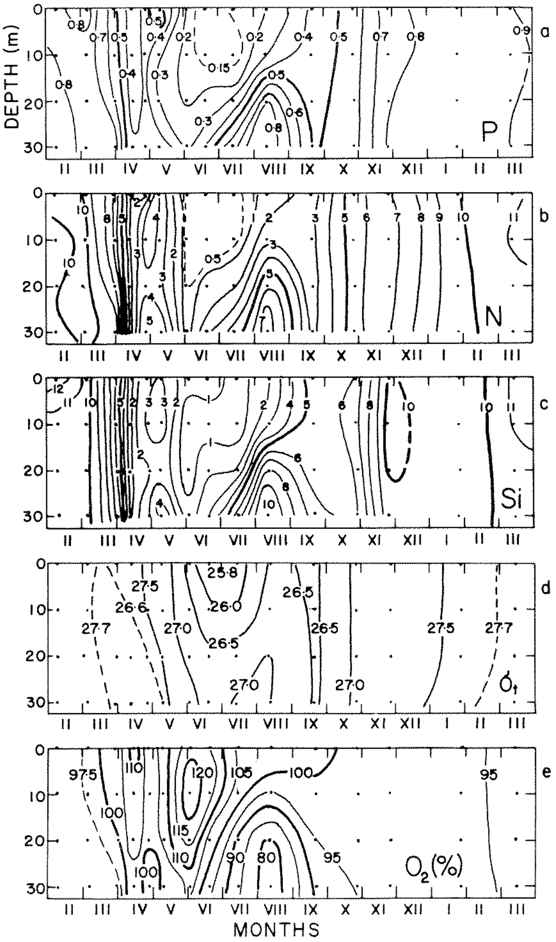

Fig. 9. Seasonal variations at station 1 (for location, see Fig. 1) in 1966–1967 of a) phosphate (μM), b) nitrate (μM), c) silicate (μM), d) % oxygen saturation and e) sigma-*t*.

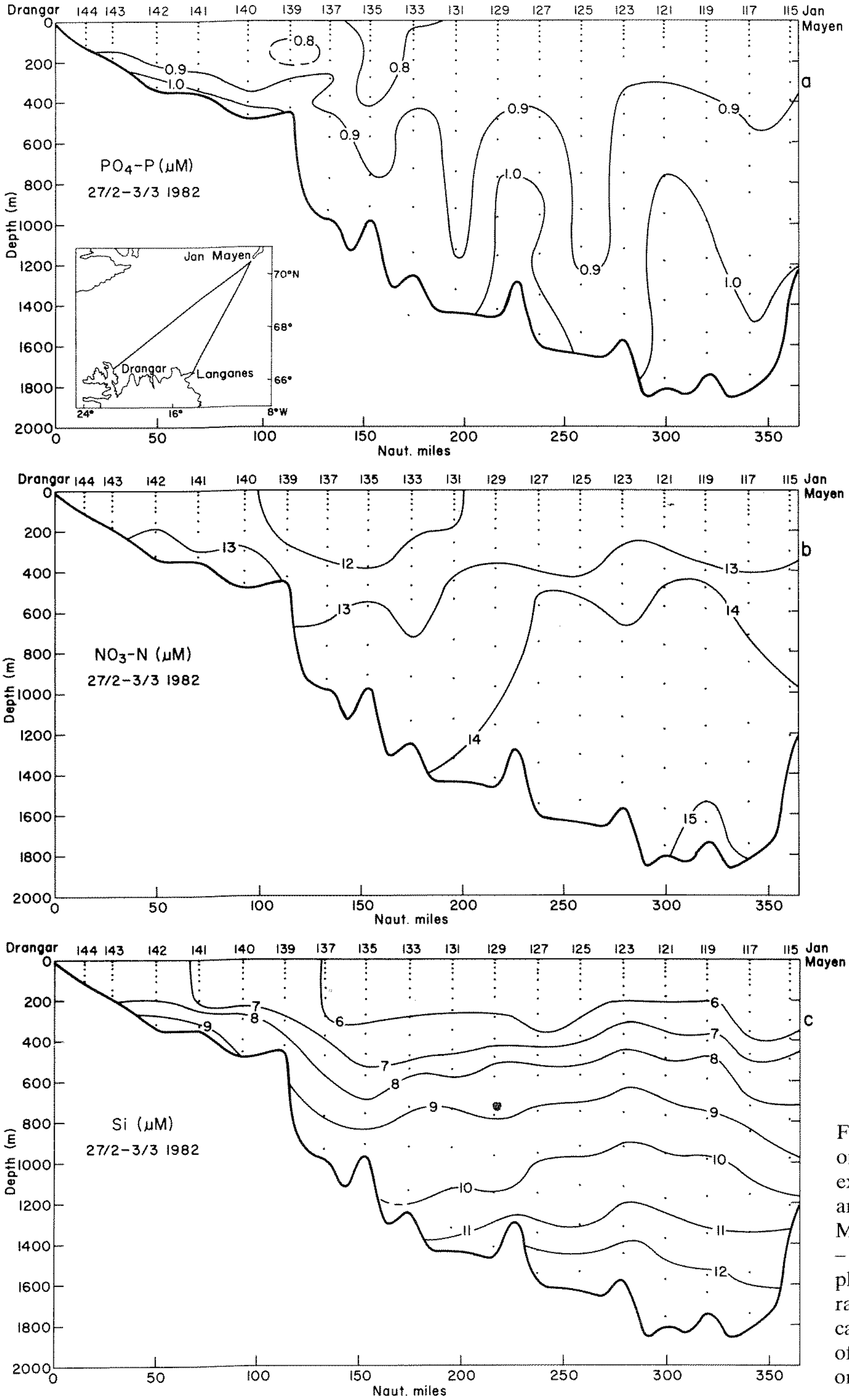

Fig. 10. Distribution on a vertical section extending from Drangar, Iceland to Jan Mayen, on February 27 – March 3, 1982 of a) phosphate (µM) b) nitrate (µM) and c) silicate (µM). The location of the section is shown on the inset diagram.

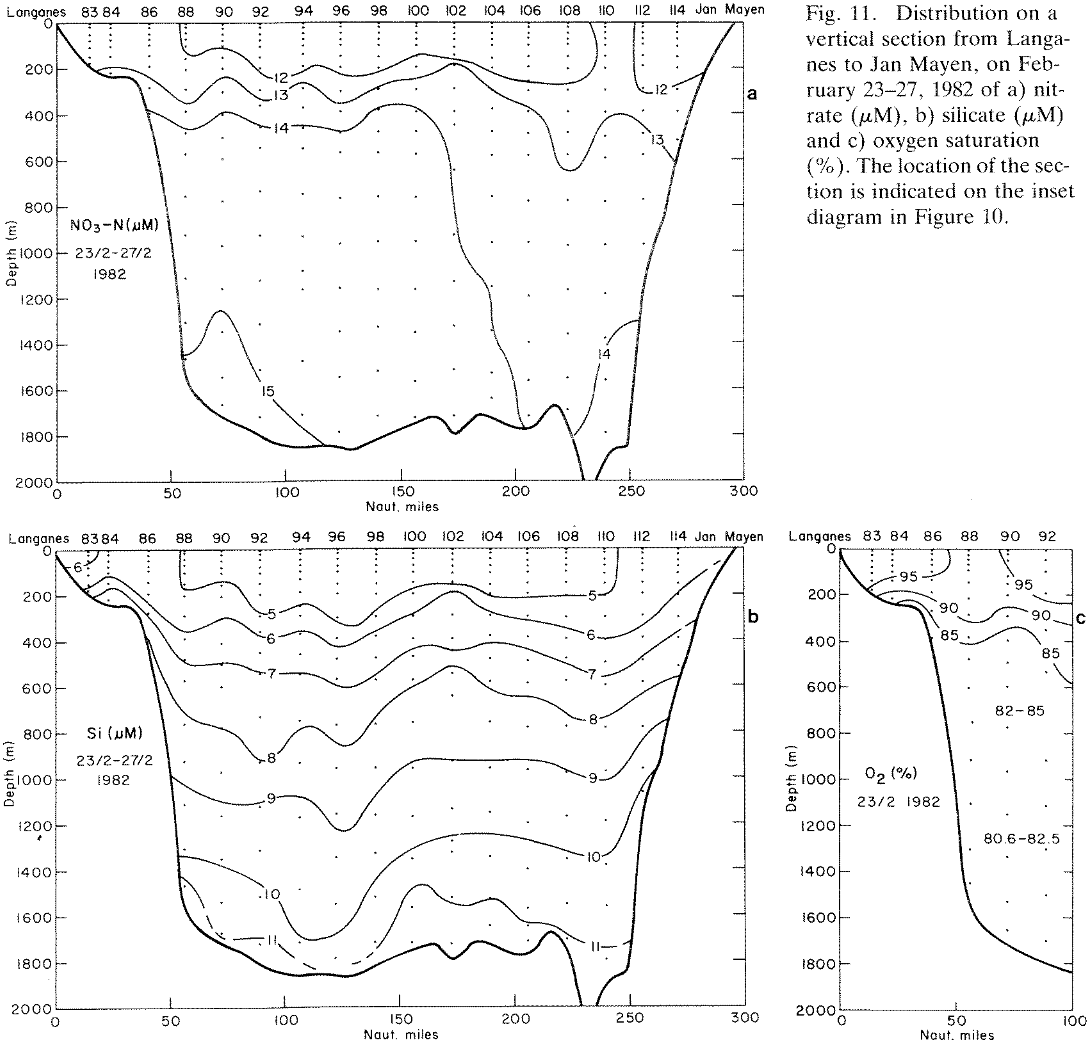

Fig. 11. Distribution on a vertical section from Langanes to Jan Mayen, on February 23–27, 1982 of a) nitrate (μM), b) silicate (μM) and c) oxygen saturation (%). The location of the section is indicated on the inset diagram in Figure 10.

No continuous seasonal nutrient data are available from the region north of Iceland. However, the numerous late spring observations, data from several years in August and from some years in winter, make it possible to compare the main features of the nutrient cycles in the areas north with those in the south and southwest.

Winter observations from two sections worked in late February and early March 1982 (Figs. 10 and 11) show that from the surface down to 200 m over the northwestern part of the North Icelandic shelf, phosphate concentrations ranged between 0.8 and 0.9 μM. Similar concentrations were also found in the upper layers over most part of the section from the edge of the shelf to Jan Mayen. Nitrate ranged between 12 and 12.5 μM for similar depths in the Icelandic shelf area, both in the western part and north of Langanes. Slightly lower values were found off the continental shelf. Silicate ranged between 6.5 and 7.5 μM over most part of the shelf in the western part and between 5 and 6 μM over the eastern part. In most part of the deep region between Langanes and Jan Mayen, between 0 and 200 m, silicate ranged from 4 to 5 μM, while on the more northerly section the concentrations ranged between 5 and 7 μM.

In February–March 1991 significantly higher nutrient concentrations were found north of Iceland than in 1982, especially over the inner part of the shelf, where phosphate was 0.05–0.10 μM higher and nitrate 1–2 μM higher than in 1982. This difference may probably be attributed to more Atlantic influence in the northern shelf area in 1991 than in 1982 (cf. Fig. 5). Silicate concentration, however, were similar in both years.

It should also be noted that in February–March 1991, when observations were made over the whole shelf area around Iceland, nutrient concentrations in the mixed layer proved to be consistently higher in the Atlantic water off the south and west coasts than in the arctic water off the north and east coasts. The mean surface values were as follows:

	Phosphate μM	*Nitrate μM*
Off the south	0.95	13.9
and west coasts	s.d.: 0.05; n = 31	s.d.: 0.7; n = 31
Off the north	0.87	12.9
and east coasts	s.d.: 0.06; n = 30	s.d.: 1.1; n = 30

Thus there are both year to year and regional variations in the nutrient winter concentrations of Icelandic waters.

Oxygen observations in the southern part of the Langanes-Jan Mayen section (Stations 83–92 in Fig. 11c) showed that in late February 1982 the oxygen saturation was 95–96% over the Icelandic shelf and 80–100 nautical miles offshore while over the slope it was somewhat lower. The values decreased sharply with depth at about 200 m over the outer part of the shelf, but at a slightly greater depth in the deep area off the slope. In accordance with the nutrients and the oxygen, the density distribution for these sections showed that on this occasion the mixed layer depth did not exceed 200 m for stations on the North Icelandic shelf, while in the deep region and in particular just west and southwest from Jan Mayen, the mixed layer reached a depth of 250–300 m. Below the winter mixed layer and above 1000 m the oxygen saturation resembled the mean values for May–June 1954–1984 in the region east of Langanes (See Appendix Table III). Between 1000 and 2000 m depth the values ranged from 81–83%. In late February 1991 the mixed layer was only 50–75 m thick at a station located at 67° 59′N, 12° 41′W, some 110 nm NNE from Langanes. In the deeper layers, however, the values were almost identical to those measured in February 1982.

In the period late October 1953 to middle of September 1955, stations 1–4 on the Siglunes section (see Fig. 1 for location) were occupied 22 times for measurements of temperature, salinity and oxygen. An example of the oxygen changes as a function of time and depth is shown for station 3 (Fig 12a). From October 1953 until February 1954, the oxygen saturation ranged from 95–100% in the surface layers. From the beginning of February 1954 until the end of April it remained just above 100%, but increased relatively rapidly in May to reach a maximum of 120–125% in late May–early June. By the end of September it had dropped below 100% and ranged between 95 and 100% from October 1954 until late March 1955. These values were similar or slightly higher than those found northeast of Langanes in February 1982. Again in 1955 the main spring increase occurred in May and the maximum values were found in late May–early June. The relatively high oxygen saturation values (> 100%) between 50 and 100 m in February–April 1954 and March–April 1955, as well as between 100 and 200 m in April–May 1954 and in June 1955 must be attributed to vertical mixing from the surface layer, probably taking place earlier in the season. In the years 1954 and 1955, saturation values between 90 and 95% were observed below the surface layer from the middle of summer until late autumn, and in late 1953, indication of this subsurface oxygen minimum clearly appeared. These were presumably due to oxidation of organic matter from the standing crop of phytoplankton, and comparable to what

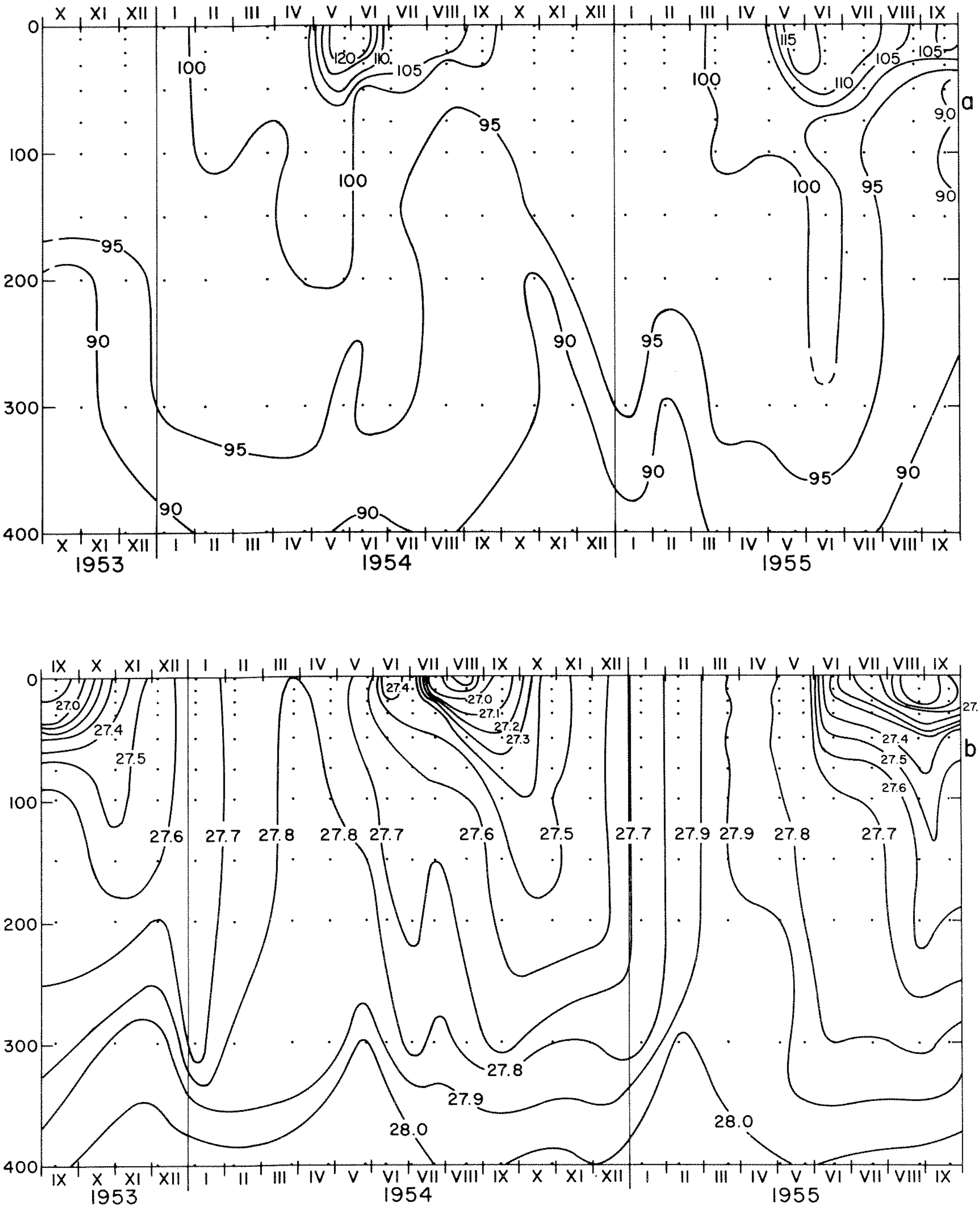

Fig. 12. Seasonal variations at station 3 (counted from land) on the Siglunes section (for location, see Fig. 1) from October 1953 to September 1955 of a) % oxygen saturation and b) sigma-*t*.

was found in late summer in the Faxaflói region (stations 8 and 14 in Figs. 7–8). Below a depth of 300 m, oxygen variations were small.

Variations in density (σ_t) as a function of time and depth at Siglunes station 3 are shown in Fig. 12b. During these and most other years prior to 1965, admixture of low-salinity polar water to the surface layers in this part of the North Icelandic area was very slight or non-existing (Fig. 5). Hence the stratification in 1954 and 1955 was much less developed than in most years in the following period, and in fact comparable to the regions south and southwest of Iceland. It is seen that in both 1954 and 1955 the mixed layer depth was about 300 m, whereas in most of the years since 1965, as revealed by data collected during the annual surveys, it has been less than 200 m at this station. Therefore, the oxygen distribution shown for the Siglunes section in the period 1953–1955 can not be considered as representative for the last 20–25 years.

From the large number of nutrient observations in Icelandic waters in late spring (Appendix Tables I–VI), it is evident, that nutrient limitations are more common in the area north of Iceland than south and west of the country. As will be described in the following sections, phosphate concentrations in the area north of Iceland, may, depending upon biological activity and stratification, range from < 0.1 μM to about 0.5 μM during the first half of June, nitrate from < 0.1 to about 6 μM and silicate from < 2 to about 4 μM. At the same time, oxygen saturation levels are normally higher in the area north of Iceland than in the regions off the south and west coasts.

Observations made off Siglunes in August and off Langanes in July–August, to be described in more detail in a later section, have revealed very low nitrate concentrations, generally from 0.1–0.5 μM, whereas south and west of Iceland they are normally appreciably higher. Similarly low values have been found north of Iceland for phosphate and silicate. Thus, in view of the available winter concentrations, which we have described, we conclude that the annual nutrient range, although variable, is generally somewhat greater in the area north of Iceland than in the regions south and west of the country.

REGIONAL COMPARISON OF NUTRIENTS AND MIXING CONDITIONS IN SPRING

Coastal effects

In the near-shore region, the physical environment, nutrient regimes and growth conditions will be modified by the interaction of land and sea, river discharge and changing bathymetry. An attempt was made to estimate the effect of the fresh water afflux on the average nutrient concentrations of the coastal water inside the 200 m isobath. According to Rist (1956, 1981) the average runoff from Iceland totals about 5.5×10^3 m^3 s^{-1}. Transport of ocean water in or out of the coastal region is difficult to evaluate. Apparently, the transport out of the area mainly takes place in two regions, *viz.* off Látrabjarg on the northwest coast, and in particular off the southeast coast. It has been estimated that the total anticyclonic transport around Iceland amounts to $\sim 1 \times 10^6$ m^3 s^{-1} (Stefánsson 1981). If we assume as a rough appraisal that about 50% of this takes place inside the 200 m depth contour, the average concentration of a given chemical constituent in the coastal water, $(c_c)_i$, should be:

$$(c_c)_i = \frac{[0.5 \times 10^6 (c_o)_i + 5.5 \times 10^3 \, (c_f)_i]}{[0.5 \times 10^6 + 5.5 \times 10^3]} \qquad (1)$$

where $(c_o)_i$ denotes the mean oceanic concentration and $(c_f)_i$ the mean fresh water concentration of constituent i. Using the values given in Table 2, the average nutrient concentrations of the coastal water will be as follows: $[PO_4\text{-}P] = 0.70$ μM, $[NO_3\text{-}N] = 9.4$ μM and $[Si] = 7.1$ μM. A comparison with the oceanic concentrations (Table 2) indicates that the coastal influence must be insignificant for both phosphate and nitrate except close inshore where nitrate might be appreciably lowered by mixing with river water. With regard to silicate, however, the effect is clearly much greater. While silicate is probably not limiting

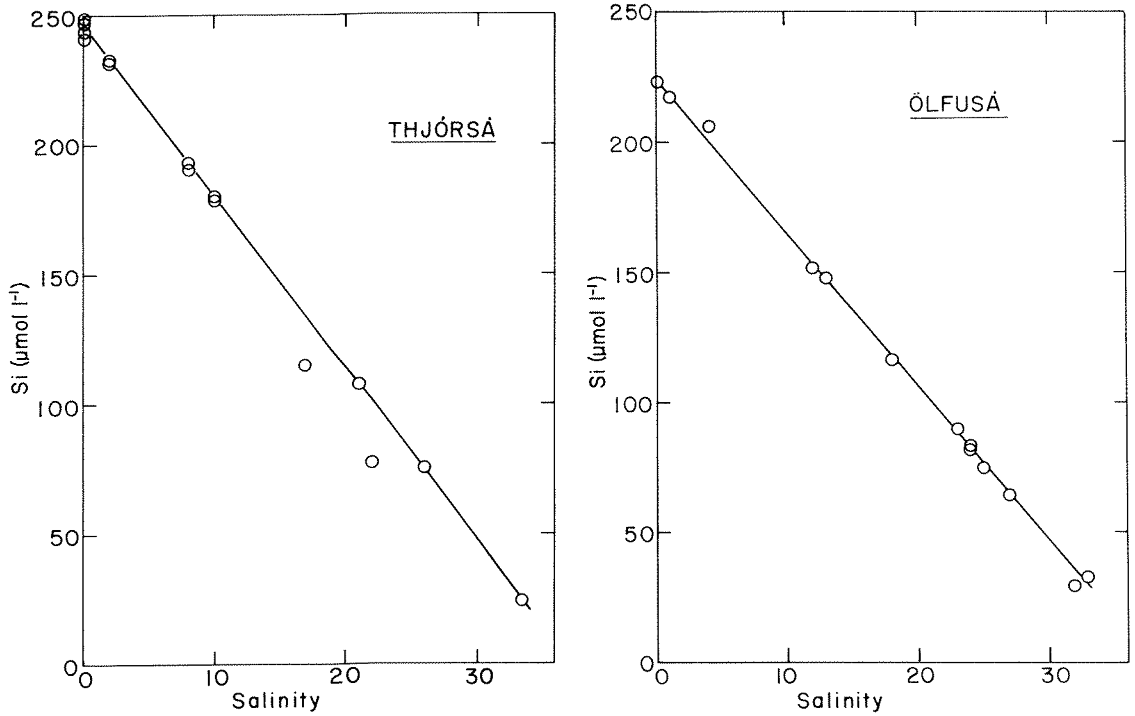

Fig. 13. Relationship between salinity and reactive silicate in the river mouths of the two glacial rivers Þjórsá (32 in Fig. 2) and Ölfusá (33 in Fig.2) on March 26, 1979.

to plant production in the sea except in special cases (see *e. g.* Riley and Chester 1971, p. 246, and Raymont 1980, p. 340), it should be pointed out that on certain occasions very low silicate concentrations, even appreciably lower than those of nitrate, have been found in the outer part of the Icelandic shelf area (cf. Fig. 7). Therefore, the high concentrations of silicate, brought by the rivers, may be of importance for prolonging diatom growth in Icelandic waters, in particular in the near-shore region.

Studies were made of the relationship between silicate and salinity in estuaries of the two largest glacial rivers in South Iceland. The measurements which were made in late winter, when biological uptake must be minimal, indicated a simple linear mixing between the dissolved silica of the fresh water and that of the sea water (Fig. 13). This result suggests that silicon is not lost during estuarine mixing in Icelandic glacial rivers by abiological removal as has been claimed for some rivers in other areas (see Liss 1976).

While fresh water admixture does not directly change the nutrient concentrations of the coastal water to any large extent, the indirect effect of runoff may be quite important, namely on the stratification of the water. As the water becomes shallower, the seasonal temperature range increases progressively and hence the temperature-induced stratification (Thórdardóttir and Stefánsson 1977; Stefánsson *et. al.* 1987). Added to this is the effect of vertical salinity gradients which become more pronounced as the shore is approached, and consequently, the near-shore area becomes stable at an earlier date than the deeper areas (Stefánsson and Gudmundsson 1978; Ólafsson 1985) and may even be stratified in winter. Because of this, nutrient removal by plants may begin already at the end of winter or in the early spring in the shallow near-shore area, as was shown in Figure 9.

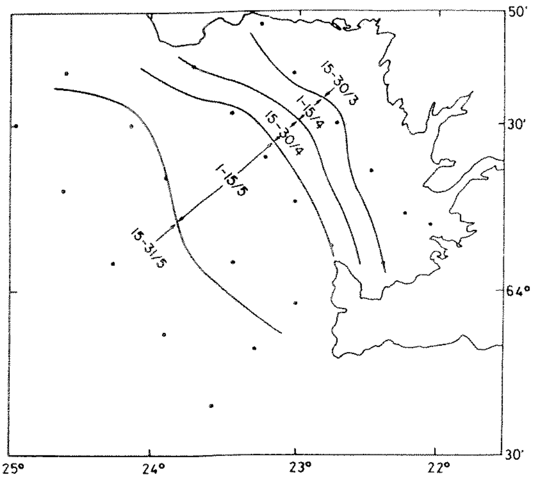

Fig. 14. Times of main nutrient uptake in the spring of 1966 in different parts of the Faxaflói region. (From Thórdardóttir and Stefánsson 1977).

The times of the main nutrient uptake for different parts of the Faxaflói region are shown in Figure 14. The range is about 2 months. On the basis of production measurements from late April and the earlier part of May (Thórdardóttir 1969, 1986) and some nutrient data from the earlier part of May (Stefánsson 1961; Thórdardóttir 1969), it is believed that similar time differences apply to other regions off the west coast. However, Thórdardóttir (1986) has shown that the onset of blooming and consequently nutrient uptake is somewhat later at comparable depths off the south coast. This delay was attributed to different topography of the coastal area along the south coast which is relatively unsheltered as compared to Faxaflói and faces the open ocean more directly so that near-shore vertical mixing is favoured.

As previously stated, detailed studies of seasonal changes in nutrient concentrations are lacking from the regions north and east of Iceland. However, from productivity measurements more than 20 years ago, Thórdardóttir (1969) came to the conclusion that phytoplankton growth within the arctic waters north of Iceland starts earlier than at comparable depths off the west coast, probably already in April, and the production peak is over in large part of the area by the time of the usual late spring cruises. This has been supported by later studies (Thórdardóttir 1979, 1980, 1981). It was also found that due to the normally increased stratification from west to east in the area, the onset of phytoplankton growth is later within the Atlantic water in the westernmost part of the area than within the cold arctic water farther to the east. These findings are in full agreement with the appreciably smaller nutrient concentrations of these arctic waters in spring than in the more mixed areas off the south and west coasts. Since the stratification of the arctic waters north of Iceland apparently does not start appreciably earlier or become more developed in the near-shore area than farther offshore, the onset of the main nutrient uptake in the north probably begins at similar times in spring for different distances from the coast, in contrast to what was found for the Faxaflói region.

Mean distribution in the surface layer.

For making a regional comparison of the nutrient distributions in the surface layer in late May–early June, mean values were computed for the years 1972–1984, during which period data were available for most of the 15 sections occupied (see Fig. 1). The results are shown in Figure 15.

It will be noted that the distribution pattern of phosphate is almost identical to that of nitrate (Figs. 15a-b), and except for near-shore localities, the silicate distribution (Fig. 15c) is also similar. A characteristic feature is a tongue of high concentrations in the outer part of the shelf region west of Iceland extending northwards along the Northwest peninsula into the western part of the North Icelandic region. This tongue is associated with the influx of Atlantic water from the shelf area west of Iceland. In the eastern part of the North Icelandic region, however, nutrients are quite low on the average, with a minimum occurring between Slétta and Langanes. This nutrient-deficient area extends southwards along the east coast, but the concentrations increase sharply at the southern boundary of the East

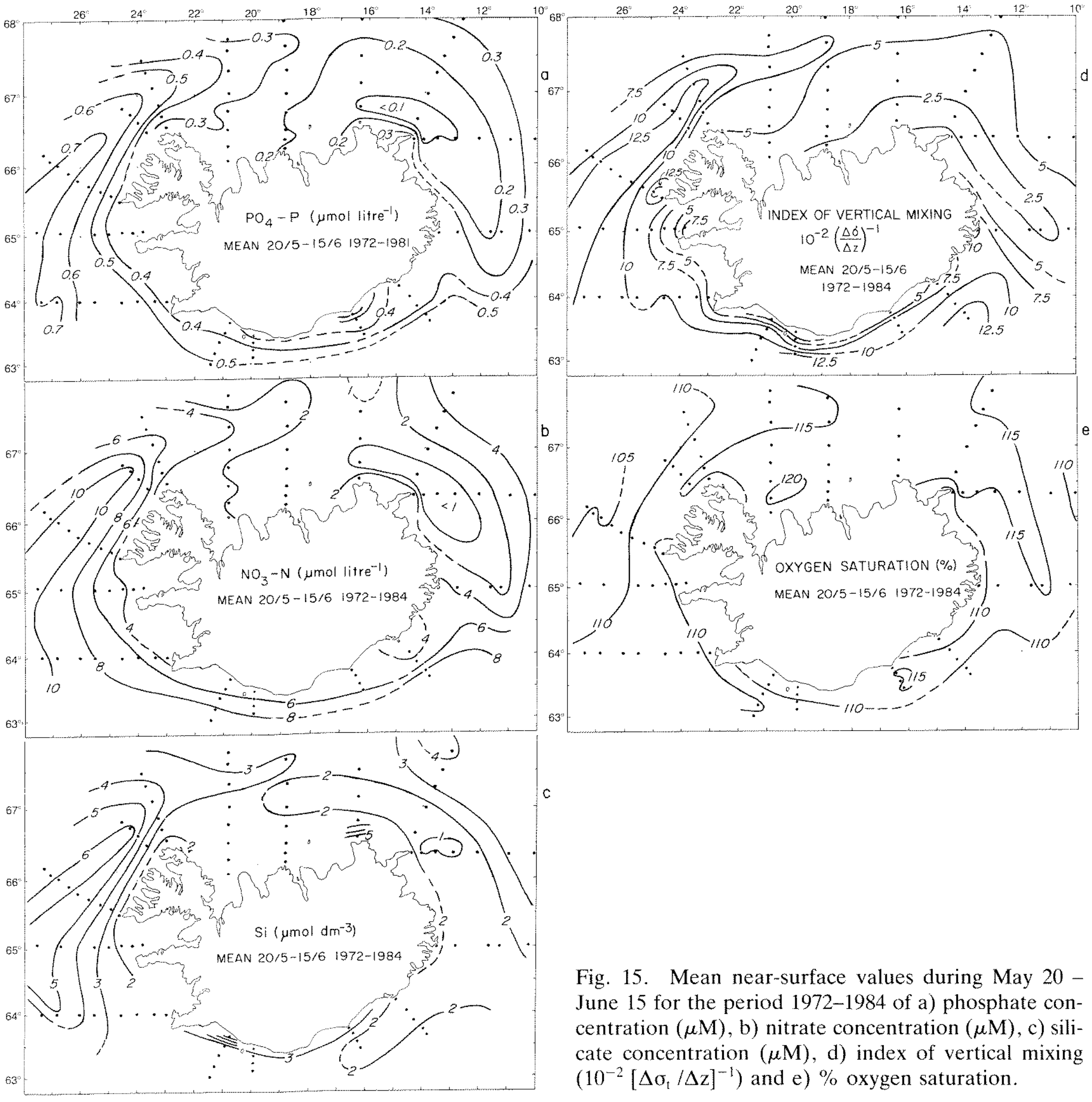

Fig. 15. Mean near-surface values during May 20 – June 15 for the period 1972–1984 of a) phosphate concentration (μM), b) nitrate concentration (μM), c) silicate concentration (μM), d) index of vertical mixing (10^{-2} $[\Delta\sigma_t / \Delta z]^{-1}$) and e) % oxygen saturation.

Icelandic Current. Along the south coast of Iceland the mean nutrient concentrations, based on these observations from the beginning of the spring cruises, are appreciably higher than those found along the north and east coasts.

It should be remarked, however, that owing to the time difference between the observations made along the south coast and those made off the north and east coasts, the values are not strictly comparable. Therefore, it was felt important to examine to which extent the time difference might have affected the results. This was possible to do with respect to the Selvogsgrunn section for the years 1974–1982, when observations were repeated at the end of the spring surveys. Nitrate concentrations at the beginning and at the end of the surveys in these 8 years are compared in Table 3 for the 5 stations on this section. Although

TABLE 3

Differences between the concentration of nitrate (μM) at stations on the Selvogsgrunn section at the end and at the beginning of the spring surveys in the years 1974–1982. St.1 denotes the shallowest station, St. 5 the deepest one; m_1 denotes the mean concentration at the beginning of the survey, m_2 at the end; S.D. denotes the standard deviation of the difference.

	0 m					*100 m*		
Year	*St. 1*	*2*	*3*	*4*	*5*	*3*	*4*	*5*
1974	−3.9	−7.7	−1.5	−1.8	−3.8	1.4	−0.6	−1.0
1976	−0.3	4.1	3.4	3.1	2.7	−1.6	0.0	0.9
1977	2.0	1.9	0.9	−1.8		1.5	1.3	
1978	−6.7	−4.3	−1.8	−1.8	−3.5	3.7	3.2	0.6
1979	−5.3	−9.5	−8.9	−4.4		0.5	0.6	
1980	−6.4	−4.7	−10.3	−4.2			1.3	
1981	−1.5	−2.4	−0.7	−1.0	−1.5			
1982	−2.1	4.5	−1.9	0.0	−2.9	−4.5	0.7	0.0
m_1	5.8	5.9	8.8	8.9	8.3	12.0	12.0	12.2
m_2	2.8	3.6	6.2	7.4	6.5	12.2	12.9	12.3
Δm	−3.0	−2.3	−2.6	−1.5	−1.8	0.2	0.9	0.1
S.D.	±3.1	±5.3	±4.7	±2.4	±2.7	±2.9	±1.2	±0.8

there was on the average an appreciable lowering of the surface concentrations over the approximately 3 week period, especially at the near-shore stations, the difference between years was highly variable. Thus in 1976 and 1977 there was, probably due to the effect of strong wind mixing, an increase during the survey at most of the stations, and at station 2 also in 1982, whereas a decrease was found for 1974, 1978, 1979, 1980 and 1981. Corresponding changes in other nutrients were also found. But even these lower values found on the average at the end of the surveys are considerably higher than those found off the north and east coasts. Furthermore, it should be taken into account that although the maximum time difference was about 3 weeks, the time interval between the observations in the Selvogsgrunn region and those carried out off the north coast was only 1–2 weeks. Therefore, with regard to major features in the distribution, these late spring observations in the different regions can probably be considered comparable. Nevertheless, it may be questioned whether the data from a single survey in spring, carried out near the time of the most rapid change in oceanographic conditions, are sufficient to assess true year to year fluctuations in the nutrient conditions of Icelandic waters.

As an indicator of vertical eddy diffusion we have computed the reciprocal of the stability, $10^{-2}(\Delta\sigma_t/\Delta z)^{-1}$, for the uppermost 50 m. In the following this property will be referred to as "the index of vertical mixing". Where the difference in density between the surface and 50 m was less than 0.02 σ_t units, the index is given as > 25. In general, there was a similarity between the mean distributions of nutrients and the index of vertical mixing (Fig. 15d). Thus, the tongue of high nutrient concentrations west of Iceland coincides with high mixing values. There are also relatively high values of the index of vertical mixing in the area south of Iceland except at the near-shore stations. Southeast of Iceland, at the boundary between arctic and Atlantic waters, a thermocline may not be developed in summer and relatively intense mixing appears to persist throughout most of the year (Stefánsson 1972). Furthermore, turbulence and consequently increased nutrient content may at times be maintained in summer by strong tidal currents in certain localized regions, e. g. off promontories such as Reykjanes, Látrabjarg, and in particular off Langanes. On the other hand, a marked stratification, i. e. very low values of the index of vertical mixing, are found in the North Icelandic region, especially over the inner part of the shelf off the northeast coast where the nutrients reach a minimum.

Although the apparent oxygen saturation is slightly affected by variations in atmospheric pressure and *in situ* temperature changes of the water, it is primarily a function of biological activity. Therefore, high supersaturation values normally result from intense plant growth. However, the supersaturation level in the surface layer is also to a large extent dependant upon stratification. Thus in Icelandic waters, high saturation values tend to coincide with marked stratification, and low values generally occur in mixing areas (Fig. 15e), although in certain small regions oxygen maxima, presumably due to local production peaks, do not seem to have a counterpart in the stratification.

Mean vertical distribution.

Mean nutrient concentrations and percentage oxygen saturation at different depths were computed for 6 standard sections which have been worked for 10 up to 19 years over the period 1954–1984. The mean values together with standard deviations are given in Appendix Tables I–VI.

It is anticipated that these tables will provide useful references for assessing future variations in these variables. Furthermore, significant differences are revealed between the Atlantic water off the southeast, south and southwest coasts on the one hand and the arctic water masses north and northeast of Iceland on the other. The following main features can be identified:

1) At the 3 sections in the arctic region, *viz.* the Kögur, Siglunes and Langanes sections, the mean near-surface nutrient concentrations are markedly lower than at the 3 sections where Atlantic water predominates, viz. the Stokksnes, Selvogsgrunn and Snæfellsnes sections.

2) In general, nutrient concentrations are almost uniform within the mixed layer, which may range from less than 10 m in thickness to more than 30 or even 50 m. On the average, however, the concentrations are slightly greater at 20 m than at the surface.

3) On most of the sections, i. e. Selvogsgrunn, Snæfellsnes, Kögur and Stokksnes, the mean near-surface concentrations increase in a direction away from the coast. On the Siglunes section almost equally low concentrations are found at all the stations. On the Langanes section relatively high values are found at the shallowest station, no doubt due to intense tidal mixing as mentioned above. Very low values were found at the other 3 Langanes stations on the shelf, while at stations east of the continental slope there was the normal increase in offshore direction.

4) At most of the stations, the main vertical increase in the nutrient concentrations occurs in the 20–50 m layer. However, the vertical concentration gradient within the uppermost 50 m is appreciably greater on the average in the stratified area north of Iceland (4–6 μM NO_3-N per 50 m) than in the mixing areas south and west (2–4 μM NO_3-N per 50 m). At a depth of 200 m the concentrations resemble typical near-surface winter values.

5) The mean oxygen saturation ranges from 105 to 117% in the 0–20 m layer, the higher values being somewhat more frequent in the stratified region north of Iceland than off the west and south coasts. Most frequently, the 100% saturation value occurs at a depth between 50 and 100 m. At 4 stations off Snæfellsnes this value is found below 100 m, and above 50 m at 2 stations east of Langanes and at the deepest station off Kögur.

6) It will be noted that at depths greater than 200 m the mean nutrient concentrations are everywhere smaller in the arctic waters north and northeast of Iceland than in the Atlantic water southeast, south and west. To test the statistical significance of this difference, the mean deep water nutrient concentrations were also computed separately for all Atlantic and for all arctic stations (Table 4), together with standard deviations. From the t-distribu-

TABLE 4

Comparison between deep water concentrations (600, 800 1000 m) of nitrate and phosphate at Atlantic water stations south and west of Iceland (from Stokksnes to Snæfellsnes) and those at stations north of Iceland (from Kögur to east and north of Langanes).

	NO_3-N (µM)			PO_4-P (µM)		
Stations	*600 m*	*800 m*	*1000 m*	*600 m*	*800 m*	*1000 m*
Atlantic stations	*15.3*	*16.0*	*16.3*	*1.01*	*1.05*	*1.08*
SD	±1.0	±0.7	±0.5	±0.07	±0.09	±0.04
n	13	11	14	6	6	6
Arctic stations	*13.2*	*13.3*	*13.7*	*0.90*	*0.90*	*0.92*
SD	±1.2	±1.0	±0.8	±0.08	±0.08	±0.09
n	37	18	14	30	20	15
Level of significance (%) of difference between Atlantic and arctic water	>99.9	>99.9	>99.9	>99	>99.9	>99.9

tion (bottom line of Table 4) it is seen that the difference between the mean nutrient concentrations of deep water samples from these two groups of stations is highly significant.

7) From Appendix Tables I–VI it will be noted that there does not seem to be a significant difference between the oxygen saturation values of the deep waters (500–1000 m) at arctic and Atlantic stations. There is, however, a significant difference in the apparent oxygen utilization values (AOU), due to the difference in the oxygen solubility of the deep waters. Thus, for a given ratio between measured oxygen (O_2) and oxygen solubility (O_2'), the difference (O_2'–O_2), will be greater in the cold deep waters north and northeast of Iceland ($t < 0$°C) than in the deep waters south or southwest of Iceland where the temperature may be in the range 4°–7°C. Consequently, for equal values of percentage oxygen saturation, the northeastern deep waters will have higher AOU-values than the southern ones.

This difference between the arctic and Atlantic regions will, however, vary from year to year, presumably due to fluctuations in biological activity, stratification and winter convection. An example of markedly higher AOU-values in arctic than Atlantic waters is shown in Figure 16a. The profiles indicate that in late February 1991 the mixed layer thickness in the Irminger Sea west of Faxaflói, extended to a depth of about 600 m, while in the deep area NE of Langanes it was less than 75 m. In the winter of 1982 the vertical AOU distribution was similar in this northern area.

From the values in Table 4 and AOU data, preformed nitrate and phosphate was computed for the 600, 800 and 1000 m level at Atlantic and arctic stations using oxidative ratios of $\Delta P:\Delta N:\Delta O_2 = 1:14.5:(-138)$ in accordance with the nitrate-phosphate relationship described in a later section. The results, given in Table 5, indicate that the Atlantic (and Irminger) water south and west of Iceland has an appreciably higher preformed nutrient content than the arctic water masses north and northeast of Iceland, in accordance with previous findings (Stefánsson 1968b). It will be noted that the difference between preformed nutrients in arctic and Atlantic waters is even greater than the difference between total inorganic nutrients shown in Table 4. This can be ascribed to higher values of AOU in the northern region and hence greater contribution to the total inorganic nutrients than in the Atlantic region.

A striking example of this difference between preformed nutrient concentrations southwest and northeast of Iceland is shown in Figure 16b and c. At the northern station pre-

TABLE 5

Mean concentrations of preformed nutrients in deep waters (600, 800 and 1000 m) at Atlantic water stations and at stations north of Iceland.

	Preformed NO_3 -N (μM)			*Preformed PO_4 -P (μM)*		
Stations	*600 m*	*800 m*	*1000 m*	*600 m*	*800 m*	*1000 m*
Atlantic stations	11.6	10.7	11.3	0.76	0.68	0.73
Arctic stations	8.0	7.7	7.9	0.54	0.51	0.52

formed phosphate and nitrate decreased from about 0.7 μM and 10 μM respectively near the surface to 0.5 μM and 7.3 μM respectively at 600 m depth and then increased slightly to 1000 m depth. At depths from 1000 m to 1800 m (not shown in Fig. 16), the preformed nutrients remained practically constant. At the southern station preformed phosphate and nitrate were constant down to 600 m, about 0.82 and 12.1 respectively, then decreased slightly down to 1000 m. Except for the uppermost 200 m, where silicate concentrations were lower in the northeastern area than southwest of Iceland, the vertical silicate distribution in the winter of 1991 was quite similar in both regions. This result for the deep water was in conformity with that given in the Appendix Tables I–VI.

YEAR TO YEAR VARIATIONS

Variations in late spring

In the section on seasonal variations it was shown that (Fig. 12) that the mixed layer depth at St. 3 on the Siglunes section was about 300 m in the years 1954 and 1955, and presumably the same applied to most of the years during the warm period prior to 1965. Since then the mixed layer depth, as evidenced by data collected during the annual

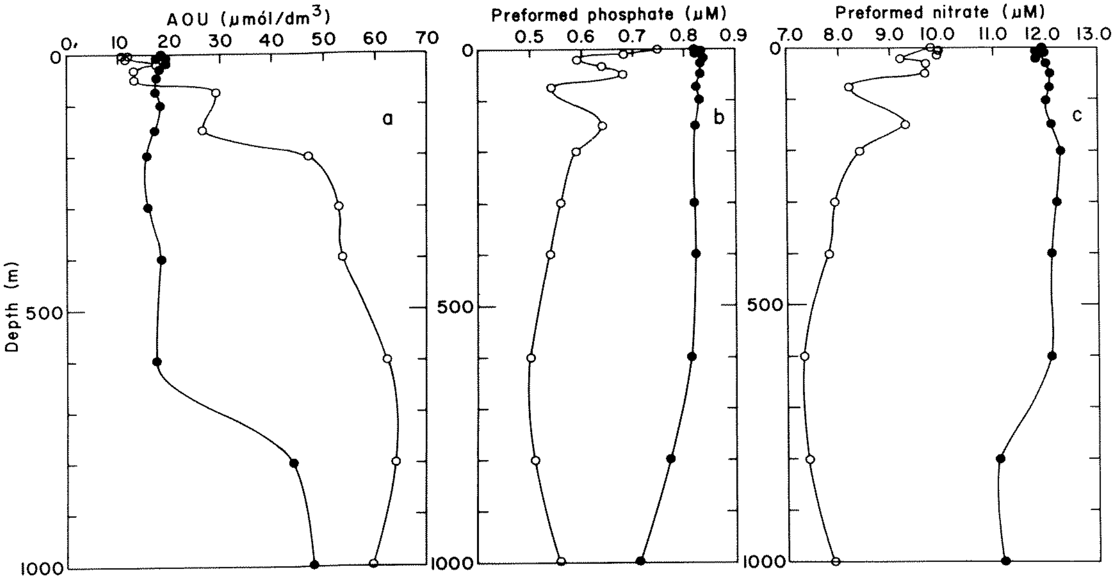

Fig. 16. Profiles of a) apparent oxygen utilization (AOU), b) preformed phosphate and c) preformed nitrate in late February 1991 for arctic water northeast of Iceland ○ (at 67°59′N, 12°41′W) and Atlantic water west of Reykjanes ● (at 64°20′N, 27°27′W).

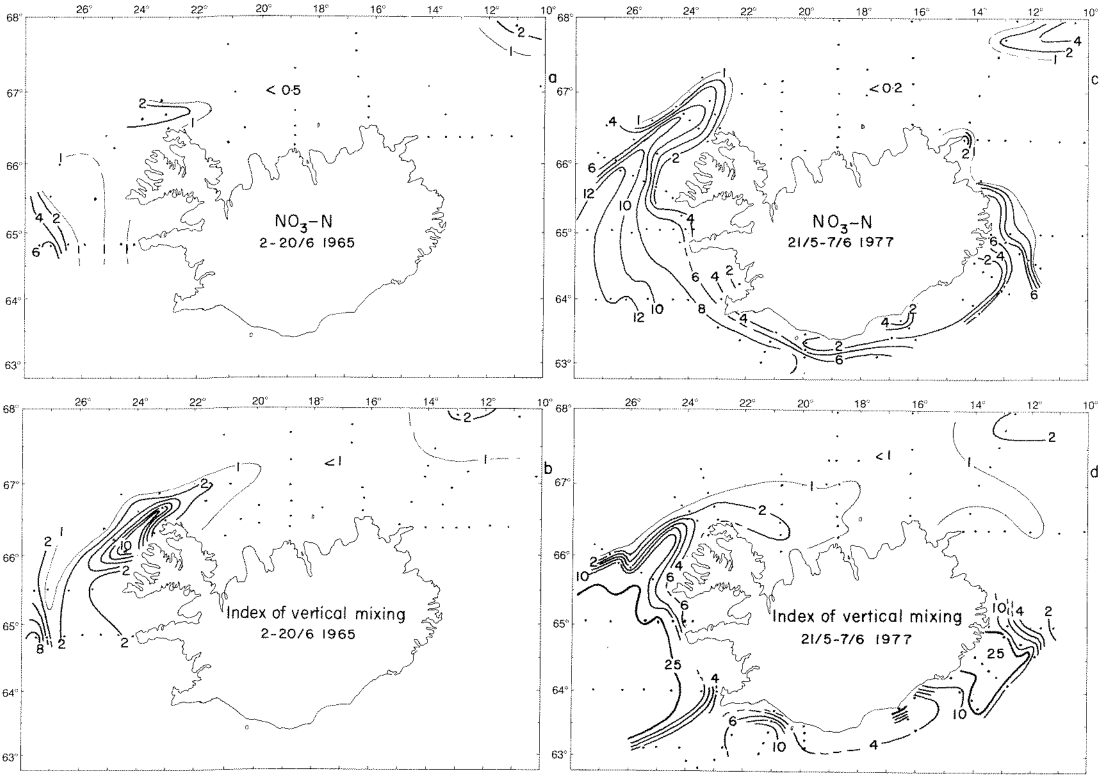

Fig. 17. Near-surface distribution of nitrate (μM) and index of vertical mixing (10^{-2} [$\Delta\sigma_t$ / Δz]$^{-1}$) during June 2–20, 1965 (a and b) and May 21 – June 7, 1977 (c and d).

surveys as well as a few winter observations, has in most years been less than 200 m. Increased stratification and decreased thickness of the mixed layer also applied to the area between Iceland and Jan Mayen during the cold years after 1964 (Stefánsson and Jakobsson 1989). Furthermore, considerable year to year fluctuations may occur in the temperature and salinity distribution of Icelandic waters, particularly as regards the water mass composition of the area north of Iceland, due to variable influx of Atlantic water and variable intrusion of polar water.

Variations resulting from such hydrographical fluctuations between years can also be identified in the distribution of nutrients and the index of vertical mixing. A few selected examples are shown in Figures 17–19. We note that during the very cold year of 1965 (Fig. 5), when admixture of low-salinity polar water was appreciable in the surface layers (Malmberg 1967), vertical turbulence was virtually suppressed and nitrate concentrations exceptionally low. The same applied to the region north of Iceland in the cold year of 1977, whereas in 1978, which was an average year, concentrations were markedly higher within the tongue of relatively high mixing index in the western part of the North Icelandic area. Again, 1979 was a cold year with limited mixing and very low nitrate concentrations, whereas in the warm year of 1980 with an extensive distribution of Atlantic water in the North Icelandic region and absence of polar influence (cf. Fig. 4), mixing conditions were favourable and nutrient concentrations quite high. Finally, in 1986, when the distribution of Atlantic water was about average, high nutrient concentrations were found in most parts of the North Icelandic area, but especially in the western part, where the index of vertical mixing was quite high. Distributions of phosphate and silicate resembled in most cases closely that of nitrate.

Year to year variations in nutrient concentrations, vertical mixing and oxygen saturation in relation to hydrographical changes were investigated at St. 3 on the Siglunes section (Fig. 20; for location, see Fig. 1) including most years in the period 1954–1988. As stated before (pp 7 and 9) these years can be roughly divided into three periods: 1) the warm period 1954–1964; 2) the cold period 1965–1971; and 3) the period 1972 to present with warm and cold years alternating. In the first of these three periods (with phosphate but no nitrate data) nutrient concentrations at this locality were clearly relatively high in late spring, coinciding with strong influx of Atlantic water (cf. Fig. 5). In the second period, characterized by intrusion of low-density polar water in the surface layer and a strong stratification, both nitrate and phosphate concentrations were exceptionally low, whereas in the third period high and low values interchanged. Conspicuously high nutrient concentrations were found in the years 1957, 1959, 1980 (phosphate) and 1985 (nitrate) with favourable mixing conditions. In most cases, but not always, the variations in the index of vertical mixing resembled those of the nutrients. Since the oxygen saturation will be highly dependant upon the degree of wind mixing as well as *in situ* warming, no definite relationship appears between the oxygen saturation and the other properties, except that the very highest

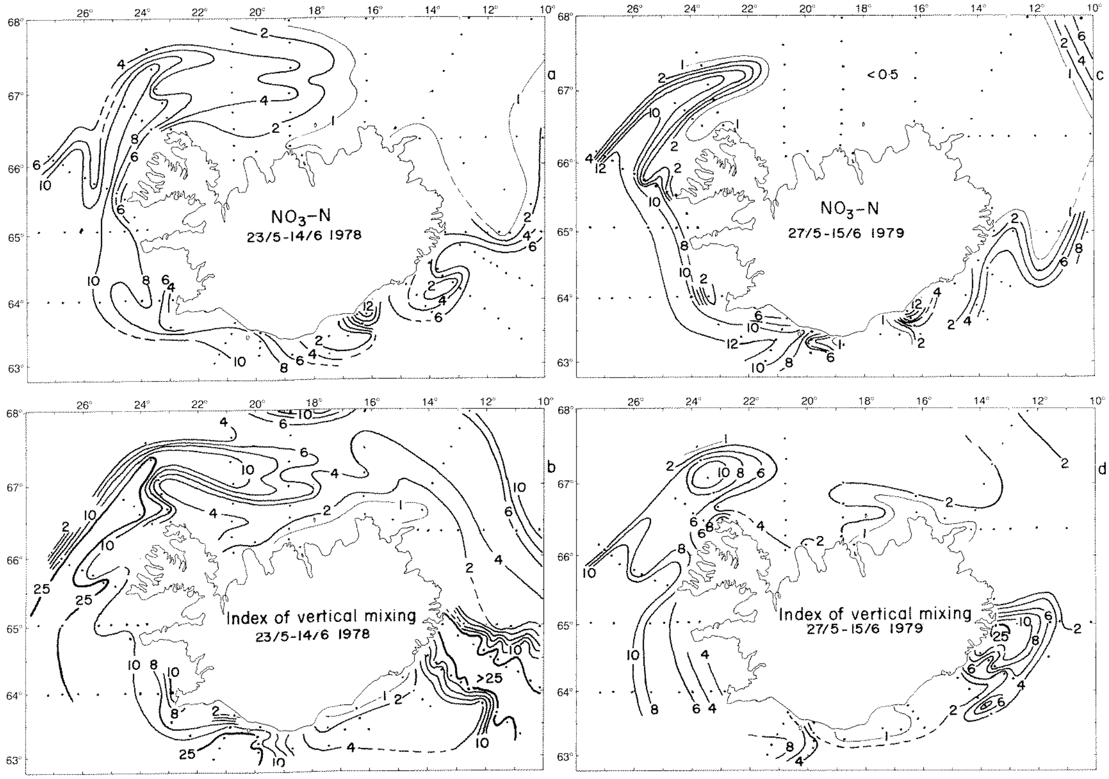

Fig. 18. Near-surface distribution of nitrate (μM) and index of vertical mixing (10^{-2} [$\Delta\sigma_t$ / Δz]$^{-1}$) during May 23 – June 14, 1978 (a and b) and May 27 – June 15, 1979 (c and d).

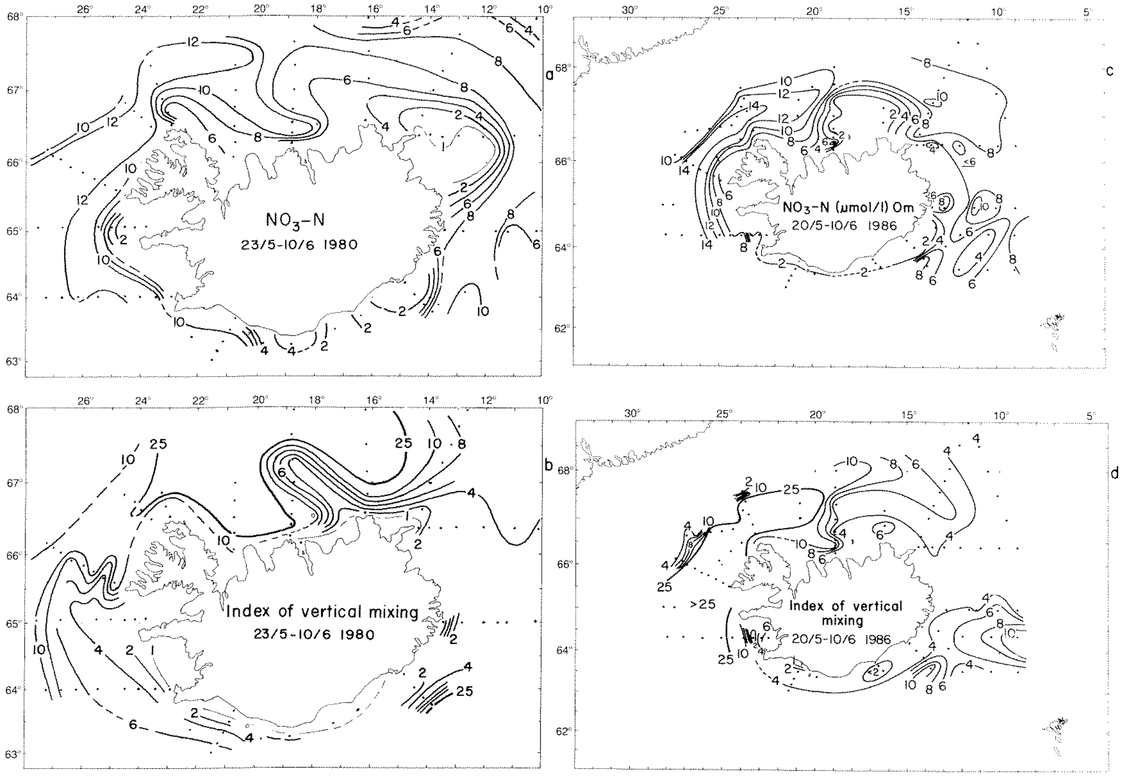

Fig. 19. Near-surface distribution of nitrate (μM) and index of vertical mixing (10^{-2} $[\Delta\sigma_t / \Delta z]^{-1}$) during May 23 – June 10, 1980 (a and b) and May 20 – June 10, 1986 (c and d).

nutrient concentrations and highest values of the mixing index coincided with the relatively lowest supersaturation values.

The relationship between nutrients and mixing conditions was further examined by comparing the mean nitrate concentration and the mean index of vertical mixing for different years in 4 sections across the shelf (Fig. 21). Comparison between Figures 20 and 21 reveals that at station 3 on the Siglunes section the index of vertical mixing was in most cases quite similar to the average value for the section as a whole, except for 1974. On the Langanes-E section both nitrate concentrations and the mixing index had quite low values in most of the years, except for 1973, 1975 and 1988, which stand out as regards mixing although nitrate concentrations were only moderately high, and 1985 when both the index value and the nitrate concentration was relatively high. On the other hand, in 1980, 1981 and 1986, nutrient concentrations were considerable on the Langanes-E section in spite of moderate or low index values. In the Snæfellsnes and on the Selvogsgrunn sections, both nitrate concentrations and the index values were highly variable, but as expected,

TABLE 6

Correlation between nitrate concentrations and the index of vertical mixing for 4 sections off the coasts of Iceland in the years 1965–1988.

Section	*Number of observations*	*Correlation coefficient*	*Level of significance (%)*
Selvogsgrunn .	17	0.52	>98
Snæfellsnes . . .	17	0.78	>99.9
Siglunes	24	0.92	>99.9
Langanes-E . .	24	0.57	>99

much higher in most years than off the north and the northeast coasts. The correlation was tested statistically and the results are shown in Table 6. Although the computed correlation coefficients were all found to be significant, the correlation was weak for both the Selvogsgrunn and the Langanes sections.

August observations

Some nutrient data are available from August both off the south, southwest and north coasts of Iceland. In most years, however, these observations were not extensive enough for drawing up horizontal charts of the distribution. The differences between years as well as regions are illustrated in Figure 22a–b.

It will be seen that on the Selvogsgrunn section (Fig. 22a) the concentrations found in different years were highly variable. They were low at all stations measured in August 1965 and 1971 (~ 0.5 μM), but appreciable at most of the stations in 1977, 1980 and 1981 (1.5–3.5 μM). In 1976 high values were found in July (6–7 μM), but remarkably low in August (0.3–0.7 μM). Thus short periodical variations, from month to month or even less, may be equally large or larger than variations found between years based on single observations. On the Langanes-E section, however, very low concentrations (< 0.5 μM) were found at practically all the stations during the 7 years with observations, except for 1964. In the Reykjanes section, as on the Selvogsgrunn section, the August concentrations were highly variable, but in almost all cases greater than in the Siglunes section, where they were

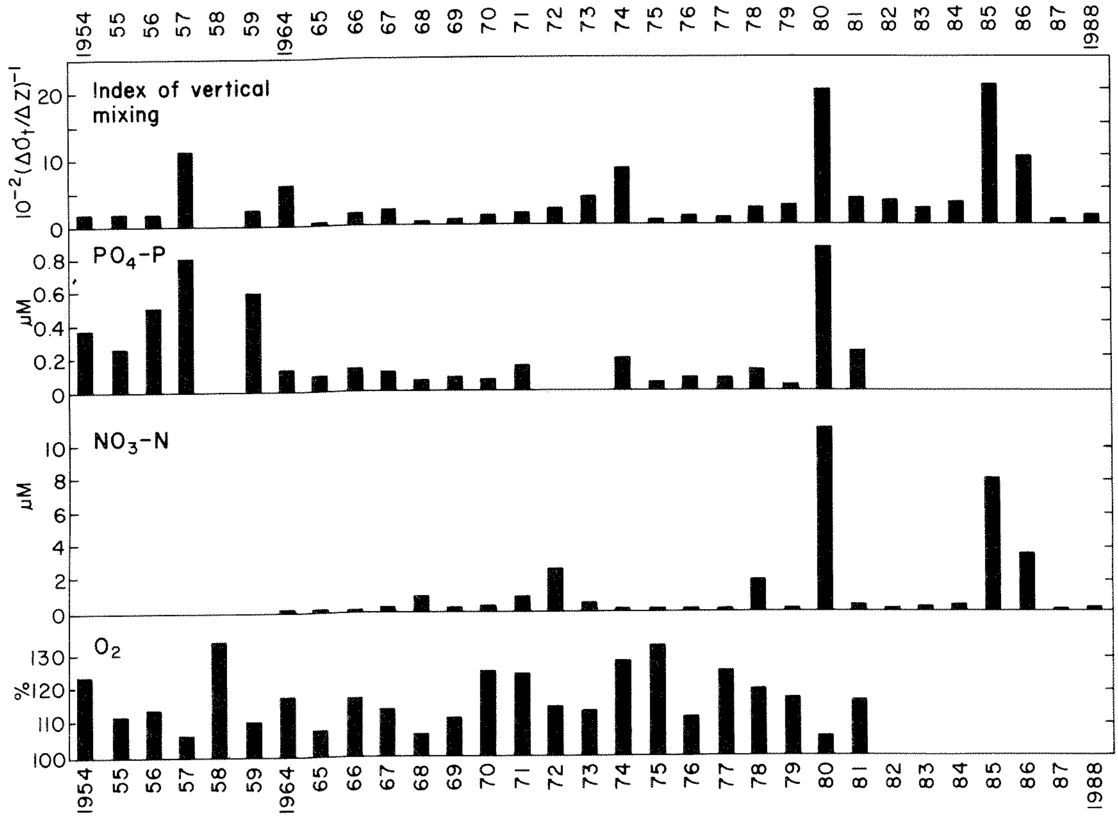

Fig. 20. Year to year variations at station 3 (counted from land) on the Siglunes section (for location see Fig.1) in index of vertical mixing, near-surface phosphate, near-surface nitrate and near-surface % oxygen saturation.

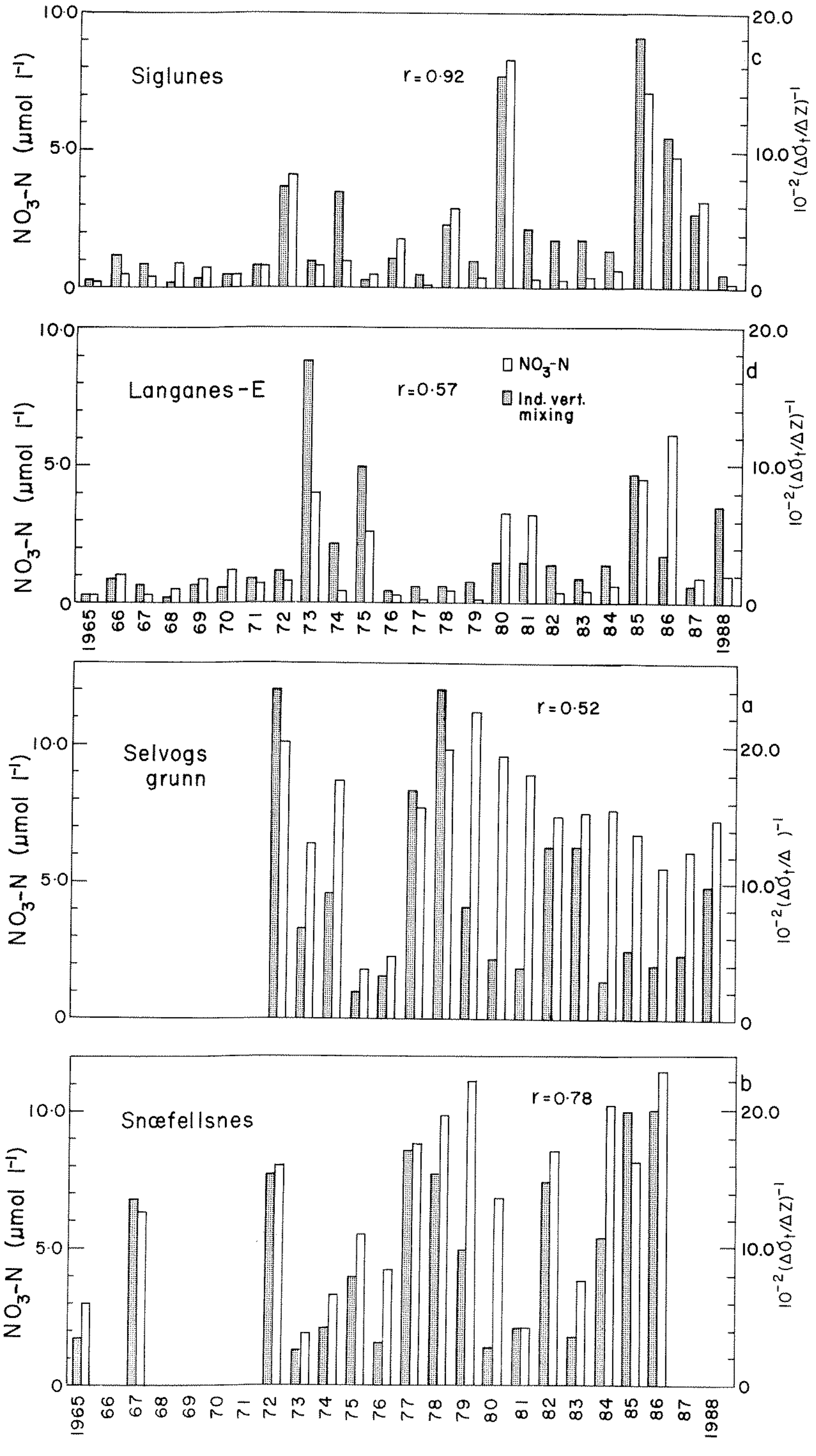

Fig. 21. Comparison between the mean near-surface concentration of nitrate and the mean index of vertical mixing in different years in 4 sections across the shelf. For location of sections see Fig. 1.

TABLE 7
Mean near-surface nutrient concentrations and stability at offshore stations, south, west, north and northeast of Iceland in August in the period 1964–1982.

Region	PO_4-P (µM)			NO_3-N (µM)			$\Delta\sigma_t$ / (50 m – 0 m)		
	Mean	S.D.	n	Mean	S.D.	n	Mean	S.D.	n
Selvogsgrunn	0.30	0.15	35	2.1	1.7	48	0.443	0.219	5
Off Reykjanes	0.31	0.14	51	2.9	1.8	58	0.392	0.192	56
Off Kögur[1)]	0.24	0.07	12	1.9	1.5	16	0.428	0.297	16
Off Siglunes	0.15	0.06	31	0.4	0.4	46	0.993	0.613	43
Off Langanes	0.09	0.04	25	0.4	0.3	30	0.697	0.296	30

[1)] Observations where polar influence was marked in the surface layers are not included.

generally less than 0.5 µM (Fig. 22b) and similar to those found east of Langanes.

A statistical comparison between mean near-surface nutrient concentrations and stability at offshore stations south, southwest, northwest, north and northeast of Iceland (Table 7) clearly reveals this difference between Atlantic and arctic water. On the Selvogsgrunn and Reykjanes sections and in most cases also at the shelf stations on the Kögur section, Atlantic water prevails with considerably higher and more variable nutrient concentrations and less stability than in the 'sections north of Siglunes and east of Langanes where the well stratified arctic water is much more predominant than in the westernmost part of the North Icelandic shelf area. This difference between the Atlantic and arctic water is highly significant (exceeds the 99.9% level) with respect to both nitrate and phosphate concentrations as well as stability.

From these data it is concluded that in late summer nutrient concentrations in the arctic regions north and northeast of Iceland are generally small, uniform within the region and similar from year to year. In contrast to this, the concentrations in the Atlantic regions south, west and northwest of the country are on the whole markedly greater but highly variable from year to year and probably also within the same month.

NUTRIENT RELATIONSHIPS

Nitrate-phosphate relationship

To compare the phosphate-nitrate relationship for the regions north and south of Iceland we have plotted nitrate concentrations against phosphate concentrations for the upper layers of the two sections, off Siglunes and across the Selvogsgrunn (for location, see Fig. 1) in the period 1974–1981. The results (Fig. 23) and their statistics (see legend to Fig. 23) reveal that for the Selvogsgrunn section the intercept of the computed regression line on the y-axis was not significantly different from zero, whereas for the Siglunes section the intercept on the y-axis was highly significant. On the other hand, the slopes of the two regression lines, 14.2 and 14.8 respectively, are not significantly different.

The results imply that in the arctic water a small but significant concentration of phosphate remains in the water when nitrate is depleted, while in the Atlantic water the two are depleted simultaneously. Thus it appears that nitrate is the limiting nutrient for plant growth, at least in the northern area. However, since ammonia was not measured, the existence of significant concentrations of ammonium-nitrogen at very low nitrate levels can not be excluded.

These results also imply that the concentration ratio between initial (preformed) nitrate and initial (preformed) phosphate is smaller

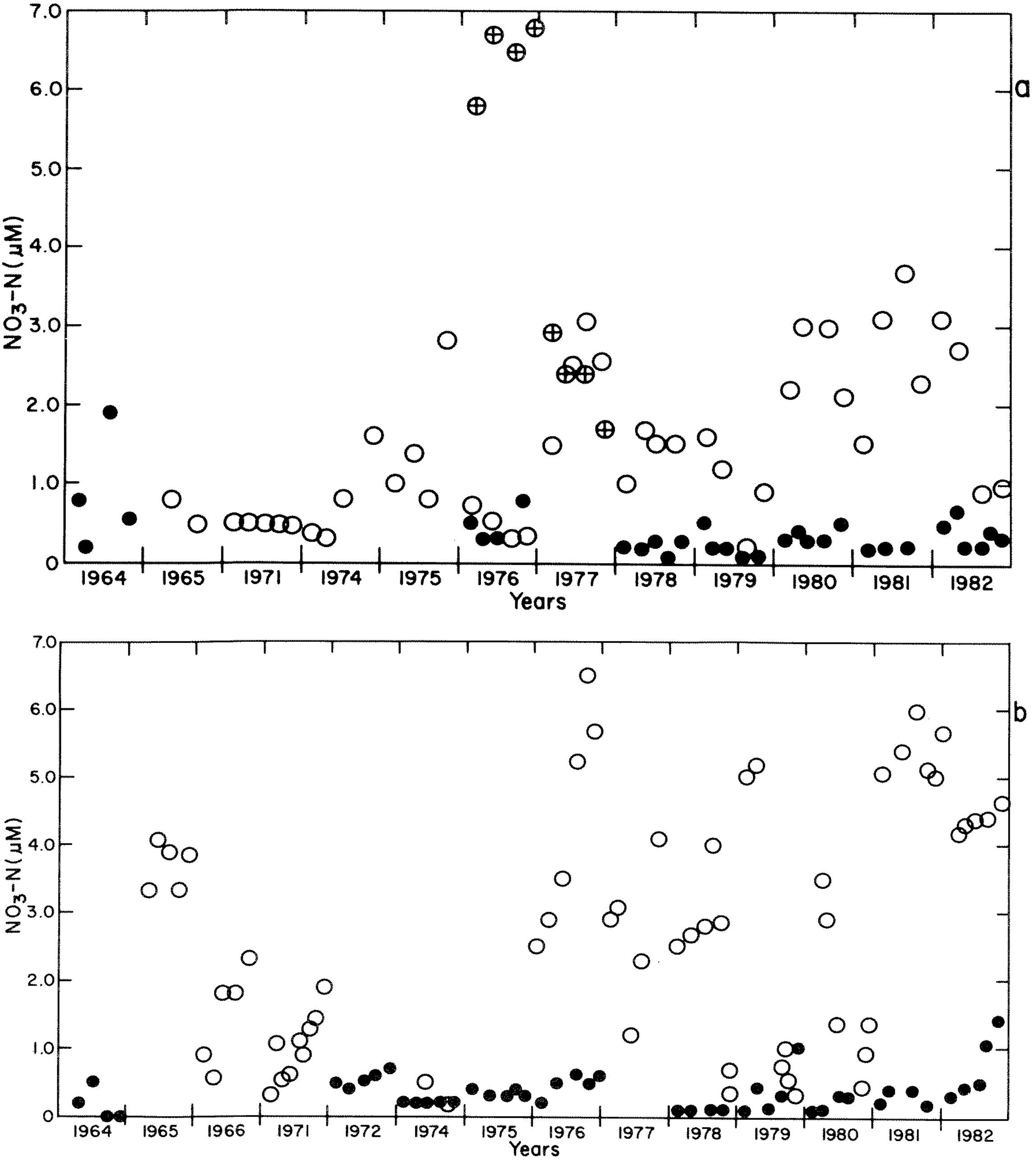

Fig. 22. a) Near-surface nitrate concentrations (μM) in July–August in the years 1964–1982: ● Langanes-E section (stations 2–6, counted from land) in August; ⊕ and ○ Selvogsgrunn section in July and August respectively. b) Near-surface nitrate concentrations (μM) in August in the years 1964–1982: ● Siglunes section (stations 2–6, counted from land); ○ Reykjanes section (west of 24° W). For each year concentrations are shown for different stations, and the values for those closest to land are farthest to the left, but farthest to the right for the deepest stations on the sections.

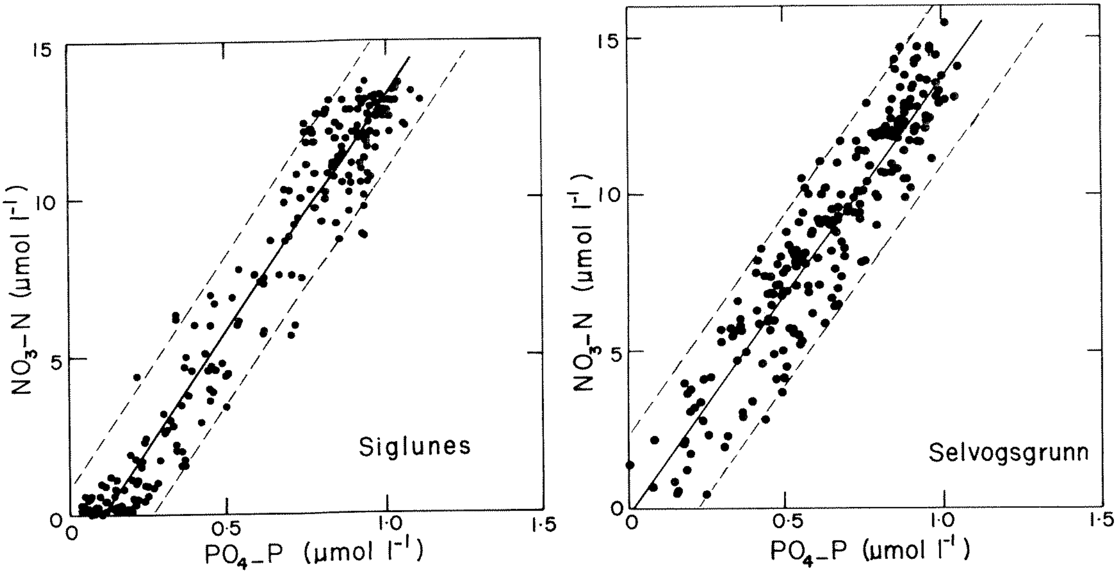

Fig. 23. Plots of nitrate concentrations against phosphate concentrations from 0–200 m for stations on the Selvogsgrunn and Siglunes sections respectively in the period 1974–1981. The broken lines indicate the 95% confidence limits. For the Selvogsgrunn section the number of observations was 215, the slope of the regression line 14.21 ± 0.40, the intercept −0.33 ± 0.27 μM and the correlation coefficient 0.93. For the Siglunes section the observation number was 210, the slope 14.79 ± 0.25, the intercept −1.57 ± 0.16 μM and the correlation coefficient 0.97.

than the rate of change of these nutrients in the arctic water, whereas the two ratios appear to be identical in the Atlantic water. From Appendix Tables I–VI it is easily calculated that the mean N/P ratio for the surface layer of deepest stations in the Atlantic area (Stokksnes, Selvogsgrunn and Snæfellsnes sections) ranges from 14.3 to 16.0, whereas in the Iceland Sea at stations where the admixture of polar water is greatest, *i. e.* at the deepest stations in the Kögur and Siglunes sections and station 6 in the Langanes-E section, the N/P range is from 7.7 to 11.0. For each of these sections the stations selected were those with the highest concentrations and hence the least advanced nutrient uptake. The result agrees well with the concentration ratios of 9.6 and 14.0, computed from estimated preformed nutrients of polar water and Atlantic water respectively in the Northern Irminger Sea (Stefánsson 1968b). Thus the mean concentration ratios based on preformed nutrients as well as observations in late spring clearly explain this difference between the northern and the southern areas. It should be recalled, however, that in the shelf area north of Iceland admixture of polar water varies considerably from year to year. For the period 1974–1981, on which the correlation shown in Figure 23 was based, polar influence was appreciable in many of the years (See Fig. 5). If the correlation had been based on the warm period prior to 1965, when Atlantic influence was much more dominating in the North Icelandic area, the computed regression would no doubt have resembled more that found for the area southeast, south and west of Iceland. However, sufficient reliable nutrient data from that period are not available.

From Table 4 we find that in the deep water (600, 800 and 1000 m) the average concentration ratios for Atlantic and arctic stations are 15.2 and 14,8 respectively. Thus, the concentration ratios differ much less in the deeper layer than in the upper layers, a result to be expected due to mixing of Atlantic water in the lower water strata south and west of the

Iceland-Faroe Ridge with overflow water originating from from the northern region.

As was previously shown (Fig. 16, Table 5), preformed nutrients are considerably higher in the deep waters south and west of Iceland than they are in the waters north of the country. From the difference, the concentration ratios for the surplus preformed nutrients of the Atlantic water can be estimated by computing the ratio $[(N^0)_S - (N^0)_N] / [(P^0)_S - (P^0)_N]$, where the superscript $_0$ denotes preformed (initial) nutrients, and the subscripts S and N denote waters south or north of Iceland. Using the values in Table 5 we obtain the following ratios: 600 m: 16.3, 800 m: 17.6, 1000 m: 16.2 From observations made in late February 1991 at one deep station northeast of Iceland (at 67°59′N, 27°57′W) and the average values observed respectively west of Reykjanes (at 64°20′N, 27°57′W) and just off the shelf edge south of Iceland (at 62°59′N, 21°29′W), the mean ratio for the depth range 200–1000 m was found to be 16.2 (± 1.4). These concentration ratios for the surplus preformed nutrients of the of the Atlantic water are similar to the computed ratio of change, when all available data are lumped together rather than computing it separately for different water masses (cf. Stefánsson 1968a).

Nitrate-silicate relationship

As stated earlier, the silicate distribution in the surface layers around Iceland generally resembled that of phosphate and nitrate. A closer study, however, revealed that in many years there were small but highly significant differences between the nitrate or phosphate distribution and that of silicate. This applied in particular to the northwestern, northern and northeastern regions.

It is well known that the proportion of diatoms in the phytoplankton is variable and the recycling process of silicate markedly different from that of phosphate and nitrate. Thus, for the Northern Irminger Sea, Stefánsson (1968b) found an exponential rather than linear relationship between phosphate and silicate. To examine this relationship for the waters around Iceland, surface nitrate was plotted against silicate for the years 1972–1984 from which period dense observations were available. It was found that in the area north and east of Iceland in the years 1978, 1980, 1982 and 1983, and west and south of Iceland in 1978, 1979, 1980, 1982 and 1983 the data, a total of 270 observations, could be reasonably well fitted by an exponential function (Fig. 24). This plot indicates that when the silicate concentration has been reduced to about 1 μM, the nitrate concentration may be as high as 5 μM, whereas when silicate is below 0.5 μM, both nutrients approach depletion simultaneously. The computed regression for the linear plot of $[NO_3\text{-}N]$ against ln[Si], had the equation

$$[NO_3^- {-} N] = 3.407 \ln[Si] + 5.2 \qquad (2)$$

with a correlation coefficient of 0.94.

Inclusion of data from other years within this period indicated a number of points which deviated appreciably from that relationship. To compute these deviations, which we refer to as silicate anomalies, the exponential curve was used. The anomalies were then determined for points falling outside the 95% confidence limits, as the distances measured along the Si-axis from the observation points in question to the curve marking the 95% confidence limit. An example of such anomalies is shown for the N/Si plot of the 1976 observations (Fig. 25). Clearly, a large number of points fell that year outside the 95% confidence limits.

Distribution of near-surface silicate anomalies were examined for all the years since 1964. Details for the years 1979 and 1984–1988 are shown in Figure 26a–f. Single anomaly values of less than 0.5 μM, were not considered significant and are not included. Two of the years, 1984 and 1988, stand out with large anomalies. The distribution is quite similar for both of these years, with remarkably high anomaly values at deep stations off the Northwest peninsula and over the western part of the North Icelandic area, that is, in the main mixing zone between Atlantic and arctic waters. Moderately high values were found

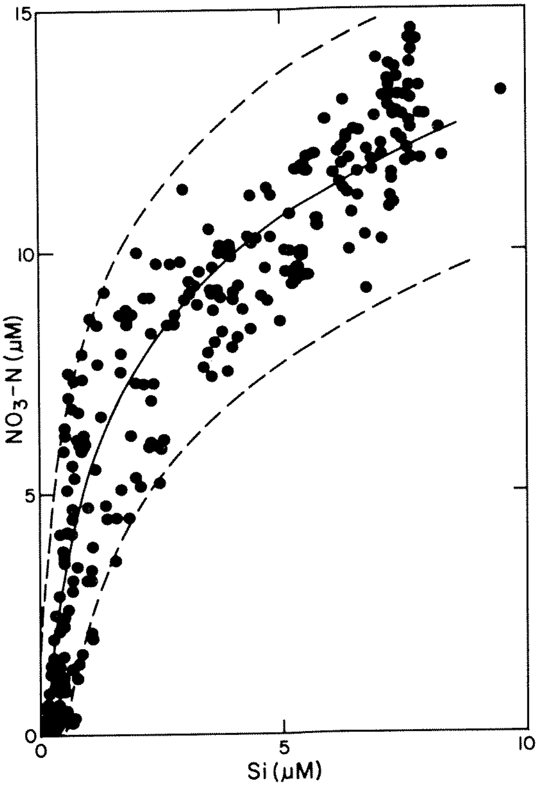

Fig. 24. Relationship between near-surface nitrate and near-surface silicate concentrations, based on data from late spring north and east of Iceland in 1978, 1980, 1982 and 1983, and west and south of Iceland in 1978, 1979, 1980, 1982 and 1983. The exponential curve and the 95% confidence limits are based on a linear regression of [NO_3-N] on ln [Si].

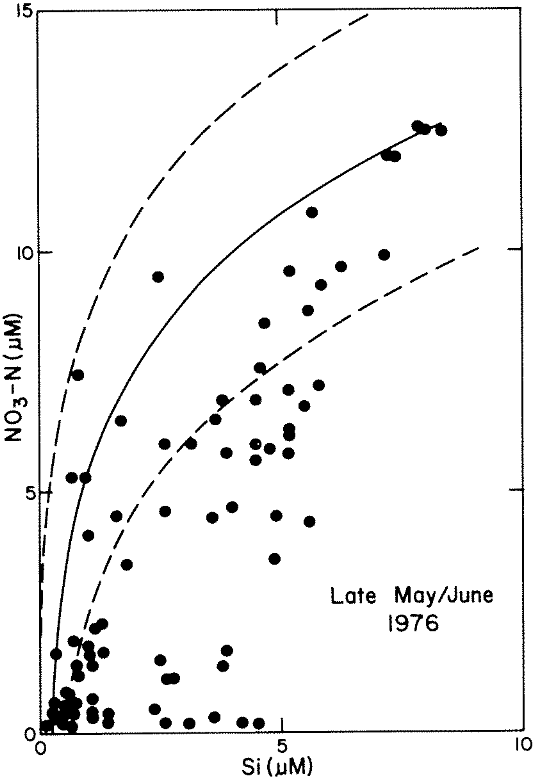

Fig. 25. Plots of near-surface nitrate against near-surface silicate concentrations around Iceland in late spring 1976. The exponential curve and the confidence limits are those shown in Fig. 24.

for the year 1976, small but significant for 1986, very small for 1985 and almost non-existing for 1987. It is of interest to note that significant anomalies were not found for the area south of Iceland except in two years, 1972 and 1976. A summarized overview of silicate anomalies in the 25 year period 1964–1988 is given in Table 8.

Relationship between vertical mixing, nutrients, oxygen saturation and productivity

As has been repeatedly shown by Thórdardóttir (e. g. 1969, 1977, 1984, 1986), primary production in Icelandic waters depends largely on the availability of nutrients and hence on mixing conditions in the surface layers. Furthermore, as pointed out in a previous section, the oxygen supersaturation measured in the surface layers depends not only on photosynthesis, but also on stratification. How then does the oxygen saturation in late spring relate to productivity and vertical mixing in different areas around the country?

We will consider this question first qualitatively by looking at the phytoplankton production in some typical years (and chlorophyll a in one year) and compare it with the distribution of oxygen saturation (Figs. 27–29) as well as mixing conditions and nutrient concentrations (Figs. 17–19).

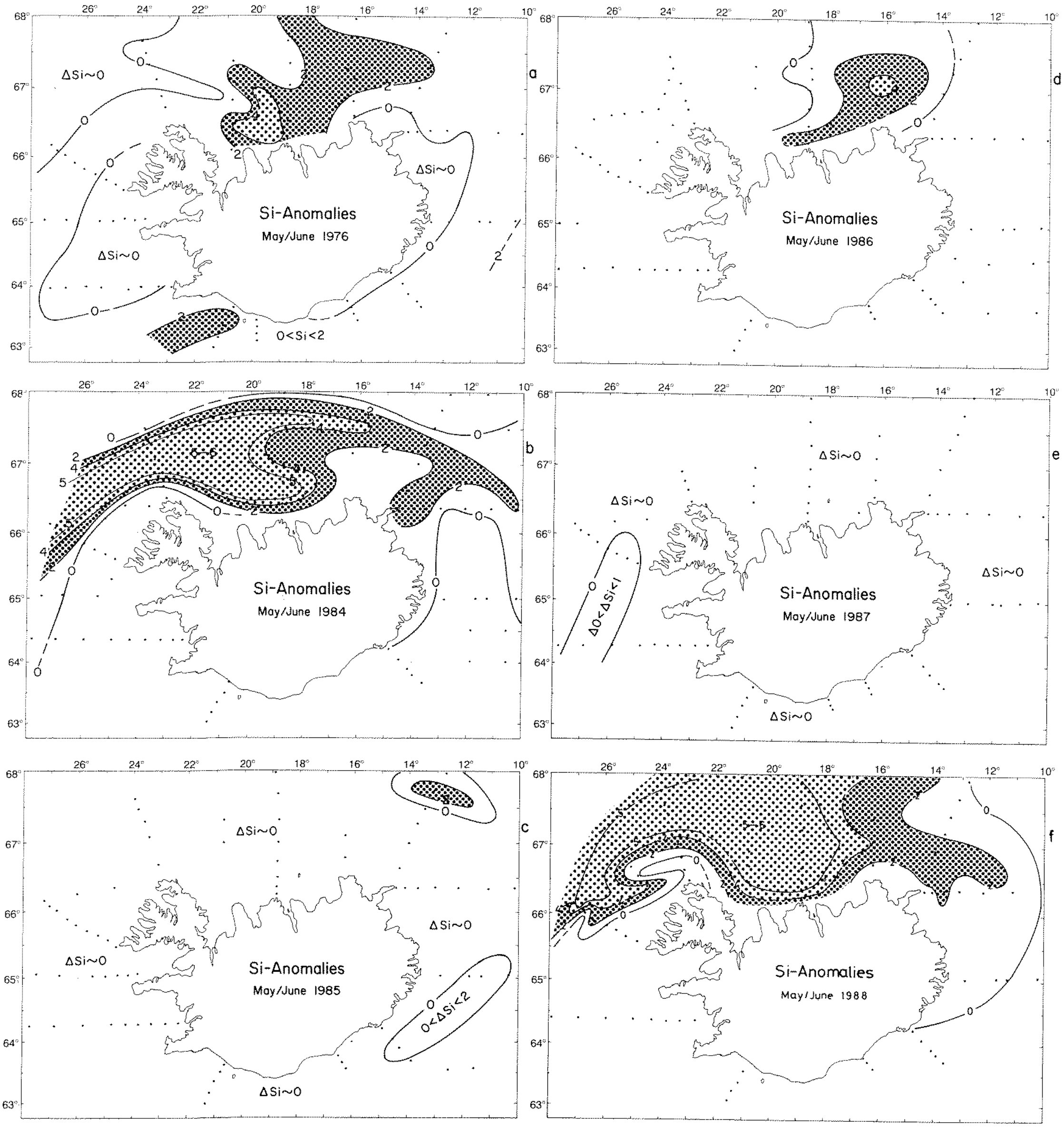

Fig. 26. Distribution of silicate anomalies (for explanation see text) in late spring of a) 1976, b) 1984, c) 1985, d) 1986, e) 1987 and f) 1988.

It will be seen that up to a certain mixing level the primary production correlated positively with the index of vertical mixing. Where mixing was very intense, however, productivity was reduced. Thus, in the deep area off the west coast in late May, very high values (≥ 25) of the mixing index generally coincided with almost winter values of nutrients, and apparently, phytoplankton growth was still at a very low level. In 1978 markedly high index values occurred within a limited area off the southeast coast, where productivity values were also relatively high, but somewhat lower than south of this area and near its northern boundary. On the Siglunes section in late May / early June 1980, the highest productivity values were found in the middle part where the vertical mixing was moderately high, but lower on both sides where the index of vertical mixing attained maximum values. In late May of 1986 the distribution provided a particularly clear example of the delicate relation between vertical mixing and productivity. At this time the productivity was relatively low in the western part of the North Icelandic area, but increased to very high values in the Siglunes section. This increase in productivity coincided with a marked drop in the index of vertical mixing from 10–25 units in the western region to 4–6 units in the eastern region.

In general, appreciable or high nutrient concentrations were found in regions of sizeable productivity, provided the vertical mixing was not too intense. Frequently, the highest productivity values occurred, when nutrient concentrations were intermediate, but as expected it was found that at very low nutrient levels ($[NO_3^- – N] < 0.5\ \mu M$), such as in the middle and the eastern parts of the North Icelandic area in 1965, 1977 and 1979 (Figs. 17 and 18), the productivity was quite low (Figs. 27 and 28). On the other hand, in the years 1980 and 1986 (Fig. 19), when appreciable nutrient concentrations were present in these regions north of Iceland, productivity was high (Fig. 29). It is striking, however, that in 1986 the productivity was relatively low in the oceanic area off the northeast coast in spite of high nutrient levels and moderate stratification. It has been suggested (Anon. 1986) that grazing by zooplankton (Fig. 29) was the main reason for the low standing crop of phytoplankton and hence reduced productivity in this oceanic area.

TABLE 8

Silicate anomalies north and northeast of Iceland in spring in the years 1964–1988

Year	*Non-existing or very small*	*Small*	*Moderate*	*Large*
1964	X	—	—	—
1965	—	X	—	—
1966	—	X	—	—
1967	—	X	—	—
1968	—	—	X	—
1969	X	—	—	—
1970	—	X	—	—
1971	—	X	—	—
1972	—	X	—	—
1973	—	—	X	—
1974	—	—	X	—
1975	—	—	—	X
1976	—	—	X	—
1977	—	—	X	—
1978	X	—	—	—
1979	—	—	—	X
1980	X	—	—	—
1981	—	—	X	—
1982	X	—	—	—
1983	X	—	—	—
1984	—	—	—	X
1985	X	—	—	—
1986	—	X	—	—
1987	X	—	—	—
1988	—	—	—	X
Total	8	7	6	4

In late May/early June of 1965 when admixture of polar water was exceptionally marked in the area north of Iceland, very limited mixing and almost depletion of nitrate (Fig. 17) coincided with very low productivity (Fig. 27). At the same time oxygen saturation values ranged from 110 to 115%, probably reflecting an accumulation of oxygen during an earlier period. In fact, considerable production had been measured about one month earlier in this area (Thórdardóttir 1969). In 1977 high productivity values were found in several regions off the southeast, south, west and northwest coasts, but low in the northern and northeastern parts (Fig. 27). At the same time, high oxygen saturation values were measured off the northwest and north coasts. There was a fair agreement between productivity and oxygen saturation in the southwest, west and northwest parts of the area. In the eastern part, however, no such similarity existed. In 1978 (Fig. 28) very high productivity prevailed in the shelf regions south and west, and moderate or considerable in the region north of Iceland. Oxygen saturation values were also high in certain localities off the

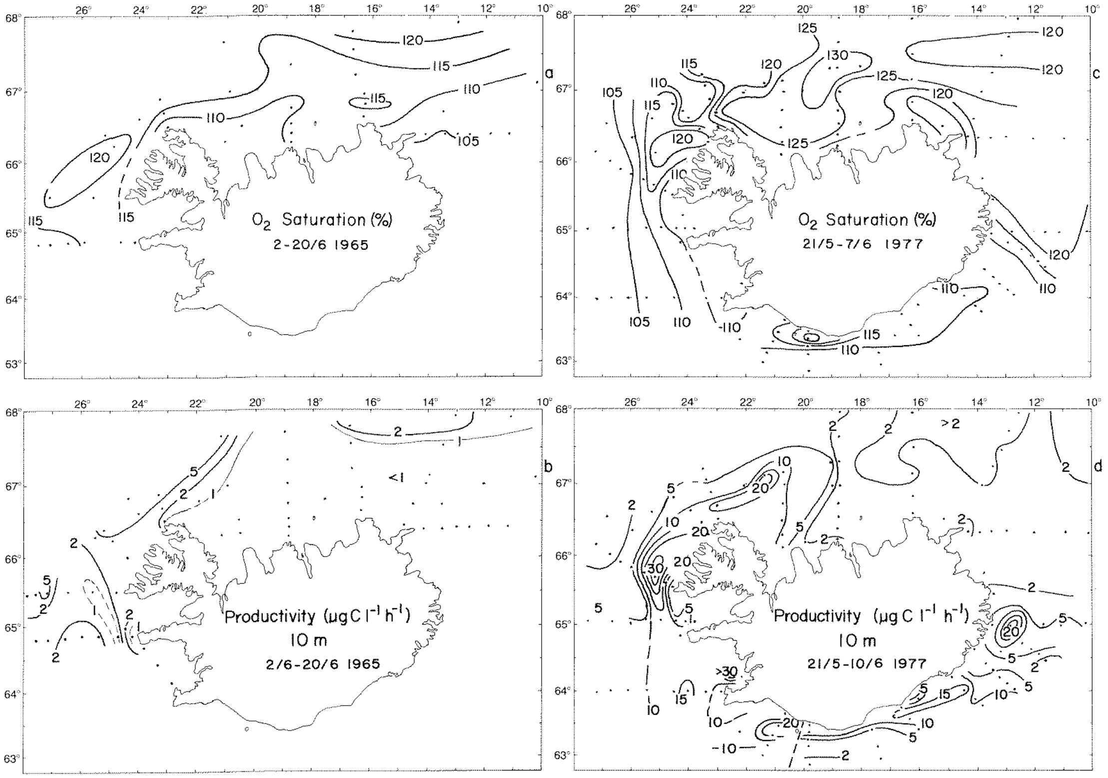

Fig. 27. Distribution of near-surface oxygen saturation (%) and productivity (μgC $l^{-1}h^{\mu 1}$) at 10 m during June 2–20, 1965 (a and b) and May 21 – June 10, 1977 (c and d). The productivity distribution is redrawn from Thórdardóttir (1969, 1978).

south and west coast as well as in the deeper part off the northeast coast. Again this year, some similarity existed between the oxygen and productivity distributions off the west coast, but hardly any off the north and east coasts. For 1979 (Fig. 28) we show the distribution of chlorophyll a, which revealed a distinct correlation with oxygen saturation off the Northwest peninsula, just north of Slétta and in the eastern part of the area south of Iceland. Otherwise, there was not much similarity between chlorophyll and oxygen saturation. Thus, high saturation values over most part of the regions off the north and east coasts coincided with very low chlorophyll a concentrations. In late May / early June 1980 (Fig. 29) very high productivity was found over most part of the shelf area north and northeast of Iceland, but appreciably lower off the south and west coasts. The distribution of oxygen saturation resembled rather closely that of the productivity over most of the study area except for minor discrepancies in the northernmost stations on the Siglunes section. According to Thórdardóttir (1981) considerable growth had started north of Iceland in early May 1980 inside the fjords and at stations close to land, but farther offshore productivity values were quite low. She pointed out that the very small phytoplankton stock found before the middle of May and the high nutrient levels near the end of the month indicated that the spring bloom was just starting at that time. Thus the spring bloom seems to have occurred considerably later in 1980 off the north coast than in most years after 1964, and the conditions there resembled more those typically found west of Iceland at this time of year.

From the data described in the present paper, evasion rates from the mixed layer, $E(O_2)$, in mol m^{-2} d^{-1}, were computed as described by Stefánsson *et al.* (1987) using the equation

$$E(O_2) = (1/z_m) \int_0^{z_m} (O_2\text{-}O_2')v(O_2)dz \qquad (3)$$

where O_2 denotes the measured oxygen concentration (mol m^{-3}), O_2' the equilibrium solubility, $v(O_2)$ the piston velocity for oxygen (m d^{-1}) and z_m the thickness of the mixed layer (m). Piston velocities were estimated by means of the relationship described by Codispoti *et al.* (1986) using the mean monthly wind data for the period May–June of the year in question. In the same way the estimated oxygen production, $B(O_2)$, in mol m^{-2} d^{-1}, within the mixed layer was calculated as

$$B(O_2) = \int_0^{z_m} Pdz \qquad (4)$$

where P denotes the production (mol m^{-3} d^{-1}) at any depth, z, within that layer. The computed production was based on ^{14}C measurements, as described by Stefánsson *et al.* (1987). Examples of evasion and production rates so computed are shown in Figures 30–31 for the sections of Selvogsgrunn, Snæfellsnes, Kögur, Siglunes, Langanes-NE and Langa-

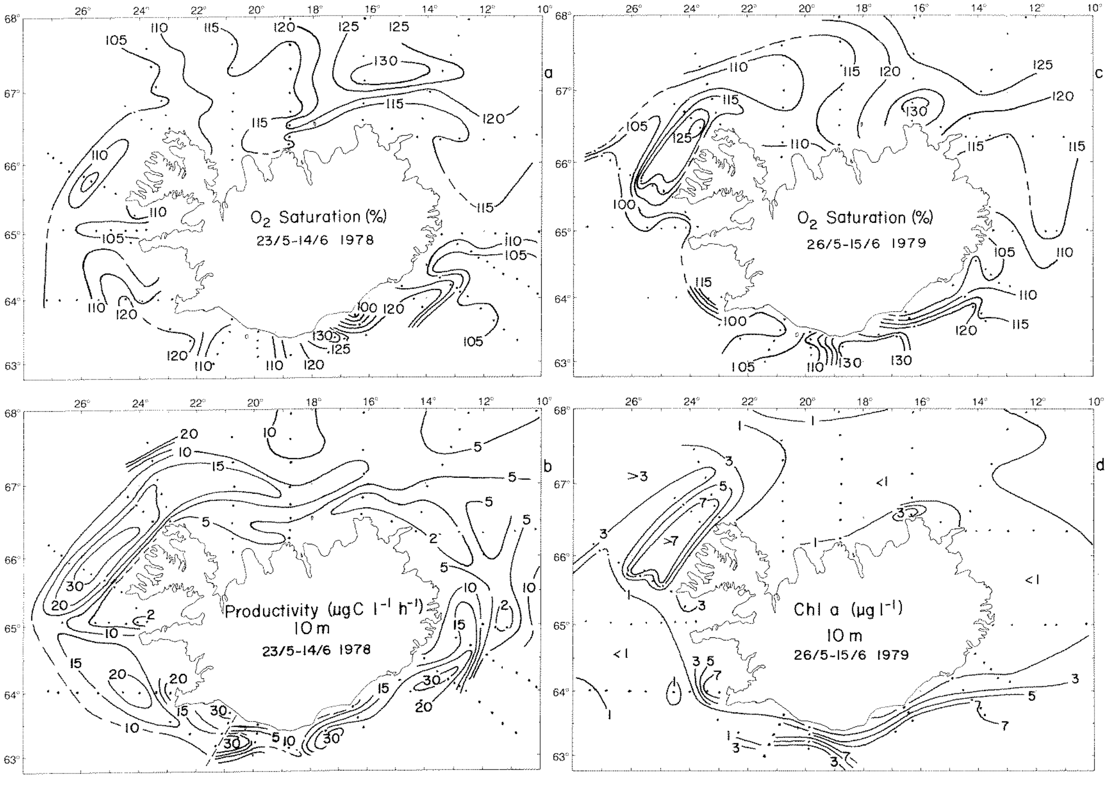

Fig. 28. Distribution of near-surface oxygen saturation (%) and productivity (μgC $l^{-1}h^{-1}$) at 10 m during May 23 – June 14, 1978 (a and b); and of near-surface oxygen saturation (%) and chlorophyll *a* (μg l^{-1}) at 10 m during May 26 – June 15, 1979 (c and d). The productivity and chlorophyll distributions are redrawn from Thórdardóttir (1979, 1980).

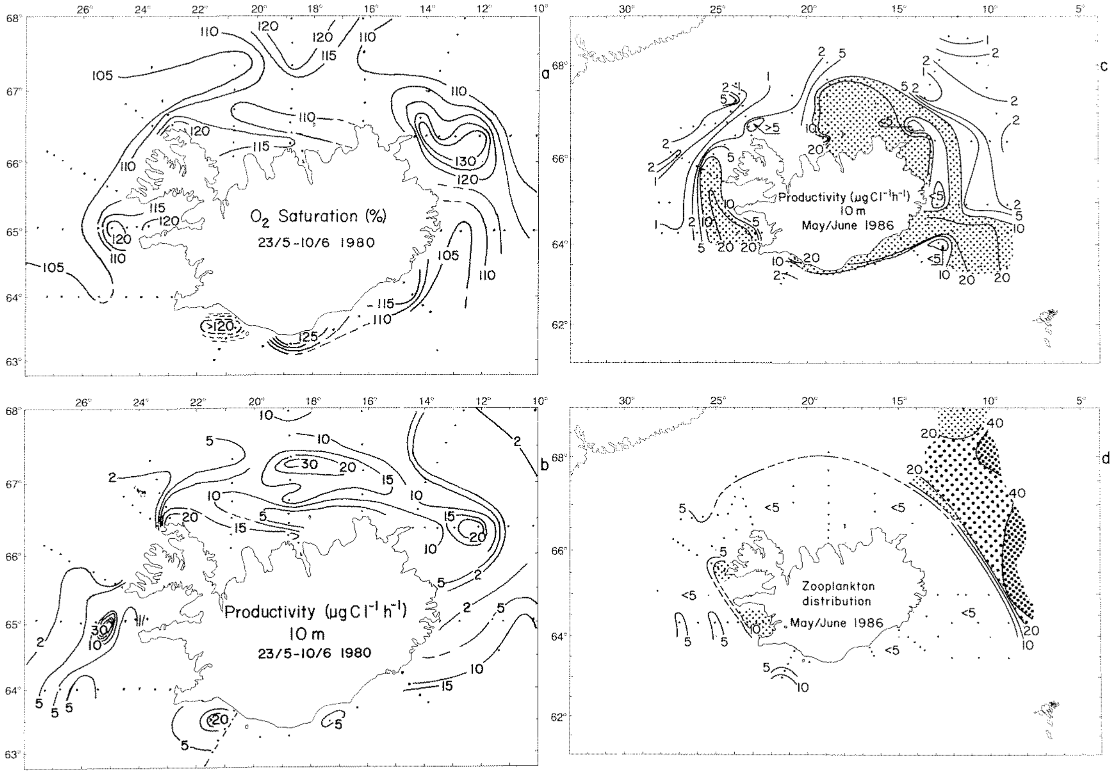

Fig. 29. Distribution of near-surface oxygen saturation (%) May 23 – June 10, 1980 (a), productivity (μgC $l^{-1}h^{-1}$) at 10 m during May 23 – June 10, 1980 (b), and May 20 – June 10, 1986 (c) as well as the zooplankton distribution 50–0 m (d, Hensen-net, ml/21m^3; from Anon. 1986). The productivity distribution for 1980 is redrawn from Thórdardóttir (1981).

nes-E in late May / early June of the years 1979 and 1980.

During the spring survey in 1979, the plant production had just started or was about to start in the areas south and west of Iceland (Thórdardóttir 1980). This is indicated by the negative values of the escape rates at many of the stations off Snæfellsnes (Fig. 30), i. e. the oxygen saturation had not reached 100%, although a slight production was measured. In the Kögur section the two rates were about equal at the shallowest stations, but at the three deeper stations the production rates were much higher than the escape rates. In the whole middle and the eastern part, Siglunes and Langanes sections, (Fig. 30) nutrients were almost completely exhausted and practically no production took place. However, the escape rates were quite high. Probably they were indicative of the high production which had been measured north of Iceland about one month earlier (Thórdardóttir 1980). At many of these stations a subsurface oxygen maximum was present underneath the shallow mixed layer with very high saturation values. Some oxygen transfer may have taken place into the mixed layer from this maximum and thus have contributed to the high evasion rates.

In the spring of 1980 there was in the Selvogsgrunn section a close correlation between the two rates (Fig. 31), but the evasion was about twice as great as the production. In the Snæfellsnes section the production at the near-shore stations was only about one half of the evasion while the opposite was true at the deeper stations. This was in full agreement with the earlier start of the production in the near-shore region than in the deeper regions. In the Kögur section there were higher production rates than evasion rates at the three shallower stations, but nevertheless a close correlation between the two rates. At the deepest stations the production rates were only slightly higher. In the Siglunes section (Fig. 31) the evasion rates were higher than the production rates at stations 1 and 8, the two rates were similar at stations 2, 3 and 7,

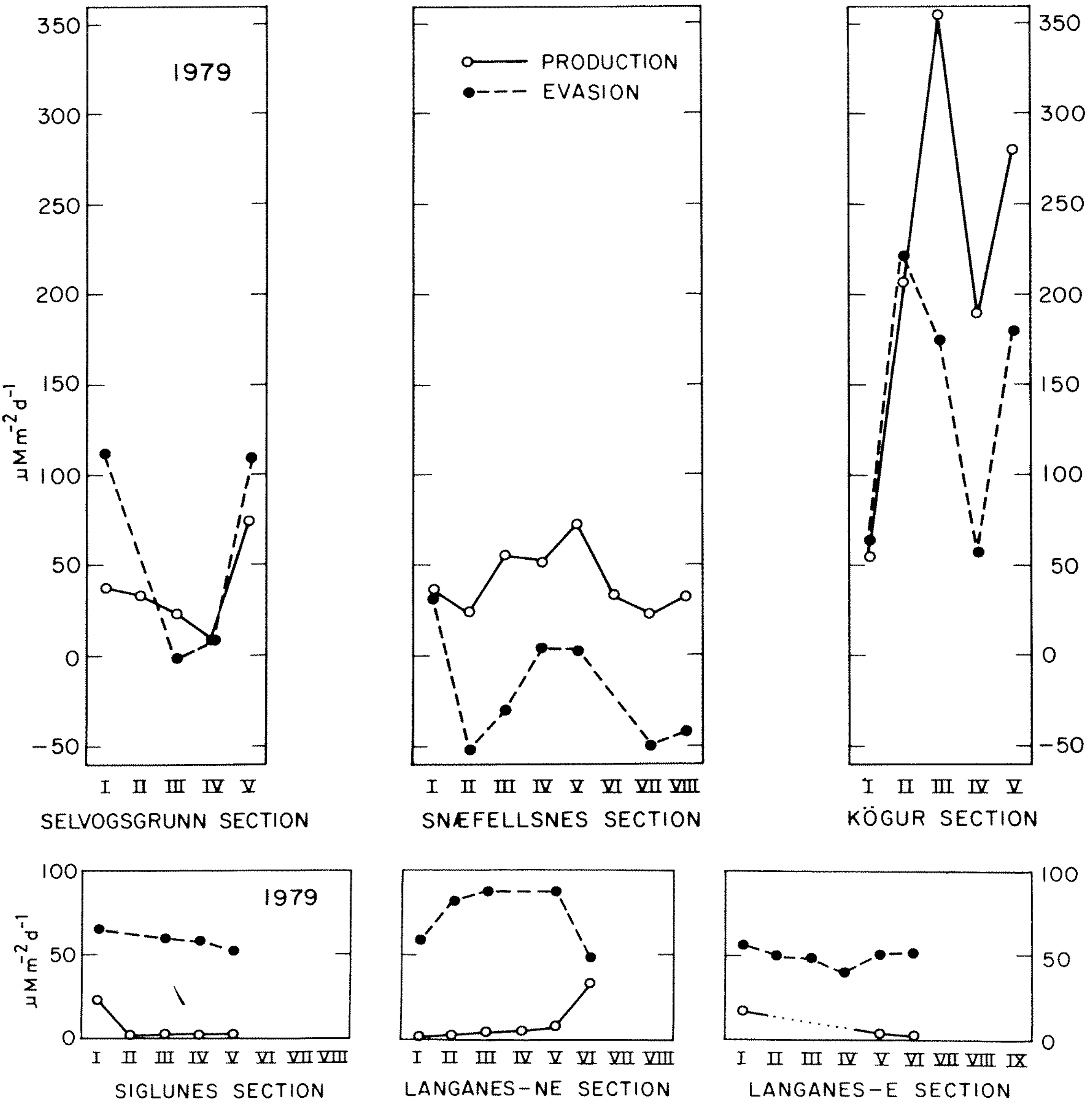

Fig. 30. Computed oxygen evasion rates and oxygen production rates for stations on the Selvogsgrunn, Snæfellsnes, Kögur, Siglunes, Langanes-NE and Langanes-E sections in late May / early June 1979. (For location of sections see Fig. 1).

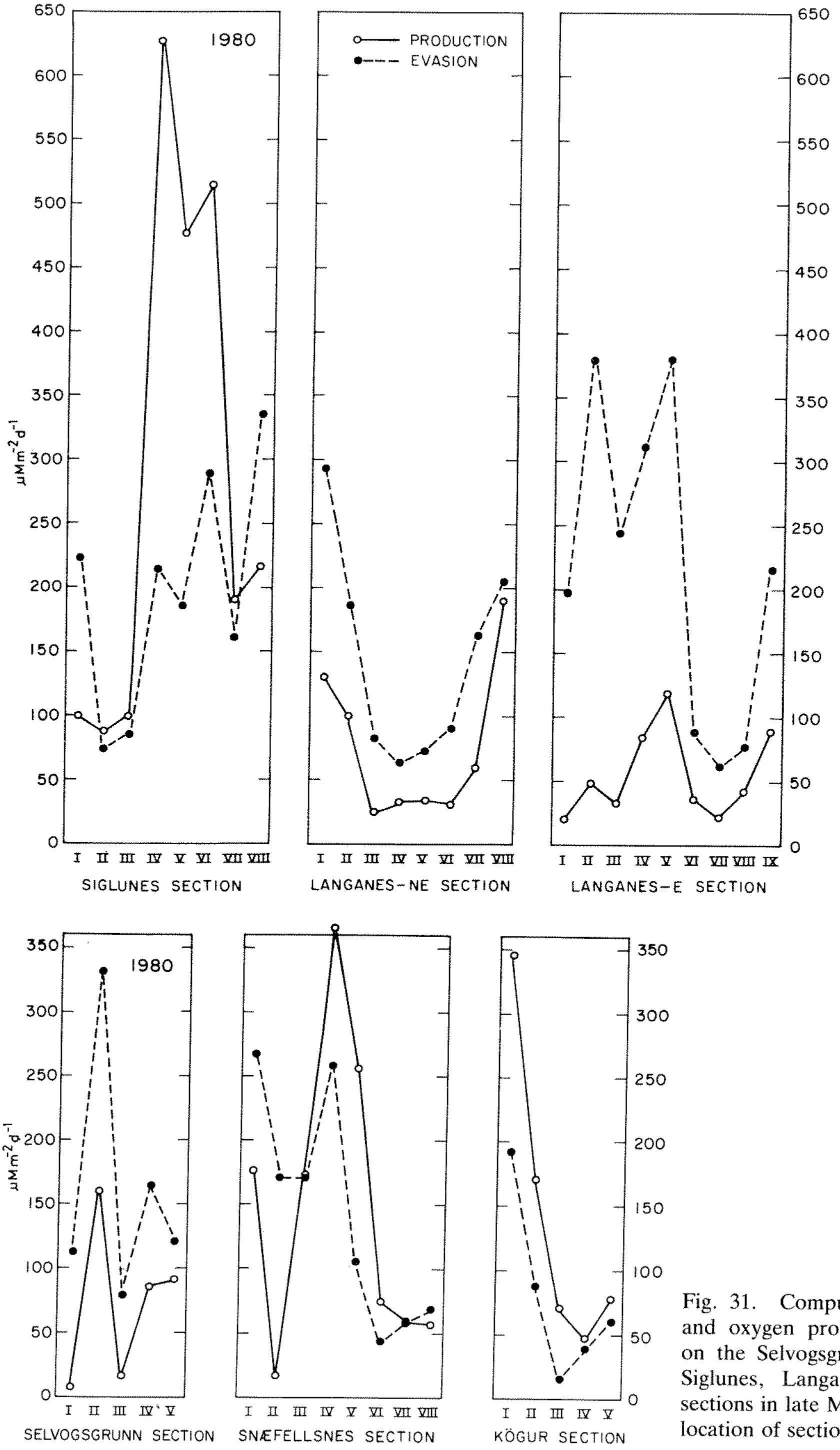

Fig. 31. Computed oxygen evasion rates and oxygen production rates for stations on the Selvogsgrunn, Snæfellsnes, Kögur, Siglunes, Langanes-NE and Langanes-E sections in late May / early June 1980. (For location of sections see Fig. 1).

but at stations 4, 5 and 6 the production rates were about three times the evasion rates. These results indicate that in most of the western and middle part of the North Icelandic area, the production was increasing and had not reached its peak, as suggested by Thórdardóttir (1981) on the basis of production and nutrient data. At the two Langanes sections, on the other hand, evasion rates exceeded the productivity in all cases, by a factor of 2 on the Langanes-NE section, and a factor of about 4 at most of the stations on the Langanes-E section. This suggests that in the eastern part of the North Icelandic area the production peak was over by the time the observations were made, which is in agreement with the decreasing nutrient levels in the eastern area, especially east of Langanes.

DISCUSSION

Results presented in this paper have demonstrated the striking contrast in late spring and throughout summer between the moderate or even intense mixing areas of Atlantic water south and west of Iceland on the one hand, and on the other, the strongly stratified arctic waters north of Iceland, in particular in the eastern part. There are probably two main reasons for this difference. One is the admixture of low-salinity and hence low-density polar water to the surface layer in the northern region. We have seen that this effect is particularly notable in cold years and leads rapidly to nutrient deficiency in the surface water, since vertical mixing from below is impeded by the strong density gradient. As a result, the plant production will be short-lasting and limited. This was clearly shown by Thórdardóttir's (1977) extensive studies in this area which revealed that much lower primary production was found in the cold period (1965, 1967–1969) than in the previous, relatively warm period (1958–1964). The other reason is related to the difference between sea and air temperature in spring which is considerably greater in the warm water area south of Iceland than in the much colder waters north of Iceland (Stefánsson 1969b). Thus in June when the sea temperature at Vestmannaeyjar is higher than the air temperature and hence a heat loss from the water to the air, the opposite is true at Grímsey off the north coast. Therefore, the heating of the sea water will be more rapid in the northern area, leading to a steeper temperature gradient and as a result a stronger pycnocline.

The onset of nutrient uptake in spring in the North Icelandic area seems to depend largely on the influx of Atlantic water to that area and/or the admixture of polar water. On the basis of data from warm and cold years Thórdardóttir (1984) has suggested that because of strong stability of the surface layers in the coldest years of the period 1970–1980 the onset of the spring bloom may have occurred about one month earlier than in the warmest years. This does not, however, imply that the annual production will be greater in cold years than in warm years. On the contrary, the Atlantic water inflow provides an important nutrient source to the North Icelandic area, both directly due to relatively high nutrient concentrations and indirectly because of much more efficient renewal in the surface layer by eddy diffusion in the Atlantic water than in the highly stratified arctic water. During warm periods with small extension of drift ice and consequently small or even negligible admixture of polar water to the surface layers, continued inflow of Atlantic water to the North Icelandic area should therefore maintain favourable mixing conditions and make a longer lasting plant production possible.

Investigations made in the Irminger Sea in the sixties (Stefánsson 1968) and more recently at two repeated deep stations west and north of Iceland (Takahashi *et al.* 1985), indicated that the Atlantic water nutrients are utilized or regenerated in approximately the same ratio as they are in the water, whereas in the polar water nitrate is practically depleted while there are still appreciable phosphate concentrations present. Furthermore, in the Irminger Sea the slope, $\Delta N/\Delta P$, was found to be between 14 and 15. The present study essentially confirms these results.

It is by no means clear, however, why nitrate should be more limiting than phosphate in the arctic waters than in the Atlantic waters. It is conceivable that this reflects a difference in the average chemical composition of the plankton organisms of these two water masses. Another more plausible explanation for the observed difference, relates to vertical mixing. In regions where low-density polar water is found in the surface layers, stratification becomes very marked in summer, and the depth of the mixed layer in winter will also be limited. The breakdown of organically bound nitrogen is more complicated than that of phosphorus which seems to be relatively rapidly released from cell walls (Raymont 1980, p. 193). Thus, the loss of nitrogen-bound material from the surface layer to the deeper strata might be slightly greater than that of organically bound phosphorus and tend to lower the N/P ratio within a relatively thin winter-mixed layer.

The presence of highly anomalous nitrate/silicate relationships in certain years, especially in the western part of the North Icelandic area, is interesting. Areas with such an anomalous distribution, as observed in 1979, 1984 and 1988, imply that within them nitrate was being depleted while silicate was utilized only to a limited extent. Thus other plankton species than diatoms must have been dominant. According to Thórdardóttir and Ásthórsson (1986) *Phaeocystis pouchetii,* a non-diatom alga, was a predominant component of the phytoplankton community in the western part of the North Icelandic area in late spring of 1984. This species is known to form dense blooms, in particular in coastal areas (Richardson 1989; Gibson *et al.* 1990). Due to the formation of large colonies and peculiarities in the physiology of *Phaeocystis,* the plant tissue in these blooms is probably utilized only to a limited extent in the pelagic zone (Lancelot *et al.* 1987). Furthermore, *Phaeocystis* produces dimethyl sulphide (DMS), a volatile sulfur compound believed to be of considerable significance in the global cycling of sulphur (Charlson *et al.* 1987). Very high DMS concentrations have been observed in association with *Phaeocystis* blooms (Gibson *et al.* 1990). We suggest that Si-anomalies may provide a useful indicator for species which do not utilize silicon, including *Phaeocystis.* It should be remarked, however, that the anomaly distribution probably reflects the integrated effects of the preceding growth period rather than instantaneous plankton composition.

The comparison between nutrients and the index of vertical mixing, oxygen saturation and productivity has brought to light several interesting points. Thus, it was found that the correlation between nutrients and the index of vertical mixing was close in some regions, e. g. off Siglunes, but not in others, e. g. Selvogsgrunn or east of Langanes. There may be several reasons for discrepancies in this relationship. Thus nutrients can be quite high in areas where plant growth has just started although stratification is considerable. This applies in particular to the Selvogsgrunn section where observations were made earlier in the season than elsewhere. A considerable time after the growth peak is over, and the nutrients depleted in the near-surface layer, such as probably was the case in early June in many of the years in the region east of Langanes, the nutrients will be appreciably lowered down to a depth of 30–50 m. Mixing of the uppermost 50 m, e. g. due to wind action, may then only result in a slight increase in the nutrients of the surface layer. Other reasons may include sudden changes in stability due to near-shore upwelling or offshore spreading of fresh water by changes in wind direction. In general, the correlation between nutrients and stratification will be greatest in areas where the nutrient uptake is moderately advanced. In the western and middle part of the North Icelandic shelf area, such as the Siglunes section, both nutrients and vertical mixing depend largely on the influx of Atlantic water from the west where appreciable nutrient uptake will start considerably later than in the more stratified arctic water predominating in the easternmost part of the area.

It is evident from our data that advection and eddy diffusion are the primary agencies controlling the supply of nutrients into the euphotic zone on the Icelandic shelf. It should, however, be recognized that nutrient regeneration as a result of grazing by zooplankton, does play a role particularly after the onset of summer stratification (Harrison, 1980). Data on grazing pressure, although limited, suggest that it may vary significantly from year to year, particularly in the central part of the north Icelandic shelf area, but was more persistent in the deep NE region (Ástthórsson *et al.* 1983).

Provided that mixing is not too intense and a slight stratification exists, the index of vertical mixing will be a good indicator of productivity. In the presence of extensive grazing, however, as was the case in the northeast area in early June 1986 (Fig. 31), this simple relationship does not hold.

It appears that the distribution of oxygen saturation shows more similarity to the productivity distribution during the initial stages of the spring bloom than after the peak is over. The reason for this is clearly that the oxygen produced tends to accumulate in the surface layers which remain supersaturated for some time, especially in highly stratified waters, after the production peak is over.

Thus, simultaneous measurements of nutrients, oxygen saturation and stratification (through temperature – salinity data) provide complementary information relating to primary production. For example, if the surface waters in an area are weakly stratified and nutrient concentrations are considerable or high, production is most likely also high. If at the same time the oxygen saturation is low, the bloom has probably just started; if high, the production has been going on for some time. If however, the index of vertical mixing is very small, nutrients depleted and the oxygen saturation quite high, the productivity is probably very low but was high in the recent past. If, on the other hand, vertical mixing is very small, nutrients depleted and the oxygen saturation close to 100%, it would indicate that the production was over considerable or long time ago.

A more quantitative information, however, can be derived from oxygen evasion data. Thus, the total apparent oxygen evasion from the mixed layer in the Faxaflói region in 1966–1967, computed from seasonal oxygen measurements and integrated over the entire period with positive evasion rates (i. e. net transfer of oxygen from the sea to the atmosphere) compared well with the photosynthetic production of oxygen within the mixed layer, derived from ^{14}C data (Stefánsson *et al.* 1987). For any given time, however, the two rates could be different. In general, it was found that the rate of formation exceeded the rate of escape during the initial phase of the plant production while the opposite applied after the main growth peak was over. The computed evasion rates, described in the present paper seem to be in agreement with those results. It is concluded that computed evasion rates, when examined in conjunction with primary production data, may yield useful information on the biological history of the water.

With modern instrumentation, continuous monitoring of oxygen concentrations should be possible from moored buoys. Such data could then be used to derive oxygen evasion rates and thereby obtain a good estimate of the primary production over the entire growing season.

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APPENDIX

TABLE I

Mean distribution of nutrient concentrations (μM) and percentage oxygen saturation in the Selvogsgrunn Section in late May – early June (NO_3 –N and Si in the period 1971–1984; PO_4 –P and O_2% in the period 1971–1981).

		NO_3 –N			*PO_4 –P*			*Si*			*O_2%*		
St.	*Depth*	*C*	*SD*	*n*	*C*	*SD*	*n*	*C*	*SD*	*n*	*%*	*SD*	*n*
I	0 m	4.9	1.9	13	0.40	0.15	9	7.2	4.0	13	112	5	13
	20 –	6.8	2.2	13	0.51	0.15	9	3.2	1.6	14	106	5	13
	40 –	7.3	2.5	12	0.51	0.11	8	3.7	1.6	11	105	6	11
II	0 m	4.8	2.5	13	0.39	0.13	10	1.9	1.3	14	115	8	14
	20 –	6.1	2.9	13	0.50	0.16	10	2.5	1.6	14	109	6	14
	50 –	8.9	2.1	13	0.71	0.16	10	3.4	1.7	13	101	5	14
	75–60 –	9.6	3.5	6	0.85	0.12	5	4.6	1.9	6	97	3	8
III	0 m	7.2	2.2	13	0.48	0.12	10	2.5	1.4	14	112	7	14
	20 –	7.3	2.3	13	0.52	0.11	10	2.6	1.1	14	109	5	14
	50 –	10.0	1.6	13	0.72	0.16	10	4.3	1.6	14	101	3	14
	100 –	12.2	1.4	13	0.84	0.14	10	6.0	1.0	14	97	3	12
	140 –				0.92	0.05	4	6.7		1	96	3	6
IV	0 m	8.5	1.5	13	0.51	0.15	10	2.9	1.6	14	109	7	13
	20 –	8.9	1.5	13	0.59	0.09	10	3.0	1.4	14	106	3	13
	50 –	10.6	1.5	13	0.75	0.12	10	4.8	1.4	14	101	3	14
	100 –	12.2	1.6	12	0.85	0.06	10	6.2	0.9	14	98	2	14
	200 –	13.5	0.6	7	0.91	0.07	7	7.0	0.8	9	95	2	9
	300 –	14.2	0.7	2	0.89	0.07	2	7.6	1.3	3	94	4	4
	400 –	14.3	0.6	6	0.91	0.06	3	7.8	0.9	7	93	2	5
	500 –	14.1	0.9	9	0.97	0.09	5	8.1	1.1	7	90	4	8
V	0 m	8.9	2.2	13	0.54	0.15	10	3.4	1.8	14	108	5	14
	20 –	9.2	2.3	13	0.59	0.16	10	3.6	1.8	14	107	2	13
	50 –	10.4	2.0	13	0.76	0.15	10	5.1	1.9	14	101	3	13
	100 –	12.6	1.0	13	0.86	0.04	10	6.5	0.9	14	97	1	14
	200 –	13.0	1.1	8	0.93	0.11	7	6.7	0.6	10	95	2	10
	300 –	14.0	1.2	2	0.93	0.05	3	7.2	1.3	3	93	2	5
	400 –	14.4	0.8	6	0.91	0.07	4	7.8	1.1	6	93	1	7
	500 –	13.3	0.4	2	0.99	0.02	2	7.7	0.6	2	90	3	2
	600 –	15.5	0.9	6	1.05	0.07	4	9.1	1.3	6	87	4	8
	800 –	16.0	1.0	4	1.06	0.11	3	10.3	1.8	4	83	2	5
	1000 –	16.1	0.6	7	1.08	0.05	4	10.6	1.6	7	85	1	7

TABLE II

Mean distribution of nutrient concentrations (μM) and percentage oxygen saturation in the Snæfellsnes Section in late May – early June (NO_3 –N and Si in the period 1974–1984; PO_4 –P and O_2% in the period 1974–1981).

		NO_3 –N			*PO_4 –P*			*Si*			*O_2%*		
St.	*Depth*	*C*	*SD*	*n*	*C*	*SD*	*n*	*C*	*SD*	*n*	*%*	*SD*	*n*
I	0 m	3.4	1.9	10	0.38	0.18	8	1.4	0.6	11	111	7	8
	20 –	3.9	1.8	10	0.44	0.20	8	1.5	0.7	11	107	5	8
	50 –	7.0	2.0	9	0.61	0.14	8	3.0	1.8	10	104	4	7
	100 –	8.7	2.0	10	0.79	0.13	8	4.3	1.5	11	101	2	8
II	0 m	3.0	2.2	10	0.36	0.18	8	1.2	0.9	11	109	5	8
	20 –	3.3	2.3	10	0.39	0.18	8	1.3	0.9	11	109	4	8
	50 –	5.5	2.0	9	0.63	0.20	8	2.1	1.1	10	104	2	7
	100 –	7.8	1.7	10	0.76	0.09	7	3.8	0.9	11	101	2	8
III	0 m	4.0	3.3	10	0.38	0.25	7	1.7	1.3	11	112	7	8
	20 –	4.8	2.8	10	0.44	0.18	7	1.7	1.2	11	110	6	8
	50 –	8.7	2.1	9	0.72	0.13	6	3.8	1.5	10	102	5	7
	100 –	10.5	1.5	10	0.81	0.17	7	4.7	1.3	11	100	3	8
IV	0 m	4.5	4.0	10	0.38	0.28	8	2.3	2.0	11	115	9	8
	20 –	6.1	3.8	10	0.52	0.26	8	2.8	2.0	11	109	6	8
	50 –	9.6	1.7	9	0.75	0.16	8	4.6	1.3	10	101	3	7
	100 –	12.1	1.0	10	0.89	0.08	8	6.7	1.3	11	99	3	7
V	0 m	6.0	4.9	11	0.46	0.32	8	3.7	2.9	12	116	14	8
	20 –	6.3	4.5	11	0.48	0.28	8	3.6	2.8	12	113	8	8
	50 –	9.9	2.4	9	0.71	0.17	8	5.3	2.0	10	103	2	7
	100 –	12.9	1.3	11	0.90	0.06	8	7.3	1.0	12	99	2	7
VI	0 m	9.5	4.5	11	0.64	0.26	7	5.1	2.4	12	111	8	8
	20 –	9.8	4.2	11	0.67	0.25	7	5.2	2.4	12	110	8	8
	50 –	12.0	1.8	10	0.85	0.15	7	6.3	1.5	12	102	2	7
	100 –	13.0	2.1	11	0.92	0.12	7	7.2	1.4	12	100	3	7
	200 –	14.0	0.6	6	0.97		1	8.7	1.0	6	97	1	4
VII	0 m	10.5	4.1	10	0.72	0.21	6	5.1	2.8	11	107	4	6
	20 –	11.1	2.5	11	0.72	0.20	7	5.6	2.5	12	107	6	6
	50 –	12.6	1.2	10	0.88	0.11	6	6.8	1.1	12	100	2	5
	100 –	13.7	0.7	11	0.93	0.08	7	7.3	0.8	12	98	2	7
	200 –	14.4	0.7	6	0.95	0.05	4	7.6	0.6	6	95	1	4
	300 –							8.9	1.3	2			
	400 –							8.5	0.1	2			
	500 –	14.7	1.0	4	0.96		1	8.7	0.9	4	97		1
VIII	0 m	11.5	2.7	10	0.80	0.12	8	5.9	2.0	11	107	7	8
	20 –	11.6	2.3	10	0.79	0.14	8	6.4	1.7	11	105	5	8
	50 –	12.4	1.2	10	0.89	0.06	7	7.0	0.9	11	101	2	7
	100 –	13.4	0.9	10	0.95	0.05	7	7.5	1.0	11	98	2	8
	200 –	14.2	0.6	7	0.93	0.09	3	8.0	0.7	7	96	2	4
	400 –	15.4	0.1	2				8.3	0.3	2			
	500 –				0.94		1	8.6		1	92		1
	600 –	15.9	0.3	2				8.6	0	2			
	800 –	16.4	0.1	2				10.0	1.1	3			
	1000 –	16.7	0.1	2				10.8	1.3	3	86		1

TABLE III

Mean distribution of nutrient concentrations (μM) and percentage oxygen saturation in the Kögur Section in late May – early June (NO_3 -N and Si in the period 1964–1984; PO_4 -P: 1954–1981; O_2%: 1954–1984).

		NO_3 -N			PO_4 -P			Si			O_2%		
St.	*Depth*	*C*	*SD*	*n*	*C*	*SD*	*n*	*C*	*SD*	*n*	%	*SD*	*n*
I	0 m	2.4	2.7	19	0.30	0.10	20	1.6	0.9	21	112	6	23
	20 –	3.6	3.0	19	0.37	0.13	20	1.6	0.9	21	110	5	23
	40 –	4.2	3.1	17	0.44	0.16	17	2.1	1.0	17	108	5	19
II	0 m	3.6	3.2	19	0.31	0.17	20	2.0	1.7	21	117	9	23
	20 –	4.8	3.1	19	0.43	0.16	20	2.4	1.8	21	111	6	23
	50 –	7.1	2.5	19	0.61	0.16	20	3.6	1.8	21	105	5	23
III	0 m	6.0	3.2	18	0.48	0.23	19	3.2	2.7	19	114	9	22
	20 –	7.6	3.3	18	0.55	0.22	19	3.5	2.3	19	110	6	21
	50 –	11.0	2.4	18	0.70	0.17	19	4.9	1.8	19	103	4	22
	100 –	12.2	1.9	17	0.86	0.13	16	6.6	1.4	19	98	2	20
	200 –	13.0	1.5	13	0.88	0.12	10	7.7	0.7	12	98	3	12
IV	0 m	4.2	4.4	14	0.45	0.29	12	3.3	2.4	14	115	12	12
	20 –	7.3	3.9	14	0.53	0.24	12	3.7	2.4	14	106	6	13
	50 –	10.4	3.8	13	0.75	0.27	12	5.4	1.7	14	100	4	13
	100 –	12.0	2.1	12	0.86	0.18	11	6.9	0.8	14	96	3	13
	200 –	12.6	2.0	9	0.95	0.10	7	7.9	0.5	9	95	2	7
V	0 m	4.9	4.9	14	0.43	0.27	10	3.4	2.5	14	113	8	13
	20 –	6.3	4.5	14	0.50	0.20	10	3.8	2.6	14	111	5	13
	50 –	9.3	3.0	14	0.73	0.11	10	5.2	1.9	14	102	2	10
	100 –	11.7	1.8	14	0.80	0.09	10	6.4	1.1	14	98	3	13
	200 –	12.4	1.9	10	0.82	0.02	4	7.2	0.9	10	94	2	9
	300 –							8.6	0.4	3	91	5	4
	400 –	13.9	1.5	4	0.95	0.01	2	8.6	1.5	5	87	1	3
	500 –	13.9	1.3	4	0.95	0.01	2	9.6	0.3	4	85		1
	0 m	4.8	3.4	10	0.35	0.21	6	4.2	2.8	10	109	9	7
	20 –	5.3	3.9	10	0.37	0.14	6	4.3	2.9	10	107	9	7
	50 –	6.7	3.1	10	0.49	0.14	6	4.4	2.5	10	100	7	7
	100 –	9.2	2.5	10	0.62	0.12	6	5.3	1.9	10	97	7	7
	200 –	11.6	0.8	6	0.80	0.04	4	6.7	1.1	7	92	2	3
	300 –							7.0	1.8	3	91	0	3
	400 –	12.6	0.5	5	0.84	0.03	3	7.0	1.2	6	90	0	4
	500 –	13.6		1	0.83	0.02	2	8.1	2.6	2	90	1	2
	600 –	13.3	0.6	3	0.84	0.01	2	7.4	0.1	2	88		1
	800 –	13.6	0.3	2	0.88	0.02	2	8.7	0.8	3			
	1000 –	13.8		1	0.91		1	10.1		1	85		1
VII	0 m	6.4	3.9	3	0.67	0.22	4	6.4	3.2	3	103	4	4
	20 –	6.9	4.0	3	0.72	0.10	4	6.8	1.4	3	102	4	4
	50 –	9.2	1.8	3	0.78	0.13	4	6.0	1.3	3	92	1	4
	100 –	10.2	1.4	3	0.84	0.13	4	6.8	1.6	3	92	1	4
	200 –	10.9	2.1	3	0.85	0.17	4	6.7	1.3	3	91	1	4
	300 –										91	1	4
	400 –	13.1		1	0.90	0.09	3				92	1	4
	500 –	12.8	0.6	2	0.95	0.09	3	6.3		1	92	1	4
	600 –	13.3		1	1.05	0.01	2	7.9		1	91	1	4
	800 –	13.5		1	1.06	0.04	2	8.7		1	89	0	4
	1000 –	13.8		1	1.06	0.04	2	9.4		1	88	0	4
	1200 –	14.5		1	1.18	0.05	2	12.2		1	87	0	3

TABLE IV

Mean distribution of nutrient concentrations (μM) and percentage oxygen saturation in the Siglunes Section in early June (NO_3 –N and Si in the period 1964–1984; PO_4 –P: 1954–1981; O_2%: 1954–1984).

		NO_3 –N			PO_4 –P			Si			O_2%		
St.	*Depth*	*C*	*SD*	*n*	*C*	*SD*	*n*	*C*	*SD*	*n*	*%*	*SD*	*n*
I	0 m	1.8	2.2	19	0.20	0.13	21	2.3	1.7	21	115	6	24
	20 –	2.7	2.8	19	0.32	0.17	21	2.5	1.8	21	115	7	24
	50 –	7.9	2.2	15	0.71	0.12	21	4.3	1.7	20	101	4	24
	75 –	9.4	1.4	7	0.75	0.11	13	4.7	1.0	10	99	3	12
II	0 m	1.7	3.0	18	0.25	0.26	21	1.9	1.9	21	115	8	23
	20 –	1.9	3.0	19	0.30	0.25	21	1.8	2.0	21	115	7	23
	50 –	6.6	3.6	18	0.59	0.24	21	3.2	2.4	21	102	5	23
	100 –	10.8	2.7	18	0.87	0.15	20	6.0	2.3	21	98	3	23
	200 –	12.6	1.3	13	0.93	0.11	14	8.0	1.0	14	97	2	20
	300 –	12.3	1.5	7	0.96	0.10	7	8.3	1.5	7	95	3	13
	400 –	12.8	1.4	9	0.95	0.14	7	9.6	1.7	9	91	3	13
III	0 m	1.1	2.5	19	0.24	0.25	21	2.2	2.3	21	117	8	24
	20 –	1.4	2.8	19	0.26	0.23	21	2.0	2.1	21	116	8	24
	50 –	7.2	3.7	18	0.65	0.26	21	3.5	2.3	21	102	5	24
	100 –	10.9	3.2	18	0.86	0.14	20	6.0	1.6	20	98	3	22
	200 –	12.7	1.4	13	0.89	0.14	14	7.7	0.8	14	97	2	17
	300 –	12.5	1.7	8	0.94	0.13	10	8.2	1.4	7	95	3	15
	400 –	13.3	0.8	10	0.99	0.13	9	9.7	1.5	10	89	2	14
IV	0 m	1.2	1.6	19	0.23	0.18	21	1.6	1.8	21	117	8	23
	20 –	1.4	1.7	19	0.27	0.19	20	1.6	1.8	20	116	6	23
	50 –	7.0	3.4	18	0.60	0.22	20	3.6	1.9	20	102	5	23
	100 –	11.7	2.1	18	0.86	0.13	19	6.2	1.4	20	97	3	22
	200 –	12.3	1.3	13	0.88	0.09	13	7.4	1.0	14	95	2	19
	300 –	12.4	1.5	8	0.93	0.14	10	8.5	1.1	8	92	2	14
	400 –	13.2	1.9	11	0.95	0.14	10	9.6	1.0	12	88	2	17
	500 –	13.3	1.7	10	0.94	0.11	7	10.2	0.7	12	87	2	15
	600 –	13.3	1.6	12	0.96	0.06	9	10.5	0.8	12	86	1	15
	680 –	13.6	1.9	10	0.93	0.07	7	10.9	1.0	11	85	1	8
V	0 m	1.4	1.9	13	0.28	0.19	14	1.7	1.3	14	117	5	12
	20 –	2.3	2.0	13	0.35	0.20	14	1.9	1.6	14	112	5	12
	50 –	8.4	3.4	13	0.68	0.20	14	4.5	2.5	14	100	3	12
	100 –	12.1	2.3	10	0.81	0.13	13	6.5	1.3	13	98	1	11
	200 –	13.1	0.9	6	0.88	0.05	6	7.7	0.4	7	96	1	7
VI	0 m	1.8	2.1	17	0.20	0.15	13	1.6	1.3	18	115	6	14
	20 –	2.1	2.0	18	0.27	0.17	13	1.6	1.3	18	115	6	14
	50 –	7.9	3.7	16	0.62	0.23	13	4.0	2.0	17	104	9	13
	100 –	12.4	1.5	13	0.84	0.13	12	6.7	0.9	14	97	3	13
	200 –	12.8	0.9	10	0.90	0.06	8	7.7	0.3	10	96	2	12
	300 –	13.7	0.6	4	0.94	0.05	5	9.4	0.7	3	91	3	9
	400 –	13.4	0.9	8	0.97	0.07	5	9.3	1.1	5	88	2	9
VII	0 m	2.0	2.5	12	0.29	0.22	10	2.4	2.2	11	115	6	11
	20 –	2.7	2.7	12	0.35	0.17	12	2.6	2.2	12	114	6	12
	50 –	6.2	3.5	9	0.58	0.17	10	3.8	2.2	10	105	6	10
	100 –	11.7	1.4	10	0.84	0.15	9	6.2	1.3	9	98	2	9
	200 –	12.4	0.6	5	0.91	0.10	5	7.2	0.3	4	95	2	9
	300 –	13.2	1.4	2	0.92	0.12	3	7.9	0.9	2	92	3	5
	400 –	13.1	0.6	5	0.97	0.07	3	8.5	0.5	3	88	2	6

TABLE IV continued

	NO_3-N			PO_4-P			Si			$O_2\%$		
St. Depth	*C*	*SD*	*n*	*C*	*SD*	*n*	*C*	*SD*	*n*	%	*SD*	*n*
VIII 0 m	1.7	2.1	13	0.22	0.17	11	1.9	1.7	15	116	9	13
20 –	2.4	2.7	12	0.32	0.18	14	2.1	1.8	15	112	6	13
50 –	7.0	2.5	12	0.57	0.20	13	3.9	1.5	14	101	6	12
100 –	10.1	1.6	13	0.74	0.09	13	5.3	1.3	14	95	2	12
200 –	11.9	0.9	8	0.81	0.06	7	6.3	0.4	9	91	2	8
300 –	12.5	0.7	4	0.86	0.02	4	6.4	0.5	4	90	3	4
400 –	12.8	0.7	3	0.86	0.07	3	6.9	0.2	5	90	1	2
500 –	12.7	0.8	2				7.0	0.1	2	90	1	2
600 –	13.2	0.7	3	0.90	0.10	3	7.9	0.3	5	88	0	2
800 –	13.4	0.6	3	0.93	0.10	3	9.1	0.4	4	87	0	2
1000 –	13.6	0.8	3	0.95	0.07	3	9.4	0.8	4	85	0	2

TABLE V

Mean distribution of nutrient concentrations (μM) and percentage oxygen saturation in the section east of Langanes in early June (NO_3 –N and Si in the period 1964–1984; PO_4 –P and O_2%: 1964–1981).

		NO_3 –N			*PO_4 –P*			*Si*			*O_2%*		
St.	*Depth*	*C*	*SD*	*n*	*C*	*SD*	*n*	*C*	*SD*	*n*	%	*SD*	*n*
I	0 m	3.5	3.2	16	0.27	0.21	14	2.6	1.7	19	108	6	16
	20 –	6.0	3.0	17	0.40	0.21	14	3.2	1.7	19	105	6	16
	50 –	8.5	2.7	15	0.66	0.16	13	4.7	1.9	18	99	4	16
II	0 m	0.6	0.5	14	0.08	0.04	13	1.0	1.3	16	113	8	13
	20 –	1.4	1.4	14	0.16	0.06	13	1.2	1.5	16	112	6	13
	50 –	9.0	2.8	14	0.72	0.20	13	4.3	2.3	16	98	5	13
	100 –	12.1	2.0	14	0.88	0.09	13	6.8	1.1	16	95	3	11
	150 –	12.8	2.2	5	0.89	0.08	4	7.9	0.6	5			
III	0 m	0.7	1.1	18	0.10	0.11	15	1.1	1.1	20	113	6	17
	20 –	1.0	1.7	18	0.13	0.14	15	1.0	1.2	20	115	8	17
	50 –	8.0	2.8	18	0.57	0.20	15	3.8	1.8	19	101	4	17
	100 –	12.0	2.3	16	0.84	0.08	15	6.3	1.1	19	96	3	17
	200 –	13.4	1.6	9	0.88	0.08	7	7.7	1.2	10	94	2	11
IV	0 m	0.6	0.8	16	0.10	0.07	14	0.5	0.6	17	113	7	13
	20 –	1.2	1.3	16	0.15	0.11	14	0.4	0.6	17	113	6	14
	50 –	8.9	2.9	16	0.67	0.23	14	4.1	1.9	16	97	5	14
	100 –	12.3	2.2	16	0.87	0.09	14	6.9	1.1	16	95	4	12
	150 –	12.5	1.9	4	0.92	0.10	4	7.5	0.8	5	92	2	5
V	0 m	1.3	2.4	18	0.15	0.18	14	1.8	2.1	19	115	10	16
	20 –	2.1	2.8	18	0.30	0.20	14	2.4	2.2	19	111	7	16
	50 –	6.7	3.3	18	0.61	0.19	14	4.3	1.6	19	102	6	16
	100 –	10.6	1.8	16	0.76	0.10	14	5.8	1.3	18	97	2	15
	200 –	11.6	1.3	8	0.78	0.08	6	6.2	1.1	8	93	2	9
	300 –	12.5	1.4	5	0.76	0.06	3	6.7	0.9	5	90	3	7
	400 –	13.2	2.1	3	0.78	0.02	3	6.5	0.6	4	87	1	5
	500 –	13.6	2.3	4	0.87	0.07	5	7.2	0.5	5	86	1	6
	600 –	(12.7)	1.2	2	0.83	0.02	3	7.9	0.6	4	85	1	4
	800 –	(12.9)	1.2	2	0.82	0.00	3	8.8	0.5	4	84	1	3
	1000 –				0.83	0.02	2	(8.7)	2.2	2	84	1	3
VI	0 m	2.2	3.5	15	0.20	0.23	13	2.3	2.3	15	112	5	13
	20 –	2.5	3.5	15	0.25	0.19	13	2.5	2.3	16	113	6	13
	50 –	8.5	2.0	15	0.67	0.15	13	4.4	1.4	16	102	4	13
	100 –	11.1	1.6	15	0.74	0.09	13	5.4	0.7	16	99	6	13
	200 –	12.2	1.3	5	0.79	0.05	5	6.3	1.3	6	93	2	5
	300 –	12.9	2.0	2	0.82	0.00	2	6.2	0.1	2	89	1	3
	400 –	12.2	0.7	3	0.86	0.01	2	6.7	0.2	3	88	0	2
	500 –	13.2	0.8	2	0.88	0.06	2	6.7	0.1	2	88	0	2
	600 –	13.5		1	(0.84)		1	7.3	0.8	2	87		1

TABLE V continued

		NO_3–N			*PO_4–P*			*Si*			*O_2%*		
St.	*Depth*	*C*	*SD*	*n*	*C*	*SD*	*n*	*C*	*SD*	*n*	%	*SD*	*n*
VII	0 m	3.9	3.3	19	0.32	0.22	15	3.1	2.5	20	109	6	17
	20 –	4.5	3.2	19	0.33	0.20	15	3.2	2.4	20	109	6	17
	50 –	9.0	2.4	19	0.62	0.14	15	4.8	1.9	20	101	3	17
	100 –	10.8	1.8	18	0.74	0.07	15	5.6	1.0	18	98	2	16
	200 –	12.1	1.9	9	0.77	0.04	7	5.9	0.9	9	92	3	11
	300 –	13.1	1.1	4	0.79	0.04	2	7.2	1.3	4	90	3	6
	400 –	12.9	1.0	2	0.81		1	(6.5)	0.4	2	89	2	3
	500 –	(12.7)	1.3	3	0.84	0.02	3	(6.8)	0.3	3	87	1	5
	600 –	13.2	1.0	2	0.88		1	7.9	0.3	2	86	1	3
	800 –				0.93		1	9.0		1	85	0	2
	1000 –										83		1
	1190 –										82		1
VIII	0 m	4.4	3.4	13	0.40	0.22	11	3.0	2.1	14	109	7	10
	20 –	5.2	3.0	13	0.42	0.19	11	3.2	2.1	14	108	7	10
	50 –	9.4	2.2	13	0.67	0.13	11	5.2	1.1	14	102	3	10
	100 –	11.0	1.2	13	0.73	0.12	11	5.3	0.6	14	99	2	10
	200 –	11.8	1.8	6	0.76	0.07	5	5.5	0.4	6	95	2	5
	300 –	12.7	2.0	3	0.77	0.02	3	6.5	0.2	3	89	2	3
	400 –	(12.2)	1.2	3	0.80	0.04	2	6.8	0.3	3	86	1	2
	500 –	(12.5)	1.4	3	0.87	0.09	3	7.4	0.3	3	85	1	3
	600 –	(12.7)	1.3	3	0.85	0.04	2	8.0	0.3	3	85	0	2
	800 –				0.87	0.02	2	8.8	0.4	2	85	2	2
	1000 –				(0.84)		1	10.1		1	83		1
IX	0 m	5.4	3.1	6	0.31	0.19	4	3.8	2.6	6	108	5	6
	20 –	5.4	2.9	6	0.34	0.15	5	3.7	2.5	6	109	6	6
	50 –	8.0	1.6	6	0.58	0.11	5	4.9	1.7	6	102	3	7
	100 –	10.3	1.4	5	0.74	0.11	5	5.4	1.2	4	96	2	5
	200 –	(11.3)	2.0	3	0.80	0.11	3	6.0	1.5	3	92	2	5
	300 –	(12.6)	1.9	3	0.87		1	7.5	1.6	3	88	1	5
	400 –				0.90	0.07	2	7.0	0.1	2	87	1	3
	500 –				0.80		1	6.9		1	85		1
	600 –				0.81		1	7.8		1	86	2	2
	800 –				0.84		1	9.2		1	85	1	2
	1000 –				0.87		1	10.1		1	83		1
	1200 –				0.88		1	10.9		1	83		1

TABLE VI

Mean distribution of nutrient concentrations (μM) and percentage oxygen saturation in the Stokksnes Section in early June (NO_3 –N and Si in the period 1974–1984; PO_4 –P: 1974–1981, O_2%: 1974–1982).

		NO_3 –N			*PO_4 –P*			*Si*			*O_2%*		
St.	*Depth*	*C*	*SD*	*n*	*C*	*SD*	*n*	*C*	*SD*	*n*	*%*	*SD*	*n*
I	0 m	3.4	2.5	9	0.31	0.17	8	1.6	1.1	10	111	6	7
	20 –	3.4	2.1	9	0.34	0.18	8	1.4	0.9	10	110	5	7
	50 –	9.1	2.0	9	0.59	0.22	8	3.8	1.3	10	100	4	7
II	0 m	3.4	3.2	10	0.30	0.22	8	1.0	1.5	11	113	9	7
	20 –	4.7	3.0	10	0.37	0.22	8	1.1	1.5	11	109	8	7
	50 –	8.5	2.3	10	0.64	0.18	7	2.9	1.8	11	103	5	6
	100 –	12.1	1.2	10	0.82	0.17	7	5.6	0.6	10	96	3	6
	140 –	12.2		1	0.93	0.04	2	5.5	0.9	3	95	3	2
III	0 m	4.3	3.1	10	0.33	0.22	8	1.6	1.9	11	111	9	8
	20 –	5.6	2.9	10	0.41	0.20	8	1.7	1.9	11	108	7	7
	50 –	8.7	2.2	9	0.70	0.11	7	2.9	1.8	11	101	4	8
	100 –	12.1	0.8	10	0.87	0.06	8	5.4	0.9	11	97	2	8
	200 –	12.7	0.3	3	0.89	0.04	2	6.1	0.6	3	95	2	2
IV	0 m	8.8	2.2	10	0.61	0.16	8	2.7	1.8	11	105	5	8
	20 –	10.0	1.5	9	0.64	0.14	8	3.1	1.6	11	104	4	8
	50 –	10.4	1.6	8	0.69	0.15	8	4.1	1.3	9	102	3	8
	100 –	12.2	1.6	9	0.84	0.10	8	5.5	0.9	11	98	1	7
	200 –	13.1	0.6	3	0.87	0.01	2	6.2	0.3	3	96	0	2
	400 –	14.1		1				7.3		1			
	500 –	15.0		1	1.05		1	7.9	0.6	2	87		1
V	0 m	8.0	2.4	7	0.56	0.17	5	2.5	1.9	8	106	8	5
	20 –	8.3	2.2	7	0.58	0.17	5	2.4	2.0	7	107	5	4
	50 –	10.2	2.1	7	0.67	0.34	4	3.5	1.9	8	102	3	5
	100 –	11.3	2.2	7	0.73	0.17	5	5.0	1.9	8	101	3	5
	200 –	13.2	0.8	2	0.89		1	6.5	0.1	2	96		1
	400 –	14.1		1				6.8		1			
	500 –	14.1	0.7	2	0.94		1	6.9		1	94		1
	600 –	14.9		1				7.7		1			
	800 –							10.0		1			
	1000 –	16.9		1				8.9		1			