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Some results of three–year investigations on the interannual variability of the Norwegian–Barents confluence zone

ABSTRACT: In the years 1987–1989, within the frames of the international program „Greenland Sea Project", the Institute of Oceanology of Polish Academy of Sciences carried out the oceanographic investigations in the energoactive zones of the Northern Atlantic.

The paper presents some results of these investigations, characterizing interannual variability of aero- and hydrophysical fields and the causal connections between hydrological and hydrobiological anomalies. Main results of these investigations indicate that the summer season of 1988 was an anomaly in the region of confluence of Barents and Norwegian Seas. This result is irrefutably confirmed by biological data concerning species, and hydrophysical data, such as light attenuation coefficient, fluorescence, spatial distributions of water temperature, salinity, density and current velocity, as well as mass and heat fluxes. It arises from these information that the southern border of the confluence zone was normally the heat „source", while in 1988 it was the heat „sink". The results obtained indicate two reasons responsible for such a situation. The first is the anticyclonic eddy structure of cold Barents Sea waters, penetrating the confluence zone. The second reason seems to be a mechanism blocking the transport of Atlantic water masses through the transect between Faeroe and Shetland Islands.

Key words: Arctic, Norwegian-Barents Seas, confluence zone, interannual variability, water and heat exchage.

Information on subject, aim and research program of Polish oceanographic investigations focused on variability of the Greenland Sea energoactive zones

In the years 1987–1989, within the frames of the international program „Greenland Sea Project", the Institute of Oceanology of Polish Academy of Sciences carried out the oceanographic investigations in the energoactive zones of the Northern Atlantic. The aim of the Polish part of this program was to study the month—to—month and year—to—year variability of hydrophysical and hydrobiological fields and the dynamics of the near—water boundary layer of the atmosphere in selected regions of the ocean in summer months July—August (Druet 1987). The main regions of these investigations were the confluence zone of the Norwegian and Barents Seas and hydrological transects determining the boundary conditions of the oceanic „container", limited by the northern section along the 77^0, parallel of latitude located west of Spitsbergen, the southern section between Faeroe Is. and Shetland Is., the western transect running along the meridian 0^0 and the eastern transect positioned along the confluence zone between the Norwegian and the Barents Seas, that means between the northern Norway and the southern Spitsbergen.

In three—year program of empirical meteorological, hydrological and biological investigations has been conducted from aboard R/V „Oceania" in three Arctic expeditions and it allowed to obtain the following data:

— data on air pressure, temperature, humidity, solar radiation and on the concentration of aerosols in the near-water layer of the atmosphere.

— data on wind velocity and direction.

— data on intensity of wind waves and degree of coverage of the ocean surface with „whitecaps".

— data concerning vertical distribution of mean values and fine structure characteristics of the salinity and water temperature.

— data on light attenuation coefficient and intensity of fluorescence in water.

— data on sound velocity and propagation of acoustic signals.

— data on concentration and species composition of phyto- and zooplankton in the ocean.

The above empirical data allow:

— to investigate the character of variability of thermohaline structure of water masses; this can be achieved through the application of mathematical models which take into account mesoscale advection. It is assumed that processes affecting the state of the upper active layer of the ocean have a mesoscale character and are generated by heterogeneity of thermodynamic atmospheric fields; it is additionally assumed that they are stationary and that they develop on the basis of macroscale oceanic circulation.

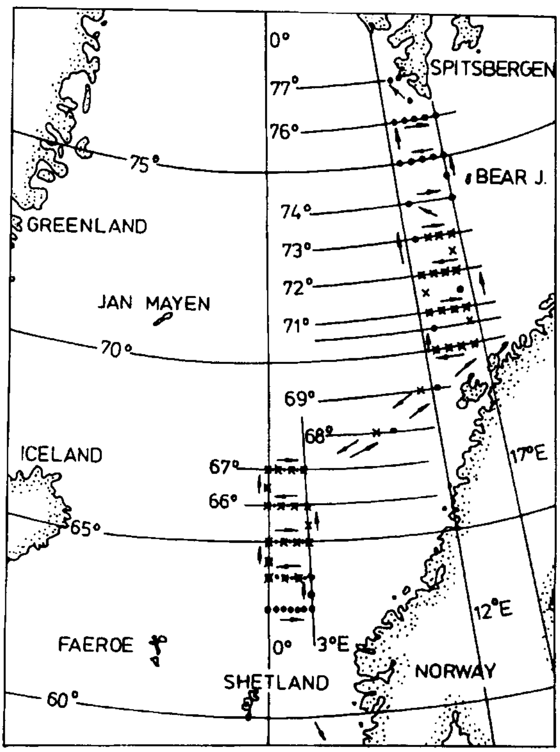
— to investigate the variability of selected parameters of thermohaline structure and variability of anomalies characterized by the above mentioned parameters.

— to investigate anomalies of the components of energy balance equation; this can be achieved through estimation of flow field components (analogue method of dynamic heights or with a β spiral or the Wunsch inversive method) and deviation of these anomalies from the average climatic values.

— to investigate the relations between the fluctuations of the hydrological regime and the quantitative changeability of marine biocenosis (quantitative changeability in spatial distribution of plankton concentration and species populations).

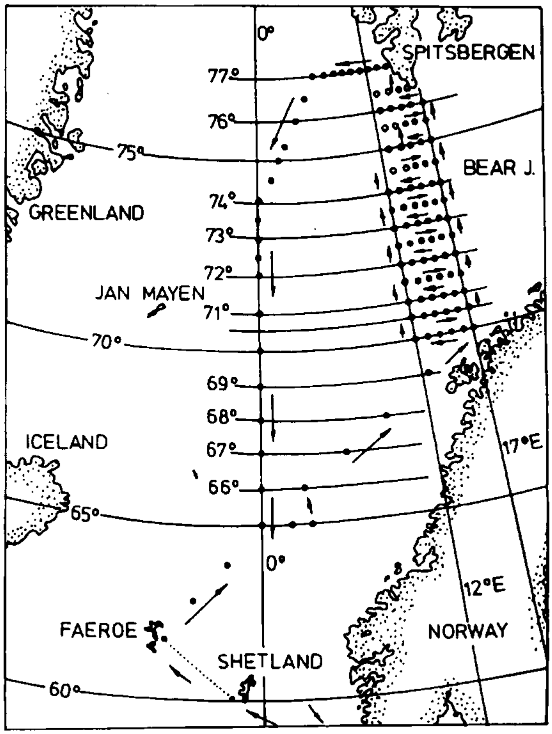
This paper presents some results characterizing the interannual variability of hydrophysical fields in the investigated regions and the causal connections between the hydrological and the hydrobiological anomalies.

Investigated regions included in the research program are shown in Figs. 1 and 2. Selection of these regions was dictated by intensive interaction processes between the ocean and the atmosphere occurring there (large heat and momentum fluxes, apparent and latent heat, significant heat content anomalies etc.) and intensive horizontal flow of water masses transporting heat along meridians with a well pronounced meandering in the direction of parallels of latitude. The chosen regions are also distinguished for intensive heat exchange between the ocean and the atmosphere.



• basic measuring points
× repeated measuring points
— direction of ship movement

Fig. 1. Location of measuring network in 1987



- • measuring points in 1988 and 1989
- ∘ additional measuring points in 1989
- —•— direction of ship movement

Fig. 2. Location of measuring network in 1988 and 1989

In 1987 the research has been conducted from 7 July to 5 September (Zieliński and Siwecki 1988). The stations were distributed both in longitudinal and latitudinal direction, in a distance of 1^0 from each other. Location of regions is presented in Fig. 1. The following measurements were done at the stations:

– vertical STD profiles down to 300 m with Plessey Environmental System probe,

– wertical STD profiles down to 80–100 m with a freely submerging high–frequency probe, constructed in IO–PAS,

– vertical profiles of fluorescence and light attenuation coefficient down to 60 m; Q–INSTRUMENT ApS fluorometer and instrument constructed by IO–PAS, measuring the light attenuation, were used,

– collection of water and plankton samples with a rosette–sampler and plankton nets,

– meteorological data (SHIP) and aerosol measurements,

– measurements of volumetric reverberation of sound with ATLAS KRUPP DESO – 20 echosounder.

The scope of study was similar in 1988 (Zieliński and Siwecki 1989) and in 1989, and the research was conducted in the regions presented in Fig. 2. Following measurements were performed there:

– vertical STD profiles down to 1000 m with Canadian GUTDELINE 8709 probe,

– vertical STD profiles down to 150 m with HS – 2000 Salzgitter Elektronik probe,

– vertical profiles of fluorescence and light attenuation coefficient down to 60 m with Q – INSTRUMENT ApS fluorometer and instrument constructed in IO – PAS mesuring light attenuation, respectively,

– collection of water and plankton samples with a rosette – sampler and plankton nets,

– recording of „whitecaps", concentration of aerosols and meteorological data (SHIP),

– measurements of volumetric reverberation of sound with LAZ – 4700 Honeywell – Elag Nautic echosounder.

Variability of Norwegian – Barents confluence zone in summer seasons 1987 – 1989

Figure 3 presents the limits of occurrence of Atlantic plankton species transported by the Norwegian current. These limits, determined on the basis of biological data collected in summer seasons of 1987, 88 and 89 indicate

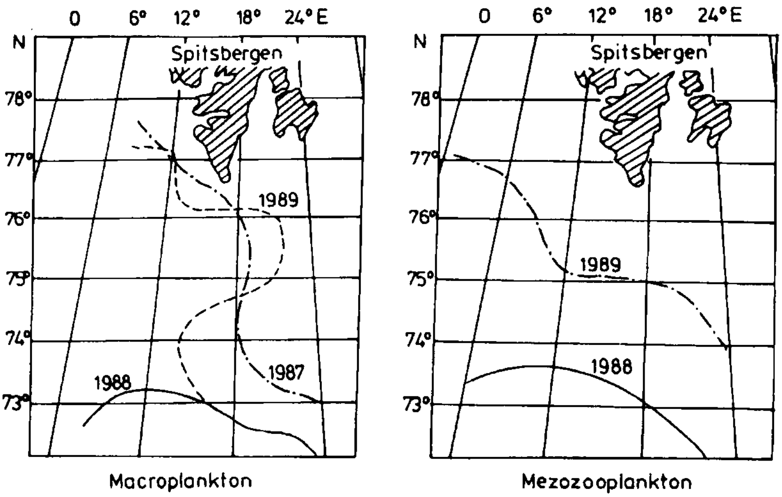


Fig. 3. Range of Atlantic species occurrence (after Węsławski, Kwaśniewski and Wiktor, *in press*)

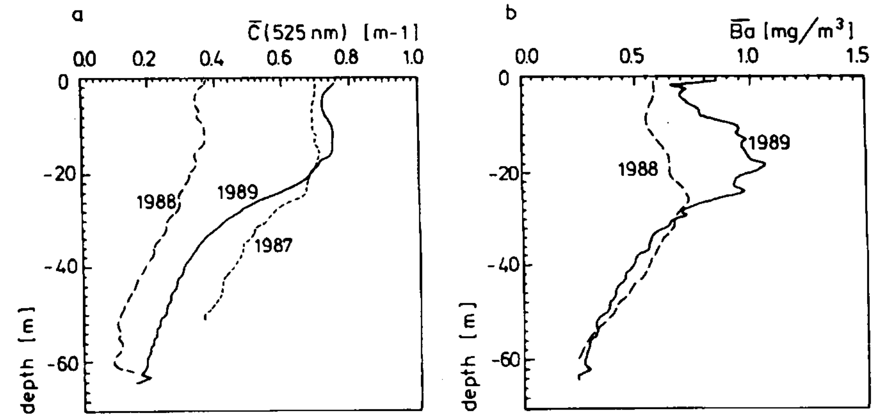


Fig. 4. Distribution of mean monthly values of light attenuation (a) and chlorophyll concentration (b) in July (after Zieliński, Hapter and Piskozub, *in press*)

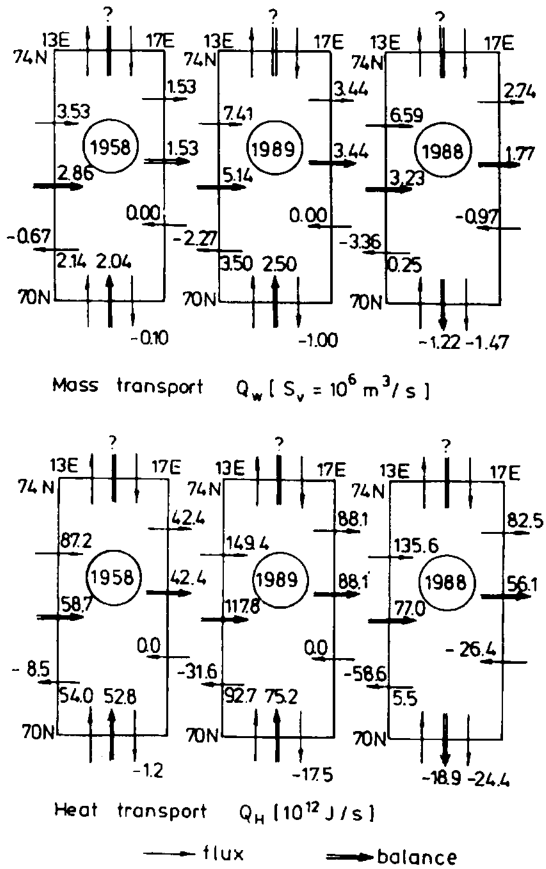


Fig. 5. Mass and heat transport in the confluence zone

a distinct barrier in northward plankton transport in 1988 (Węsławski, Kwaśniewski and Wiktor, *in press*). In the confluence zone of the Norwegian and Barents Seas this year was additionally characterized by a significantly lower mean phytoplankton concentration and higher values of light attenuation coefficient (Zieliński, Hapter and Piskozub, *in press*) (better transparency of water: Fig. 4). It can be assumed, therefore, that significant deviations of hydrological characteristics of the confluence zone from long–term means and from characteristics of summer season of 1987 and 1989 occurred in 1988. Schemes of heat and mass balance presented in Fig. 5 indicate that summer seasons of 1958 (Dietrich Atlas, 1969) and 1989 were characterized by similar qualitative conditions. Assuming that 1958 did not differ from the average (Jankowski and Schlichtholtz, *in press*) it can be concluded that summer season of 1988 was anomalous indeed. It is visible from Fig. 5 that the southern border of the confluence zone in the years 1958 and 1989 was the heat „source", while in 1988 it was the heat „sink". Assuming hypothetically stationary and comparable (from the quantitative point of view) balances on the upper border (along the 74°N parallel of latitude) it can be calculated that the heat influxes to the discussed „container" were as follows: $+2.0 \times 10^{12}$ J/s in 1988, $+104.9 \times 10^{12}$ J/s in 1989 and $+69.1 \times 10^{12}$ J/s in 1958. A comparison of these data shows an anomalously low heat influx to the confluence zone in 1988. Some hypothetical circumstances and empirical data show that the main reason for such a situation is the anticyclonic vortical structure of cold Barents Sea waters, penetrating the confluence zone (Jankowski and Swerpel 1990, Druet and Jankowski 1991). These structures are of a convergent character and cause vertical downwelling of cold water masses, forming local baroclinic frontal structures and intrusive quasi–horizontal penetration of cold water towards the Norwegian Sea.

A vast high pressure area occurred at the confluence zone from 6th to 9th July, 1988 (Fig. 6a). This anticyclonic system of atmospheric pressure gradually moved east, giving way to a cyclonic system created from the south (Fig. 6b). Between 10th and 15th July the high and low pressure systems disappeared, and a new broad anticyclonic system started to form from 16th July, its center located close to the Bear Island. This system was stable until 20th of July. Beginning from 21st of July this system started to move northward, giving way to a cyclonic system that started to form at the southern border of the confluence zone beginning from 23rd July (Fig. 6d).

Such a meteorological situation in July 1988 forced the anticyclonic circulation of water masses with the center near the Bear Island. Since the prevalence of anticyclonic systems is not typical of this region in summer, when usually neutral systems or short–lasting low pressure systems occur, July 1988 can be treated as an anomaly with respect to the long–term mean and similar seasons of 1987 and 1989. Circulation of water masses

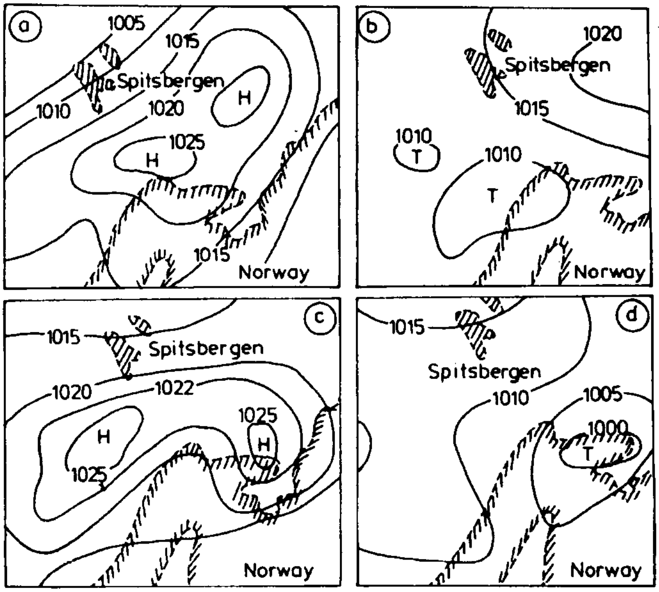


Fig. 6. Barometric charts at 6.00 A.M. for:
a – 1988.07.06. b – 1988.07.10.
c – 1988.07.16. d – 1988.07.23.

generated by dextrorotary anticyclonic system, fed by cyclonic boundary conditions from the south in the periods from 10th and 23rd of July (Fig. 6b and c), was amplified and stabilized by the conservative character of potential vortexity, which must be compensated for by vortical circulation of water masses under the conditions of irregular conical bottom relief (Fig. 7) and constant angular velocity of Earth rotation (Pedlosky 1987).

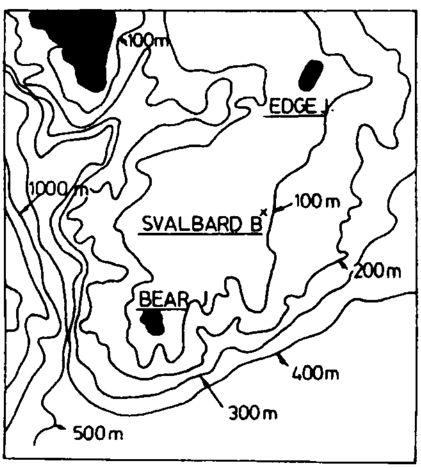


Fig. 7. Bathymetric chart of South Svalbard

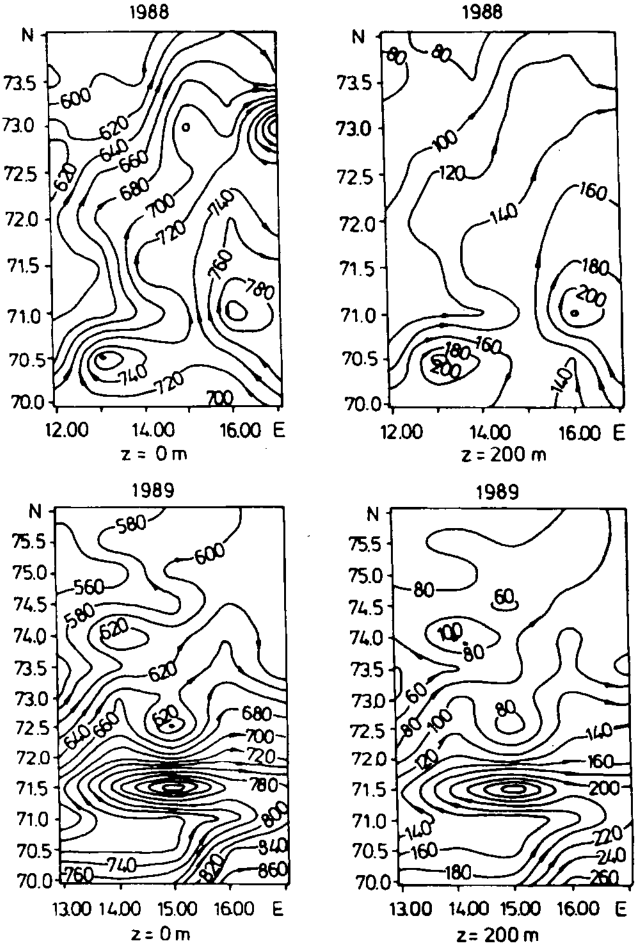


Fig. 8. Isolines of geostrophic stream function (dynamic topography related to 1000 m)

To sum up it can be stated that specific meteorological conditions occurred in July 1988. These conditions, together with topographic conditions in the confluence zone, created a hydrological anomaly with respect to 1987 and 1989, viz. anticyclonic circulation of water masses, transporting cool and less saline waters from the Barents Sea westwards (Figs. 8 and 9). At the same time the convergent character of this circulation caused downwelling of these waters (Fig. 10). For this reason the Atlantic 35 psu isohaline lied deeper in 1988 than in 1958 and 1989 (Fig. 11). This downwelling of water masses within the region of anticyclonic circulation caused a transfer of almost all plankton species transported by the Norwegian current down into the sea. The life span of these species was probably shorter than the duration of the downwelling processes, hence

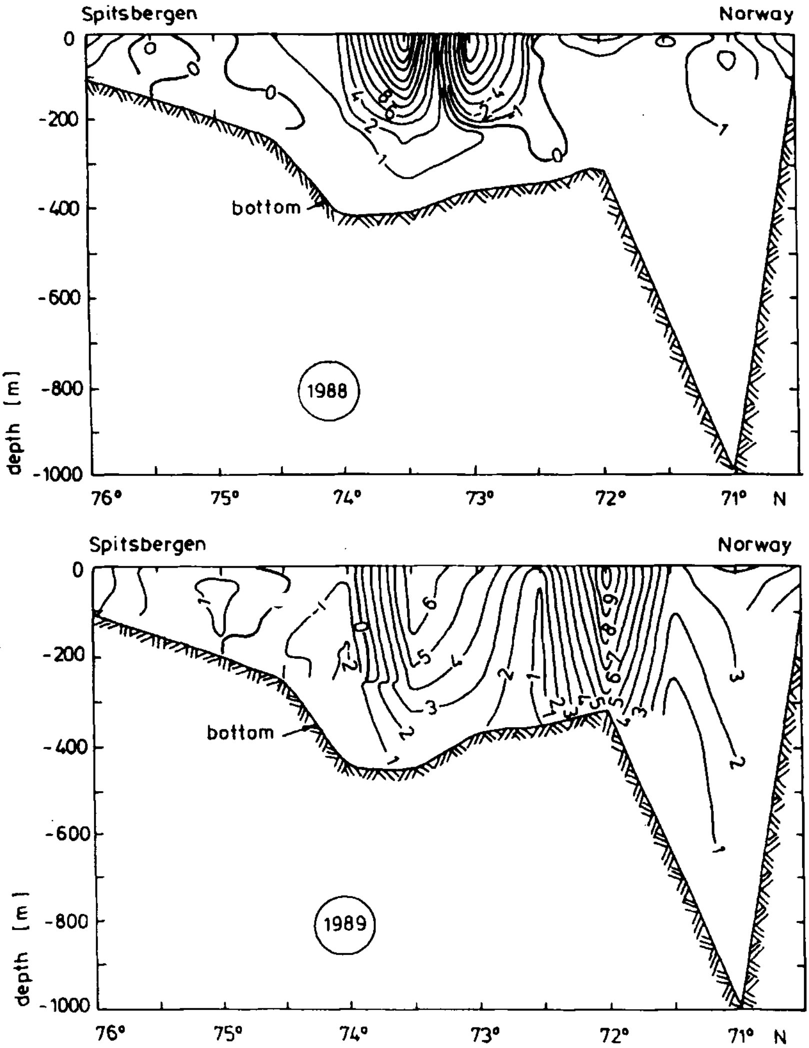


Fig. 9. Vertical distributions of geostrophic flow velocity along the 17°E meridional section (no-motion level chosen at the depth of 1000 m; positive values towards the Barents Sea)

the anticyclonic circulation in July 1988 probably constituted the northern limiter of plankton expansion, not occurring in 1987 and 1989 (Fig. 3).

The baroclinic character of anticyclonic circulation was also responsible for the horizontal hydrodynamic instability of water masses (generation of baroclinic pressure). The intensive processes of lateral intrusion, due to this baroclinic instability and interpenetrating of different water masses (Fig. 12), constituted the main mechanism of mixing of these masses, influencing the specific mass and heat transfer in the confluence zone in summer 1988 (Druet

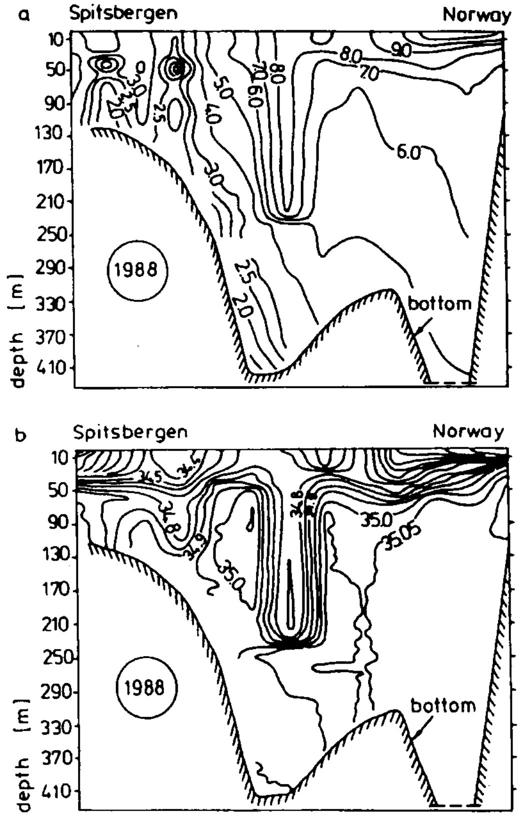


Fig. 10. Vertical distributions of temperature (a) and salinity (b) along the 17°E meridional section

and Siwecki, *in press*). It also cannot be excluded that the differences in mass and heat balance in particular years (Fig. 5) were caused by a smaller flow in a part of the North–Atlantic current, transporting water masses through the vertical cross–section between Faeroe and Shetland Islands. This mechanism is shown in Fig. 13. The vertical distributions of temperature, salinity and water density, as well as component of current velocity, clearly show that a considerable amount of water characteristics, similar to this of oceanic water turns back towards the Faeroe–Shetland channel (Fig. 14). Empirical data irrefutably show that the amount of heat transported through the Faeroe–Shetland channel was much lower in 1988 than in 1989 (Tab. 1). This confirms the supposition that a part of Atlantic waters inflowing across the transect between Iceland and Faeroe turns back to the Atlantic Ocean between Faeroe and Shetland Islands. Recirculation of a part of water masses, transported exclusively through this channel, is also probable.

A more detailed information of processes taking place in the investigated regions can be obtained from a hydrodynamic–numerical model. Empirical data collected during the three–year investigations are the assimilation data for this model. A complete scientific report called: „Results of three–year Polish oceanographic investigations of the interannual variability of Greenland Sea energoactive zones" with full set of oceanographic data will be published by IO PAN (in English) in 1992.

Table 1

Water and heat volume transport through the hydrographic section Faeroe-Shetland Channel in summer 1988 and in summer 1989

Level of no motion	Year	Water volume ($10^6 m^3 s^{-1}$)			Heat volume (10^{12} J s^{-1})		
		into A.O.	into N.S.	diff	into A.O.	into N.S.	diff
450 m	1988	−2.14	4.44	2.30	−63.8	85.1	21.3
	1989	−2.17	2.61	0.45	−48.1	63.5	15.4
550 m	1988	−3.12	4.20	1.07	−94.3	115.5	21.3
	1989	−2.22	3.12	0.90	−59.3	91.0	31.7
800 m	1988	−4.36	3.72	−0.64	−122.7	125.2	2.4
	1989	−2.25	3.38	1.13	−60.7	101.9	41.2
1000 m	1988	−4.62	3.71	−0.91	−125.8	125.2	−0.6
	1989	−2.23	3.32	1.09	−59.3	99.8	40.6

Notice: Positive values were assumed for the volume transport directed towards the Norwegian Sea.

Abbreviations: A.O. – Atlantic Ocean, N.S. – Norwegian Sea.

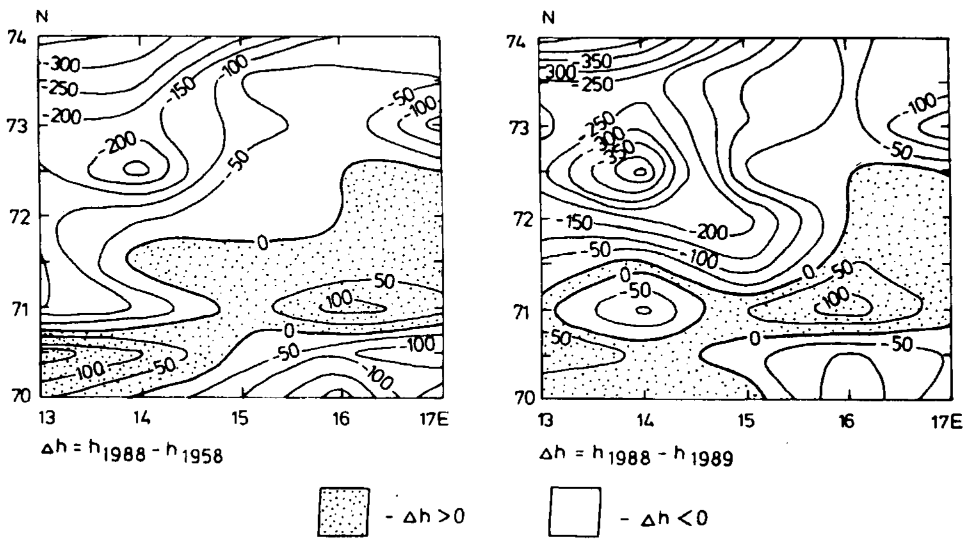


Fig. 11. Map of bathymetric differences Δh of isohaline surfaces of 35 psu

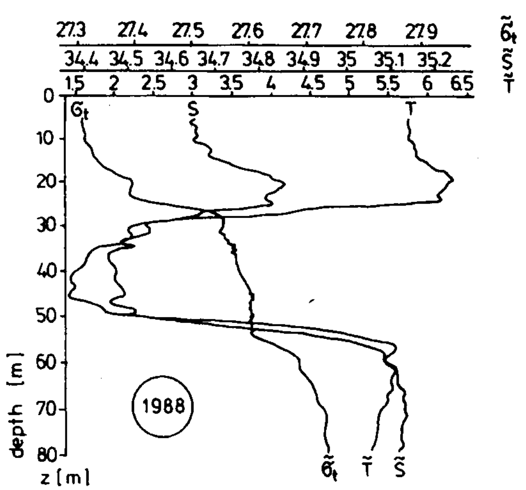


Fig. 12. Example of momentary vertical distributions of temperature (T), salinity (S) and density (σ_t) in the confluence zone

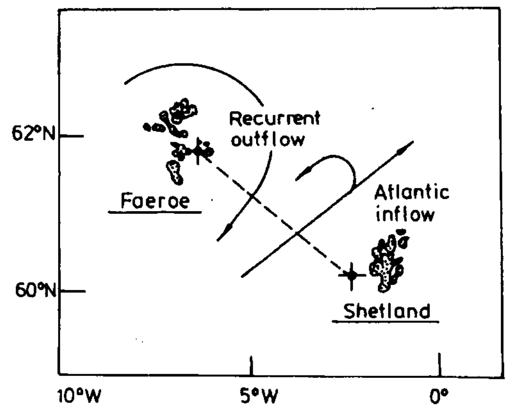


Fig. 13. Scheme of Faeroe-Shetland hydrological section

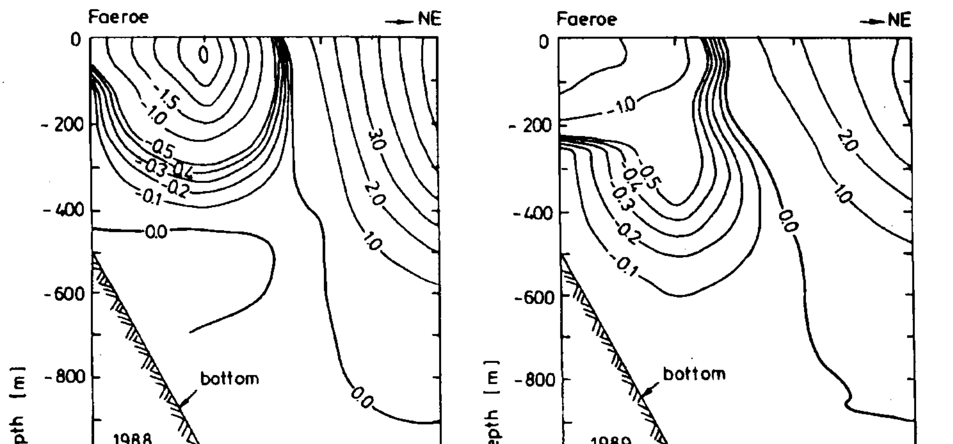


Fig. 14. Vertical distributions of geostrophic flow along the meridional section Faeroe – North East (no-motion level chosen at the depth of 1000 m; positive values towards the Greenland Sea)

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Streszczenie

Od roku 1986 kraje europejskie, USA i Kanada realizują interdyscyplinarny program badań oceanogeograficznych w obszarach arktycznych północnego Atlantyku pod nazwą „Greenland Sea Project". Zasadniczym celem tych badań jest wyjaśnienie roli oceanu w kształtowaniu krótkookresowych zmian atmosferycznego klimatu oraz poznanie hydrologicznych procesów generujących anomalie w przestrzenno-czasowej strukturze mas wodnych.

Polskie zespoły naukowe Instytutu Oceanologii PAN w Sopocie uczestniczyły w realizacji tego programu na statku naukowo-badawczym „Oceania", a głównym obszarem badań w dorocznych oceanograficznych wyprawach była frontalna strefa konfluencji Morza Norweskiego z Morzem Barentsa. W sezonie letnim 1986–1990 badano również inne rejony Morza Norweskiego i Grenlandzkiego o zwiększonej intensywności procesów wymiany masy i energii (przekrój Faeroe–Shetlands, równoleżnikowy przekrój przez południk $+10^{\circ}$ na przedłużeniu spitsbergeńskiego Fiordu Hornsund, energoaktywny obszar centralnego Morza Norweskiego w rejonie stacji M).

Publikacja niniejsza prezentuje niektóre wyniki tych badań, charakteryzujące międzyletnią zmienność aero- i hydrodynamicznych pól oraz wzajemne powiązania między nimi. Badania ujawniają hydrotermiczną anomalię letniego sezonu roku 1988 w strefie konfluencji Morza Norweskiego z Morzem Barentsa w stosunku do okresów letnich lat 1958, 1987 i 1989. Jej istnienie dokumentują dane biologiczne (blokada w transporcie gatunków planktonu atlantyckiego), dane meteorologiczne (przeważający wpływ antycyklonicznych układów ciśnienia atmosferycznego z ośrodkiem nad Wyspą Niedźwiedzią) oraz dane hydrofizyczne (charakterystyki średnich pól temperatury, zasolenia, gęstości, prędkości mezoskalowych geostroficznych antycyklonalnych cyrkulacji mas wodnych, zwiększenie przezroczystości wody itp.). Analizowane bilanse transportu

masy wodnej i ciepła w południkowych przekrojach strefy konfluencji oraz przekroju między wyspami Faeroe – Shetlands ujawniają ewidentnie zmniejszenie w roku 1988 strumieni ciepła transportowanego na północ przez Prąd Norweski oraz wynoszenie zimnych mas wodnych z Morza Barentsa na zachód i zapadanie tych mas w głąb. Wpływ tych procesów ujawnia się ostatecznie w postaci hydrotermicznej anomalii oraz blokady w transporcie biomasy planktonu na północ.