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Report

THE EUROPEAN SUBPOLAR OCEAN PROGRAMME (ESOP) — INVESTIGATIONS OF THE ROLE OF SEA ICE IN GREENLAND SEA CONVECTION

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Abstract: The European Subpolar Ocean Programme (ESOP) has the overall objective of understanding the roles played by sea ice in the energetics of the Greenland Sea system and in the specific ice-ocean interactions involved in the process of deep convection in the winter Greenland Sea with its attendant sequestration of carbon dioxide. The scope and nature of the project are described, together with results obtained to date.

1. Introduction

The Greenland Sea is one of only four ocean areas where ventilation occurs through open ocean convective renewal of intermediate and deep waters in winter, the others being the Labrador Sea, the western Mediterranean and the Antarctic. Convection occurs in the centre of a cyclonic gyre which is bounded to the west by a cold current (the East Greenland Current) advecting ice and water of polar origin into the system from the Arctic Basin; to the east by a warm northward-flowing current (West Spitsbergen Current); and to the south by the Jan Mayen Current, a cold current which diverts to the eastward from the East Greenland Current. The Greenland Sea also represents the main route for water and heat exchange between the Arctic Ocean and the rest of the world. Ice is transported into the Greenland Sea from the Arctic Ocean and melts as it moves southward, so that the Greenland Sea as a whole, when averaged over a year, is an ice sink and thus a fresh water source. However in winter local ice can form within the Greenland Sea, associated with high ocean-atmosphere heat fluxes, in the region influenced by the Jan Mayen Current. The consequent brine release acts locally to destabilise the surface layer and is believed to be one factor leading towards mid-gyre convection. The convection is associated with a carbon flux which may be significant in the sequestration of anthropogenic CO_2.

The role of sea ice is thus important on two scales. On the large scale, the sea ice entering from the Arctic Basin via Fram Strait contributes some 2230 $km^3\ a^{-1}$ to the fresh water budget of the Greenland Sea system (Aagaard and Carmack, 1989), the largest single item in its overall net fresh water gain of 1800 $km^3\ a^{-1}$. On the mesoscale, the local ice growth in winter is a factor in the convection process. The area in which the growth occurs takes the form of a tongue, called Odden (Norwegian: headland), which grows eastwards from the main East Greenland ice edge in the vicinity of 72–74°N latitude and often curves round to the northeast until it reaches east of the prime meridian. During 1993, unusually, it actually developed into a separate island of ice later in the winter. Its curvature embraces a bay of ice-free water, centred on the gyre centre, which is known as Nordbukta. Because of the exposed nature of Odden, open to wave action from many directions, the local ice which forms within it is observed to occur mainly as frazil and pancake ice, which are incapable of forming large floes or ice sheets because of wave energy. Such ice has a high continuing growth rate because there is no continuous thermal barrier created between atmosphere and ocean, and can thus be associated with large pulses of salt rejection into the upper ocean.

Until recently, the relative contributions of local ice production and the advection of older ice from the East Greenland Current to the creation of Odden were not known for certain, because no systematic glaciological observations had been made in the region. If local ice formation dominates, then it must occur on a cyclic basis related to cold air outbreaks from Greenland, and would explain why remote sensing imagery of the region shows rapid excursions in ice extent. Some models of winter convection (*e.g.* RUDELS, 1990; J. BACKHAUS, personal commun.) require such a periodic salt flux to trigger convective plumes. The sequence of events is that a cold air outbreak causes rapid local ice growth, giving a pulse of salt which triggers convective overturning. Subsequent melt then halts convection but further cold outbreaks drive convection deeper; a number of such cycles are required to enable the convection to reach mid-depths or the ocean bottom. Other models (*e.g.* SCHOTT *et al.*, 1994; PAWLOWICZ, 1995; HÄKKINEN, 1995) stress the importance of cooling and mixing phases in open water, with ice formation playing a vital preconditioning role early in the winter.

In either case, it is important to assess the role of ice in the convection mechanism because if ice were to retreat from the central gyre region on account of climatic change it may cause convection to cease. Already there is evidence from tracer studies (SCHLOSSER *et al.*, 1991) of a severe reduction in the volume of deep convection during the last decade. The same end could be accomplished by an increase in the area-averaged melt rate, causing increased stability in the surface layer, and so it is equally important to map the ice flux into the Greenland Sea through Fram Strait and its fate within the Greenland Sea system. If convection were to cease it would have a positive feedback effect on global warming, since the ability of the world ocean to sequestrate CO_2 through convection would be reduced.

In 1987 a collaborative research programme was initiated by the Arctic Ocean Sciences Board, known as the Greenland Sea Project (GSP), to study the rates of water mass transformation and transport, the food chain dynamics and the life cycles of dominant plankton species (GSP GROUP, 1990). The chairman of the project was J. MEINCKE. The GSP carried out field work in summer 1987, then an intensive field programme during 1988–9 including a tomography experiment, with plans for a second intensive field phase during winter 1993. As these field plans developed, ESOP was proposed as an EC programme focusing on the large scale and mesoscale roles played by sea ice-ocean interactions in the Greenland Sea system, and the influence of convection on the carbon cycle. The second field phase of GSP became the first field season of ESOP, which thus started its work in 1993 and has involved further field operations in 1994 and 1995. Table 1 is a list of institutions and Principal Investigators who are partners in ESOP. ESOP ends in December 1996 but is being followed by ESOP-2 (1996–9), a fol-

Table 1. Principal investigators in European Subpolar Ocean Programme, listed by EC participant number.

No.	Investigator	Affiliation
1	Dr. Peter WADHAMS	Scott Polar Research Institute, University of Cambridge, England
2	Dr. Jan BACKHAUS	Institut für Meereskunde, Universität Hamburg, Germany
3	Dr. Michael SPINDLER	Institut für Polarökologie, Christian-Albrechts-Universität zur Kiel, Germany
4	Dr. Thor JAKOBSSON	Icelandic Meteorological Office, Reykjavik, Iceland
5	Dr. Leif LAURSEN	Danish Meteorological Office, Copenhagen, Denmark
6	Dr. Peter LEMKE	Alfred-Wegener-Institut für Polar-und Meeresforschung, Bremerhaven, Germany
7	Dr. Erland RASMUSSEN	Danish Hydraulic Institute, Horsholm, Denmark
8	Dr. Leif TOUDAL	Electromagnetics Institute, Technical University of Denmark, Lyngby, Denmark
9	Dr. Barry USCINSKI	Dept. of Applied Mathematics and Theoretical Physics, University of Cambridge, England
10	Mr. Hans VALEUR	Danish Meteorological Institute, Copenhagen, Denmark
11	Dr. Torgny VINJE	Norsk Polarinstitutt, Oslo Lufthavn, Norway
12	Dr. Jean-Claude GASCARD	Laboratoire d'Océanographie Dynamique et de Climatologie, Université Pierre et Marie Curie, Paris, France
13	Dr. Hans-Jürgen HIRCHE	Alfred-Wegener-Institut für Polar-und Meeresforschung, Bremerhaven, Germany
14	Dr. Torkel NIELSEN	Department of Marine Ecology and Microbiology, National Environmental Research Institute, Denmark
15	Dr. Francisco REY	Institute of Marine Research, Bergen, Norway
16	Prof. Leif ANDERSON	Department of Analytical and Marine Chemistry, Chalmers University of Technology, Gothenburg, Sweden
17	Dr. Eystein JANSEN	Centre for Environment and Resource Studies, University of Bergen, Norway
18	Dr. Ola JOHANNESSEN	Nansen Environmental and Remote Sensing Centre, Bergen, Norway
19	Dr. Egil SAKSHAUG	Trondheim Biological Station, University of Trondheim, Norway
20	My. Dag SLAGSTAD	SINTEF Automatic Control, Trondheim, Norway
21	Dr. Knut BORSHEIM	Laboratory of Biotechnology, University of Trondheim, Norway
22	Dr. François CARLOTTI	Laboratoire d'Ecologie du Plancton Marin, Université Pierre et Marie Curie, Villefranche sur Mer, France

low-on programme concentrating on the role of the thermohaline circulation.

2. Scope and Approach

To understand the role of sea ice in the ocean system it is necessary to investigate the Greenland Sea on two scales: basin-wide studies, to determine the large-scale role of the ice cover, and mesoscale studies in the region of the Odden ice tongue and gyre centre, to determine the mechanisms by which sea ice is involved in deep convection in winter, and to estimate CO_2 uptake through cooling, convection and biological fixation.

The basin-wide scale programme studies the following parameters:

- the seasonal extent and variability of the sea ice;
- the dynamics of the ice;

- its mass flux;
- the exchanges of fresh water and heat between the ice and the upper ocean;
- large-scale air-sea energy interactions in the region;
- carbon chemistry; and
- spring bloom dynamics.

The mesoscale programme is studying:

- the physical and acoustical properties of the ice edge region in winter and spring;
- the physics of deep convection and its relationship to air-sea-ice interaction;
- CO_2 uptake during convection events and surface cooling;
- the air-sea fluxes of momentum, moisture and heat; and
- the dynamics of the spring plankton bloom and its impact on CO_2 sequestration.

The approach on two scales enables the two ways in which sea ice contributes to the energetics of the Greenland Sea to be assessed in an integrated programme. The large scale programme maps the flux of ice into the Greenland Sea, its rate of melt, and energy exchanges in the ice-covered zone. The mesoscale processes in Odden are studied by an intensive shipborne programme throughout the winter and spring periods, using acoustic and float techniques to locate and measure the plumes themselves, hydrographic surveys to measure the impact of the convection on ocean structure, biological sampling to estimate carbon fluxes, and finer-resolution remote sensing to examine the sea ice changes which occur concurrently with the convection process.

The techniques used to accomplish these tasks are as follows.

Basin-wide tasks

- Satellite (AVHRR, SAR and SSM/I) and some airborne data (from the C-130 aircraft of the Danish Meteorological Institute) are used to map the time variability of ice extent and ice type distribution over the whole East Greenland region south of Fram Strait.
- The ice thickness distribution is measured using two series of upward sonar moorings at 75°N and 79°N, inserted across the main East Greenland ice drift, with a further sonar in Denmark Strait.
- The exchanges of momentum, moisture and heat are measured at the ocean surface in ice-covered and ice-free conditions.
- The results of the ice and ocean measurement programmes are applied to appropriate large-scale models in order to describe the physics of the Greenland Sea system more adequately. The relevant model used within the project is a high resolution limited area atmospheric model GRE-HIRLAM coupled to an ocean-ice model, developed by Danish Hydraulics Institute and Danish Meteorological Institute.
- Within the context of sea ice studies, the role of sea ice biota in the overall ecology of the Greenland Sea is examined, and the biological impact of the physical variability of the sea ice in space and time. These results are used to assess the role of biology and chemistry in carbon dioxide sequestration during convection.
- The seasonal and regional variability of surface water and atmospheric pCO_2, the dissolved inorganic CO_2, and related chemical and physical parameters are measured along transects across the basins.

Mesoscale tasks

- The structure, distribution, and the rate of formation and decay of ice types in the

Odden region are determined throughout the winter, using a time step of the order of one day. This is done partly by direct shipborne observation but mainly by airborne and satellite observation, with the shipborne observations being used to validate the signatures of the remote sensing systems for the various types of young ice which are important in the region.

- The ice thickness distribution in Odden is estimated, using direct measurement from ships, inference from remote sensing signatures, and interpretation of ocean gravity wavelength changes in SAR imagery in terms of ice thickness.
- The overall hydrographic structure of the central part of the Greenland Sea gyre and its development are surveyed by cruises during the winter, in particular changes which may be associated with the formation of Greenland Sea Deep Water.
- Direct observations and measurements are made of the physical process by which deep convection is occurring in winter, whether it be in the form of convective plumes over relatively large areas, "chimneys" or another mechanism (*e.g.* instabilities). This is done using Seasoar and underwater drifters tracked acoustically for macro-structure and towed thermistor chains, ADCP and acoustic Schlieren techniques for smaller scale processes.
- The results of the joint mesoscale ice and ocean programmes are combined and related to appropriate mesoscale ice-ocean models which describe the way in which sea ice influences or controls the water mass transformations and which quantify the water mass changes which occur.
- The historical framework for an association between ice variability and convection in Odden is studied through an analysis of ice extent and variability from past years.
- The surface water and atmospheric pCO_2, the dissolved inorganic CO_2 and related chemical/physical parameters are measured during convection periods to estimate winter atmosphere-ocean CO_2 fluxes and transports.
- The dynamics of the intense spring bloom in the Greenland Sea are studied and modelled, and its effects on ocean-atmosphere CO_2 transfer estimated. The effects of mesoscale variability of surface waters and ice on biological productivity and on the light dependence of primary and new production are studied; and the fluxes of particulate and dissolved organic carbon are measured, estimated and modelled.

3. Cruises Completed

3.1. 1993

During 1993 a series of cruises was carried out in the Greenland Sea, beginning in the winter season. The first cruise was a two-ship survey of the central gyre region in January–February 1993 by *Valdivia* (University of Hamburg) and *Northern Horizon* (UK Defence Research Agency), including a survey of upper ocean structure by a towed array and an attempt to observe and measure convective plumes acoustically using a source towed by *Valdivia* and a line of sonobuoys dropped by a BAC 1-11 of Defence Research Agency operating out of Andenes. Both ships encountered extremely bad weather conditions which limited their programme (QUADFASEL, 1993; RUDELS *et al.*, 1994). The second cruise was a two-leg operation by *Polarstern*:: the first leg, ARKTIS IX/1a, involved a three-week drift in the ice NW of Svalbard with a large meteorological array deployed, while the second leg, ARKTIS IX/1b, involved work in Fram Strait, at 75°N and on the Odden ice tongue (February–April). The census hydrography stations in the central Greenland Sea (a standard set of stations designed to cover the mid-gyre region) were occupied (EICKEN and MEINCKE, 1994). During February 1993 *Håkon Mosby* also operated in the Odden region and further to the north-east along the main East Greenland ice edge, with O.M. Johannessen as Chief Scientist.

In spring (May) *Johan Hjort* worked in the Norwegian-Greenland Sea during the time of the plankton bloom, on a mainly biological programme, and again in August. In May–June *Valdivia* undertook a second cruise to reoccupy some of the census hydrography stations at the end of winter (cruise 136). The cruise lasted from May 15 to June 17, with Bert Rudels as Chief Scientist. The cruise involved a CTD survey (74 stations plus 70 XBTs) of the central Greenland Sea to study the remnants of the winter's convection and the interactions between Greenland Sea Deep Water and deep waters from the Arctic Ocean. Some zooplankton work was also done with bongo and multi nets, a mooring was deployed for Hamburg/Kiel and two LODYC sound sources retrieved (RUDELS, 1993).

In August *Lance* (NPRI, Oslo) deployed four upward looking echo sounders on moorings at 79°N and recovered one at 75°N. Finally, during August–September 1993 the newly built icebreaker *Fennica* operated in the Fram Strait area carrying out ice protection work for the Ocean Drilling Program but also being used as a ship of opportunity for ESOP studies; an ice physics and remote sensing ground truth programme were carried out on board (WELLS *et al.*, 1995).

3.2. 1994

FS *Valdivia* operated again in the central gyre region during the winter. She sailed from Hamburg on 7 February 1994, with Dr. D. QUADFASEL as Chief Scientist, returning on 25 March. During the two legs of the cruise she worked in a 100 km rectangle in the vicinity of 75°N 5°W, the gyre centre (leg 1), then carried out towed CTD surveys and an acoustics experiment in the suspected convection region (QUADFASEL, 1994). There was no Odden ice tongue this year, with a continuous straight ice edge to the East Greenland Current, sitting at a longitude of approximately 9°W at 75°N. In the open water region NE of Jan Mayen heavy icing conditions were experienced by the ship. The mixed layer depth in the central gyre region was 150 m at the start of the experiment, deepening to 600–700 m during the experimental period. 80 CTD stations were occupied, as well as 5 transects across the East Greenland polar front with the towed CTD chain of FWG Kiel, which was then lost in heavy weather. Argos drifters were also deployed. Thermal convective plumes were observed extending to 600–700 m (absolute maximum 1000 m). Three trials of the acoustic imaging procedure were carried out, in which a sound source was suspended from a buoy while the ship steamed past nearby recording the pattern of received intensities, from which the size and shape of thermal plumes can be inferred. Despite high background noise levels these experiments worked well. Sea ice data were supplied to the ship from Bergen and Hamburg, including SAR imagery received from Tromsø and interpreted in near-real time. The ship observed and measure convective plumes and examined the ocean structure occurring in the plume convection region. During the voyage J-C Gascard deployed 9 subsurface RAFOS floats, mostly in pairs at 200 m and 600 m depth.

Håkon Mosby operated in the same region during a cruise from 2 February to 18 March. On leg 1 (Prof. O. JOHANNESSEN, Chief Scientist) she worked in the convection region towing a Seasoar and doing shallow and deep CTDs between 75°N and 78.5°N as well as some biological work. Leg 2 (E. JANSEN, Chief Scientist) focused on CO_2 fluxes, dissolved inorganic carbon studies and deep CTD casts. On leg 2 the ship sailed N from Tromsø towards Bear Island then W to the ice edge at 75°N, also carrying out deep CTDs. She repeated this work in August–September, completing two years of measurements in winter, spring and late summer. In this case the total carbon system was measured, with an underway continuous profiling pCO_2 instrument. *Johan Hjort* also carried out a biological programme in the vicinity of 75°N in May–June during the spring bloom, and later in November.

Lance spent three weeks in Fram Strait in August, deploying and recovering moorings (including three upward looking sonars). Jean-Claude Gascard chartered the Norwegian vessel *Jan Mayen* later in summer 1994 to recover the moorings of the acoustic positioning stations deployed from *Valdivia* early in the year. During summer 1994 *Polarstern* carried out some ESOP work during a cruise from 6 July to 15 August (ARK X), involving moorings, biology and oceanography in 75°N and 79°N regions, with deployment and recovery of upward sonar and ice roughness studies.

3.3. 1995

In 1995 a February–March winter cruise took place with *Håkon Mosby*, involving convection work, CO_2 studies (including calibration of pCO_2 sensor), Seasoar work and chemistry (Gothenburg group). This was followed by *Johan Hjort* in April–May 1995 for a plankton bloom study at 75°N. *Lance* visited Fram Strait and East Greenland in summer 1995.

3.4. Data archiving

The oceanographic data produced by ESOP are accepted for quality control and data banking by ICES, Copenhagen. Ice data are archived at the World Data Centre "C" for Glaciology, Cambridge, except for ice velocity data which are archived by the International Arctic Buoy Programme of WCRP.

4. Some Results

4.1. Basin scale physics

4.1.1. Ice fluxes

A key aspect of the project is to measure the ice flux in the Greenland Sea at different latitudes, the downstream decline defining the contribution from melting ice to the fresh water budget in different latitude ranges. This is done by equipping a series of oceanographic moorings straddling the East Greenland Current at 79°N, 75°N and Denmark Strait, with upward looking sonars (ULS), which measure the draft of the ice passing overhead. AVHRR images of the East Greenland Current are used to determine the field of ice motion over the moorings and the large scale sea ice concentration in the region. By combining these two types of data the ice flux is obtained. ERS-1 SAR imagery is used to augment the AVHRR data.

In ice kinematics studies of this kind the determination of sea ice motion from sequential satellite images is an important element. Algorithms for the determination of ice motion by tracking common features in pairs of sequential satellite images have been developed and applied by several authors in recent years. Generally the techniques are based on local cross-correlation of the brightness. The sea ice drift algorithm of FILY and ROTHROCK (1986, 1987) has been applied by the AWI group and optimised to work with SAR and AVHRR data. The strategy in this algorithm is to acquire a crude displacement field from highly averaged images, and then to redefine this field with images of successively higher resolution.

For the case of deriving small-scale ice drift from SAR data, the algorithm works well for pairs of very similar data. The calculation of ice drift from SAR is limited by the low number of cases with comparable pairs of SAR frames. Nevertheless, NPRI (R. KORSNES) has developed an appropriate algorithm which has yielded a complete drift series for Fram Strait for the two ice phases of ERS-1. This has been published in four papers on the automatic relocation of rigid areas from consecutive SAR scenes (KORSNES, 1993a, b, c, 1994; see also ALEXANDROV and KORSNES, 1993).

The use of ULS to give the ice thickness is rendered necessary by the fact that synoptic techniques of obtaining ice thickness are either available at irregular intervals (submarine voyages of opportunity) or are still at an experimental stage (AUVs). The ULS gives ice draft at a single point over a long period of time, which is an excellent method of yielding ice flux so long as a sufficiently representative line of ULSs is used so as to adequately sample the whole width of the East Greenland Current, and so long as ice velocity can be obtained reliably as described above. The ULS measures two values simultaneously: (a) the distance from the ULS to sea level; (b) the distance from the ULS to the underside of the sea ice. The ice draft is the difference. The first distance is derived from the hydrostatic pressure at the ULS. The second is derived from the elapsed time for an acoustic pulse to travel from the ULS to the bottom of the ice and return. This technique has been applied for several years, but nevertheless, the equipment and the data interpretation are still in an experimental state. The data analysis of the first recovered ULSs was carried out using methods described by UNTERSTEINER and MORITZ (1989), VINJE and BERGE (1989), KVAMBEKK and VINJE (1992) and R. MORITZ (pers. commun., 1993).

The ULSs are mounted on the top of a mooring at a nominal depth of 50 m. At a time interval of 5 min the ULS transmits an acoustic signal. Twice a day (at 0 and 12 GMT) the ULS switched to a high resolution record mode with a interval of 10 s during 25 min. One important step in the data processing is to reconvert the elapsed time and the hydrostatic pressure into distances. The vertical density and sound velocity profiles between the ULS and the ice are unknown. The assumptions of constant vertical profiles provides ice draft values of limited accuracy, because of the variability in the vertical salinity and temperature structure. Figure 1 shows some typical low resolution data (interval 5 min) for October 8, 1992. The intention is to develop a more realistic model of the sound velocity profile which is more adjusted to the conditions in the East Greenland Current. Work at NPRI is also being carried out on the beam footprint effect, which causes the ice draft to be systematically overestimated. In all these ways the ESOP group seeks to refine the accuracy of the ULS-satellite technique for measuring ice fluxes.

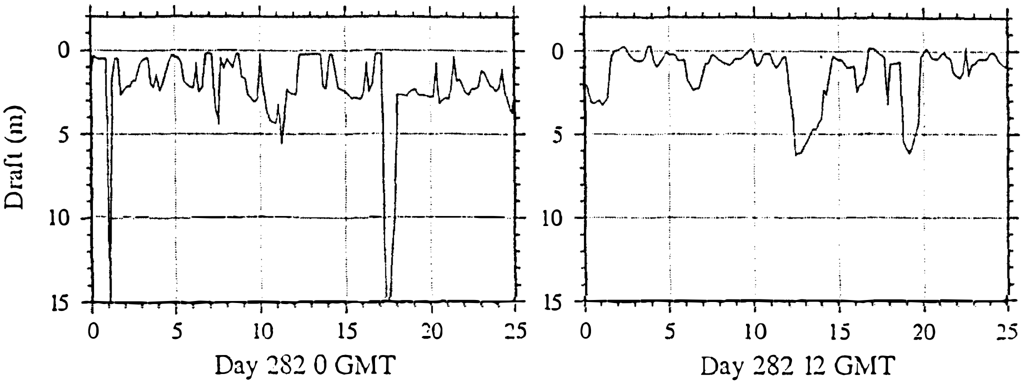

Fig. 1. Ice draft of ULS sonar No. 31 data with an interval of 5 min for the day 282 (8.10.93). a) period 0000–0025 GMT; b) 1200–1225 GMT.

Some calculations by Kvambekk and Vinje (1992, 1993), based on older ULS data from 79°N obtained in 1990–1, give an annual ice volume export through Fram Strait of 2600 km^3. All ULS data obtained by the partners in ESOP will be stored at NPRI in a repository managed by Nina Nordlund on behalf of WCRP, this dataset forming part of its Arctic Ice Thickness Project (AITP).

4.1.2. Nature of Greenland Sea Deep Water

Oceanographic data from winter and spring cruises in 1993 by *Polarstern* and *Valdivia*, when compared with 0-S diagrams from earlier cruises such as the 1982 *Hudson* cruise, showed a warmer (by about 1°C) and more saline deep temperature maximum in 1993, indicating lack of renewal from the surface. This lack of renewal over the last decade had already been postulated from tracer results by Schlosser *et al.* (1991) and Rhein (1991), and the confirmation of the tracer conclusions by oceanographic data is a most important result.

The Greenland Sea had been recognized early as a source of deep water, not only for the Greenland Sea but also for the Norwegian Sea and for the Arctic Ocean (Helland-Hansen and Nansen, 1909). The improvement of observational techniques during the last decades have revealed differences in temperature and salinity between the basins of the Arctic Mediterranean Seas, which cannot be explained if the Greenland Sea were the only important deep water source. The Arctic Ocean deep waters are warmer and more saline, a feature, which could be understood if brine enriched, dense water from the arctic continental shelves sinks down the continental slope, entraining warmer intermediate waters. Aagaard *et al.* (1985) proposed a circulation scheme where the Arctic Ocean and the Greenland Sea both are sources of deep waters. The different deep waters interact along the Greenland continental slope and then flow along the Jan Mayen Fracture Zone to provide the deep water of the Norwegian Sea.

The relative strength of the two sources as well as the interactions between the different basins were estimated from θ-S characteristics (Rudels, 1986). and by box models using additional tracers (Heinze *et al.*, 1990; Smethie *et al.*, 1988). These studies showed that the European Basin Deep Water, apart from contributing to the Norwegian Sea Deep Water, also must supply an advective part to the Greenland Sea Deep Water. This gives the Greenland Sea θ-S curve its characteristic hook-like shape with a deep salinity maximum located at around 2000–2500 m.

An outflow of deep water from the Canadian Basin, which may be identified in Fram Strait (RUDELS, 1986), was thought to bypass the Greenland Sea and either enter the Icelandic Sea across or the Norwegian Sea along the Jan Mayen Fracture Zone (AAGAARD *et al.*, 1991; RUDELS, 1986).

A third deep water component supplied by the Arctic Ocean is the lighter Upper Polar Deep Water, which fills the Arctic Ocean between the Atlantic Layer and the sill depth of the Lomonosov Ridge. It is formed in both basins of the Arctic Ocean and it lies in the same density range as the Arctic Intermediate Water formed in the Greenland Sea. In contrast to the latter, it is identified by vertical gradients stable in both heat and salt.

The distinct characteristics of the Arctic Ocean and the Greenland Sea deep waters make them easily recognizable and make it possible to deduce the influence and the importance of the Arctic Ocean waters for the ventilation of the deep Greenland Sea. The evidence for a reduced volume of convection in recent years shifts the balance in the ventilation of the Greenland Sea towards a state where the deep water contributions of the Arctic Ocean become more prominent.

Hydrographic observations in the Greenland Sea were made in late winter and spring 1993 and in late winter 1994 from *Polarstern* and *Valdivia*. The winter convection had ceased and advective processes dominated the mixing. On the *Polarstern* cruise a NBIS Mark IIIb CTD was used while a SBE-11 CTD was employed on the *Valdivia* cruises. The conductivity was calibrated by water samples analyzed on board using a Guildline Autosal. The accuracy in p.s.u. is 0.003.

A comparison between θ-S curves for the central Greenland Sea from *Valdivia* and those obtained from *Hudson* in 1982 (Fig. 2) shows that there was a notably warmer and more saline deep temperature maximum in 1993. The salinity is in fact so high that a second shallower salinity maximum is present at about 1000 m. This maximum is seen at most stations in the western and in the southern Greenland Sea although it is absent at station 8, nearest to station 12 towards the east. The maximum is too deep and too dense to be created by an influx of Atlantic Water, either from the Norwegian Atlantic Current in the east or from the Atlantic Return Current in the west. Since the maximum is strongest to the west and to the south it is probably the signal of Canadian Basin Deep Water, CBDW, penetrating from the Greenland continental slope and from the Jan Mayen Fracture Zone towards the upwelling regime in the centre of the cyclonic Greenland Sea gyre.

The θ-S curves from stations in the south, close to the fracture zone, exhibited a slope perpendicular to the isopycnals above the upper salinity maximum. This shows that also the upper part of the deep boundary current exiting the Arctic Ocean through Fram Strait might detach from the continental slope and penetrate into the deep central basin albeit along the Jan Mayen Fracture Zone.

In the winter of 1992/93 the convection was limited to the upper 1000 m and only water in the range of Arctic Intermediate Water, AIW, was formed. The strength of the convection can be assessed from the thickness of the associated cold, low salinity lens. In the central gyre the lens is close to 100 m thick but the thickness diminishes towards the periphery of the gyre. The interaction between the cold lens and the periphery occurs through isopycnal interleaving and it is strongest towards the west and south. Especially

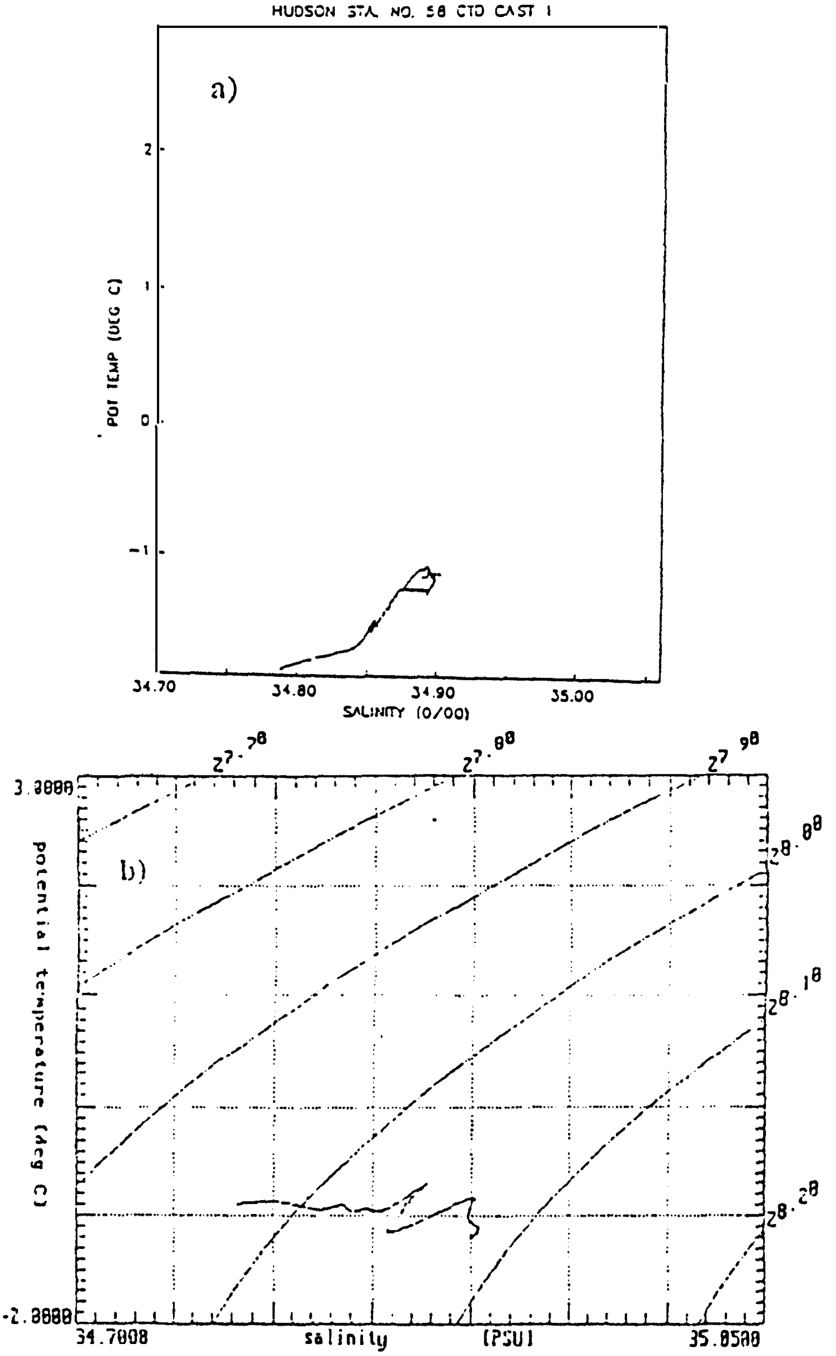

Fig. 2. θ-S diagrams. a) RV Hudson, station 58 (75°N; 06°W; March 1982), b) RV Valdivia, station 12 (74°N; 06°W; May 1993).

prominent is the intruding shallow salinity and temperature maximum of the Atlantic Return Current, which was present on most of the western stations.

Thus, the shallower convection occurring in recent years must be responsible for the differences between the observations from 1982 and from 1993. Normally the convecting water would be denser and the CBDW would be entrained into and mixed downward by the convecting plumes. The upper salinity maximum would then be removed and the temperature maximum would be reduced, heat and salt being added to the bypassing convecting water.

The spreading of newly formed AIW from the center of the gyre will result in a compensating inflow of CBDW, which - because of the shallow convection - is easily detected by its salinity and temperature maximum. Inversions are seen in the profiles and in θ-S curves which indicate intrusive mixing with older Greenland Sea Deep Water, GSDW. The deeper penetration towards the centre thus also appears to be isopycnic.

The convective and the advective contributions to the deep waters of the Greenland Sea thus alternate in strength and importance. At times the local convection is even stronger than in 1982 and capable not only of removing the upper salinity maximum but also of penetrating the deeper maximum and renewing the bottom water. Most of the time, however, the outflow from the Arctic Ocean dominates and rapidly reforms the temperature and salinity structure of the deep waters.

This simple picture is complicated by the observation that the freon content of GSDW above 2000 m has increased as compared to 1988 (M. RHEIN, pers. commun.). This is at odds with a penetration of low freon CBDW into the central Greenland Sea. It can only be understood if the convection events down to 2200 m reported from the winter 1988/89 were more extensive than previously believed (MEINCKE, 1991). That would provide the necessary freon injection, and the high freon content of the convecting surface water would more than compensate for the influx of "older" CBDW. The possibility that the freon content has increased by turbulent diffusion from above appears less likely, since this would mean that no convection was needed to ventilate the deeper layers of the Greenland Sea.

The most conspicuous effect of the reduced convection in the Greenland Sea is the overall decrease in density of almost the entire water column as compared to 1982. The winter of 1992/93 was extremely stormy and the lower densities found at all levels in 1993 in comparison with 1982 suggest that the doming of isopycnals in the central Greenland Sea (HELLAND-HANSEN and NANSEN, 1909) might to a large extent be caused not by the wind but by the convection itself. When the convection is reduced, the isopycnals will slump down, spread out of the gyre and induce a compensating inflow at higher levels. If this inflow occurs along isopycnals it will, because of the relaxation of the doming, lead to a reduction in the density of the central water column. This in turn weakens the cyclonic circulation and the arctic deep waters will be pushed less against the continental slope and will enter the Greenland Sea instead of bypassing it. This will further increase the temperature and salinity in a sense which reduces the density of the water column in the central gyre.

The higher densities, found also at intermediate levels after periods of active convection, suggest that a convective build up of denser water is needed in the entire water column before the local convection can reach the bottom. This could imply that the observed trend of increasing temperature and salinity and decreasing density in the bottom layers, caused by turbulent vertical mixing of intruding European Basin Deep Water EBDW with the Greenland Sea Bottom Water, does not indicate the possibility of an imminent deep convection event penetrating through and renewing the bottom water. A massive convective situation appears necessary, gradually involving almost the entire water column. This requires a strong surface forcing and appropriate conditioning of the upper water column, the nature of this conditioning still being an active scientific problem.

4.2. Physics of convection

4.2.1. The ice cover in Odden

The early winter work from *Valdivia*, *Northern Horizon* and the BAC 1–11 established that Odden developed in early winter 1993 as a tongue of dense pancake ice, with almost no older ice present. Passive microwave and SAR images showed that the Odden ice tongue began to develop in late December in a classic tongue shape, which persisted until a major storm on February 25–27 caused Odden to vanish altogether from the SSM/I record. A passage through the region on March 3 by *Polarstern*, with the storm still at its height, showed that only a few flooded pancakes remained, insufficient to give an ice signal on SSM/I. After the storm died down Odden began to grow again as an island of ice, completely separated from the main E Greenland pack. This island later broke into separate north and south islands, and (on passive microwave) the north island appeared to dissolve and reform late in March while the south island steadily shrank.

Polarstern carried out her intensive studies of the Odden in early April. Her ice physics programme (Wadhams and Viehoff, 1994; Wadhams *et al.*, 1995) showed that the southern island was composed of a dense mass of pancake ice. The pancakes had a typical diameter of 1–2 m. Pancakes recovered and brought on board ranged in thickness from 9 cm to 40 cm, and the larger pancakes had low salinities (2.8–5.5 psu) normally regarded as characteristic of first-year ice, implying that they had been stable components of the ice cover for some time. Frazil sampled between the pancakes had a thickness corresponding to 4–20 cm fresh water equivalent. Our conclusion from direct physical examination and a concurrent study of SAR imagery (which distinguishes frazil from pancake by the dark return from the former and bright return from the latter) is that after the late February destruction of Odden its new development as an island comprised a core of pancake ice which retained its identity until April, drifting under wind action within the area of influence of the Jan Mayen Current. It grew into thicker and larger cakes with salinities and brine drainage systems characteristic of older ice sheets, but the high ambient wave energy prevented the cakes from freezing into larger floes or ice sheets. The very unusual low salinities, approaching those of multi-year ice, can be explained by supposing that the pancakes were subject to periodic warming above 0°C, leading to some surface melt. The meltwater would be retained on the pancake surface by the high fringing walls, and would be supplemented by rainwater; the overlying fresh water would then percolate through the pancake, flushing out brine, a process ("flushing") which in normal ice sheets is very effective during summer in transforming first-year into less saline multi-year ice. In the outer fringes of Odden the ice cover consisted of much thinner pancakes and frazil, which are subject to rapid freezing and melting episodes, depending on local air temperature and wind or wave conditions. This gave the shape of the Odden a rapidly changing appearance on SSM/I images. However the absolute volume changes of ice involved in these fluctuations were small, because the parts of the Odden which fluctuated never possessed ice more than a few centimetres thick, as opposed to the stable core region of the ice tongue or island.

Based on field observations of the salinity of the pancakes and the interstitial frazil ice, in relation to their presumed ages based on SSM/I imagery, WADHAMS *et al.* (1995) were able to form an estimate of the daily salt flux into the Odden region from ice formation. The estimate was based on the following assumptions:

1) Odden grows outwards from a core region (the region visited by *Polarstern* on April 3 1993), and during periods of melt it is the outer fringes of Odden, *i.e.* the most recently formed pancakes, which disappear.

2) When ice forms in Odden, it does so in the way observed on April 3 and 10, *i.e.* during the first 5 days 2.26 kg m^{-2} of salt are ejected and during the next 30 days a further 3.81 kg m^{-2}. The rate of salt rejection per day (M_t) is parameterised by a simple two-slope linear model which fits these values, *i.e.*

$$M_t = 0.649 - 0.0789\,t \quad (t = 1 \text{ to } 5),$$
$$M_t = 0.297 - 0.0085\,t \quad (t = 6 \text{ to } 35),$$
$$M_t = 0 \ (t > 35).$$

3) As soon as ice forms, the rejected salt triggers convective plumes which move it away from the surface to an (unspecified) depth. Thus the fresh water rejected during melt periods is not counted in the summation, which only takes account of positive episodes of salt rejection. In fact during retreat periods there is still a positive, though reduced, salt flux from the Odden as a whole because the central core region is still emitting salt as the pancakes in it age.

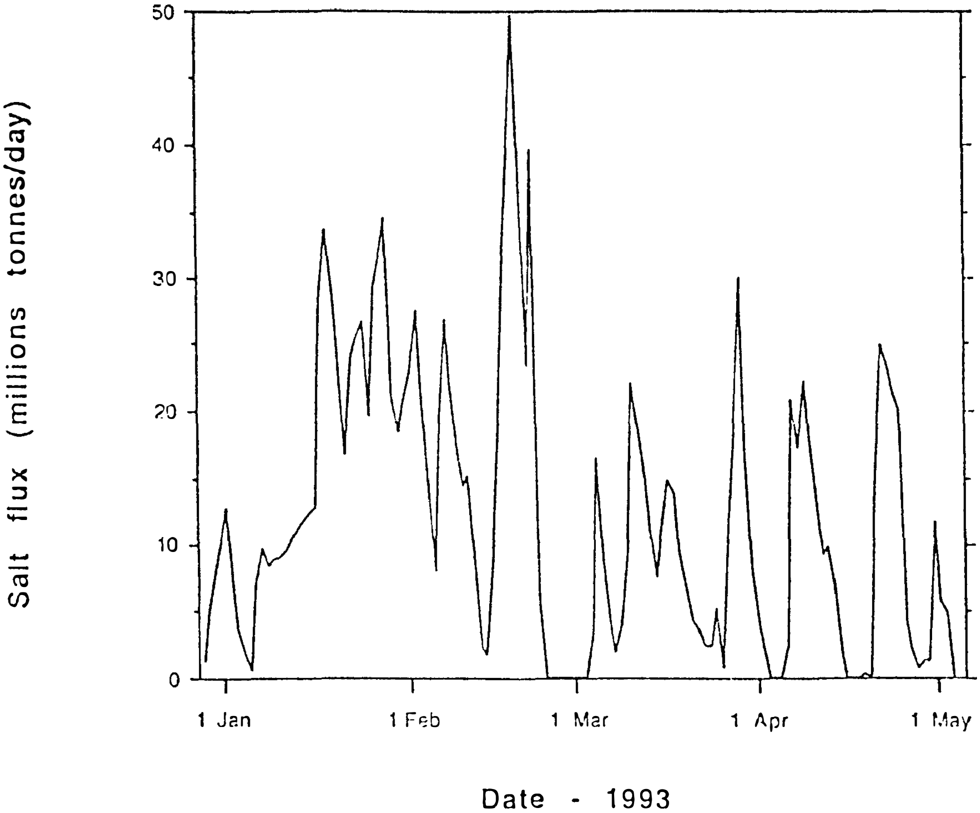

Fig. 3. Estimated salt flux within Odden for the winter 1993 (After WADHAMS et al., 1995)

Based on these assumptions, the estimates of salt production rates in Odden are as shown in Fig. 3. It can be seen that the salt flux occurs in cycles, with a single sustained period of salt rejection lasting from January 6 to February 12. The largest single pulse has a peak value, on February 19, of 49.7 million tonnes. As winter progresses the pulses become more modest, with short intervening periods of negligible or zero salt flux. Thus the winter can be characterised by a long sustained period of salt rejection through January into mid-February, a short but very intense pulse of salt later in February, and then four moderate but still significant pulses after March 1, ending at the beginning of May. The GRE-HIRLAM model has been used for a data assimilation cycle for the winter of 1993, giving time scales for atmospheric driving forces which match the time scale of the salt flux fluctuations of Fig. 3 (Cederskov, 1995).

4.2.2. Physics of convective plumes

The problem of how penetrative convection occurs in the Greenland Sea has been receiving increasing attention from a number of modellers. The model being developed within ESOP and used as a testbed for field observations is that of J. Backhaus (Backhaus, 1993; Backhaus *et al.*, 1993). This is a 2.5-dimensional model which begins with a two-layer ocean which is then subjected to surface cooling and/or ice production. Model runs show that resulting patterns of convection are most dependent on the initial salinity of the upper layer. Too much fresh water resulted in rapid ice growth, a shut-off of the surface heat flux and only weak mixed layer deepening. A small fresh water content of the upper layer, as observed in winter 1994, led to rapid thermal convection with little or no ice formation. The model had now been expanded to a full three dimensions, includes the thermobaric effect and allows for wind forcing at the surface. It has also been coupled to an atmospheric convection model.

In its latest form (Kämpf and Backhaus, 1994) the model deals also with the effect of the convective process upon surface motion and hence the production of openings in the ice. These openings can be caused in two different ways: melting due to upwelling warm water and/or ice drift divergence. Both mechanisms are induced by the thermohaline convection. Heat flux to the atmosphere is a maximum over these spatially periodic leads: the air is heated locally from below and thermal convection may occur, reacting thermodynamically and dynamically upon the ice and the ocean. These couplings are largest in relatively calm conditions, when the model predicts that in fact no leads will form. A constant 10 m/s wind, however, creates ice streaks aligned in the wind direction, moving with the Ekman drift. Leads, created by forced thermohaline convection, help to maintain high heat loses in the ocean and thus help support the effective formation of dense saline water masses.

A further model has been developed at NERSC (Thorkildsen and Haugan, 1995) in streamline co-ordinates, which predicts steady state non-rotating plume development with thermobaricity as a major driving effect. This too is being tested against data.

The observational programme to detect convective plumes in winter began with high-resolution (5 × 5 m) temperature and salinity observations employing a towed CTD chain from *Valdivia* during her February 1993 cruise, covering the uppermost 250 m of the water column. The large-scale stratification in the region of the Odden, where the ice cover consisted of about 70% pancake ice as descibed above, showed a low salinity upper layer about 180 m thick with temperatures near the freezing point. Below, in the layer of Atlantic water, temperatures rose to 0.5°C. Convective cells with horizontal scales of about 500 m were observed to have penetrated up to 100 m into the warm intermediate layer. Remnants of convective events had created strong subsurface fronts with the thermo- and halocline dropping from 50 m to more than 150 m over a distance of less than 200 m. In regions with a shallow upper layer also Langmuir-type circulation cells were seen to erode the pycnocline.

In the follow-up experiment in March 1994 from *Valdivia* a 600 m towed CTD chain was used. There was no local ice in the Odden region, and so the mixed layer deepening had to be solely due to thermal convection. A survey of wind and heat fluxes to the atmosphere showed that the mixed layer deepening and oceanic heat loss were indeed compatible with the local heat flux to the atmosphere. It was found that under strong wind conditions a negative temperature anomaly was trapped in the surface (0–100 m) layer. Outbreaking plumes were observed to penetrate into the deeper layers, with horizontal scales of order 200 m and temperature anomalies of order 0.1°C (LATARIUS *et al.*, 1994).

Some very striking results on upward vertical movement were obtained by J-C Gascard from four floats deployed at 400 m depth. During a 2-week period in March 1994 upward displacements of several km were detected by the floats. Similar results (3 km upward displacement, equivalent to a few mm s^{-1}) were seen from a float at 500 m in April 1993. This probably comprises the upwelling associated with, or alternating with, the downward convection.

4.3. *Biology and chemistry*

4.3.1. Summary

The large number of collaborative cruises involving physical and biological oceanographers that have taken place give a good description of the state of the carbon system, both the organic (biological) and inorganic side, in relation to physical parameters. The combination of convection process studies and chemical tracer studies during winter cruises has also proved very fruitful, and there is a joint benefit in the sense that chemical data help in the understanding of convection processes and *vice versa*. The winter cruise in 1994 also included the Gothenburg group (CUT, Gothenburg), so that the cruises have facilitated cross-institutional and cross-disciplinary teams operating on the same ships.

Explicit studies of spring bloom dynamics were carried out during three of the cruises. The spring 1993 cruise deployed a mooring with sediment traps aimed at sampling the vertical flux of organic carbon to the deep ocean (IMR, Bergen). The traps were set to sample twice per month and lasted a year, the mooring being successfully retrieved and redeployed in spring 1994. The samples which will describe the vertical flux of particulate organic matter through a full year have been distributed among the participants for detailed analysis.

A 3-D mathematical model has been developed by SINTEF for estimates of biological carbon flux and air-sea carbon uptake. The model domain was initially set to include the Greenland and Barents Seas, and a version including the whole Nordic Sea realm is now running. The first results have been obtained, estimating air-sea differences in the partial pressure of carbon dioxide (pCO_2) during the full season, and the model is now being tested against field observations and data from weather Station M.

The spring bloom was delayed in 1993, hence the measurements provide a description of the status of the pre-bloom period rather than peak bloom, as was captured in 1994. The data indicate that the area is a sink for CO_2 throughout the year and that strong underpressure of CO_2 prevails in surface waters during winter, documenting a rather strong CO_2 uptake as a result of wintertime cooling. This will be used to constrain the carbon modelling done by SINTEF and NERSC. With three years of measurements the interannual variability will be determined, and it should be feasible to obtain a quantitative estimate of CO_2 fluxes.

4.3.2. Spring bloom dynamics

A strong active spring phytoplankton bloom in the central Greenland Sea was sampled in May 1994 (F Rey, IMR). Nitrate concentrations were near to zero in the surface water of the central gyre while chlorophyll-*a* values were over 5 $\mu g\ l^{-1}$. Figure 4 gives a general picture of the spring situation in surface water along 75°N. There are three distinct biological regimes. In the east a diatom bloom, fuelled primarily by new production (*i.e.* based on nitrate) was still in progress, indicated by a surplus in the nutrients nitrate and silicate. In the central region *Phaeocystis* was the main algal component; nitrate and silicate were present in small but non-limiting concentrations, and the system was based on new production. To the west the biological regime was dominated by a mixture of diatoms and *Phaeocystis*; nitrate was in surplus, while silicate was

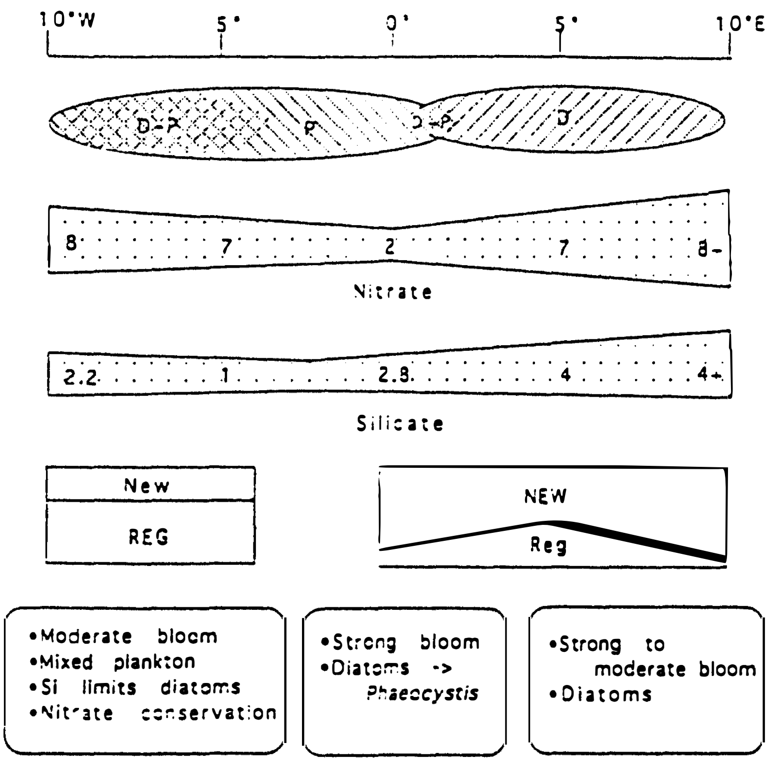

Fig. 4. Scenario of nutrient supply, phytoplankton composition and mode of primary production along 75°N during the spring cruise with R. V. Johan Hjort (27 April to 24 May 1995). D=Diatoms: P=Phaecystis.

reduced. Regenerated production, *i.e.* based on ammonium, was here significantly larger than new production, suggesting that silicate was the limiting nutrient in this regime. The zooplankton biomass showed peaks of over 50 gm^{-2}, corresponding to the large chlorophyll biomass.

This situation differed from that of the May 1993 cruise, undertaken 2 weeks earlier in the year, which appears to have encountered a pre-bloom situation with little reduction in nutrients and a small chlorophyll biomass. Thus the spring bloom appears to peak in mid- to late May, and the 1994 cruise appears to have sampled it at its peak. It is significant that zooplankton-mediated control of phytoplankton biomass, theorized by some scientists to dominate the spring situation, did not occur in 1994.

4.3.3. Sedimentation

A sediment trap rig was deployed in the central Greenland Gyre in 1993 at 75°N 0°, with traps at 185 m, 775 m and 1950 m, recovered in 1994 and redeployed until 1995. The traps collect sedimenting material at 2 week intervals. The highest values for total particulate matter (TPM) and particulate organic carbon (POC) were recorded in late summer and autumn of 1993. The data for chlorophyll-*a* and pheopigments at 180 m showed first signs of spring bloom sedimentation in late May 1994, with high rates also measured as deep as 1735 m. Diatoms were the major identificable component, indicating fresh phytoplankton as the source of sedimentation. This was a highly unusual phenomenon for late summer whern a mass flux of diatoms is not expected. It was suggested by Rey that the sedimentation may be the result of rapid downward and cross-gyre transport of surface material originating from the NW Greenland Sea near the East Greenland Current, where phytoplankton biomass and nutrient supply were still large in September 1993. The mechanism is assumed to be isopycnal transport from the surface to mid-depths, mediated by a relic chimney.

Dissolved organic carbon (DOC) occurred in the traps at a concentration, and with a fraction of C present, which suggested excretion or leaching from living zooplankton. Laboratory experiments on these processes are being conducted.

The measurements of POC do suggest an unreported process of enrichment in the central Greenland Sea in summer. The source is uncertain. Possible hypotheses are the microbial loop; physical advection into the Greenland Gyre from active sites of summer plankton production; and new production fuelled by diapycnal nitrate input.

4.3.4. Biological modelling

The role of zooplankton in the carbon flux is being modelled by Slagstad, Hirche and Carlotti, concentrating on the dominant species *Calanus hyperboreus*. Two approaches are used:-

1) A population dynamics model taking account of the different physiological processes on the successive developmental stages, calibrated for *C. hyperboreus*, which enables the development and growth rates under different temperature and food conditions to be estimated.

2) Parameters from this model are implemented into a 3-dimensional zooplankton model coupled to a phytoplankton and circulation model. The carbon flux resulting from phytoplankton growth and zooplankton grazing is then fed into a carbon chemistry model which calculates the effect on pCO_2 and the CO_2 flux through the sea surface. The models are being run for 1993–4 and compared with ESOP field data on hydrography, CO_2

chemistry, nutrients, phytoplankton and zooplankton.

5. Conclusions

The ESOP programme is still in progress. Preliminary conclusions reinforce the discoveries of a decade of work on the Greenland Sea system. It is clear that winter convection has slowed appreciably, causing the deep waters of the Greenland Sea to increase in salinity and temperature as they come more under the influence of Arctic Basin deep water. The convection process itself has been shown to occur in the form of plumes of diameter 100–200 m. A significant salt flux from the growth of frazil-pancake ice in Odden occurs in early winter and is an important preconditioning factor for destabilising the surface waters, but the later roles of cooling and mixing in open water parts of the region (such as Nordbukta) are also important, and the whole sequence of water mass modification leading to convection still remains a matter of discussion and ongoing modelling attempts. It is significant that the Odden ice tongue has failed to develop two years in succession, an indicator of regional climatic change. A large-scale ice-ocean-atmosphere model of the Greenland Sea has been implemented, and also a biological model which accounts for the large depletion of pCO_2 observed in the Greenland Sea. Final conclusions should emerge within the coming year as the multidisciplinary results are brought together.

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