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TWO MODES OF APPEARANCE OF THE ODDEN ICE TONGUE IN THE GREENLAND SEA

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The Odden ice tongue of the Greenland Sea normally forms locally in winter as frazil-pancake ice, allowing high positive salt fluxes during freezing that leads to open ocean convection. We report observations from satellites, aircraft, ships and submarines which show that in two recent years (1987 and 1996) a late-season Odden developed composed of old ice advected by the East Greenland Current. The impact of such Odden is different in that it is in a state of melt and serves to stabilize the surface water in the region. The history of Oddens since 1978 is reviewed to examine the frequency of both modes.

The Odden ice tongue (*1-6*) develops almost every winter in the central Greenland Sea. It occupies a sea area of some 250,000 km^2, lying over the old Jan Mayen Polar Current which diverts eastward from the southward-flowing East Greenland Current at latitudes of approximately 72-73° N. It's shape is promontory growing outwards to the NE from the main ice edge, sometimes separating to form an island. The open water bight to the NW of Odden, lying between it and the East Greenland ice, is known as

Nordbukta; may be filled with ice in heavy years so that Odden appears as a large bulge rather than a tongue. The region is of climatic importance as a centre for deep open ocean convection in winter(*5*), which may be stimulated by salt fluxes from the formation of the frazil and pancake ice which dominate the ice cover.

The shape and extent of Odden can most easily be tracked by the use of satellite passive microwave sensors(*7,8*), and this has enabled Oddens to be classified since 1973. What is more difficult, however, is to track the composition and type of the ice in Odden. Observations made in Odden during field programmes in winter have almost always shown that the primary type of ice found throughout the ice tongue is a mixture of frazil and pancake ice, an ice type which grows locally within the tongue, which is prevented from developing into a continuous ice sheet by the high level of wave activity. This permits continued high ocean-atmosphere heat flux during times of low air temperature and thus high ice growth rates because the open water surface is not completely blanketed off by ice. The resulting salt fluxes destabilize the surface water and precondition it for subsequent thermal convection. Direct observations of frazil-pancake icefields have been made, for instance, in 1982(*9*), 1989(*10*), 1993(*11,12*) and 1997(*13*).

Our study, however, indicates that during two recent years (1987 and 1996) a late-season Odden developed composed of old ice that had apparently been driven by wind and/or current stress out of the East Greenland Current. The oceanic implications are different in that the ice has come from elsewhere, is in a state of melt, and in melting it stabilizes the surface waters of the region. We term this newly-described feature an *advective Odden* as opposed to the normal feature which we call the *thermodynamic Odden*.

Table 1 shows the history of Odden development from 1979 to 1997, derived from an examination of passive microwave imagery from the SMMR and SSM/I sensors. In each case periods when the Odden was a "bulge" (with Nordbukta filled with ice) are distinguished from those when it was a "tongue" or an "island" (with some substantial part of the feature completely separated from the East Greenland ice). During 1984, 1994 and 1995 the Odden did not develop at all. We see that in 1987 and 1996 the Odden persisted into spring or summer. There were also some late-season features during other years but some are "mini-Oddens" (shown in brackets), consisting of a small protuberance from the main ice edge. Fig. 1 shows a time series of color-coded ice concentration images from 1979 through 1997 (except 1995) derived from passive microwave data(*14*). The set of images depicts three Odden features each year corresponding to its development during an early stage, maximum extent, and a mid-to-late stage. The Odden appear as either a "bulge" or a "tongue" during maximum extent, the persistence and recurrence of which vary substantially from year to year, as illustrated in Table 1.

The 1987 Odden

A clear case of old ice appearing in the Odden region in spring occurred in 1987. A British submarine had carried out a research program involving transects of the Greenland Sea and Arctic Basin, recording upward looking and sidescan sonar profiles of the ice canopy whilst a NASA aircraft used a passive microwave radiometer, laser profilometer and camera system along the same track and a Canadian aircraft obtained an X-band SAR swath along the track. This multisensor and multiplatform experiment has been previously reported (*15-20*), but the last part of the experiment, when the submarine exited from the ice edge on 26 May in the vicinity of 73° N through the centre of the ice tongue, has not been separately examined.

Fig. 2a shows the ice tongue as seen on a NOAA AVHRR image (Channel 1, visual range) on 26 May 1987. This was an unusally clear day in the Greenland Sea and the image provides a detailed view of the Odden. The island of Jan Mayen is visible in the south-east (isolated white spot), while the limit of fast ice off the east coast of Greenland is clearly defined. The main East Greenland pack ice is seen to have ice concentrations ranging from 60% to 100% and composed of a distribution of floe sizes, with many of the floes being very large, of diameter several km. The size and shape of these floes are indication that these are multi-year and/or thick first-year floes. Along the East Greenland Current ice edge, the fainter more wispy streaks are ice which has been broken up by wave action into smaller floes unresolvable by the instrument. A prominent Odden ice tongue exists, leading off the main East Greenland pack, and along its central "spine" one can see a number of large floes of diameter 1 km or more, of the same kind as the big floes in the East Greenland Current, providing conclusive evidence that at least some of the ice in Odden is old ice which has been advected from the East Greenland Current. The rest of the Odden is composed of the same kind of wispy streamers as seen on the East Greenland ice edge.

Figure 2b shows an X-band SAR image obtained by the Intera STAR-2 system over the part of the outer Odden ice edge along the track shown as a white line in fig.2a. More detail is visible; the floes shown as having high backscatter (i.e., bright) in the image indicating floe sizes about the same size as the pixel diameter of the SAR (15.4 m).

Such signature and scale are indicative of rough and thick ice (e.g., multiyear ice) as opposed to recently formed pancakes.

Fig. 2c shows sidescan sonar imagery obtained by the submarine from the same region as it emerged from the ice. It shows the pack as composed of angular floes of typical diameters 10-20 m, characteristic of older (first- and multi-year) ice which has been broken up by wave action, a typical East Greenland MIZ morphology. New pancakes in the region, usually attain diameters of only 1-3 m. Fig. 2d shows the ice draft distribution within the ice tongue obtained along approximately the same track shown in fig. 2a. It can be seen that although the modal ice draft is low (0.6 m), at a level which is not incompatible with thicknesses reached by pancake ice, the presence of ridges of draft up to 7 m shows that older ice had been present in the ice cover.

The multisensor data thus provide a convincing evidence of the presence of older ice floes broken up by waves and partly melted but still retaining some traces of their Arctic topography in the form of eroded pressure ridging. This kind of ice was clearly part of the drift ice in the East Greenland Current, and it has intruded into the area of the Jan Mayen Current (JMC) to create the late-season Odden tongue.

The 1996 Odden

The 1996 Odden is of particular interest because Odden did not develop during 1994 and 1995, the first two-year sequence in which it has failed to appear since satellite observations began. In 1996 there was only a minor bulge along the ice edge at Odden latitudes until late March, when the bulge became more pronounced with some evidence of reduced ice concentration down the western side of the bulge, allowing it to evolve towards a tongue. During early April the feature alternated in shape between a simple ice edge bulge and a partially separated tongue.

During April 21-23 the ice was observed from FS "Valdivia" on a hydrographic cruise (J. Backhaus, personal commun.). "Valdivia" was unable to enter the tongue as she is not ice-strengthened, but observations made around the edges showed that the ice cover was composed of old, decayed thick floes of diameters 1-20 m and estimated thickness 1-3 m. Fig. 3a shows a photograph taken by Backhaus of ice near the edge of the feature, showing this kind of ice in a low concentration region. Fig. 3a is an AVHRR image that shows the state of the Odden on July 17 (see also the corresponding SSM/I imagery in fig. 1). The image shows that, large floes having the characteristics of multiyear ice floes, are present in the Odden region.

Analysis of the sequence of daily SSM/I images of the tongue shows that it persisted extraordinarily late into the summer, with the last ice occupying a small "island" on July 31 which finally vanished on August 12. On September 1-4 this region (73-74°N, 10-12°W) was visited by one of us (PW) aboard the British submarine HMS "Trafalgar", which carried out five excursions to periscope depth in which on-board temperature and salinity sensors were used to give a profile of near-surface conditions. Fig. 3c shows the presence of a thin surface layer, some 15 m thick, which has been warmed during the summer (with temperatures up to 4°C compared to -1 to 0°C at 20 m and below) and which has salinities as low as 31.3 psu. By analyzing the thickness and magnitude of the surface salinity deficit we can estimate the thickness of ice which must have melted to create this layer. The average of results from the 5 stations is 1.4 m of water equivalent, which would correspond to the melt of some 1.8 m of sea ice (allowing the ice to have some remanent salinity). This agrees with the submarine ice thickness data for 1987, showing that the late-season 1996 tongue was indeed composed of thick, melting ice from the East Greenland Current rather than frazil-pancake ice (which in any case would be impossible so late in the season).

Conclusions

Two basic types of Odden feature have been identified. The first, which we term a *thermodynamic Odden*, is definitely a winter feature, occurring between November and late April or early May. It is composed primarily of locally formed frazil and pancake ice, although a few older floes may occur within this matrix (as was seen by one of the authors in March 1997 aboard the "Jan Mayen"(*13*)). The ice grows during cold air outbreaks, may suffer a number of partial meltbacks, and changes shape (tongue, island, bulge) due to wind stress. Locally, high salt fluxes may occur due to ice formation, with consequences for the destabilization of the surface water and the initiation of convection.

The second, rarer, type of feature is an *advective Odden*, which shows itself in a pure form in spring or summer when thermodynamic conditions do not permit new ice growth. It is composed of older ice (first- and/or multi-year) derived from the East Greenland Current, in the form of floes of moderate diameters (5-20 m) and thickness 1-2 m with occasional ridge remnants achieving 7 m. Local melt, of which the consequences were detected in September 1996, would act to freshen and stabilize the surface water.

During the years 1979-97 no Odden developed in 1984, 1994 and 1995. In all other years a thermodynamic Odden developed, while in 1987 and 1996 a late-season advective Odden was observed after the thermodynamic Odden had disappeared. Other time periods when the advective Odden may have occurred, as suggested by passive microwave images were in spring of 1982, 1988, 1989, 1991, and 1992.

In estimating the role played by Odden, it is essential to understand the nature and origin of the ice in Odden in addition to its extent. The themodynamic Odden causes the introduction of saltwater that may lead to deep ocean convection, while the advective Odden causes the introduction of meltwater that stabilizes the water column.

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Figures

1. Some states of Odden ice feature in 1979-97 seasons excluding 1995 (a year when no Odden occurred according to passive microwave data); the 1987 and 1996 advective Oddens are enclosed by a red box. Color scale show inferred ice concentrations, and geographical co-ordinates are given at top left.
2. 1987 Odden and May 26 data:

a. AVHRR image of Greenland (centre) and Greenland Sea (right); Odden is tongue protruding into open sea at bottom right;

b. X-band SAR image of Odden tongue;

c. Sidescan sonar image from HMS "Superb";

d. Distribution of level and rough ice from upward sonar profile in region of (b).

3. 1996 Odden:

a. Part of an AVHRR image, July 17. Greenland coast on left; East Greenland Current drift ice in centre; Odden is large mass of ice protruding to right;

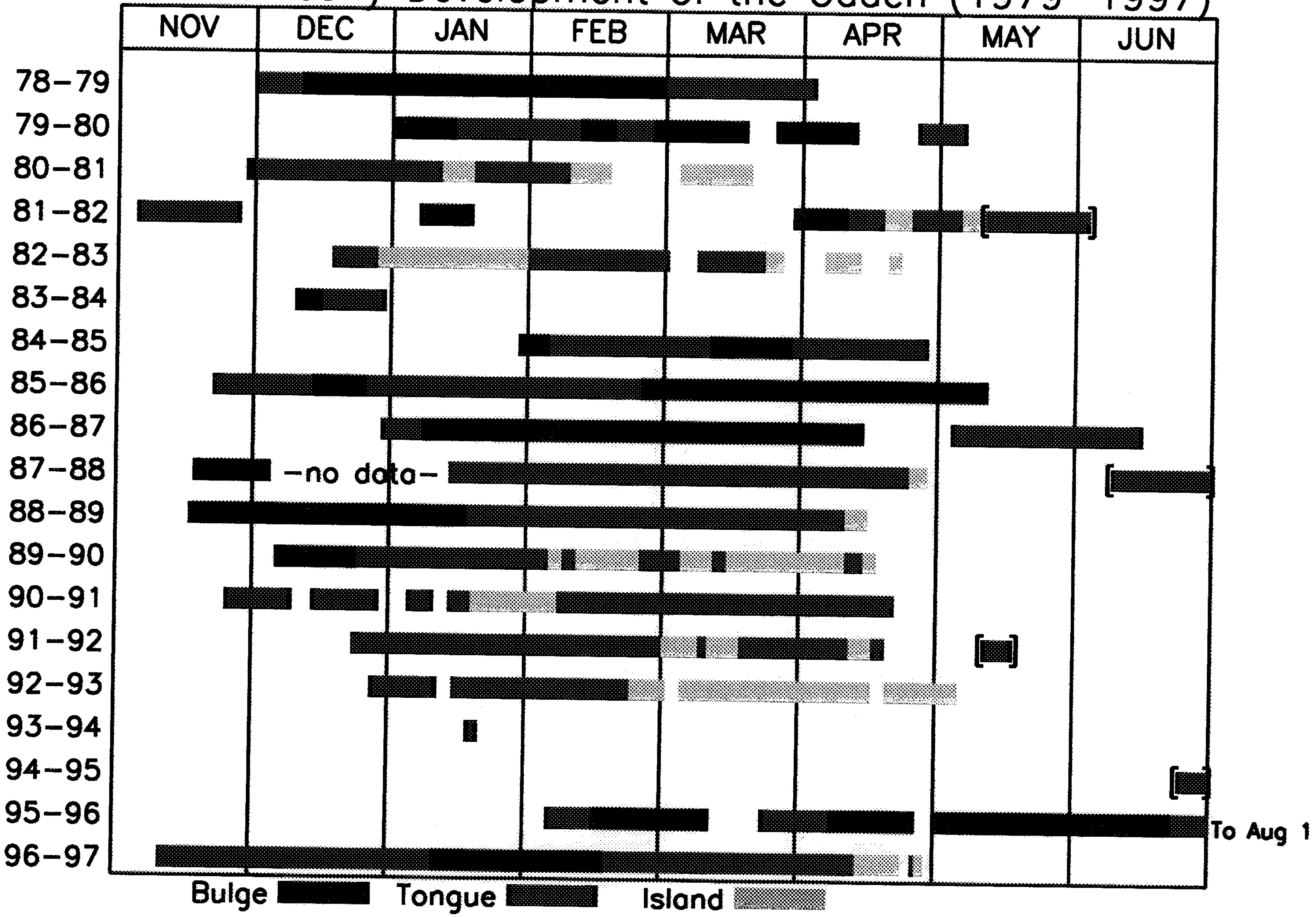
b. Photograph taken by J. Backhaus from deck level on April 22;

c. Salinities from five partial surfacings in region 72°35' to 73°42'N, 1°17'W to 10°26'W, HMS"Trafalgar", September 1-4.

Table 1

Yearly development of the Odden from 1979 to 1997.

Table 1. Yearly Development of the Odden (1979–1997)



Odden Ice Tongue in the Greenland Sea, 1979–1997

Fig. 1

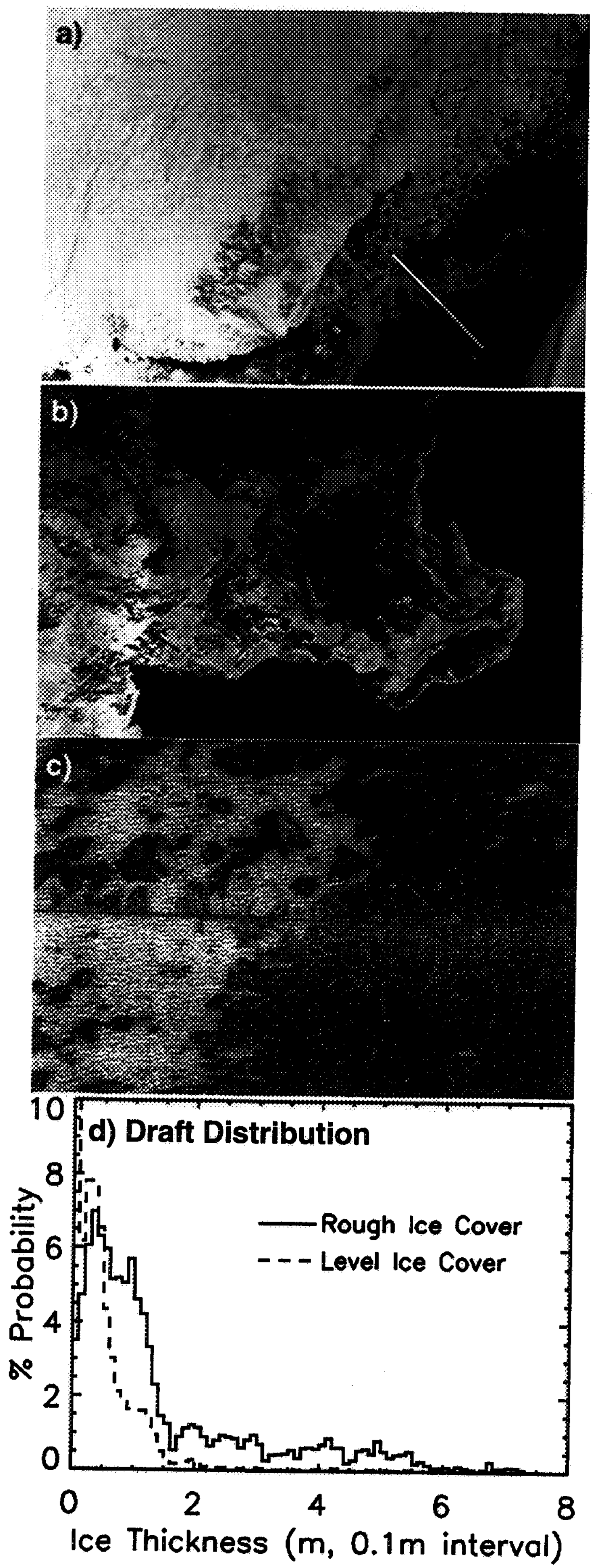
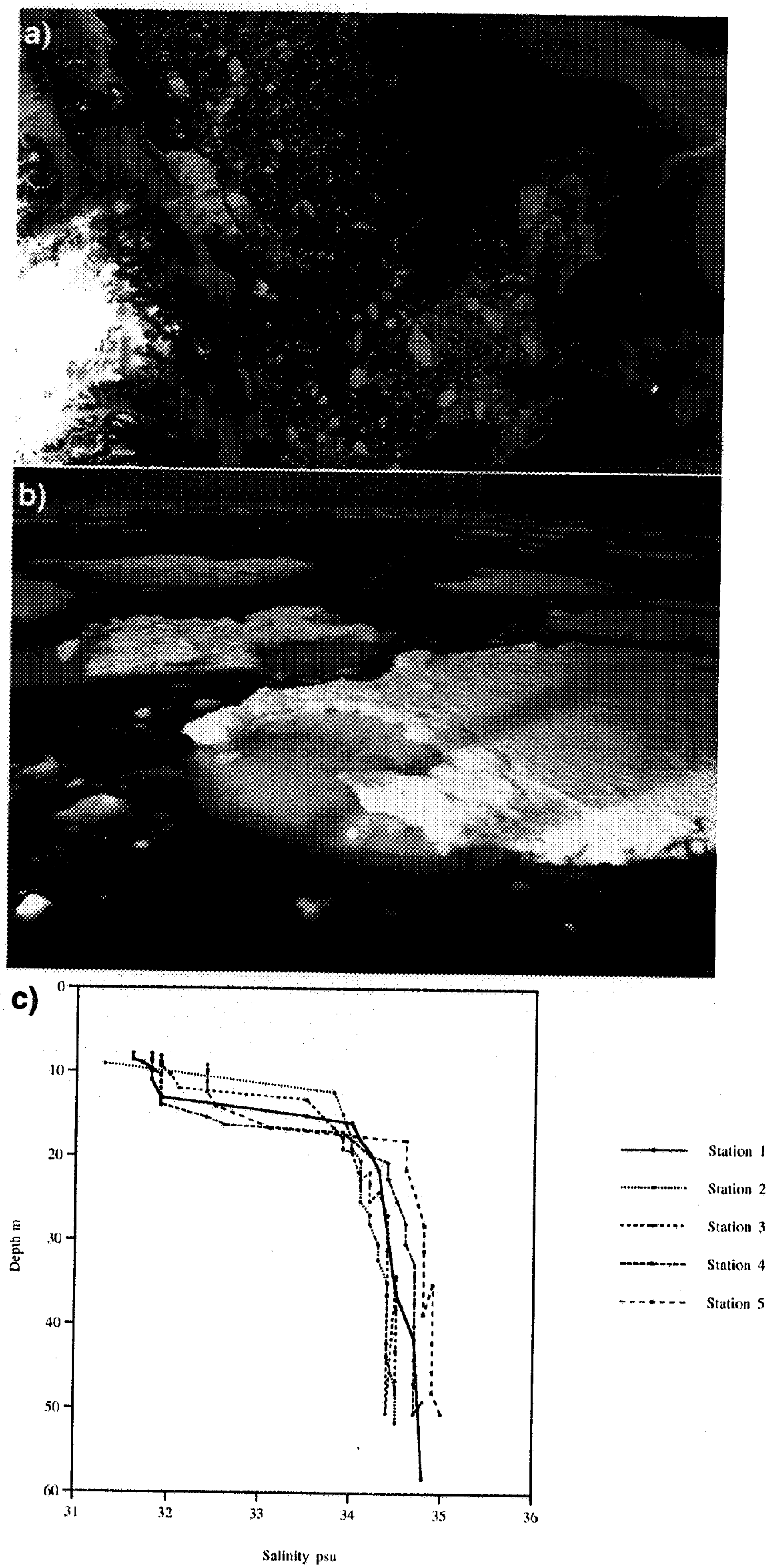

a)
b)
c)
d) Draft Distribution
Rough Ice Cover
Level Ice Cover
% Probability
10
8
6
4
2
0
0
2
4
6
8
Ice Thickness (m, 0.1m interval)

Fig. 2



a)
b)
c)
0
10
20
30
40
50
60
Depth m
31
32
33
34
35
36
Salinity psu
Station 1
Station 2
Station 3
Station 4
Station 5

Fig. 3