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The sunken nuclear submarine in the Norwegian Sea -
A potential environmental problem?

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7. april sank den sovjetiske kjernefysiske ubåten "Komsomolets" i Norskehavet omkring 185 km sørvest av Bjørnøya. Denne rapporten oppsummerer vår kunnskap om den mulige forurensingsfare fra ubåten basert på målinger av radioaktivitet, hydrografi og strøm samt modellsimuleringer. Konklusjonen er at faren for spredning av radioaktivitet fra ubåten til de øvre vannlag i Norskehavet og Barentshavet anses som meget liten.

Emneord - norsk:
1. Radioaktivitet
2. Ubåt
3. Norskehavet

Emneord - engelsk:
1. Radioactivity
2. Submarine
3. Norwegian Sea

Prosjektleder

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SAMMENDRAG

Den 7 april 1989 brøt det ut brann i den sovjettrussiske kjernefysiske ubåten "Komsomolets". Den sank i Norskehavet 185 km sørvest av Bjørnøya hvor bunndypet er omkring 1700 m og 42 sjømenn omkom. Mulig kilde til radioaktiv forurensning er den kjernefysiske reaktoren og de kjernefysiske stridshodene ombord. De radioaktive elementene som først og fremst kan bli oppløst og transportert med vannmassene er cesium og strontium som er produsert i reaktoren. Mengden av disse stoffene i den avslåtte reaktoren ombord i "Komsomolets" er anslått til henholdsvis 630 g og 350 g.

Ikke-radioaktivt cesium og strontium finnes naturlig i store mengder i havet. For cesium utgjør dette 500 kg · km^{-3} og for strontium 8000 tonn · km^{-3}. De radioaktive isotopene av cesium og strontium fra "Komsomolets" vil altså ved blanding utgjøre kun en forsvinnende del av totalmengden av disse to stoffene i vannmassene omkring ubåten. Biologiske organismer skiller ikke mellom den ikke-radioaktive og den radioaktive versjonen av samme stoffet. Forhodet mellom disse to versjonene i det biologiske opptaket vil derfor være det samme som det man finner i havet.

I tillegg til radioaktivt cesium og strontium inneholder stridshodene ombord i "Komsomolets" 6-8 kg plutonium. Dette stoffet er meget giftig, men løser seg nesten ikke i vann. Plutonium fra ubåten vil være i partikkelform og spre seg fra ubåten ved sediment-transport. Denne vil være begrenset til noen få kilometer fra ubåten. Sjansene for å få påvirkning av plutonium oppover i næringskjeden ansees som meget liten.

Den russiske konstruktøren av ubåten har gått sammen med et konsortium av hollandske bergingsselskaper og noen miljøorganisasjoner og dannet "Stiftelsen Komsomolets". Målet for stiftelsen er å få internasjonal økonomisk støtte for enten å heve ubåten, heve de kjernefysiske torpedoene eller å "støpe inn" deler av ubåten. En norsk ekspertgruppe opprettet av Utenriksdepartementet, har konkludert med at den beste løsningen er å la "Komsomolets" ligge som den er.

Denne rapporten tar sikte på å se på hva som vil være det sannsynlige spredningsmønsteret for de radioaktive elementene dersom en lekkasje fra ubåten oppstår. I dette arbeidet har man brukt observasjoner av radioaktivitet, strøm og hydrografi fra området omkring ubåten samt simuleringer ved hjelp av matematiske modeller. Arbeidet har vært gjort i samarbeid med Det norske meteorologiske institutt og Forsvarets forskningsinstitutt, Kjeller.

Konklusjonen fra dette arbeidet er at radioaktiv påvirkning i de øvre og biologisk aktive vannlag ansees for å bli så liten at den ikke representerer noen fare. Dypet hvor et mulig utslipp vil finne sted og tetthetsfordelingen i vannmassene ovenfor vil begrense den vertikale utbredelsen av en eventuell forurensning. Selv dersom man forutsetter at ubåten representerer en varmekilde på 10 MWatt vil oppstrømmingen neppe rekke høyere opp enn omkring 500 m over bunn.

Ved en eventuell lekkasje fra ubåten vil radioaktive komponenter bli spredt av den pulserende strømmen i området men denne spredningen vil hovedsaklig skje langs tetthetsflater . En forurensning vil forbli i dypvannmassene i de Nordiske hav og Polhavet som har et volum på omkring 10 millioner km^3. Her vil en eventuell radioaktiv påvirkning bli kraftig fortynnet før dypvannet strømmer ut i Atlanterhavet over Skottland - Grønnland ryggen. Derfra vil det inngå i dypvannsirkulasjonen i de store verdenshav og det vil ta mange hundre år før dette vannet igjen vil befinne seg i overflatelaget.

ABSTRACT

On 7 April 1989 the Soviet nuclear submarine "Komsomolets" sank in the Norwegian Sea about 185 km southwest of the Bear Island at bottom depth of about 1700 m. Potential sources of radioactive contamination are the reactor and the nuclear warheads.

A Komsomolets Foundation has been established consisting of the Russian constructor of the submarine, a Dutch salvaging consortium and some environmentally oriented parties. The goal of this foundation is to get international financial support for its plans to either salvage the submarine totally, to salvage the torpedo part or to seal off the torpedo part of the submarine. A report from an expert working group to Norwegian Minister of Foreign Affairs, however, concludes that the best solution is to leave "Komsomolets" where it is.

Radioactive components in the wreck which may be dissolved and spread in the water masses include cesium-137 and strontium-90. Insoluble plutonium will settle in the sediments and remain in the vicinity of the wreck. The present study is dealing with the most likely pattern of the distribution of radioactive elements in the water masses if a leakage from the wreck occurs. The study is based on hydrographic observations, current measurements and numerical models.

By assessing the potential radioactive pollution from "Komsomolets" it is concluded that the sunken nuclear submarine represent a minor radioactive pollution problem for the following reasons:

- the great depth where the possible release of radioactive material will take place,
- the relatively small amount of radioactive material available for release,
- the enormous water masses available for dilution,
- the additional "chemical/biological dilution" (the radioactive isotopes of strontium and cesium are only a very small fraction of the total amount of these elements in sea water. The biological uptake will reflect this ratio between the radioactive and the non-radioactive isotope),
- the relatively biologically inactive plutonium will be confined to particulate form in the sediments close to the release point.

The distribution of possible radioactivity in the water masses will be along isopycnic surfaces. The radioactive components will be spread by the pulsating current in the area, but they will remain in the deep water and gradually be diluted as they are dispersed from the source. It is not likely that watermasses to any measurable extent will rise from the depth of about 2000 m to the surface. If so, the concentration will only be a small and insignificant fraction of the concentration near the wreck. Even

assuming that the submarine might represent a 10 MWatt heat source, a hot plume possible containing radioactive material, would rise to a maximum height of about 500 m above the bottom. The radioactive components will therefore gradually be dispersed in the deep water masses of the Nordic Seas and the Arctic Ocean which has a volume in the order of 10 million km^3. The deep water which is advected out of the area, flows as bottom water across the deeper passages in the Greenland-Scotland Ridge to sink into the abyssal depths in the Atlantic from where it spreads in the deep circulation of the world oceans. Residence time in this system is assessed to range from a few to about 15 centuries.

1. INTRODUCTION

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On April 7, 1989 the nuclear submarine "Komsomolets" sank in the Norwegian Sea about 100 nautical miles, or approximately 185 km, to the southwest of Bear Island. The geographical position of the wreck is 73° 43′ 31″ N and 13° 15′ 52″ E, at a bottom depth of 1658 m. An official Russian report (Anon, 1993a), describes the accident in the following manner:

" - a fire broke out in the stern section of the former Soviet nuclear submarine "Komsomolets". The vessel surfaced, but after several hours' struggle for survival, it sank, killing 42 crew members. --- "

"One difference between this accident and others, including those involving American nuclear submarines, is the threat of accelerated release of radionuclides into the marine environment. The reason is that the "Komsomolets" has a titanium pressure hull. The rate of corrosion is increased manyfold when a titanium hull reacts in seawater with the steel reactor parts and other ship components made of various metallic materials.

The reactor was switched to stable cool-down mode, ensuring nuclear safety, both at the time of sinking and when the vessel remained sunken. From the time of sinking, engineering design features of its nuclear warheads made a nuclear explosion absolutely impossible, so the problem of nuclear safety for the ship in its sunken position can be regarded as solved. However, the problem of ensuring radiological safety remains."

Figure 1.1 shows an echogram of the wreck as recorded by echo-sounders on board R/V "Johan Hjort".

The potential sources for radioactive contamination are the reactor and the nuclear warheads. The reactor used, according to Russian authorities, is water cooled and water moderated with medium enriched uranium fuel. Norwegian authorities believe that the fuel is uranium - aluminium alloy canned in stainless steele. A reactor of this type will have an original content of about 200 kg uranium 235. Of this an estimated amount of 20 - 25 kg was used, at the time of the accident, resulting in a produced quantity of approximately 2 kg plutonium 239 in the reactor core. The reactor core contains 42 kCi ($1{,}55 \cdot 10^{15}$ Bq) strontium-90 and 55 kCi ($2{,}03 \cdot 10^{15}$ Bq) cesium-137 (Anon, 1993a). Nilsen and Bøhmer (1994), however, quote other Russian authorities to have stated the content of the reactor to be 81 kCi ($3 \cdot 10^{15}$ Bq) ^{137}Cs and 75,6 kCi ($2{,}8 \cdot 10^{15}$ Bq) ^{90}Sr.

The reactor vessel was made of special steel with a corrosion protection on the inside. The reactor vessel itself is probably without damage. However, sea water may have intruded the tank. Small discharges of cesium and strontium to the water surrounding the submarine have been observed. The ratio of ^{134}Cs to ^{137}Cs indicates that the leakage must be from "Komsomolets". The source is most likely the primary circuit only.

The radioactivity resulting from the ^{239}Pu content of the nuclear warheads is about 430 Ci ($1.6 \cdot 10^{13}$ Bq) (Anon, 1993a). This amount represents 6 - 7 kg plutonium. A Norwegian expert group appointed by the Ministry of Foreign Affairs, estimates that each warhead contains 10 kg highly enriched uranium or 4 - 5 kg plutonium (Anon, 1990a). From Russian authorities it is pointed to an extensive corrosion due to a galvanic corrosion process accelerated by the titanium hull. The corrosion of the warheads will be rather fast, and the first of ^{239}Pu release can be expected in 1995-96, (Anon, 1993a).

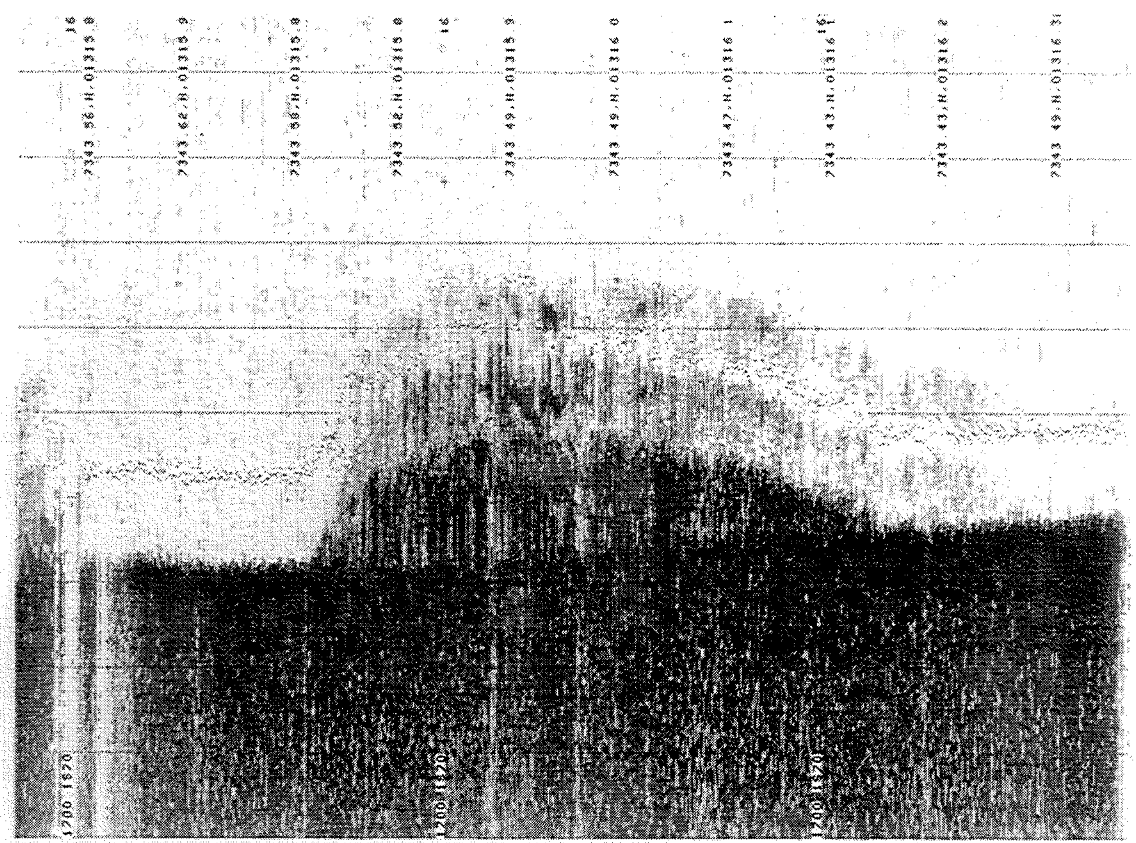

Fig. 1.1 Echo recording of the sunken submarine in the Norwegian Sea at about 1700 m depth.

2. TO MOVE OR NOT TO MOVE

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2.1 Basic information

Plutonium (Pu) is a synthetic radioactive metallic element. It has a half-life of approx. 24.000 years. It is highly radiotoxic, especially by inhalation. It is almost insoluble in water. Data from the Irish Sea show that plutonium associates rapidly with particulate matter. More than 90% is associated with the sediments close to the point of discharge at Sellafield (Williams *et al.*, 1988). Only the soluble oxidation state Pu^{+5} can be remobilised from sediments.

Uranium 235 (^{235}U) has a half-life of 7,13 x 10^8 years. It occurs naturally as 0,7% of total uranium ^{238}U with a half-life of 4,51 x 10^9 years and represents 99% of background concentration uranium. The natural contents of uranium in oceanic water is 3 mg $\cdot$ m^{-3} or 3 tons $\cdot$ km^{-3} (Goldberg, 1965). Uranium dioxide (UO_2) which is used in crystalline or pellet form to pack nuclear fuel rods, is insoluble in water (Hawley,1977).

Cesium 134 and **137** have half-lives of 2 years and 30 years respectively. Radiocesium is one of the main products from the uranium and plutonium fissions. As an alkali-metal element, cesium is present in water as a salt-ion, Cs^+. Because of its chemical properties resembleing potassium, it enters the food chains where it can be found in muscle tissues. Concentration factors of 11.0 and 10.9 respectively for potassium and cesium in haddock, *Melanogrammus aeglefinus*, in the Barents Sea have been reported (Polikarpov, 1966).

Radiocesium has a rather short biological half life It is the chemical properties of the element which determines the uptake of cesium to an organism. Therefore, uptake of radiocesium in an organism will be in the same proportion to natural cesium as it is found in the surrounding medium. Oceanic water has a cesium content of 0,5 mg $\cdot$ m^{-3} or 500 kg $\cdot$ km^3. The contents of 2,03 $\cdot$ 10^{15} Bq ^{137}Cs in the reactor of "Komsomolets" amounts to 630 g by weight. If this amount is released to the sea and diluted in the available water masses of the Norwegian Sea, the radioactive fraction of available cesium for uptake by an organism will be insignificant. The chemical dilution due to the fact that seawater have a considerable content of non-radioactiv isotopes like cesium, differs considerably from that of fresh water.

Strontium 89 and **90** have half-lives of 51 days and 29 years respectively. ^{89}Sr and ^{90}Sr are fission products. In a radio-ecological context ^{90}Sr is the important strontium isotope. The amount of ^{90}Sr in the reactor of "Komsomolets" is calculated to be 1,55 · 10^{15} Bq (Anon,1993a). This represent about 300 g. Strontium is similar to calcium in chemical properties, and will, like calcium enter into the skeletal parts of an organism to build the bone structure. Strontium will only to a minimum extent be removed from the bone structure during the life of the organism. This is contrary to cesium, which like potassium is included in the natural equilibrium of salts in living cells. Consequently, strontium has a long biological half-life in an organism, and will therefore represent a continuous radioactive source in the skeletal parts of an organism.

Oceanic water contains 8 g Sr · m^3 (8000 tons · km^3), with the principal species being Sr^{2+} and $SrSO_4$. This implies that an additional 300 g strontium released from the submarine will represent an insignificant contribution given the enormous volume of seawater available for dilution. The chemical dilution factor between radioactive and non - radioactive strontium in seawater is of considerable importance for the uptake of ^{90}Sr into marine organisms.

2.2 Assessing the potential radioactive pollution

Due to the location of the wreckage and possible influences on Norwegian waters, the Norwegian Ministry of Foreign Affairs established an expert working group, with the following terms of reference:

"assess the danger of radiation from the sunken Soviet submarine in a short and long time perspective, both from the reactor and the nuclear weapons in the submarine."

and to:
"assess the radiation dangers that may occur in an eventual rescue operation".

The working group presented its report to the Norwegian Minister of Foreign Affairs in June 1990, (Anon, 1990a). Its conclusions were that the best solution to the problem, with the least unknowns, is to let the "Komsomolets" rest in peace where it is. However, a principal standpoint is taken by Norway against all forms of radioactive waste disposal in the oceans. A complete removal of the submarine would satisfy this principle, and also secure the nuclear weapons from falling in unauthorized hands. Given that the submarine could be rescued, it would still represent a disposal problem.

The technical challenge of a salvation operation is enormous. The uncertainties and risks associated with this kind of operation are considerable. Release of radioactive material to the productive surface layers of the ocean could take place if the wreck should break open during the rescue operation or during transport through vulnerable fishing grounds in the Barents Sea.

There have been so far three extensive Russian expeditions to the wreck. By the use of manned mini-submarines, inspections by "Mir 1" and "Mir 2", have taken place. From these inspections in 1992 and 1993, it is clear that the "Komsomolets" has more severe damage to its hull than what was observed in 1990 when plans for a salvage operation were made. At present it seems impossible to rescue the submarine as it lies However, the Russians consider to rescue the front part with the nuclear missile-torpedoes or alternatively to seal off this part.

The purpose of such operations is stated to be to protect the environment. It is specifically underlined that the release of plutonium will be a tremendous threat to marine life and the fisheries in particular. The plutonium present in the nuclear warheads is about 8 - 10 kg. It is in a metallic form and will disintegrate slowly into the seawater when the enclosure of the warheads is corroded. Some Russian experts claim that the release of plutonium will start in 1995-96, (Anon, 1993a). Other Russian experts are more in line with the western estimates that it may take hundreds of years before plutonium is released to the water masses around the wreck.

The ecological importance of a release of 6-10 kg plutonium at the depth of more than 1600 meters is rather insignificant. As a comparison, there have been discharges from Sellafield into the Irish Sea during the last 30 years which amounts to 200 - 400 kg Pu. Ninety persent of this is found in the sediments close to the discharge point (Williams *et al.*, 1988). This does not seem to have an impact on the regular fishing industry in the Irish Sea.

There are also incidents of other plutonium releases. For example, the crash of an US B-52 aircraft carrying four nuclear bombs, on the ice off Thule air base at the northwest coast of Greenland in January 1968. The bombs were destroyed in the crash but no nuclear explosion took place. Both the ice and the bottom sediments were contaminated by plutonium as a result of the accident. Approximately 0,4 kg plutonium ended up at the bottom and is distributed at the sea floor at a depth of 100 -300 meter. The transfer of plutonium into the actual marine ecosystem have been studied since the accident in 1968. There is observed plutonium contamination in bottom living biota, but there is a distinct discrimination against plutonium when we move to higher trophic levels in the food-chain (Aarkrog, 1993).

The movement of the plutonium at the bottom and in the sediment, is described by the median distance, i.e. the distance from the place of accident to where half of the activity is found. The median distance increases by about 400 meters a year, (Anon, 1990a). Both the experiences with plutonium releases to the marine environment from the Sellafield discharge as well as the Thule accident show that the threat, as expressed by some Russian and other sources, to the marine life and in particular to the marine fisheries from the plutonium of "Komsomolets", is exaggerated.

For the assessment of the potential pollution from "Komsomolets" it can be concluded that the sunken nuclear submarine represents a minor radioactive pollution problem due to;

- the great depth where the release of radioactive material will take place,
- the actual and relatively small amount of radioactive material available for release,

- the enormous water masses available for dilution,
- the additional "chemical dilution"
  (derived from the fact that the radioactive isotopes of strontium and cesium are only a very small fraction of the total amount of non-radioactive strontium and cesium in sea water, and their biological uptake depends on the chemical behaviour of the element and not whether it is a radioactive or a non radioactive isotope),
- the relatively biologically inactive plutonium which will be found in particulate form in the sediments close to the release point.

The major problem with the "Komsomolets" is the media focus on this particular submarine, a focus which tend to concentrate on a potential damage of the fish resources of the Barents Sea. The "Komsomolets" is, however, isolated from the Barents Sea and its fish resources.

Altogether eight nuclear submarines with nuclear weapons are reported lost at sea, of which two were American and six from the former Soviet-Union. The latest was the wreckage of "Komsomolets", and this one seems to be the only incident of interest to the media.

2.3 Efforts to establish a salvage operation

"Komsomolets" was designed by the Central Design Bureau for Marine Engineering (CDB ME) "Rubin" in St. Petersburg. It carried, according to their deputy chief designer Nicolai A. Nosov, a water-cooled and water-moderated reactor and two missile-torpedoes with nuclear warheads together with conventional torpedoes.

Further, according to N. A. Nosov, the hydrostatic pressure has caused the casings of the nuclear ammunition to become leaky. The automatic system of the ammunition is out of action.

"Komsomolets" has a pressure hull of titanium or titanium alloys. It weights approx. 6000 tons, it is about 120 m long with a hull diameter of 11 m. Around the pressure hull there is a shock absorbing hull of titanium or titanium alloy, covered with a sort of bitumen.

According to a newspaper article by J. Tepljakov in "Moskovskije novosti" of November 11 1992, the "Komsomolets" was a very special submarine. The submarine was designed to have an ordinary working depth of 1000 meters. The former Soviet Union used nearly twenty years to build it. According to this article, "Komsomolets" represents an enormous value not only due to the titanium but due to its secrets which are still not available to others. Therefore, it is too early to regard the submarine as lost. "It should be rescued" is the concluding remark in the article.

With technology which enables a working depth of 1000 meters implying that the submarine could fire its missile-torpedoes from this depth, is a military advantage that may explain the efforts to do something with the submarine, and the torpedo compartment in particular. The pollution aspects hardly justifies the efforts to rescue it.

Soon after the wreckage, the Russian constructors CDB ME "Rubin" came up with a proposal for rescue in cooperation with a Dutch consortium established by the two well known ocean salvaging and construction companies, Heerema and Smit International. The cost of a rescue operation was estimated to approximately 250 millions US dollars. According to CDB ME "Rubin" the financial part was granted by the then Soviet Union authorities. However, after the dissolution of the Soviet Union, the now Russian authorities obviously withdraw their financial support.

The technical challenge of the salvaging operation could in it self justify the efforts put down by the Dutch consortium, considering all other objects in the deep oceans that may have to be salvaged in the future. The need for international financial support initiated the formation of the Komsomolets Foundation, an organization that assembled to its board of directors both the parties directly involved, the CDB ME "Rubin" and the Dutch consortium as well as more environmentally oriented members. The Komsomolets Foundation have not yet succeeded in having international financial support for its plans either to salvage the submarine totally, to salvage the torpedo part, or to seal off the torpedo part of the submarine.

Occational press releases from the office of the Komsomolets Foundation in Bruxelles have pointed to the enormous environmental risk the submarine "Komsomolets" represents. The purpose of this activity is obviously to generate publicity so that the international community feels obliged to give financial support to a rescue operation. From a scientific point of view, there is a lack of allegatious documentation of the press releases. The information provided does not include considerations of the potential pollution from "Komsomolets" in relation to other sources of radioactive contamination in the oceans.

A recent example of misleading information about the "Komsomolets" is an article in The Times of January 14, 1994, written by their environment correspondent Nick Nutall with the following headline: "Nuclear sub could leak at any time." The report continuous with the following: "A Russian nuclear submarine wrecked in a fishing ground used by European trawlers could begin discharging big quantities of radioactive materials at any time, a British nuclear engineer said yesterday". "The radioactive pollution could stretch over "several thousands of kilometres," studies by a Moscow nuclear safety centre show. John Large, a British nuclear engineer who has just returned from a meeting in St.Petersburg, said Russian military scientists now feared widespread fish contamination could be triggered within three years."

The latest article in the press was presented as headline news in the Norwegian newspaper "Aftenposten" of May 20, 1994. Here it was again stated that there was an urgent need to seal off the nuclear warheads of "Komsomolets" before leaking started and destroyed valuable fishing grounds. The report stated that the Russian authorities were willing to pay approximately half of the cost of an estimated 12 millions USD operation and that the rest of the sum had to be contributed by the international community. The very latest is an indication of a substantial contribution from the Dutch government to some work on the wreck this summer.

There is a reason to ask; where do all this misinformation come from, and why? Why can not these efforts and this money be used in securing other sources of radioactive contamination in the marine environment? Sources which really could harm the marine environment, the often primitive storage facilities for radioactive waste at the Kola peninsula included.

2.5 Observations on radioactivity at the wreck site

There have been three officially known Russian expeditions to the wreck site. Unofficial reports of their measurements conclude that there is no observation of release of plutonium. Of fission products from the reactor, only a slight elevation of ^{137}Cs close to the wreck is recorded. The Russian expeditions used manned submersibles (MIR 1 and MIR 2) to take samples close to, and in the vicinity of, the wreck.

Nezhdanov (1993) reported results from the use of submersible gamma detectors mounted on the "MIR", both from the 1991 and the 1992 expeditions. He reports recordings of ^{137}Cs for the reactor compartment area of 0,11 ±0,03 nCi (4070 ±1110 Bq · m^{-3}) in 1991 and 0,8 ±0,2 pCi/l (29,6 ±7,4 Bq ·m^{-3}) in 1992.

Table 1 present ^{137}Cs values from our surveys of the wreck site. We sampled water using water bottles mounted on a Rosette sampler and sediments using a Smøgen boxcorer, both devices connected to the end of a wire extending to the depth of 1658 m. The precision of the location of our samples is therefore poor, i.e. it is just by chance that we will have samples close to the wreck. Most important we will not be able to know how close or how far we have sampled from the wreck. By means of echosounding and satellite positioning we do, however, know that our samples represent the area fairly close to the wreck.

Our measured values of ^{137}Cs in water samples collected in the vicinity of the wreck show values from <10 Bq to 30 ±5 Bq · m^{-3}. In comparison values from the Kara Sea measured in 1992 range from 3,3 - 20,4 Bq · m^{-3} (Anon,1993b).

Average ^{137}Cs values for the period 1980 - 1985 have been reported from the various ICES fishery statistic areas. For area VIa, the north-west coast of Scotland, the average value is 190 Bq · m^{-3}. For IVa, northern North Sea, the reported average value is 49 Bq · m^{-3}, and for area IIa, the Norwegian coast north of 62° N and the Norwegian Sea, the average value for the period 1980 - 1985 for ^{137}Cs is 23 Bq · m^{-3}, (Anon, 1990b).

Our cesium 137 values for sediment samples near the wreck is low, from 1-2 Bq · kg^{-1} (Table 1). These values can be compared to values from the Kara Sea, where preliminary measurements of cesium 137 ranged from 4 Bq · kg^{-1} to 90 Bq · kg^{-1}, (Føyn and Nikitin, 1993).

Table 1. ^{137}Cs in water and sediment samples at the location of «Komsomolets».

Year	Type of sample	^{137}Cs activity
1990	sediment	<2 Bq · kg^{-1}
1991	water	30 ± 5 Bq · m^{-3}
1991	sediment	<1 Bq · kg^{-1}
1992	water	<10 Bq · m^{-3}
		21 ± 5 Bq · m^{-3}
1993	water	14 ± 5 Bq · m^{-3}
		<10 Bq · m^{-3}
1993	sediment	<1 Bq · kg^{-1}
		<1 Bq · kg^{-1}
		2 ± 1 Bq · kg^{-1}
		<1 Bq · kg^{-1}
		2 ± 1 Bq · kg^{-1}
		2 ± 1 Bq · kg^{-1}

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3. PHYSICAL CHARACTERISTICS OF THE AREA

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3.1 Bottom topography

The wreck of the submarine is lying in the transition zone between the northern deep basin of the Norwegian Sea, the Lofoten Basin , and the Fram Strait. This strait, between Svalbard and Greenland, which is about 450 km wide and has a sill depth of 2600 m, forms the main connection between the Arctic Ocean and the Nordic Seas (Greenland, Iceland and Norwegian Seas). The bottom topography of the regions surrounding the wreck site is shown in Fig. 3.1. The wreck is located in the deeper part of the slope between the shallow shelf area of the Barents Sea and deep basins to the west and south. Toward the Barents Sea the bottom slopes up to depths less than 400 m along the shelf edge. The deeper parts along this shelf edge are located on the Storfjord Deep, south of Spitsbergen, and in the Bear Island Trough, south of Bear Island, which form valleys in the shelf. In the Bear Island Trough there is a sill depth of 450 m near the shelf break while the trough reaches depths of 500 m further to the east. The Storfjord Deep slopes up from depths of about 400 m at the shelf edge.

West of the wreck, bottom depths increase toward the mid-ocean ridge. This ridge is generally shallower than 2600 m (Fig. 3.1), but many crests in its very complex topography rise above 2000 m depth. North of 74°N it approximately follows 6°E toward the Arctic Ocean, while further south it stretches in a southwesterly direction toward Jan Mayen under the name of Mohns Ridge. Along its eastern side there is a narrow, elongated ridgetrough which is mostly deeper than 3000 m. West of the ridge there are floor depths greater than 3500 m in the Greenland Basin, while the Lofoten Basin southeast of Mohns Ridge has floor depths of about 3200 m.

3.2 Water masses

Water masses in the ocean are bodies of water which can be characterized by their properties, most often by their temperature/salinity relationship. Water masses can be formed by change in temperature throuh heat exchange with the atmosphere or by mixing of water from different water masses. A water mass may be formed and remain in an area, or it may be transported into the area by a current system. Both these types are among the major water masses in the Nordic Seas and before their distribution can be described, it is necessary to define them.

Atlantic Water bears its name from its origin, the Atlantic Ocean. On entering the Nordic Seas in the Faroe-Shetland area it is typically of temperature 6-9°C and salinity 35.1-35.3. In the Nordic Seas water with temperature above 0°C and salinity above 35 has traditionally been defined as Atlantic Water. Polar Water is primarily cold and fresh waters which are carried from the Arctic Ocean by the East Greenland Current where it is found in the upper layers. It is characterized by temperatures ranging from freezing point to 0°C and salinity below 34.5. Greenland Sea Deep Water is formed in the central Greenland Sea by cooling during winter. It has temperatures below -1°C and salinity between 34.8 and 34.9.

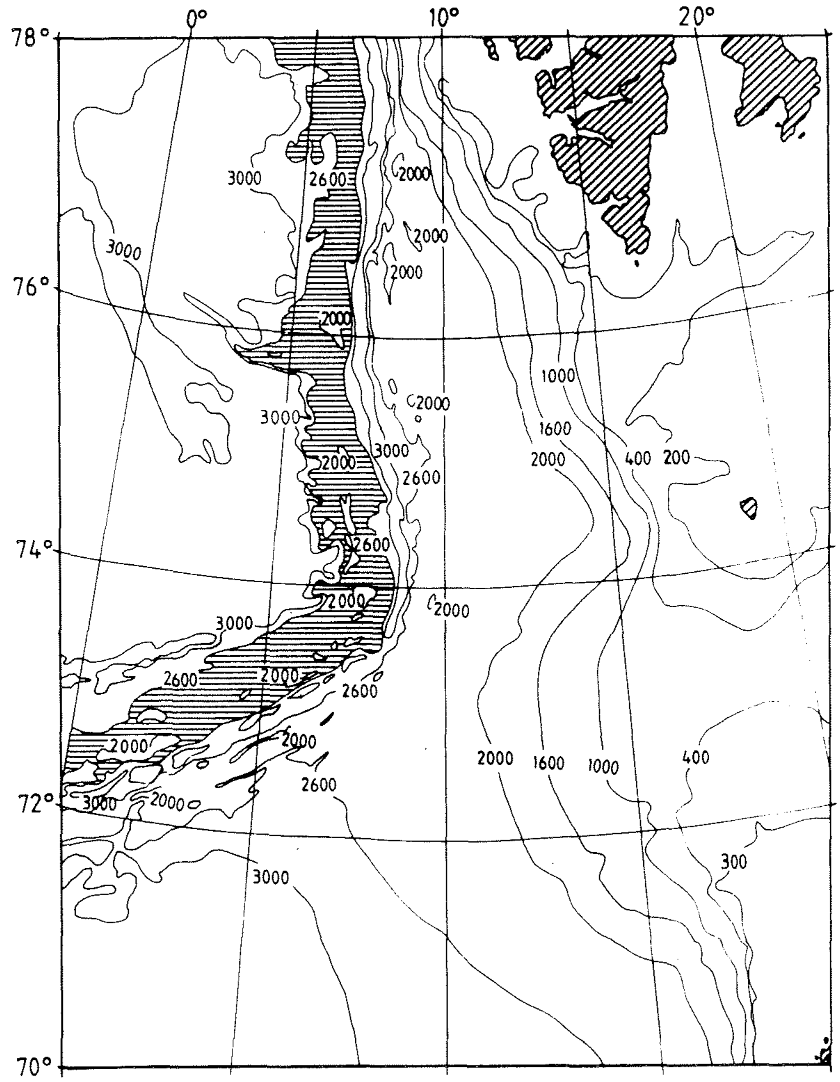

Fig. 3.1 Bathymetry in the northeastern Nordic Seas, depths in metres.

Norwegian Sea Deep Water is slightly warmer and saltier than the Greenland Sea Deep Water, with salinity close to 34.91 and temperature close to -1°C. It is a mixture of Greenland Sea Deep Water and somewhat warmer and saltier deep water originating from the Arctic Ocean. Intermediate waters occur in several modifications, two of which will be mentioned here. Arctic Intermediate Water is found under the Polar Water in the East Greenland Current, it is a water mass with an Atlantic component and has temperatures of 0-3°C and salinity of 34.9-34.95. In the Norwegian Sea an intermediate water mass originating from the Iceland and Greenland Seas, occurs between the Atlantic Water and the Norwegian Sea Deep Water. Its temperatures range from -0.5 to +0.5°C and the salinities are between 34.7 and 34.9. The deep and intermediate water masses in the Nordic Seas are often collectively called Arctic waters.

3.3 Surface circulation

Even though the mid-ocean ridge is mostly rather deep, it is of decisive importance for the circulation and distribution of water masses in the northern part of the Nordic Seas. Hence, north of Jan Mayen the Arctic Front follows the ridge, forming a border zone between Arctic and Polar water masses in the Greenland Basin to the west, and waters of Atlantic origin east of the front. This front is most conspicuous in the upper layers, north of 70°N above approximately 700 m depth and further south even shallower. Fig. 3.2 shows the location of this front as observed in the summer of 1981 north of 70 °N and in 1984 further south. Observations over several years indicate that north of 71 °N the front is permanently located in the area over the mid-ocean ridge with no locational variations larger than frontal meanders.

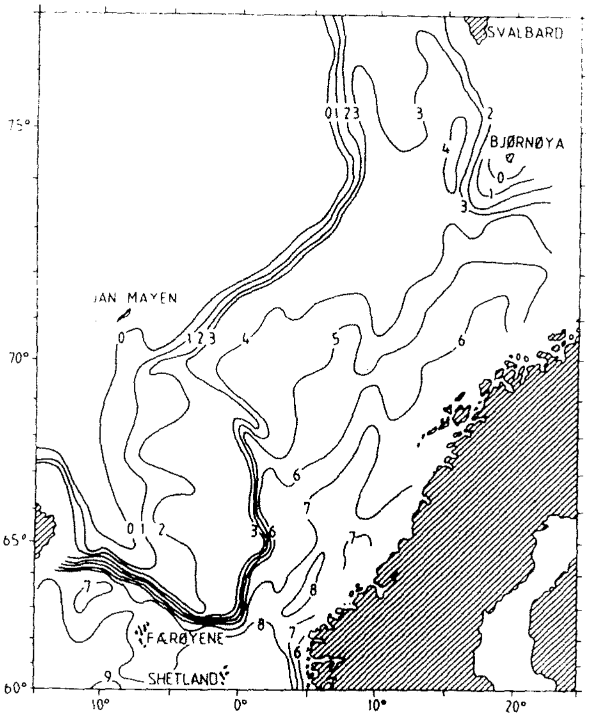

Fig. 3.2 Temperature distribution at 200 m depth as observed in August in 1981 north of 70°N, in 1984 south of 70°N. The Arctic Front is indicated by the zone with increased horizontal temperature gradients.

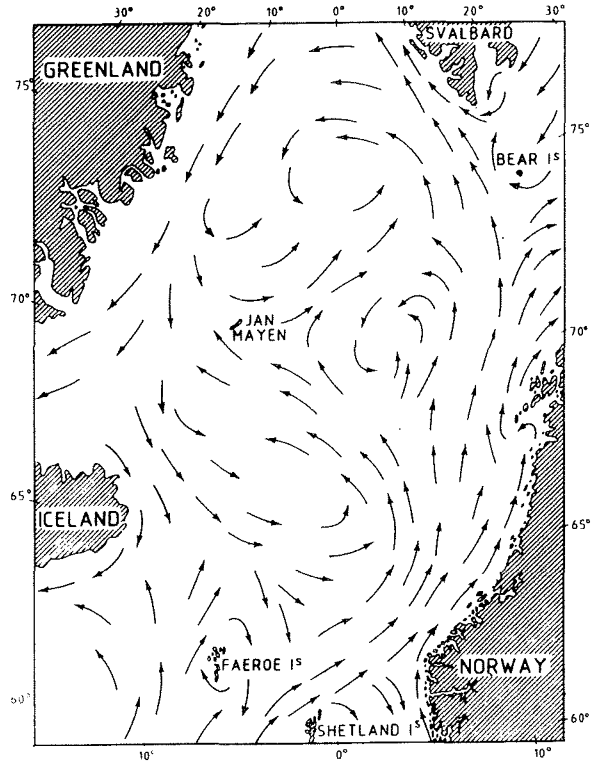

Fig. 3.3 Surface circulation in the Nordic Seas, modified mainly after Alekseev and Istoshin, 1956.

In general, such bathymetric steering is an important factor for circulation and water mass distribution in the Nordic Seas. As shown in Fig. 3.3, the broad features of the surface circulation are a northward flow on the eastern side and a southward flow on the western side, both with some branching into interior basins and bordering shelf seas. The Norwegian Atlantic Current, which represents the warm northward flow, carries Atlantic Water from the northeastern Atlantic through the Faroe-Shetland area, along the coast of Norway, the Barents Sea shelf edge and further, under the name of the West Spitsbergen Current, along the west coast of Svalbard, into the Arctic Ocean. Under way, Atlantic Water is advected into several branches. On passing the Vøring Plateau, off mid-Norway, the current widens and branches into the Norwegian Basin. Reaching Jan Mayen, the larger portion of the waters in the western branch turns northeast along Mohns Ridge. Approximately at the latitude of Bear Island this water merges again with the main branch which flows along the shelf edge. Along the southern slope of the Bear Island Trough a branch deflects from the Norwegian Atlantic Current into the Barents Sea where it forms the North Cape Current. Along the northern side of the Bear Island Trough, however, cold surface water from the East Spitsbergen Current and Barents Sea bottom water flow towards the west. The cold surface flow turns north on the western side of

Bear Island and flows parallel to the Atlantic Water toward West Spitsbergen, while the bottom water sinks into the intermediate or deep water masses in the Norwegian Sea, depending on variations in its density.

The southward current on the western side is a flow of cold Polar and Arctic waters carried by the East Greenland Current. At least in the upper layers this is mainly a transport passing through the Nordic Seas along the East Greenland shelf edge, with entrance through the western Fram Strait and exit through the Denmark Strait. However, from this current there also branches into the interior of the Nordic Seas. In the southern Greenland Basin the Jan Mayen Current turns eastward from the East Greenland Current. On passing Jan Mayen it turns northeast and flow along Mohns Ridge. This branch feeds Arctic and Polar waters into the large cyclonic gyre in the Greenland Basin. Further south the East Icelandic Current forms a second branch where mainly Arctic waters advect into the Iceland Sea and further to the southwestern Norwegian Sea. A more comprehensive description of the physical oceanography of the Nordic Seas is recently presented by Hopkins (1991).

3.4 Deep circulation

The deep circulation in the Nordic Seas is not well known. Although it is generally believed that the pattern of the surface currents to some extent mirrors deeper circulation patterns, very little is known about current velocities. Current measurements exist mainly from the bordering areas, in the Faroe-Shetland area, the Denmark Strait and the Fram Strait. (Dobberphul, 1992, Gould et al., 1985, Hansen et al. 1988, Hanzlick, 1983, Kristmannsson, 1991). In the deep basins there are reports on some current measurements from the Greenland Basin and in the sills through Mohns Ridge (Foldvik et al. 1988, Sælen, 1986); while in the deep basins of the Norwegian Sea there are virtually no current measurements at all. Hence, the circulation pattern in the deep basins is better known in the Greenland Sea than in the Norwegian Sea. In the Greenland Basin the circulation is cyclonic at all depths. This is indicated both by current measurements and the water mass distribution. In general, it is believed that there is cyclonic circulation also in the Norwegian Basin, although this is less documented. The deep circulation in the northern basin in the Norwegian Sea, the Lofoten Basin, is possibly least known. In this basin the current pattern is rather complex both in the upper layers and most probably also in the deeper strata. The Russian report to the International Maritime Organozation (IMO, 1993), mentions current velocities up to 150 cm/sec in the area near the submarine, however, without reference to depth or to source.

3.5 Current measurements

To obtain more knowledge of the currents in the locality of the wreck site, the Institute of Marine Research, Bergen, deployed a current meter mooring with four Aanderaa RCM7 current meters in the position 73° 43.19'N, 13° 15.60'E during the period from 3 May to 4 August 1993. The current meters were placed at depths of 167m, 667 m, 1567 m and 1642 m over a bottom depth of 1697 m. The upper instrument was most likely torn away by fishing gear after only four days. The rig had, however, buoyancy above each instrument and the remaining part did therefore function without the buoy on the top. The instruments at 667 and 1567 m depths functioned properly during the whole period, while at 1642 m the velocity was observed only until the end of June. Recording frequency in the current meters was set to six recordings per hour.

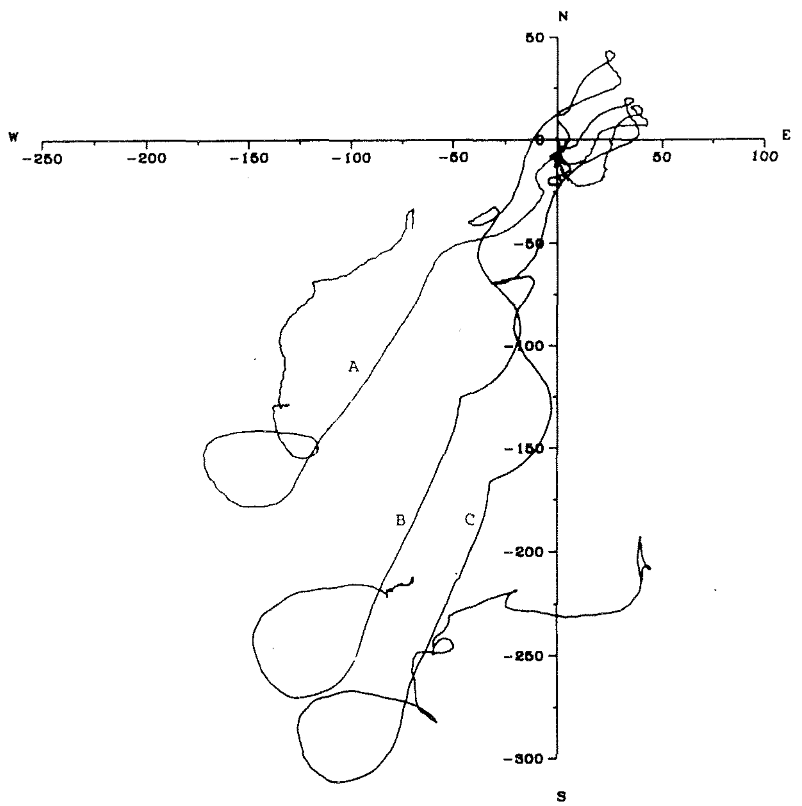

Fig. 3.4. Progressive vector diagrams showing 25-hour running means of the current at depths of A) 667 m, B) 1567 m and C) 1642 m.

Progressive vector diagrams for the three depths are presented in Fig. 3.4. Tidal effects are filtered out in these diagrams by applying 25-hour running means of the current recordings. The smoothed currents show dominant direction mainly in the quadrants 0-90° or 180-270°. This is roughly along the isobaths (Fig. 3.1) as might be expected in a slope area. Periodic reversals of the current, with dominant direction changing between the two quadrants, occurred several times during the observation period. These variations were similar at all three depths. This is better shown in Fig. 3.5 in which daily maxima of the dominant current components are plotted for the whole period from 4 May to 3 August. The three instruments showed strict simultaneity in the reversals of the current. For example, on 21 May the current abruptly reversed from a northerly direction to a southward flow which went on for the rest of the month. As seen in Fig. 3.5 , there were several similar reversals during the period. The general flow pattern is therefore mainly characterized by alternating pulses along the slope, at least during the summer season. To what extent this is also true during winter remains to be measured. As described for example by Dobberphul (1992), similar pulsations have also been observed in the Fram Strait. It is therefore likely that the flow patterns at the wreck site are determined by pressure generated pulses through the Fram Strait.

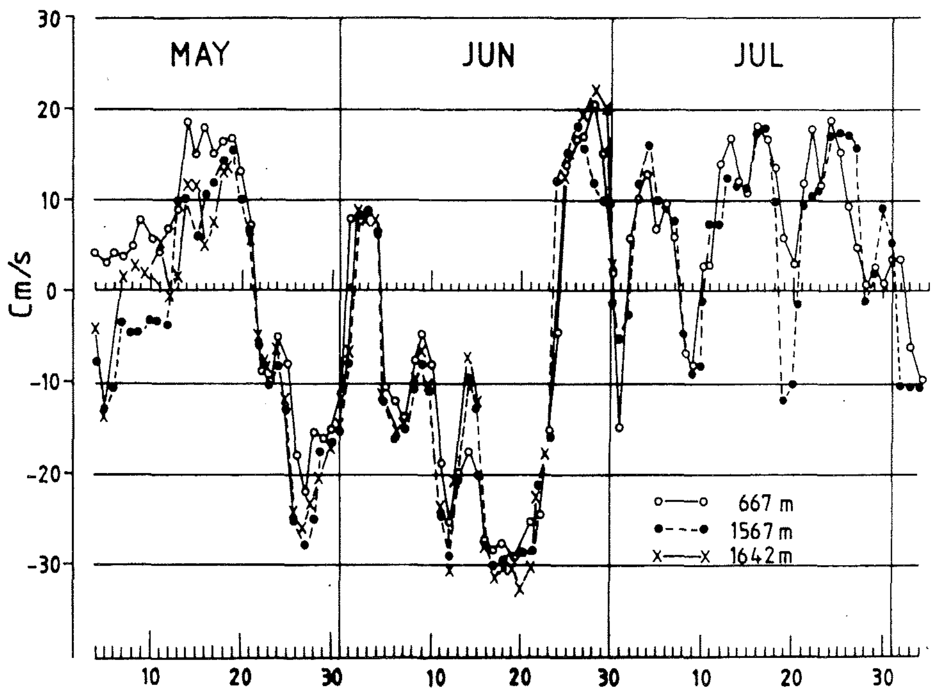

Fig. 3.5 Daily maxima of the dominant current component.

The measurements indicated a very strong barotropic signal in the current pattern throughout the observed part of the water column. Except during the period from 3 to 20 May, Fig. 3.5 shows a remarkable constancy with depth in the dominant current component. This is contrary to the more common current pattern observed in many oceanic areas, where current velocities decrease with depth. In many cases the current meter at 1642 m depth, 55 m from the bottom, measured higher velocities than the upper instruments, in fact, the maximum velocity for the whole period, 34.2 cm/s towards the southwest, was observed at this depth. The residual current during the period was on average toward southwest with mean velocity increasing from 1 cm/s at 667 m depth to 2.8 cm/s at the deepest instrument.

With regard to the forcing of this current pattern, it is clearly not directly wind driven. Rather, it is a result of variations in atmospheric pressure over the Arctic Ocean and the Nordic Seas. For example, an increase of 1 hPa in atmospheric pressure over the Arctic Ocean relative to the pressure over areas to the south, requires that a water volume of almost 100 km^3 flows out of the Arctic Ocean before equilibrium in potential energy is restored.

The current velocities which are shown in Fig. 3.5 are based on single recordings which also include the tidal currents. In this area the semidiurnal tidal component is dominant with an amplitude theoretically evaluated to be near 50 cm (Schwiderski, 1986), while the diurnal component is about 1 cm. The current recordings showed that velocities in the tidal current component decreased with depth. At 667 m depth amplitudes from the 25-hour running mean were in the order of 10 to 15 cm/s while at 1642 m depth amplitudes were typically less than 5 cm/s. As an example, Fig 3.6. shows the tidal currents along with the 25-hour running mean for the dominant current component at 1642 m depth during the period from 6 to 11 June. The semidiurnal character of the tidal current component can be clearly seen and it is also clear that the tidal component is of little importance in the general current pattern. Obviously, the north-south pulses shown in Fig. 3.5 are not associated with any tidal effect, simply because of the irregular periodicity.

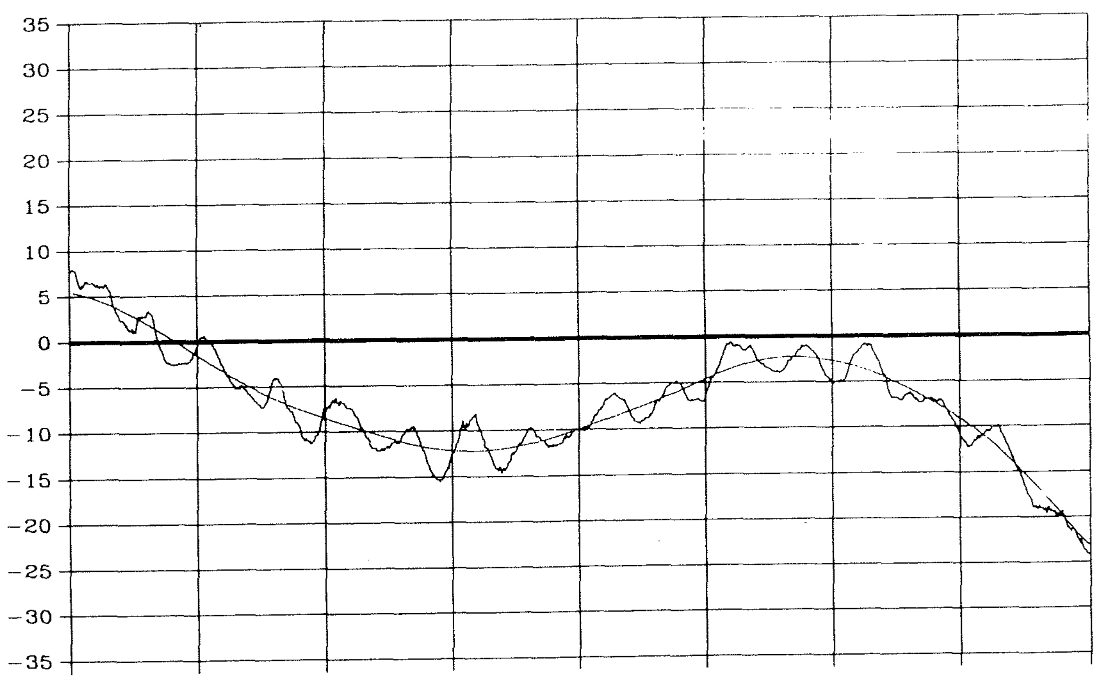

Fig. 3.6 Current velocities (cm/s) in dominant direction (35°) at 1642 m depth, 4-11 June 1993.

3.6 Distribution of water masses

Fig. 3.7 shows potential temperature, salinity and potential density observed in November 1991 in a section along 74°30′ N between 5°W and the Bear Island. (Potential temperature, θ, is observed temperature compensated for pressure difference between observation depth and the surface. Potential density, expressed as σ_θ, is the density at atmospheric pressure, calculated from potential temperature and salinity , given as kg/m^3-1000) . Although this section is about 140 km north of the wreck site, it gives a representative picture of the distribution of water masses in the area. In the section the mid-ocean ridge is indicated by the structure at 6°E with a crest depth of 2500 m. The Arctic Front, in the upper layers above the ridge, is indicated by relatively large horizontal gradients both in temperature and salinity. East of the front the Atlantic Water in the Norwegian Atlantic Current is indicated by temperatures ranging from about 2°C to 5.5°C and salinity values above 35. Temperatures above 5°C and salinities in excess of 35.1 were observed only in the core of the Atlantic Water near the shelf edge. Between about 400 and 700 m depth there is a transition zone between the Atlantic Water and Arctic water masses below. In the area over the mid-ocean ridge this zone bends toward the surface to form the Arctic Front.

In the Greenland Basin, to the left in the section, there are temperatures below -1°C in the surface layers. This is Polar water originating from the East Greenland Current. The small core of water with temperature above 0°C underlying this cold surface water is Arctic Intermediate Water recirculated from the West Spitsbergen Current and flows south off the Greenland shelf. In the other parts of the section temperatures decrease with depth, and generally there are somewhat lower temperatures in the Greenland Basin than in the Norwegian Sea east of the ridge. In the Greenland Sea the isotherms have a dome shaped pattern with the top of the dome in the center of the cyclonic gyre in this basin. During late winter this doming is more pronounced than in the autumn situation which is shown in Fig. 7. When such a winter situation is well developed, it also creates favourable conditions for deep convection. This area is therefore known as an important locality for formation of Greenland Sea Deep Water. It is believed that convection in some years may reach the bottom, although this process has never been observed. The surface layers in the Greenland Sea are typically characterized by relatively low salinities which are an important factor in the process of bottom water formation. The reason being that the density of water at low temperatures is far more dependant on salinity than on temperature. Hence, there is a delicate balance between salinity and the possibility for bottom water formation. If surface salinities are too low, there will be no deep convection even if the water is cooled to freezing.

Salinity in deep water is generally somewhat lower in the Greenland Sea than in the Norwegian Sea although differences are small, between 34.89 and 34.90 in the central Greenland Sea and close to 34.91 in the Norwegian Sea. As shown in Fig. 3.7, salinities in the Greenland Sea are below 34.89 at depths less than approximately 1000 m. At this depth water of salinity below 34.89 also spreads into the Norwegian Sea as Arctic Intermediate Water, forming an intermediate salinity minimum which is traceable along the whole section to the slope. At least some of this water sinks down to intermediate depths in the frontal area, probably to a larger extent further southwest toward Jan Mayen than at the latitude of the section.

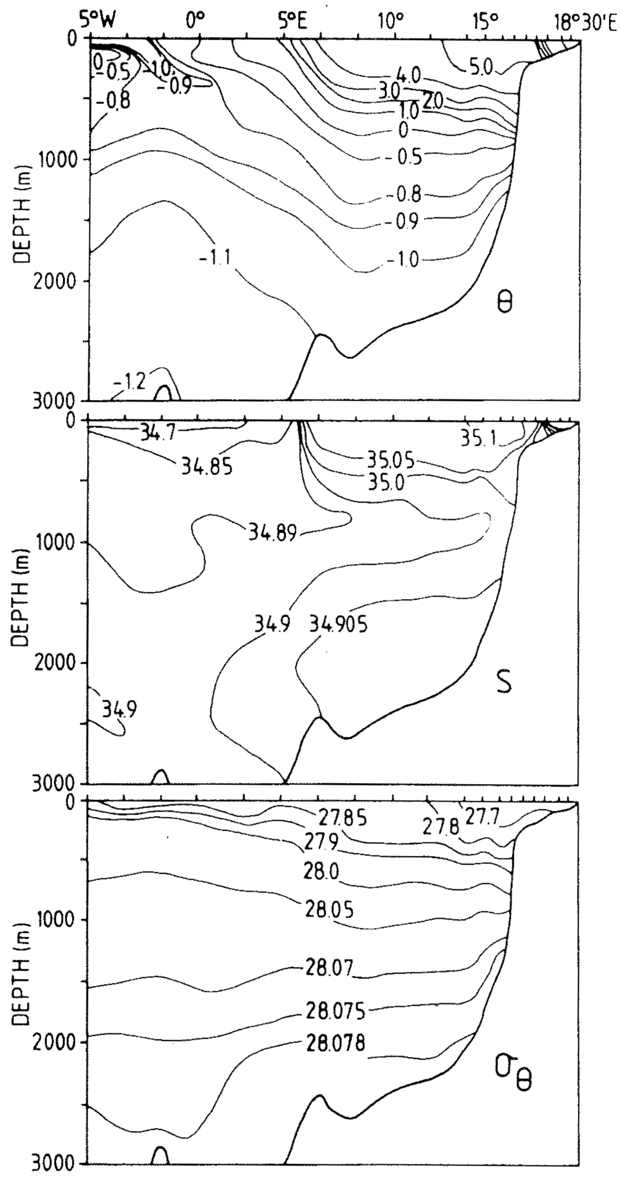

Fig. 3.7 Potential temperature, salinity and potential density along 74°30′N, November 1991.

The density distribution in Fig. 3.7 shows the situation before onset of winter. The highest vertical density gradients occur in the upper layers. In the Greenland Basin there is a relatively sharp transition zone (pycnocline) below the cold surface layers. In spite of very low temperatures, the density in the surface layers of the Greenland Basin is low because of low salinity. In the Norwegian Sea the highest vertical density increase is found in the transition layer between the Atlantic Water and the underlying water mass. Along the whole section the vertical density increase across this zone amounts to about 0.15 kg/m^3, but the transtiton zone is narrower and with a larger vertical density gradient in the Greenland Sea than in the Norwegian Sea. Above this transition zone there will be increased density gradients near the surface during summer, depending on the seasonal warming to 40 – 50 m depth. Such a seasonal pycnocline with a σ_θ of about 27.52 in the mixed surface layer is indicated in Fig 3.8 which shows the density profile near the wreck site in early October 1991.

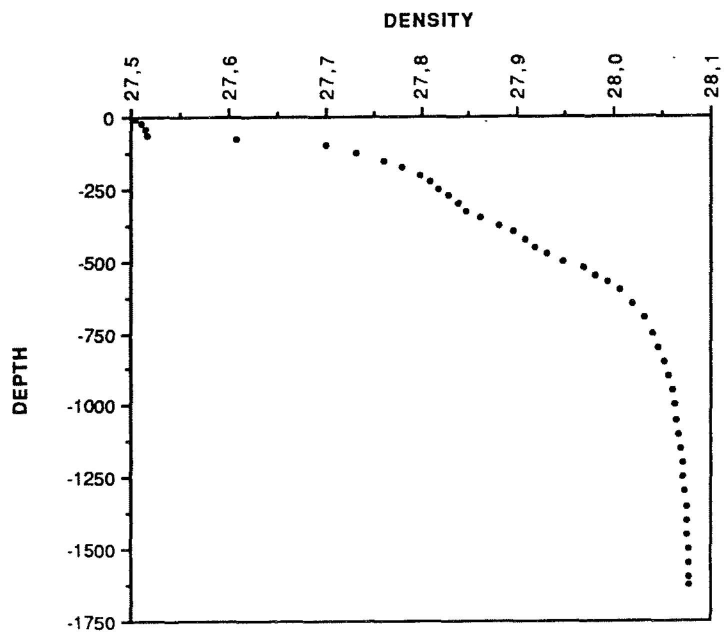

Fig. 3.8 Density profile in the water column near the wreck site, 8 October 1991.

In the deeper part of the water column density gradients are considerably lower, with σ_θ increasing from about 28.0 in the deeper layers of the transition zone to almost 28.08 near the bottom. Above about 800 m depth the isolines for density (isopycnals) slope downwards from the Greenland Sea to the Norwegian Sea, but at greater depths it is opposite, with a downward slope toward west. Hence, at depths greater than approximately 1000 m, the water masses in the Norwegian Sea are heavier than the water masses at the same depth in the Greenland Sea. The relatively steep upward tilt against the continental slope (Fig. 3.7) is a common feature in sections crossing the slope area in the Norwegian Sea. Most likely, this is associated with the circulation pattern, but the relation to variations in the circulation is not well known.

3.7 Possible spreading by turbulent mixing

Radioactive components in the wreck which will be dissolved and spread in the water masses include ^{137}Cs and ^{90}Sr, while ^{239}Pu, which does not disolve, will settle in the sediments and remain near the locality of the wreck.

Motion in the ocean is generally turbulent and the conditions around the wreck site show no exception to this. The turbulent exchange coefficients are much larger than the coefficients for molecular diffusion, but they vary with local conditions and it is not a trivial task to determine their magnitude. Generally the horizontal coefficients are considerably larger than the vertical ones. The reason for this is the buoyant stabilizing forces in a stratified ocean which reduce vertical motion. Increased vertical density gradients in the water column will therefore result in decreased vertical mixing. Vertical velocity shears in the current will have an opposite effect and increase the vertical exchange. Similarly, in a slope area the bottom topography may bring about increased turbulence in general, with varying effect depending on bottom roughness or irregularities in the topography.

In the present case the source of the spreading agents is situated in a water column with stable stratification and exceptionally low vertical velocity shear. Exchange and mixing of water will therefore be almost exclusively horizontal and spreading will occur along the isopycnic surfaces. Some topographically generated turbulence will, however, occur along the slope. This effect is probably noticeable in the intermediate salinity minimum between 800 and 1100 m depth in the section shown in Fig. 3.7, as the minimum is less pronounced within a distance of about 50 km from the slope than farther west. However, this does not necessarily mean that there is an upward exchange of deep water along the slope. On the contrary, it is shown that bottom water from the Barents Sea sinks down along the slope both from the Bear Island Trough and from the Storfjord Deep. The bottom water from the Bear Island Trough sinks into the intermediate water or deeper, depending on its density (Blindheim, 1989). Similarly, heavy bottom water formed by salt accretion in the water when ice is formed, flows out from the Storfjord Deep and may be traced to the bottom in the Fram Strait (Quadfasel et al., 1988). Possibilities for circulation of deep water up the slope are therefore small in this area.

In conclusion, the most likely pattern of spreading of radioactive components from the wreck is along the isopycnic surfaces. The radioactive components will be spread by the pulsating current in the area, but they will remain in the deep water and gradually be diluted as they are dispersed from the source. As shown in Fig. 3.7, the density at the depth of the wreck corresponds to a σ_θ value of about 28.075. The isopycnal for this density is on average tilting down toward the west and in the Greenland Sea it occurs at depths of almost 2000 m. The central Greenland Sea is the only locality with considerable vertical exchange which may occur by deep convection when Greenland Sea Deep Water is formed during winter. In this process there may be some lifting of ambient water masses at depth when new deep water sinks down, but it is not likely that water will rise to any measureable extent from about 2000 m depth to the surface. Any radioactivity originating from the wreck of the submarine which may reach the surface through this process will be diluted to a very minor fraction of the concentration at 2000 m depth, which in itself will be only a small fraction of the concentrations near the wreck. The radioactive components will therfore gradually be dispersed in the deep water masses of the Nordic Seas and the Arctic Ocean which has a volume in the order of 10 million km^3. The deep water which is advected out of the area, flows as bottom water across the deeper passages in the Greenland-

Scotland Ridge to sink into the abyssal depths in the Atlantic, from where it spreads in the deep circulation of the world ocean. Residence time in this system is assessed to range from a few to about 15 centuries.

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4. MODEL SIMULATION OF LONG TERM TRANSPORT OF WATER SOLUBLE SUBSTANCES

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4.1 Introduction

The sunken Russian nuclear submarine ``Komsomolets'' is situated on the shelf break west of Bear Island at approximately 1700 m depth. Water soluble radioactive material such as Caesium and Strontium may leak from its reactor. Such substances act as passive tracers and are advected and dispersed by water movement. It is assumed here that the reactor is ``cold'', meaning that there is no hot water plume extending from the submarine carrying the radioactive material up through the water column.

A model study of spreading from the submarine was done at The Norwegian Meteorological Institute (DNMI) by Hjøllo (1993). Here an atmospheric particle tracking model was used in the ocean with current fields from the same current model. This work addressed short term dispersion based on the assumption of a ``warm'' source. At Nansen Environmental and Remote Sensing Centre (NERSC) current fields from Oberhuber's current model has been used to drive a Eulerian (concentration based) advection and dispersion model.

The purpose of this contribution is to present results of a model study of the advection and diffusion of a passive tracer released close to the submarine. This study was done in cooperation between the Institute of Marine Research (IMR) and DNMI for the Norwegian Defence Research Establishment. The results obtained so far are quite preliminary and can with more effort be enhanced in several ways.

4.2 The Model System

4.2.1 The Hydrodynamic Model

The hydrodynamic model used is the well known three-dimensional Princeton Ocean Model (POM), developed by Blumberg and Mellor (1987). The model variables are sea surface elevation, three current components, two variables describing vertical turbulent mixing and, optionally, salinity and temperature.

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Driving forces are the density structure of the ocean, wind stress and air pressure and, optionally, tidal forcing. In the vertical, bottom-following σ -coordinates are used. Some modifications of the model have been done at DNMI and IMR. Most important is the use of the Flow Relaxation Scheme (FRS) at the open (sea) boundaries. This technique is described by Martinsen and Engedahl (1987).

4.2.2 The Transport Model

The transport processes were modelled by a simple Lagrangian particle tracking model developed at IMR. A more comprehensive description of this model will be given in Ådlandsvik (1994). The model is driven by the stored current velocity fields from the hydrodynamic model. These fields are interpolated in time to the internal time step of the transport model, and used to move the particles to their next position in an Euler forward way. Spatial and temporal variability in the current leads to a spreading of the particles. Further diffusivity is added by giving each particle a random walk velocity every time step. The standard deviation of this velocity distribution depends on the eddy diffusion coefficient and the time step.

In this study the particles are not allowed to be moved on land. If the computed advection velocity would put the particle on land, this velocity is halved repeatedly until the particle ends up in a sea position. Similarly for the random walk diffusion step, if this would put the particle on land, a new random step of smaller variance is chosen repeatedly until the new position is at sea.

A concentration field can be computed from the particle distribution. Here this is done horizontally by summing up a bell-shaped function for each particle. This depends on an influence radius, the width of the bell. The influence radius may depend on the age of the particle. This gives another way to parametrize diffusion, where the mass of an old particle is spread out over a larger area. To obtain concentrations per volume the distribution is averaged over the actual depth interval.

4.3 Model setup

4.3.1 The Hydrodynamic Model

For this study the hydrodynamic model was driven by density gradients and wind forcing. Tidal forcing was not taken into account. The density fields were taken from the monthly climatology for the Nordic Seas compiled by Ottersen and Ådlandsvik (1993). This is mainly based on the global climatology by Levitus (1982). The model was run in diagnostic mode, this means that the equations for salinity and temperature were not solved. These fields were instead interpolated in time from the climatology. The meteorological forcing was taken from the Hindcast Archive of DNMI (Eide *et al.* 1985). Here wind and air pressure data are given on a 75 km grid every sixth hour. The model was run for the three months May, June and July 1992. The initial water level and current description are taken from Martinsen *et al.* (1992). These fields have been obtained by running the model diagnostically without wind forcing. These fields are also used at the open lateral boundaries of the model.

The model area is shown in Fig. 4.1. It consists of horizontal grid cells of size 20 km. In the vertical 17 σ-levels were used with increased resolution near the surface and bottom. The levels were at 0, 0.5, 1, 3, 6, 10, 20, 40, 60, 70, 80, 85, 90, 94, 97, 99 and 100% of the water depth. Sea surface elevation and all three velocity components were stored at all levels every day at 00.00 GMT. In addition vertical profiles of horizontal velocity, vertical eddy viscosity, salinity, temperature and horizontal eddy viscosity from the two grid cells closest to the submarine were stored every hour.

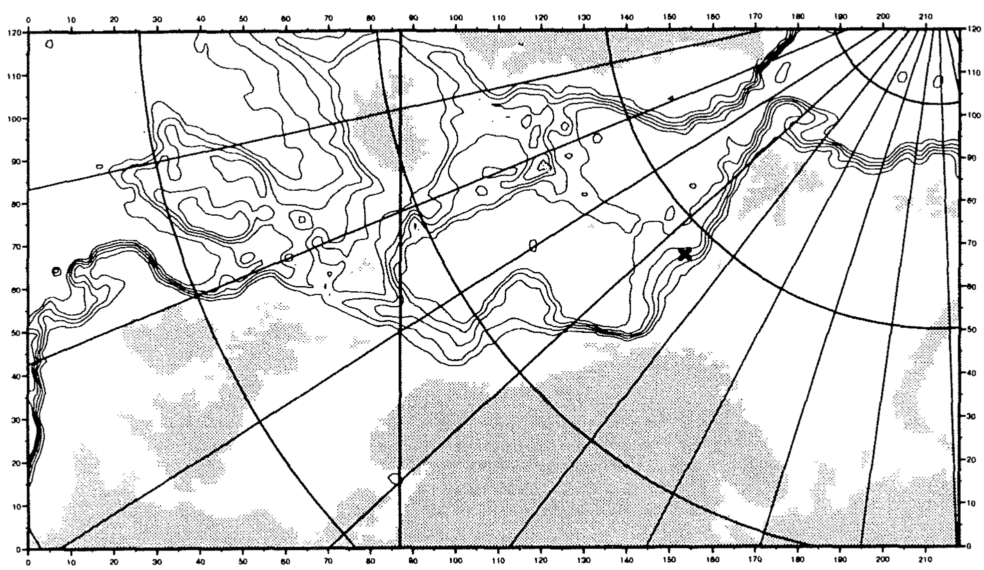

Fig. 4.1 Model domain with bathymetri.

4.3.2 The Transport Model

The transport model was run on the smaller domain to the right of the vertical bar in Fig. 4.1. In coordinates of this subgrid the submarine position is (66.16, 68.12). This belongs to grid cell (67, 69) which in our bottom matrix has a depth of 1969 m. The particles were therefore released at the center of the adjacent cell (67, 68) where the model depth is 1751 m. This position is marked with a "X" in Fig. 4.1. The release depth is at 1730 m. The release rate was 10 particles daily. To obtain a longer simulation time than the three months with current input from POM, this input was repeated cyclically. The total running time was 600 days. The internal time step were 6 hours.

For diffusion constant values of 100 m^2s^{-1} were used horizontally and 10^{-4} m^2s^{-1} vertically. To compute the concentrations the horizontal influence radius increases with time. This corresponds to an additional horizontal Fickian diffusion of 100 m^2s^{-1}, see Ådlandsvik (1994).

Two different runs were performed with the transport model. In run A all three velocity components were used for the advection. In run B the vertical advection was set to zero. All other parameters were the same for the two runs.

4.4 Model results

4.4.1 Results from the Current Model

Fig. 4.2 shows a snapshot of the model current at 98 % of the bottom depth. The model current at this depth is rather weak. The most prominent feature is the shelf edge current following the isobaths cyclonically around the deep part of the Nordic Seas. In particular, on the shelf edge west of the Barents Sea the current flows northwards into the Polar Ocean and continues eastwards along the northern break of the Barents Sea. Qualitatively, this circulation picture looks reasonable.

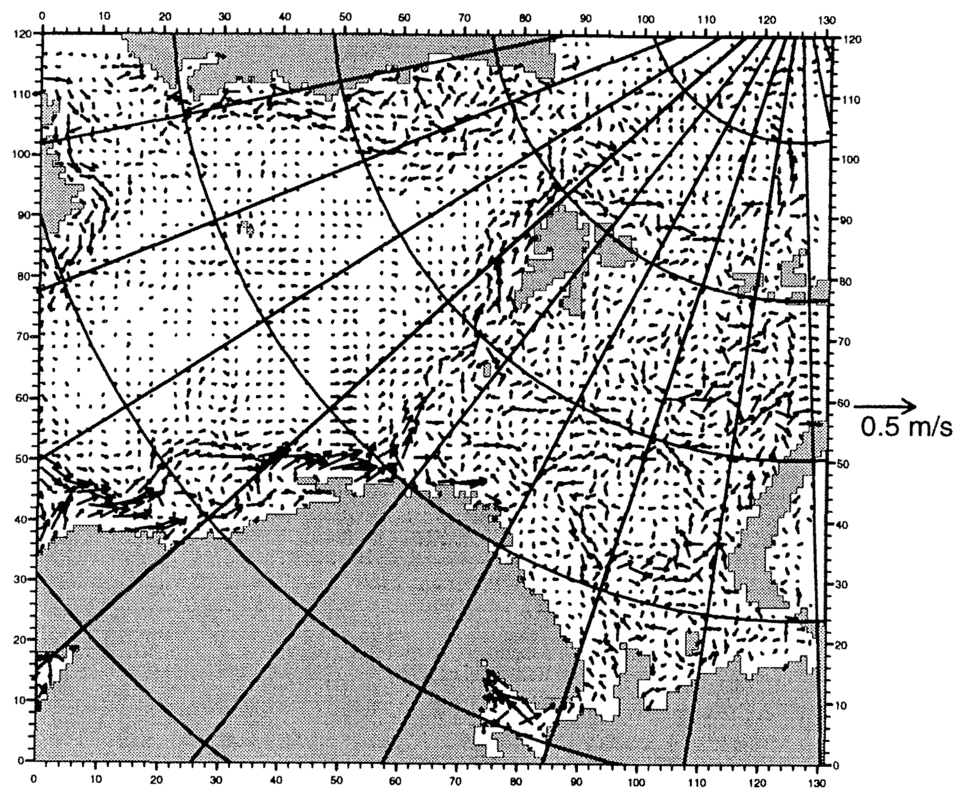

Fig. 4.2 Modelled current field 1 May 1992 at 98 % of the bottom depth.

Fig. 4.3 show the model current at 1716 m (98% depth) in the center of the particle release grid cell (67,68) for the model period (May, June, July 1992). Note that the current components are in the grid directions, not east and north. The current is quite stable towards north-east, with velocity about 0.05m s^{-1}. This is similar to what one would expect, but current measurements from the same months in 1993 (Chapter 3) show a stronger and more variable current with residual towards the south.

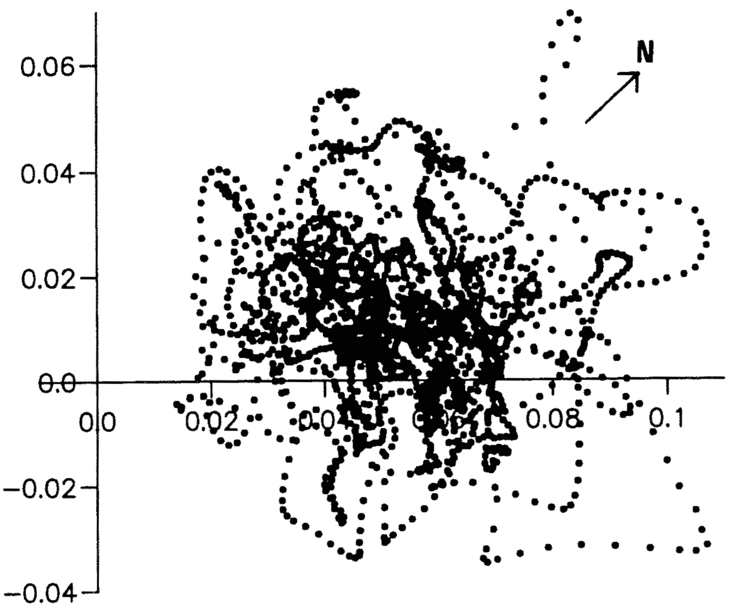

Fig. 4.3 End points of model current vectors in grid cell (67, 68) at 1716 m from May-July 1992. The axes are in the grid direction and the unit is ms^{-1}.

4.4.2 Results from Run A with the Transport Model

The left panel of Fig. 4.4 gives a horizontal view of the 3010 particles after 300 days together with bottom contours every 500 m. The right panel shows the derived depth integrated concentration field. The outermost isoline is at 0.01 particle per cell. For each succeeding isoline the level is multiplied by a factor of $\sqrt{10}$.

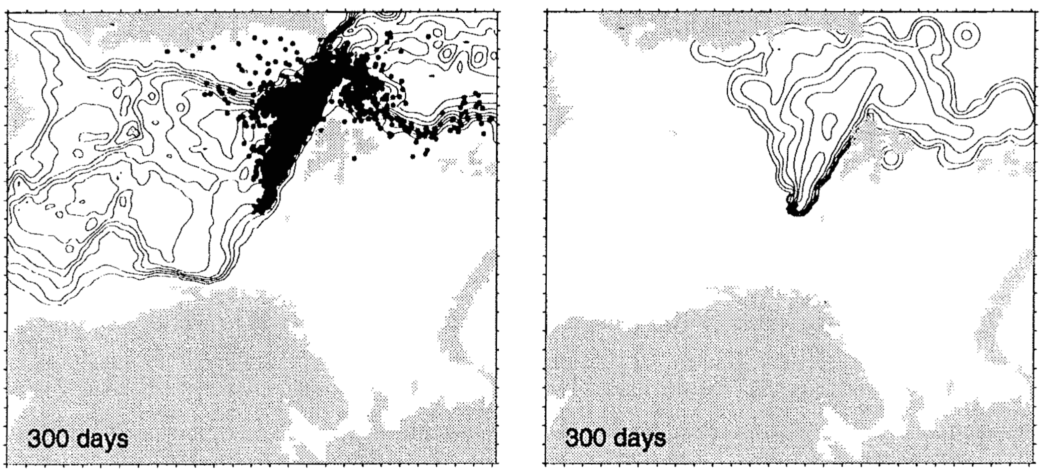

Fig. 4.4 Run A: Horizontal particle distribution and corresponding depth integrated concentration after 300 days. The contours in the left panel are isobaths every 500 m.

The particles have been transported northwards. A major branch enters the Polar Ocean and turns east along the northern Barents Sea shelf break. The particles spread out and cover the deep area between the Barents and East Greenland shelves. On the Greenland side some particles have turned southwards and some of them have entered the shelf. The concentration panel in Fig. 4.4 shows peak concentration of particles per grid cell in the submarine grid cell and an elongated high concentration plume west of Svalbard.

For each particle its depth (from the surface) and its height (over the bottom) is recorded. The frequency distribution for each 100 m interval in percentage of the total is shown in Fig. 4.5 after 300 days. The peak of the distribution is in the release interval 1700--1800 m. But the distribution is spread out over the whole water column with a secondary maximum in the top 100 m. The right panel shows that nearly 50% of the particles are situated less than 500 m above bottom with peak concentration in the lowest 100 m. The rest of the particles are spread out up to 3000 m above the sea bed.

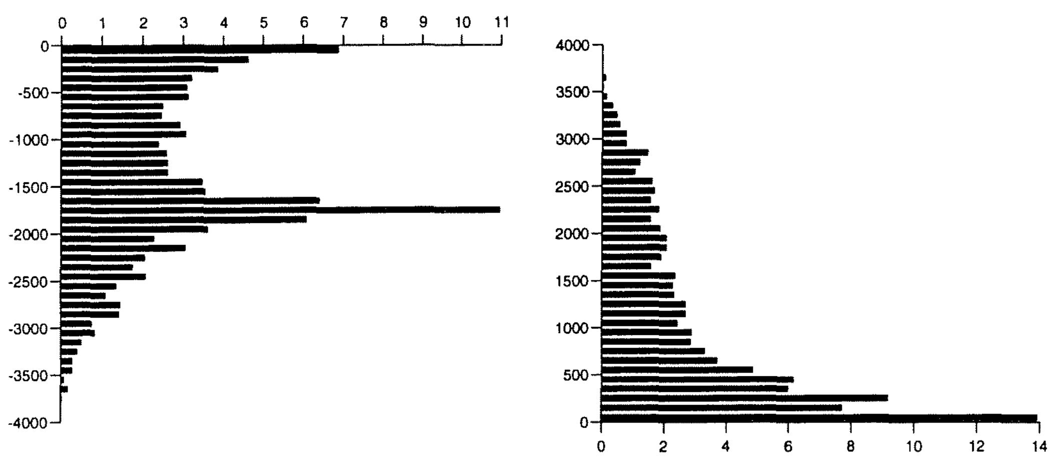

Fig. 4.5 Run A: Vertical frequency distribution of depth and height over bottom of the particles after 300 days.

The vertical distribution in the grid cell (77,87) west of Svalbard is shown in Fig. 4.6. The depth in this cell is 1739 m. The maximum concentration is at the release level. The particles has spread out over the whole water column as in the general picture (Fig. 4.5).

Fig. 4.7 shows the horizontal concentration fields for the depth interval 0--100 m (left) and 1700--1800 m (right) after 300 days. These are the depth levels with the most particles as shown in Fig. 4.5. In these plots the outermost isoline is at 10^{-14} particles/m^3 and for each succeeding isoline the level is multiplied by 10. In the top layer the concentration is zero at the submarine position. The maximum concentration is found to the north with a value of $1.6 \cdot 10^{-11}$ particles/m^3 in grid cell (84,100). The extent of the concentration field is similar to the depth averaged picture (Fig. 4.8), but the concentrations are higher near the boundary of the field. In the release interval 1700-1800 m the peak concentration is in the submarine cell. The direction of the transport is the same but the velocities are smaller.

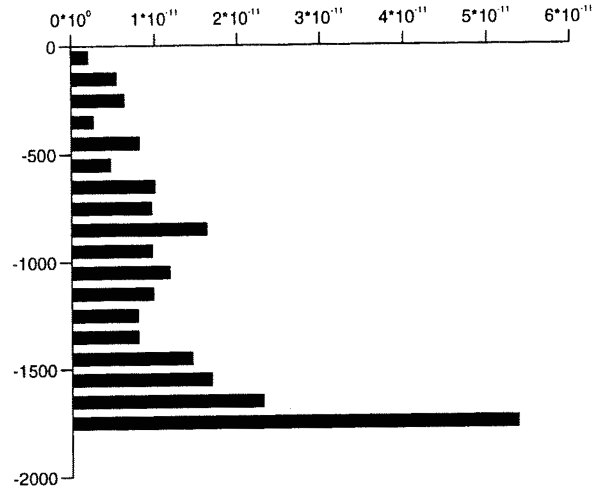

Fig. 4.6 Run A: Vertical distribution of concentration in grid cell (77, 87).

The time evolution of the vertical integrated concentration field is depicted in Fig. 4.8. After 200 days the concentration has progressed northwards and is entering the Polar Ocean. This trend continues during the rest of the period, but the spreading and southwards transport near East Greenland becomes more prominent with time. In the last planes the field has reached Iceland. After 400 days a few particles enter the Barents Sea shelf from north. The extent of the highest concentration levels seem to approach a stationary state.

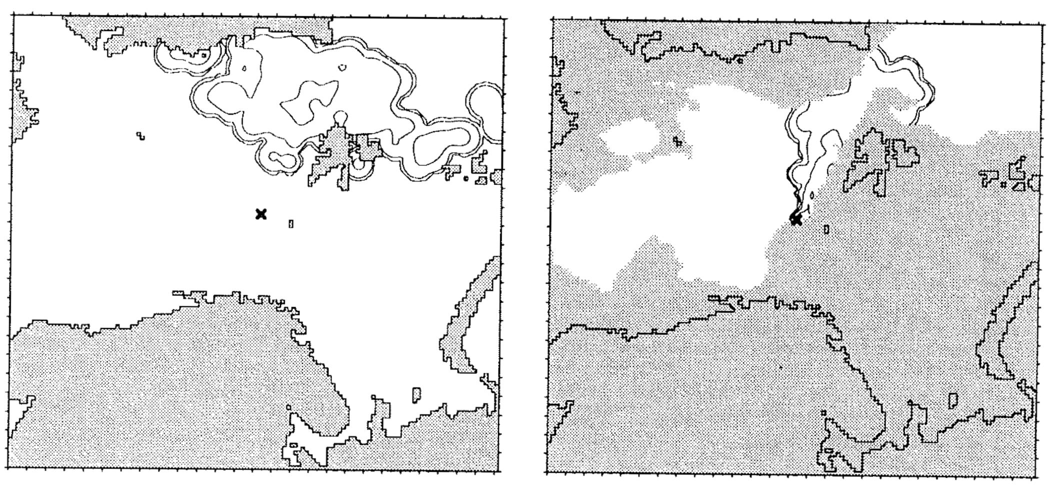

Fig. 4.7 Run A: Concentration field in depth intervals 0-100 m (left) and 1700-1800 m (right) after 300 days.

4.4.3 Results from Run B

In run B the vertical advection was turned off. The vertical diffusion was still included. The figures presented here are comparable with the figures from run A. The horizontal projection of the distribution after 300 days is given in Fig. 4.9. The particles have been transported northwards and are entering the Polar Ocean. The distribution is spread out over the Fram Strait region between Spitzbergen and Greenland but is limited off shelf by the 1500 m isobath. The highest concentrations are found close to the submarine and northwards west of Svalbard. The maximum depth integrated concentration is particles is 46.5 particles per grid cell in the submarine grid cell.

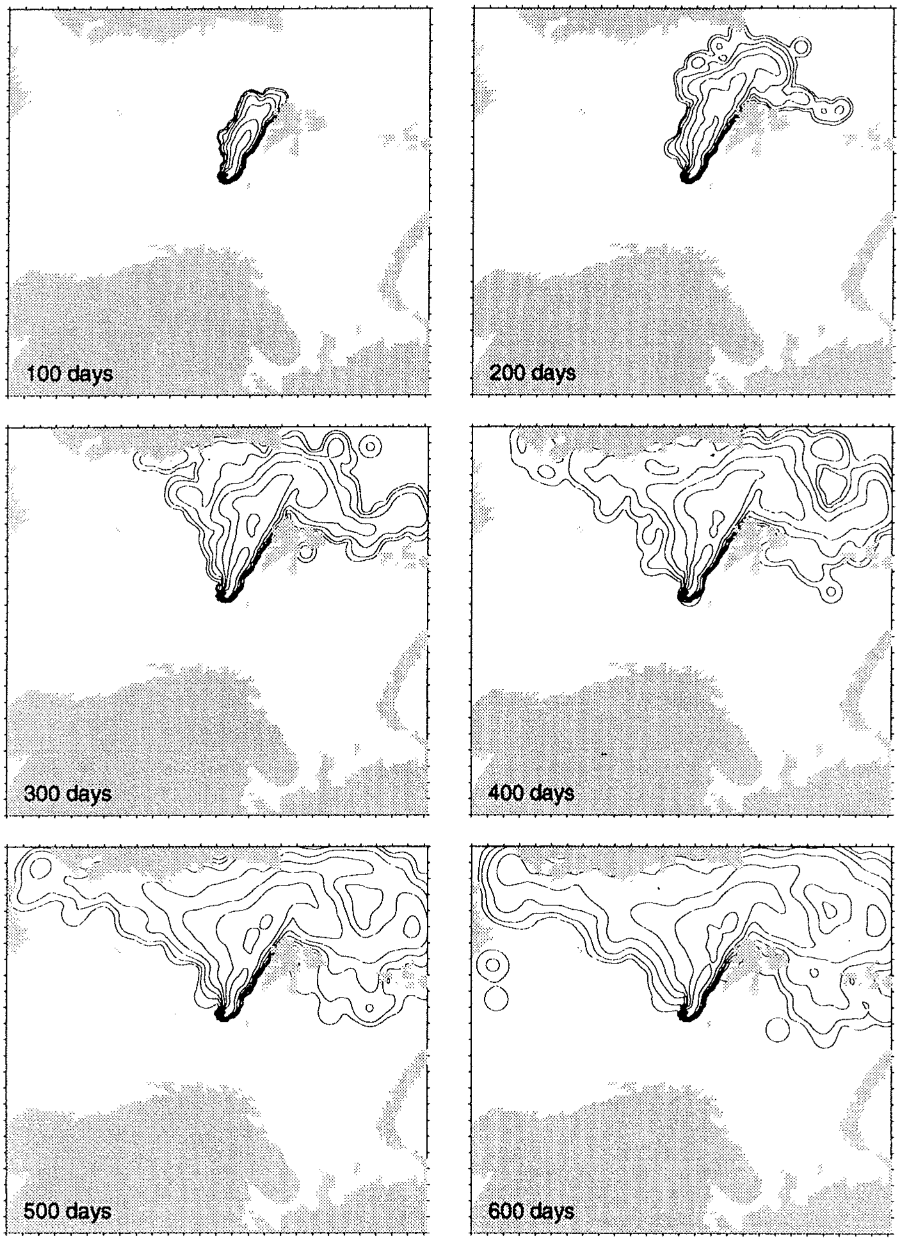

Fig. 4.8 Run A: Time evolution of the vertical integrated concentration.

The vertical distribution after 300 days is presented in Fig. 4.10. It shows a narrow peek with more than 50 of the particles remaining in the release depth interval 1700--1800 m. Viewed from the bottom up, the particles are distributed more or less uniformly in the lowest 1500 m. The peak at the release level is even more pronounced in the vertical distribution at grid cell (77,87) as depicted in Fig. 4.11.

The concentration field in the release level 1700--1800 m after 300 days is given in Fig. 4.12. The maximum concentration is in the submarine cell, the same as in run A. The concentration at this depth is higher in run B since almost 70% per cent of the particles are still at this level. Except from some singular particles in run A, the extent of the fields are similar.

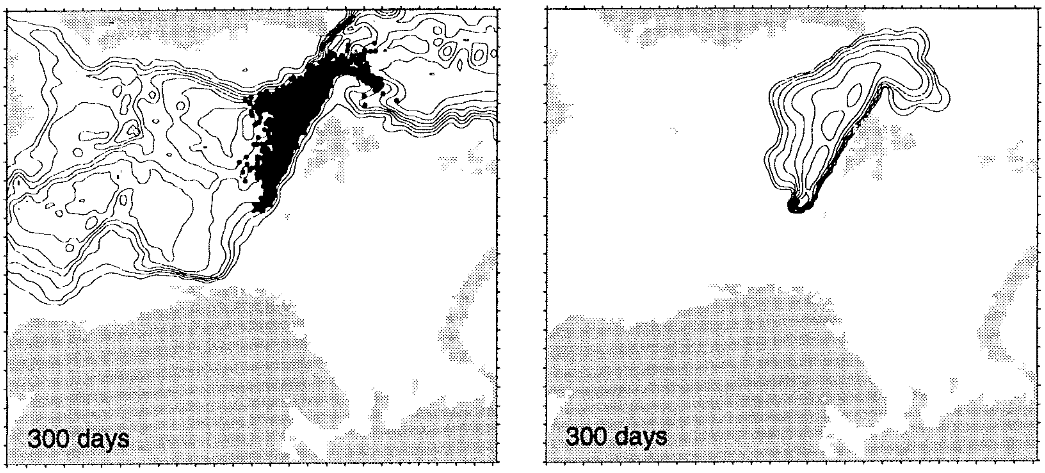

Fig. 4.9 Run B: Particle distribution and corresponding concentration after 300 days.

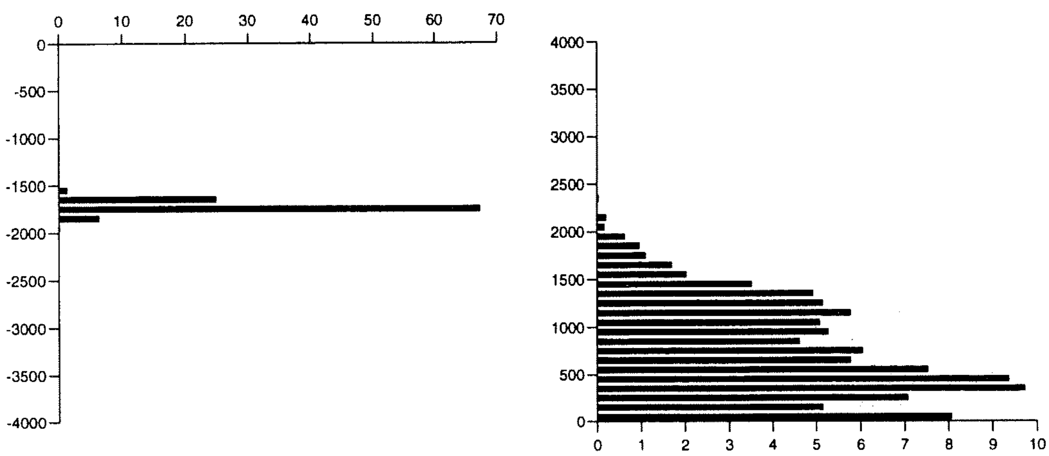

Fig. 4.10 Run B: Vertical frequency distribution of depth and height over bottom of the particles after 300 days.

The time evolution in run B is shown in Fig. 4.13. The main transport is northwards and into the Polar Ocean. With time the concentration spreads out and reaches the East Greenland shelf break and the associated southward transport. No particles enters the Barents Shelf in this case.

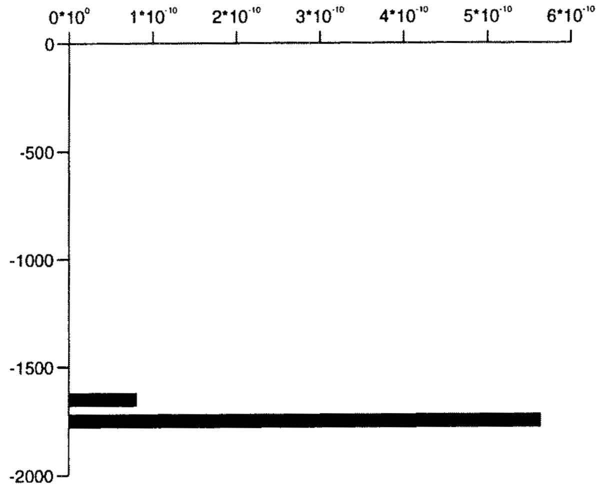

Fig. 4.11 Run B: Vertical distribution of concentration in grid cell (77, 87).

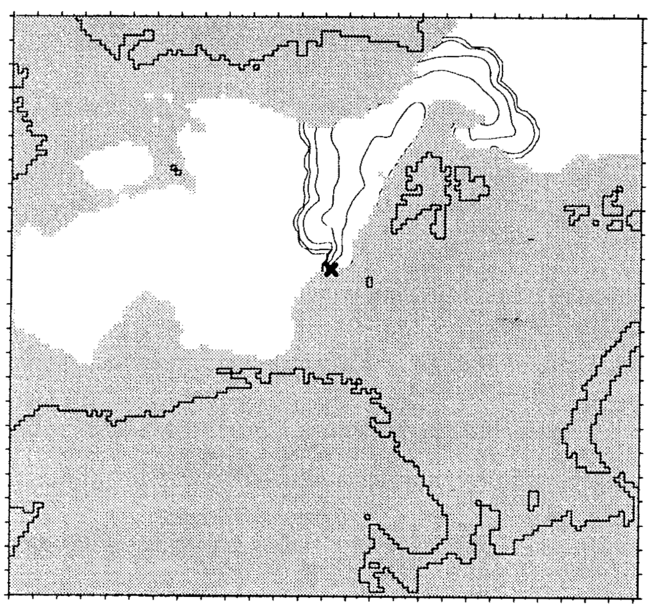

Fig. 4.12 Run B: Concentration field in depth interval 1700-1800 m after 300 days.

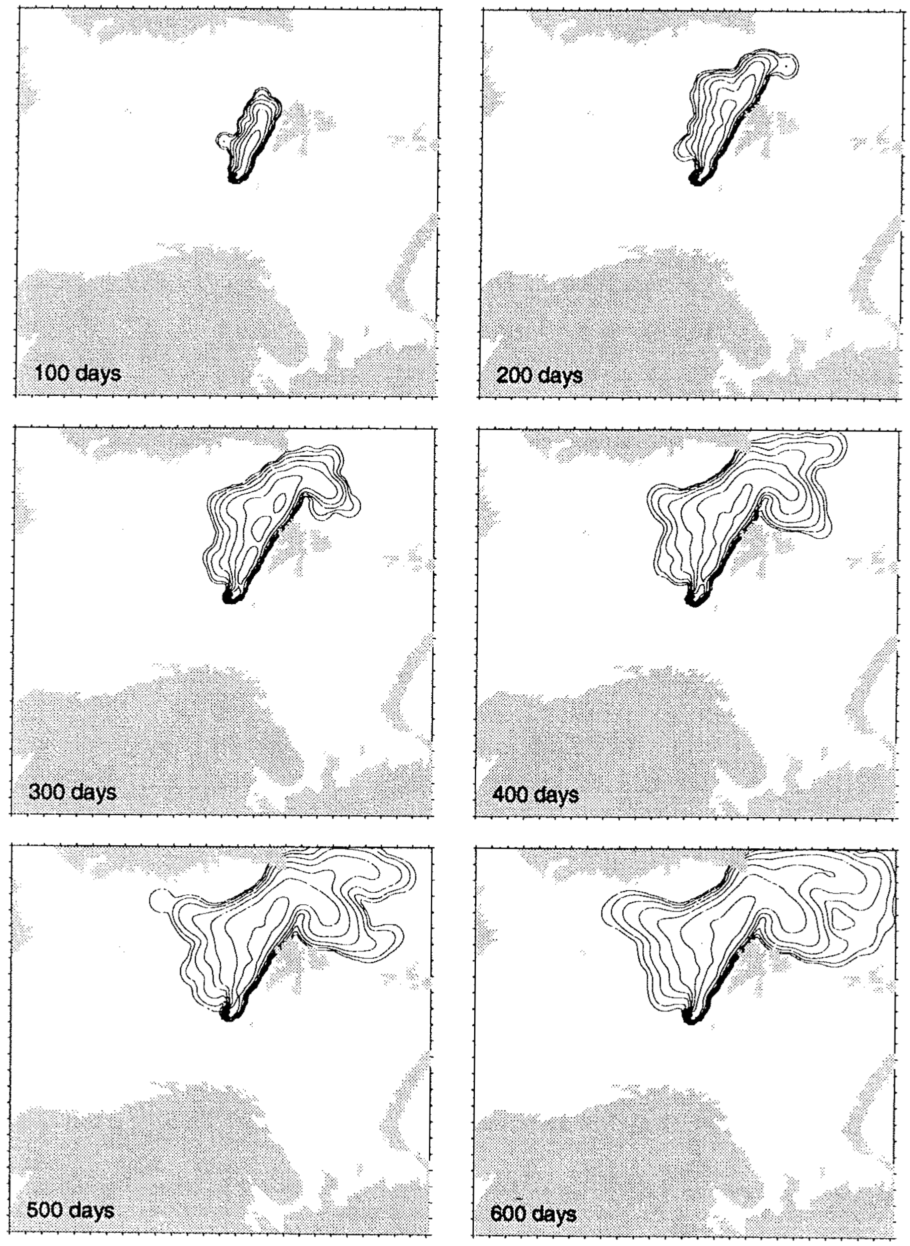

Fig. 4.13 Run B: Time evolution of the vertical integrated concentration.

4.5 Discussion

The vertical advection in run A lead very rapidly to relatively high concentrations near the surface. Such transport of water from 1700 m to the surface is not consistent with the observed salinity and temperature structures.

The vertical current in the model depends on the near bottom cross-isobath current component and the horizontal divergence of the current field. Too large a current across the isobaths might be caused by problems with the sigma-coordinate system in regions with strong bottom slope. A probably more important cause of the error is that the current model was run in a diagnostic mode. Imbalances in the density field can create convergence in the horizontal current which leads to an upwards transport. In nature and in a prognostic simulation this uplift of heavier water will increase the pressure and thereby counteract the convergence. Keeping the pressure field constant makes the imbalance permanent.

In an attempt to avoid the problem above a new run B of the transport model was performed with the vertical advection turned off. In this run, the particles tended to stay at the release depth. In this case transport associated with bottom current across the isobaths was not handled realistic. For further numerical studies the hydrodynamic model will be run in prognostic mode.

The diffusion part of the transport model distinguishes between horizontal and vertical mixing. Physically more correct would be to distinguish between the isopycnal and the diapycnal directions. This can be achieved in the transport model by a rotation of the mixing tensor, but this feature has not been implemented yet. In regions where the isopycnals are strongly sloping this effect leads to an increased vertical mixing component. Because of the vertical gradient in the concentration this gives a net transport upwards.

The differences between runs A and B show that the model results are sensitive to the uncertainties in the vertical transport. The near surface particles in A experience stronger and more variable currents leading to a more rapid transport and wider distribution.

The two runs may be viewed as extremes regarding vertical behaviour. Common features might therefore be valid for a large range of possible vertical treatments in the model system. Such common features are the transport direction towards North, the largest portion entering the Polar Ocean and that none or very few of the particles are transported onto the Barents Shelf. Regarding the East Greenland Shelf the results in the two runs are different and no conclusions can be drawn.

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5. VERTICAL TRANSPORT FROM A HOT SOURCE

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5.1 Introduction

During the first months after the "Komsomolets" accident, there were speculations on the possibility of some nuclear reaction continously taking place. If so, it was assumed that this could represent a heat source of the order of 1-10 MWatt. This would cause an upward flux of water or a plume similar to the smoke from a chimney. The questions were how high this water would rise before levelling out and could it possibly rise to the sea surface?

When seawater is heated at the bottom, its density is reduced so that it rises due to the buoyancy force. This is proportional to the density difference $\Delta\rho(z)$ between the surrounding watermasses and the plume. When the water within the plume is rising, a continuous entrainment of the surrounding watermasses will occur, such that the density difference (and thereby the buoyancy force) gradually decreases. The plume will rise to the level z (z=height above bottom) where $\Delta\rho(z)\rightarrow 0$ or, if this does not happen it will rise to the surface.

A simple model was developed to simulate this process, and for simplicity it was assumed there were zero currents in the surroundings. In the literature there are different opinions about the intensity of entrainment, with the entrainment parameter C (see below) varying typically between 0.06-0.14. We have here chosen a constant of C=0.08, although it can be argued that this should vary with the varying kinematics as a function of depth (Turner, 1973, p. 173).

5.2 Model formulation

Conservation of mass and volume gives:

1) $$\rho q + \rho_\omega \delta q = (\rho + \delta\rho) * (q + \delta q)$$

where δq and $\delta\rho$ are the increase respectively in the volume transport ($q=\pi r^2 w$) and density (ρ) within the plume over a vertical distance δz, ρ_ω is the density of the surrounding water masses, r is the radius of the plume assumed to be circular, and w=w(z) is the horizontal mean vertical velocity.
Deleting the second order term in 1), gives:

2) $$\rho_\omega dq/dz = q\, d\rho/dz + \rho\, dq/dz$$

Solving the equation with respect to $\Delta\rho = \rho_\omega - \rho$, gives:

3) $d/dz\,(\Delta\rho) = -\,1/q\; dq/dz\,(\Delta\rho) + d\rho_{\omega}/dz$

After Svendsen (1978), a constant entrainment coefficient is defined:

$$C_1 = 2\gamma\, Ueo/Wo = 2\gamma\, Ue/w$$

where γ is assumed as a constant (between 1 and 2) depending on the velocity distribution within the plume and Ue is the entrainment velocity at the "plume wall". Index o relates to z=0 (at the submarine). Integration of the continuity equation gives:

4) $dq/dz = Ue * 2\pi r = 1/\gamma r * C_1 * q = C/r * q$, which incerted in 3) gives:

5) $d/dz\,(\Delta\rho) = -\,C/r^* (\Delta\rho) + d\rho_{\omega}/dz$

We choose to solve 5) by use of numerical integration, such that:

6) $\Delta\rho_{i+1} = \Delta\rho_i + \Delta(\Delta\rho)_i = \Delta\rho_i\,(1 - C/r_{i+1} * \Delta z) + \rho_{\omega i+1} - \rho_{\omega i}$

The density profile $\rho_{\omega}(z)$ in the area was measured just after the accident by the Institute of Marine Research, Bergen, Norway, and a good approximation is given by the equation:

$\rho_{\omega}(z) = 28.082 - 5.73 * 10^{-6} * z + 5.94 * 10^{-9} * z^2 + 5.76 * 10^{-11} * z^3$ graphically shown in Fig. 5.1.

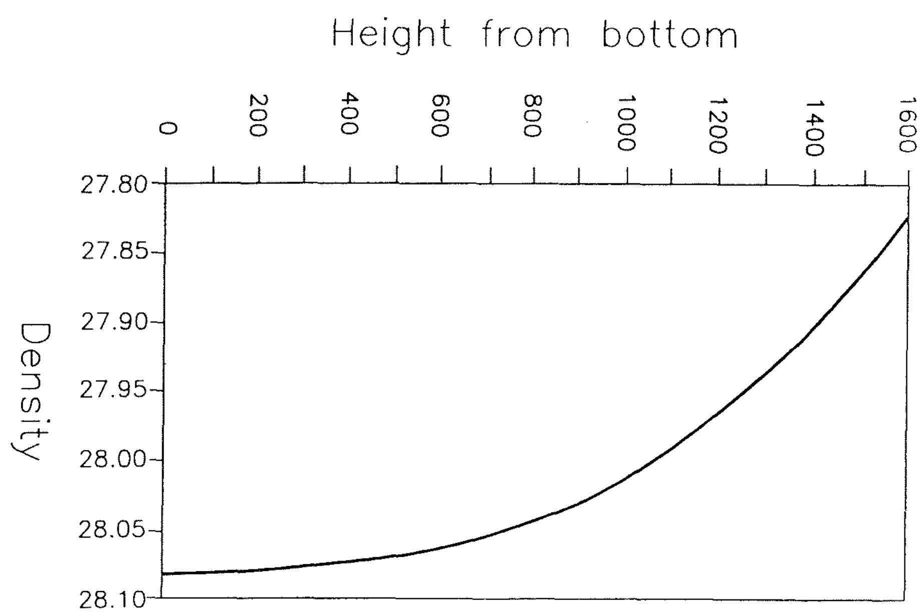

Fig. 5.1 Typical density profile at the submarine location.

To find the initial condition $\Delta\rho_o$ related to a given heatflux H (watt) from the submarine, we have:

7) $$H = c_p q_o(\rho_o T_o - \rho_{\omega o} T_{\omega o}) = c_p q_o(\rho_\omega \Delta T_o - \Delta\rho_o T_o) \approx c_p q_o \Delta T_o * 10^3$$

where $\Delta T_o = T_{\omega o} - T_o$, c_p is the specific heat capacity, and the following approximation is used:

8) $\Delta\rho_o = 0.09\Delta T_o + 0.005\Delta T_o^2$ (deduced from tables in Neumann & Pierson, 1966).

To find q_0, the vertical equation of motion is integrated, and defining the interface where $w \rightarrow 0$ (Svendsen, 1978, Magnusson, 1985), this gives:

9) $$\gamma(q\, dW/dz + W\, dq/dz) = g\pi r^2 \Delta\rho/\rho$$

After some calculation, equations 4 and 9 give:

10) $$q_o^2 = \Delta\rho_o * (\pi^2 g\, r_o^5) / \rho_o C\gamma$$

where gis the acceleration of gravity. From equations 7, 8, and 10 with inserted typical values one arrives at:

11) $$0.09\Delta T_o^3 + 0.005\Delta T_o^4 = 4H^2 * 10^{-14} * r_o^{-5} = \Delta T_o^2 * \Delta\rho_o$$

From equations 4 and 9, we also find:

12) $$dr/dz = C - \Delta\rho * (\pi^2 g\, r^5) / (2q^2 \rho C\gamma)$$

(If $dw/dz << dr/dz$, we find from equations 9 and 4 that $r = r_0 + 0.5Cz$).

We can now calculate $\Delta\rho_o$, (given r_0 and H), which are used as starting criteria in equation 6 to solve $\Delta\rho$ as a function of z (height from bottom). At the same time equation 12 and 4 are solved numerically. We see that $\Delta\rho_o$ is very dependent on r_0, i.e. whether the heat from the submarine is released to the environment through a larger or smaller area, while the reduction of $\Delta\rho$ with increasing height mainly is steered by the entrainment coefficient C.

5.3 Results

Solutions for $\Delta\rho$ as a function of z for different values of r_0 are shown in Fig. 5.2, where we have used H=10MWatt. (NB! Figs. 2a,b,c shows the results plotted with different scales on the axis). It is important to notice here that whatever choise of r_0, the plume at maximum rises to about 500 m above the bottom (with this typical density profile of the surrounding water masses). The figure legend also shows the temperature differences ΔT_o calculated from Eqs. 10 and 11 for different choices of r_0 (0.3m, 0.4m, 0.5m, 0.7m, 1.0m, 2.0m, 4.0m). Density differences are given in kg/m^3). If all the energy is released through a small plate with radius of 0.3m, the initial plume temperature would be above 50 ^{0}C, while if released through a much larger area of radius 4 m, the initial temperature increase would only be slightly above 1 ^{0}C. The thickest plume is estimated to reach to about 400 m and the thinnest (warmest) to about 520 m above the bottom.

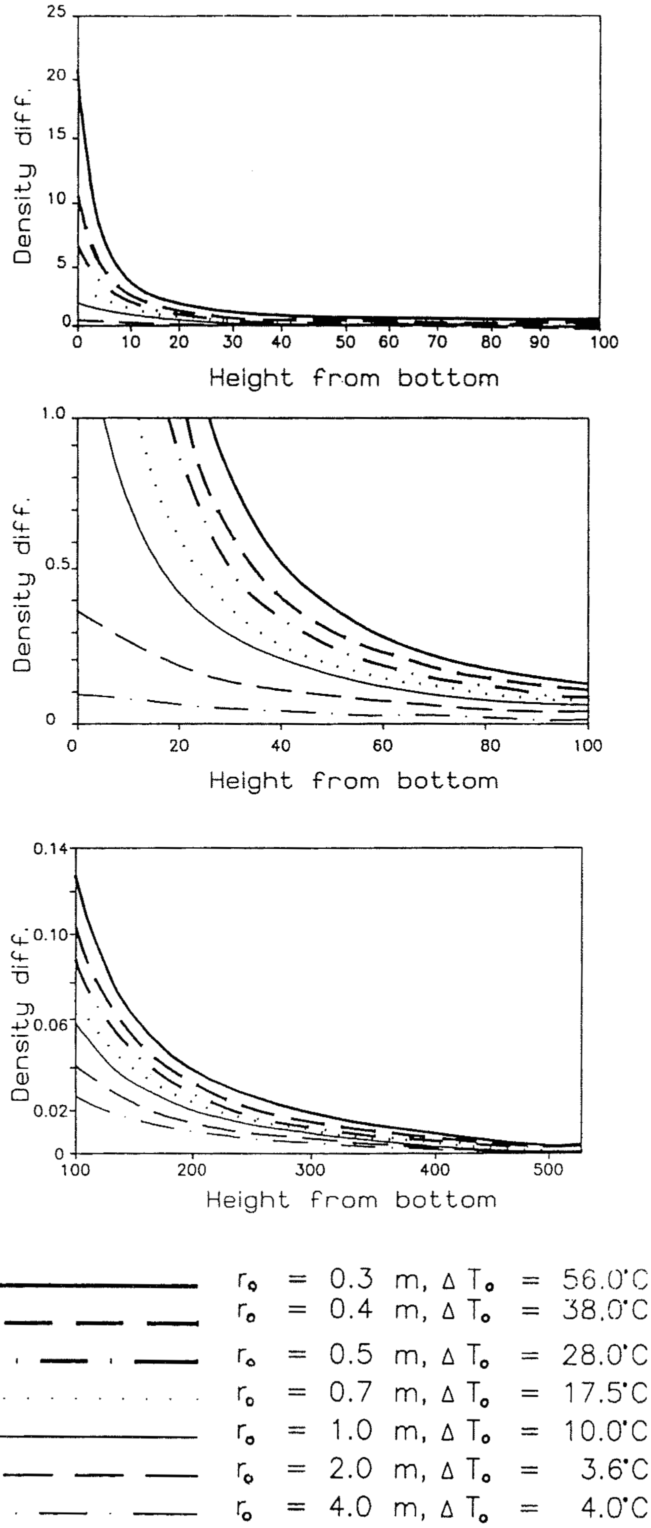

Fig. 5.2 Density differences (kgm^{-3}) between surrounding water and the plume as a function of height from the bottom (for different initial radii and temperature differences).

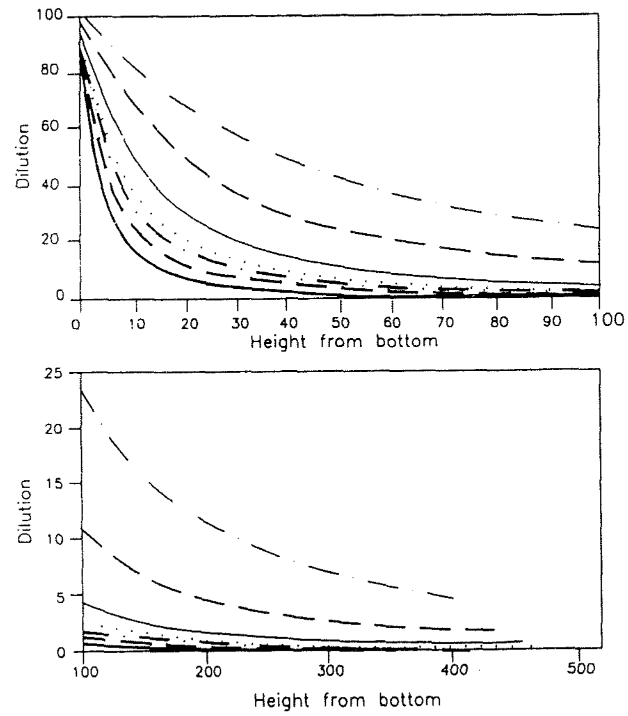

Fig. 5.3 Dilution (%) of plume water as a function of height from the bottom (for different initial radii, curve def. as in Fig. 5.2).

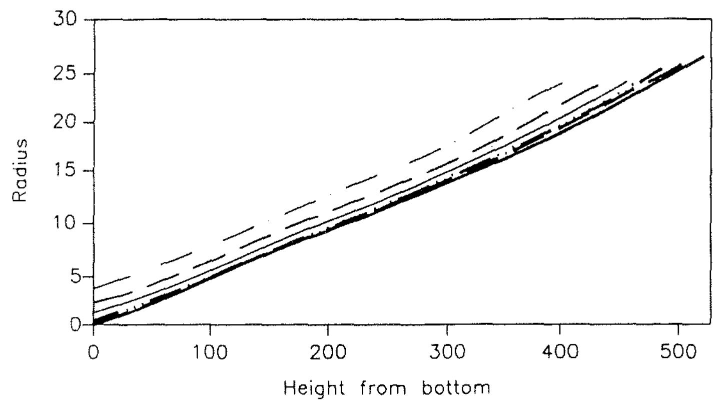

Fig. 5.4 Plume radii (m) as a function of height from the bottom (for different initial radii, curve def. as in Fig. 5.2).

The dilution due to entrainment (in %, defined as q/q_0) is shown in Fig. 5.3 from 0-100 m and from 100 m to maximum rising height. The dilution occurs as expected much more rapidly with an initially thin plume compared to the thickest plume which near maximum height still transports 5% of the initial water masses at the submarine.

The increases of the plume radius (Fig.5.4) demonstrates an approximate linear increase to maximum 25 m independent of the choice of initial radius r_0. The linear increase confirms as earlier mentioned that dw/dz<<dr/dz, agreeing with Turner (1973). Clearly, strong currents could significantly disturb such a regular cone-shaped plume.

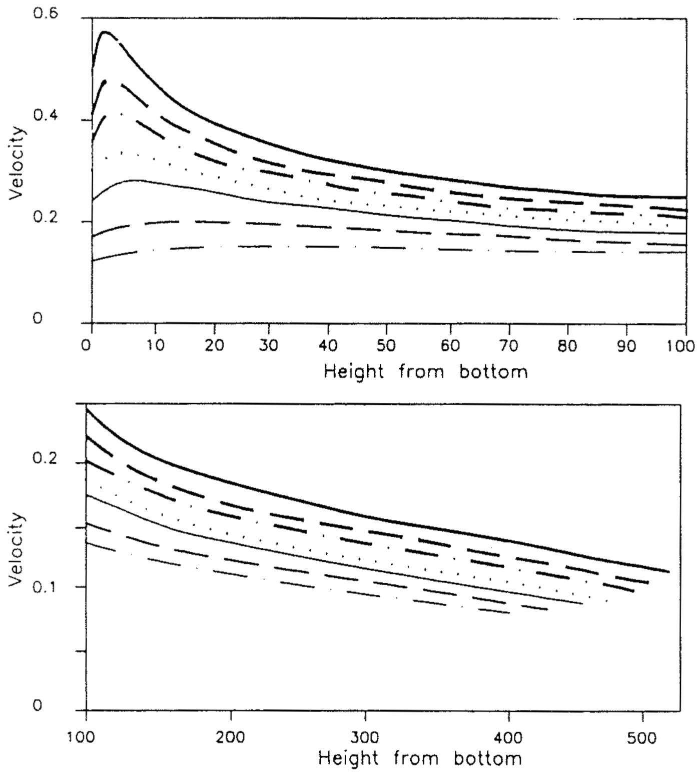

Fig. 5.5 Varying plume rising speeds (ms-1) as a function of height from the bottom (for different initial radii, curve def. as in Fig. 5.2).

The vertical rising speed (m/s) is given from 0-100 m and from 100 m to maximum rising height in Fig. 5.5. During the first few meters the speed increases (especially for the thinner plumes) decreasing thereafter. At maximum rising level a rapid decrease in the upward velocity would be expected, however at this level the plume water will rapidly spread horizontally (possible connected with internal waves), and this motion is not represented by this simple model.

Finally the increasing volume transports (m^3/s) are shown in Fig. 5.6. As above this should also decrease rapidly at maximum height, however this could not be resolved by the model for the same reason as above.

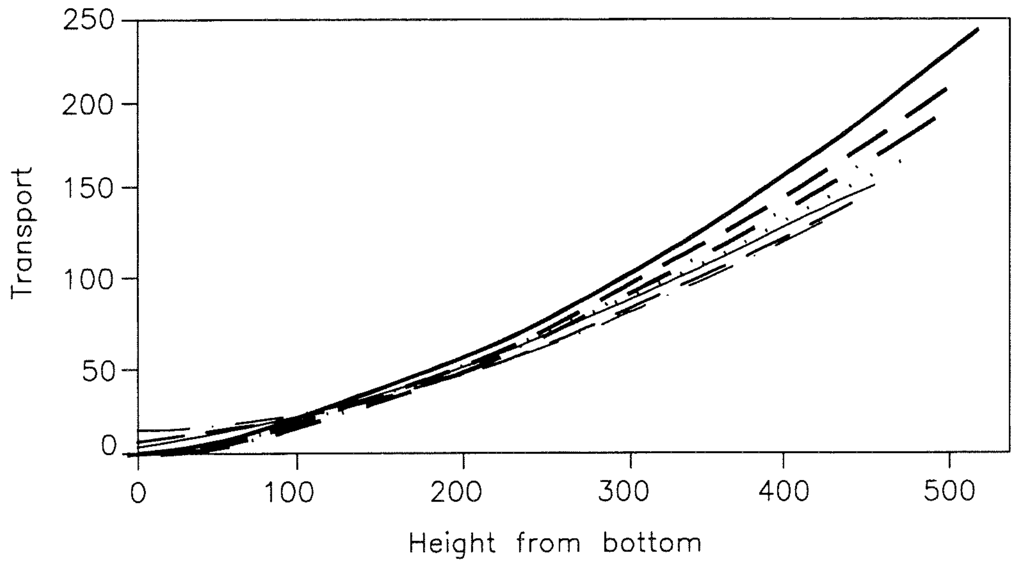

Fig. 5.6 Volume transports (m^3s^{-1}) as a function of height from the bottom (for different initial radii, curve def. as in Fig. 5.2).

5.4 Conclusion

Assuming the submarine might represent a 10 MWatt heat source, a hot plume, possibly containing radioactive material, would rise to a maximum height of about 500 m above the bottom. This is based on a simple model assuming the entrainment parameterization well documented in the literature is correct, and that the typical vertical density structure always is present. Clearly the only way such a plume could reach the surface would be if the surrounding water masses became quite vertically homogeneous, which is highly unlikely in this area.

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