Climatic importance of large scale and mesoscale circulation in the Lofoten Basin deduced from lagrangian observations during ASOF

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1. Introduction

The Nordic Seas (Norwegian, Iceland and Greenland Seas) is one of the regions that have been best covered and continuously monitored with hydrographic observations. The view of the large-scale ocean circulation in the Nordic Seas has traditionally been based on hydrography due to the relatively few direct current measurements. It has been known for a century that the ocean circulation in the Nordic Seas is influenced by the basin topography (Helland-Hansen and Nansen 1909). However, the large number of surface drifters that have been released during the last 10-15 years have increased our knowledge of the surface circulation in the Nordic Seas (Orvik and Niiler 2002). The main features of the upper circulation in the Nordic Seas are a northward flow of warm water on the eastern side and a cold current flowing southward on the western side (Helland-Hansen and Nansen 1909). The flow of warm waters into the Nordic Seas represents the final poleward transport of the global thermohaline circulation system before being transformed by cooling processes into intermediate and deep waters that flow back into the North Atlantic. As the Figure 6.1 shows, two main branches of warm, saline Atlantic water of approximately equal magnitude enter the Norwegian Sea.

Fig. 6.1

The Norwegian Atlantic Current (NwAC) is revealed as a two branch current system through the entire Norwegian Sea (Poulain et al. 1996; Orvik and Niiler 2002). The eastern branch follows the shelf edge as a barotropic slope current while the western branch is a polar jet current associated with the Arctic Front (Orvik et al. 2001). While the inshore branch passes north against the Norwegian Continental Slope and is covered by current meter arrays in the Faroe–Shetland Channel, off Svinøy, across the Barents Sea Opening and in eastern Fram Strait, the offshore branch, passing north through the Norwegian Sea as a free jet, is unmeasured. Both will be involved in the spread of warmth to the Barents Sea and Arctic Ocean, and the issue of determining what might control this warm, saline flux and its variability is of such central importance to understanding the imposition of change on the Arctic Ocean from subarctic seas that its solution must be of first priority. Yet although Orvik and Skagseth (2003) have now recovered lengthy (10-year) time-series of transport for the along-Slope branch and have developed some sense of its local and remote forcing, the offshore jet and its forcing remain less known. A mix of modern and classical methods has become available to tackle these issues such as floats, gliders, bottom pressure gauges, PIES, remote sensing, conventional hydrography and tracers, profiling CTDs, shipborne and moored ADCPs etc. Here we describe the application of lagrangian techniques for understanding the circulation in this vital area.

2. Hydrographic structures

The general hydrography of the Nordic Seas has been described and reviewed in Blindheim and Østerhus (2005). The transition zone between the domains of the NwAC and the Arctic waters to the West is known as the Arctic Front, located both South and North of Jan Mayen. The front along the Mohn Ridge, northeastward from Jan Mayen, is topographically controlled and shows only small fluctuations in position. The position of the Arctic Front South of Jan Mayen is to a large extent controlled by variations in the volume of Arctic waters carried by the East Icelandic Current (EIC) and thus experiences large shifts (Blindheim et al. 2000).

The Norwegian Sea consists of the Norwegian and Lofoten Basins that have rather different hydrographic conditions. The Norwegian Basin in the South is occupied by Atlantic Water in the East and Arctic waters deriving from the EIC in the West. While Atlantic Water reaches westward ~250 km from the shelf edge in the southern Norwegian Basin it covers the whole ~500 km width of the Lofoten Basin. In the Norwegian Basin, Atlantic water typically reaches to 500 m depth, depending on the sill depth of the Faeroe-Shetland Channel. In contrast the whole Lofoten Basin is occupied by Atlantic Water in the upper ~800 m depth (e.g. Blindheim and Rey 2004; Blindheim and Østerhus 2005). This makes the Lofoten Basin the major reservoir of Atlantic Water. Orvik (2004) explained the difference in the Atlantic Water thickness between the Basins by a deep counter current influencing the northward volume transport of Atlantic Water in Lofoten Basin. The Lofoten Basin is also characterized by a large eddy activity and a long residence time (Poulain et al. 1996).

Fig. 6.2

The hydrographic conditions of the Lofoten Basin and the Greenland Sea are shown in two sections, taken in June 2000 (Figure 6.2). One section, ‘Gimsøy-NW’, runs from the Norwegian coast, crossing the Lofoten Basin, and into the Greenland Sea while the other section, ‘Bjørnøya-W’ (equals to ‘Bear Island-W’), runs westward at 74.5°N from Bear Island into the Greenland Sea (Figure 6.1). Atlantic Water, with salinities above 35 and temperatures above 2°C, reaches down to approximately 700 m depth. The sharp front that separates the Atlantic and Arctic water masses in the Lofoten Basin and Greenland Sea, respectively, is the Arctic Front located over the Mohns Ridge. Arctic intermediate water (AIW) is seen as a tongue between the Atlantic and deep layers with salinities less than 34.90 (Blindheim, 1990).

In addition to the NwAC, the Norwegian Coastal Current (NCC) is a well defined current structure covering most of the shelf regions to the south, west and north of Norway (Figure 6.1). The NCC is mainly characterized by fresh water originating from the Baltic Sea. The NCC fresh water is also tagged by Iodine 129 an anthropogenic tracer originating from nuclear waste re-treatment plant in France (La Hague) and UK (Sellafield) as shown on Figure 6.1.

Fig. 6.3

The hydrographic conditions of the Barents Sea Opening are shown on the Fugløya section (Figure 6.3 upper panels) extending from the northern coast of Norway up to Bear Island 400 km northwards. The NCC fresh water (blue) is clearly visible on the salinity section near the coast of Norway. The NCC anthropogenic tracer Iodine 129 enriched water, clearly identified on the Gimsøy section (lower panel Figure 6.3), is now well spread all over the Fugløya section (Figure 6.3 upper panel) which indicates a very efficient mixing process occurring in the Lofoten Basin. This is also confirmed by a strong dilution of the NCC fresh water (blue) into the NwAC salty water (red) producing a fresher Atlantic current (orange) entering in the Barents Sea. Figure 6.4 shows the remarkable distribution of anthropogenic tracer ratio as function of salinity in the Lofoten Basin along the three sections (Gimsøy, Bjørnøya and Fugløya). The variability of the Iodine ratio depends mainly on the Iodine 129 distribution. A striking split appears in Iodine 129 distribution between Bjørnøya section representing the Fram Strait branch of the NwAC and the Fugløya section representing the Barents Sea branch of the NwAC. Much larger concentration of Iodine is observed in the Atlantic water along the Fugløya section compared to the Bjørnøya section. The Gimsøy section is the sum of the two (before surface fresh NCC waters mix with subsurface salty NwAC waters).

Fig. 6.4

3. Lagrangian observations

The oceans have traditionally been monitored with measurements from ships and moored instruments. Observations from ships are weather- and ice-dependent which means that a preponderance of observations has been made during summer. Collecting oceanographic data of high quality is also both time and effort consuming. The need for systematic and near-real-time monitoring of ocean climate has resulted in an increased attempt to take advantage of new technology. This has led to the development of autonomous floats that can be deployed in areas where there is little cruise activity (and therefore few ship-measurements) and provides measurements throughout the year. In addition, Lagrangian techniques are particularly effective since trajectories provide much detailed spatial information that is almost impossible to get in any other way, including the sensitivity of fluid motion to topography since there is every reason to believe bottom relief plays a major role in shaping the circulation.

3.1 ARGO floats

Within the international Argo programme the Institute of Marine Research, Bergen, has deployed eleven Argo floats in the Norwegian Sea drifting with ocean currents at 1500 m depth. The first floats were deployed in 2002 while the last two floats were deployed in March/April 2006. Of the eleven floats, eight were deployed in the Norwegian Basin while the other three floats were deployed in the Lofoten Basin. However, several floats drifted from the Norwegian to the Lofoten Basin and vice versa. In addition, the last years University of Hamburg deployed more than 20 Argo floats in the Nordic Seas drifting at 1000 m depth. At present there are about 20 active Argo floats in the Nordic Seas drifting at 1000-1500 m depth.

An Argo float drifts passively with the ocean currents at a chosen reference depth, usually at 1500 m depth in the Norwegian Sea. The float is battery driven with a life time of about 4 years and is programmed to ascend to the surface every 10th day. During the ascent it measures pressure, temperature and salinity (i.e. a vertical profile of temperature and salinity) with the potential to add oxygen and fluorescence (chlorophyll) sensors as well. When the float surfaces, the data, together with its position, are sent to land via satellite. The float positions can be used to estimate the ocean currents at the reference depth. After the data are transmitted, the float descends to its reference depth, repeating this cycle every ten days. The data transmission rates are such as to guarantee error free data reception and location, and in all weather conditions the Argo float must, in the Nordic Seas, spend about six hours at the surface. The float positions are accurate to ~100 m depending on the number of satellites within range and the geometry of their distribution.

Fig. 6.5

Trajectories of four Argo floats drifting at a reference depth of 1500 m in the Lofoten Basin are shown on Figure 6.5. The 1500 m reference depth corresponds to the Norwegian Sea Deep Water, below the Arctic intermediate water, with potential temperature less than –0.5 ^{o}C and salinity near 34.91. Two of these floats were deployed in the Lofoten Basin while the other two were deployed in the Norwegian Basin but drifted into the Lofoten Basin. For all four floats a deep cyclonic circulation is revealed in the Lofoten Basin. One of the floats (id: 6900218) circulated cyclonically two and half times around the Basin before ending at the Mohn Ridge nearly 3 years after deployment. The other floats circulated between one and two times around the Basin before ending in the Lofoten or the Norwegian Basin. All floats followed nearly-constant isobaths over long periods. For instance float 6900219 followed the ~3000 m isobath for about two years switching abruptly to the ~3500 m isobath when reaching the Norwegian Basin. Typically drift speeds of the floats are from a few cm/s up to 10 cm/s but in some cases reached 15 cm/s. The float 6900218 took about one year to complete one cycle around the Basin and its mean drift speed was 6.7 cm/s. The mean drift speed was calculated as the average of all drift speeds between two neighbouring locations. The mean speeds for all floats were estimated between 4 and 7 cm/s with lowest values for the two floats that also drifted in the Norwegian Basin. All floats show the strong influence of topography, but they also exhibit different behaviour in different areas. In the Eastern part of the Lofoten Basin the floats have a more irregular pattern of motion than in the other areas due to mesoscale turbulence as we will see later on.

Argo floats thus reveal a large-scale deep cyclonic circulation in the Lofoten Basin and a strong topographic influence. Near the Mohn Ridge, between the Greenland and the Lofoten basins, the direction in the deeper layer is also in the opposite sense to the surface current (Orvik and Niiler 2002). Using wind stress and density fields, Nøst and Isachsen (2003) modelled the stationary bottom geostrophic circulation in the Nordic Seas. Their results revealed a cyclonic circulation in the Greenland and Norwegian Seas with typical speeds of 5-10 cm/s which is in agreement with the Argo floats as far as the Lofoten Basin is concerned.

3.2 RAFOS Floats

In five float deployments between April 2003 and November 2004 (April 2003, October 2003, April 2004, June 2004 and November 2004) a total of 42 RAFOS floats were deployed for periods of 6 months approximately as part of the ASOF-N programme. Figure 6.6 indicates the location of float deployments (circles) and the end-points (crosses) where the floats popped up to the surface 6 months later for transmitting data to satellites. In addition to ASOF, we also show observations obtained from May 2001 to October 2001 during the EU-MAIA project (Monitoring the Atlantic Inflow towards the Arctic) using the same lagrangian techniques. It is quite remarkable that the floats split equally between those heading northward before merging with the West Spitsbergen Current and those turning eastward before entering in the Barents Sea.

Fig. 6.6

Detailed float trajectories are shown on Figures 6.7 and 6.8. Most of the deployments occurred west of the Lofoten Islands in the NwAC and above the continental slope where bottom depths vary from 1000 m down to 2500 m. Most of the ASOF floats (34) were ballasted to sink and drift at a constant depth of about 300 m according to the following prescribed initial conditions: P=300 dbar, T=5.667 °C, S=35.133 psu, in situ density = 29.0805, while during the MAIA experiment in 2001, float depths were slightly deeper at ~500 m depth. A few ASOF-N floats (8) were ballasted for 1000 m depth and the duration of the drift for these deep floats was extended to about one year. Deployments usually occurred during the spring and the fall of each year (2003 and 2004). After 6 months (1 year) drifting at an average depth of about 300m (1000 m), floats were released to pop up at the surface and start to transmit 6 months (1 year) worth of data to the satellites (Argos link). At depth, floats were recording in situ temperature and pressure every hour and every four hours they recorded the time of arrival (TOA), of acoustic signals transmitted by sound sources deployed in April 2003 and September 2003, the first year of the experiment.

Fig. 6.7
Fig. 6.8

From the float trajectories (Figures 6.7 and 6.8), mesoscale turbulence, characterized by large scale eddies, 50 km to 100 km diameter and 1 to 2 weeks rotating period, is clearly identified as the dominant and ubiquitous mechanism influencing the general circulation in this part of the Lofoten Basin. It appears that most of these large scale anticyclonic eddies were capped off by a layer of relatively fresh water originating from the NCC as shown on Figure 6.9. The mean transport associated with a mesoscale turbulent vein, 100km wide, 700 m deep moving at an average speed of 6 cm/s would correspond to about 4 Sverdrups (1 Sverdrup = 10^6 m^3s^{-1}).

Figure 6.9 represents a large-scale Lofoten eddy identified in July 2001 by a) trajectories of 5 RAFOS isobaric floats drifting at 350 m depth approximately and b) Sea Level Anomaly (SLA) observed by satellite altimetry. The RAFOS floats are influenced by a large and persistent anticyclonic eddy (100km diameter, 2 weeks period, located between 13°E and 16°E longitude and 71°N and 72°N latitude) and by unstable mesoscale cyclonic eddies migrating around the main anticyclonic eddy feature. The anticyclone is capped off by a thick layer of relatively buoyant fresh water originating from the NCC, also clearly visible on the SLA maps. Similar anticyclonic eddies were observed during ASOF in November-December 2003 located between 13°E and 16°E longitude and 70°N and 71°N latitude (Figure 6.8b).

Fig. 6.9

This sea level anomaly was created by the large buoyancy input of the fresh water layer inducing a strong deviation of the sea surface topography. This fresh water originates from the Baltic Sea in addition to the run-off from Norwegian Fjords distributed all along the Norwegian coast. This fresh water is tagged with anthropogenic tracers such as Iodine 129 originating from La Hague in France and Sellafield in UK. Gascard et al. (2004) published a detailed analysis of Iodine 129 concentrations all along the coast of Norway. The high mixing rate between NwAC and NCC water masses passing the Lofoten islands and entering the Barents Sea is clearly identified along the Fugløya section from the distribution of temperature, salinity and Iodine properties. The large scale eddies generated by the interaction between the NwAC and NCC northwest of Norway are the most likely cause, as illustrated on Figures 6.7, 6.8b and 6.9. This area is characterized by intense mixing between the Norwegian coastal water masses and Norwegian Atlantic water masses as illustrated by the Fugløya section (Tromsø to Bear Island; Fig. 6.3) showing an intense mixing across the whole Fugløya section and through the entire water column from top to bottom. This is also a sound explanation for the fact that higher concentrations of Iodine 129 spreading away from the NCC affect most of the Atlantic water masses entering in the Barents Sea. This intense mixing was reported by Gascard et al. (2004) but not the process responsible for it, i.e. a very active and sustained interaction between the fresh Iodine-enriched NCC and salty NwAC triggered by intense mesoscale activity entraining NCC coastal fresh water offshore past the Lofoten Islands. This mesoscale interaction between NCC and NwAC, developing a large scale stationary eddy offshore, might also be involved in controlling the overwintering of the copepod *Calanus Finmarchicus* at great depths under the Atlantic water layer (Halvorsen et al. 2003) --- an important issue for a region that is among the most productive regions in the world ocean.

4. Conclusions

Though the analysis is incomplete, three main results of climatic importance have emerged from this set of Argo and RAFOS quasi lagrangian observations:

1) The first concerns the deep recirculation in the Lofoten Basin (900-1500 m), and its control by bottom topography. This cyclonic recirculation has the important effect of storing a large quantity of Atlantic Water and increasing the residence time of Atlantic water masses circulating in the area. Even some of the shallow (RAFOS) floats injected in the core of the Norwegian Atlantic Current close to the Lofoten Islands, revealed a very strong recirculation component. The deep Argo and RAFOS floats confirmed the topographic influence on the deep cyclonic circulation that characterizes the Lofoten Basin. The kinetic energy associated with this deep circulation is weak but the mass transport is important due to large scale horizontal spreading and deepening of the Atlantic layer across the whole Lofoten basin.

2) The second result concerns the mesoscale eddies dominance in the inshore branch of the Norwegian Atlantic Current. In consequence, of this, the Norwegian Atlantic Current does not resemble the narrow, swift boundary jet that the literature often describes, but rather a turbulent, broad (100 km) and slow current (~6 cm/s mean velocity) progressing to the north, in the Lofoten Basin or passing east into the Barents Sea. Half of the shallow floats (300 m depth) launched west of the Lofoten Islands entered through the Barents Sea Opening, the other half continuing North towards Fram Strait.

3) The third result of general importance to our understanding of Arctic-subarctic ocean fluxes concerns the strong interaction between the relatively fresh water of the Norwegian Coastal Current and the Norwegian Atlantic Current offshore, particularly West and North of the Lofoten Islands. The mesoscale interactive processes are well described by the RAFOS float trajectories and satellite altimetry North of the Lofoten Islands and West of the Tromsøflaket. This is a region prone to a high mesoscale turbulence activity and intense mixing between Norwegian Coastal Current and Norwegian Atlantic Current water masses as also revealed by anthropogenic tracer distribution and temperature-salinity properties.

None of these results would have been acquired without the extensive use of a new Lagrangian High Technology represented by neutrally buoyant isobaric floats (Argo and RAFOS) drifting at depth in the Ocean in addition to more conventional techniques.

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Figure legends

Figure 6.1. Large scale Ocean circulation in the Nordic Seas (left) and observed surface salinity along the Norwegian coast (right). The Norwegian Atlantic Current (NwAC), East Icelandic Current (EIC), Norwegian coastal Current (NCC) and the three setions (Gimsøy, Bjørnøya and Fugløya) are indicated.

Figure 6.2. Hydrological sections of temperature, salinity and Iodine ratio (I^{129}/ I^{127}) taken from the Lofoten Islands (Gimsøy, lower figures) and from Bear Island (Bjørnøya, upper figures) to the Greenland Sea in June 2000. See also Fig. 6.1 for locations of the sections.

Figure 6.3. Fugløya (upper figures) and Gimsøy (lower figures) sections of temperature, salinity and Iodine ratio (I^{129}/ I^{127}) in June 2000. Variability of the Iodine ratio depends mainly on the Iodine 129 distribution.

Figure 6.4. The anthropogenic tracer ratio I^{129}/ I^{127} as function of salinity in the Lofoten Basin along the Gimsøy, Bjørnøya and Fugløya sections. a) linear scale, b) logarithmic scale.

Figure 6.5. Trajectories of four Argo floats in the Norwegian Sea (August 2003 – 2005/2006) drifting at 1500 m depth. Dots indicate surfacing of the float and the interval between each surface position is 10 days. Dashed line is missing positions. Location of deployment is marked by "D" in a green dot while red dot indicates last position. There are blue dots every 6 months after deployment and the numbers (1, 2, 3) indicate number of years after deployment. The averaged drift speeds are estimated to 6.7, 4.3, 6.4 and 4.5 cm/s for Argo floats 6900218, 6900219, 6900220 and 6900223, respectively. Bathymetry shades change at every 500 m. The trajectories are smoothed before plotting (20 days moving averages).

Figure 6.6. First (o) and last (+) Rafos float locations for 6 months duration from May-October 2001, April-September 2003 and October 2003-April 2004.

Figure 6.7. a) Rafos Floats trajectories at 300 m depth from May to October 2001, April to August 2003 and October 2003 to January 2004. b) Rafos Floats trajectories at 350 m depth (red) and 900 m depth (black) from May to October 2001. On Figure 6.7b, one can easily distinguish between the general drift pattern of the shallow floats (350 m depth) compare with the deep floats (900 m depth) drift pattern more constrained by topography.

Figure 6.8. a) Rafos float (RF 518) drifting at 300 m depth from April 2004 until October 2004. Strikingly this float drifted over 1000 km but corresponding to a net drift close to zero after 6 months total drift period. b) Rafos float (RF12) drifting at 300 m depth from October 2003 to January 2004 indicating the presence of a quasi stationary anticyclonic mesoscale eddy (50 km diameter and 1 week period) for about 3 months.

Figure 6.9. Large Scale Lofoten eddy identified by 5 RAFOS floats (a) and Sea Level Anomaly from satellite (b).