

## Climatic variability in the Skagerrak and coastal waters of Norway

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The Institute of Marine Research in Norway collects marine data from all national waters. Data are primarily collected from vessels, but observation buoys, manual measurements, and oceanographic gliders are also used. The most valuable long-term data for elucidating decadal hydrographic variability in the Skagerrak and along the Norwegian coast are the time-series from the transect between Norway and Denmark, and observations carried out at eight fixed coastal stations in the region. The time-series date back to the 1950s and the 1930s, respectively, and the observation frequencies range from approximately once a month to 3–4 times per month. The hydrographic data and their long-term fluctuations have been used in several studies, with particular emphasis on the increased salinity and temperature of the 1990s. Trends during the past decade, however, indicate that warming has continued but that a salinity increase is less evident, implying signs of regional warming in parallel with the global warming observed both on land and in the sea. The overall temperature increase off the Norwegian coast at deeper layers from the 1961–1990 period to the 2000–2009 decade is  $\sim 0.8^{\circ}\text{C}$ , but some of this can be related to natural variability in the North Atlantic circulation pattern.

**Keywords:** decadal hydrographic variability, Norwegian coast, Skagerrak.

### Introduction

Norwegian coastal water originates from a mixture of the outflow of brackish water from the Baltic Sea through the Kattegat, North Sea coastal water, and freshwater run-off from Norwegian rivers. This low-saline coastal water mixes to the north with Atlantic water to form the Norwegian Coastal Current (NCC), which flows westwards in the Skagerrak and northwards along the Norwegian coast as a wedge-shaped low-salinity current bordered by the Norwegian Atlantic Current (NAC; Figure 1). A detailed description of the characteristic features of this current system and its water masses is given in Sætre (2007) and references therein.

The Norwegian shelf is the spawning and nursery area for several commercially important fish species. It was acknowledged almost a century ago that variability and trends in hydrographic conditions along the coast could influence the recruitment, growth, and distribution of fish stocks. These were important arguments for establishing oceanographic observing and monitoring systems within the Institute of Marine Research (IMR) in Norway. Some of the longest continuous oceanographic time-series in the world, with sampling intervals between 2 and 4 weeks, are represented by the Skagerrak transect between Norway and Denmark (Torungen–Hirtshals), and the fixed coastal stations distributed along the Norwegian coast (Figure 1). The Skagerrak data consist of observations from 1952

on, and the fixed hydrographic stations started delivering measurements in the 1930s and the 1940s. Data from this part of the monitoring system have been used in a large number of reports and publications for various purposes, including highlighting long-term variations (e.g. Sætre *et al.*, 2003, and references therein).

The forerunner to this paper, Sætre *et al.* (2003), elucidated the long-term variability in hydrographic patterns along the Norwegian coast and identified possible regional differences, with special emphasis on the situation in the 1990s. Adding a new decade of measurements allows further analysis of the long-term variability in hydrographic patterns of large-scale Atlantic inflow to the Norwegian Sea, by focusing on the deeper waters along the Norwegian coast, as well as on the regional and local response in the surface layer.

### Material and methods

During the period 1935–1947, Jens Eggvin at the IMR established a number of fixed hydrographic stations in Norwegian coastal waters (Eggvin, 1938). Vertical temperature and salinity profiles are measured 2–4 times per month by local observers. Mean values and long-term variations based on measurements from the coastal stations have been presented previously by Aure and Østensen (1993). Here, we assume that measurements obtained



**Figure 1.** A schematic map of Norwegian waters. The solid curved lines indicate the main position of the NAC, typically found as slope currents 100–200 m deep as northward flow in the Norwegian Sea, the Atlantic flow entering the North Sea north of Shetland, and the return flow along the Norwegian coast. The dashed curved line denotes the position of the coastal currents (mainly the Jutland current and the NCC). The positions of the fixed coastal stations are indicated by names along the Norwegian coast (Utsira)—Orkney transect and the Skagerrak (Tórungen–Hirtshals) transect—are drawn as solid, black lines. The isobaths for 200, 500, and 1000 m are denoted by different shading.

10 and 200 m deep are representative of surface- and deeper-layer variations corresponding to fluctuations within the NCC and the NAC, respectively.

Since 1952, the IMR has operated a standard hydrographic section across the central part of the Skagerrak between Torungen on the Norwegian side and Hirtshals on the Danish side (Figure 1). From 1961, the section has on average been sampled 8–12 times per year. Along with the coastal stations, this collection represents a substantial record that can be used to investigate regional climatic variations. The Skagerrak transect consists of 12 stations. The two stations closest to Denmark, 3 and 8 nautical miles (hereafter, miles) off Hirtshals, are used to characterize the coastal water off Jutland. Off Torungen (Norway), the stations 1 and 5 miles from the coast are taken to represent the NCC. Hydrographic properties of the Atlantic inflow from the North Sea are determined from the station 30 miles off Torungen, and the properties of the corresponding flow of Atlantic water below the NCC are represented by values from the station 5 miles off Torungen. As for the other coastal stations, deeper layers are characterized by measurements made 200 m deep. Note that the slope current in the Skagerrak at 100–200 m is more diffuse on the Norwegian side than on the Danish owing to entrainment of surrounding water masses in the Skagerrak basin. The salinity at fixed depth is then generally highest off Hirtshals, although the relative long-term hydrographic variations are comparable at the two locations.

One of the main contributions of the Atlantic water that flows into the Norwegian Sea and the North Sea follows the eastern slope of the Faroe–Shetland Channel. A portion of this northward slope current peels off to flow into the North Sea, and this inflow is important in that it is the main contributor of high salinity water in the North Sea and Skagerrak and is a significant heat source during winter.

An alternative approach to observational data analysis in studying the variability of Atlantic inflow into the North Sea is to apply a numerical ocean model. The Norwegian Ecological Model system (NORWECOM/POM) is a three-dimensional coupled physical chemical biological model system (Skogen *et al.*, 1995), and the volume flux of water entering the North Sea has been calculated from a simulation covering the period 1955–2008. The inflow between the Orkneys, Shetlands, and Utsira (Norway) is calculated from the daily mean current component, and the average winter (January–March) volume flux is used in our analysis. The model realization is run on a 20-km grid applying the POM (Princeton Ocean Model) as the physical model. Further details about this model's performance and applications can be found in Iversen *et al.* (2002).

In our analysis of long-term hydrographic variations and trends, we have collected values within bins representing decades. Although the sampling frequency (1–2 times per month) is lower than typical internal frequencies in the ocean, we assume that the collection of measurements over decadal intervals achieves a valid statistical representation. Decadal means have been normalized by taking the ratio between the long-term change, i.e. the anomaly based on a reference period, and the standard deviation for the same reference period. It is then possible to relate all decadal averages to a standard norm and to quantify them with respect to the variability in the dataset. The reference period is chosen to be equal to the World Meteorological Organization (WMO) climatological 30-year reference period 1961–1990. Normalization of the decadal averages

permits trends to be compared in both the highly variable surface layer and the less variable deeper layer. It is also more convenient to compare the hydrographic properties in the Skagerrak and along the Norwegian coast, because the variability decreases towards the north. In addition, the analysis here refers primarily to the winter situation, defined as the months January–March, the season we believe better reflects the long-term climatic signal.

## Results and discussion

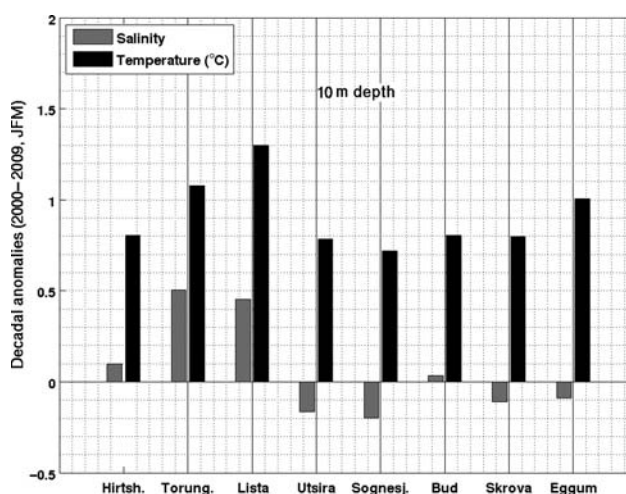
### Long-term fluctuations in the surface layer

Warmer temperatures during the past decade (2000–2009) are seen in Figure 2, in which decadal winter anomalies are shown relative to the 1961–1990 reference period. The increase in surface-layer temperature is observed to be between 0.7 and 1.3°C. Because of the gradual decrease in hydrographic variability from the Skagerrak north, the normalized increase in temperature is largest for the northernmost location (Figure 3). For instance, a decadal increase in winter temperature off Torungen of 1°C implies an increase of ~0.6 s.d. above the 1961–1990 reference period. The same absolute temperature anomaly off Ingøy in northern Norway implies a warming of the surface layer of ~2 s.d.

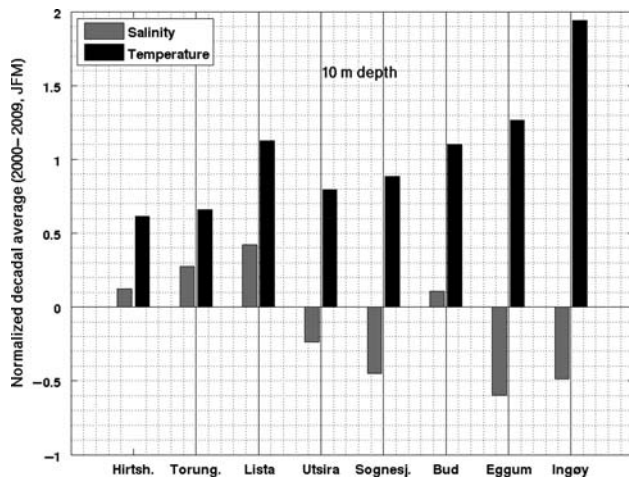
The change in surface salinity during the past decade is less pronounced than the temperature change. Stations located in the Skagerrak have experienced higher salinity than in the reference period, whereas the opposite is observed at the coastal locations off western and northern Norway.

### Long-term fluctuations in the deeper layer

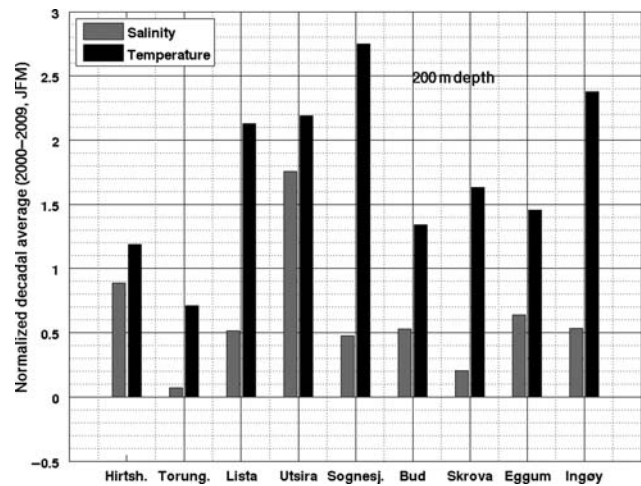
The deeper layer, here referred to as depths between 100 and 200 m, contains an important flow of Atlantic water directed northwards as a slope current off the Norwegian west coast, along the slope of the Norwegian Trench in the North Sea and Skagerrak. The hydrographic properties of these water masses are indicators of climatic trends in Norwegian waters. We have selected measurements from 200 m to represent Atlantic water, and for all stations, the temperature anomaly for the past decade



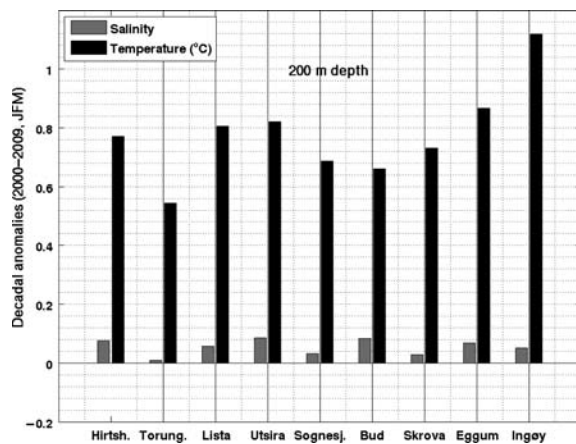
**Figure 2.** Decadal anomalies of salinity (grey) and temperature (black, °C) for selected locations (names along the horizontal axis) in the Skagerrak and along the Norwegian coast 10 m deep. The anomalies are found by subtracting the averaged observed values between 2000 and 2009 in winter (January–March) from the corresponding mean of the reference period 1961–1990.



**Figure 3.** Normalized decadal averages (anomalies/standard deviations) of salinity (grey) and temperature (black) in winter (January–March, JFM) for selected locations (names along the horizontal axis) in the Skagerrak and along the Norwegian coast 10 m deep. The normalized values for the decade 2000–2009 refer to the 1961–1990 reference period.



**Figure 5.** Normalized decadal averages (anomalies/standard deviations) of salinity (grey) and temperature (black) in winter (January–March, JFM) for selected locations (names along the horizontal axis) in the Skagerrak and along the Norwegian coast 200 m deep. The normalized values for the decade 2000–2009 refer to the 1961–1990 reference period.



**Figure 4.** Decadal anomalies of salinity (grey) and temperature (black, °C) for selected locations (names along the horizontal axis) in the Skagerrak and along the Norwegian coast 200 m deep. The anomalies are found by subtracting the averaged observed values between 2000 and 2009 in winter (January–March, JFM) and the corresponding mean from the reference period 1961–1990.

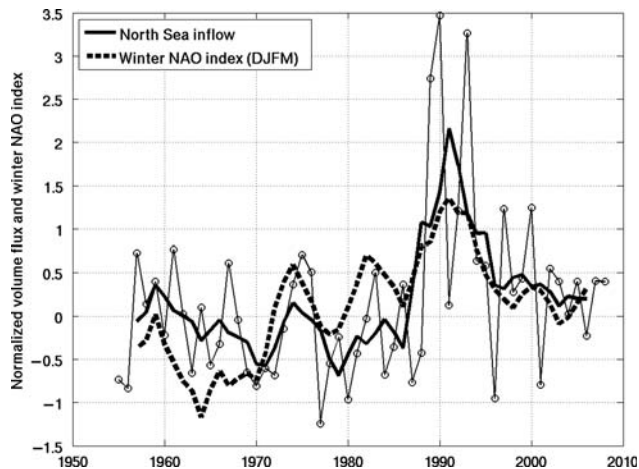
(2000–2009) is between 0.6 and 1.1°C (Figure 4). The average warming for all stations is  $\sim 0.8^\circ\text{C}$ . The temperature anomaly for the northernmost station, Ingøy, which is next to the Barents Sea, is slightly higher than for the other stations. Although the increase in temperature is comparable between surface and Atlantic waters, the normalized increase is considerably greater for the deeper layers (Figure 5). Stations off the western and north coasts of Norway have experienced an increase in temperature of between 1.3 and 2.8 s.d. above the 1961–1990 reference period, whereas the Skagerrak sites have had values close to 1 s.d. above the reference period.

In terms of the salinity of deeper layers during the past decade, there has been an increase at all stations except off Torungen, with

anomalies of between 0.03 and 0.09. However, the normalized increase clearly shows ranges of between 0.2 and 1.8 s.d. The normalized decadal averages of temperature and salinity for the decade 2000–2009 indicate that the increase in temperature of Atlantic water in the Skagerrak and along the Norwegian coast is greater than the increase in salinity.

The simulated flow of water masses has been analysed to determine whether there has been a change in volume flux. The variable inflow of Atlantic water to the Norwegian and North Seas will influence the hydrographic conditions along the Norwegian coast and in the Skagerrak. As the large-scale wind pattern is the main driving force, the fluctuation in North Sea inflow will most likely also reflect the variability in the Atlantic inflow to the Norwegian Sea. We have extracted a time-series of winter inflow between the Orkney Islands and Norway (Utsira) from a numerical ocean model simulation ranging from 1955 to 2008 (Figure 6). This time-series reflects the evolution of the winter NAO (North Atlantic Oscillation) index (also seen in Figure 6). When comparing the modelled winter inflow of Atlantic water into the North Sea and the station-based winter (December–March) NAO index (Hurrell and Deser, 2009), the correlation coefficient is significant (0.7). The increase in inflow around 1990 and the relatively high volume flux during the 1990s are clear in Figure 6. The past decade, however, has experienced a more normal winter inflow with only small positive anomalies compared with the 1961–1990 reference period. In other words, the increase in temperature and salinity within Atlantic water during the past decade is apparently not caused by enhanced inflow but rather by a change in the hydrographic properties.

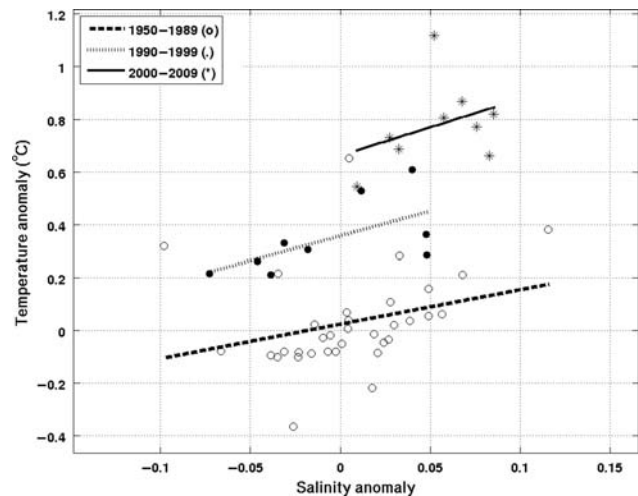
The Atlantic inflow from the North Atlantic to the Nordic Seas between Greenland and Scotland consists of contributions from both the North Atlantic Subpolar Gyre (SPG) and the Subtropical Gyre (STG). The main pathway for the Atlantic water influencing the Norwegian coast is through the Rockall Trough west of the British Isles. Hátún *et al.* (2005) showed that on interannual to interdecadal time-scales, the salinity of



**Figure 6.** Normalized values of winter (January–March, JFM) inflow to the North Sea between Norway (Utsira) and the Orkneys based on modelled currents (NORWECOM) and the winter (December–March, DJFM) NAO index. The time-series are retrieved from the period 1955–2008. Individual winter values of inflow are shown (open circles and thin solid line). A 5-year running mean of this inflow is also shown (thick solid line), and the NAO index is presented as a 5-year running mean only (thick dashed line). All values are normalized with respect to the 1961–1990 reference period.

Atlantic inflow to the Nordic Seas is tightly linked to the dynamics of the SPG circulation and its effects on the location, intensity, and composition of the NAC in the northeastern Atlantic. Those authors concluded that in periods with intensive SPG circulation, the relatively high tropical salinity and temperature will tend to make a smaller contribution to volume flux in the NAC. They also linked this to a gyre index, where a low index indicates weaker SPG circulation. Hátún *et al.* (2005) also stressed the need to distinguish internal variability modes in a climate system from the fingerprints of more-gradual global warming. From the temporal evolution of the gyre index, associated with the leading North Atlantic sea surface height mode, and anomalies in surface salinity, Hátún *et al.* (2005) demonstrated a shift in the mid-1990s towards a lower index value and hence higher salinities in the NAC, the latter also linked to higher temperatures. During a positive (negative) phase of the NAO, the SPG typically strengthens (weakens) and expands towards the east (contracts towards the west), resulting in relatively low (high) salinities and temperatures influencing the NAC.

By displaying decadal averaged salinity and temperature anomalies from the selected stations in the Skagerrak and along the Norwegian coast in a salinity–temperature diagram and applying a linear regression line to unify all stations, we see that the characteristics of Atlantic water masses have changed during the past two decades (Figure 7). The shift in the SPG circulation in the late 1990s seems to have introduced higher salinity and temperature within the deeper layers since that period (Hátún *et al.*, 2005). The reduction in strength of the SPG may also be in accord with the reduced (normalized) NAO and the resulting decrease in winter inflow of Atlantic water into the North Sea, as shown in Figure 6. The increase in salinity, however, is not evident in the 1990–1999 decadal average, but is clearly seen in the 2000–2009 average, where the overall positive salinity anomaly for all stations



**Figure 7.** Salinity and temperature ( $^{\circ}\text{C}$ ) anomalies for the winter (January–March) decadal averages from the nine selected stations in the Skagerrak and along the Norwegian coast 200 m deep displayed in a salinity–temperature diagram. Values have been separated into three categories, representing observation date for the decades from the 1950s to the 1980s (open circles), the 1990s (dots), and the decade 2000–2009 (asterisks). The anomalies refer to the 1961–1990 reference period, and the straight lines display the estimated linear regression line for all three categories, as indicated.

is  $\sim 0.05$ . In terms of temperature increase, the temperature anomaly during the decade 2000–2009 for every observed salinity anomaly is  $\sim 0.6^{\circ}\text{C}$ , half of this increase visible in the 1990–1999 decadal average. The discrepancy between the positive temperature anomalies for all deeper stations of  $\sim 0.8^{\circ}\text{C}$  (Figure 4), and the  $0.6^{\circ}\text{C}$  warming when positive salinity anomalies are present (Figure 7), may then be related to natural variation in the SPG circulation.

## Summary

Between 1990 and recently (2009), there has been an obvious increase in temperature in both upper and deeper waters along the Norwegian coast. In the upper Norwegian coastal water, the hydrographic variability is due to both direct changes in heat transfer within the region and to advected signals from outside. Surface-layer temperatures in the Skagerrak and off the Norwegian coast primarily reflect long-term atmospheric fluctuations. The effect of warming in the 1990s was progressively less from south to north (Sætre *et al.*, 2007). However, surface-layer conditions in the Skagerrak may depict a more complex pattern. The NCC off the Norwegian west coast and to the north is influenced mainly by Atlantic water, whereas Skagerrak water consists of mixed Atlantic water, Central North Sea water, and Coastal North Sea water on the Danish side, and a blend of these water masses along with brackish Baltic water on the Norwegian side. The different sources constituting Skagerrak water make it difficult to determine the effect of atmospheric variability on the hydrographic properties of the surface layer. The long-term decreasing salinity along the western and northern Norwegian coast is probably caused by increased precipitation leading to increased freshwater run-off from rivers, as pointed out by Sætre *et al.* (2003).

In the deeper layers characterizing Atlantic water, the temperature increase is  $\sim 0.8^{\circ}\text{C}$ . Some of this warming seems to

be related to the reduction in strength of the SPG. During periods with lower winter NAO index values (close to normalized values), or correspondingly little winter inflow of Atlantic water into the North Sea, as observed during the past decade, the SPG is displaced towards the west, allowing there to be a greater proportion of more-saline, warmer water with the STG origin. A significant portion of the temperature increase in Atlantic water along the Norwegian coast during the decade 2000–2009 can be related to the weakening of the SPG, as shown by Hátún *et al.* (2005). We find it difficult to explain the rest of the temperature increase, i.e. a positive anomaly of  $\sim 0.6^{\circ}\text{C}$ . Some of this may be attributed to large-scale hemispheric warming, but the mechanisms affecting the hydrographic variability and trends off the Norwegian coast make it too complicated to address the warming source.

Lohmann *et al.* (2008) investigated the response of the SPG to a persistent positive or a negative phase of the NAO, using an ocean general circulation model. They found that in the positive NAO case, the well-known cooling and strengthening of the SPG was replaced by a warming and subsequent weakening of the SPG after about a decade. In the negative NAO case, Lohmann *et al.* (2008) noted that the SPG gradually weakened throughout their model integration, without any sign reversal. Their findings are examples of complex non-linear ocean response to atmospheric forcing and suggest that predicting the hydrographic variability in the Skagerrak and along the Norwegian coast is a challenge. Our results show the importance of long and continued observational time-series for climate monitoring, not only in the local area of interest, but also in a global context.

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