# Oceanography and Environmetrics

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## Abstract.

In this article, we provide some background on the topic of environmetrics within the context of oceanography, and give examples applied to both the coastal ocean and the large scale ocean/climate system.

## Introduction

Oceanographic science tends to be split according to whether the focus is primarily the coastal ocean, or the large scale. The coastal ocean feels the most pressure from human activities on a day to day time scale, whereas the large scale ocean is important for climate. Historically, the coastal ocean has been a source of food through the harvesting of fish, but it is also the depository for much of our waste and sewage, as well as being vulnerable to oil spills and discharges from ships. More recently, oil and gas exploitation is presenting new hazards, and the increasing pressure on the coastal ocean is leading to demand for the development of coastal ocean prediction systems. For example, oil rig operations need accurate predictions of approaching severe weather, including surface wave heights, and in some locations the movement of pack-ice and icebergs (e.g. the Newfoundland/Labrador Shelf). There is also a need to determine the best locations to bring oil and gas pipelines onshore. Likewise, municipalities need advice on the optimal locations for sewage discharges. Coastal ocean communities also require warning of storm surges and associated flooding events, a concern that will grow in the future if sea level rise associated with global warming becomes a reality, and the migration of the world's population to coastal regions continues.

The importance of the ocean in climate is a consequence of the large heat capacity of the ocean compared to the atmosphere. In fact, the top 2.5m of ocean has the same heat capacity per unit area as that of the whole of the overlying atmosphere. It is the large heat capacity that gives the ocean the ability to store and transport heat, and provides the ocean with a memory of its past state that far exceeds that of the atmosphere. In fact, the typical limit of predictability of the atmosphere is about three weeks, whereas some authors have suggested that the large scale structure of the ocean may be predictable out to decades [16]. The most obvious example of the ocean influencing variability in the atmosphere is the El Nino/Southern Oscillation phenomenon [33]. However, there is also interest in trying to determine whether other low frequency (interannual and longer) features of the atmospheric circulation can be linked to the underlying ocean, thereby providing some hope of predicting the atmospheric state years, or perhaps even decades ahead [16]. On still longer time scales, the ocean plays a role in climate change. Manabe and Stouffer [30] describe the role of the ocean in a coupled ocean/atmosphere model driven by increasing greenhouse gas concentration in the model atmosphere. Some authors have suggested that global warming could lead to rapid and dramatic changes in regional climate because of changes in the ocean circulation, e.g. [9]. Rahmstorf [34] has argued that even if this is only a remote possibility, the consequences would be so serious (in particular for western Europe) that the possibility should be not be ignored.

In the following, we discuss some typical environmetrics problems strongly influenced by oceanographic science, including fisheries management, the dispersal of pollutants, search and rescue, and storm surge prediction. Finally, we give an example, on the basin scale, of recent attempts to harness the ocean to predict the North Atlantic Oscillation, the most important mode of variability in the northern hemisphere atmospheric circulation. To illustrate possible solution techniques, we describe some of the on-going work at Dalhousie University. It is important to note, however, that the principles can be applied worldwide, and similar modelling activities exist in other groups at other institutions.

## Fisheries Management

All but a small part of the world fishery occurs within 160 km of the coast. Recent events such as the collapse of the cod fishery in Atlantic Canada have led to many scientific and management questions regarding the relative roles of over-fishing, environmental change and natural ecosystem variability, e.g. [25]. In addition, nearshore aquaculture is a rapidly growing industry. Commensurate with this growth is a demand for coastal ocean models that can be used to determine optimal sites for aquaculture activities and predict future changes in water quality.

The influence of the physical environment on fisheries production has been the subject of scientific research for most of the last century. (See, for example, the seminal work of Hjort [22].) A comprehensive review of this early work, and the more recent studies of fisheries and climate is provided by [11]. Numerical models of shelf seas [15] have been developed over recent decades to both reconstruct past changes in ocean circulation (i.e. "hindcast") and, more recently, to predict future conditions (i.e. "forecast"). Model hindcasts have been used, for example, to better understand the advective pathways for herring larvae in the North Sea (e.g. [2]), and the structure of the marine ecosystem on Georges Bank (e.g. [19]). Forecasts of the state of shelf seas can be used to optimize the sampling of fish eggs and larvae, and thereby obtain a better understanding of how the physical environment can affect recruitment of commercially important stocks. An example of such a study is given below. A number of groups are working on such systems at the present time.

During the early 1990's, a ship-borne system was developed at Dalhousie University for nowcasting and forecasting circulation on the continental shelf, offshore from Nova Scotia, Canada, on what is known as the Scotian Shelf. "Nowcasting" refers to the use of a model to construct a best estimate of the circulation at the present time, based on the available observations (*cf.* "hindcast" and "forecast" above). Observations were assimilated in near real-time into an ocean circulation model, including data from drifting buoys, telemetering moored current meters, the ship's acoustic doppler current profiler and the local wind [6]. With the aid of this assimilation model the ship was able to successfully track a cohort of cod larvae on the outer Scotian Shelf for a period of 19 days that included two major storm events. During these 19 days a large number of biological measurements were made with the objective of better understanding the reasons for mortality during what is the critical period in the early life history of cod ([29], [36]). Details of the physical modelling and related references are given in [17] and

[44].

Shelf-wide models have been used to hindcast the loss of fish larvae from their nursery grounds on the outer Scotian shelf. In one such study, a circulation model was seeded with particles that were then tracked following the flow field. The particles can be thought of as buoyant fish eggs or larvae moving passively with the flow. Typical model output is shown in Figure 1. Hindcasts for different years show different levels of retention on the offshore banks. Comparison of the retention indices with the year class success of Scotian shelf cod suggests a relationship, with the stronger year classes generally associated with the retention of eggs and larvae in well defined nursery areas [10]. For example, the spring of 1971 showed retention of particles over Banquereau and Western Banks, known nursery grounds for cod and other species, in what was a successful spawning year. By contrast, simulations for the stormier spring of 1987 showed almost no retention over the shelf, and the catch in 1987 was poor. Other groups are also developing models to help understand and manage the fisheries on the Scotian Shelf, e.g. [8] and [20].

## The Dispersal of Pollutants

Point source pollution is often the most visible candidate for coastal management. The immense cost, potential environmental impact and political controversy surrounding sewage treatment projects requires much reliable information and years of planning. Models can be used to assess the fate of sewage discharges in much the same way as they can be used to study the retention of fish larvae. A review of the mathematical and computer modelling of many of the physical processes that effect the fate of pollutants released in tidal flows is given by Smith and Scott [41]. As pointed out by these authors, careful selection of the position, timing, and release rate of a discharge can enhance the dilution of effluent and minimize the environmental impact. Smith [40] discusses the use of holding tanks, and the timing of the release to minimize the impact in a tidal estuary, and Kay [26] gives analytic solutions that can be used to verify models, and which show that the use of long outfalls can drastically reduce the shoreline concentration of discharge. Earlier work by Smith [39] discussed the effect of buoyancy on dispersion in estuaries, and concluded that the River Thames downstream of London Bridge is buoyancy dominated.

## “Search and Rescue” and Oil Spill Tracking

Search and rescue operations at sea involve an immediate determination of the sea condition and the search area. As time passes, the search area increases and the likelihood of finding survivors diminishes. A greater understanding of the physical environment and its currents, along with the ability to provide short-term predictions of flow, would better focus the search area and increase the success rate of ocean search and rescue.

A prototype forecast system for near surface currents was developed at Dalhousie University in the mid-1990’s as part of an IBM sponsored Environmental Research Prediction Initiative. The background flow is the result of a diagnostic calculation based on all available hydrographic data for the region collected over the last 70 years [38]. The barotropic model used for the forecast is based on the modified Galerkin spectral technique proposed by Sheng and Thompson [37]. The forecast model is driven by wind fields provided by the Meteorological Service of Canada and the assimilation of coastal sea level [45]. In February of 1996 the Canadian Coast Guard, Bedford Institute of Oceanography and Dalhousie University tested the model skill by collecting an independent verification data set on the inner Scotian Shelf. The verification data consisted of the trajectories of various types of surface drifters released in clusters and tracked for periods of about one week. The model predictions were encouraging (see Figure 2.). The model accounts for about 65% of the observed near-surface current variance and the root mean square error in the predicted displacements of the surface drifters was about 19 km after 5 days.

Initial results from the forecast system motivated the development of the new Dalhousie Coastal Ocean Prediction System (DALCOAST) that started in 1998. This forecast system is based on the Princeton Ocean Model [4] nested within the storm surge model described in the next section. The model is fully baroclinic, three-dimensional and based on seasonal climatology for temperature and salinity and 3-hourly forecasts of surface wind and pressure. The open boundary forcing consists of tidal and mean flows estimated using data assimilation and synoptic forcing from the storm surge model. The model provides two-day forecasts of sea level and three-dimensional temperature, salinity and current fields. Initial results from a drifter experiment similar to the one described above suggest that model predictions are improved by using tides and baroclinic forcing.

Unpredictable events such as oil spills, and discharges associated with offshore drilling activity and tanker traffic, require a rapid response akin to that needed for search and rescue. Models can be used to track oil spills and to provide information that can be used to minimize the overall impact of a spill. A review of oil spill modelling is given in [42].

The new generation of models include prognostic equations for temperature and salinity and permit the development of mesoscale eddies through baroclinic and barotropic instability (see [15]). Eddies typically have scales of order several tens of kilometers and could play an important role in the transport and dispersal of fish larvae and pollutants, e.g. [28]. Some preliminary results from a model of the Northwest Atlantic are shown in Figure 3.

## Storm Surge Prediction

Storm surge modelling represents one of the early success stories for operational modelling of the ocean, dating back to the early 1950s in the UK and the Netherlands (for an overview see [21]). In Atlantic Canada operational storm surge modelling has become more and more important as low lying areas around the upper reaches of the Bay of Fundy and the Gulf of St. Lawrence are flooded regularly by a combination of high tides and powerful storm surges. With the recent rise in sea level these problems are becoming more serious and more frequent.

In most cases strong surges come as a result of deep low pressure systems that move along the eastern American seaboard (extra-tropical storms). In addition, during the hurricane season, it is not uncommon that one or two hurricanes per year extend their life into Canadian waters causing a great deal of damage through heavy rain and storm surge induced flooding. This motivated the development of an operational storm surge model for the whole of the Atlantic Canadian coast [5].

The model is two-dimensional, barotropic, and nonlinear with lateral diffusion. It covers the whole Canadian Atlantic shelf from 38°N (Cape Cod) to 60°N (Cape Chidley, northern tip of Labrador) with a resolution of 1/12th of a degree. The forecast model is driven daily by three-hourly forecast winds and atmospheric pressure supplied by the Canadian Meteorological Centre. The model has been validated extensively and produces reliable 48 hour forecasts of synoptic variability in coastal sea level. On average, the model can account for about 85-90% of the variance in sea level [5]. A recent example of a model forecast field is shown in Fig. 4. The model runs operationally at Dalhousie University and has been recently transfered for eventual operational use to Environment Canada, the agency responsible for storm surge warnings in Canada.

## The North Atlantic Oscillation

The North Atlantic Oscillation (NAO), first identified by Walker [47], is the most important mode of variability in the northern hemisphere (NH) atmospheric circulation, and is the major influence on European winter climate variability [27]. The NAO is also the most important component of the atmospheric forcing for the North Atlantic

Ocean (see [18], [12] and [13]). An overview of the NAO, its role in climate, and its likely dynamics is given by Greatbatch [14]. In simple terms, the NAO measures the strength of the westerly winds blowing across the North Atlantic in the $40^oN - 60^oN$ latitude belt. The influence of the NAO is, nevertheless, hemispheric in extent. Indeed, the NAO is closely related to a hemispheric mode of variability known as the Arctic Oscillation (AO) [43].

Hurrell [23],[24] has defined an index for the NAO as the difference between normalised mean winter (December to March) sea level pressure (SLP) anomalies at Lisbon, Portugal and Stykkisholmur, Iceland. The normalisation is achieved by dividing the SLP anomalies at each station by the long term (1864-1994) standard deviation. Figure 5 shows the time series of Hurrell's index from 1864-1994. Geostrophic balance implies that when the index is high, the westerly winds across the North Atlantic are stronger than normal, whereas when the index is low, the westerly winds are weaker than normal.

The observed surface temperature departure associated with one standard deviation (positive) of the NAO index is shown in Figure 6. It is remarkable that the change in winter temperature associated with the NAO extends all the way across the Eurasian continent from the Atlantic to the Pacific, with the NAO apparently having just as much influence on winter temperature in Siberia as in western Europe. Hurrell [24] has shown that the NAO alone can account for 31% of the winter surface temperature variance over the northern hemisphere north of $20^o$N, and that the NAO and El Nino combined can account for 44% of the winter surface temperature variance (based on 60 years of data from 1935 to 1994).

The time series of the NAO index (Figure 5) shows low values during the period from the early 1950s to the early 1970s, relatively high values in the early part of this century, and high values during the last 25 years when there has also been strong decadal variability. Caution should nevertheless be exercised when interpreting these changes.

Wunsch [48] has pointed out that the estimated power density spectrum computed from Hurrell's time series shows only a weakly red spectrum, with no particularly striking peaks. As such, the characterisation of the NAO as an "oscillation" is misleading since its spectrum is much more akin to that of white noise. Wunsch also shows that statistically there is no reason to attach any significance to the variations in the character of the time series, such as the periods of high and low index noted above, or the enhanced decadal variability in recent years. Furthermore, on the basis of the time series alone, there is essentially no predictability of the NAO from one year to the next.

Recent studies by Rodwell et al.[35] and Mehta et al.[31] appear to contradict Wunsch [48]. These authors have shown that the ensemble average of a set of atmospheric general circulation model (AGCM) experiments, all with different initial conditions but driven by the observed time series of sea surface temperature (SST) and sea-ice, has skill at reproducing the observed time evolution of the NAO, apparently holding out the prospect of predicting the NAO several years in advance. Bretherton and Battisti [7] have questioned this interpretation. They point out that to predict the NAO, one must first predict the SST and sea-ice, a problem that is very difficult when, as for the NAO, the atmosphere contains a large random component that is itself an important local forcing for SST and sea-ice. The difficulty pointed out by Bretherton and Battisti [7] can be circumvented when some process other than local atmospheric forcing is driving the SST, an example being changes in oceanic heat transport (Bjerknes [3]; Eden and Jung [12]). The almost-white spectrum of the winter NAO index suggests, however, that even on the decadal time scale, there is little hope for prediction of the NAO. More exciting from the predictability point of view is the possibility, suggested by the study of Baldwin and Dunkerton [1], that the winter stratosphere can be used to provide information on the likely phase of the AO/NAO in the lower troposphere one month ahead. The relationship between the NAO and quasi-stationary regimes of the atmospheric circulation ([46]; [32]) also requires further investigation. Sometimes the atmospheric circulation remains close to one of these regimes for extended periods, exceeding the typical three week limit of predictability. It follows that understanding these regimes and transitions between them could prove helpful for improving prediction several months ahead.

## Summary and Discussion

As a result of the pressure on the coastal ocean from fishing, pollution and the offshore oil and gas industry, environmetrics, as applied to the coastal ocean, is a growing area of activity. In this article, we have seen how models and prediction systems can be applied to aid in search and rescue, to assist in coastal management (e.g. the fisheries and pollution control) and to predict storm surges and coastal flooding. On longer time scales, we considered the example of the North Atlantic Oscillation [14]. In that case, it appears that despite attempts to harness the ocean to predict the NAO several years in advance, most of the variability of the NAO is independent of the ocean. The ocean, nevertheless, has a role to play in climate, and concern continues to exist that global warming could lead to rapid regional changes in climate associated with changes in the ocean circulation [34].

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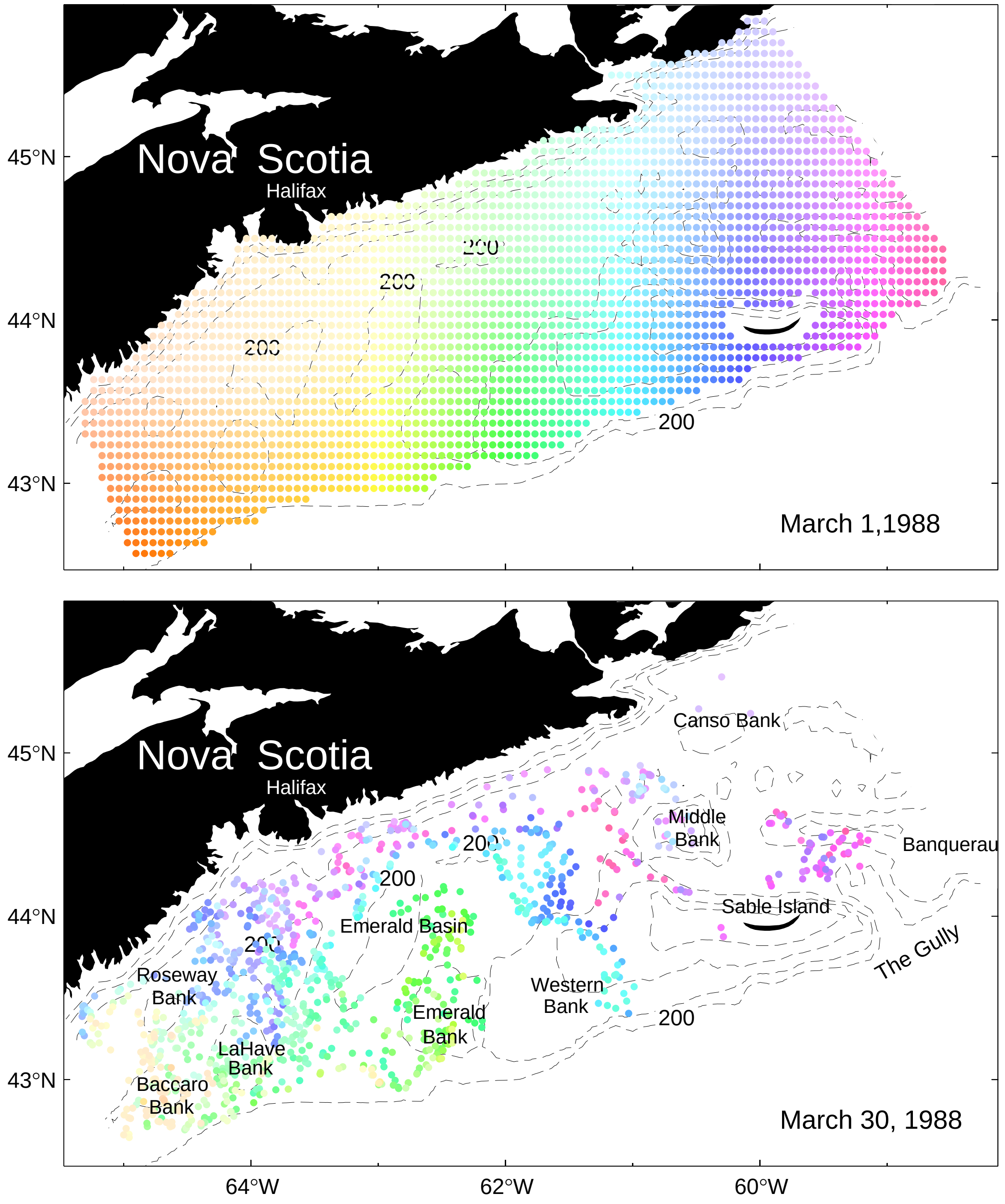

Figure 1. Retention of particles on the Scotian Shelf. The upper panel shows the initial distribution of colored particles, all of which are seeded at the surface. The bottom panel shows their position 30 days later, having been advected by the time-varying flow fields predicted by the assimilation model. The dashed contour lines are constant water depth. Note the spreading of the pink and blue particles along the coast, with greater retention being exhibited by the green particles over the banks offshore.

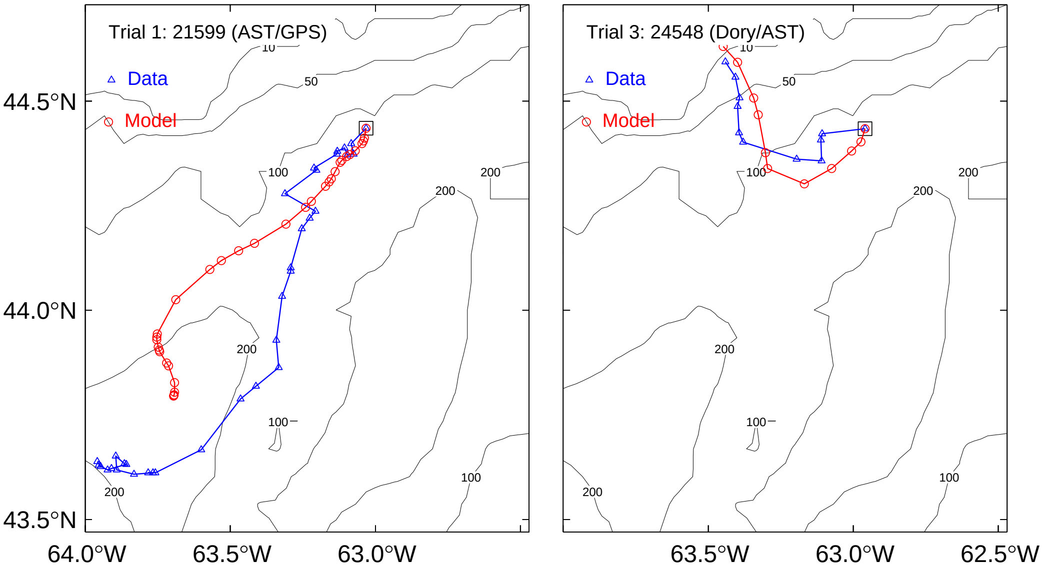

Figure 2. Observed and predicted trajectories of near-surface drifters deployed on the inner Scotian Shelf during February 1996. The observed positions are shown by triangles and the predicted positions by circles.

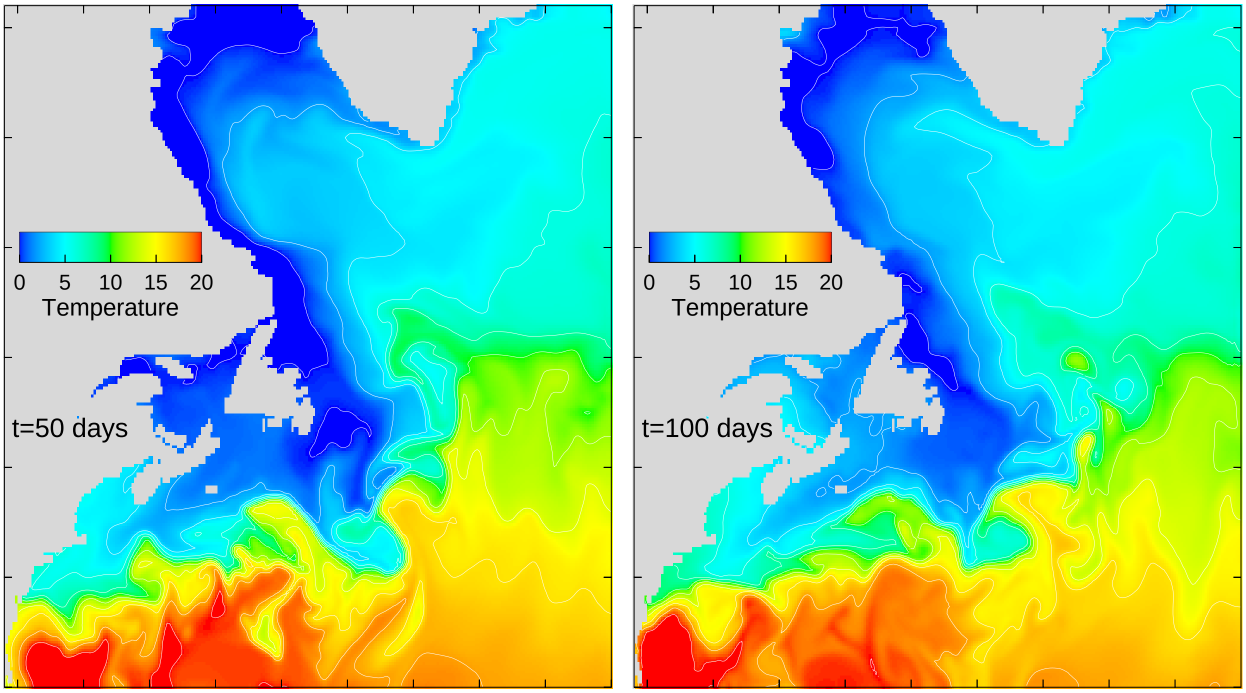

Figure 3. Model-computed sea surface temperature at days 50 and 100 from a model of the Northwest Atlantic. Note the strong eddying motion near the model Gulf Stream south of Nova Scotia.

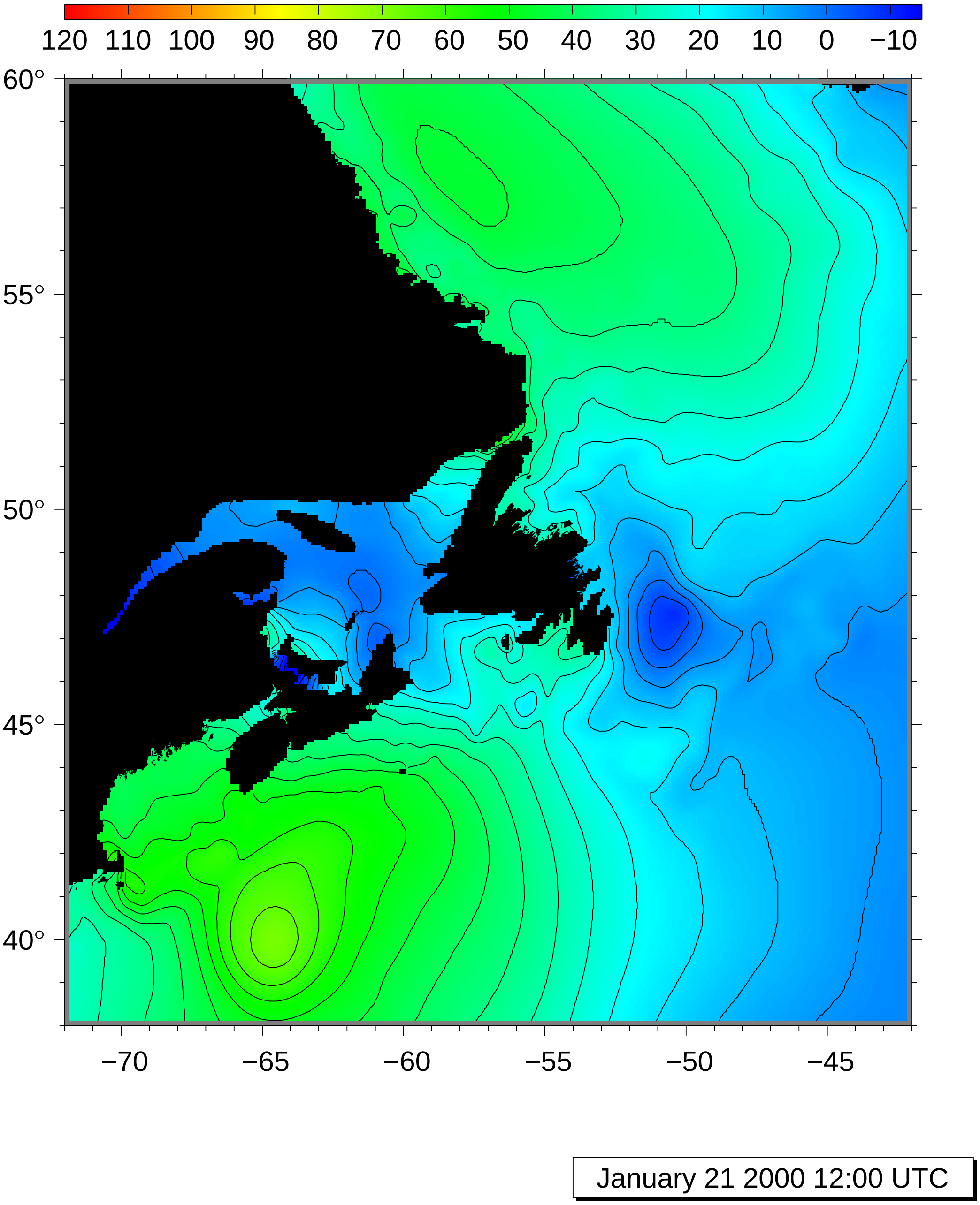

Figure 4. Sea level forecast map from the storm surge model for 12:00 UTC January 21st 2000 (tides not included). Color scale is in centimeters and contours run every 10 cm. The whole model domain is shown. The positive anomaly south of Nova Scotia is associated with a deep low pressure system.

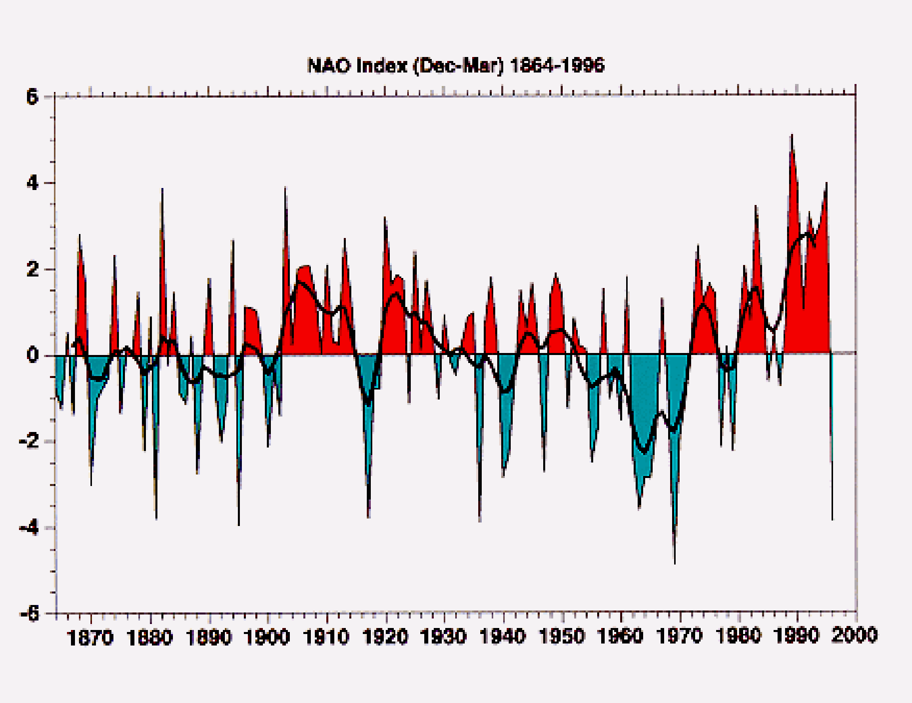

Figure 5. The NAO index from 1864 to 1996 defined as in Hurrell [23]. The heavy line shows the time series after filtering to remove periods less than 4 years.

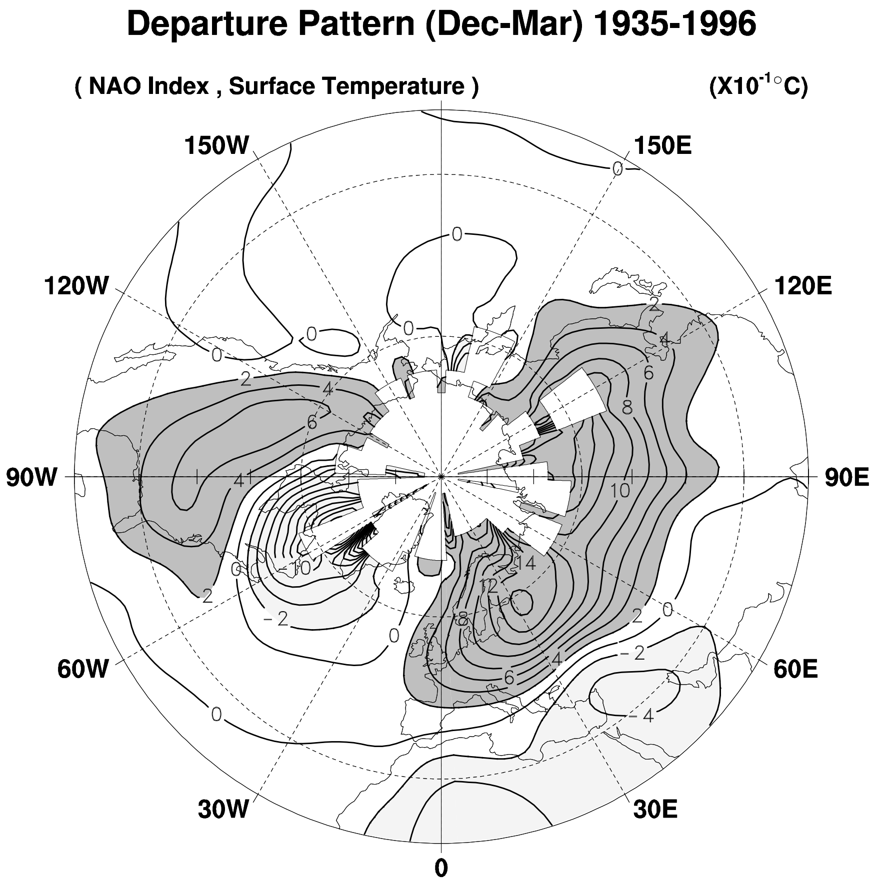

Figure 6. Surface temperature change (sea surface temperature over the ocean, air temperature over land) associated with one standard deviation (positive) of the NAO index. From Hurrell [24], courtesy of J. Hurrell.