NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE SECRETARIAT

Northwest Atlantic Fisheries Organization

Serial No. N6298 **NAFO SCR Doc. 14/008**

SCIENTIFIC COUNCIL MEETING – JUNE 2014

Physical oceanographic conditions on Newfoundland Shelf / Flemish Cap – from a model perspective (1990-2012)

Zeliang Wang and Blair J.W. Greenan

Abstract

The model results from 1990 to 2012 are presented for the Newfoundland Shelf and adjacent ocean in order to help better understand physical oceanographic conditions in the region. The model used in this report is a 1/12 degree North Atlantic model developed at Bedford Institute of Oceanography. The model is driven by CORE (Common Ocean-ice Reference Experiments) and NCEP (National Centers for Environmental Prediction) surface forcing for the 1990-2007 and 2008-2012 periods, respectively. The comparison between modeled mean states and observations demonstrates that the model does a good job of depicting oceanographic conditions in the region. Over the period of the study, there is a general warming trend for the sea surface temperature and bottom temperature for the Newfoundland Shelf and Flemish Cap regions. The model estimates a warming trend of 0.02 ^{o} C/ year for both SST and bottom temperature for the Newfoundland Shelf region, and trends of 0.05 ^{o} C/ year for SST and 0.005 ^{o} C/ year for bottom temperature for the Flemish Cap region. We note that the model probably underestimates the trend for the Newfoundland Shelf. The mean transports through Flemish Pass and over Flemish Cap are 7.4 Sv and 0.3 Sv, respectively.

INTRODUCTION

The ocean circulation features over the Newfoundland shelf and Flemish Cap regions are comprised of the equatorward inshore Labrador Current along the coast, the offshore Labrador Current along the shelf edge, and the cross-shelf flows following seaward trenches and canyons on topography. The offshore Labrador Current separates into two branches, one flowing through the Flemish Pass, the other flowing eastward at the northern flank of the Flemish Cap, then partially continuing eastward. The remaining part of the current flows along the eastern flank of the Cap ,and interacts with the Gulf Stream, making the current system very complicated, and poses a significant challenge both for observational and modelling efforts in terms of obtaining a reliable flow pattern in the region from the ocean surface to seabed. Furthermore, the circulation in the region has significant temporal and spatial variability, and understanding the variability at different time and space scales can enhance the knowledge level for this region, which is one of the most productive areas in the global marine system.

The hydrographic conditions and currents on the Newfoundland shelf and Flemish Cap regions are largely governed by the water mass and inflows from the Labrador Sea. The area to the east of the Flemish Cap is influenced both by the Labrador Sea and Gulf Stream. The local atmospheric system over the region can also play a role in the variations of hydrography and currents in this region.

The large-scale atmospheric conditions, commonly expressed by the North Atlantic Oscillation (NAO) index, play an important role in setting the deep convection events in the Labrador Sea. this index is often used to explain development of significant long-term hydrographic phenomena in the Labrador Sea, and to some extent, the currents in the subpolar region. Hence, it is expected that the hydrographic conditions and current system on the Newfoundland shelf and Flemish Cap regions should display a relationship with the NAO.

The regular surveys of transects by the DFO(Department of Fisheries and Oceans) Atlantic Zone Monitoring Program (AZMP) and Atlantic Zone Off-shelf Monitoring Program (AZOMP) , such as the Flemish Cap and AR7W lines, can provide important *in situ* information on hydrographic conditions and currents for this region. However, these “snapshot images” are limited in their spatial and temporal coverage due to the nature of ship-based observation programs. These data sets provide important ground-truthing for ocean models, which are tools to investigate the ocean environment in regions or periods where data are sparse.

A North Atlantic model discussed here has a resolution of 1/12 degree and can provide detailed structures of the currents and hydrography for the Newfoundland Shelf – Flemish Cap region. The model has simulated the whole North Atlantic Ocean from 1990 to 2012, so the temporal variations of hydrography and currents can also be investigated for the past 2 decades.

This report will show the comparison between model results and available observed data. The variations of hydrography and currents for the past two decades will also be presented.

Model description and validation

The model is based on NEMO 2.3 (Nucleus for European Modelling of the Ocean) which includes an ocean component OPA (Madec et al., 1998) and the sea ice module LIM (Fichefet and Morales Maqueda, 1997). The model grid used in this study is a subset of ORCA12 for the North Atlantic sector. It has a nominal resolution of $1/12^o$ (model domain shown in Figure 1). The latitudes range from 8^o N to 76^o N with the whole Baltic Sea included in the model domain along with most of the Mediterranean Sea to account for the dense salty water mass discharged into the North Atlantic. The available computer resources did not allow inclusion of the whole Mediterranean Sea. There are a maximum of 50 layers in the vertical, with layer thickness increasing from 1 m at the surface to 200 m at a depth of 1250 m and reaching the maximum value of 460 m at the bottom of the deep basins. The maximum depth represented in the model is 5730 m.

There are two open boundaries in this model configuration, the northern and southern boundaries. The northern open boundary includes three segments: 1) the Fury and Hecla Strait which connects the Hudson Bay with Arctic, 2) the Baffin Bay segment which receives the Arctic water from the Canadian Arctic Archipelago and transports part of the west Greenland current water mass out of the region, and 3) the Barents Sea which is a key part for the water mass exchange between the Arctic and North Atlantic. The southern open boundary is set at 8^o N so that it includes as much of the subtropical gyre as possible within the constraints of available computer resources. Open boundary conditions are climatological monthly data compiled from GLORYS reanalysis product. Normal velocity, T/S, and sea surface height are specified at the open boundaries, and the Flather approach is used for the open boundary treatment.

For the 1990-2007 period, the CORE surface forcing (Large and Yearger, 2004) was used to drive the model; this product does not extend beyond 2007, so for the 2008 to 2012 period, the NCEP surface forcing was used to drive the model. A 10-year spin up simulation was driven by climatological CORE forcing – the CORE Normal Year forcing, then the model was subsequently driven by CORE and NECP forcings.

The Bedford Institute of Oceanography archives current meter data mostly for the Northwest Atlantic, including the Labrador shelf, the Newfoundland Shelf and the Scotian Shelf dating back to 1960s. The model was forced by the climatological forcing for 10 years before switching to the inter-annual surface forcing in 1990, so the year of 1990 can exhibit a strong influence from the climatological forcing, especially in the deep ocean. Therefore, in the comparison for the ocean currents, the year of 1990 is not included. The monthly averaged current meter data from 1991 to 2009 are used in this comparison. The modelled monthly mean velocities were interpolated onto the mooring sites (lon/lat/depth) for comparison.

Previous studies have used correlation coefficients between modeled and observed velocities to assess the model performance, e.g., Han et al. [2008], but this approach is unable to show spatial patterns in the model performance. In order to visualize the model performances at different regions and depths, we have developed a new mapping technique for the comparison. Since the moorings were mostly on the shelves or along the shelf break from north to south, and the baroclinic feature of the currents, particularly the Labrador Current in this study, is an important aspect of the circulation system in this region, the observed and modeled velocities were binned into 0.5^{o} (in latitude) by 250 m (in vertical) boxes to access the model performance in terms of representing observed currents. Figure 2 shows the comparison between the observed velocities and modelled ones in zonal and meridional directions. The model can reasonably represent the observed currents latitudinally and vertically.

In order to quantitatively show the comparison between the modeled currents and current meter data, a number of summary statistics were calculated at the observational sites. These statistics include the means and standard deviations of the observed and the modeled current speeds, the modeled velocity and speed errors, the difference angle between the observed and model velocities, and the model-observation correlation coefficient. For the velocity and speed errors, we applied the metrics used by Han et al. [2008] for velocity difference ratio (VDR=$\sum|V_m - V_o|^2/\sum|V_o|^2$, V_m: model horizontal velocity; V_o: observed horizontal velocity) and speed difference ratio (SDR=$\sum(|Vm| - |Vo|)^2/\sum|V_o|^2$). Lower VDR and SDR indicate better agreement. The correlation coefficient (R) is the correlation between modeled and observed velocities components, averaged between the x and y components. DA is the difference of the angle between the observed and modeled velocities. Table 1 lists the statistics defined above. These statistics demonstrate that the model can capture the observed velocities in general, but large discrepancies are also clearly seen, especially for some years (e.g., 2001-2003), mainly due to the model performance for the Scotian Shelf region, as can be seen in Figure 2 (to the south of 45^{o} N).

Mean states of the ocean

In this section, the oceanic mean states of this region are derived from the model, and observed corresponding means will be shown when observations are available.

Sea surface variables

Sea surface temperature

The mean sea surface temperature derived from the model for the period of study is compared to the Levitus climatology (Levitus et al., 1998), which was used for the model initial conditions for temperature and salinity (Figure 3). The general patterns of these two are consistent, but the model results show more detailed structures in the vicinity of Flemish Cap; this is not surprising since the Levitus data only has a resolution of 1 degree in latitude and longitude. The mean SST is ~ 8 ^{o}C for both the Grand banks and Flemish Cap. The cold water carried by the inshore and offshore Labrador Currents contributes to the cooler temperature for the Newfoundland coastal region and the Flemish Pass region. The warm water transported northward by the North Atlantic Current brings the SST to the east of Flemish Cap up to ~14 ^{o}C. The variations of SST from 1990 to 2012 in this region will be shown in section 4.

Sea surface current

Figure 4 shows the surface currents derived from both the 1/12 degree model and drifter data. The Global Drifter Program is an array of satellite tracked surface-drifting buoys designed to provide observations of mixed layer currents and sea surface temperature (Lumpkin and Pazos, 2007; Higginson et al. 2011).

The buoys are of various designs but are mostly comprised of a surface float attached to a drogue at 15 m depth. Data are transmitted via the ARGOS satellite system, with the drifter position inferred from the Doppler shift of its transmission as the satellite passes over. The data are quality controlled by the Drifter Data Assembly Center and are interpolated to a regular 14 day interval. This drifter data is used to compute the mean surface current for the region.

The model demonstrates good skill in estimating the flow strength and direction for this region. The offshore Labrador Current trifurcates at the northeast corner of the Newfoundland Shelf. One branch flows southward through the Flemish Pass, one flows southeastward over the Flemish Cap, and another one continues eastward at the northern flank of the Flemish Cap before turning southward at the eastern flank of the Cap. The North Atlantic Current meanders northward to the east of the Grand Banks and Flemish Cap before turning eastward in the Orphan Knoll area. The modelled North Atlantic Current tends to move further north before turning east, however it is important to note that the number of drifters in this Northwest corner area is far less than that in the adjacent areas and this could cause the derived current from those drifters to be biased due to eddy activity in this area.

The surface currents from the model and drifter data indicate that there are persistent southward flows across the Newfoundland Shelf, Flemish Pass, Flemish Cap and the eastern flank of the Flemish Cap. These southward flows influence movements of nutrients, plankton and fish larvae. Variations of this ocean circulation can affect the distribution of these variables and, hence, impact fisheries in the region. Variations of the transport through Flemish Pass and Flemish Cap will be presented in section 4.

Near-bottom quantities

Estimating large-scale distribution patterns of ocean near-bottom quantities based solely on observational field survey data is a significant challenge. Some near-bottom quantities, such as, currents and temperature, can have substantial impacts on benthic species (e.g. Beazley et al., 2013]. Here, we report the near-bottom temperature from the model and the Levitus climatological data, as well as the near-bottom current from the model.

Near-bottom temperature

Figure 5 shows the bottom temperature derived from the model output and Levitus data. These two sources indicate a general agreement in terms of the distribution pattern with cold temperatures on the northern Newfoundland Shelf, warm temperatures on the southern tip of the shelf and southern edge of the shelf. Another warm region is over the Flemish Cap, however the Levitus data indicate the area is 2-3°C warmer than what is predicted by the model. The difference may be explained by the fact that the Levitus climatology is based on data from a much longer period than the model period of from 1990 to 2012. The variations of the bottom temperature from 1990 to 2012 will be reported in section 4.

Near-bottom currents

Figure 6 shows the near-bottom currents for the Newfoundland Shelf and the Flemish Cap region with the arrows indicating magnitude (by length of arrow) and direction. In order to better demonstrate the magnitude of the flow, Figure 7 shows the current speed color-coded, and it is clear that the bottom currents are stronger along the edge of the Newfoundland Shelf and the edge of the Flemish Cap where the water depth gradients are largest for this region. It should be noted that the Labrador Current is stronger in these regions as well. The speed of near-bottom current can reach up to 10 cm/s even at depths greater than 2500 m. The bottom current has been found to be strongly associated the population of sponges in this area (Beazley et al., 2013).

Barotropic circulation

The vertically integrated transport is a frequently-used variable to describe observed circulation patterns. The interpretation of the vertically integrated transport is not very straightforward as it constitutes a sum over flows that may have quite different origin and dynamics.

Figure 8 shows the barotropic stream function averaged over the 1990 to 2012 model period. The pattern of the barotropic flow is consistent with previous model studies with similar model resolutions. Much of the transport is confined to rather narrow regions near the continental shelf break. The transport reaches approximately 35 Sv for the Labrador Current in the Orphan Basin region; most of the current continues eastward with only a portion of the current bifurcating into the Flemish Pass and passing around the tip of Grand Banks. The northward flow from the North Atlantic Current is indicated by the red contours in the figure; this warm and salty current, together with the cold and fresh water mass carried by the Labrador Current, has a significant influence on the temperature and salinity in the Flemish Cap area.

Large-scale oceanic variability

Many studies have related variations of the subpolar gyre to the winter North Atlantic Oscillation (NAO) index, e.g., Wang et al. [2013]. The NAO is an important teleconnection pattern influencing atmospheric processes in the Labrador Sea (Barnston and Livezey, 1987). NAO phases are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport (Hurrell, 1995), which results in changes in temperature and precipitation patterns. The NAO exhibits considerable interseasonal and interannual variability, and prolonged periods of both positive and negative phases of the pattern are common. The wintertime NAO also exhibits significant multi-decadal variability (Hurrell, 1995). An upward trend of the NAO index from the 1960s through the 1990s was noted by Visbeck et al (2001), however, since the peak in the 1990s there has been a slight downward trend in the index (Figure 9).

Sea surface temperature variability

The variability of SST on the Newfoundland Shelf and Slope and Flemish Cap (Figure 10) for the period of 1990 to 2012 is presented in Figures 11 and 12. In addition to the modelled SST, we have analyzed three gridded and interpolated datasets of historical monthly data which includes:

1. HadISST1 (version 1) which is the United Kingdom Met Office's Hadley Centre Interpolated SST dataset, with 1^o x 1^o resolution extending back to 1870 (Rayner et al., 2003);
2. ERSST (version 3b) which is the United States NOAA's Extended Reconstruction of SST dataset, with 2^o x 2^o resolution extending back to 1854 (Smith et al., 2008)
3. COBE SST which is the Japanese Meteorological Agency's Centennial in-situ Observation-Based Estimates of variability of SST, with 1^o x 1^o resolution extending back to 1891 (Ishii et al., 2005).

Data quality, especially during the early part of the records and in remote and/or ice-covered regions, is an issue with these datasets (e.g. Yasunaka and Hanawa 2011) and, therefore, the results in some periods and areas need to be interpreted with caution. These datasets were derived from differing combinations of ICOADS (International Comprehensive Ocean-Atmosphere Data Set) (http://icoads.noaa.gov/) and other observations, using different methodologies for quality control and interpolation. HadISST1 used reduced-space optimal interpolation, ERSST used Empirical Orthogonal Functions (EOFs), and COBE an optimal interpolation scheme.

The modelled trend and variability in SST for the Newfoundland Shelf and Slope and Flemish Cap is consistent with the SSTs from the three products (Figure 11 and 12). The model results are closer to the data from ERSST and COBE in these two regions. The model seems to underestimate the SST for the years after 2008, particularly in the Newfoundland Shelf, while this is not evident from the three data products. We suspect the NCEP forcing used for this period may be the cause of this discrepancy and further investigation is necessary to determine the issue in the model.

There is a clear sign of warming trend from 1991 to 2006 for the Newfoundland Shelf region from the model and three data products this is followed by a cooling trend of similar magnitude from 2006 to 2011. The cooling trend is exaggerated in the model results from 2006 to 2009. The warming trend for the 1990 to 2012 period from the model simulation is 0.02 ^{o} C/ year, and the model probably underestimates the actual warming trend.

The warming trend is also observed for the Flemish Cap region from1991 to 2006 in both the model and data reanalysis products. While the cooling trend from 2006 to 2011 is captured by the model and shown in data products, there is again a larger downward trend in the model but the discrepancy between the model and data products is significantly smaller than that observed for the Newfoundland Shelf. The warming trend for the 1990 to 2012 period from the model is 0.05 ^{o} C/ year for the Flemish Cap region.

Near-bottom temperature

Near-bottom temperature is important for fisheries and non-commercial benthic species, however, observations are much more sparse than the surface temperature. Ship cruises can only provide spatially and temporally sparse data, not quite suitable for constructing spatial means and showing variations in time. In this section, we provide the annual mean bottom temperature variations from 1990 to 2012 for the Newfoundland Shelf (Figure 13) and Flemish Cap regions (Figure 14).

On the Newfoundland Shelf, near-bottom temperature ranges from a low of 1.75 ^{o}C in 1993 to a high of 2.55 ^{o}C in 2004. The near-bottom temperature decreased from 2 ^{o}C in 1990 to 1.75 ^{o}C in 1993, then steadily increased to 2.35 ^{o}C in 1999, followed by a slight decrease until 2003. The bottom temperature changed abruptly from 2.15 ^{o}C in 2003 to 2.55 ^{o}C in 2004 and then sharply declined to 1.97 ^{o}C in 2009; following this the temperature began to increase. The warming trend for the 1990 to 2012 period based on the model simulation is 0.02 ^{o} C/ year; this is similar to the rate of increase observed in the surface temperature.

The spatial pattern in bottom temperature over the Flemish Cap is similar to that of the Newfoundland Shelf, but differs in timing. The near-bottom temperature ranges from a low of 2.97 ^{o}C in 1995 to a high of 3.18 ^{o}C in 2006. It appears to indicate there is an approximately 2-year lag of the two extremes observed on the Newfoundland Shelf. The warming trend for the 1990 to 2012 period estimated from the model is 0.005 ^{o} C/ year; this rate is a factor of ten times smaller than the trend observed in the surface temperature.

Transport variability in the Flemish Pass

Volume transport is an important indicator of the ocean dynamics in the region of the Flemish Cap. The transport presented here is defined by the flow through the two following areas: the Flemish Pass (from the western 300 m isobath to the eastern 300 m isobath in the Pass, Figure 10) and the Flemish Cap (from the western 300 m isobath to the eastern 300 m isobath on the Cap, Figure 10). The mean transports through the Flemish Pass and Flemish Cap are southward at a rate of 7.4 Sv and 0.3 Sv, respectively, where one Sverdrup (Sv) is equivalent to 10^6 m^3 s^{-1}.

Figure 15 shows the monthly variations of transports through the Flemish Pass and Flemish Cap. The model results show that the variations from the means of the transports through these two sections can be very large with a range of 2 to 11 Sv for the Flemish Pass and 0 to 1 Sv for the Flemish Cap during the 1990 to 2012 period. In addition to the inter-annual variability, the seasonal variations can also be significant, implying that derived transports from any short term moorings could be strongly biased to the period of the deployment. It should be noted that over the Flemish Cap, there was a short period of northward net flow in 2006, which was the only time this segment had the net northward flow over the Cap in this 23-year period.

Figure 16 shows the normal velocities through the AZMP Flemish Cap transect at 47^{o} N during the high (1994) and low (2006) NAO years. The model suggests that the Labrador Current on the eastern flank of the Flemish Cap was stronger in the low NAO year. The current through the Flemish Pass has an interesting feature which is that the surface current intensifies in high NAO year while deeper layers intensify in low NAO year.

These changes could imply some shift in the circulation system when the large-scale atmospheric pattern shifts from one regime to another, e.g., from high NAO to low NAO (1990s vs 2000s); this could potentially affect the fisheries in the region through changes in transport of fish larvae, nutrients and others variables which can affect habitat. Furthermore, the changes in the circulation can also reflect changes in temperature and salinity, which could impact fisheries.

SUMMARY

(1) The North Atlantic 1/12 deg model provides a tool to complement existing data sets to represent the circulation, temperature and salinity for the Newfoundland Shelf and Flemish Cap regions.

(2) There is a general warming trend for the SST and bottom temperature for the Newfoundland Shelf and Flemish Cap regions. The model estimates a warming trend of 0.02 ^{o} C/ year for SST and also of 0.02 ^{o} C/ year for the bottom temperature for the Newfoundland Shelf region, and 0.05 ^{o} C/ year for SST and 0.005 ^{o} C/ year for the bottom temperature for the Flemish Cap region.

(3) The mean transports through the Flemish Pass and Flemish Cap are 7.4 Sv and 0.3 Sv, respectively. There is significant inter-annual variability in these transports.

(4) The flow through the eastern flank of Flemish Cap is stronger in low NAO year than those in high NAO year. The top and bottom layers of the flow through the Flemish Pass have a notable feature in the low and high NAO years - the flow is stronger in high NAO years for the top layers and stronger in low NAO years for the bottom layers.

ACKNOWLEDGEMENTS

The authors thank Drs. David Brickman and Simon Higginson for reviewing the document.

This research was financially supported by the DFO International Governance Strategy (IGS) program

REFERENCES

Barnston, A. G., and R. E. Livezey, 1987, Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon. Wea. Rev., 115, 1083-1126.

Beazley, L. I., Kenchington E. L., Murillo, F. J., and Sacau, M., 2013, Deep-sea sponge grounds enhance diversity and abundance of epibenthic megafauna in the Northwest Atlantic. – ICES Journal of Marine Science, doi:10.1093/icesjms/fst124.

Fichefet, T., Morales Maqueda, M. A., 1997. Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics, J. Geophys. Res., 102, 12609-12646, doi:10.1029/97JC00480.

Lumpkin, R. and M. Pazos, 2007: Measuring surface currents with Surface Velocity Program drifters: the instrument, its data and some recent results. Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics, A. Griffa, A. D. Kirwan, A. Mariano, T. Ozgokmen, and T. Rossby, Eds., Cambridge University Press, chap. 2, 39–67.

Han, G., Z. Lu, Z. Wang, J. Helbig, N. Chen and D. deYoung, 2008, Seasonal variability of the Labrador Current and Shelf circulation off Newfoundland, J. of Geo. Res., vol. 113, C10013, doi:10.1029/2007JC004376.

Higginson, S., K. R. Thompson, J. Huang, M. Véronneau, and D. G. Wright (2011), The mean surface circulation of the North Atlantic subpolar gyre: A comparison of estimates derived from new gravity and oceanographic measurements, J. Geophys. Res., 116, C08016, doi:10.1029/2010JC006877.

Hurrell, J. W. (1995), Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. Science, 269, 676-679.

Ishii, M., A. Shouji, S. Sugimoto and T. Matsumoto. 2005. Objective analyses of sea-surface temperature and marine meteorological variables for the 20th century using OCOADS and the KOBE collection. International Journal of Climatology 25: 865-869.

Large, W. G., Yeager, S. G., 2004. Diurnal to decadal global forcing for ocean and sea-ice models: The data sets and flux climatologies, Technical Report TN-460+STR, NCAR, 105pp.

Levitus S, Boyer, T. P., Conkright, M. E., O'Brian, T., Antonov, J., Stephens, C., Stathopolos, L., Johnson, D., Gelfeld, R., 1998. World Ocean Database 1998, NOAA Atlas NESDID, 18.

Madec G., Delecluse, P., Imbard, M., Levy, C., 1998. OPA8.1 Ocean general Circulation Model reference manual. Note du Pole de modelisazion, Institut Pierre-Simon Laplace (IPSL), France, 11.

Rayner, N.A., D.E. Parker, E.B. Horton, C.K.Folland, L.V. Alexander, D.P. Rowell, E.C. Kent and A. Kaplan. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J. Geophys. Res. 108, No. D14, 4407, doi:10.1029/2002JD002670.

Smith, T.M., R.W. Reynolds, T.C. Peterson and L. Lawrimore. 2008. Improvements to NOAA’s historical merged land-ocean surface temperature analysis (1880-2006), J. Clim. 21, 2283-2296.

Visbeck, M.H., J.W. Hurrell, L. Polvani and H.M. Cullen (2001), The North Atlantic Oscillation: Past, Present and Future. Proc. Nat. Acad. Sci., 98, 12876-12877 doi: 10.1073/pnas.231391598

Wang, Z., Y. Lu, F. Dupont, J. Loder, C. Hannah and D. Wright, 2013, Variability of sea surface height and circulation in the North Atlantic: Forcing mechanisms and linkages, Progress in Oceanography. Doi: 10.1016/j.pocean.2013.11.004.

Table 1. Statistics (Means and Standard Deviations and error metrics) from the comparison between observed and modeled monthly currents in the Northwest Atlantic from BIO Archived database.

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
1991	351	8.1±6.7	6.4±7.2	0.28	0.44	0.75	69.9±69.4
1992	472	8.5±6.3	7.4±7.2	0.38	0.53	0.60	40.7±78.1
1993	308	12.5±11.1	7.9±7.2	0.45	0.73	0.56	75.6±69.3
1994	762	11.1±9.9	8.4±8.0	0.48	1.08	0.48	75.2±69.4
1995	654	6.7±8.0	4.6±4.0	0.59	0.90	0.39	74.8±67.0
1996	388	10.3±7.2	6.4±6.5	0.34	0.57	0.74	86.3±42.8
1997	328	10.8±8.1	8.8±9.6	0.38	0.51	0.71	74.7±59.3
1998	230	11.0±8.2	10.8±11.6	0.52	0.65	0.76	88.8±37.7
1999	352	12.4±8.2	5.2±5.2	0.61	0.80	0.53	74.6±26.0
2000	264	9.0±7.1	5.3±5.3	0.42	0.75	0.58	89.4±51.7
2001	595	7.8±5.1	18.4±11.3	2.54	3.12	0.58	89.1±46.6
2002	862	8.6±6.0	18.7±8.7	1.87	4.29	0.24	76.5±69.9
2003	701	9.4±7.0	17.9±11.8	1.75	5.08	-0.1	56.4±49.6
2004	693	10.6±6.9	12.1±8.7	0.87	1.14	0.57	60.8±84.2
2005	1126	8.1±5.3	8.2±6.5	0.63	1.33	0.42	66.5±83.9
2006	344	7.0±5.0	8.0±5.5	0.36	0.64	0.72	62.2±82.6
2007	1165	10.0±6.4	7.3±5.9	0.48	0.99	0.46	85.5±67.6
2008	632	9.9±6.1	7.1±5.9	0.33	0.61	0.52	59.3±89.8
2009	958	9.2±7.6	7.2±6.4	0.13	0.20	0.86	72.7±20.0

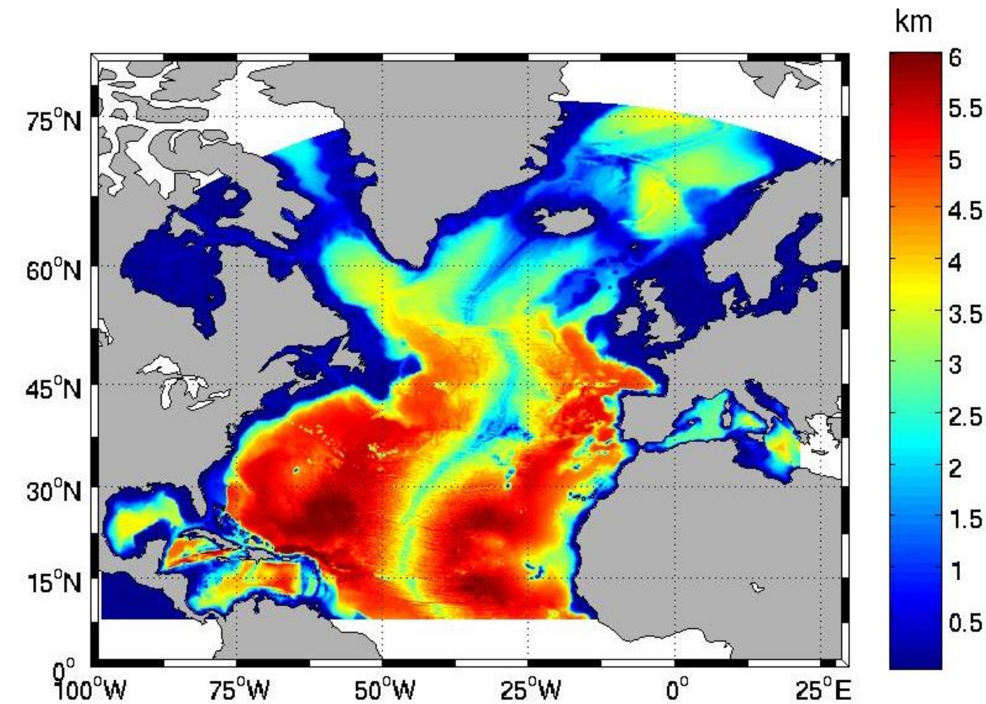

Figure 1. Map of the model domain with the color indicating ocean depth.

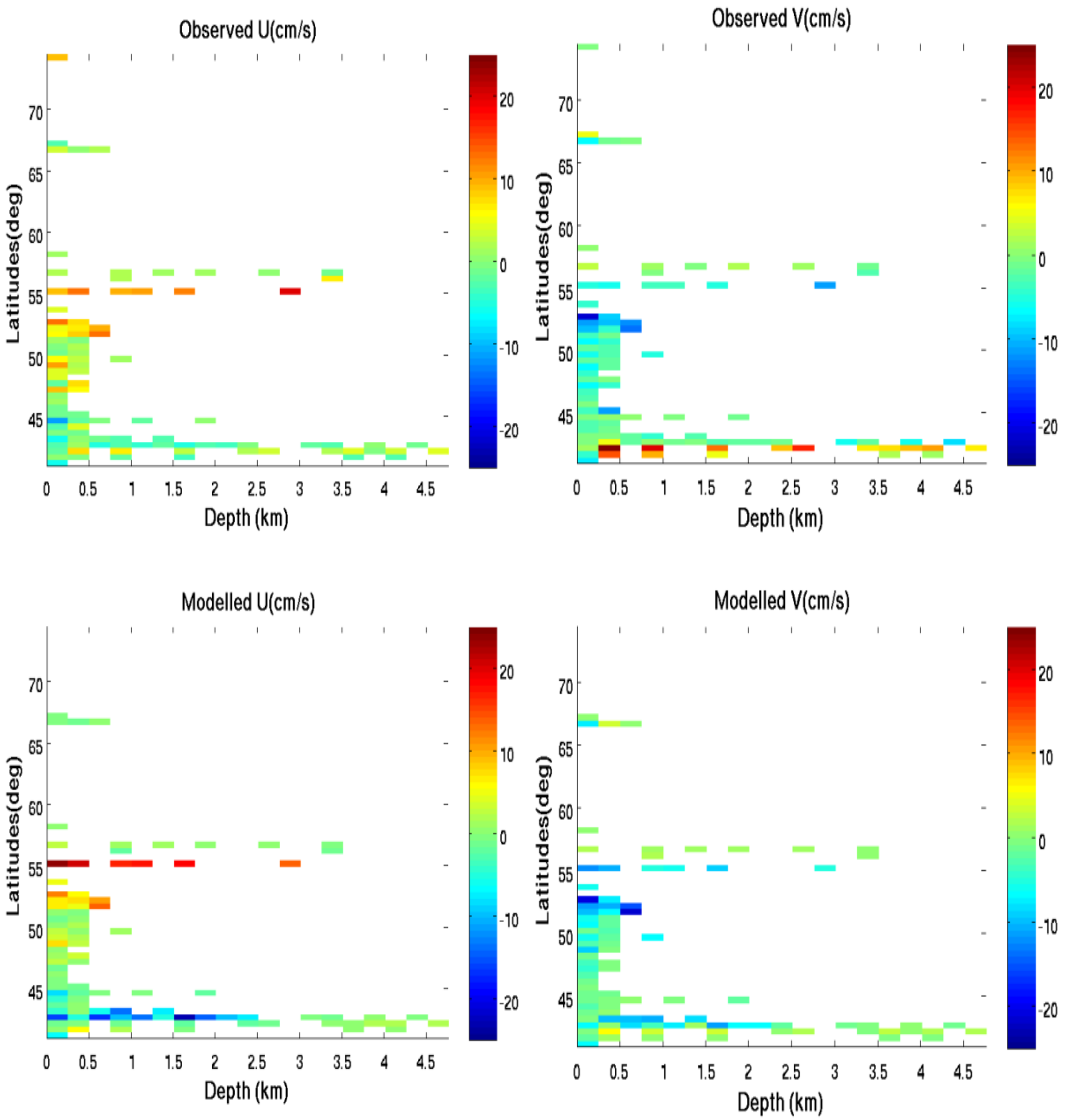

Figure 2. Comparison between observed (top) and modelled (bottom) velocities. U and V represent zonal and meridional velocities.

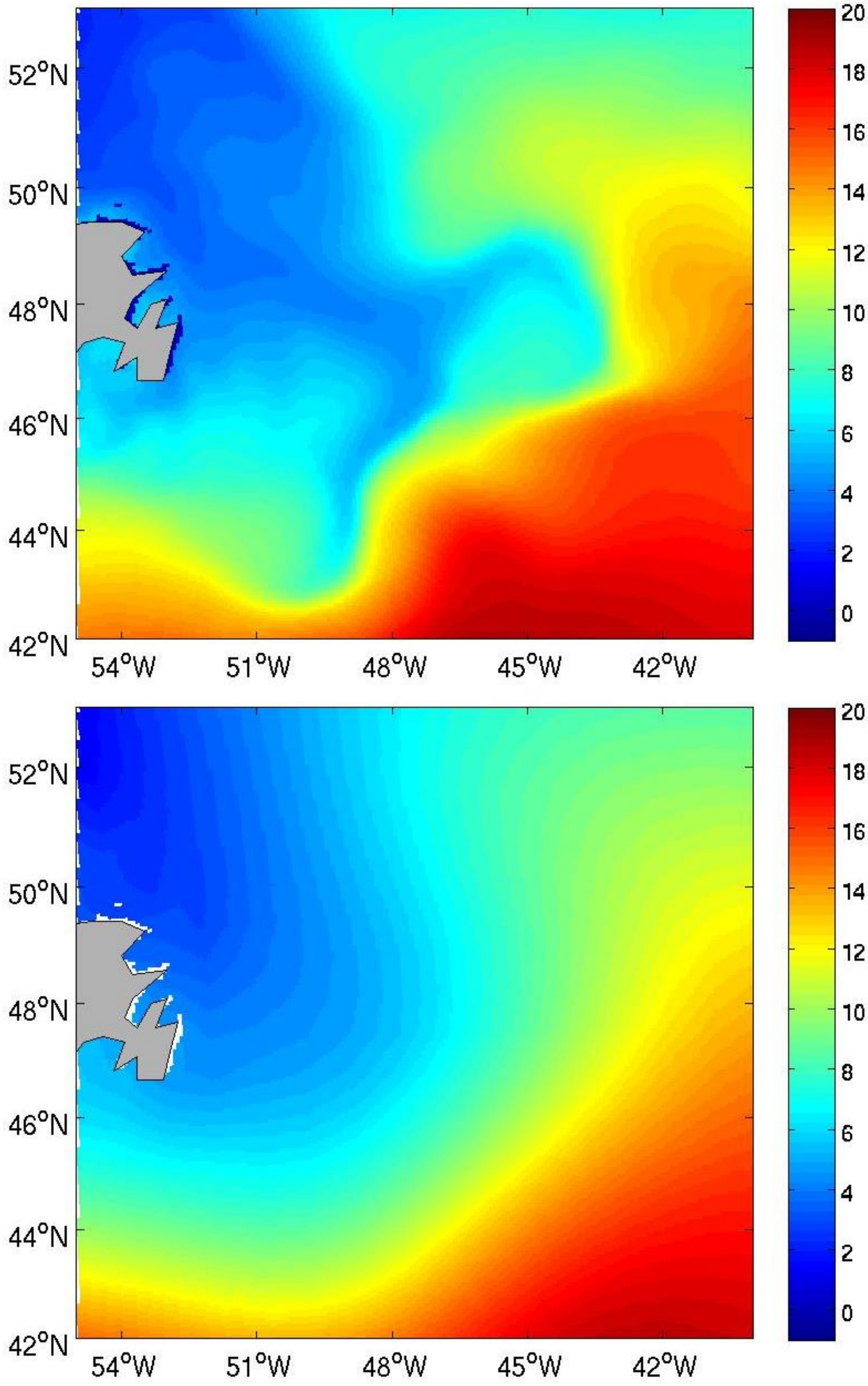

Figure3. Mean sea surface temperature (SST) from the model (top panel) and Levitus climatology (bottom panel).

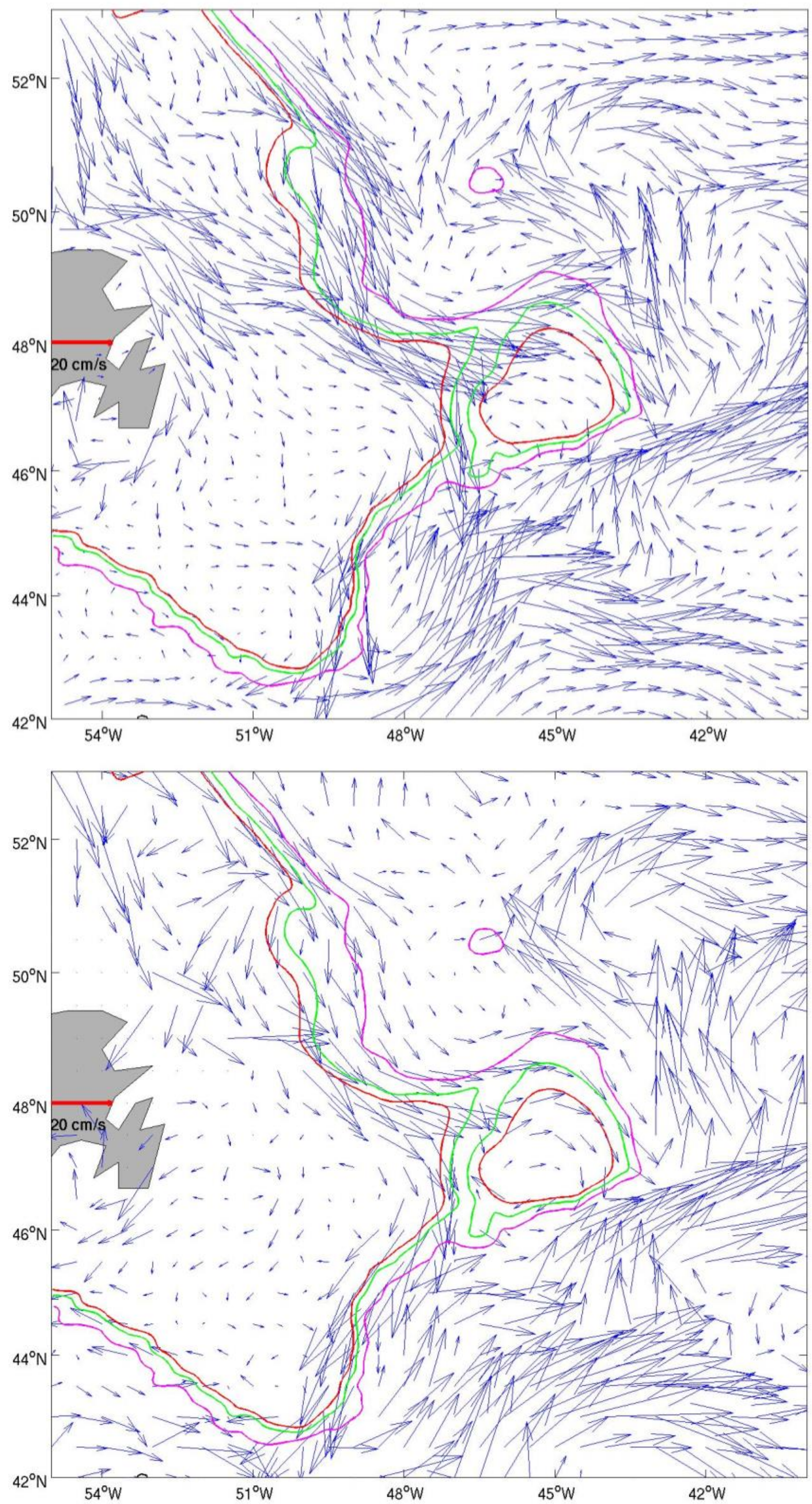

Figure 4. Mean sea surface currents from the model (top panel) and drifter data (bottom panel). A unit scale of 20 cm/s is shown in red on the center left of the panels. The red contour is for 500 m isobath, green for 1000 m and magenta for 2000 m.

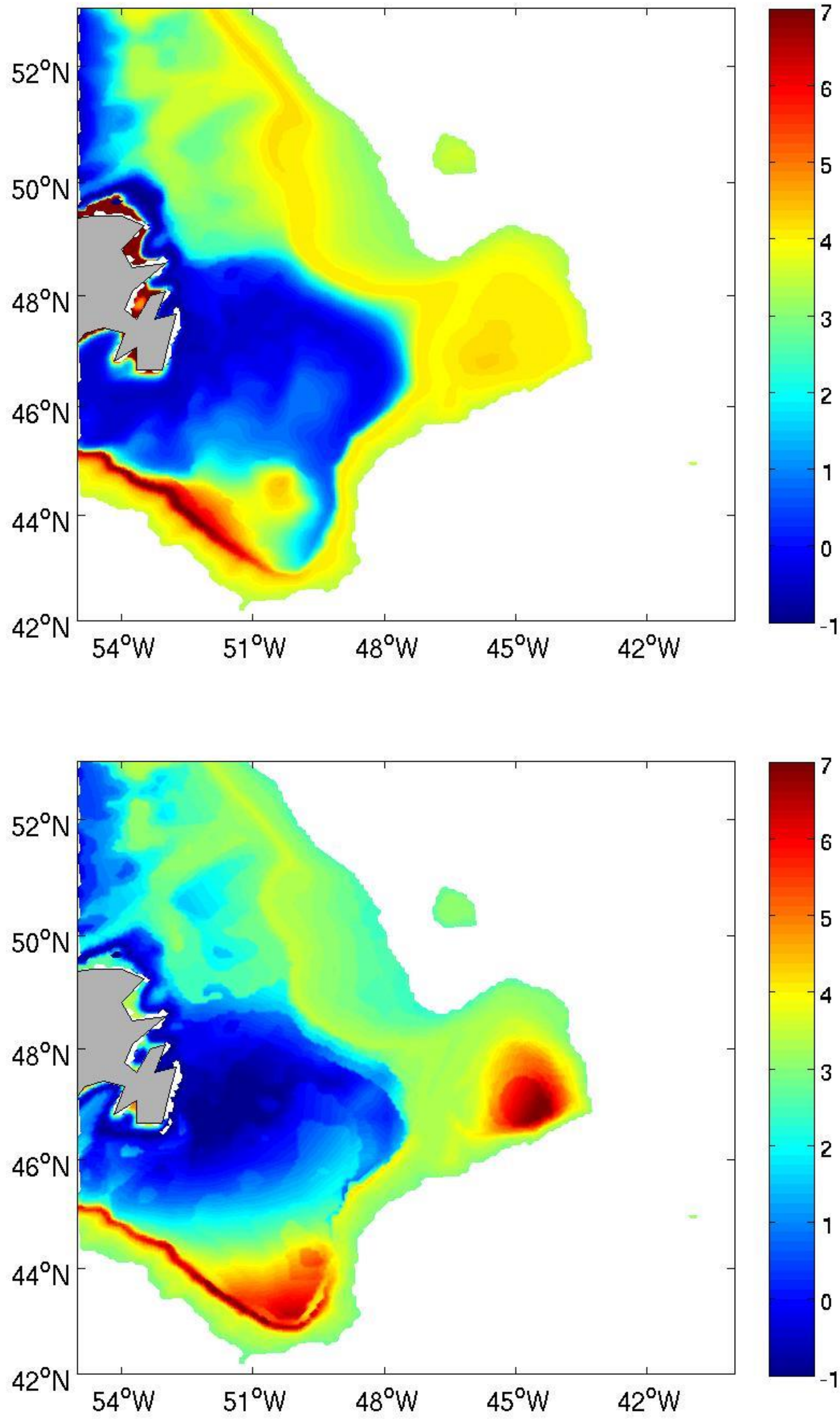

Figure 5. Mean bottom temperature from the model(top panel) and Levitus (bottom panel). Note: the bottom temperatures for regions deeper than 2600m are not shown.

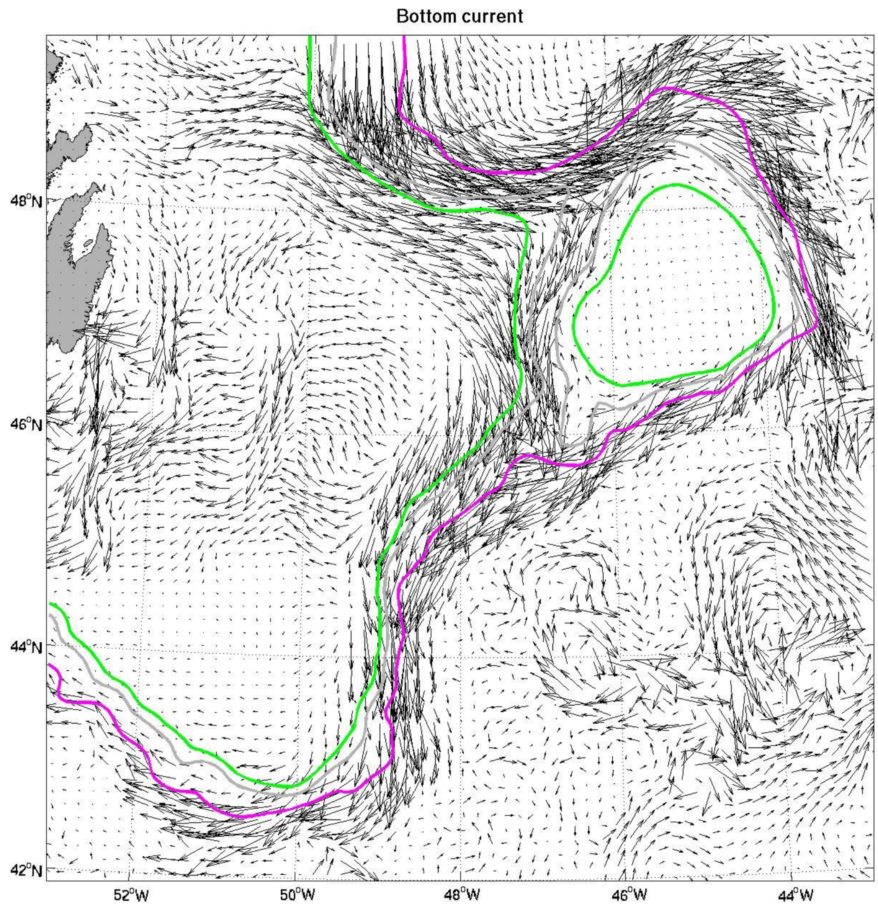

Figure 6. Mean model bottom current for the Newfoundland Shelf and Flemish Cap region. The red contour is for 500 m isobath, green for 1000 m and magenta for 2000 m.

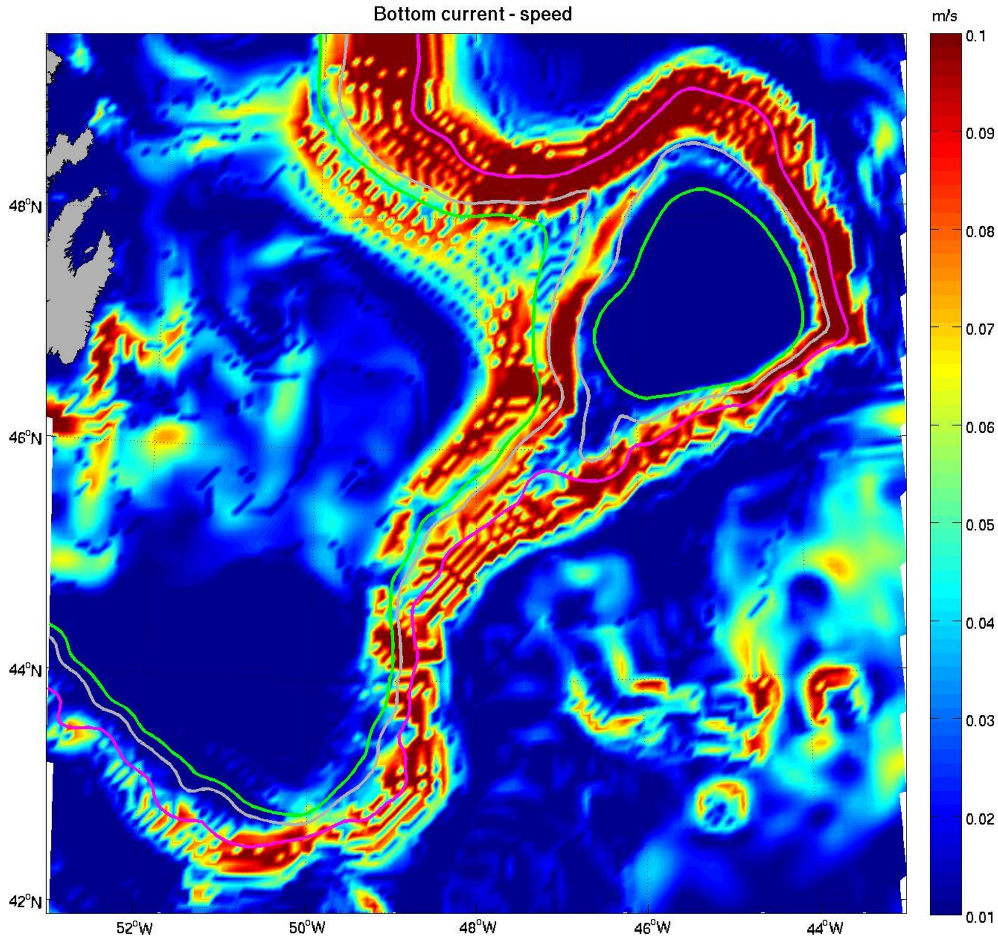

Figure 7. Mean model bottom current speed for the Newfoundland Shelf and Flemish Cap region.

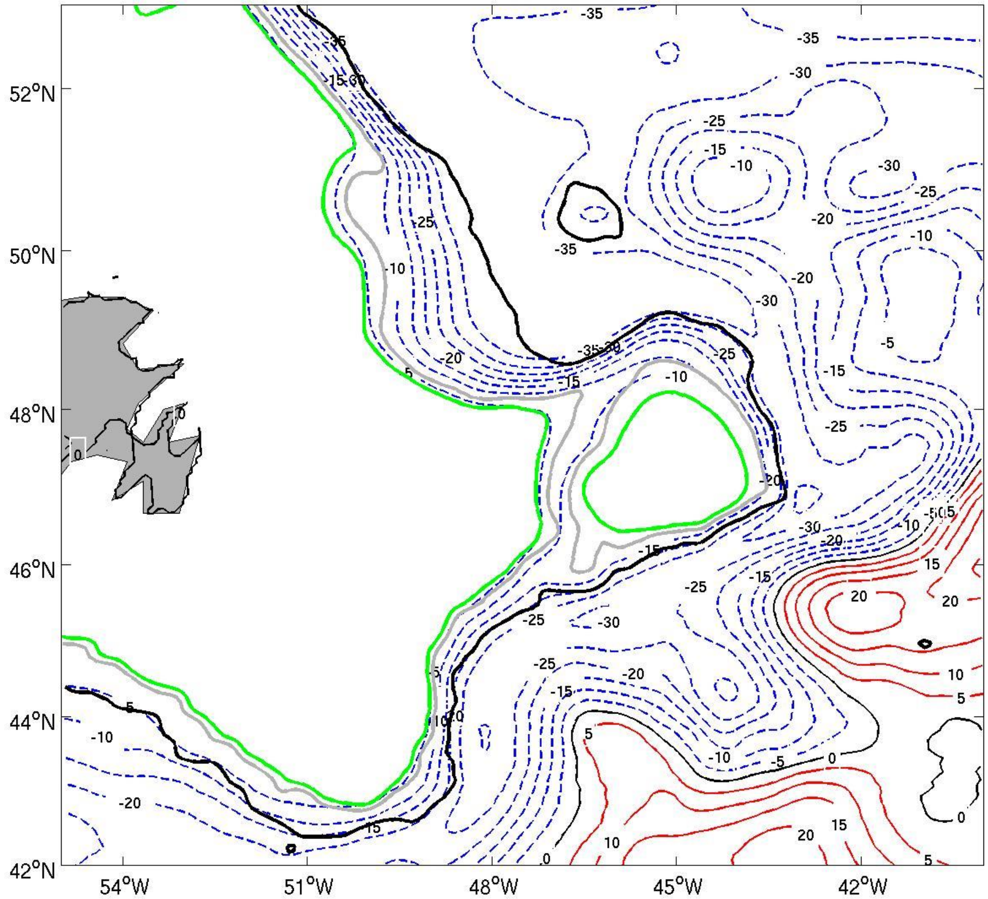

Figure 8. Barotropic stream functions for the Newfoundland Shelf and Flemish Cap region. The green contour is for 500 m isobath, gray for 1000 m and black for 2000 m.

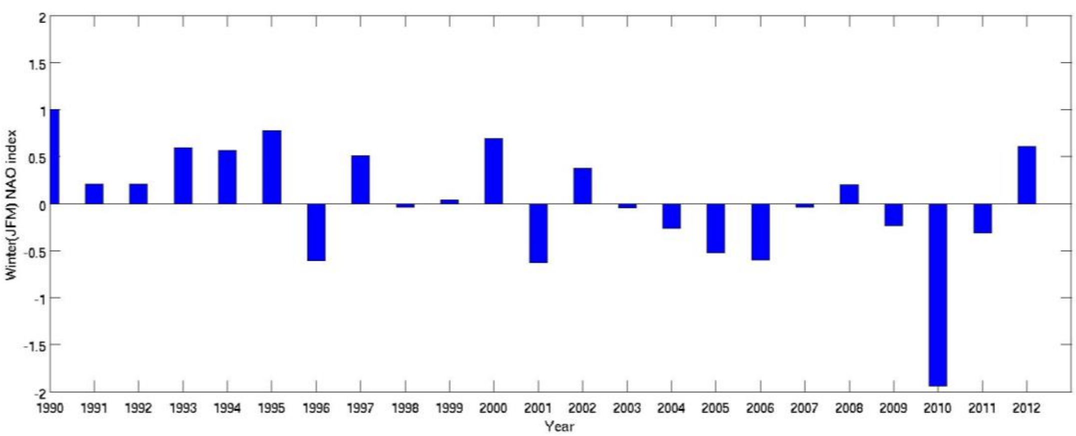

Figure 9. The winter (JFM) NAO index from 1990 to 2012.

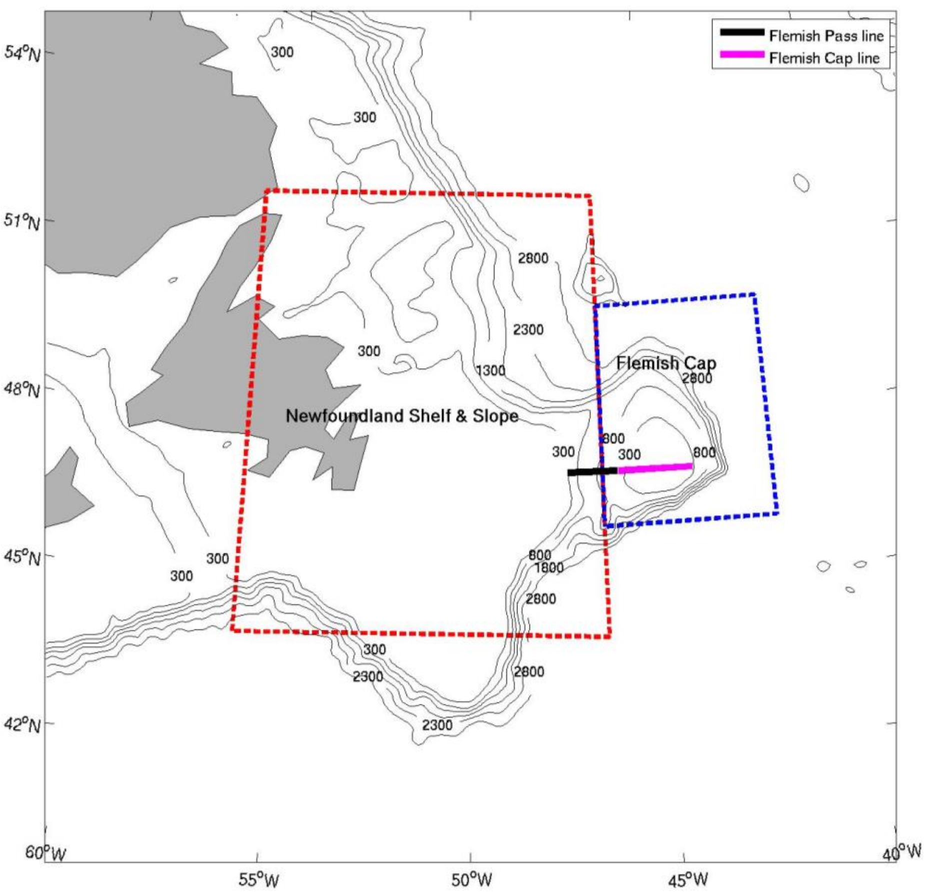

Figure 10. The area of the Newfoundland shelf and Slope (red) and that of the Flemish Cap (blue) for the calculation of SST and bottom temperature; the Flemish Pass line (black line) and Flemish Cap line (magenta line) for the calculation of transports.

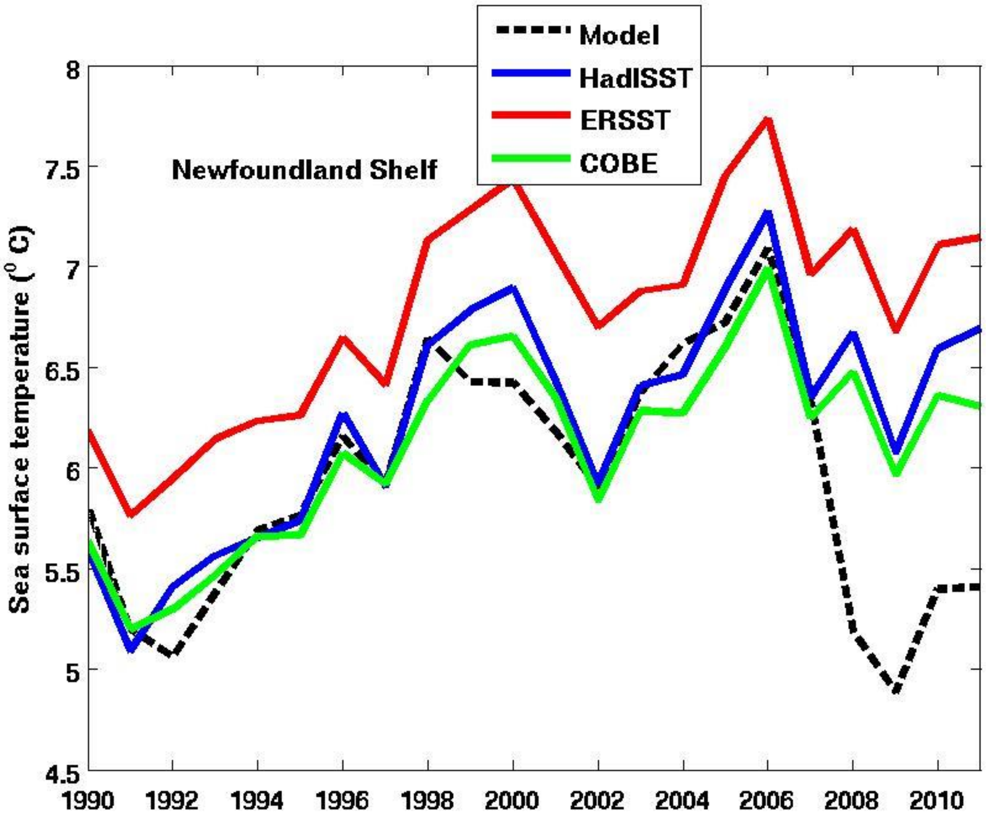

Figure 11. Time series of the annual mean sea surface temperature at Newfoundland shelf from the model, HadISST, ERSST and COBE.

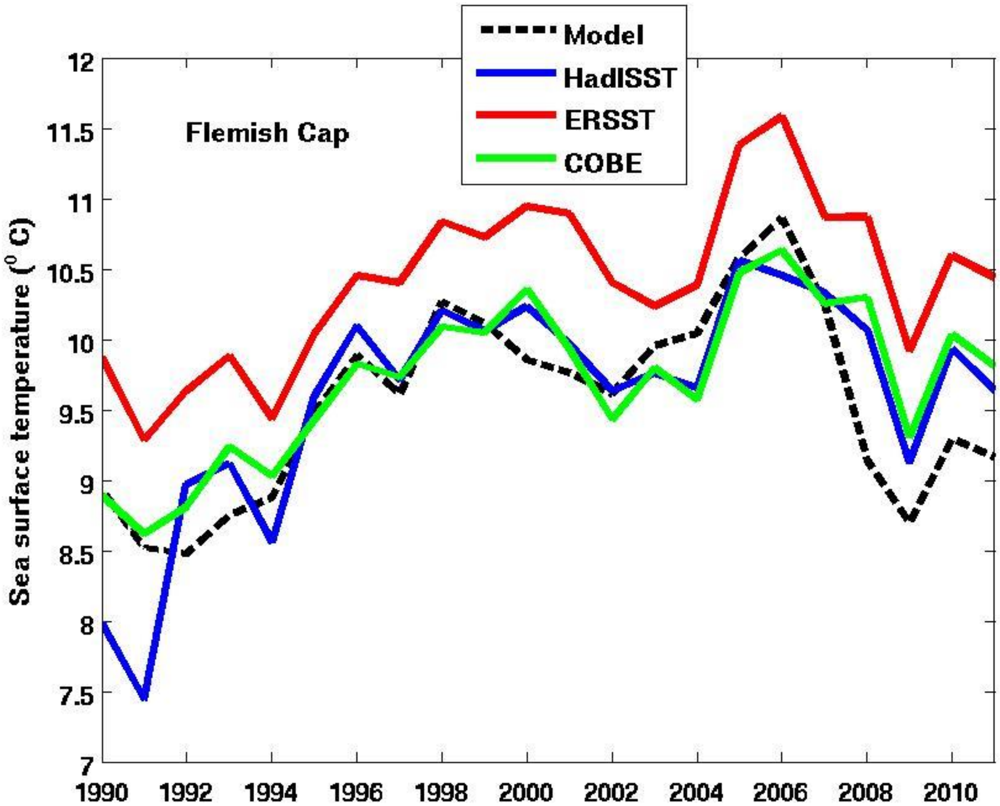

Figure 12. Time series of the annual mean sea surface temperature at Flemish Cap from the model, HadISST, ERSST and COBE.

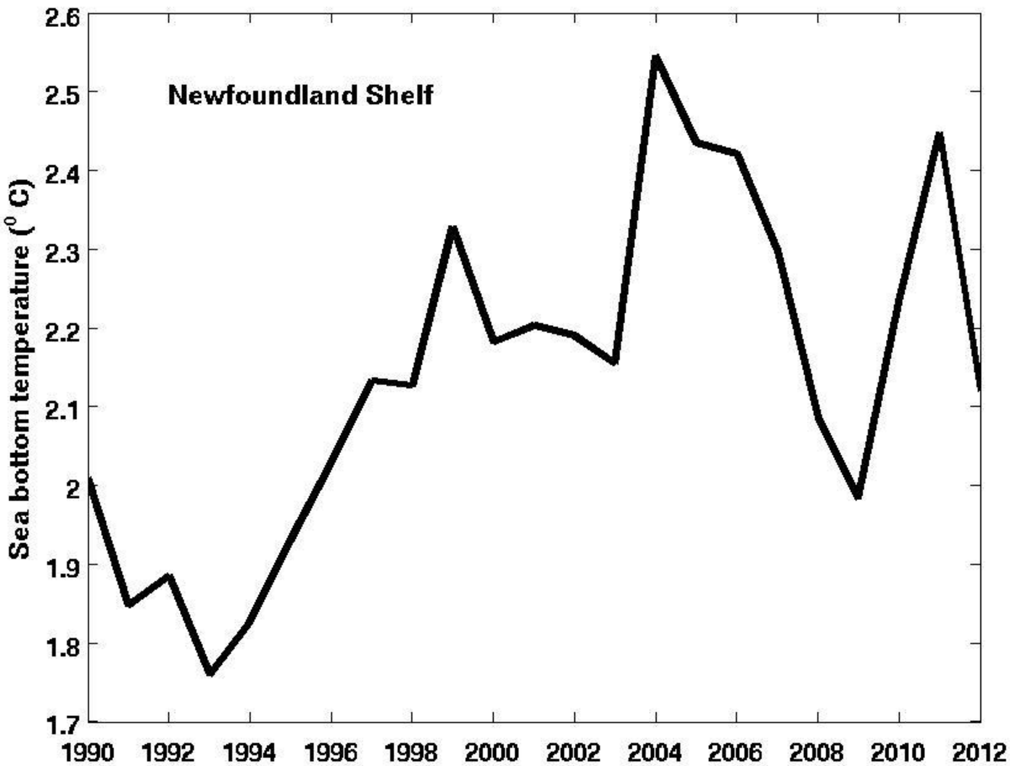

Figure 13. Time series of the annual mean bottom temperature at Newfoundland Shelf.

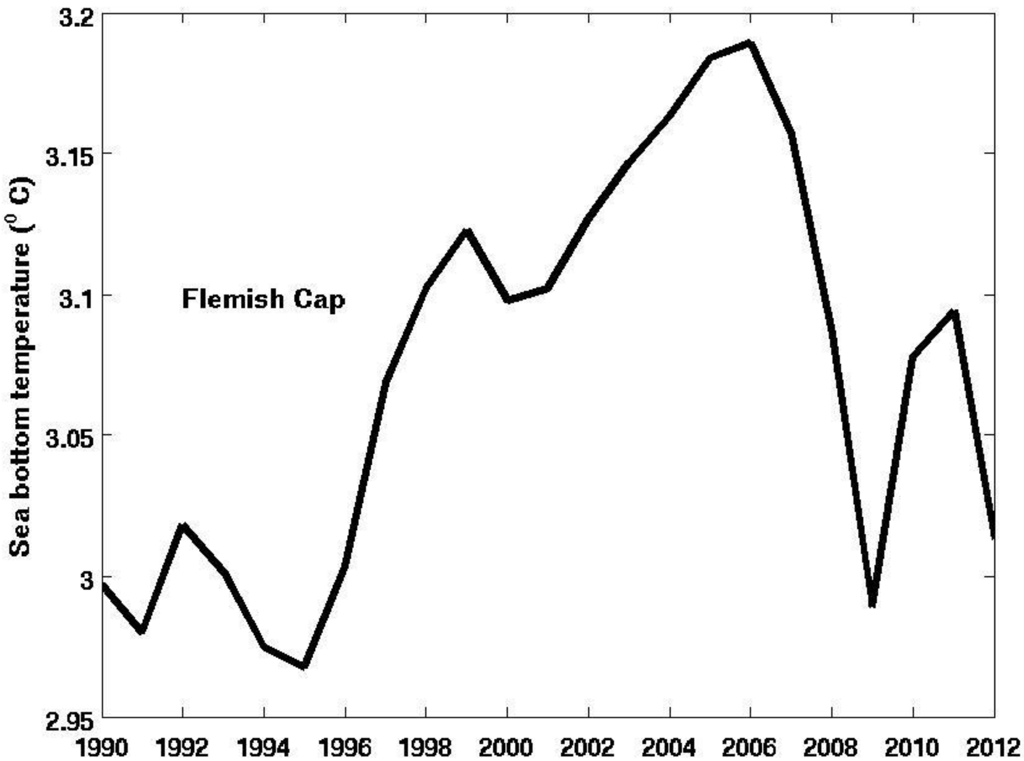

Figure 14. Time series of the annual mean bottom temperature at Flemish Cap.

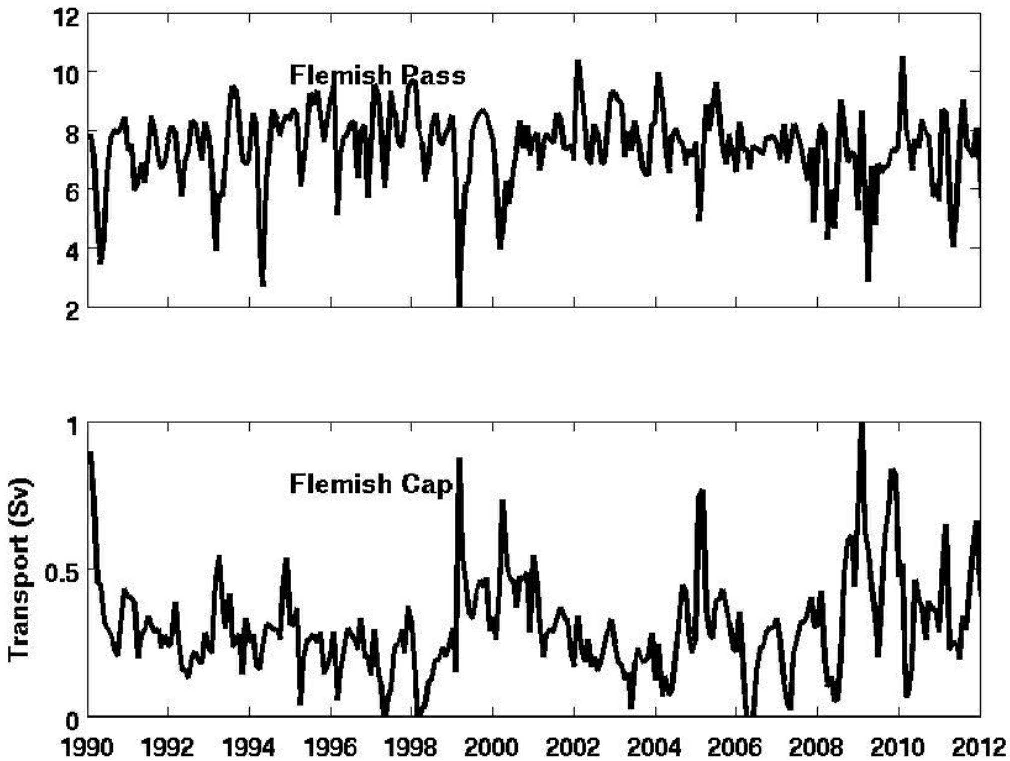

Figure 15. Time series of transports through Flemish Pass (top panel) and Flemish Cap (bottom panel).

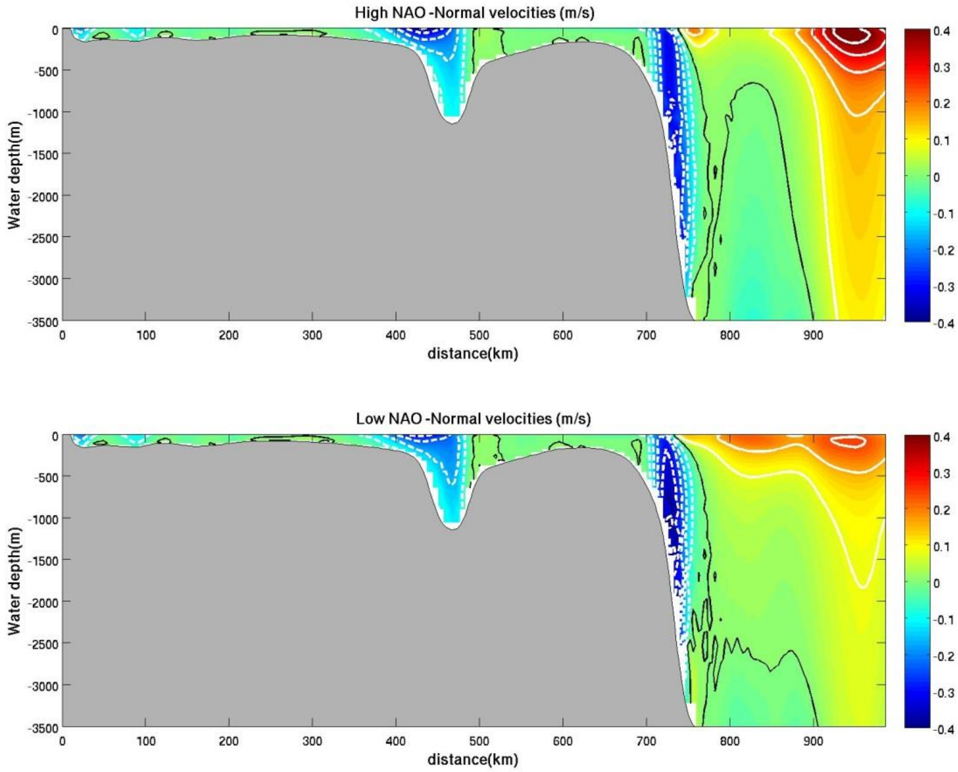

Figure 16. The normal velocities through the Flemish Cap transect, as derived from the model, for the high NAO year (top panel) and low NAO year (bottom panel)