Ocean Circulation in the Northwest Atlantic: an Evaluation of the GLORYS Reanalysis

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ABSTRACT

Wang, Z. and B.J.W. Greenan 2013. Ocean Circulation in the Northwest Atlantic: an Evaluation of the GLORYS Reanalysis. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 294: vi + 31 pp.

The GLORYS1 and GLORYS2 reanalysis products are validated using current meter data archived at BIO (Bedford Institute of Oceanography). The two products show reasonable skill in representing the observed currents. The level of skill varies from one region to another with the products demonstrating good skill for the Labrador and Newfoundland Shelves. The mean transport of the subpolar gyre is ~ 27 Sv from the reanalysis products. The reanalysis products show that the Labrador Current is at it maxima in winter with a transport of 28 Sv, and it reaches its minima in summer with a transport of 26 Sv. The seasonal circulation patterns and transports through the Labrador Sea AR7W monitoring section and the Atlantic Zone Monitoring Program 47N line are reported.

RÉSUMÉ

Wang, Z. et B.J.W. Greenan 2013. Ocean Circulation in the Northwest Atlantic: an Evaluation of the GLORYS Reanalysis. Rapp. tech. can. hydrogr. sci. océan. No. 294: vi + 31 pp.

Les produits de « réanalyse » GLORYS1 et GLORYS2 sont validés à l'aide de données fournies par courantomètre et archivées à l'Institut océanographique de Bedford. Les deux produits présentent des capacités raisonnables en représentation de courants observés. Le niveau d'efficacité varie d'une région à l'autre, les produits offrant de bons résultats à l'échelle des plateaux de Terre-Neuve-et-Labrador. Selon les produits de « réanalyse », le tourbillon océanique subpolaire se déplace à environ 27 Sv. Les produits indiquent que le courant du Labrador atteint sa vitesse maximale en hiver (28 Sv) et qu'il atteint sa vitesse minimale en été (26 Sv). Les tendances saisonnières et en matière de circulation à l'échelle de la zone de surveillance AR7W de la mer du Labrador et à l'échelle de la section 47N du Programme de monitorage de la zone Atlantique sont signalées.

1. INTRODUCTION

The GLORYS (Global Ocean ReanalYses and Simulations) project has been carried out by MERCATOR Ocean in France (http://www.mercator-ocean.fr/eng). It has provided two global ocean reanalysis products so far, GLORYS1 and GLORYS2. GLORYS1 covers ARGO period – from 2002 to 2008, and GLORYS2 covers Altimeter period – from 1992-2009.The reanalysis products are model runs with data assimilation – designed to reproduce the ocean state. GLORYS assimilated satellite altimetry data, sea surface temperature data, and temperature and salinity data from ARGO (www.argo.net) and ship-based CTD data.

This report describes the comparison between the modelled currents from GLORYS products and current meter data for the Northwest Atlantic Ocean archived at Bedford Institute of Oceanography. The current meter data are not assimilated in the GLORYS products, so the comparison between the observed velocities and modelled velocities can objectively reveal the performance of the numerical models/assimilation scheme in terms of representing the observed currents. The GLORYS products have been used by Environment Canada and Fisheries and Oceans either to initialize their models or to provide open boundary conditions. The purpose of this report is to quantitatively demonstrate the performance of the GLORYS products in terms of "point to point" representation of the observed ocean currents. Based on the evaluation of the products, the report presents the seasonal circulation patterns of Labrador Sea and Newfoundland Basin, and the transports through AR7W (http://www.bio.gc.ca/science/monitoring-monitorage/azomp-pmzao/labrador/labrador-eng.php) and 47N (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/hydro/section/yearly-annuelle-eng.html?a=1&y=2013) transects.

There are several modelling efforts at BIO, attempting to represent the ocean circulation system in the eastern seaboard of Canada (Brickman and Drozodowski, 2012; Wu et al. 2012). The models used at BIO are all regional models, and model domains are constrained in the northwestern part of the North Atlantic Ocean. The open boundaries in these regional models play important roles in the modelled circulation system. The GLORYS modelling system covers the global oceans, which avoids the open boundary issue.

This work intends to investigate how well the GLORYS modelled circulation system for the North Atlantic represents results from in situ current meters installed on deep ocean moorings. It is worth noticing that the ¼ degree solution by GLORYS is lower than the resolutions of BIO models mentioned above, both of the BIO models are using ~ 1/12 degree resolution. The report also intends to determine whether the ¼ degree resolution of the GLORYS model is high enough to accurately represent observed velocities from moorings.

2. MODEL DESCRIPTION

The model used in the GLORYS products is the ocean/sea-ice NEMO numerical framework. The model grid is the ORCA025 configuration developed by the European DRAKKAR collaboration. The numerical details of the model can be found in Barnier et al. (2006). The ocean model component is a free surface, primitive equation ocean general circulation model. The sea-ice component is the LIM2 sea-ice model (Fichefet and Morales Maqueda, 1997). The geographical domain extends from -77°S to the North Pole.

The data assimilation scheme is an extended Kalman filter based on the SEEK approach developed at LEGI (e.g. Testut et al. 2003). The SEEK formulation requires knowledge of the forecast error covariance of the control vector.

3. COMPARISON BETWEEN CURRENT METER AND MODELED VELOCITIES

In this section, the GLORYS products are evaluated for the Northwest Atlantic with current meter data archived at Bedford Institute of Oceanography. Monthly mean currents were derived from the archived data for months with a minimum of 20 days of data to create a current meter database. The database covers a period from 1963 to 2010. The current meter data were collected for various projects, and the number of the moorings varies from year to year, as can be seen from Figure 1 which shows the locations of moorings for the GLORYS1 period (2002-2008) and GLORYS2 period (1993-2009). The moorings are mostly clustered along Labrador Shelf, Newfoundland Shelf, Grand Banks and Scotian Shelf. There were also some moorings in the deep ocean as indicated in Figure 1.

To compare the modeled velocities with the those observed, modeled horizontal velocities were linearly interpolated to instrument depths and location for each site. In this analysis, we take out all the points with the observed speed less than 1cm/s (some older-generation current meter motors, such as the Aanderaa RCM8, do not work well when the current is weak, < 1cm/s) .

Figure 2 shows the comparison between the observed velocities and modeled ones for u(zonal direction) and v(meridional direction). Velocities from both of the products show good agreement with the observed velocities in general, though large discrepancies are also clearly seen. The correlation coefficients between the observed velocities and modelled ones are 0.62 and 0.36 for zonal and meridional velocities, respectively, for GLORYS1, and 0.60 and 0.55 for GLORYS2; they are significant at the level $p<0.05$. In order to quantitatively show the comparison between the results from the two products and current meter data, a number of summary statistics were calculated at the observational sites. These statistics included 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 and Table 2 show that the two model products underestimate the strength of currents in general, and the underestimation can be as high as by a factor of 2 for some years (2007 and 2008 for GLORYS1, 1996, 1999, 2000, 2004, 2007, 2008 and 2009 for GLORYS2). Tables 1 and 2 indicate that modeled velocities are even weaker than the observed ones when close to the end of the simulation, implying a possible spin-down of the model. This was investigated by checking the total kinetic energy (KE) in the Northwest Atlantic region, but no clear decreasing trend of KE was found and this issue was be communicated to the researchers at MERCATOR. The correlation coefficients are mostly higher than 0.6, although in 2008the GLORYS1 value is only 0.1.

The current system is complex in the Northwest Atlantic due to coexistence and interaction of the poleward Gulf Stream and equatorward Labrador Current. The areas of the Northwest Atlantic where the subpolar and subtropical gyres strongly interact incclude the Northwest corner, the region to the east of Grand Banks, and Scotian Shelf region. This report investigates in which regions the models achieves better skill in simulating observed velocities. The mooring locations are grouped into the following areas for analysis: Labrador Shelf, Newfoundland Shelf, Gulf of St. Lawrence, Bay of Fundy, Scotian Shelf, to the east of Grand Banks, Central Labrador Sea and Cabot Strait. Note that the statistics are not shown for the years with the number of observations being less than 5.

For GLORYS1, the modeled velocities are weaker than the observed ones in general for all the subregions - Labrador Shelf, Newfoundland Shelf, Gulf of St. Laurence, Bay of Fundy, Scotian Shelf and Central Labrador Sea. That weaker currents in each sub-domain were obtained in the GLORYS1 is consistent with the statistics from the data for the whole Northwest Atlantic Ocean, indicating that this is not region-specific issue in this model product. The analysis demonstrated the lowest correlation in 2008 of GLORYS1 (Table 1) is in the Scotian Shelf region.

For GLORYS2, the modeled velocities are generally weaker than observed ones, consistent with GLORYS1, while over Labrador Shelf, for the years of 1993 and 1994, modeled velocities are actually stronger than observed ones. In a region to the east of Grand Banks, modeled velocities agree well with the observed ones.

From the correlation perspective of the comparison from these two products, the model performs well in the regions of the Labrador Shelf, Newfoundland Shelf and Gulf of St. Lawrence. The model does not achieve a consistent level of good skill through the simulation years for the Scotian Shelf region.

4. SEASONAL CIRCULATION PATTERNS

This report will not focus on inter-annual variations of the Northwest Atlantic; instead, the intent of the report is to provide a large scale view of the circulation in the region, and also provide some information on the climatological circulation, which will be beneficial to studies using such data for the open boundaries in regional models.

The 7- year GLORYS1 and 17-year GLORYS2 products potentially allow us to check the seasonality of the circulation patterns in the Northwest Atlantic. The seasonal 3-D velocity fields were compiled from these two products separately, and they demonstrate significant similarity. Hence, in this report, the focus will be placed on GLORYS2 to study the seasonal circulation patterns.

The Labrador Shelf and Newfoundland Shelf are well represented by the two products as showed in section 3, while Scotian Shelf is not well represented. In this section, to the focus will be on the patterns in the Labrador Sea and Newfoundland Shelf.

Before discussing the seasonality of the circulation in these regions, the barotropic stream function for these regions is presented in Figure 3 and the depth average velocities are shown in Figure 4. The GLORYS product shows that the mean transport in the subpolar region is ~25 Sv. Smith et al. (1937) estimated that the total transport of the Labrador Current was about 5 Sv without deep currents included. Sarmiento and Bryan (1982) found a total transport of 40 Sv flowing westward past Cape Farewell using a "robust" diagnostic model. Provost (1983) got a transport of over 50 Sv past Cape Farewell. Clarke (1984) indicated a westward transport of 34 Sv around Cape Farewell and into the Labrador Sea. The mean transport of ~25 Sv seems weaker than previous estimates. Wang et al. [2012] obtains 27 Sv from their 1 deg. model, and Wu et al. [2012] reports ~26 Sv from their 1/12 deg. regional model. The mean strength of the subpolar gyre in the North Atlantic remains a topic of open discussion. Figure 4 clearly shows the current system in the region, the inshore and offshore Labrador Currents flow southward, separating over Newfoundland Shelf into several branches due to topographic steering.

Figure 5 – 9 show seasonal velocity fields at different depth for the Labrador Sea. It is clear that there exist two-way flows along the Hudson Strait: the northern current flows into the Hudson Bay and the southern one joins the Baffin Current. The southern current bifurcates at the western end of the Ungava Bay with one branch following the coast of the bay and joining the Baffin Current, and the other continuing eastward to join the Baffin Current. The in and out currents in the Hudson Strait clearly demonstrate a seasonal cycle, weakest in winter and strongest in autumn. In autumn when the southern current is the strongest, this current is mostly following the coast of the bay. The eastward branch of this current is very weak and diffusive.

The GLORYS product shows that the Labrador Current has several sources (as is consistent with general understanding of the current) – Baffin Current, Southern Hudson Strait Current, and Irminger Current. There are several pathways of Irminger Current joining the Labrador Current, and these banding currents are mostly parallel to each other from north to south.

At the 47 m depth (Figure 5), the inshore Labrador Current is strongest in Autumn, which is consistent with the southern Hudson Strait Current. During the winter and spring seasons, the inshore Labrador Current is weak in the northern part, the southern part is much stronger, and the origin of the current is mostly from the bifurcation of the offshore Labrador Current; this phenomena is also shown at110 m depth (Figure 6).

At 454, 644 and 1062 m (Figure 7-9), there is a narrow current flowing northward at the eastern edge of the Labrador Current. The northward current has a potential to bring in salty watermass from the south into the central Labrador Sea, which could influence the salinity in the region, preconditioning the deep convection.

Figure 10– 14 show the velocity fields at different depth for the winter, spring, summer and autumn, for the Newfoundland shelf and adjacent regions. The current system in the region includes the equator-ward inshore and offshore Labrador Currents and the meandering North Atlantic current. The seasonality of the inshore and offshore Labrador Currents is clear in this model solution. The inshore Labrador Current is weakest in winter and spring, strongest in summer and autumn, and follows the same temporal patterns for shallow and deep layers.

Changes in the current system in the Northwest Corner can be found from season to season, but due to the strong eddy activity, it is not easy to determine whether the seasonal variations are driven by the surface forcing or eddies; it is possible that both mechanisms both play a significant role in the seasonal variations of the current system.

5. SEASONALITY OF TRANSPORTS THROUGH MAJOR SECTIONS

In order to quantitatively demonstrate seasonal variations of the circulation in the Northwest Atlantic Ocean, the climatologically monthly mean transports through major segments were calculated. This analysis will focus on the AR7W and N47 sections (Figure 15). DFO carries out regular survey along the AR7W transect in the late Spring every year since the early 1990s. The N47 transect is an important section for understanding the circulation over Newfoundland Shelf and water masses coming into Scotian Shelf region; this section has been occupied 2-3 times per year since 1998 as part of the Atlantic Zone Monitoring Program (AZMP).

Figure 16 – 19 show the normal velocities through the AR7W line from Labrador coast to west Greenland coast. The vertical distributions of the two boundary currents are clearly shown in all four seasons with the strongest velocities at the top, and gradually decreasing in magnitude with depth. The section plots show a current flowing northward by the eastern side of the Labrador Current; this recirculation could be an important feature for the studies focusing on the subpolar gyre. This northward current shows a strong baroclinic feature, the maximum velocities are at the depth range from 500 to 1500 m – the core of this current. This current reaches its maximum strength in summer and weakest in winter and spring.

Figure 20-23 provide a summary of the seasonal normal velocities through N47 line. The southward currents include the inshore Labrador Current over the shelf region, the current flowing through the Flemish Pass, and a strong current hugging the eastern flank of the Flemish Cap. In addition, the GLORYS product indicates the deep southward current at the eastern flank of the Flemish Pass, and this current shifts its core from season to season. The northward current is mostly the meandering of the extension of the Gulf Stream.

A result of calculation of the cumulative volume transport from Labrador coast to west Greenland coast for the AR7W line is presented in Figure 24. The Labrador Current reaches its maximum of 28 Sv (1Sv $=10^6$ m^3/s) in winter, and a minimum of 26 Sv in summer. The Irminger Current also reaches its maximum of 28 Sv in autumn, and a minimum of 26 Sv in spring.

Figure 25 shows the cumulative volume transport from Newfoundland coast to deep sea region. It is clear that southward transport varies significantly seasonally, and the location of the maximum southward transport for each season shifts, which is caused the meandering of the North Atlantic Current in the area.

6. SUMMARY

The GLORYS products can reasonably represent observed currents in the Northwest Atlantic, in general, however the discrepancies between modeled and observed currents are large in some subregions of the domain.

Among the selected regions, the GLORYS products demonstrates good skill in representing observed velocities for the Labrador and Newfoundland shelves. The Scotian shelf region is not as well represented as Labrador and Newfoundland shelves.

In general, the modelled velocities are weaker than those observed*in situ*, which indicates that the ¼ degree resolution might be not high enough for obtaining magnitudes of observed velocities in the Northwest Atlantic. Previous studies using models with resolution not lower than 1/12 degree demonstrate a good skill in obtaining observed strength of velocities.

The GLORYS products show that mean strength of the subpolar gyre is ~ 27 Sv, which is weaker than previous estimates of 40 Sv, but is close to 27 Sv computed by Wang et al. [2012], and 26 Sv by Wu et. al [2012].

The GLORYS products show that Labrador Current reaches its maximum in winter with a transport of 28 Sv, and a minimum of 26 Sv in summer. The strongest Irminger Current occurs in autumn with a transport of 28 Sv, and weakest in spring, 26 Sv in transport.

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VDR=$\sum|V_m - V_o|^2 / \sum|V_o|^2$, V_m: model horizontal velocity; V_o: observed horizontal velocity;

SDR=$\sum(|Vm| - |Vo|)^2 / \sum|V_o|^2$). Lower VDR and SDR indicate better agreement;

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.

TABLES

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 – GLORYS1.

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
2002	866	8.6±6.0	6.6±5.9	0.43	0.69	0.66	79.2±56
2003	701	9.4±6.9	6.4±7.7	0.38	0.60	0.75	80.3±56
2004	249	10.6±6.0	6.0±3.5	0.31	0.50	0.61	62.0±77
2005	26	7.7±5.6	5.7±3.3	0.21	0.26	0.90	40.5±65
2006	48	5.5±5.3	4.6±3.3	0.22	0.29	0.89	48.9±74
2007	453	10.5±7.4	4.6±4.6	0.35	0.53	0.75	67.3±87
2008	632	9.9±6.1	3.5±2.5	0.59	1.00	0.10	89.0±64

Table 2: 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 – GLORYS2

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
1993	307	12.5±11.1	9.8±9.8	0.36	0.62	0.71	58.9±89.8
1994	762	11.1±9.9	8.7±8.0	0.36	0.64	0.67	76.2±66.2
1995	656	6.7±7.9	4.6±6.3	0.46	0.72	0.56	76.7±65.5
1996	385	10.3±7.2	4.2±3.2	0.52	0.87	0.44	54.0±15.6
1997	337	10.8±8.1	6.0±5.5	0.41	0.63	0.60	68.7±26.0
1998	244	10.6±8.2	6.5±6.1	0.44	0.70	0.62	44.5±7.1
1999	362	12.4±8.2	4.9±3.1	0.52	0.84	0.40	63.3±22.3
2000	288	8.7±7.1	4.0±2.7	0.52	0.86	0.47	68.4±28.2
2001	632	7.7±5.1	4.9±3.2	0.30	0.63	0.70	56.1±11.1
2002	866	8.6±6.0	6.3±4.5	0.40	0.64	0.68	82.8±53.0
2003	701	9.4±7.0	5.3±5.2	0.44	0.75	0.62	83.4±62.0
2004	249	10.6±6.0	5.2±3.0	0.33	0.42	0.76	71.8±55.4
2005	26	7.7±5.6	5.3±2.6	0.23	0.27	0.94	35.0±50.0
2006	48	5.6±5.3	3.6±3.2	0.20	0.24	0.93	47.8±75.0
2007	453	10.5±7.4	4.0±3.2	0.51	0.80	0.44	87.7±64.9
2008	632	9.9±6.1	4.1±3.0	0.45	0.77	0.42	87.1±58.8
2009	949	9.2±7.6	4.0±3.4	0.45	0.53	0.63	88.9±38.3

Table 3: Regional statistics (Means and Standard Deviations) from the comparison between observed and modeled monthly currents – GLORYS1

Labrador Shelf

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
2003	21	6.0±1.2	2.9±1.5	0.29	2.00	0.60	50.8±69.4

Gulf of St. Laurence

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
2002	14	5.4±2.2	2.1±2.4	0.44	0.58	0.63	65.2±71.8

Bay of Fundy

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
2003	36	13.0±3.0	1.8±1.3	0.76	0.79	0.37	88.1±46.8

Scotian Shelf

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
2002	791	8.5±6.1	6.8±6.1	0.42	0.70	0.67	81.6±53.1
2003	582	8.7±6.7	7.2±8.3	0.25	0.49	0.81	77.5±57.5
2004	237	10.6±6.1	5.9±3.6	0.32	0.51	0.59	65.6±75.0
2005	14	1.8±1.0	3.1±1.6	1.60	2.70	-0.54	76.9±80.8
2006	36	2.6±1.9	3.1±2.0	0.54	0.84	0.26	63.0±87.0
2007	449	10.4±7.4	4.6±4.6	0.34	0.53	0.74	67.7±88.3
2008	632	9.9±6.1	3.5±2.5	0.59	1.00	0.10	89.0±64.0

Central Labrador Sea

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
2002	45	11.5±5.0	5.7±2.2	0.38	0.54	0.75	46.6±72.6
2003	54	14.7±8.9	4.0±2.2	0.69	0.93	0.35	86.2±54.1
2004	12	11.6±2.8	8.0±1.9	0.14	0.16	0.49	10.9±4.7
2005	12	12.5±1.5	7.9±2.6	0.18	0.20	0.40	10.1±2.7
2006	12	13.4±2.9	8.9±2.3	0.18	0.20	0.40	11.1±2.5

Table 4: Regional statistics (Means and Standard Deviations and error metrics) from the comparison between observed and modeled monthly currents – GLORYS2

Labrador Shelf

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
1993	29	10.9±9.8	18.2±14.1	0.87	0.98	0.64	25.2±22.0
1994	65	6.6±7.3	11.1±6.9	1.09	1.19	0.63	22.3±33.6
2003	21	6.0±1.2	3.4±1.4	0.28	1.53	0.57	58.9±57.1

Newfoundland Shelf

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
1993	29	9.9±7.9	4.8±3.3	0.45	0.50	0.61	28.6±42.8
1994	95	8.5±6.3	4.4±3.9	0.42	0.49	0.54	38.7±59.9
1995	8	5.9±3.6	1.5±0.9	0.62	0.76	0.59	73.4±31.5
1998	20	2.9±1.6	1.4±0.7	0.40	0.76	0.66	63.7±54.9
2000	10	1.7±0.4	2.2±0.9	0.34	2.87	0.88	44.0±82.8

Gulf of St. Laurence

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
2000	18	4.7±1.9	2.3±3.0	0.35	0.37	0.88	32.1±48.5
2001	26	7.6±2.7	5.3±3.0	0.11	0.14	0.84	10.3±10.7
2002	14	5.4±2.2	4.4±2.9	0.11	0.30	0.87	51.7±69.8

Bay of Fundy

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
2003	36	13.0±3.0	1.5±0.8	0.80	0.90	0.27	45.9±49.0

Scotian Shelf

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
1995	306	2.5±0.8	2.1±1.2	0.23	0.79	0.12	61.1±82.5
1996	30	13.1±9.5	4.7±4.2	0.45	0.67	0.76	71.9±1.8
1997	126	6.9±6.8	2.5±3.1	0.44	0.71	0.56	10.7±39.6
1998	111	10.4±9.1	4.7±4.5	0.40	0.67	0.44	45.5±81.2
1999	98	8.1±6.6	4.1±2.9	0.50	1.21	0.21	16.4±11.3
2000	181	8.8±7.4	3.8±2.5	0.57	0.90	0.38	38.4±1.3
2001	562	7.8±5.2	4.9±3.2	0.31	0.65	0.68	47.4±4.6
2002	791	8.5±6.1	6.4±4.6	0.40	0.64	0.68	86.8±48.2
2003	581	8.7±6.7	5.7±5.5	0.35	0.67	0.65	78.8±68.4
2004	237	10.6±6.1	5.1±3.0	0.34	0.43	0.68	75.0±52.2
2005	14	1.9±1.0	3.1±1.6	1.57	2.66	-0.06	66.9±73.5
2006	36	2.6±1.9	1.8±1.3	0.36	0.53	0.41	62.4±86.8
2007	449	10.4±7.4	3.9±3.1	0.51	0.80	0.42	86.9±64.4
2008	632	9.9±6.1	4.1±3.0	0.45	0.77	0.42	87.1±58.9
2009	877	9.6±7.7	3.9±3.5	0.45	0.49	0.67	84.6±40.2

To the east of Grand Banks

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
1993	197	12.9±10.3	10.7±9.7	0.21	0.58	0.71	65.6±83.6
1994	428	13.2±11.7	11.3±8.8	0.29	0.58	0.64	81.7±61.0
1995	124	10.5±11.3	11.6±10.8	0.32	0.59	0.77	71.3±73.10

Central Labrador Sea

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
1994	42	6.8±3.2	5.7±3.9	0.32	2.27	0.30	28.8±27.1
1995	53	5.6±2.5	4.2±2.1	0.24	0.97	0.45	89.9±58.2
1996	44	10.2±5.4	7.4±4.6	0.23	0.58	0.69	89.9±48.0
1997	113	12.2±7.0	9.9±6.2	0.23	0.36	0.64	49.7±76.3
1998	90	11.6±7.2	9.8±7.0	0.42	0.72	0.39	55.1±76.1
1999	78	12.6±8.5	5.9±2.9	0.55	0.76	0.48	54.8±74.4
2000	61	11.3±6.6	5.6±2.7	0.41	0.80	0.37	52.9±64.1
2001	17	9.2±4.1	6.2±1.8	0.19	0.22	0.94	17.4±25.0
2002	45	11.5±5.0	6.0±2.0	0.34	0.51	0.89	31.9±39.1
2003	54	14.7±8.9	5.2±2.5	0.60	0.96	0.55	89.1±50.2
2004	12	11.6±2.8	8.3±1.3	0.12	0.14	0.38	9.4±4.6
2005	12	12.5±1.5	7.1±1.5	0.19	0.21	0.51	8.5±3.3
2006	12	13.4±2.9	8.5±0.8	0.17	0.19	0.35	9.2±3.3

Cabot Strait

Year	Number of Observations	Averaged Speed (cm/s)		SDR	VDR	R	DA
		Observed	Model				
1993	19	24.7±20.5	7.2±5.5	0.56	0.59	0.86	44.7±80.9
1995	20	17.4±14.0	3.0±3.67	0.67	0.72	0.83	74.6±51.0
1996	171	10.4±7.7	3.1±2.3	0.64	1.09	0.02	49.2±26.7
1997	33	18.5±12.1	5.1±3.8	0.58	0.86	0.83	68.4±83.2

Figures

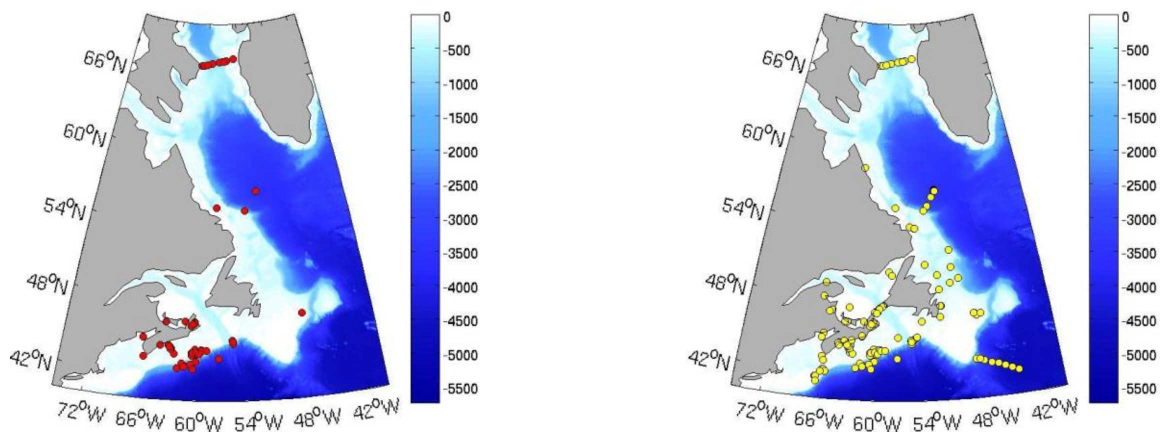

Figure 1: The locations of current meter moorings for the 2002-2008 period(GLORYS1 period , left panel) and 1993-2009 period (GLORYS2 period, right panel)

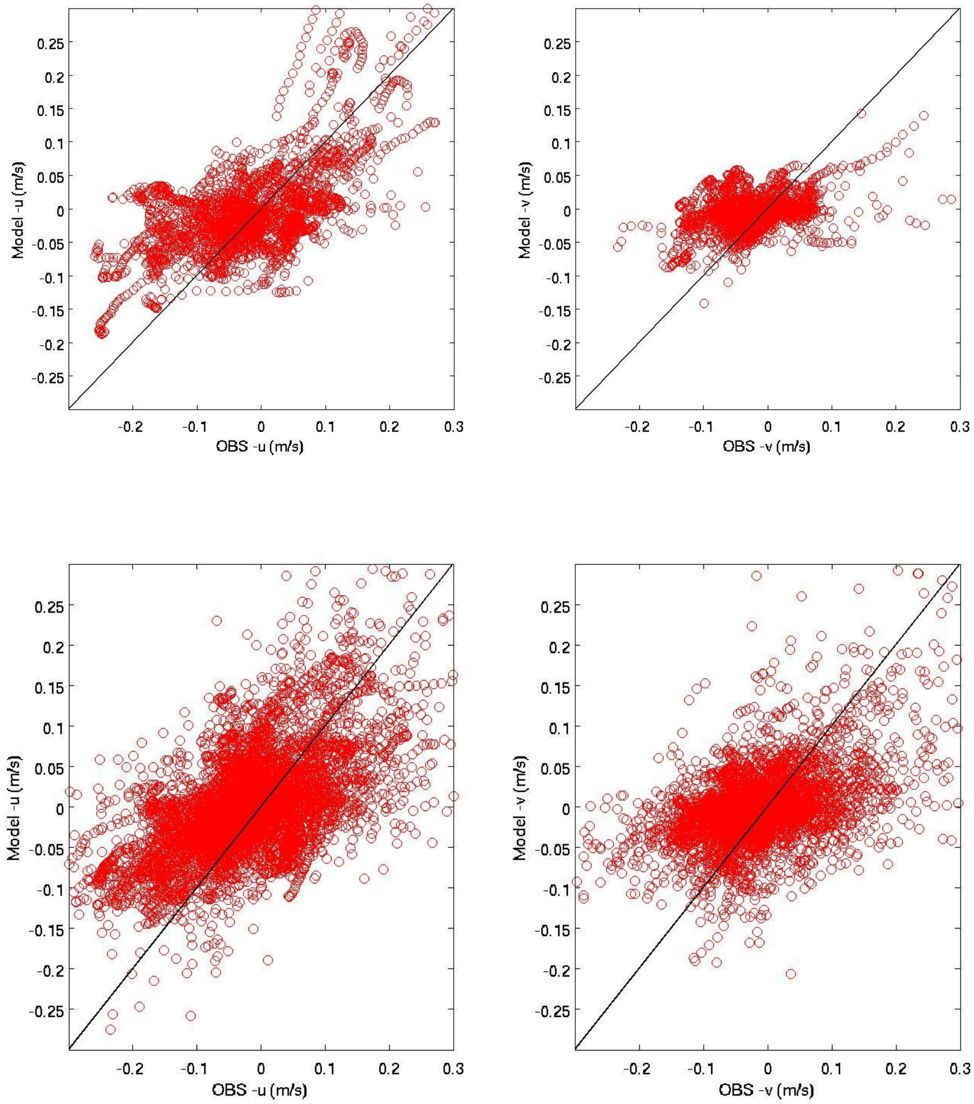

Figure 2: Comparison between observed velocities and modeled ones. Left panels for x-direction velocity, right panels for y-direction velocity. Top panels for the GLORYS1, bottom panels for GLORYS2.

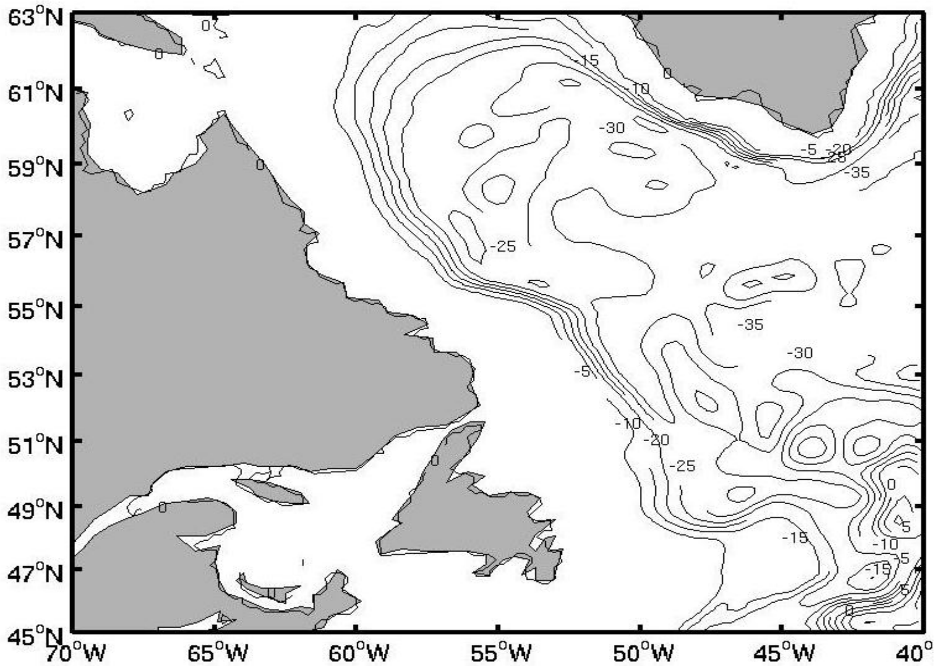

Figure 3: Mean barotropic streamfunction (unit: Sv) computed from the GLORYS2 model product. The contour interval is 5 Sv.

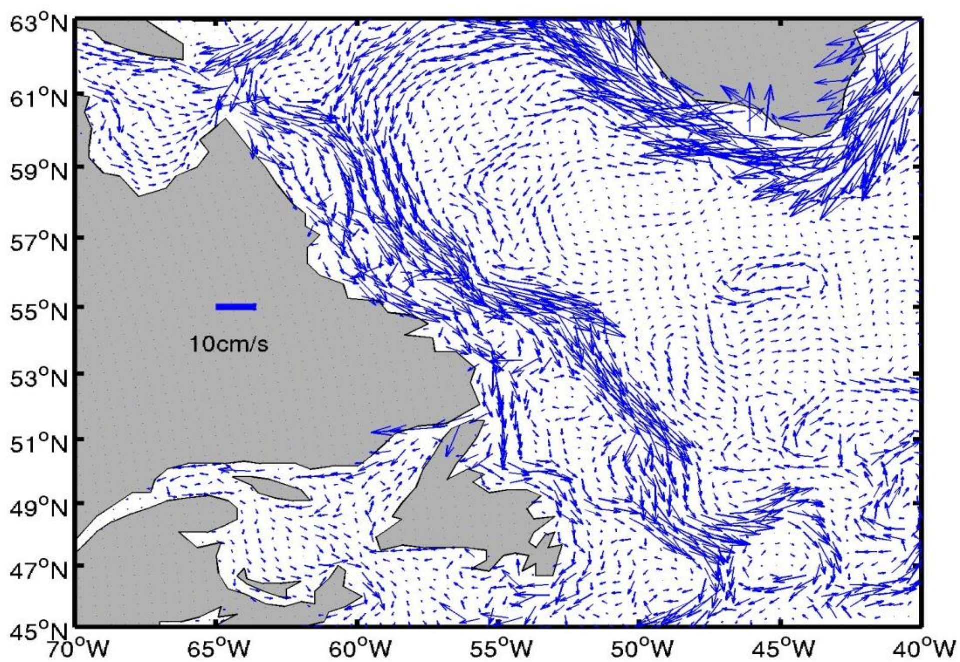

Figure 4: Depth averaged velocities from the GLORYS2 model product. The magnitude of the velocity is indicated by the length of the arrows and can be referenced to the legend.

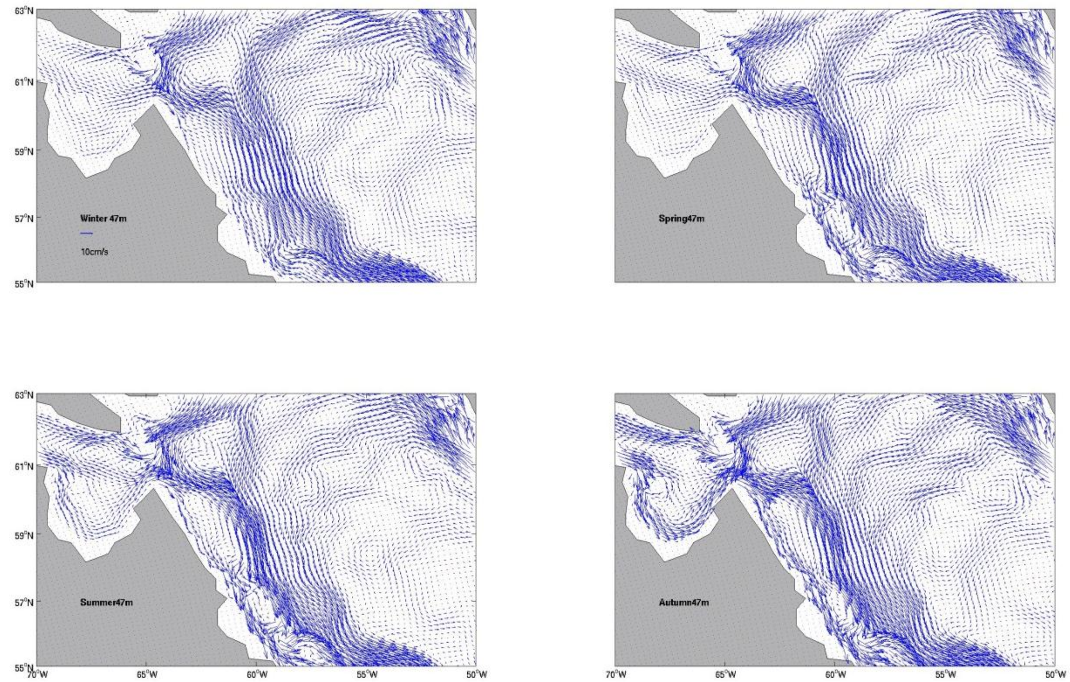

Figure 5: GLORYS2 velocity field in Labrador Sea for each season, depth=47m

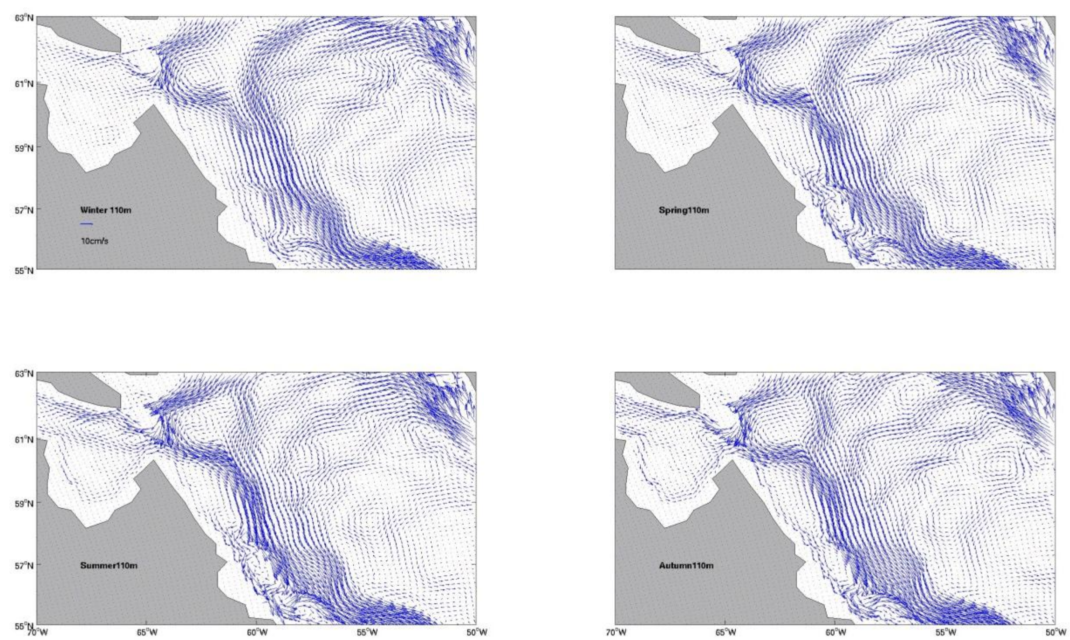

Figure 6: GLORYS2 velocity field in Labrador Sea for each season, depth=110m

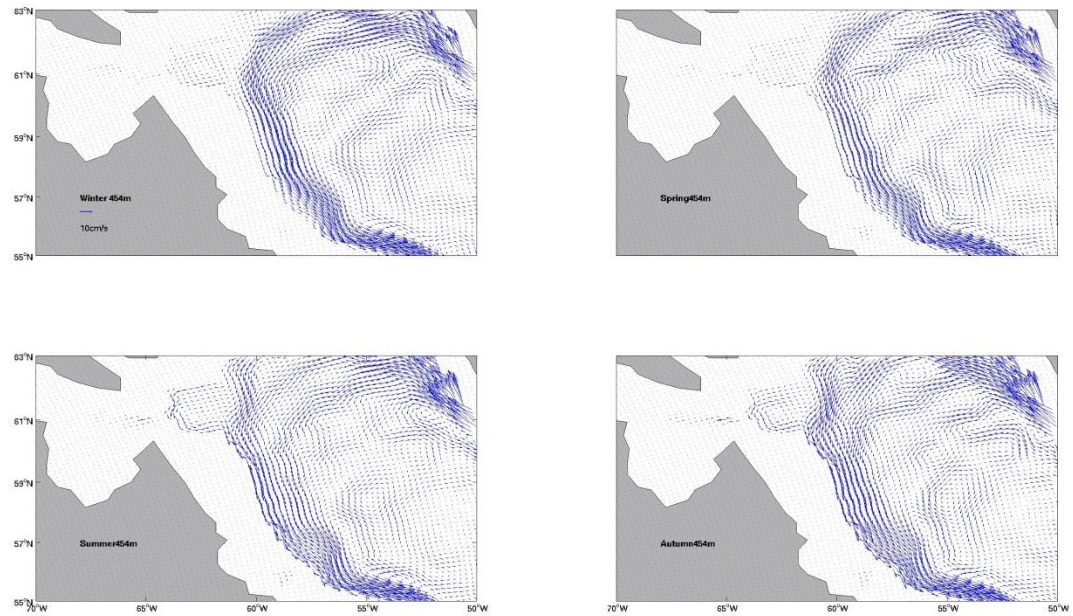

Figure 7: GLORYS2 velocity field in Labrador Sea for each season, depth=454m

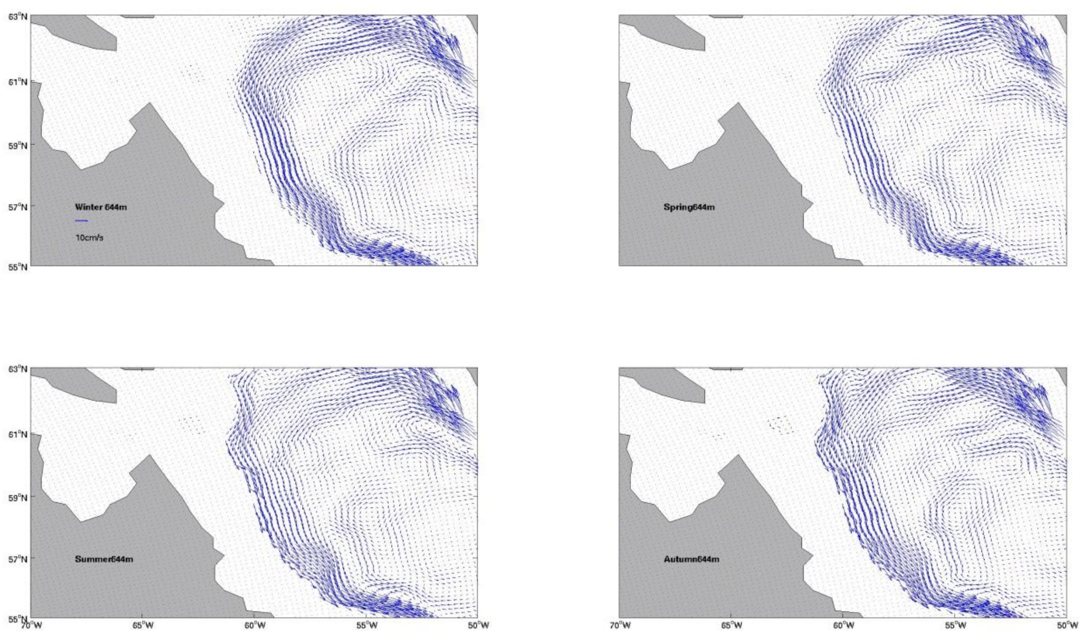

Figure 8: GLORYS2 velocity field in Labrador Sea for each season, depth=644m

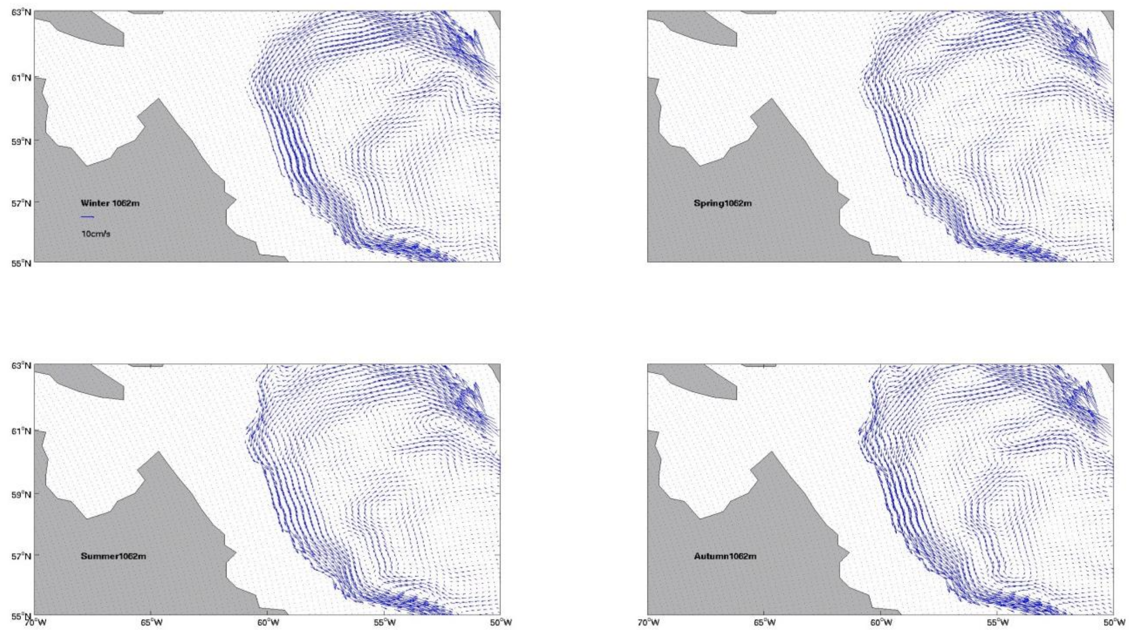

Figure 9: GLORYS2 velocity field in Labrador Sea for each season, depth=1062m

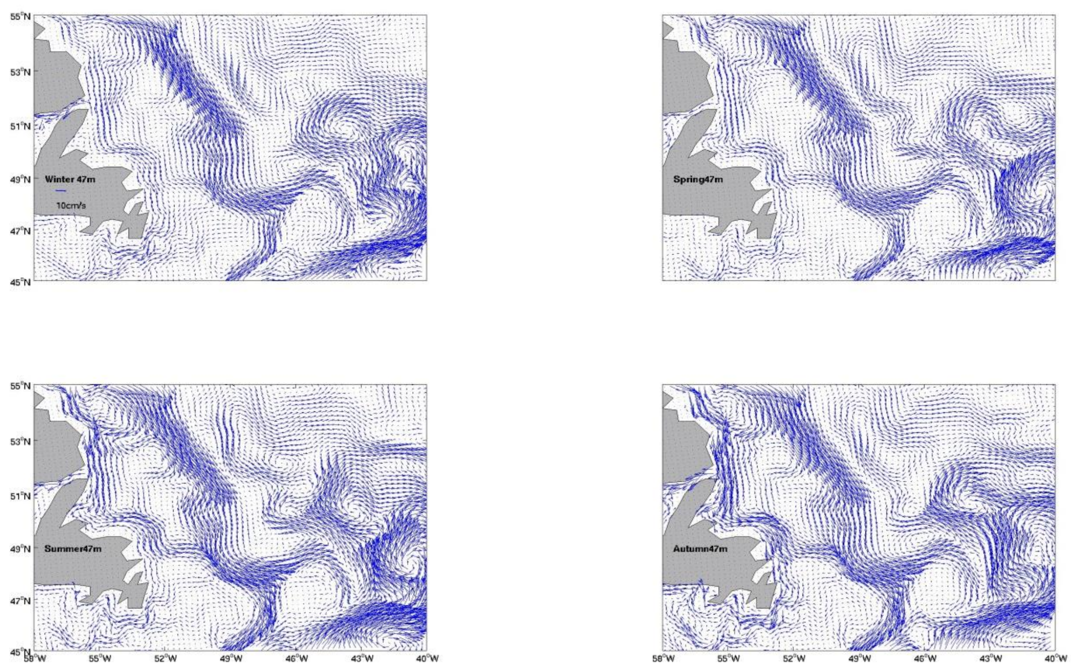

Figure 10: GLORYS2 velocity field in Newfoundland shelf and adjacent ocean for each season, depth=47m

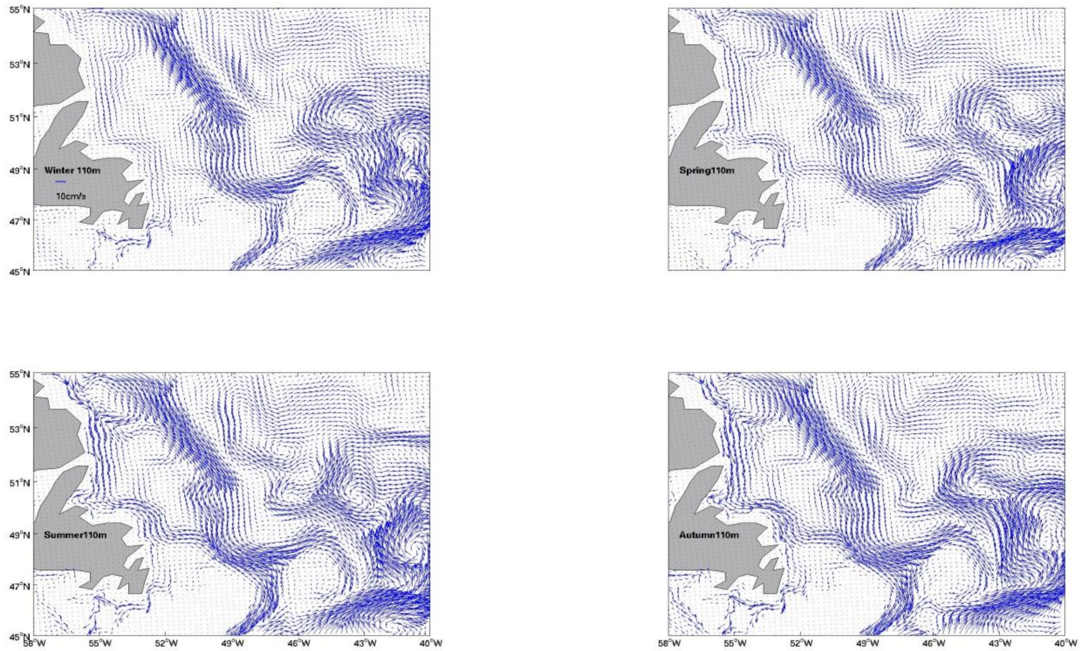

Figure 11: GLORYS2 velocity field in Newfoundland shelf and adjacent ocean for each season, depth=110m

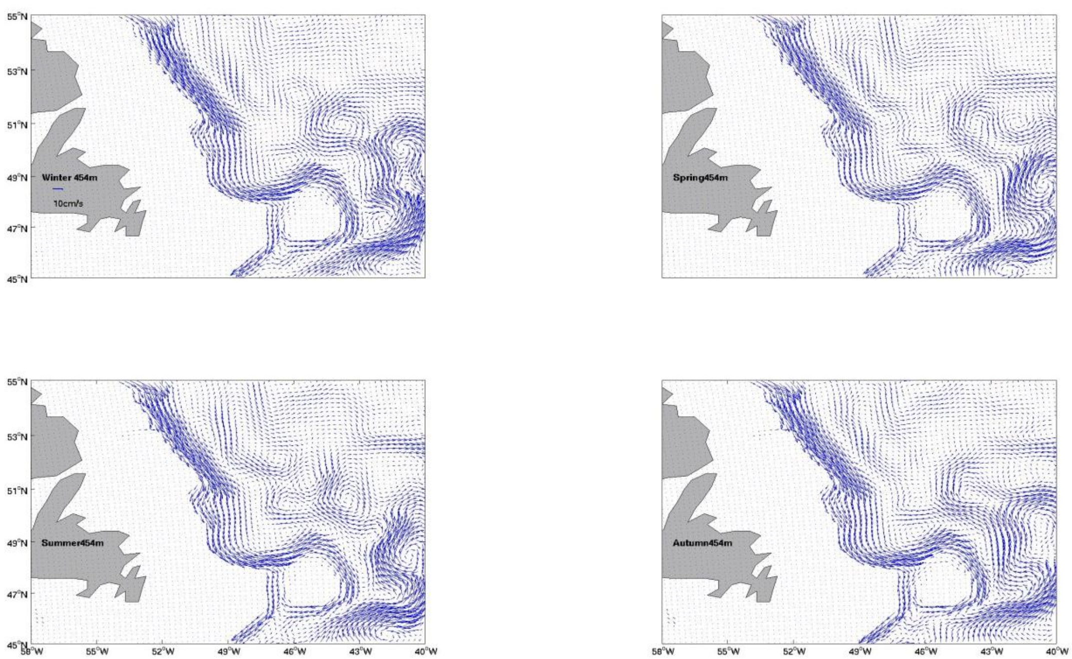

Figure 12: GLORYS2 velocity field in Newfoundland shelf and adjacent ocean for each season, depth=454m

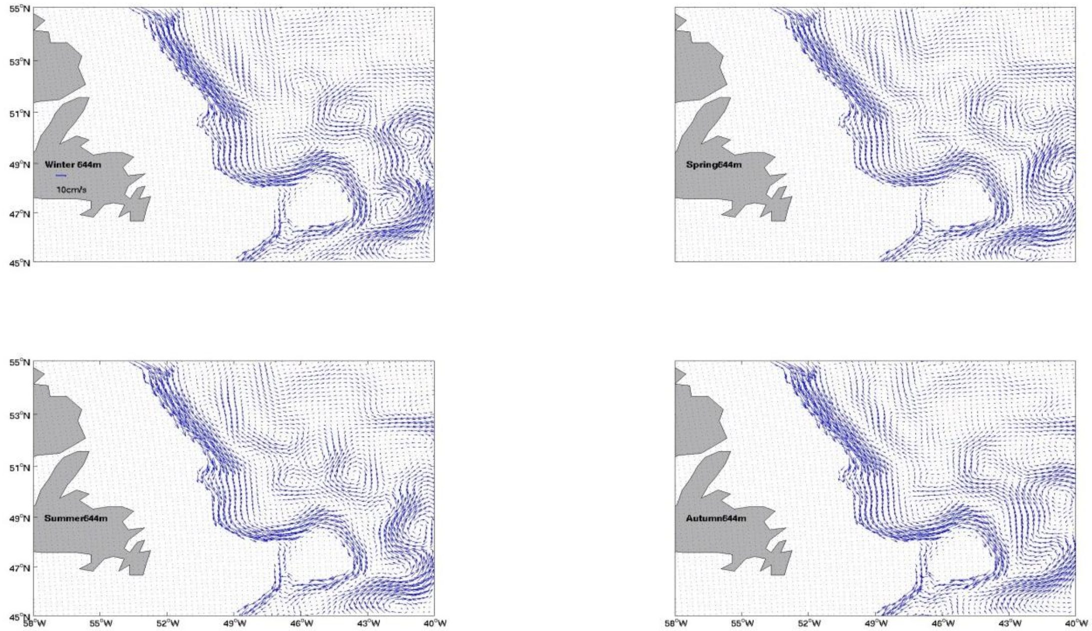

Figure 13: GLORYS2 velocity field in Newfoundland shelf and adjacent ocean for each season, depth=644m

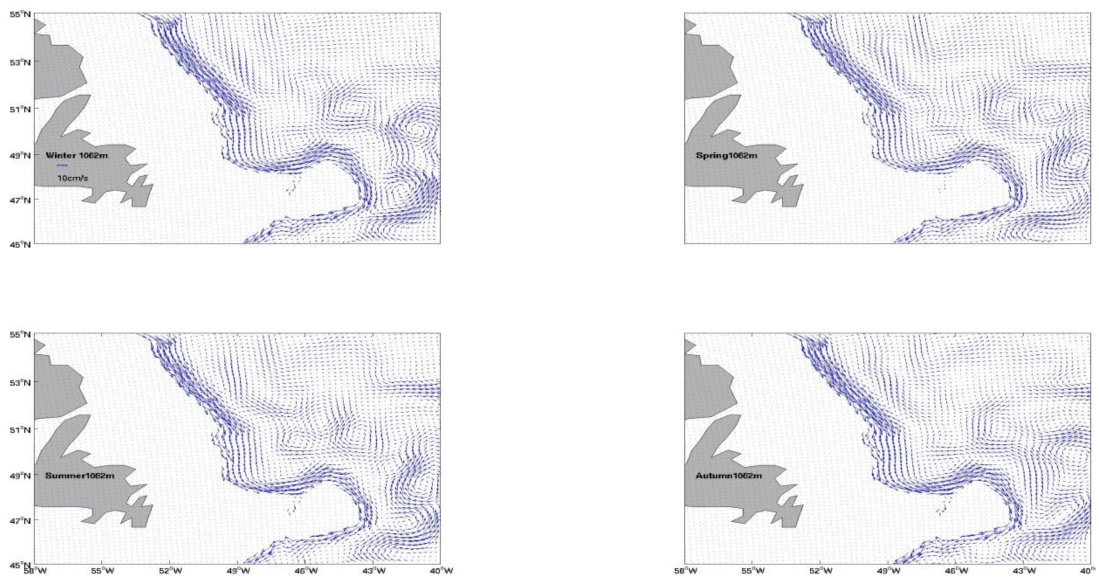

Figure 14: GLORYS2 velocity field in Newfoundland shelf and adjacent ocean for each season, depth=1062m

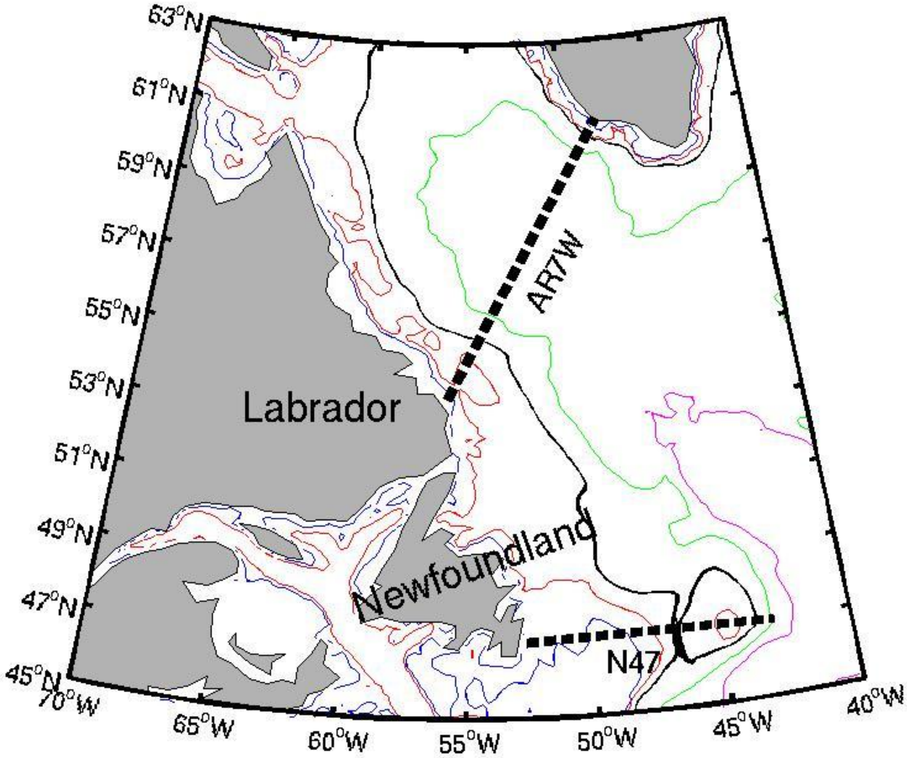

Figure 15: The map of the subpolar North Atlantic. The AR7W and N47 transects are shown in thick dashed lines. The isobaths displayed are 100 (blue), 200 (red), 1000 (black) ,3000 (green) and 4000 (magenta) m.

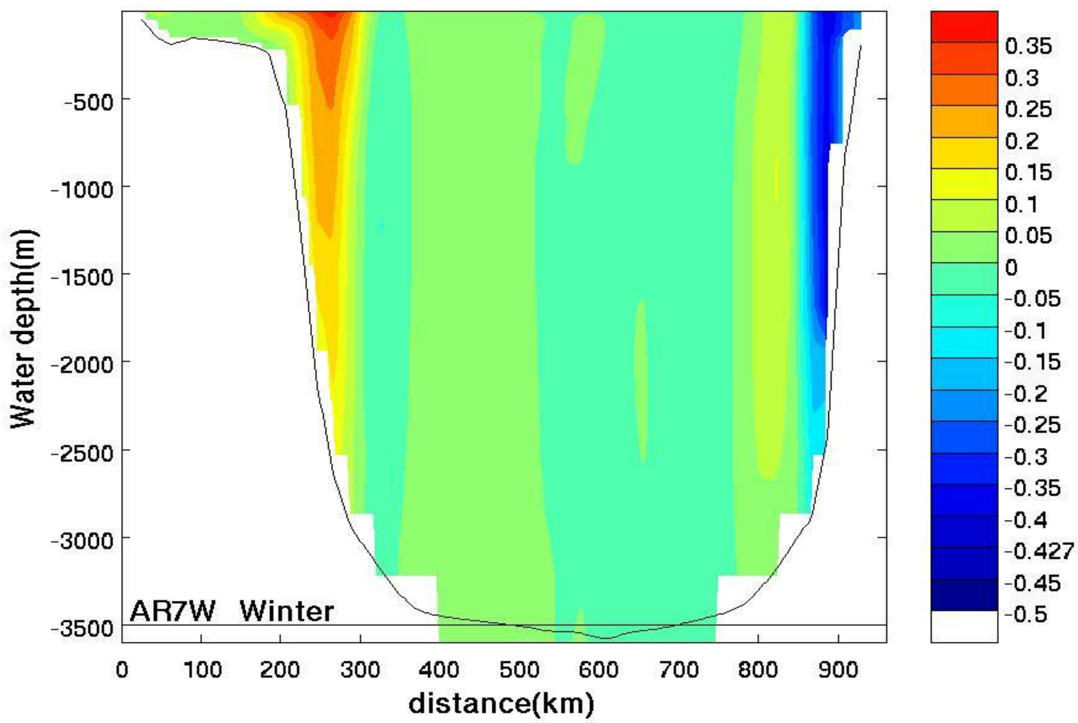

Figure 16: Normal velocities through AR7W line, winter.

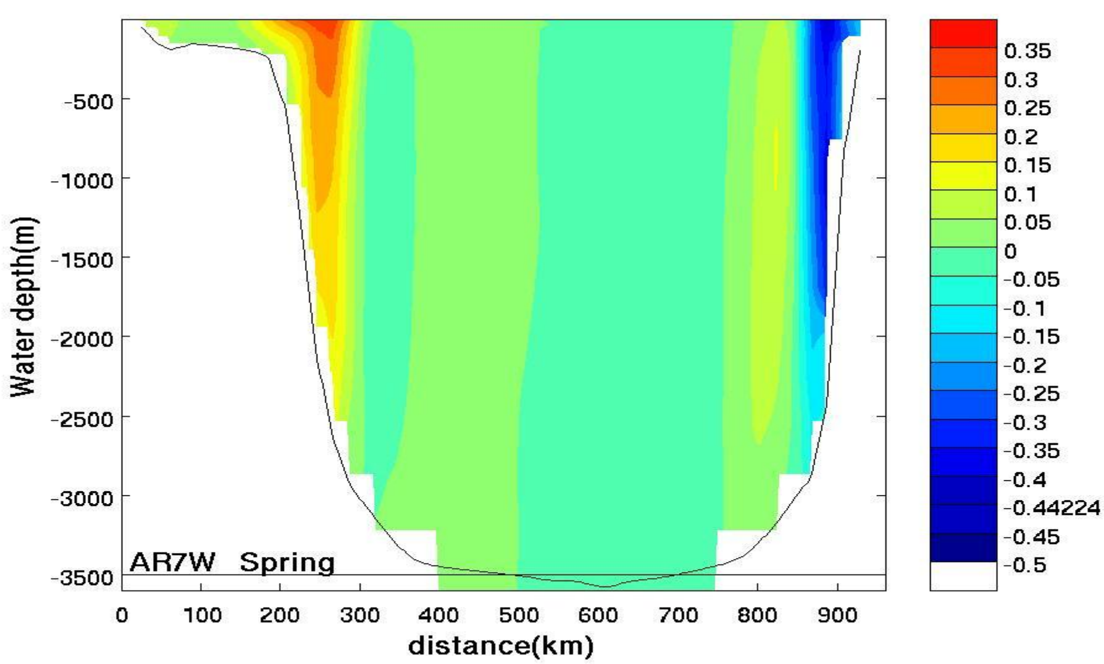

Figure 17: Normal velocities through AR7W line, spring.

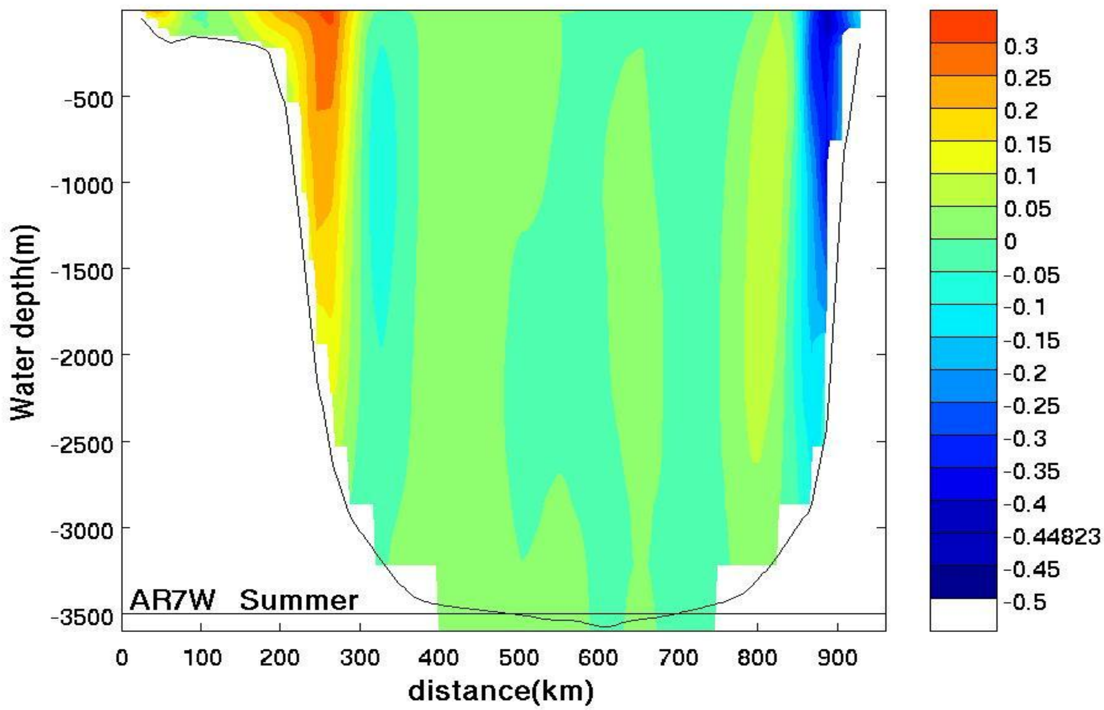

Figure 18: Normal velocities through AR7W line, summer.

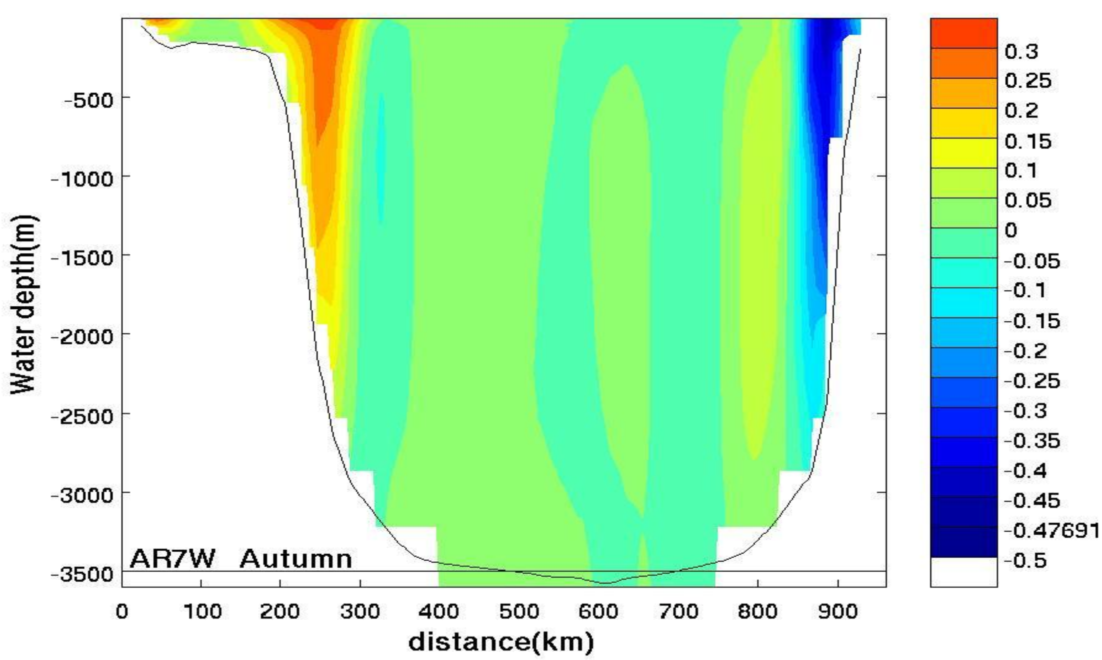

Figure 19: Normal velocities through AR7W line, autumn.

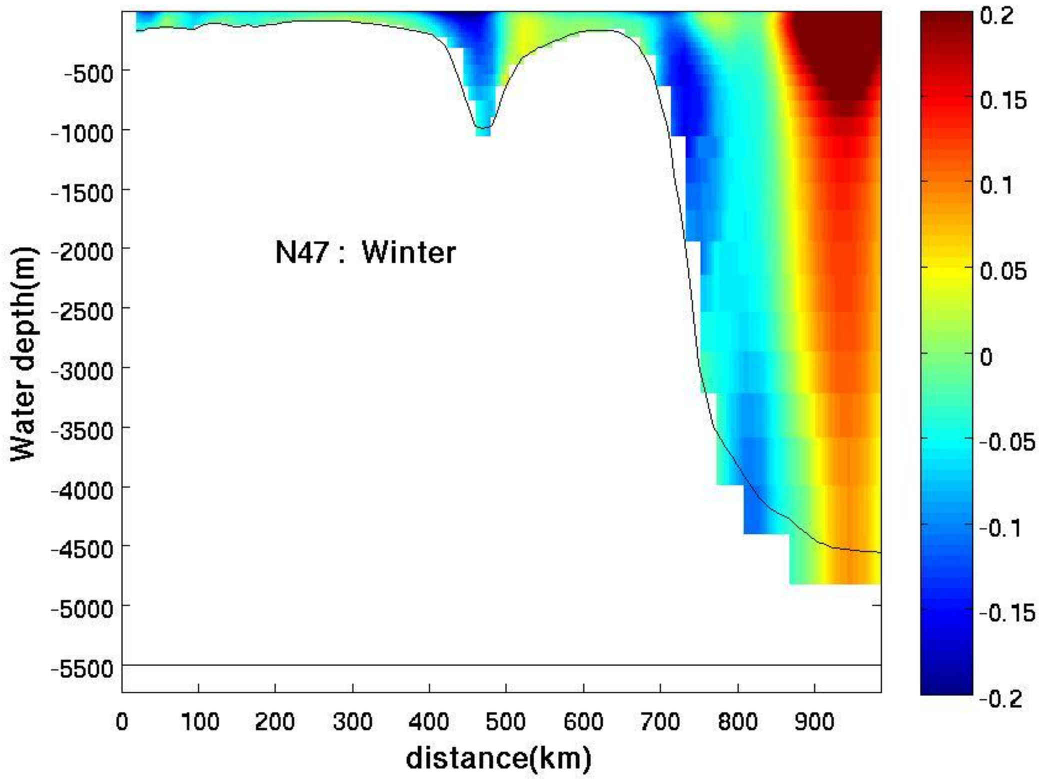

Figure 20: Normal velocities through N47 line, winter.

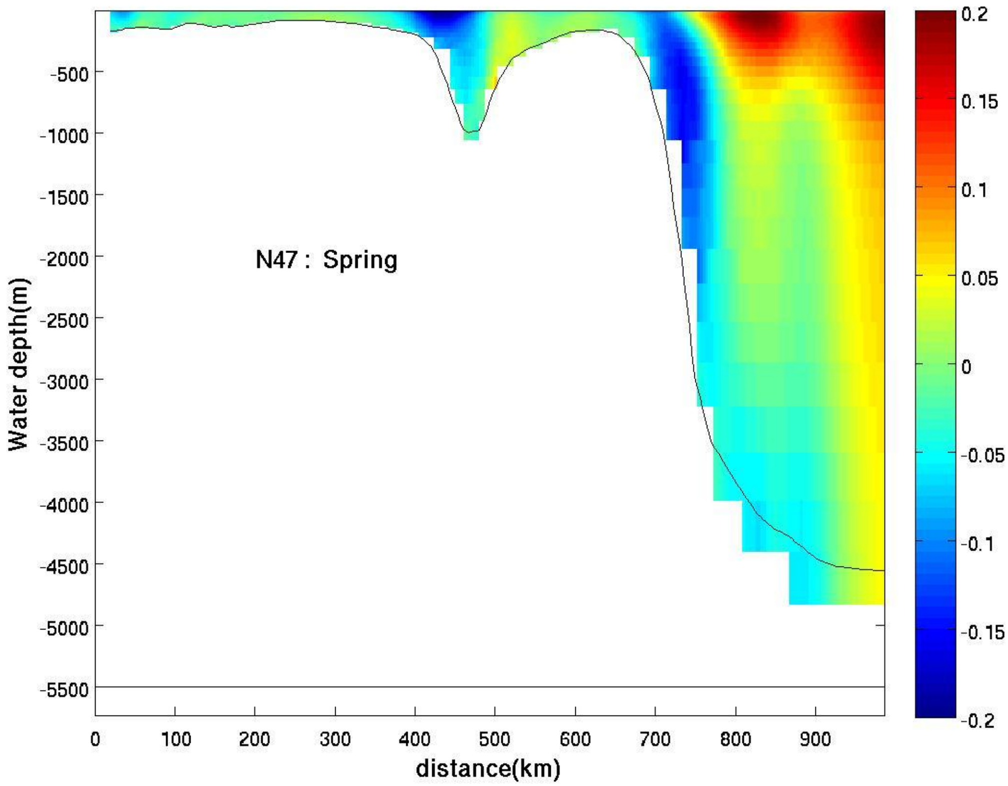

Figure 21: Normal velocities through N47 line, spring.

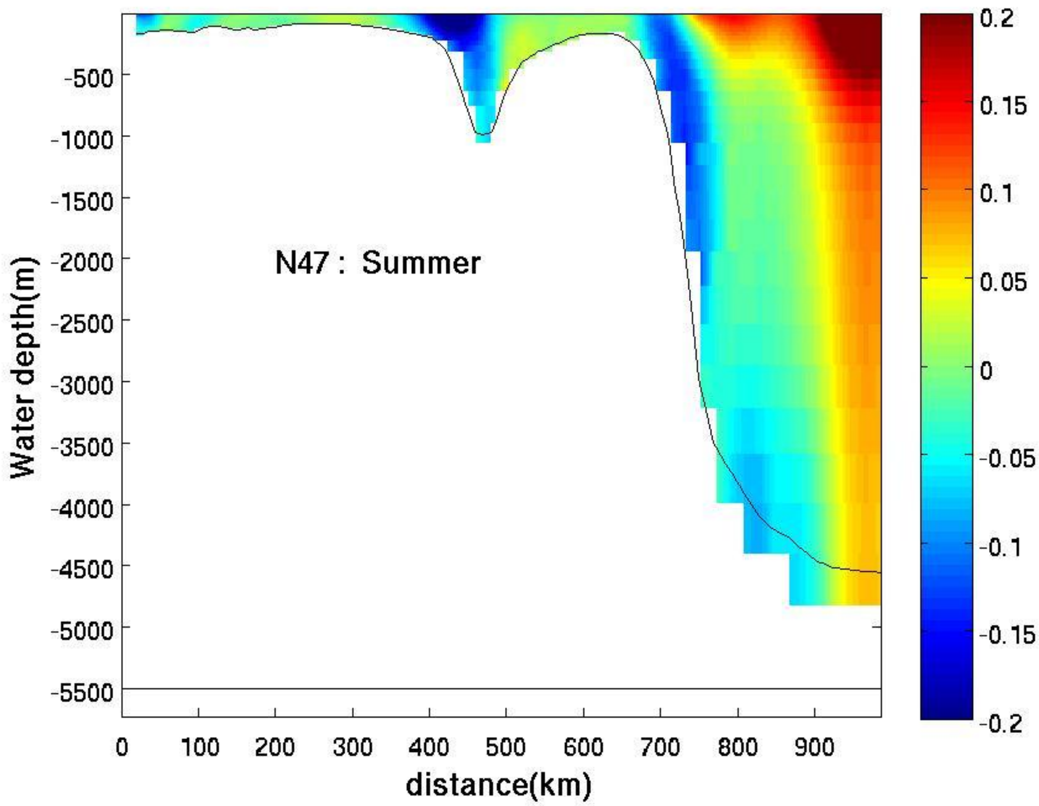

Figure 22: Normal velocities through N47 line, summer.

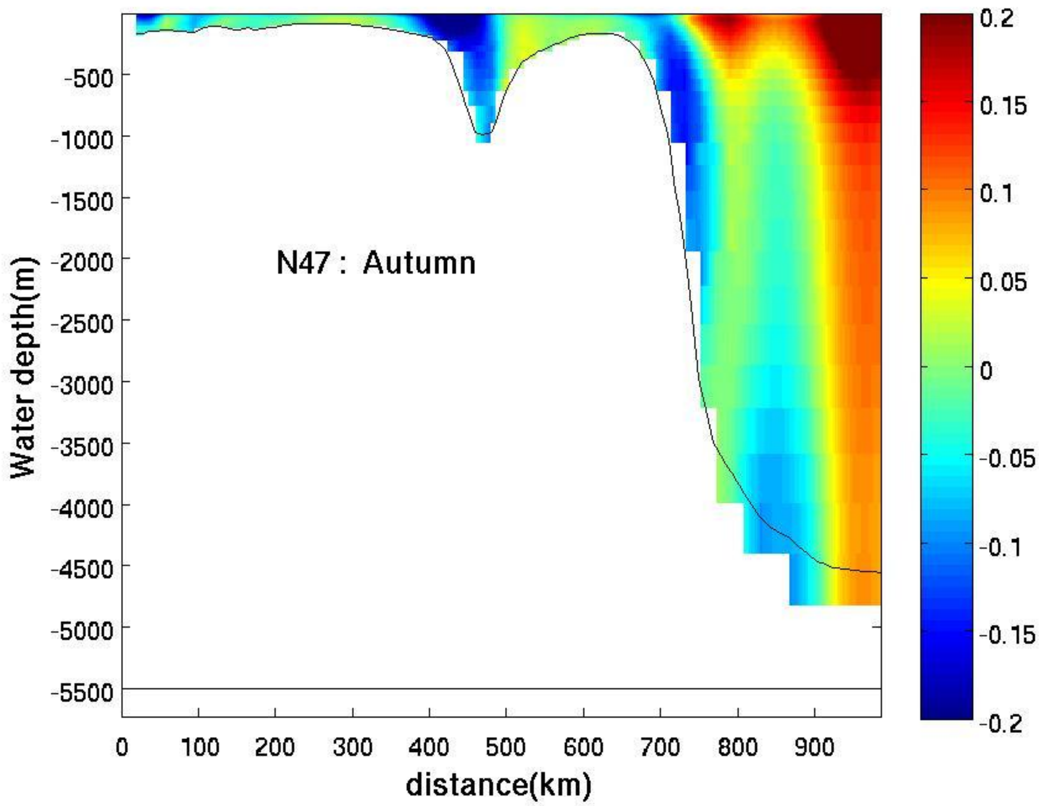

Figure 23: Normal velocities through N47 line, autumn.

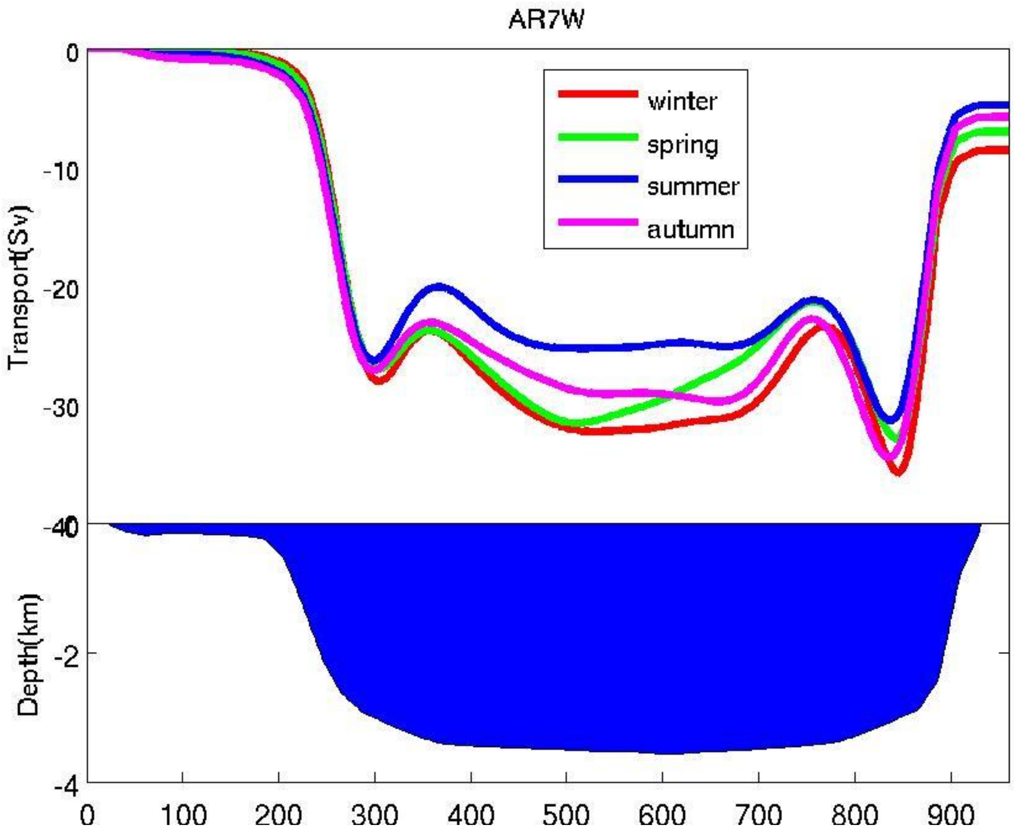

Figure 24: Cumulative volume transport of the AR7W line for each season.

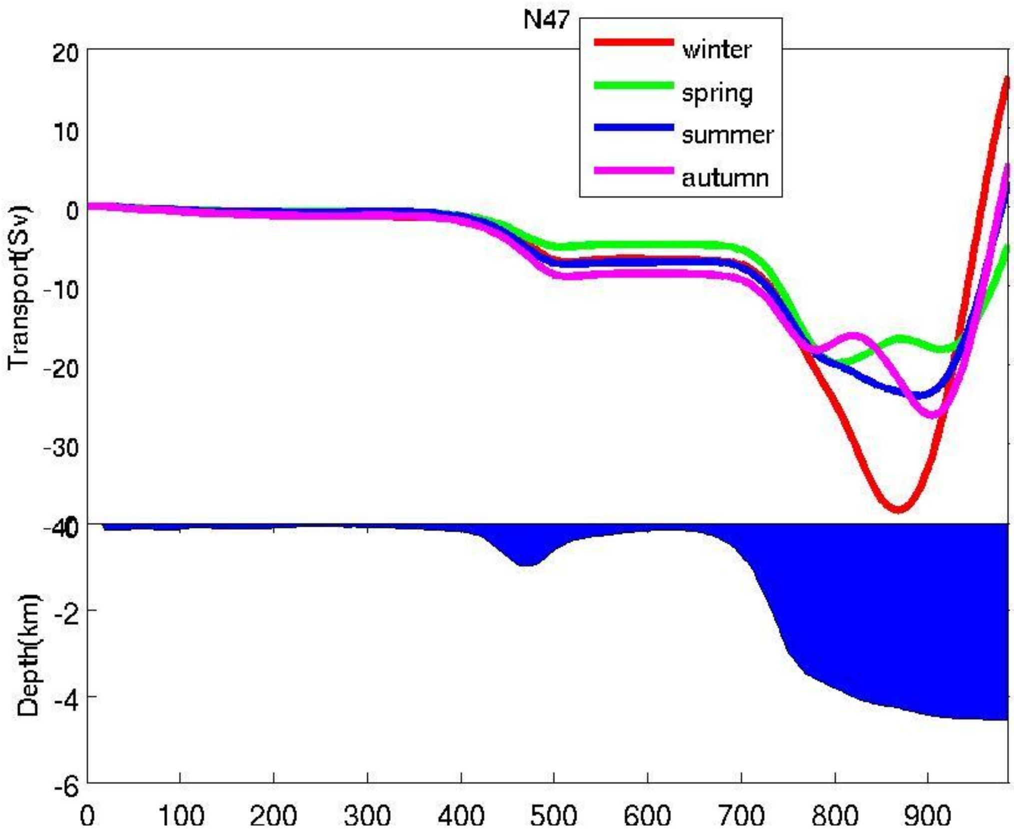

Figure 25: Cumulative volume transport of the N47 line for each season.