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The North Icelandic Jet and its contribution to the Denmark Strait overflow water

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Denmark Strait overflow water (DSOW) is a main contributor to the formation of the deep branch of the Atlantic Meridional Overturning Circulation, which has an essential function in determining the climate of the North Atlantic region. The origin of this overflow is generally attributed to the East Greenland Current (EGC). However, recent observations reveal that the North Icelandic Jet (NIJ) has a main role in the formation of the dense overflow water. Here we investigate the NIJ and its role among the current system north of the Denmark Strait by using an ocean general circulation model coupled to a prescribed atmosphere. The model gives a reliable depiction of the circulation and shows good agreement with the latest estimates of the mean transport of the NIJ, the North Icelandic Irminger Current and the DSOW. A good correlation between the time series of the NIJ and the DSOW implies that the jet significantly contributes to the formation of the overflow water. The analysis of the dense water paths suggests that different sources feed the NIJ and, in particular, a southeastward branch of the EGC might be the main contributor to its transport.

1. Introduction

The GIN Sea, the area between Greenland, Iceland, Norway and Svalbard, has a great importance for the Atlantic Meridional Overturning Circulation (AMOC) [Drange et al., 2005]. In this area the inflowing warm and saline Atlantic water is densified by cooling, giving rise to sinking [Aagaard et al., 1985]. Most of the North Atlantic Deep Water stems from the overflow of the dense waters flowing from the GIN Sea through the Greenland-Scotland Ridge (GSR). The amount of deep water formed in the GIN Sea greatly influences the strength of the AMOC [Cheng et al., 2011]. Changes in the deep water formation, and thus modifications in the AMOC, seem to have a major impact on climatic changes [Ganopolski et al., 1998].

Overflow water is commonly identified as water denser than $\sigma_\theta = 27.8$ kg m^{-3} [Dickson and Brown, 1994]. Using this definition, the total transport of overflow water across the GSR is about 6 Sv (1 Sv = 10^6 m^3 s^{-1}). Since half of this overflow passes through Denmark Strait, this channel is the primary gateway for the overflow towards the Atlantic Ocean [Hansen and Østerhus, 2000]. Moreover, simulations with a coupled model demonstrated that the strength of the overflow across Denmark Strait impacts the European climate [Kösters et al., 2005].

Identifying the sources that feed the Denmark Strait Overflow Water (DSOW) has been a debated question since exchanges across Denmark Strait have been studied. In the last decades the East Greenland Current (EGC) was generally thought to be the main pathway supplying the DSOW [Mauritzen, 1996; Rudels et al., 2002; Jeansson et al., 2008]. This view falls onto the more general notion that the cyclonic boundary current system of the

GIN Sea has a main role in the transformation of the inflowing warm Atlantic water into the DSOW.

Recently, however, it was suggested that a big contribution to the DSOW comes from a current flowing westward along the continental slope north of Iceland [Jónsson and Valdimarsson, 2004]. Subsequent measurements northwest of Iceland allowed Våge et al. [2011] to confirm the presence of a largely barotropic current which accounts for roughly half of the total DSOW (about 1,5 Sv). The authors called this current the North Icelandic Jet (NIJ). Using a simplified model, they found that the formation of the NIJ is strongly connected to lateral exchanges between the North Icelandic Irminger Current (NIIC) and the interior Iceland Sea. The NIIC transports warm and saline water northward through Denmark Strait and along the northern coast of Iceland.

Understanding the role of the NIJ within the circulation pattern of the GIN Sea is a crucial step to the full comprehension of the DSOW. Thus the main objectives of this study are to analyze the characteristics of the NIJ, to investigate its possible sources, and to establish the relation between the NIJ and the DSOW by means of an ocean general circulation model driven by prescribed atmospheric forcing.

2. Model

The model run analysed in this paper is run KNMI01 from Barnier et al. [2007], in which the NEMO ocean model [Madec, 2008] was forced by prescribed atmospheric conditions derived from the ERA-40 reanalysis. The run covers the ERA-40 period 1958-2001, from which we use averages over the last 25 years (1977-2001). The model is run in the ORCA025 configuration. Its curvilinear grid has an average horizontal resolution of 0.25°

and 46 vertical layers, 22 of which are above the sill depth of Denmark Strait. In the GIN Sea the horizontal resolution roughly varies between 2 and 10 km.

3. Results

Fig. 1 shows the simulated time-mean currents over temperature (a-b) and salinity (c-d) around the northwest part of Iceland at two different depths, 110 m (a-c) and 450 m (b-d). At 110 m we can notice the south-westward flow of the EGC on the East Greenland shelf and the flow of the NIIC passing through Denmark Strait and then continuing eastward north of Iceland where a great part of the flow is topographically steered. Northwestward of Iceland, where the cold (-1.5 - 1°C) and low-salinity (32.9 - 34.3 psu) waters of the EGC meet the warm (5 - 8°C) and saline (34.5 - 35.3 psu) Atlantic waters of the NIIC, we find strong horizontal (Fig. 1) and vertical (not shown) temperature and salinity gradients.

The deep overflow across Denmark Strait is evident at 450 m. The well-known contribution from the EGC reaches the strait after flowing along the Greenland shelf. What comes as an indication of the existence of the current first observed by Jónsson and Valdimarsson [2004] is the presence of a barotropic flow north of Iceland that tightly follows the bottom topography while flowing towards Denmark Strait. Following Våge et al. [2011], we will call this current the NIJ. The topographic steering is most evident between 17°W and 20°W, where the current seems to perfectly trace the bathymetry. The time-mean velocities of the NIJ range between 3-4 cm/s in the eastern part of the current and 10-15 cm/s as it approaches Denmark Strait.

The NIIC and the underlying NIJ are clearly noticeable in a vertical section of the mean zonal current at 17.5°W (Fig. 2a). The NIIC is positioned over the Icelandic continental shelf and, at this longitude, reaches a maximum depth of about 300 m. Its core is located between 50 and 200 m depth and has a time-mean velocity of 6-7 cm/s. The NIJ lies on the Icelandic continental slope between 200 and 800 m depth with a time-mean core velocity of 3-4 cm/s. In spite of its vertical extension, the jet is characterized by a small range of densities concentrated between 27.80 and 28.00 kg m^{-3} (Fig. 2b). Vertical sections at different longitudes reveal a nearly constant density structure of the NIJ, with the core maintaining a density between 27.80 and 28.00 kg m^{-3}. On the contrary, the NIIC exhibits a wide range of densities varying between 26.55 and 27.85 kg m^{-3} at 22°W (not shown) and between 26.80 and 27.85 kg m^{-3} at 17.5°W (Fig. 2b). As the current flows further eastward it becomes even denser, showing densities between 26.95 and 27.90 kg m^{-3} at 15°W (not shown). This densification is accompanied by a weakening of the modelled NIIC along its path, also present in the observations [Valdimarsson and Malmberg, 1999].

The dependence of the zonal mean transports of the NIIC and the NIJ on longitude is shown in Fig. 2c. The different overlapping lines are due to ambiguous positioning of the currents, so the transports are integrated over different latitudinal extensions, in order to have an estimate of the error in these areas. The latitudinal extension is chosen by selecting only eastward (westward) velocities for the NIIC (NIJ) and analysing the vertical sections of the currents at every model longitude. For the NIJ we put a further constraint on the density by selecting only waters with $\sigma_\theta \geq 27.8$ kg m^{-3}.

The NIIC mean transport (red lines in Fig. 2c) is about 1.35 Sv at 22°W, and it decreases to about 1.20 Sv at 16.5°W. This reduction is partly due to the sinking of the NIIC waters between 100 and 600 m, as shown by the profile of the vertical transport integrated over the region of the NIIC and NIJ (Fig. 2e). In fact, the NIIC does not extend beyond 300-350 m depth and, below this level, the only current in this area is the NIJ, meaning that it receives waters from the NIIC. The sinking occurring in this area is in agreement with the results obtained by Spall [2004]: the dominant downwelling is found within the boundary current (corresponding to the NIIC), while it is negligible in the interior of the basin (corresponding to the Iceland Plateau). In fact, we find no downwelling by integrating the vertical transport over the inner Iceland Plateau (Fig. 2d, white box). East of 16°W the mean transport of the modelled NIIC increases because of the convergence with the flows coming from the interior of the Iceland Plateau and from an eastward flowing branch of the EGC. Our modelled NIIC transport of 1.2-1.3 Sv is greater than the estimate of 0.75 Sv for the period 1994-2000 [Jónsson and Valdimarsson, 2005], but is close to the 1.5 Sv estimated for the period 1985-1990 [Kristmannsson, 1998].

The mean transport of the NIJ (black lines in Fig. 2c) increases as the NIJ flows westward, rising from 0.2 Sv at 14.5°W to 1.2 Sv at 20°W. The sinking occurring in the region of the NIIC gives a contribution of about 0.1 Sv - mainly concentrated in the eastern part of the current (black box in Fig. 2d) - to the volume transport of the NIJ. Major contributions come from a southeastward branch of the EGC and, in minor part, from the boundary waters of the Iceland Plateau. This is recognizable by looking at the dense ($\sigma_\theta \geq 27.8$ kg m^{-3}) time-mean currents at 380 m depth (Fig. 3). We find that 0.45 Sv is added at 67.6°N between 14.4 and 15.1°W, 0.16 Sv at 67.8°N between 15.7 and 17.2°W, and 0.41 Sv is added at 68.4°N between 18.1 and 19.6°W. These contributions perfectly match the increase of the NIJ mean transport along its path (Fig. 2c). West of 20°W the zonal NIJ transport decreases because the current acquires a northward component (see Fig. 1b,d at 20°W-68°N) which, when added to the westward component, gives a total transport of 1.2 Sv. At 68°N-22°W the NIJ turns towards south-west joining the EGC (Fig. 1b,d). Our modelled NIJ transport of 1.2 ± 0.3 Sv (at 20°W) is close to the latest estimate of 1.5 ± 0.2 Sv [Våge et al., 2011].

Let us consider now the DSOW and its relation with the NIJ and the EGC. The modelled time-mean transport of the DSOW is 3.2 ± 0.7 Sv, which is in good agreement with the estimated 3.1-3.7 Sv for the period 1999-2003 [Macrander et al., 2005], and only slightly greater than the newest estimate of 2.9 ± 0.5 Sv for the period 2008-2009 [Våge et al., 2011]. In order to verify that the NIJ is a main contributor to the transport of the DSOW, we compared the time series of the NIJ and DSOW, with a time lag of one month (Fig. 4). Two sections of the NIJ are considered, one at 17.5°W, where the transport is 0.65 ± 0.23 Sv, and one at 20°W, where the transport is 1.23 ± 0.31 Sv. The correlation coefficient with the time series of the DSOW transport is 0.82 for the first section, and 0.85 for the second one. If we require that the water of the NIJ should be shallower than 650 m in order to fit with the sill depth of Denmark Strait, the NIJ transports become 0.54 ± 0.20 Sv and 0.98 ± 0.25 Sv, respectively for the first (17.5°W) and the second (20°W) section. In this case, the correlation coefficient increases to 0.88 for both sections. This result suggests that the NIJ contributes significantly to the DSOW supplying more than one-third of its total transport. The remaining DSOW transport is provided by the southwestward branch of the EGC, which gives a contribution of 1.95 ± 0.18 Sv (Fig. 4).

The time series of this transport has a correlation coefficient of 0.77 with the DSOW transport, meaning that the current undergoes some changes when mixing with the NIJ.

4. Discussion

The global ocean model used gives a realistic depiction of the current system northwest of Iceland. In particular, the modelled DSOW transport of 3.2 ± 0.7 is in good agreement with the latest estimates [Macrander et al., 2005; Våge et al., 2011]. A possible overestimation of the NIIC transport arises if we compare the simulated 1.2-1.3 Sv with the newest estimate of 0.75 Sv [Jónsson and Valdimarsson, 2005]. However, an older estimate of the transport is 1.5 Sv [Kristmannsson, 1998], suggesting that the NIIC is characterized by marked interannual variability. Periods of larger NIIC transports are associated with enhanced northward advection and weak winds from the north [Logemann and Harms, 2006]. The recently discovered NIJ is well reproduced by the model, showing features that are in good agreement with the observations. The jet increases as it flows westward reaching a transport of 1.2 ± 0.3 Sv at 20°W. A good correlation between the time series of the NIJ at different sections and the DSOW transports proves that the NIJ is instrumental in the formation of the DSOW. Although the contribution of about one-third of the total DSOW transport is slightly smaller than the estimated 1.5 Sv [Våge et al., 2011], the high correlation implies that the NIJ is a fundamental source of the dense overflow towards the Atlantic Ocean. The model suggests that the jet does not originate from a single source, but stems from different contributions coming mainly from a southeastward branch of the EGC and from the boundary waters of the Iceland Plateau. The contribution coming from the sinking in the region of the NIIC accounts for only 0.1

Sv of the total NIJ transport, at variance with the results obtained by Våge et al. [2011], who found that two-thirds of the NIJ transport originates from vertical advection within the continental boundary of Iceland. Our results confirm that the NIJ plays a central role in the formation of the DSOW and open new questions about the origins of the jet, concerning especially the role of the EGC in its formation.

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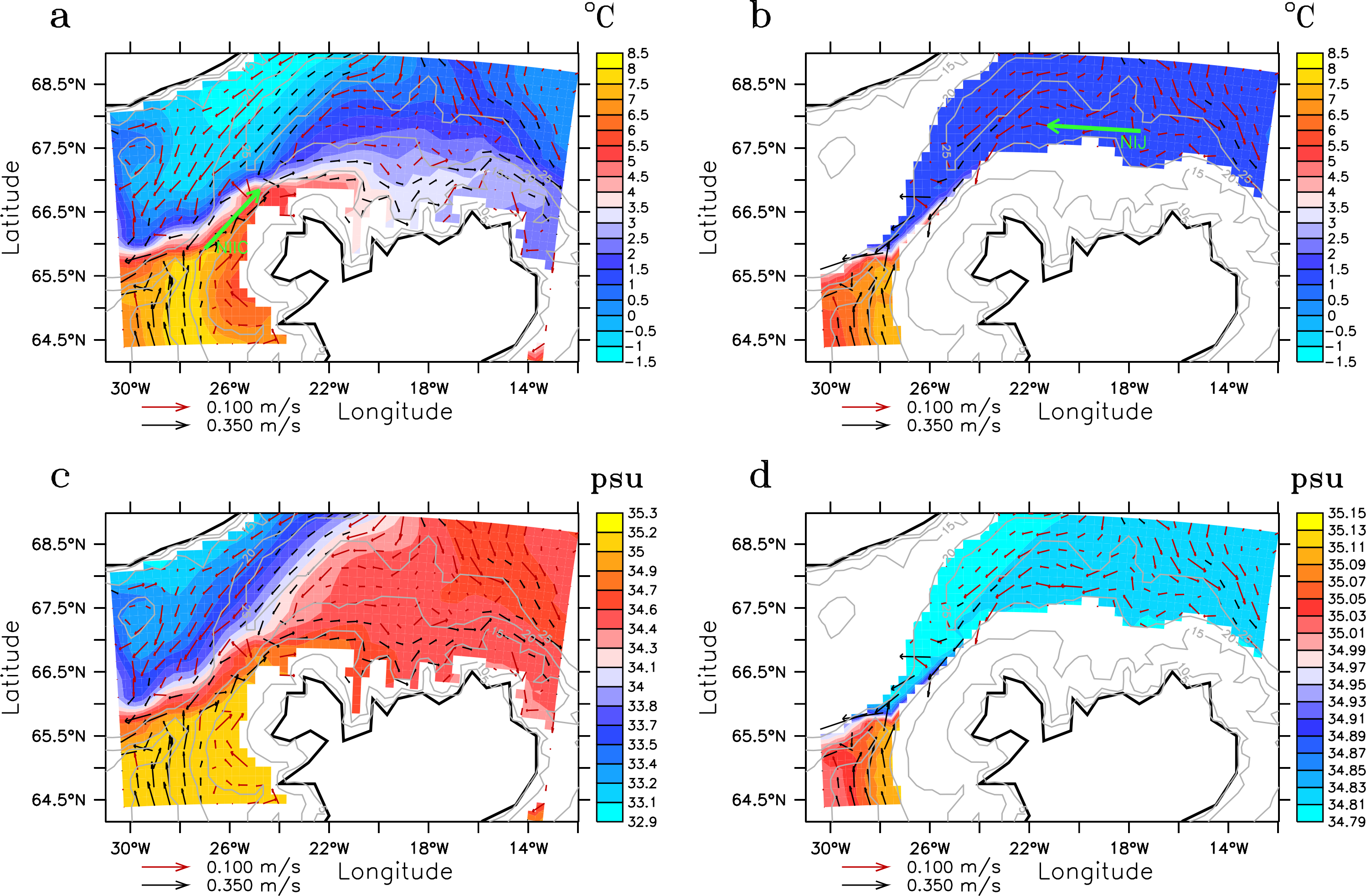
Figure 1. Time-mean currents over temperature (a-b) and salinity (c-d) around the northwest part of Iceland at two different depths, 110 m (a-c) and 450 m (b-d). Different velocity scales are used to emphasize areas of low (red arrows - velocity smaller than 10 cm/s) and high velocity (black arrows - velocity smaller than 35 cm/s). Note also the different scales used for the salinity. NIIC, North Icelandic Irminger Current; NIJ, North Icelandic Jet.

Figure 2. **a-b**, Vertical section of the mean zonal current with depth (**a**) and with density(**b**) north of Iceland at 17.5°W. Positive values represent eastward flows. **c**, Mean zonal transports of the NIIC (red lines) and NIJ (black lines - also the westward transport is plotted with positive values, in order to ease comparison between the two curves) as function of longitude. Only waters with $\sigma_\theta \geq 27.8$ kg m^{-3} are considered for the NIJ. The different overlapping lines are due to uncertain areas of integration for the transport. **d**, Mean sea surface temperature and horizontal velocity. The boxes indicate the areas of integration for the vertical transport. **e**, Profiles of vertical transport integrated over the region of the NIIC. The red and the black lines correspond respectively to the red and the black boxes in **d**.

Figure 3. Mean horizontal over meridional velocity at 380 m depth, and bottom topography. Only waters with $\sigma_\theta \geq 27.8$ kg m^{-3} are considered. The black sections are situated just to the north of the area of the NIJ. Across these sections the NIJ receives contributions from a southeastward branch of the EGC and from the boundary waters of the Iceland Plateau.

Figure 4. Time series of the DSOW (black line), EGC (blue line), NIJ at 17.5°W (red line) and NIJ at 20°W (green line) with a 1-yr running-mean filter. The purple line is the sum of the EGC and the NIJ at 20°W. Only waters with $\sigma_\theta \geq 27.8$ kg m^{-3} are considered.


a
°C
b
°C
c
psu
d
psu
NIIC
NIJ
68.5°N
67.5°N
66.5°N
65.5°N
64.5°N
30°W
26°W
22°W
18°W
14°W
Latitude
Longitude
0.100 m/s
0.350 m/s
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
35.3
35.2
35
34.9
34.7
34.6
34.4
34.3
34.1
34
33.8
33.7
33.5
33.4
33.2
33.1
32.9
35.15
35.13
35.11
35.09
35.07
35.05
35.03
35.01
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34.97
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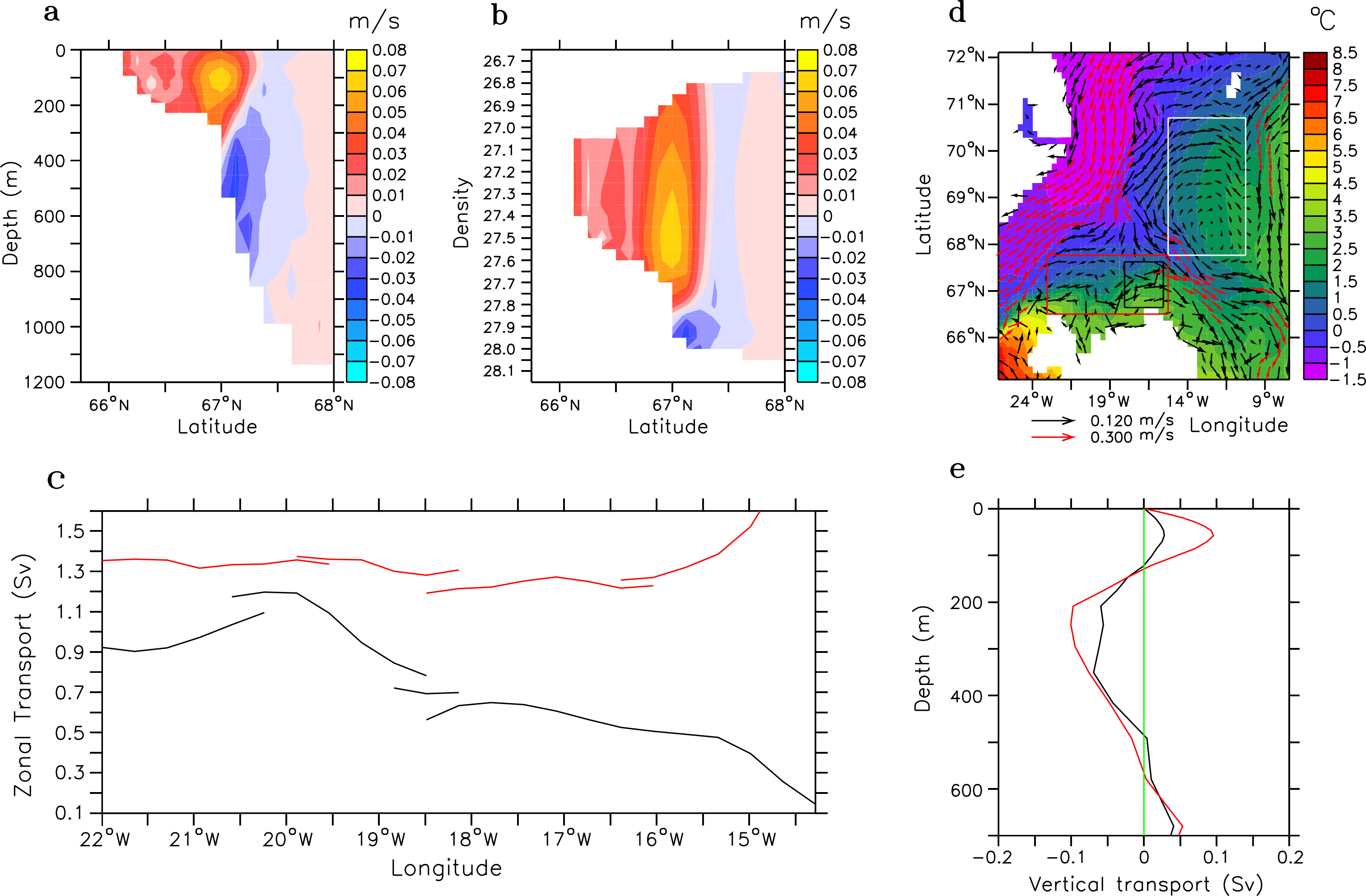
34.83
34.81
34.79
15
20
25
10
5


a
m/s
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0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
−0.07
−0.08
Depth (m)
0
200
400
600
800
1000
1200
66°N
67°N
68°N
Latitude
b
m/s
Density
26.7
26.8
26.9
27.0
27.1
27.2
27.3
27.4
27.5
27.6
27.7
27.8
27.9
28.0
28.1
66°N
67°N
68°N
Latitude
d
°C
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
Latitude
72°N
71°N
70°N
69°N
68°N
67°N
66°N
24°W
19°W
14°W
9°W
0.120 m/s
0.300 m/s
Longitude
c
Zonal Transport (Sv)
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
22°W
21°W
20°W
19°W
18°W
17°W
16°W
15°W
Longitude
e
Depth (m)
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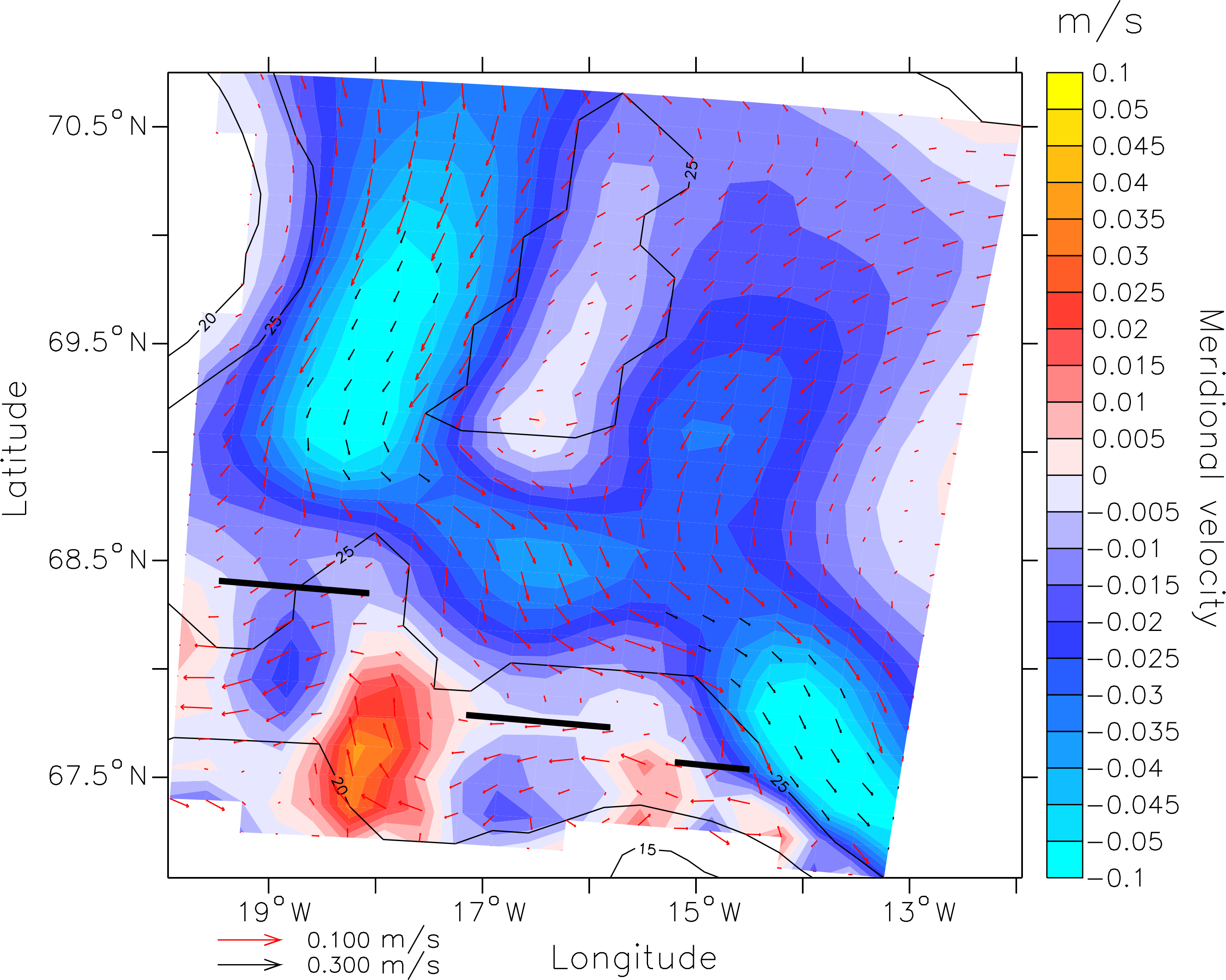
200
400
600
−0.2
−0.1
0
0.1
0.2
Vertical transport (Sv)


m/s
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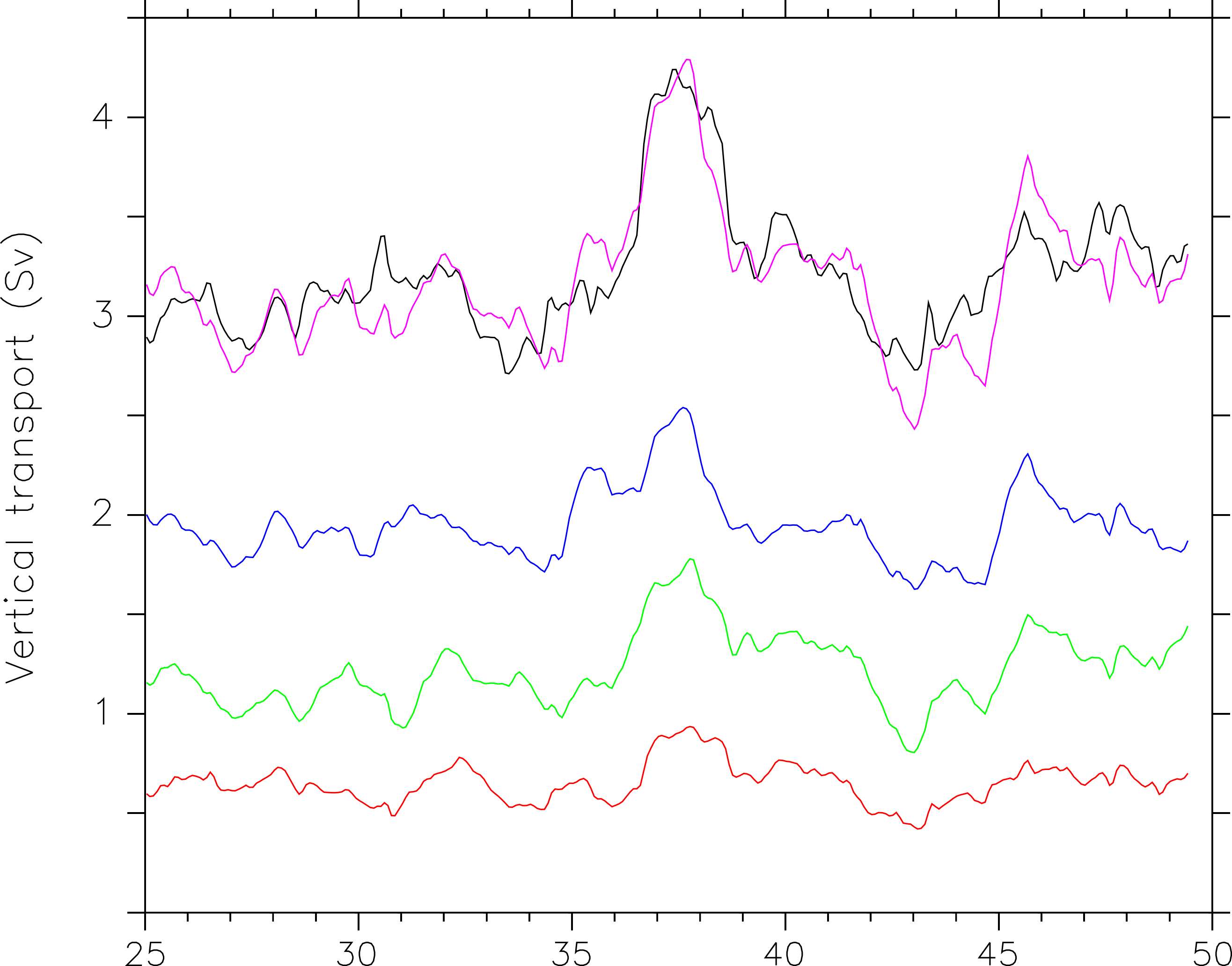
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−0.005
−0.01
−0.015
−0.02
−0.025
−0.03
−0.035
−0.04
−0.045
−0.05
−0.1
Meridional velocity
70.5° N
69.5° N
68.5° N
67.5° N
Latitude
19° W
17° W
15° W
13° W
Longitude
0.100 m/s
0.300 m/s
20
25
25
25
25
20
15


Vertical transport (Sv)
4
3
2
1
25
30
35
40
45
50