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The circulation of Icelandic waters – a modelling study

by K. Logemann, J. Ólafsson, Á. Snorrason, H. Valdimarsson, and G. Marteinsdóttir

In this manuscript the hydrography and circulation in the vicinity of Iceland are examined using high-resolution numerical simulations that include a hydrological component and assimilation of hydrographic profiles. The known currents appear to be realistically represented in general, and their transports and hydrographic properties are quantified. Several features are revealed that as of yet have not been observed.

Given its location at the intersection of the Mid-Atlantic and Greenland-Scotland ridges, the circulation around Iceland is of key importance for the exchange flow across the Greenland-Scotland Ridge. I think that we can gain much insight from realistic numerical simulations in this critical area, but have some reservations about the fidelity of this model. In particular, I am not convinced that the assimilation scheme employed is the ideal way of combining observations and model physics and think that the model output needs to be verified more extensively against hydrographic and velocity data that have not been assimilated. As such, I recommend that the paper must be revised before it can be accepted for publication.

General comments

A collection of hydrographic profiles has been used to adjust the model using the incremental analysis updating technique. The result appears to be an improvement in the transport of the North Icelandic Irminger Current and a better comparison against a sparse drifter data set, at the cost of "un-physical" corrections to the model fields. I have some concerns regarding this approach.
i) The collection of CTD profiles is assumed to be errorless and there is no mention of any quality control of the assimilated data beyond the rudimentary efforts that took place during the compilation of the profiles into the NISE and VEINS data bases. In case of erroneous profiles, this could have significant consequences for the resulting model fields.
ii) Established assimilation procedures such as "ocean state estimation" (Wunsch and Heimbach, 2007) take into account observational errors and avoids un-physical flux terms. While more complicated computationally, the results are also likely to be far more robust.

It would be very interesting to see the model output evaluated against a greater number of observations that have not been assimilated, in particular high-resolution hydrographic/velocity sections, current meter records, and transport time series. For example, how well does the model reproduce the transport and hydrographic time series of Denmark Strait Overflow Water recently published by Jochumsen *et al.* (2013)?

The description of the sensitivity experiments in Section 4 must be expanded to much greater detail or removed. At present, the results listed here are not sufficiently documented to be included in the paper.

A number of previously unknown currents are discussed and named. Without observational evidence, I am not convinced that their existence has been sufficiently verified to warrant their own names. The proposed circulation scheme (Figure 7) contains a number of features that are not in accord with the present understanding of the circulation in the majority of the literature (see details below) and dynamical explanations are lacking.

Specific comments:

Page 764, line 21
It should probably be specified which water masses are separated by the Arctic Front.

Page 765, line 19
More recent estimates of the Irminger Current transport are greater than 10 Sv (Pickart *et al.*, 2005; Lherminier *et al.*, 2010; Våge *et al.*, 2011a; Sarafanov *et al.*, 2012).

Page 766, line 5
According to Jónsson and Valdimarsson (2012b) Polar Waters rather than Arctic Waters are mixed into the North Icelandic Irminger Current.

Page 766, line 6
Please be more specific about how and where Atlantic Waters are transformed into Arctic Waters (e.g. Mauritzen, 1996; Eldevik *et al.*, 2009; Våge *et al.*, 2011b).

Page 766, line 10
The East Icelandic Current also transports a substantial amount of Polar Water from the East Greenland Current (Jónsson, 2007).

Page 766, line 13
The words "volume flux" are repeated.

Page 767, line 8 and page 768, line 15
It would be appropriate to cite Jónsson and Valdimarsson (2012b) here.

Page 772, line 7
It is unclear to me how surface heat and freshwater fluxes are derived from astronomical tables. Please elaborate.

Page 773, line 7
It should be "great-grandchildren".

Page 773, line 24
I do not quite agree that the area outside of the region where data are assimilated is the "far field" – this is no farther away than across the Denmark Strait, which is pretty much still within the back yard. I am also not convinced that the PHC data set used as a climatology for restoration is the best choice. This data set is more than 10 years old (or at least its reference is), which implies that much of the simulated period is not included. If this product has a poor spatial resolution or does not include a sufficient amount of data from the vicinity of Iceland, it could be part of the reason why data assimilation is needed in order to make the circulation in the study area more realistic.

Page 774, line 8
What is the seasonal distribution of the assimilated profiles?

Page 775, line 15
How come NCEP was chosen instead of ERA-Interim for the atmospheric forcing?

Page 776, line 8
How does the output from the PSU/NCAR MM5 numerical weather model compare to the NCEP fields?

Page 778, line 10
What was the mean absolute difference between the observed and the modelled flows?

Page 779, line 13
Defined as such, it is probably not a surprise that the offshore freshwater thickness appears to have very little seasonal variability. The freshwater content north of the GSR should be much greater than the discharge from Iceland, in particular within the polar domain, and would probably dominate the freshwater signal. As such, seasonal differences in the wind field and resulting changes in Ekman transport might have a bigger impact than the seasonal variability in the discharge. In order to identify a coastal current, it might be better to look for a near-coast salinity front. A discontinuous coastal current that exists only in some regions (presumably downstream of large rivers) is probably not the expected result.

Page 780, line 1
Please explain how the western and south-western areas are more shielded from an exchange with the ambient ocean.

Page 780, line 26
The 3 or 4 model sections that indicate the presence of a coastal undercurrent are intriguing. This may provide sufficient motivation for an observational study to attempt verification of its existence. If successful, that would be a more appropriate moment to name the current. At present I think the authors convey the impression that its existence is asserted with more confidence than is prudent. Also, if the dynamical hypothesis would explain the existence of an undercurrent, why is it not a ubiquitous feature of the coastal current system?

Page 780, line 29
It should be (Pickart, 2000).

Page 781, line 11
I do not think that the average temperature and salinity of the waters transported by the full-depth Irminger Current are very meaningful quantities considering the large differences between two of the main water masses in question, Atlantic Water and Subpolar Mode Water. Please also consider the more recent references provided above for the hydrographic properties of this current.

Page 781, line 14
Without looking at the circulation schematic (Fig. 7), it is not so clear why this should be the third northward current.

Page 781, line 17
It appears that the inner branch of the Irminger Current flows across isobaths from the upper continental slope and onto the shelf. Currents, in particular in these northerly regions, tend to follow isobaths quite closely. What are possible mechanisms that makes this branch flow across isobaths?

Page 782, lines 4 and 10
The NIIC is rather well studied. Is there any observational evidence that the current splits into four different branches?

Page 782, line 14

It appears from the text that the outer branch of the NIIC west of the Kolbeinsey Ridge becomes, with the addition of some Arctic Water, the EIC east of the ridge. This view contradicts much of the recent observations of the EIC, which suggest an origin to the east of the Spar Fracture Zone (e.g. Jónsson and Valdimarsson, 2012a) and does not explain the presence of fresh Polar Water in the EIC (e.g. Jónsson, 2007; Dickson *et al.*, 2007). There is also a mismatch between the larger transports east of the ridge in the various branches of the NIIC and the smaller transport of the EIC, so what happens to the remaining Atlantic Water in the outer branch of the NIIC? There is occasionally evidence of Atlantic Water at the Langanes North East hydrographic section (see http://www.hafro.is/Sjora), typically near the shelf break, which does not match the schematic that has only an inner branch of the NIIC present at that location. In this context, the schematic circulation north of Iceland presented in Figure 7 and on page 782 involving the NIIC and the EIC is controversial, and requires more discussion.

Page 782, line 18

It is not specifically mentioned in the text, but appears from Figure 7 that the NIJ originates north of Iceland near the Langanes North East section. As such, it is puzzling that the volume transport of the NIJ is larger on the eastern side of the Kolbeinsey Ridge, in particular considering the entrainment that must take place upstream of section 4 in order to explain the temperature increase of almost 1°C. This is clearly an overestimate, sufficient to eradicate the supply of Arctic-origin overflow water through the Denmark Strait via the NIJ, and inconsistent with the results of Jónsson and Valdimarsson (2004) and Våge *et al.* (2011b).

Page 783

The so-called South Icelandic Current is another new feature, hypothesized to be the origin of the Faroe Current. Unlike most of the other new features, the SIC is discussed extensively in this section as well as in the Discussion part of the paper, which is certainly warranted, and Figure 16 is also very helpful in this. The circulation south of the Iceland-Faroe Ridge and the upstream pathways of the waters forming the Atlantic Inflow into the Nordic seas are still not well known. I would caution against relying very much on satellite altimetry for flow on shelves and in coastal areas (page 795, line 16), as the altimeter data are known to have issues in these areas and on small spatial scales. I am also not convinced about the Atlantic Water crossing isobaths to form the SIC on the Icelandic shelf. This is another example where I would rather expect to see the current flow along isobaths on the south Icelandic continental slope. Based on one drifter in Figure 5, the observed flow does appear to consistently follow the shelf break.

Page 783, line 27

If the total transport of the overflows east of Iceland is only 0.32 Sv, the majority of overflow water is missing or the eastern overflows are grossly underestimated.

Page 784, line 1

Much of the temporal variability of the NIIC, in particular in terms of the hydrographic properties, are likely due to non-local effects, such as the strength of the subpolar gyre circulation (page 784, line 7).

Page 784, line 13

It is unclear to me what a mean relative model error of -1% implies. The correlation between the two timeseries in question does not look very high in Figure 13.

Page 784, line 22

If the local winds play such an important role, I think that timeseries should be added to Figure 13.

Page 784, line 25 and page 796, line 24
Is there any evidence of the close connection between the NIJ and the NIIC that was hypothesized by Våge *et al.* (2011b)?

Page 785, line 14
Why were the sensitivity experiments carried out for less than half a year? Is that a sufficient amount of time to spin up a steady circulation under a quite diverse set of forcing scenarios?

Page 789, line 24 and elsewhere
This is but one example of a reference from Icelandic gray literature that is inaccessible to most readers, hence should be used as sparingly as possible.

Page 789, line 26
What is "the related south-westward momentum"?

Page 791, line 4
Is there observational evidence that such upwelling and resulting increased primary production actually takes place in the locations where the model predicts the existence of a coastal current and an opposite undercurrent?

Page 792, line 13
Do both of the NIIC and the EIC arise due to the presence of the Arctic Front? How can the Arctic Front explain the presence of both currents east of the Kolbeinsey Ridge – surely only one current can flow along the front?

Page 792, lines 15 and 17
Please explain how a signal of high dynamic sea level height is **led**.

Page 795, line 20
The NIJ is a narrow, mid-depth intensified current centered above the same isobath as the Denmark Strait sill (Jónsson and Valdimarsson, 2004; Våge *et al.*, 2011b). How does that structure compare against the model?

Page 796, line 7
A more appropriate mooring-based estimate of the Denmark Strait Overflow Water transport is 3.4 Sv (Jochumsen *et al.*, 2013).

Page 796, line 9
There is no collision between Arctic and Atlantic waters, the flow next to each other.

Page 796, line 12
By which mechanism are the deeper Arctic waters pumped up the North Icelandic continental slope?

Figure 2, right panel
It would be great to see the bottom topography on this figure.

Figure 4
It would be easier to compare these figures if they show the exact same domain.

Figure 6
Please add bottom topography to this figure. This would make it much easier to examine the circulation relative to the bathymetry.

Figures 9 through 12
It would be easier to look at these figures if Iceland were consistently located on the left or the right hand side of the figure. Better correspondence between the color maps and the vertical and horizontal scales would also improve the figures substantially.

Figure 15, c and d
These vectors are very hard to see.

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