Response to Anonymous Referee#2 comments for "The circulation of Icelandic waters – a modelling study" by K. Logemann et al.

K. Logemann et al.

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We would like to thank the anonymous reviewer for the helpful comments. The reviewer's comments are displayed with a bold/italic font.

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.

We do not think that the efforts regarding the data quality of the NISE and VEINS data bases can be called rudimentary. Here, even before delivery to the data base, a standard high level quality control was performed by each data contributor and an additional data cleaning has been applied to the data sets afterwards (Nilsen et al., 2008). The precision of a modern state-of-the-art CTD profile is at least by one order of magnitude higher than the precision of our numerical simulation. In the very unlikely case of a highly erroneous profile leading to unrealistic simulated T,S fields or even to a crash of the model, the respective profile would have been removed from the model input.

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.

We agree that the used data assimilation algorithm is certainly not the last word on the subject. Our intention was to bring the simulation closer to the observations without an enormous increase of the computational costs, which was successful.

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 drifter data used for the model validation was not assimilated. We have added a comparison with the FC observations of Hansen et al. (2010) which is more relevant for this study than overflow measurements.

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.

Chapter 4 was extensively expanded including two further experiments, graphics added, the results discussed in more detail.

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.

The extended version of chapter 4 provides more precise dynamical explanations. Regarding the other points, we consider them as generally positive aspects. In 2004, when Jónsson & Valdimarsson published their NIJ discovery, ocean modellers immediately found this current within their models. Hence, the current could have been postulated decades before.

Specific comments:

Page 764, line 21

It should probably be specified which water masses are separated by the Arctic Front.

Now, we write about the barotropic pressure field which is "dominated by the sea level height gradient between Arctic and Atlantic waters."

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).

Now, the higher estimates are mentioned as well.

Page 766, line 5

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

Jónsson and Valdimarsson (2012b) discuss the NIIC composition at Hornbanki section, i.e the NIIC immediately after leaving Denmark Strait (where mixing with PW may occur). Our sentence describes the NIIC mixing with the AIW of the Iceland Sea.

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).

Now the sentence contains the formation areas as well as the detailed pathways of the AW inflow.

Page 766, line 10

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

Now, the admixture of PW is mentioned.

Page 766, line 13

The words "volume flux" are repeated.

corrected

Page 767, line 8 and page 768, line 15

It would be appropriate to cite Jónsson and Valdimarsson (2012b) here.

done

Page 772, line 7

It is unclear to me how surface heat and freshwater fluxes are derived from astronomical tables. Please elaborate.

done

Page 773, line 7

It should be "great-grandchildren".

corrected

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.

The use of the term "far field" was removed.

We agree that the PHC data set is not perfect. That is why the PHC relaxation was set to a minimum, just in order to avoid a model drift into completely unrealistic state.

Page 774, line 8

What is the seasonal distribution of the assimilated profiles?

Now, the seasonal signal of the profile number is given (Dec-30, Jan-23 – May-206, Jun-143).

Page 775, line 15

How come NCEP was chosen instead of ERA-Interim for the atmospheric forcing?

Mainly the easy availability of the NCEP data. Daily comparison of the GFS-based and ECMWF-based regional weather forecasts for Iceland do not show a significant difference in quality, e.g. regarding forecast wind fields.

Page 776, line 8

How does the output from the PSU=NCAR MM5 numerical weather model compare to the NCEP fields?

We assume that both re-analysis products are reproducing the basic elements of the air temperature and precipitation variability over Iceland.

Page 778, line 10

What was the mean absolute difference between the observed and the modelled flows?

The mean values (-0.0122 m/s, -6.11°) are added.

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.

We have replace the word "offshore" by "coastal", and use the word "near-shore" afterwards to stress and clarify that we discuss the seasonality of the near-shore, or coastal freshwater thickness and not those of the Iceland Sea. Maybe the rather large area shown by figure 8 was misleading, we have reduced the area shown by figure 8 which now focusses on the coastal area.

Page 780, line 1

Please explain how the western and south-western areas are more shielded from an exchange with the ambient ocean.

We have added "by the more sluggish flow field."

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?

We state within manuscript that we propose or postulate structures which should be checked in future. We have introduced the names like ICUC, WIIC or SIC mainly because something has to be used to identify the structures within the tables, figures and sentences, and using numbers or other symbols instead of these names, which were carefully fit into the traditional naming system, would create a rather strange expression. Names help to formulate thoughts more precisely. The reviewer is using the name "coastal undercurrent" as well in this text.

Maybe it is a ubiquitous feature.

Page 780, line 29

It should be (Pickart, 2000).

corrected

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, AtlanticWater and Subpolar ModeWater. Please also consider the more recent references provided above for the hydrographic properties of this current.

A good point. We removed the statements regarding the mean quantities. The recent works of Lherminier et al. and Våge et al. are mentioned now.

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.

We change "third northward current" into "IC branch".

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?

First we have to keep in mind that there are numerous examples, maybe especially in Icelandic waters, of currents crossing isobaths. Without them we would not see any exchange across the Greenland-Scotland-Ridge, would not find any AW over the Icelandic shelf.

Our sensitivity experiments (new Fig. 16) indicate that the WIIC is related to density differences between the shelf areas of Faxaflói and Breiðarfjörður and the waters further offshore. We have added this point to the list of the sensitivity experiments results in chapter 4.

As a near-surface current the WIIC is not controlled by topographic steering further offshore.

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?

Unfortunately not. The regional hydrography has just started to capture the basic structures (e.g. the recent NIJ discovery). Our manuscript describes structures of the multi-annual mean fields and corresponding measurement campaigns would entail enormous efforts.

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 ArcticWater, 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).

Good point. The words "origin of EIC" are wrong in this context and even contradict to our proposed circulation scheme. We have added the Jónsson and Valdimarsson suggestion about the origin instead.

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?

Now, we state that the NIIC branches only partly join the EIC.

There is occasionally evidence of AtlanticWater 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.

We do not discuss occasional events in this manuscript, but describe the simulated mean state of the period 1992-2006. However, we have added the occasional appearance of the oNIIC north-east of Iceland.

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).

Now, we mention the over-estimated volume flux east of the ridge, also a possible over-estimation of the core depth east of the ridge is mentioned.

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.

We agree that the signal of low sea surface height along parts of the southeast coast within the satellite altimetry derived map may have other reasons than the SIC, however it would be a curious coincidence. Again, without any Atlantic Water crossing isobaths there would be no Atlantic Water inflow to the Nordic Seas at all. Actually, our SIC is the less isobath-crossing solution of all proposed structures.

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.

Good point. Now, we state that the ISC contains only parts of the overflow.

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).

Yes, and we are referring to that in page 784, line 7, as you have noted.

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.

Good point. Now we compare the absolute values, including the uncertainty of the observational based value. We also specify the correlation coefficient of 0.77 now.

Page 784, line 22

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

We have included the southward wind component north of Denmark Strait in Figure 13. The curve confirms the statements about the role of the wind stress.

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)?

As far as we understand Våge et al. propose a downwelling of cooled NIIC water which feeds the NIJ. So, interestingly, here it the erosion of the Arctic Front is seen as a crucial element of the NIJ formation whereas we propose more or less the opposite process – a stronger front which causes a stronger undercurrent, in order to explain the positively correlated signals of both currents.

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?

Please note that it was not our intention to spin up steady solutions but to analyse the model's reaction to the deactivation of the different terms. We have clarified this more precisely in the new chapter 4.

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.

When writing the manuscript we were aware of the Ocean Science guideline to keep the number of references to grey literature at the inevitable minimum. The number of papers about Icelandic waters is rather limited. Furthermore, technical details about ocean models are normally published in grey technical reports.

Page 789, line 26

What is "the related south-westward momentum"?

Sentence changed to "…but also counteracts the development of a south-westward flow."

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?

Now, we refer to the observation of increased phytoplankton productivity by Guðmundsson (1998) over the south-western shelf compared to the adjacent open sea.

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?

We agree. The sentence was misleading and was removed.

Page 792, lines 15 and 17

Please explain how a signal of high dynamic sea level height is led.

We have added a paragraph describing the distortion of the pressure field more precisely. This was also further illuminated by the two additional experiments in chap. 4.1.

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?

Now, we refer explicitly to the over-estimated core depth of the current, as well as to the over-estimated volume flux east of Kolbeinsey Ridge.

Page 796, line 7

A more appropriate mooring-based estimate of the Denmark Strait OverflowWater transport is 3.4 Sv (Jochumsen et al., 2013).

Now, we are using this reference.

Page 796, line 9

There is no collision between Arctic and Atlantic waters, they flow next to each other.

The “collision” was removed.

Page 796, line 12

By which mechanism are the deeper Arctic waters pumped up the North Icelandic continental slope?

By the up-slope near-bottom flow being part of the secondary circulation, mentioned in the previous sentence, which was re-formulated to clarify this.

Figure 2, right panel

It would be great to see the bottom topography on this figure.

Figure 2 was completely re-designed reacting to the comments of Reviewer#1. Now, also vertical sections are shown which also illustrate the horizontal mesh adaption based on geographical/topographical criteria.

Figure 4

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

Now, all four figures show exactly the 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.

We have added the bottom topography.

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.

Iceland is located on the left hand side in figure 10, 11 and to 12. Only in figure 9 the right hand side is chosen. All section plots follow the rule that the left hand side (the mathematical negative direction in standard Cartesian coordinates) corresponds to the west or south. We think that this consistent. Because the vertical and horizontal scales vary intensively between the figures the corresponding projections had to be adjusted.

Figure 15, c and d

These vectors are very hard to see.

The vectors were enlarged.

Reference

Guðmundsson, K.: Long-term variation in phytoplankton productivity during spring in Icelandic waters, ICES J. Mar. Sci., 55, 635–643, 1998.

Nilsen, J.E.Ø., Hatún, H., Mork, K.A., and Valdimarsson, H.: The NISE Data Collection, Report published on CD-ROM, 20 pp., 2006.