

Interactive comment on “Large-scale forcing of the European Slope Current and associated inflows to the North Sea” by Robert Marsh et al.

Robert Marsh et al.

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Anonymous Referee #2

General Comments:

This is a nicely written and well set out paper and I found it easy to follow. The main results from the modelling study have the potential to add to our understanding of the drivers of North Sea inflow. However my main concern is in the analysis of North Sea inflow and the development of the SSH proxy, this aspect of the paper is poorly developed and I don't feel that the conclusions are not well supported. I feel there was limited effort made to validate the model observations, and as a result, that sections 3.4 and 3.5 in particular need some revision.

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Response: We thank the reviewer for broad support and a very thorough review.

Changes in the manuscript: The manuscript will be extensively revised, paying particular attention to Sections 3.2, 3.4 and 3.5.

(1) The use of the SSH metric is puzzling. The authors note that previous researchers have failed to establish a Shetland current transport series based on tide gauge records (Page 2, Line 8) but then fail to return to the subject as promised. This statement should be revised to be more accurate; but more preferable would be a more explicit discussion of this result in Section 4. More importantly there is no mention in this paper of the established pattern of Faroe-Shetland Channel circulation, particularly the recruitment of an additional branch of Atlantic water from the Western Atlantic through the Faroe Bank/Wyville Thomson Ridge region and the recirculation of the North Faroe Current in the channel. Recent estimate of transport through the channel using altimeter data (Berk et al., 2013) demonstrates for example, why a simple SSH metric might not be so useful.

Response: We appreciate this comment, and agree that further discussion and clarification is necessary.

Changes in the manuscript: We will extend the Introduction, selected parts of the Results, and the Discussion accordingly.

(2) Logically we would expect some relationship between SSH variability and slope current but it would be worth examining some the different mechanisms for transport of water into the NNS in the NE and the NW for example. This paper could be improved if there was some examination of the relationship between stronger slope current and/or stronger onshelf transport and/or stronger North Sea inflow - the links between these three transports could be the key focus of the paper.

Response: We agree that further analysis may provide helpful insight as to the relative contributions of Slope Current (as currently defined – see Sect. 3.2) and on-shelf

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transport to North Sea inflow.

Changes in the manuscript: We will diagnose transport inshore of the Slope Current at the “Shetland Slope section”, and compare this to Slope Current transport. We will further diagnose North Sea inflow at the Feie-Shetland and Jonis-Utsire sections. Pending the results of this new analysis, we will revise Sect. 3.4 and the Discussion.

(3) There is no statement in the methods of how the particle backtracking was performed. The first mention of backtracking is in the results section. Also the depth distribution of the tracked particles within the North Sea is not described/discussed. This is of concern because the main Atlantic inflow in NW North Sea is known to flow at depth below the Baltic outflow.

Response: ARIANE (as other tracking methods) can be used in backward mode, as forward mode, simply by time-reversing the analytical calculation of particle progress through grid-cells. Depth per trajectory is recorded. Depth distributions within the North Sea will be examined, to establish whether indeed inflow in the NW North Sea in ORCA12 is found below the fresh Baltic outflow.

Changes in the manuscript: This will be explained in Sect. 2.3. North Sea particle depth distributions will be plotted as for particle density and age. Figures will be shown in either the main section or as Supplementary Material. Sect. 3.2 will be revised accordingly.

(4) Following on from this, it is not clear why the authors chose to examine surface (only) salinity data within the North Sea (only). Changes in salinity within the North Sea are not just linked to a change in transport of Atlantic Water but also the changing properties of the water that is transported. There was a strong trend of salinification in Atlantic water over the period of the 1990's. This trend is well documented and the reported/observed trend in the NNS is also one of salinification. Having modelled data should offer the authors a chance to investigate these trends and relationships. I believe that doing this would really add value to the paper. Alternatively can the authors

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explain why they chose surface salinity? Surely the surface salinity metrics are most likely to show the variability of freshwater flows.

Response: Our choice to analyse only surface salinity within the North Sea is admittedly limiting, and we agree that a more analysis is warranted here. Indeed, both v' (changes in transport) and S' (changes in property) should be considered.

Changes in the manuscript: We will undertake a wider analysis of salinity variability, across the study region and for different depths, also informed by the depths followed by particles through the North Sea region in particular. Rather than over-lengthen the manuscript with an entirely new section, we will incorporate an expanded salinity analysis into Sect. 3.4, with additional figures added to Supplementary Material.

(5) The authors appear surprisingly unaware of the long time-series of data available, both in the northern North Sea and in the Faroe Shetland Channel where there are both hydrographic observations and long-term transport estimates. And also the Ellett Line. Before extracting salinity metrics from the North Sea it might be valuable to check how the model represents other observed patterns of salinity.

Response: Thank you for pointing out the available observations. Our awareness of this data is implicit in citation of Sherwin et al. (2008), but we will indeed look to model validation alongside observed transport estimates and salinity variations, as published. We have already obtained relevant data provided online with the ICES Report on Ocean Climate (<http://ocean.ices.dk/iroc/>).

Changes in the manuscript: If and where practical, we will co-plot observed and model estimates. Otherwise, we will discuss model transports and variability in the context of published observations. We will revise Sect. 3.2 and 3.4 accordingly.

(6) From my understanding of these observations, I am not convinced that there is evidence of a decline in salinity during the 1990's in the North Atlantic-influenced regions of the northern North Sea. Curiously, the modelled decline in salinity almost mirrors the

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actual increase in salinity observed over the same period in the Slope Current regions and the central North Sea.

Response: Clearly, this is an important matter for clarification. Once we have addressed the broader 3D changes in salinity, and compared these with observations, it will be evident whether model is reliably simulating observed changes in the Slope Current system, both transports and properties. We can then re-visit statements about North Sea salinity and links with variable Slope Current transport.

Changes in the manuscript: In line with previous outlined changes, Sect. 3.4 will be revised accordingly.

(7) I would suggest the following observational evidence be examined.

B. Berx, B. Hansen, S. Østerhus, K. M. Larsen, T. Sherwin, and K. Jochumsen, 'Combining in-Situ Measurements and Altimetry to Estimate Volume, Heat and Salt Transport Variability through the Faroe Shetland Channel', *Ocean Sci. Discuss.*, 10 (2013), 153-95.

Larsen, K. M. H., Gonzalez-Pola, C., Fratantoni, P., Beszczynska-Möller, A., and Hughes, S. L. (Eds). 2016. ICES Report on Ocean Climate 2015. ICES Cooperative Research Report No. 331. 79 pp

N. P. Holliday, S.L. Hughes, S. Bacon, A. Beszczynska-Möller, B. Hansen, A. Lavín, H. Loeng, K.A. Mork, S. Østerhus, T. Sherwin, and W. Walczowski, 'Reversal of the 1960s to 1990s Freshening Trend in the Northeast North Atlantic and Nordic Seas', *Geophysical Research Letters*, 35 (2008).

S. Dye, N.P. Holliday, S.L. Hughes, M. E. Inall, K. Kennington, T.J. Smyth, J. Tinker, O. Andres, and A. Beszczynska-Moller, 'Impacts of Climate Change on Salinity', in *MCCIP Science Review*, www.mccip.org.uk/arc, ed. by MCCIP, (2013).

N.P. Holliday, S.L. Hughes, S. Dye, M. E. Inall, J. Read, T. Shammon, T. Sherwin, and T.J. Smyth, 'Salinity in MCCIP Annual Report Card 2010-11', in *MCCIP Science*

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Review, 16pp. www.mccip.org.uk/arc, ed. by MCCIP, 2010).

Data from the Feie-Shetland, JONSIS and UTSIRE sections can be obtained from the host institutes or extracted from databases such as BODC, ICES and WODC.

Response: Thank you for drawing these publications and data to our attention.

Changes in the manuscript: Relevant publications will be cited, and selected observations will be sought and used to evaluate the simulation.

Specific comments:

(8) Page 2, Line 11. I'm not convinced that there is "some evidence of surface freshening through the 1990's". Established time series either show no trend in salinity or a slight increase during this period, following the increases seen in Atlantic Water. The freshening that has been observed is limited to the southern North Sea.

Response: This statement was based on inspection of figures in Højillo et al. (2009), as indicated. We accept the referee's point about different salinity changes elsewhere, and we will re-visit the broader patterns and character of salinity change.

Changes in the manuscript: The Introduction will be revised accordingly, with reference to further observations, outlining the pattern and character of salinity changes across the North Sea.

(9) Page 7, Line 6-8: The definition of the sections is based on the slope current in the model, but what criteria was applied to define the slope current? See also comments relating to the area of Atlantic water.

Response: The Slope Current was identified as a narrow band of high velocity current confined between isobaths, in 5-day averaged ORCA12 datasets.

Changes in the manuscript: In Sect. 3.2, we will specify the criteria for locating the Slope Current, both for calculating transport and for specifying initial particle locations.

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(10) Page 7, Line 21 onwards: The authors fail to acknowledge the established knowledge of Faroe-Shetland Channel circulation, particularly the recruitment of an additional branch of Atlantic water from the Western Atlantic through the Faroe Bank/Wyville Thomson Ridge region and the re-circulation of the North Faroe Current in the channel. These offer some explanation as to why a single index of SSH might not represent slope current variability.

Response: Thank you for raising this point, which we should certainly bear in mind, in regard to the drivers of variability in a SSH slope index. From the ORCA12 simulation, We will extract SSH differences across just the Slope Current, for comparison with SSH differences between Lerwick and Torshavn. The strength of correlation between time series of these two indices will inform this issue.

Changes in the manuscript: We will revise Sect. 3.5 accordingly, with the utility of a Lerwick-Torshavn SSH index for Slope Current transport more or less supported by the correlation between this index and SSH slope across just the Slope Current.

(11) Page 11, Line 27. The strong freshening trend from your model data is in the surface salinity of the NW North Sea. Terschelling is a station in the central North Sea and as presented, offers little in support of your observations. The Utsire station as presented by Hjollo sits well within the Baltic Outflow which would link much more strongly to your NE time-series and as mentioned before is likely to mostly reflect variability of freshwater input.

Response: Thank you for pointing this out. We will indeed look more widely to the available salinity observations and in particular those at locations/depths sensitive to variations in Atlantic inflow to the North Sea.

Changes in the manuscript: Pending further analysis of salinity observations, we will revise Sect. 3.4 accordingly.

(12) Page 11, Line 34 to Page 12, Line 4: Could the authors elaborate on the spatial

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variability of what would be their defined Atlantic water mass to highlight what this impact may be?

Response: We can further analyse the spatial distribution of salinity in the ORCA12 hindcast to substantiate this remark. The principal water mass in the Faroe-Shetland slope is North Atlantic Water (McKenna et al., 2016), but we will look to the wider literature in regard to on-shelf water masses.

Changes in the manuscript: Pending further model analysis and a review of relevant literature, we will provide clarification accordingly.

(13) Page 12, I'm worried about these correlations. All three time-series have a similar downward trend and hence they would always be reasonably correlated. Has this been accounted for in the correlation analysis? If not then by the same argument the wind forcing metric that you include in Figure 8 would also be correlated.

Response: Trends are included in the correlated data. We agree that there is limited value in correlations between short time series (given only 20 annual values) that are characterized by similar trends.

Changes in the manuscript: We may omit correlations from Sect. 3.4 and Sect. 3.5 of the revised manuscript.

(14) Page 12, Line 4. Have you examined how the salinity of the slope water has increased over the period? Is this reflected in your model? During the periods of weaker modelled transport we know that the slope current became saltier.

Response: We can address changing salinity in the model via the salinity along each trajectory (already calculated), and we will further seek observational evidence for any changes.

Changes in the manuscript: We will develop and substantiate statements in Sect. 3.4 that relate to the Slope Current influence on North Sea salinity, due to changes in both transport or salinity, distinguishing between “anomalous volume transport of mean

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salinity” and “mean volume transport of anomalous salinity”.

(15) Page 12, Lines 15-17: Are the seasonal cycles in the Shetland Slope transport and SSH differences in phase?

Response: Yes, Shetland Slope transport and the Lerwick-Torshavn SSH difference are in phase.

Changes in the manuscript: We will emphasize this in-phase relationship in Sect. 3.5.

(16) Page 13, Line 9. It would be nice to see some comparison of the modelled slope current with some of the observations of the slope current and more sophisticated estimates from altimeter data.

Response: We are aware of transport estimates for the Atlantic inflow between the Faroes and Shetland since December 1992 (Fig. 10 in Berx et al., 2013) in the range 1-5 Sv – similar to the range seen in ORCA12 (our Fig. 4c).

Changes in the manuscript: We will obtain ORCA12-N01 transports for the full Faroes-Shetland section (as Berx et al., 2013), and present this time series as an additional panel (Fig. 4d) below that for our “Shetland Slope” transport estimate (Fig. 4c). We will thus directly compare ORCA12 transports with corresponding observations, and also determine the extent to which Slope Current variability on the Shetland Slope accounts for variability across the full section.

(17) Page 14, Line 11. ref to limited observations. The Northern North Sea is relatively rich in observations, being sampled across two sections (Feie-Shetland and JON- SIS/Utsire) least 5 times per year by UK (Scotland) and Norway. These data are publically available for you to use in your research.

Response: We will access the necessary data, as recommended.

Changes in the manuscript: We will refer to salinity variations at the Feie-Shetland and JON- SIS/Utsire sections, and revise our conclusions accordingly.

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(18) Page 15, Line 6. Sentence starting "These transient events..." In which case presumably we would see a return to higher salinities - has anyone noticed this? I'm not sure you can evidence this statement.

Response: This is a good point. We are currently examining the GODAS ocean analysis (<http://www.esrl.noaa.gov/psd/data/gridded/data.godas.html>) for evidence of recent changes in the Slope Current and regional salinity that are consistent with strengthened meridional density gradients and geostrophic inflow.

Changes in the manuscript: We will revise the discussion in accordance with our findings and any other evidence.

(19) Page 15, Line 13. Reference is also made here to observed trends in the Ellett line data, this raises the question of why the authors did not examine/compare the trends in salinity from the EEL observations as these also shows an increase in salinity during the 1990's?

Response: We will access the EEL salinity observations, specifically in the Slope Current, as recommended. Repeating an earlier response, we can address changing salinity in the model via the salinity along each trajectory (already calculated), which we can compare to the EEL data. Following Fig. S1 and Fig. S2, we will plot mean particle salinity for January and July releases of each year. At the EEL section, we can plot this salinity as a time series, for comparison with observations.

Changes in the manuscript: We will include further plots in Supplementary Material, as outlined above, refer to these in Sect. 3.2. In Sect. 4, we will discuss observed and simulated salinity changes, over 1988-2007, in the Slope Current to the west of Scotland.

(20) In methods/supplementary material: You examine average surface salinity values over relatively large box areas (NW and NE). The size of these regions makes it likely that both of salinity time-series are capturing variability in Norwegian Coastal current.

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This is evidenced by the salinity minima in summer in this region. Away from the regions of Baltic influence, in the northern North Sea we would expect salinity maxima in Autumn (September) as a result of Atlantic Inflow. I think it might be valuable to consider different regions and examine data at depth - not just surface values?

Response: Thank you for this insight. We will re-calculate salinity, this time also for full-depth (rather than just the surface), for re-defined, perhaps irregular, sub-regions that are informed by the pattern of inflow evident in Fig. 2.

Changes in the manuscript: We will replace Fig. 10 with time series of salinity anomalies for the redefined sub-regions, possibly with additional panels relating to the salinity anomalies in the upstream Slope Current (see previous responses). We will revise the text in Sect. 3.4 accordingly.

Minor/Technical comments:

(21) The most common spelling is Faroe and not Faeroe.

Response: Accepted

Changes in the manuscript: Text will be revised accordingly.

(22) Fig 1, Lerwick is not accurately positioned in Figure 1d. The position of the Shetland Slope transect (3) seems to have moved between 1c and 1d.

Response: Accepted

Changes in the manuscript: Fig. 1c,d will be revised accordingly.

(23) Fig 1, I find scales hard to read on Figures 1a and 1b, the font size used in 1c and 1d is more reasonable.

Response: Accepted

Changes in the manuscript: Fig. 1a,b will be revised accordingly.

(24) Fig 2, I note a reference to the log scale - but I think the scale used could be

described more clearly.

Response: Agreed

Changes in the manuscript: The purpose of “particle density” shown in Figs. 2a,b and Fig. 3a,b is to reveal dominant pathways through the region. We will elaborate in the caption that the density diagnostic records particle presence per grid cell in the range 0.01-10% (of all particle positions).

(25) Fig 5, the number of colours in the scale could align better to the scale intervals.

Response: Point taken

Changes in the manuscript: We will re-plot the figure accordingly.

(26) Page 3, Line 18: ...are used...

Response: Noted (as Referee 1)

Changes in the manuscript: Text will be corrected

(27) Page 6, Line 1. the position of the FASTNEt, EEL and Shetland Shelf sections should be defined. In section 2.3, floats are mentioned which were deployed for FASTNEt (but which aren't analysed in this manuscript and their position is not described). Is the "FASTNEt section" the line where the ORCA particles were released, if so it needs to be stated on Page 4, Lines 8-10 that this is henceforth referred to as the FASTNEt section. In Table 1 the central locations of EEL and Shetland shelf are mentioned, but the length/endpoints of each section is not defined.

Response: The position of the “FASTNEt section” is indeed as defined in Sect. 2.3. We agree that full details of the EEL and Shetland Shelf sections should be defined.

Changes in the manuscript: We will make clear in Sect. 2.3 that we are defining the FASTNEt section, from which particles are tracked forwards and backwards. The endpoints for EEL and Shetland Shelf sections will be provided in Sect. 3.2 and in the

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caption for Table 1.

(28) Page 6, line 3. 'northwest' and 'northeast' sectors not adequately defined until 3.4 (Page 11, Line 15) please move that to here or put into methods.

Response: This is an oversight.

Changes in the manuscript: We will define northwest and northeast sectors of the North Sea in Sect. 2.3, where we introduce the Lagrangian methodology.

(29) Page 7, line 9. referenced correctly as Sherwin et al 2007. Elsewhere in the paper and in the reference list it is incorrectly noted as Sherwin et al 2008.

Response: Noted

Changes in the manuscript: The citation will be corrected to Sherwin et al. (2008).

(30) Page 7, Line 16. I don't find the more vigorous transport in the early part of the year is 'clearly evident' in this figure. A monthly plot might demonstrate this better.

Response: We agree that this is not easy to discern in Fig. 4, although it is evident in the mean seasonal cycle.

Changes in the manuscript: In the text (p.7, line 16), we will refer to a figure of monthly mean transport for each section, to be included in Supplementary Material.

(31) Page 7, Line 17. Is it possible to quote decadal mean figures rather than relying on our 'general impression'

Response: We agree that it is appropriate to quantify this statement.

Changes in the manuscript: We will cite in the text decadal-mean transports for 1988-97 and 1998-2007 (for each section), as suggested.

(32) Page 12, Line 13. Some statistics could be used to determine if this 'impression of generally smaller differences' is correct

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Response: This statement is supported by the anomalies in annual-mean sea level difference shown in Fig. 12b, but we can provide 1988-97 and 1998-2007 averages of sea level difference to quantify the statement.

Changes in the manuscript: Decadal averages will be noted in the text.

(33) Page 13, Line 4. It would be good to know how much smaller - please quote some numbers to back up your statement.

Response: SSH differences during the 1990s typically vary in the seasonal range from 10 cm (summer) to 25 cm (winter); since 2000, summer differences fall as low as 5 cm while winter differences rarely exceed 20 cm; SSH differences are thus smaller by around 5 cm. We will quantify our statement more thoroughly on revision.

Changes in the manuscript: Accordingly, we will elaborate on the extent to which SSH differences have diminished since the 1990s. The extent to which these differences relate to changes in Slope Current transport will be revealed through our further attention to the utility of the SSH proxy (see response to specific comment above).

(34) Page 15, Line 9. Please put a date/timescale on 'recent'. It might not be recent when someone reads this next.

Response: The AMOC decline to which we refer is between the early 1990s and the mid 2000s (Balmaseda et al. 2007; Grist et al. 2009), as mentioned elsewhere in Sect. 4.

Changes in the manuscript: We will clarify the text accordingly.

(35) Page 15, Line 11. It might be better to say that this study provides "an estimate of the fraction" or "quantifies the fraction".

Response: Agreed

Changes in the manuscript: Revised as suggested

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(36) Page 15, Line 13. starting "Existing EEL observations" These final two sentences feel to me oddly tagged on to the end and of little to do with the conclusion of this paper. If needed, they should be presented within the discussion.

Response: Agreed

Changes in the manuscript: In the revised discussion, we will review the need for these statements, and – if necessary – re-locate the text to discussion of transport across the EEL/OSNAP-East section.

References: McKenna, C., Berx, B. & Austin, W.E.N. (2016) The decomposition of the Faroe-Shetland Channel water masses using Parametric Optimum Multi-Parameter analysis. Deep-Sea Research Part I: Oceanographic Research Papers, 107: 9-21. <http://dx.doi.org/10.1016/j.dsr.2015.10.013>

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