THOR Deliverable D23

Deliverable description:	Assessment of uncertainty in THC predictions arising from limited ocean resolution and uncertain physics in current generation climate models				
Associated with milestone (No.)	10. THC sensitivity and ocean-ice-atmosphere feedback studies completed				
WP No.	2.3	Lead Beneficiary:	8. IFM-GEOMAR		
WP Title	Assessing modelling uncertainty: Ocean fresh water distribution				
Work duration[1)]	1-36	Delivery deadline[2)]:	2011-11-30	Delivery date:	2011-11-29

[1)] Work duration = project month
[2)] Delivery deadline: as contracted in Description of Work (Annex 1 to Grant Contract)

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1. Executive Summary

This deliverable gives an overview on key factors causing a spread in model results in respect to uncertainty in future THC predictions. Possible reasons are:

(1) Unresolved mesoscale eddy processes in coupled climate models (resolution dependence of results)

(2) The unknown ocean state (initial state of experiments)

(3) SSS restoring in ocean-only simulations

(4) The effect of natural variability on long term changes (NAO)

(5) Differences of the freshwater distribution under Greenland melting scenarios among different models, and under different atmospheric forcings.

(6) Atmospheric-oceanic feedback mechanisms

(7) Sensitivity of assimilation models on the amount of observations and their representation in the model system

In paragraph 3 we show results for each of these reasons affecting the model results and causing model uncertainty. The goal is to assess this uncertainty for each of these factors. The diagnostics being presented here focus on large scale changes like Meridional Overturning Streamfunction/Index (MOC,MOI respectively) and the spreading of freshwater in the North Atlantic which are important factors and can trigger long-term changes, due to involved feedback mechanisms.

The results show that increasing the resolution improves the representation of the eddy field in the North Atlantic and shows a better agreement with observations.

We find that unresolved eddies have an affect on the freshwater distribution (at least off Greenland) and that eddy parameterisations are not fully able to simulate this effect. Considering the Arctic fresh water outflow to the North Atlantic, its fate was shown to be highly dependent on the atmospheric forcing in relation to the NAO. Idealized NAO forced experiments indeed indicate that the wind stress has a small impact on the MOC through modification of the Arctic fresh water export which only damps the dominant response of the MOC to the heat flux. The initial strength of the MOC in Greenland melting scenarios shows only little effect on the results, relative changes are very similar between sensitivity runs. A large effect on the MOC results from details in the restoring setting needed for ocean-only simulations (also shown in D15), which controls the northward salt transport into the Nordic Seas. We found in the multi-model comparison under a fixed Greenland melting scenario a large set of robust results among all models and a mechanism controlling how this freshwater can affect the MOC. It seems that the exchange between subpolar and subtropical gyre is a key factor restricting the propagation of the signal to the south. Assimilation experiments have shown that the resolution of the ocean component is important and it has to be sufficient high to assimilate the additional observations (ARGO) with an improvement of the model. Further analyses are ongoing, and further sensitivity experiments are required to confirm the results.

2. Main objectives, description of work and role of participants (Annex I: DoW)

Objectives

-To assess the uncertainty in THC predictions arising from limitations in the ocean component of current-generation climate models (especially resolution)

-To determine the pathways and mechanisms by which fresh water and climate anomalies in the Nordic and Labrador Seas influence the dense overflows and the THC

-To determine the importance of atmospheric feedbacks in the decadal response of the ocean to fresh water anomalies

Description of work and role of participants

Processes linking climate and fresh water variability in the Nordic and Labrador Seas (including variability of the Atlantic inflow) to the overflows and THC will be analysed in the ocean simulations of 1965-2005 [IfM-GEOMAR, UPMC-LOCEAN, NERSC, DMI] and in idealised forcing simulations [UPMC-LOCEAN]. Sensitivity to model resolution, forcing and formulation will be established.

Ocean models of various resolutions [IfM-GEOMAR, NERSC], and coupled climate models [MPG-M, MetO, NERSC, DMI], will be rerun from 1965-2005, with an additional idealised, but plausible, fresh water input (defined in WP 2.2). These integrations will allow us to assess the importance of ocean model resolution and physics, and of atmospheric feedbacks, in determining the distribution of fresh water input and its impact on the THC. Note this is a *process study*, not a simulation.

A second batch of experiments will be designed and run, using more detailed patterns of fresh water input derived from results of WP 2.2, and possibly different start dates (with stronger/weaker THC state).

Deliverables

-D15 Assessment of processes linking climate variability in the Nordic and Labrador Seas with the overflows and THC, and its dependence on model resolution and physics (this has been delivered in month 24).

-D23 Assessment of uncertainty in THC predictions arising from limited ocean resolution and uncertain physics in current generation climate models. (Month 36, this is the current deliverable due)

-D35 (Joint with WP2.2) Recommendation of model development priorities to improve THC forecasts in future (this is planned for month 48).

3. Report on Deliverable D23

Many actual studies with coupled atmosphere-ocean and ocean-only models tried to answer how the ocean circulation and hydrography will change under a warmer climate. One important influencing factor is the observed accelerated melting of the global ice-sheets [Rignot et al. 2011]. This leads to an enhanced freshwater release into the ocean, with important consequences, e.g. by reducing the winterly formation of dense water masses in the northern North Atlantic and its large-scale impact on the slow down of the Atlantic Meridional Overturning Circulation (AMOC) [Hu et al. 2009].

However the results of such model simulations do not show consistent results, due to different reasons which we try to asses with this study. Possible reasons for the large spread of results could be caveats in the representation of the ocean, for example the location of deep convection in the high latitudes, unresolved mesoscale eddies, the unknown real initial state of the ocean (high/low NAO and AMOC) and also a model dependency of the results. In the following the contributors in WP2.3 tried to asses the uncertainty for the possible reasons leading to differences between models and their results. Therefore we set up a large set of (idealized) sensitivity experiments and produced in a multi-model comparison.

3.1 Resolution refinement and resolving mesoscale eddies in the high latitudes (IFM-GEOMAR)

The present coupled climate models typically have grid scales of ~100km which (in theory) would only be sufficient to resolve mesoscale eddies in a narrow latitudinal band near the equator, where the Rossby radius of deformation (thick black curve) is of similar range (see Figure 1). Further north the radius decreases rapidly and none of the coupled models and most of the ocean only models are capable of representing mesoscale eddies explicitly. Parameterizations (such as the GM parameterization, Gent and McWilliams, 1990) were used instead to parameterize the effect of eddies.

To understand the eddy effect we used a set of consistent ocean-only simulations which differ only in there horizontal resolution to explore the impact of mesoscale eddies and simulated nonlinearities on the spreading of freshwater from Greenland melting experiments.

Individual members of the model hierarchy are:

(1) The global model ORCA05 (blue line) at coarse resolution and with GM (Gent and McWilliams, 1990) eddy parameterization, the global

(2) ORCA025(light blue line) that resolves eddies in the subtropics and is performed without an eddy parameterization, and the regional version

(3) VIKING20 (orange line), which is a 1/20° refinement in the North Atlantic nested in ORCA025. This version is able to resolve eddies even in the subpolar North Atlantic, thereby allowing evaluating the impact of mesoscale eddies in the seas around Greenland.

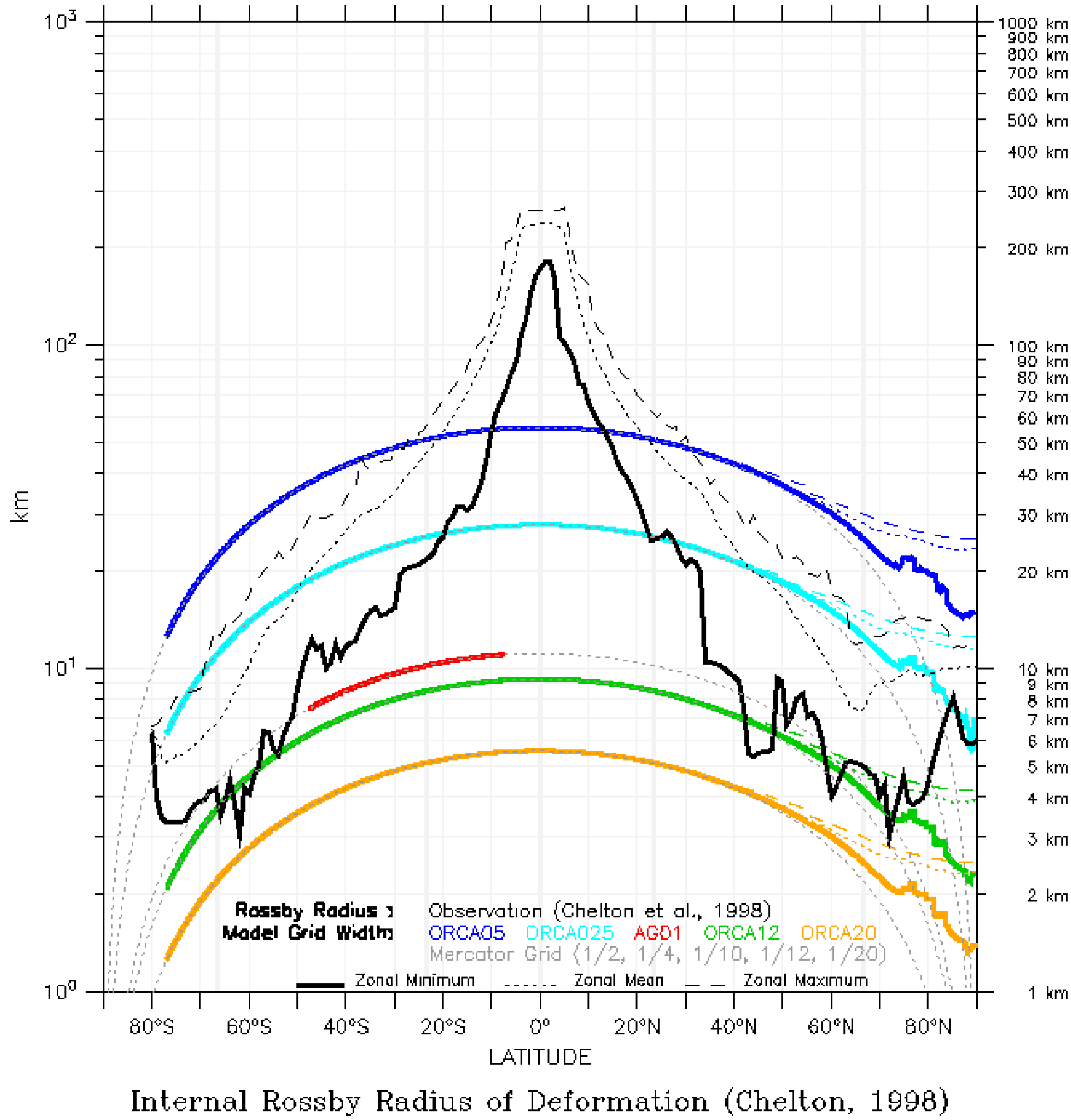

Figure 1: Internal Rossby radius of deformation proposed by Chelton (1998)(thick black curve), and horizontal grid resolution in various model configuration performed by the IFM-GEOMAR modeling group (figure provided by M. Scheintert).

The effect of the increasing resolution and model improvement can easily been seen in the representation of eddies, tracked by the sea surface height (SSH) variance in comparison with a satellite product (AVISO) (Figure 2). ORCA05 (Fig. 2a) shows a significantly underrepresentation of SSH variance, therefore eddy kinetic energy in comparison to observations (Fig. 2d). ORCA025 (b) shows the magnitude of SSH variance similar to the observations in the NAC region, but deficits in the exact representation of the path of the flow such as the Northwest-Corner. The black box indicates the region where the grid refinement to 1/20° takes places in the VIKING20 configuration. VIKING20 (Fig. 2c) compares very well with the observed variance, clearly showing the swing of the North Atlantic Current into the Northwest Corner, an actual hot topic even in high-resolution ocean modeling. The high variance in the Canary branch are also present, contributing to an overall good agreement of the flow paths.

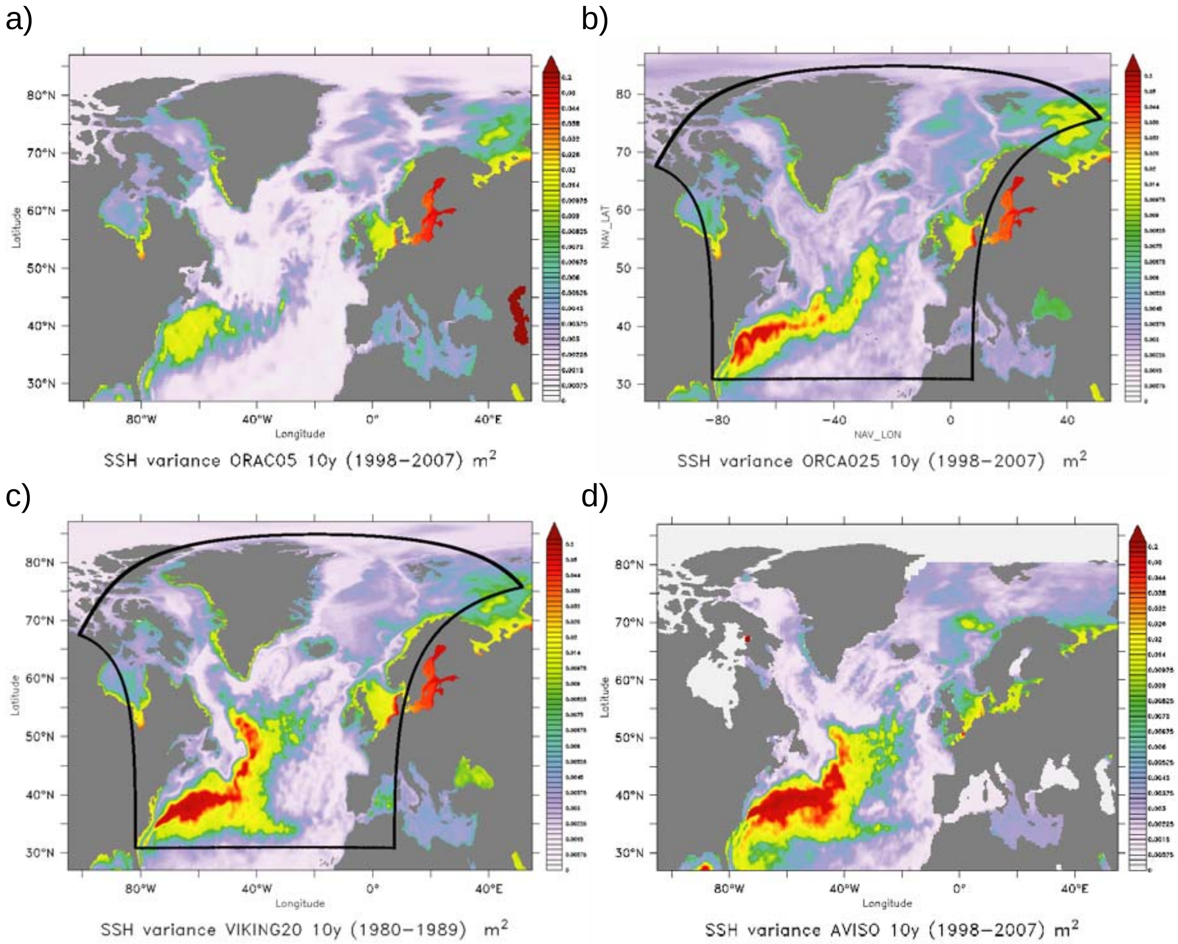

Figure 2: SSH variability computed over 10 years from 5- daily data for 3 model configurations and observations, ORCA05 (a, coarse), ORCA025 (b, eddy-permitting, box indicate location of high resolution in VIKING20), VIKING20 (c, eddy-resolving, box indicate location of high resolution), AVISO (d)

3.2 Impact of mesoscale eddies in Greenland melting scenarios (IFM-GEOMAR)

With the above described model set we performed identical Greenland melting experiments according to the WP2 -THOR protocol. We added a passive tracer representing the runoff to track the pathways of the released fresh water. The results of the vertical integral of this passive tracer are shown in Figure 3.

The general pattern of the additional freshwater (represented by the tracer content) is qualitatively similar in all experiments: We find an accumulation of freshwater in the Baffin Bay, then a release into the subpolar North Atlantic and merging with the western boundary currents around the Labrador Sea. Differences are seen in the timescales and pathways of the spreading into the subpolar North Atlantic, in particular the communication between the boundary currents and the interior of the Labrador Sea. The exact analysis of the communication is underway within THOR, a specific understanding is crucial due to the importance of the region in the formation of dense water masses and a potential capping of the convection by the additional freshwater from the Greenland melting.

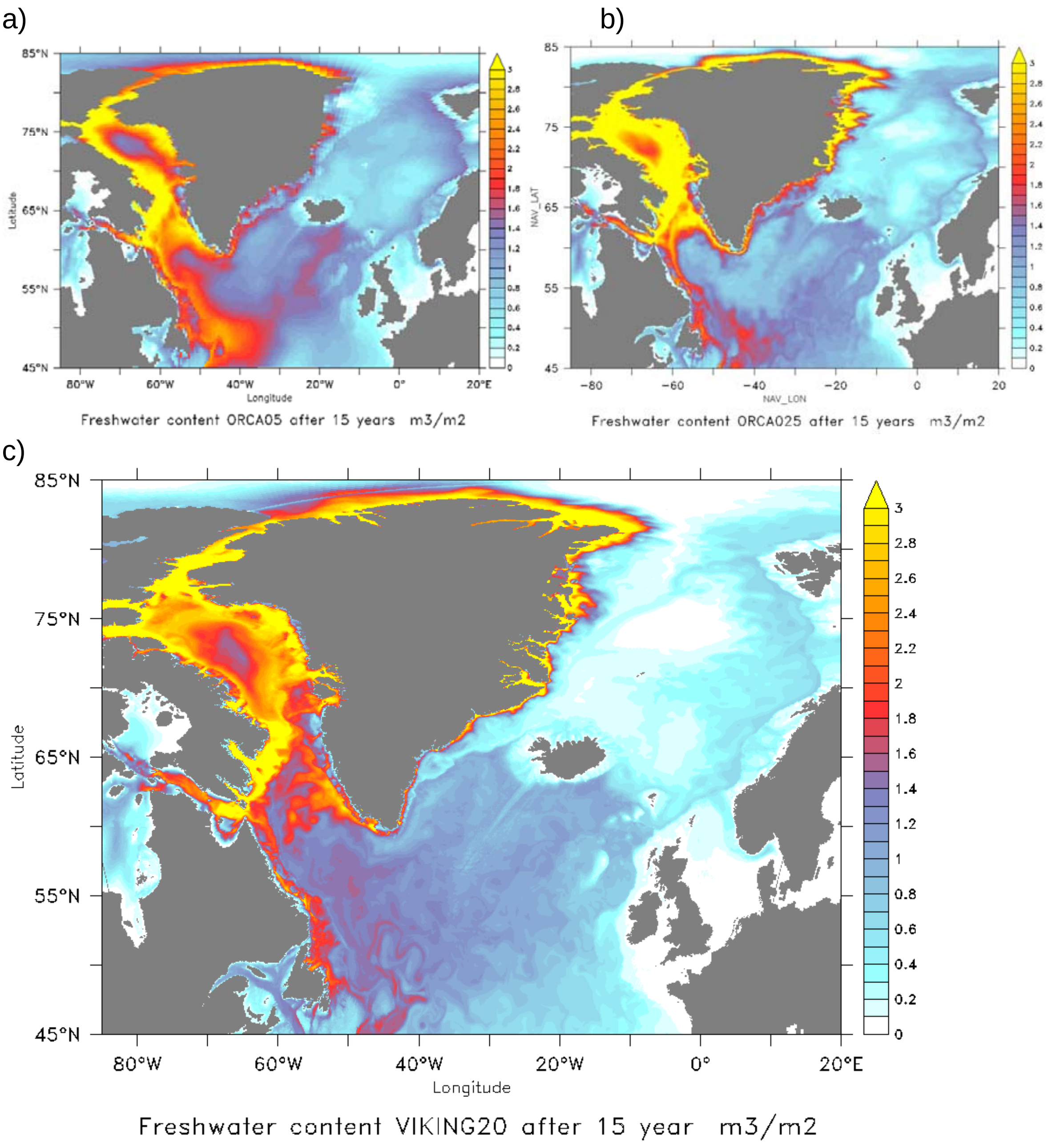

Figure 3: Vertical integral of passive tracer in Greenland melting simulations after 15 years. Tracer is released with an additional runoff around Greenland a) ORCA05 b) ORCA025 c) VIKING20

3.3 Uncertainty in initial ocean state and effect of additional freshwater (IFM-GEOMAR)

Beside the resolution dependence, uncertainty exists about the initial ocean state and the effect of a melting of Greenland. Therefore we repeated identical melting scenarios with different ocean initial states. These cases differ between a strong and weaker AMOC/THC than observed (see Figure 4.a). The AMOC varies at the beginning of the hosing in 1965 (vertical pink line) between 16 and 10 Sv. The reference experiments (solid) show multidecadal variability with large values around 1990, years where strong winterly convection occurred related to a high NAO phase.

All melting scenarios show a decline in AMOC from the initial state with some weaker variability, caused by a reduced convection in Labrador Sea, an important factor causing variability on short timescales.

However, the relative change/decline (Figure 4.b) to the reference case between all experiments is very small, maximal after 20 years and varies between 10% and 20% decline compared to reference experiment. In ORCA05 it seems that simulations with stronger AMOC are more sensitive to changes and react more strongly to freshwater perturbations. However, all experiments show a decline of the AMOC around 50% after 40 year of such additional freshwater forcing, while the decline is less steep compared to the beginning of the hosing, which might indicate a new equilibrium state for the ocean under such a freshwater forcing.

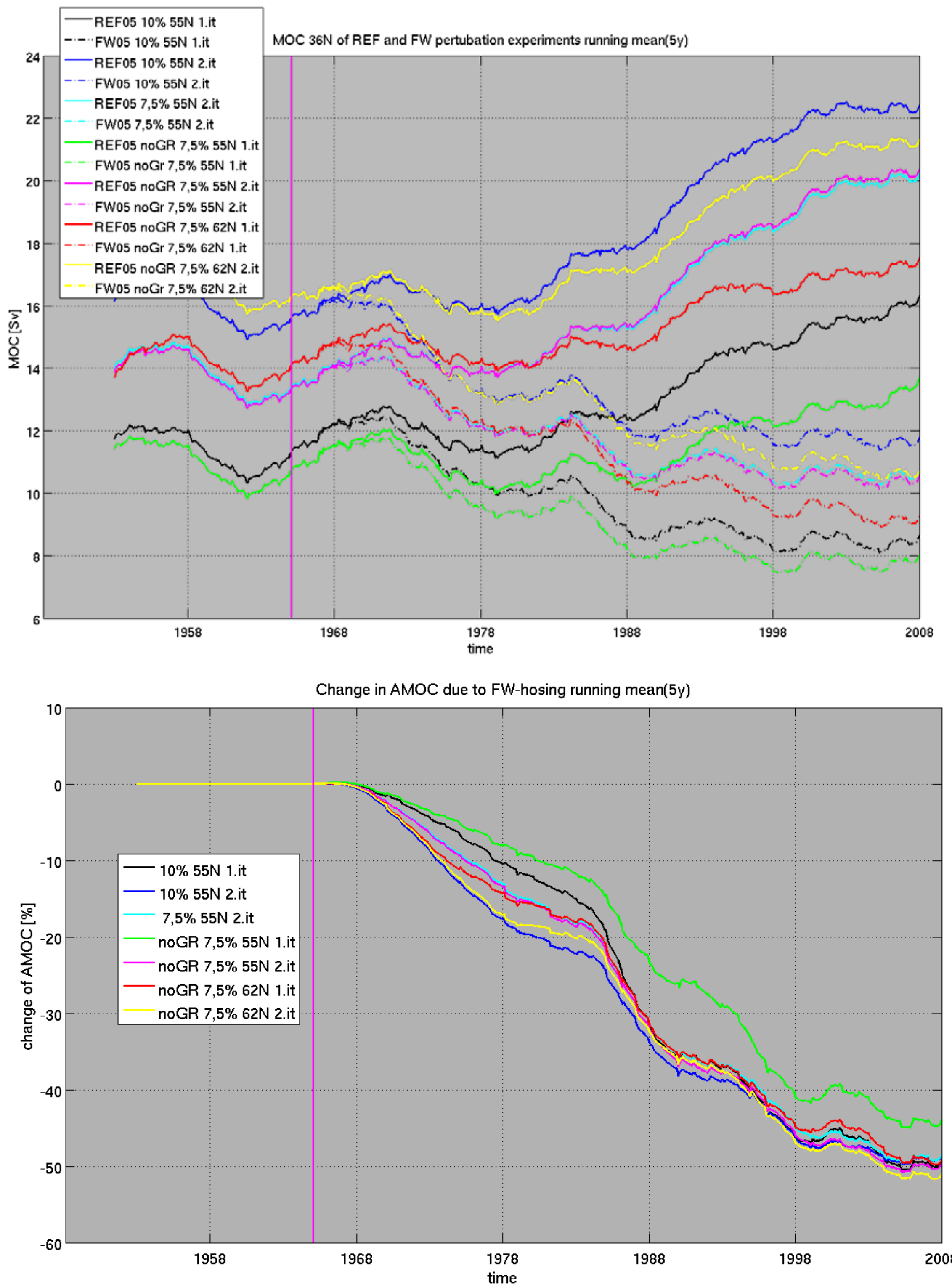

Figure 4: Impact of the initial state on the reaction to a Melting of Greenland. a) AMOC (36°N) timeseries of reference run (solid) differing in initial states (due to different surface boundary conditions and or different iterations) and corresponding hosing experiments (dashed); b) percentage change of AMOC reaction compared to reference run.

3.4 Impact of surface boundary and flux on the AMOC (IFM-GEOMAR)

As already mentioned in D15 the ocean simulations and there ocean state are very sensitive to chances in the surface boundary condition and fluxes, for example the SSS restoring that is typically required in global ocean-only simulations (see Figure 5, Behrens et al. in prep) and freshwater and heat fluxes in the high latitudes. These settings have an important effect on the salt transport into the Nordic Seas, leading to a remote control for the formation of dense water masses in high latitudes with implication for the AMOC (see D15).

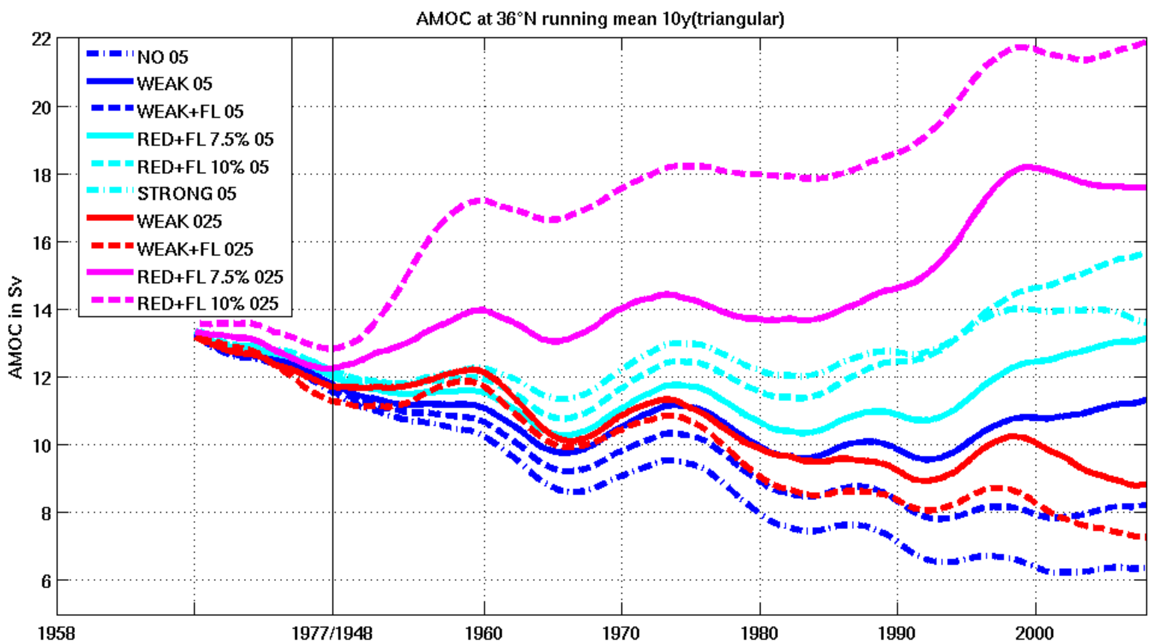

Figure 5: AMOC timeseries at 36°N in simulation differing in the formulation of the SSS restoring (Behrens et al. 2011 in prep).

3.5 Response of the AMOC to the Arctic fresh water outflow (UPMC-LOCEAN)

In order to understand how the distribution of the Arctic fresh water released through the different passages to the North Atlantic (Fram Strait and the Canadian Arctic Archipelago) impacts the MOC, a hindcast simulation with the regional Arctic-Atlantic ORCA05 model (ARCNA05) forced by the ERA40 reanalysis (1958-2001) has been analysed. Atmospheric sea level pressure anomalies, which are best correlated with these fresh water outflows, have been derived through regression analysis. The anomaly pattern linked to the CAA resemble much the NAO (Figure 6) with in-phase correlations of the NAO index reaching up to 0.55 with the fresh water transport through Nares Strait and up to 0.48 with the sea ice export through Fram Strait (Houssais et Herbaut, 2011).

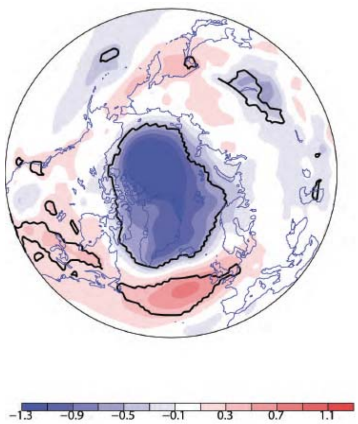

Figure 6: Simultaneous regression of the mean winter SLP (hPa) on the annual transport through the CAA (regression shown for enhanced export from the Arctic)

Based on the above results, NAO-like wind stress and air sea heat and fresh water flux anomalies have been applied to the same regional model in idealized simulations in which these anomalies are kept constant for 10 years. The delayed MOC response to the NAO depends on the predominance of the wind driven response over the buoyancy driven response. When, wind stress together with surface heat and fresh water anomalies are applied in a positive NAO phase, convection in the Labrador Sea is enhanced after 4-6 years, under the effect of atmospheric cooling, leading to a reinforcement of the MOC (Figure 7, right). By contrast, the actual effect of the wind stress, retrieved from a simulation in which only wind anomalies are applied, is to generate a rapid (after 1 year) slowing-down of the MOC in response to enhanced wind-driven export of Arctic fresh water through Fram Strait and its delivery to the Labrador Sea (Figure 7, left), thus acting to damp the response of the MOC to the heat flux. This analysis stresses the importance of understanding the nature of the MOC response to the atmosphere in order to be able to predict its behaviour.

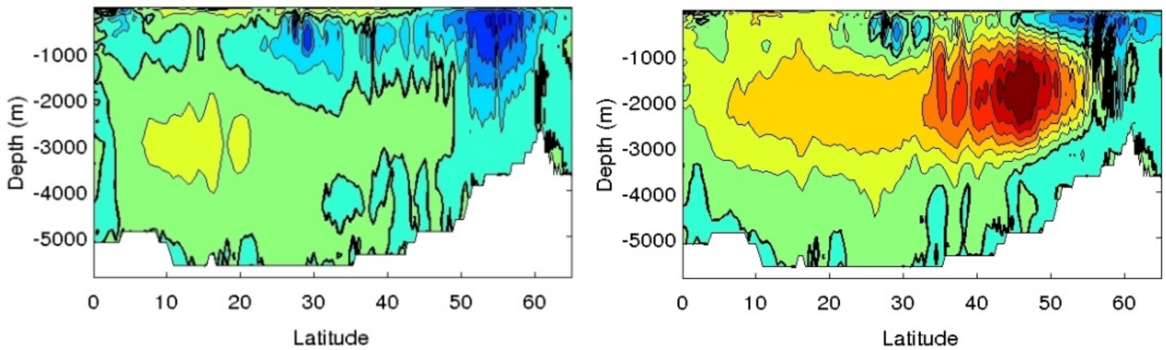

Figure 7: Atlantic MOC anomalies in idealized experiments forced by NAO-like atmospheric forcing anomalies. Anomalies are averaged over 3 years and shown at lag 1-3 years for experiment forced by NAO wind stress only (left) and at lag 4-6 years for experiment by NAO wind stress and air-sea heat and fresh water fluxes (right).

3.6 Fresh water hosing in a multi-models framework (UPMC-LOCEAN, MPI, IFM-GEOMAR, DMI, NERSC, MET-O)

Former model projections show a very different sensitivity to the Greenland ice sheet melting, it seems therefore necessary to use a multi-models ensemble to evaluate the impact of such a melting. For this purpose we use six models: one of them is the ocean-only model ORCA05 described earlier and the others are state-of-the art AOGCMs (Table 1). Such a multi-model framework allows to decipher the oceanic responses from the coupling and to evaluate the pertinence of hosing in ocean-only models. In order to properly include the ocean-only model, we use an idealized framework where we release 0.1 Sv around Greenland for the historical era 1965-2004. The AOGCMs are using observed external forcings in their control simulation and additional fresh water input in the hosing simulations.

Model	Type	Ocean	Atmosphere
HadCM3	AOGCM	NoName 1.25°– L20	HadAM3 2.5° x 3.75° – L19
IPSLCM5-LR	AOGCM	NEMO_v3 2° – L31	LMD5 1.8° x 3.75° – L39
COSMOS	ESM	MPI-OM 1.5° – L40	ECHAM6 T63 – L47

EcEarth	AOGCM	NEMO_v3 1° – L42	IFS T159 – L67
BCM2	AOGCM	MICOM 2.8° – L35	ARPEGE T63 – L31
ORCA05-Kiel	OGCM	NEMO_v3 0.5° – L46	X

Table 1: Different models used in the multi-model hosing intercomparison

We found similar fingerprints after 4 decades of hosing in the different models and a general weakening of Atlantic Meridional Overturning Circulation (MOC) and of the gyres. The fresh water spreads along the main currents. A large part of the negative salinity anomalies can be found along the Canary Current after 4 decades, which we call the “fresh water leakage” (Fig. 8). This leakage is actually an escape path for the fresh water anomalies from the North Atlantic. As a consequence, we show that the AMOC weakening is smaller when the leakage is large. Another important fingerprint concerns a warming in the Nordic Seas in response to the emergence in these Seas of Atlantic subsurface waters capped by the fresh water in the subpolar gyre. This subsurface water even reaches the Arctic, where their emergence produces a positive salinity anomaly there (Fig. 8).

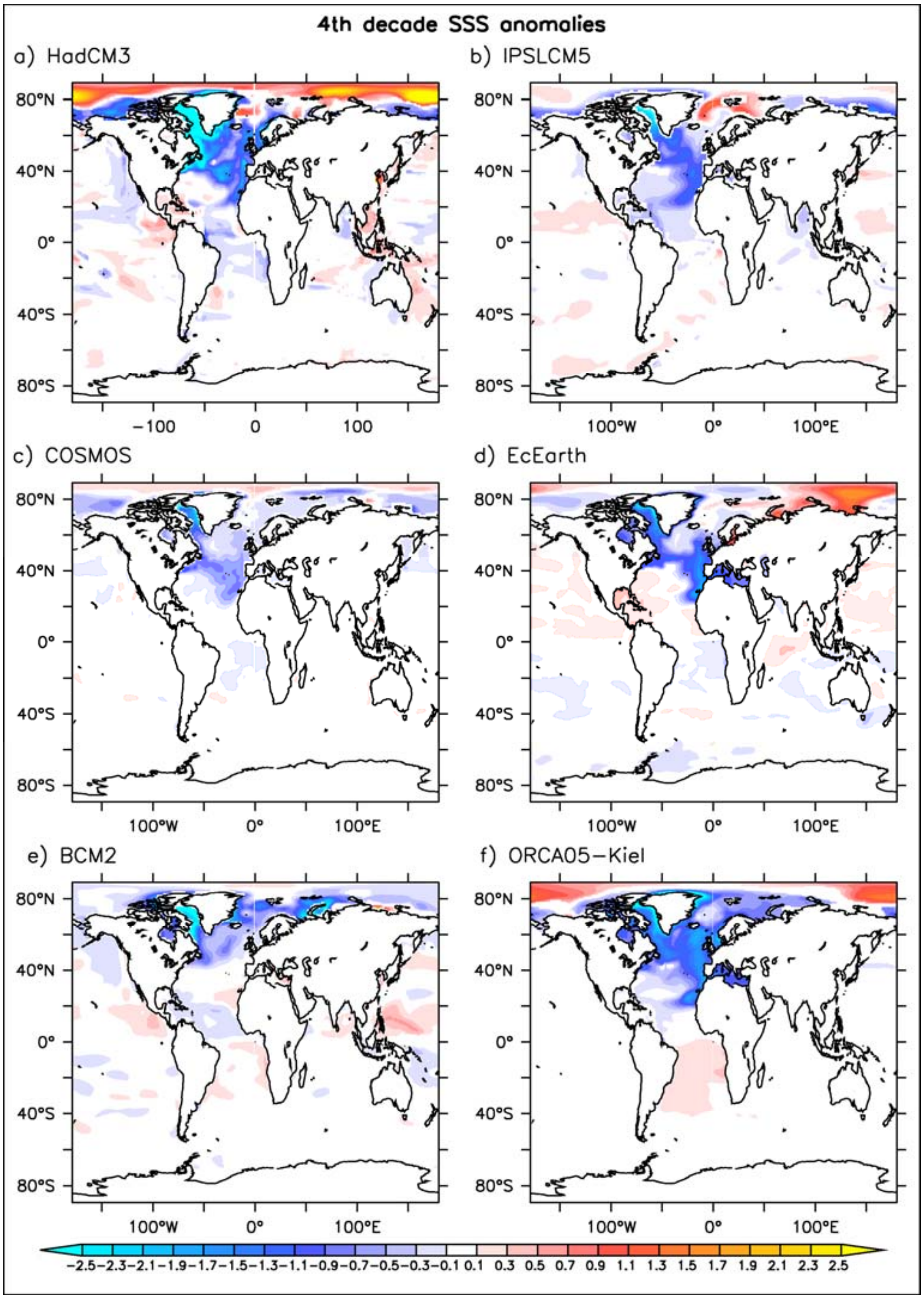

Figure 8: Sea Surface Salinity difference (SSS) between hosing and control experiments averaged over the 4th decade for the different models. Only the 95% significant anomalies following a student t-test are shown. a) HadCM3, b) IPSLCM5, c) COSMOS, d) EcEarth, e) BCM2 f) ORCA05-Kiel. The color interval is 0.2 PSU.

We found similar climatic impact in the ocean-atmosphere models with a cooling of the North Atlantic except in the region around the Nordic Seas and a slight warming south of the equator in the Atlantic. This is associated with a southward shift of the tropical rainbelt. The free surface models also show similar sea-level fingerprint notably with a comma-shape pattern of high sea-level rise following the Canary Current (not shown). Finally we argue that the magnitude of the fresh water leakage is related with the shape of the subpolar-subtropical gyres limit in the control simulations, which may ultimately be a primary cause for the AMOC spread in this hosing multi-models ensemble (Fig. 9). When compared with observation-based estimates (Rypina et al. 2011) of this asymmetry, we find a better agreement with ORCA05 or EcEarth. This result indicates that the impact of freshwater input due to Greenland ice sheet melting may be larger than previously thought in lower resolution ocean model (Swingedouw et al. 2006, Jungclaus et al. 2006), where the gyre asymmetry was not well represented.

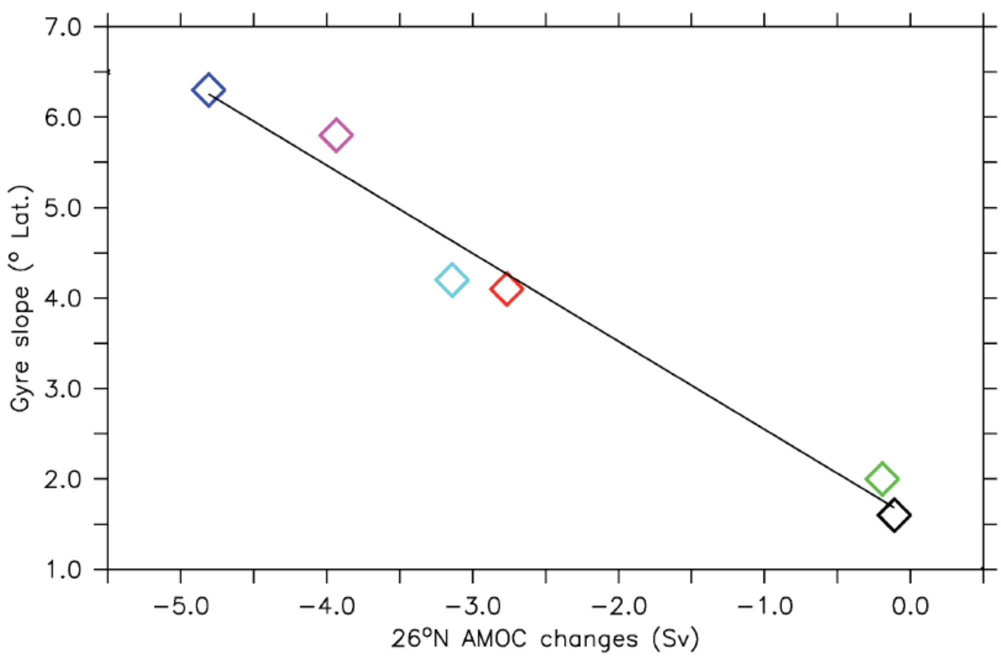

Fig. 9: AMOC changes at 26°N for the 4th decade versus the slope of the gyres in control simulations computed using a linear regression of the zero line between 50W-20W and 40°N-50°N expressed in °Lat for 30° of longitude. In blue is ORCA05 in green is COSMOS, in red is IPSL-CM5, in light blue is EcEarth, in magenta is BCM2 and in black is HadCM3.

3.7 Assimilation progress and the effect of ARGO, ocean resolution and atmospheric feedbacks on the AMOC (MET-Office)

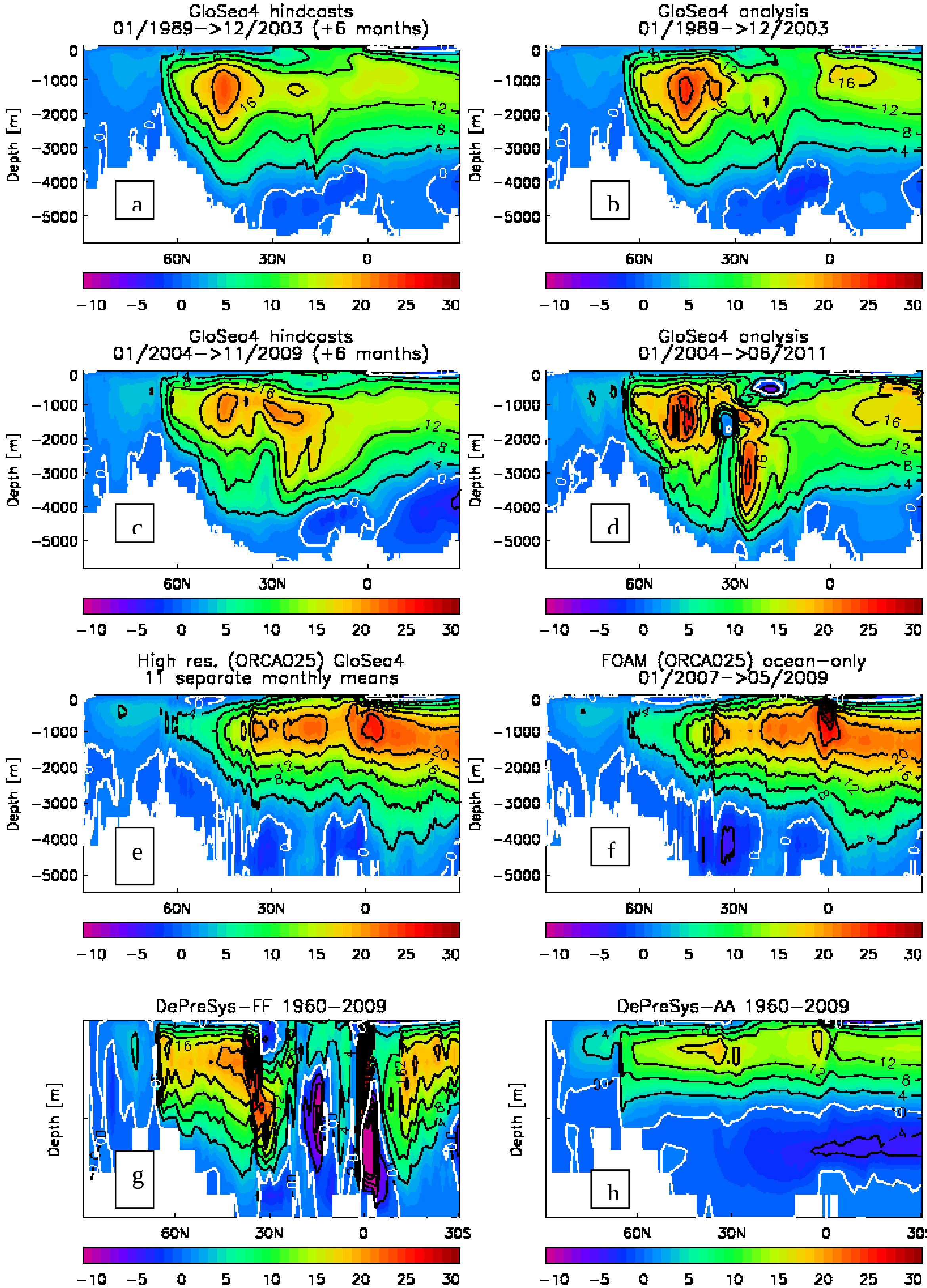

Figure 10: AMOC in hincast and (re)analysis products in assimilation models: (a) GloSea4 system (assimilates T+S) coupled atmosphere/ocean system in hindcast mode, atmospheric resolution of N96L85 + ORCA01, pre ARGO period; (b) GloSea4 system (assimilates T+S) ocean-only system (hindcast) in analysis mode, ORCA01, pre ARGO period; (c) same as (a) but for post ARGO period; (d) same as (b) but for post ARGO period; (e) same as (a) but with ORCA025 instead ORCA01; (f) the FOAM ocean-only system ORCA025; (g) DePreSys full-field assimilated in HadCM3 ocean model (1.25 degree, 20 levels); (h) DePreSys anomaly assimilated in HadCM3 ocean model (1.25 degree, 20 levels)

The Figures 10 a-d indicate which impacts more observations (ARGO) have on the assimilation system and how they affect the MOI (Meridional Overturning Index) in the end. Therefore results are being compared between pre and post ARGO data in a coupled (a,c) and ocean-only (b,d) set up.

The MOI in GloSea4 shows a mean of around 20Sv prior to 2004. However, once additional ARGO data is assimilated the AMOC strengthens significantly to around 30Sv. This is in contrast to direct observations (RAPID) which suggest the AMOC to have mean of 18Sv over the last 5 years. This disparity appears to be due to the assimilation system in GloSea4, which attempts to introduce a tight thermocline into the model. Due to limited resolution the model is unable to cope with these temperature gradients and the Gent and McWilliams (1990, GM) scheme quickly removes them, returning the model to a state with a more diffuse thermocline. The 'bolus' velocities associated with the GM parameterisation are of a similar magnitude to the non-eddy velocities in the model, resulting in a spurious overturning streamfunction and measurements of the Fov (Freshwater overturning). The addition of a tight thermocline and the subsequent attempt by the model to remove it continues throughout the analysis post 2004. Hindcasts initialised from throughout this time reveal the model succeeding in quickly drifting to a state with a more diffuse thermocline in a matter of months.

In the FOAM ocean-only analysis sea surface height (SSH) is assimilated as well as T and S. Assimilating SSH results in a stronger MOI, suggesting that it is not simply a lack of dynamic-like measurements that result in a poor analysis of the MOC state in GloSea4. The MOI in FOAM compares favourably to that reported from direct observations. The model captures both the seasonal cycle and, especially from 2008 onwards, the absolute magnitude well. The AMOC reveals a strong NADW cell but a much smaller and meridionally incoherent AABW cell. There is large variability at the equator due to tropical instability waves, with a period of the order 10 days and a range of ~100Sv. Removing SSH data results in a weaker MOI throughout the year by around 1Sv, but does not appear to affect the structure of the resultant streamfunction. This would suggest that the improved representation of the overturning streamfunction in FOAM is not merely due to the assimilation of a more dynamic variable (SSH).

In a coupled hindcast model (High res. GloSea4, Figure 8e), initialised from the FOAM analysis and the GloSea4 atmosphere analysis, the MOI and overturning streamfunction appear similar to the FOAM analysis. However, the coupling appears to have significantly weakened the strong equatorial overturning cell associated with tropical instability waves. Another difference is the much reduced MOI at Feb 2008 compared to either FOAM or RAPID.

References

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Hu, A., G. A. Meehl, W. Han, and J. Yin (2009), Transient response of the MOC and climate to potential melting of the Greenland Ice Sheet in the 21st century, *Geophys. Res. Lett.*, 36, L10707, doi:10.1029/2009GL037998.

Jungclaus, J. H., H. Haak, M. Esch, E. Roeckner, and J. Marotzke (2006), Will Greenland melting halt the thermohaline circulation?, Geophys. Res. Lett., 33, L17708, doi:10.1029/2006GL026815.

Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. Lenaerts (2011), Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophys. Res. Lett.*, 38, L05503, doi:10.1029/2011GL046583.

Rypina II, Pratt LJ, Lozier MS. 2011. Near-surface transport pathways in the North Atlantic ocean. *J. Phys. Oceanogr.* 41:911–25.

Swingedouw, D., P. Braconnot, and O. Marti (2006), Sensitivity of the Atlantic Meridional Overturning Circulation to the melting from northern glaciers in climate change experiments, Geophys. Res. Lett., 33, L07711, doi:10.1029/2006GL025765.

4. List of Publications (cumulative, add the new publications)

Peer reviewed articles:

Houssais, M.-N. and C. Herbaut, (2011) : Atmospheric forcing on the Canadian Arctic Archipelago fresh water outflow and implications for the Labrador Sea variability. J. Geophys. Res., 116, doi:10.1029/2010JC006323.

Plan for future publication:

Behrens et al. (2012): a manuscript in prep. (on surface boundary condition)

Bamber et al. (2011): manuscript in prep. (on realistic Greenland runoff)

Behrens et al. (2012): a manuscript in prep. (on Greenland melting results+eddy impact in the North Atlantic)

Herbaut, C., Houssais M.-N. and D. Iovino, (2011): Seasonal features of the interannual variability of the Beaufort Gyre as revealed by a hindcast experiment forced by the ERA40 reanalysis, in prep..

Iovino, D., C; Herbaut and M.-N. Houssais, (2011): Sensitivity of the exchanges over the Greenland Scotland Ridge to model resolution in the Nordic Seas – Overflows region, in prep.

5. The project/delivery is delayed: ☐ Yes ☒ No

6. Changes made and difficulties encountered, if any

None.

7. Efforts for the deliverable D23

Institute	Person-Months	Period
8. IFM-GEOMAR	30	12.2008 – 11.2011
2. MPG-M	9	12.2008 – 11.2011
3. Met O	4	12.2008 – 11.2011
4. UPMC-LOCEAN	15	12.2008 – 11.2011
10. DMI	8	12.2008 – 11.2011
19. NERSC	5	12.2008 – 11.2011

Total estimated effort for this deliverable was 40 person-months, actual amount 71 including in-kind person-month.

8. Sustainability

These dedicated/idealized analyses provide an important part for the required model improvement and model development to reduce the uncertainty in climate predictions.