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Develop recommendations on the CORE-II protocol to be included on the CORE-II website and as part of the CORE V2 forcing release notes (H. Drange, G. Danabasoglu, S. Griffies).

Recommend that CORE-II participants follow the CMIP5 Griffies *et al.* (2009a) guidelines on saving ocean model fields.

Reach agreement on which density bins to use to calculate density overturning online (G. Madec).

Make a recommendation on how to treat marginal seas by restoring.

Distribute newly extended IAF and corrected NYF Large and Yeager (2008) surface forcing datasets on the GFDL and CLIVAR websites (G. Danabasoglu to A. Pirani, S. Griffies) and raise awareness of CORE forcing mailing list (A.Pirani).

Improve the user-friendliness of the run-off dataset distributed as part of the CORE Large and Yeager (2008) forcing fields (A. M. Treguier and G. Danabasoglu).

Ensure that for CORE-II all are restoring to the PHC3 SSS field (G. Danabasoglu).

Compare CORE IAF with DRAKKAR surface forcing product (G. Madec, A. M. Treguier).

Provide guidance and links on how to implement CFC forcing as part of CORE Large and Yeager (2008) surface forcing fields and supply a protocol for using CFC11, CFC12 and ideal age (G. Danabasoglu).

Explore the possibility of forcing ocean models with the Compo *et al.* (2009) 20th Century Reanalysis Project (H. Drange, R. Gerdes).

Develop a way forward to explore partial coupling of ocean-ice models (R. Gerdes, H. Drange, G. Madec).

Solicit recommendations from CliC on how to evaluate sea ice models (M. Holland)

Strengthen ties between CORE and AOMIP, with a member of WGOMD attending the next AOMIP meeting.

Liaise with VOCALS, SPICE and other observational programs with regards to participating in CORE-II.

WGOMD recommends the development of a multi-model statement explaining the variability of the sub-polar North Atlantic during the second half of the 20th Century (C. Böning, H. Drange, G. Danabasoglu and others).

Provide the community with recommendations and guidelines on running CORE-II simulations and accessing CORE-II data by means of the WGOMD CORE website (All, A. Pirani).

1. Introduction

The eighth WGOMD panel meeting was held on 30April-01May 2009 at the UK Met Office in Exeter, UK, hosted by Helene Banks and Malcolm Roberts. The meeting agenda is in Appendix A and the list of participants is in Appendix B. The presentations given by the meeting participants, together with some pre-meeting reports, are available on the meeting webpage (http://www.clivar.org/organization/wgomd/wgomd8/wgomd_exeter.php). The meeting focused on the main topics being addressed by WGOMD with presentations and discussions on the Co-ordinated Ocean-ice Reference Experiments (CORE), the Repository for Evaluating Ocean Simulations (REOS) and WGOMD's role in helping the research needs of decadal climate variability and prediction. The participants also gave some short presentations on ocean modelling activities and developments in their institutes and countries. Written summaries are available at the end of this report in Appendix D.

The WGOMD leadership has undergone some changes this year with H. Drange joining S. Griffies as co-Chair. S. Griffies will be standing down at the end of 2009, to be replaced by G. Danabasoglu. WGOMD, was very pleased to welcome back H. Banks after a period of absence. M. England was unable to attend but we were fortunate that S. Marsland was able to take his place. M. England has since stepped down from WGOMD and S. Marsland has taken his place. WGOMD was very happy to invite M. Roberts and D. Smith of the UK Met Office and M. Balmaseda of ECMWF to join the panel meeting.

The panel meeting followed the WGOMD Workshop on Ocean Mesoscale Eddies: Representations, Parameterizations, and Observations. Since 2004, each WGOMD panel meeting has been associated with a science-based workshop aimed at stimulating discourse and understanding on a particular aspect of oceanography. The mesoscale workshop is the fourth organized by WGOMD. A short summary (Griffies, 2009) is given in Appendix C and the presentations and posters are available on the workshop webpage (http://www.clivar.org/organization/wgomd/meso/meso.php). An Ocean Modelling special issue on Ocean Mesoscale Eddies: Representations, Parameterizations, and Observations is planned for 2010 as the main deliverable of the workshop.

The workshop had the following main goals:

- To educate the research community regarding the importance of mesoscale eddies in the World Ocean, and correspondingly for establishing features of the ocean climate system:
- To identify best practices for parameterising ocean mesoscale eddies in coarse-resolution climate models, and to discuss various research avenues for improved parameterisations;
- To evaluate the ability of state-of-the-science numerical models to accurately represent the ocean mesoscale in eddying simulations.

The three-day workshop consisted of roughly six invited speakers per day. Each speaker presented views on the state-of-the-science in ocean mesoscale eddies as seen through observations, models, and theory. Participants of the workshop were invited to contribute posters. WGOMD was awarded a joint 15K USD funding award to support the travel costs of young researchers from NASA, NOAA and NSF that was allocated to 13 successful applicants.

1.1 Summary of WGOMD 2008-2009 Activities

WGOMD is in the process of developing the experimental protocol for the CORE-II Experiment (described in Section 2). CORE-II focuses on interannually varying forcing based on the new Large and Yeager (2008) merged reanalysis and observational product and will provide a common framework for running ocean-ice models for hindcast purposes. Notably, CORE-II efforts will feed directly into CLIVAR basin panel activities aiming to use ocean models to identify mechanistic descriptions of observed variability and change.

Significant progress has been made on the development of the Repository for Evaluating Ocean Simulations (REOS), a website that has recently gone live as part of the WGOMD website: www.clivar.org/organization/wgomd/reos/reos.php. The motivation for this website stems from the growing needs of the modelling community to provide benchmarks, thorough evaluations of their simulations, and to make use of observational datasets that have been generated during the past decade. WGOMD is interacting with the CLIVAR basin panels for input on metrics to basin processes, as well soliciting recommendations and input from the wider ocean observational, data assimilation and modelling community.

A central focus for WGOMD is its contribution to the World Climate Research Programme (WCRP) decadal prediction cross-cutting topic. Together with the CLIVAR Global Synthesis and Observations Panel (GSOP), WGOMD will provide essential input into the decadal prediction initialization problem. WGOMD members are authors on the OceanObs'09 (Venice, Italy, 21-25 September 2009) White Papers by Hurrell *et al.* (2009) on 'Decadal Climate Prediction: Opportunities and Challenges' and Latif *et al*. (2009) on 'Dynamics of Decadal Climate Variability and Implications for its Prediction'. WGOMD also contributed to the OceanObs'09 White Paper 'Problems and Prospects in Large-Scale Ocean Circulation Models' (Griffies *et al.*, 2009c) on the expectations for developments in ocean models over the next ten years or so. WGOMD members are participating in the CLIVAR workshop on 'Earth-System Initialization for Decadal Predictions' to be held in the Fall 2009.

WGOMD continues to support the WCRP/CLIVAR Working Group on Coupled Modeling (WGCM) in its objectives to develop coupled climate models and model intercomparisons, notably providing recommendations on 'Sampling Physical Ocean Fields in WCRP Coupled Model Intercomparison Project (CMIP5) Simulations' (Griffies *et al.*, 2009a). This document serves the following purposes:

- To rationalize a list of physical ocean model fields to be archived for CMIP5 supporting the 5th Assessment Report of the Intergovernmental panel on Climate Change (IPCC-AR5).
- To offer guidance to ocean climate modellers for enhancing the scientific relevance of sampled model output.
- To articulate certain needs of ocean scientists aiming to analyze CMIP5 model output, and whose research directly supports IPCC Working Group 1 (WG1) goals.

In anticipation of a future CMIP6, WGOMD will need to start contemplating the implications and issue recommendations for the move towards higher resolution, eddy permitting ocean models and their output, such as eddy correlation terms to compare eddy diagnostics.

1.2 Reports from CLIVAR and WCRP

The CLIVAR organization and its future strategy have been under discussion, as part of the overall discussion on the World Climate Research Program (WCRP) structure, since the Scientific Steering Group (SSG) meeting in 2008 and these issues were revisited at the May 2009 SSG meeting. CLIVAR is no longer facing a clear sunset in 2013 so that its future is now being viewed in terms of an evolution or transition of its activities to a new structure for WCRP. The following seven CLIVAR Imperatives were defined at the 2009 SSC meeting:

- Anthropogenic Climate Change
- Decadal Variability, Predictability and Prediction
- Intraseasonal and Seasonal Predictability and Prediction
- Improved Atmosphere and Ocean Components of Earth System Models (ESM)s
- Data Synthesis and Analysis
- Ocean Observing System
- Capacity Building

The WCRP is developing two documents over the course of this year that will be published in time for distribution at the World Climate Conference-3 (WCC3) in August 2009. The first is the implementation plan for the WCRP strategic framework as defined by the Coordinated Observation and Prediction of the Earth System (COPES). All four WCRP Projects have been charged with identifying imperatives for the next five years or so and these will be synthesized in terms of WCRP research strategy as a whole, as well as providing a vision of the frontiers of science that WCRP should address in the long term. The second is a document on the accomplishments of the WCRP and its Projects, focusing on the activities since the launch of the COPES strategic framework in 2005.

The Third World Climate Conference (WCC3) is being organised under the theme 'Climate prediction and information for decision-making'. It will take place in Geneva, Switzerland on the 31 August - 4 September 2009. CLIVAR (and WCRP more widely) will have a presence, with M. Visbeck being a member of the Conference Organising Committee and being Chair of the Programme Committee. Past WCCs have had a major impact on the climate research landscape, with WCRP and the IPCC launched after WCC-1, and the United Nations Framework Convention on Climate Change (UNFCCC) and the Global Climate Observing System (GCOS) launched after WCC-2. The next conference will address the need for an international framework to provide the interface between research and users, particularly for the seasonal to decadal timescale.

2. CORE-II

Coordinated Ocean-ice Reference Experiments continue to be the focus of WGOMD activities. The normal year forcing CORE-I paper (Griffies et al., 2009b) has been published this year and provides the community with an example of how WGOMD can address projects of use and interest to the broader ocean modeling community, where cross-institutional collaboration is required for success. Groups around the world now routinely use the CORE-I protocol to evaluate their ocean-ice models.

With the release of version 2 of the CORE interannual forcing (IAF, Large and Yeager, 2008, hereafter L&Y08), there has been interest in testing this dataset, and examining experimental protocols for CORE-II. The CORE-II protocol and initial results were the central focus of WGOMD's discussions in Exeter, in particular to:

- Develop an agreed upon experimental protocol for global ocean-ice simulations using version 2 of the CORE interannual forcing (IAF) (L&Y08).
- Garner commitments from a large part of the WGOMD panel to coordinate their CORE-II simulations and analysis during 2009-2010, running suites of experiments examining issues such as boundary forcing, initialization, spin-up, analysis metrics and methods, etc.

WGOMD recognizes that the final experimental design will likely represent a consensus that will not satisfy all. The goal is to design a baseline protocol that is both of scientific interest and can be readily implemented, even if that protocol has certain (hopefully minor) shortcomings. Different approaches have been used in terms of initialization and spin up, temperature and salinity restoring and sea-ice initialization and modeling. Refer to the presentations from C. Böning, H. Drange, G. Danabasoglu that are available on the meeting webpage. The following sections go into more detail in the discussions on the surface forcing, the experimental protocol, ocean initialization, surface restoring and sea ice.

A note on the treatment of marginal seas: G. Madec recommends using 3D restoring of T,S monthly with a 50 day and 1 year restoring timescale for above and below 500m respectively, though this leads to a source of heat and salt, compromising the comparison to oceanic heat uptake. G. Danabasoglu restores the surface fields when the model seas are enclosed (Black, Caspian, Baltic, Red) for aesthetic reasons.

ACTION: Develop recommendations on the CORE-II protocol to be included on the CORE-II website and as part of the CORE V2 forcing release notes (H. Drange, G. Danabasoglu, S. Griffies).

ACTION: Recommend that CORE-II participants follow the CMIP5 Griffies *et al.* (2009a) guidelines on saving ocean model fields.

ACTION: Reach agreement on which density bins to use to calculate density overturning online (G. Madec).

ACTION: Make a recommendation on how to treat marginal seas by restoring.

Various groups have been working for a number of years with the CORE interannual forcing (IAF, L&Y08) on studies aimed at contributing to the understanding of mechanisms of observed interannual to decadal variability. This includes (a) looking at the variability of the meridional overturning circulation (MOC), whether it is driven by intrinsic variability and basin-scale changes in the buoyancy forcing and whether there are any detectable long-term trends, (b) the dynamics of the gyre variability of the sub-polar North Atlantic and its effect on the MOC, (c) changes in tropical interannual variability and in regional current systems that affect local fisheries and the local climate, such as drought events in Australia affected by the Leeuwin current, and (d) attempting to identify oceanic mechanisms that could give predictability. For a comprehensive list of publications, refer to the CORE-II website (http://www.clivar.org/organization/wgomd/core/core_II.php). Section 2.6 below gives an overview of the science questions being addressed with CORE-II with Section 2.7 providing a focus on the variability of the North Atlantic Sub-Polar gyre.

2.1 Surface Forcing

The CORE version 2 of the L&Y08 forcing dataset covers the period 1948-2006. B. Large and NCAR are committed to updating the dataset as the data become available.

The river runoff climatology is being updated to include a time varying runoff. Runoff is prescribed according to Dai and Trenberth (2002) and Dai *et al.* (2009) and includes data from the Global Runoff Data Centre. The river runoff dataset file that is distributed as part of the L&Y08 forcing currently contains runoff from the 50 largest rivers plus a residual to balance the budget. A suggestion was made that these two components be given in separate files to make the dataset more user-friendly.

Some of the limitations of the CORE forcing that make other groups prefer reanalyses are errors in the precipitation, uncertainty in polar forcing and the fact that interannual variability for all fields only truly begins after 1984. Improvements in the precipitation of the latest version have led to better MOC simulations. A comparison between using CORE IAF (L&Y08) and the surface forcing product developed for DRAKKAR is planned.

ACTION: Distribute newly extended IAF and corrected NYF Large and Yeager (2008) surface forcing datasets on the GFDL and CLIVAR websites (G. Danabasoglu to A. Pirani, S. Griffies) and raise awareness of CORE forcing mailing list (A. Pirani).

ACTION: Improve the user-friendliness of the run-off dataset distributed as part of the CORE Large and Yeager (2008) forcing fields (A. M. Treguier and G. Danabasoglu).

ACTION: Provide guidance and links on how to implement CFC forcing as part of CORE Large and Yeager (2008) surface forcing fields and supply a protocol for using CFC11, CFC12 and ideal age (G. Danabasoglu).

ACTION: Ensure that for CORE-II all are restoring to the PHC3 SSS field (G. Danabasoglu).

ACTION: Compare CORE IAF with DRAKKAR surface forcing product (G. Madec, A. M. Treguier).

2.2 Extended 20th Century Surface Forcing

There is interest in developing a reconstructed extended forcing dataset for the 20th Century. Two pronounced surface air temperature warming events, both amplified in the Arctic and linked to sea-ice variability, have occurred in the 20th Century (Johannessen *et al*., 2004), shown in Figure 1. While the event that occurred during the 1990s is captured by the L&Y08 dataset, the epispode during the 1930s is missing.

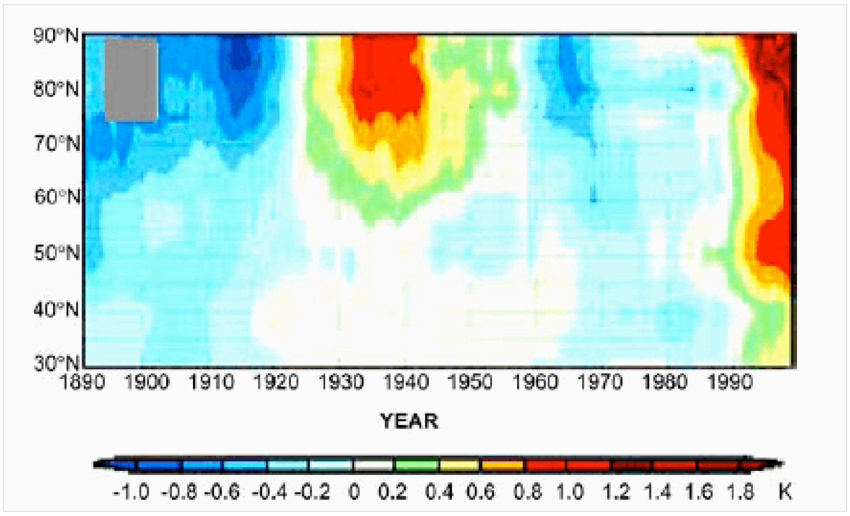

Figure 1: Hovmoeller diagram of observed zonally averaged time–latitude variability of monthly-mean surface air temperature anomalies north of 30°N, 1891–1999 (from Johannessen et al., 2004).

Modern data assimilation systems can use the available historical surface pressure observations to produce daily surface weather maps and to reanalyze the whole extratropical tropospheric circulation from the end of the 19th Century to the present day (Compo *et al.*, 2006). For the Northern Hemisphere winter, the analysis errors are substantially lower than the climatological standard deviation. The reanalysis is also useful in the Northern Hemisphere summer, despite larger errors. There are insufficient observations in the Tropics and Southern Hemisphere to produce a useful reanalysis prior to 1935 though the analysis quality improves with increased observations and there is the prospect of further digitized surface pressure observations from the Pacific Islands from before 1935. However, whether it is possible to produce useful tropical wind analyses using only surface pressure observations is an open research question. This study has matured into the 20th Century Reanalysis Project (Compo *et al*., 2009) that supplies objectively-analyzed weather maps with the associated uncertainties for 6-hourly, daily averaged or monthly values for 1908 – 1958 (and is being extended for the whole 20th Century) on a 2x2^{o} global grid. The dataset is freely available at http://www.cdc.noaa.gov/data/gridded/data.20thC_Rean.html.

Atmospheric surface fields have also been reconstructed by statistical means for the period 1900 to 1997 and applied to a coupled sea ice-ocean model of the North Atlantic/Arctic Ocean, using a statistical model which uses a redundancy analysis to reconstruct the atmospheric fields linking NCEP/NCAR reanalysis and observational data (Kauker *et al*., 2008). Results of the simulations with the sea ice-ocean model forced by the reanalysis have been compared with historical sea ice extent observations for the Arctic and Nordic Seas and are found to be highly consistent with these historical data. The 1930-1940s and the present surface air temperature anomalies are captured by the reanalysis.

ACTION: Explore the possibility of forcing ocean models with the Compo *et al.* (2009) 20th Century Reanalysis Project (H. Drange, R. Gerdes).

2.3 CORE-II Protocol

The protocol is the same as the one used in the CORE-I experiments (Griffies *et al.*, 2009b) except for the 59-year repeat IAF (L&Y08) forcing cycle covering the 1948-2006 period instead of the repeated single annual cycle used in the normal year forcing (NYF). The ocean model is initialized using the January-mean PHC (Polar Science Center Hydrographic Climatology) temperature and salinity data and from rest, with zero velocities. The 1948-2006 period should be repeated for a minimum of four to six cycles, depending on the application. Some processes require a longer spin up with significantly more cycles, such as studies involving the mid-depth and abyssal ocean. Figure 2 shows the behavior of the Atlantic overturning circulation of the Bergen/NERSC model during 7 repeat cycles.

The initial condition shock diminishes after the first 10-15 years of each forcing cycle so the analysis should focus on the remaining period (Doney *et al*., 2003, Doney *et al*., 2007). One can potentially use de-trending to allow more of the low frequency variability to be distinguished. A guiding principle is that the main focus of a study should stay rather robust across cycles, e.g., the difference between the last cycle and the previous one should be "small". For variability studies the relevant question is not so much the absolute magnitude of the drift but rather the amplitude relative to the variability signal. There is also an ambiguity in how to separate numerical drift from long-term secular trend driven by the L&Y08 IAF data.

The approach used for salinity restoring and the initialization of the sea ice model is left to the discretion of the participating modeling groups since the choice will depend on each group's experience and the sensitivity of each model. All groups should be restoring to the PCH3 SSS field used in CORE-I and described in Section B3 of Griffies *et al.* (2009b). Simulations that restore to PHC2 are nevertheless acceptable and the forthcoming version, PHC4, should also be tested. Sections 2.4 and 2.5 describe some examples of the approaches used for salinity restoring and sea ice initialization, respectively.

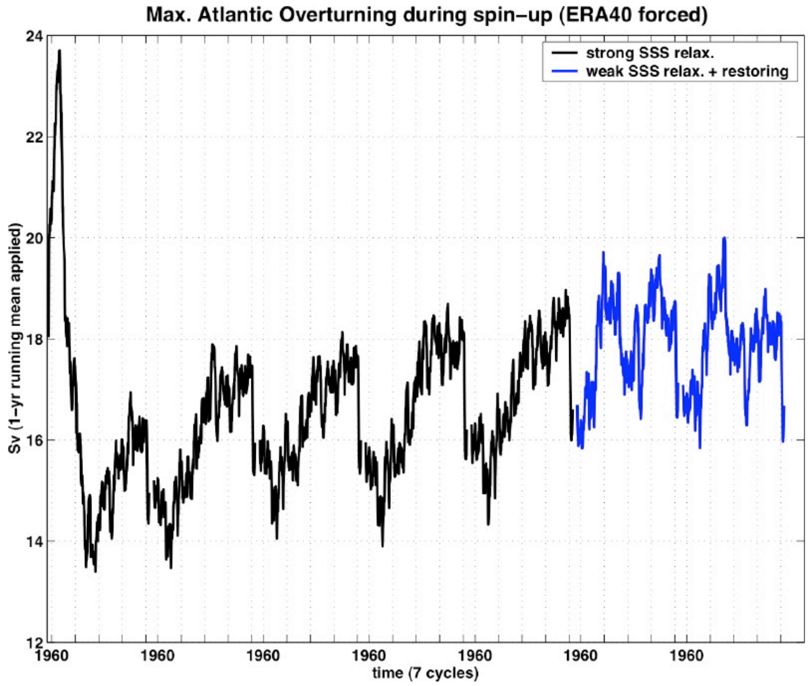

Figure 2: Example of maximum strength of the simulated Atlantic Meidional Overtuning Circulation during a spin-up phase with the Bergen Isopycnic Coordinate Ocean Model (H. Drange).

2.4 Surface Restoring

There is no restoring to temperature. The approach selected for applying salinity restoring to stabilize the solution is model dependent according to each model's sensitivity and each group's experience. Appendix B3 and Table 3 of Griffies *et al*. (2009b) gives a summary of the salinity restoring approaches used by the models that participated in the CORE-I simulations. Figure 3 shows one example of model sensitivity with the widely different solutions of the NERSC-Bergen model depending on the choice of the unphysical salinity restoring term.

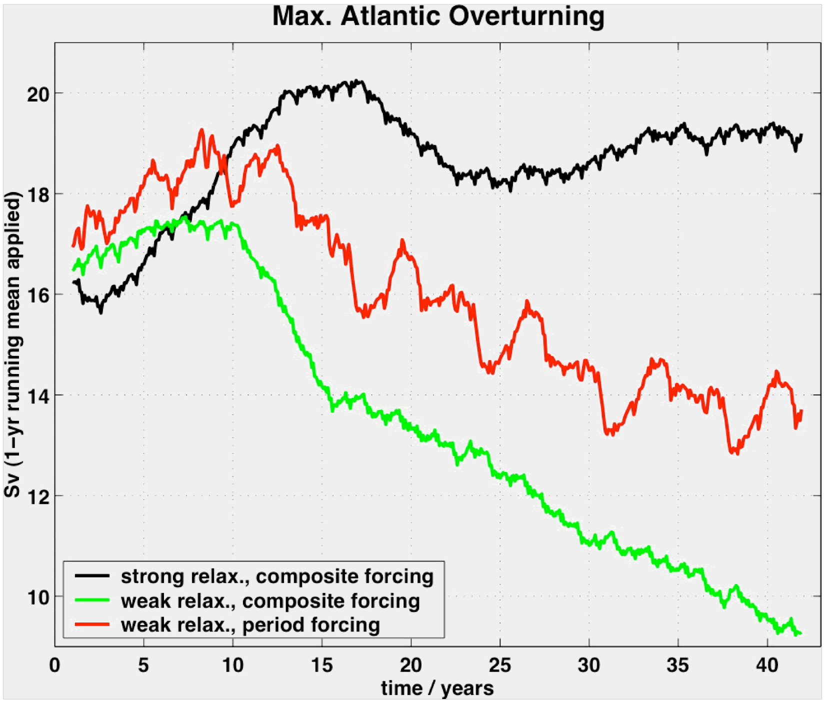

Figure 3: Sensitivity of NERSC model maximum Atlantic overturning on salinity restoring (H. Drange).

With the NERSC model, a cyclic spin-up with reanalysis forcing for at least 200 years is required to avoid strong (unaccented) drift in surface salinity. During the spin up phase the model is integrated with strong Newtonian relaxation of sea surface salinity (SSS) with a relaxation time of 30 days for a 50m deep mixed layer, linearly decreasing with thicker mixed layers. There is no relaxation of subsurface waters. Thereafter, weak relaxation is introduced (180-360 days relaxation time scale for a 50m deep mixed layer) for another 50-100 years. The mismatch between model and climatological SSS, ΔSSS, is limited to $|\Delta SSS| < 0.5$ in the computation of the Newtonian relaxation. This avoids extreme relaxation fluxes e.g. in the vicinity of the western boundary currents that are generally not realistically represented in OGCMs. Continental runoff is included by adding freshwater into the appropriate coastal grid cells.

When a quasi-steady solution is obtained after *N* cycles, based on quantities like the Atlantic Meridional Overturning Circulation (AMOC; see Figure 2), the applied Newtonian salt (or fresh water) fluxes from the last integration with weak Newtonian relaxation is stored on the horizontal model grid with a weekly temporal resolution, averaged over cycle *N+1*. The production run starts with cycle *N+2*. Now the diagnosed, weekly averaged (but inter-annual invariant) Newtonian salt (or fresh water) flux from cycle *N+1* is applied. In addition, the conventional Newtonian relaxation (used until cycle *N*) is applied but with the relaxation time reduced by an order of magnitude, to 360 or 720 days. Relaxation is never applied at high northern and southern latitudes covered by sea ice.

In the case of the NCAR model, weak salinity restoring of 50m/4yr, with its horizontal-mean subtracted and a precipitation factor, are used over the whole domain, including under sea ice. The AMOC strength and variability are strongly dependent on the choice of salinity restoring, as shown in Figure 4. Strong salinity restoring (piston velocity (V_p) = 50m/30 days) maintains the sea ice and damps the AMOC. No salinity restoring further enhances the AMOC and induces a spurious oscillation.

The GFDL MOM CORE simulations are initially spun-up with 5 repeating cycles and a restoring piston velocity of 10m/6days. During the analysis phase, the restoring is reduced to a piston velocity of 10m/300days.

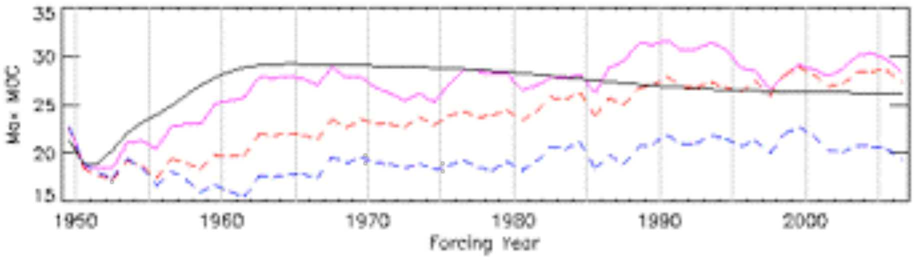

Figure 4: Temporal evolution of maximum strength of NCAR model AMOC during IAF hindcast (from G. Danabasoglu). Solid pink is with weak salinity restoring (V_p = 50m/4 years), dashed red is with weak salinity restoring + restoring melt flux, and dashed blue is with strong salinity restoring (V_p = 50m/30 days) (from S. Yeager and G. Danabasoglu).

Experience with the CORE-III freshwater perturbation experiments has also shown the sensitivity of the Atlantic Meridional Overturning Circulation to the choice of surface restoring. Figure 5, from Gerdes *et al*., 2006, shows different solutions with a range of restoring, from simple restoring of surface salinity to the use of an energy balance model (EBM) for the atmosphere. The results show that using a partially coupled climate model may be a good solution, coupling the freshwater balance while prescribing wind stress, thus maintaining the negative feedback due to a closed freshwater budget with a stable ocean-ice solution. There is considerable potential in moving the restoring away from the sea surface and out of the atmospheric boundary layer to achieve dynamic restoring outside the atmospheric boundary layer and have consistency in the thermodynamic coupling.

ACTION: Develop a way forward to explore partial coupling of ocean-ice models (R. Gerdes, H. Drange, G. Madec).

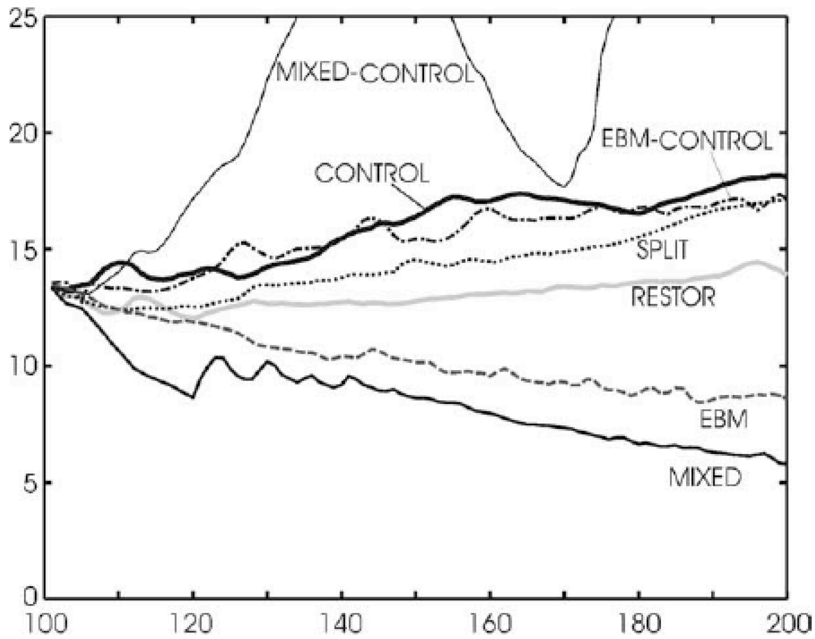

Figure 5: Maximal strength (in Sv) of the NADW meridional overturning cell in the North Atlantic (see text) during the duration of the experiments with different surface boundary conditions, ranging from simple restoring of surface salinity to the use of an energy balance model (EBM) for the atmosphere (from Gerdes et al., 2006).

2.5 Sea Ice

There are various sea ice model initialization options. The NCAR sea ice model is initialized from a spun up state generated by either a NYF or IAF simulation, which will yield very different initial states, as shown in Figure 6. The Bergen/NERSC sea ice model is initialized from a 2m thick sea ice cover with ice extent according to climatology (for example http://nsidc.org/data/seaice_index).

CORE-II NEMO simulations will be run using three different sea ice models. This will help address the question of whether sea ice melt depends on the ice model itself. The DAMOCLES sea ice archive is being included in the NEMO data assimilation system that will be producing a state estimation. DAMOCLES (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies) is an integrated ice-atmosphere-ocean monitoring and forecasting system designed for observing, understanding and quantifying climate changes in the Arctic.

ACTION: Solicit recommendations from CliC on how to evaluate sea ice models (M. Holland)

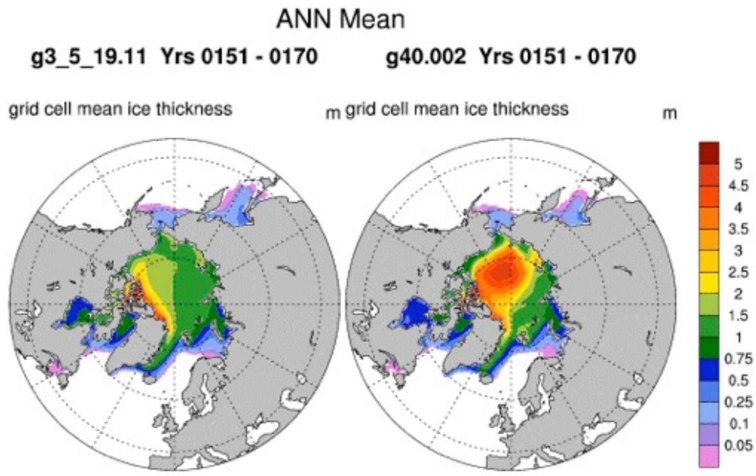

Figure 6: Annual mean sea ice thickness of NCAR ice model spun up from either IAF (left hand side) or NYF (right hand side).

2.6 CORE-II Science

The 1948-2006 CORE-II hindcast simulations provide a highly anticipated framework to both evaluate ocean model performance and study mechanisms of ocean phenomena and their variability from seasonal to decadal timescales. CORE-II simulations can be applied to the attribution of recent ocean-climate events to trends or natural variability, in conjunction with CMIP5. CORE-II will directly feed into CLIVAR basin panel activities where ocean model simulations are used to develop mechanistic descriptions of observed climate variability and change and will serve as a useful direct comparison to observational studies, such as the CLIVAR VAMOS (Variability of the American Monsoon System) Ocean-Cloud-Atmosphere-Land Study (VOCALS) and the Southwest Pacific Ocean Circulation and Climate Experiment (SPICE).

The hindcasts are suited for testing the sensitivity of ocean simulations to atmospheric forcing and model configuration. The sensitivity to configuration and model bias attribution to individual model components or parameterizations will help with model development and tuning. The use of CFCs is a good way to test parameterizations and to identify model physics shortcomings. The natural variability differences between participating models will be interesting for understanding and evaluating the robustness of modeled ocean variability and the propagation of anomaly signals that has been observed during the 20th Century and to identify forced variability changes and climate shifts and trends, complementing data assimilation and coupled modeling studies. CORE-II studies in AMOC variability will look for consensus in the low frequency variability during the CORE-II period at all latitudes, as well as for comparison with the high frequency variability monitored by the RAPID array, and will be relevant for decadal prediction.

Numerous opportunities exist for the CORE-II simulations to contribute to other on-going modeling studies. The DRAKKAR consortium is carrying out CORE-II simulations in a hierarchy of models with different resolutions, up to a resolution of a ¼ degree. This group will be addressing the generalization of moving to higher resolution simulations and the problem of having to do multiple spin up repeat cycles, looking at whether lower resolution cycles could be used before increasing the resolution. There is also interest in including biogeochemistry in models with different resolutions.

The Arctic Ocean Model Intercomparison Project (AOMIP) has officially accepted CORE IAF as their forcing data set. The CORE-II protocol can be used in collaboration with AOMIP, with CORE benefiting from the regional expertise and global modelers being entrained into working on Arctic problems. AOMIP held its 12th workshop in February 2009 with the purpose of planning the next phase of the AOMIP program by identifying new scientific priorities, potential collaborations and deliverables. The report, available on the workshop webpage (http://www.whoi.edu/page.do?pid=31495) describes the following eleven research topics:

- Bering Strait volume, heat and salt fluxes
- Canada Basin: shelf-basin exchange and mechanisms
- Pacific Water circulation (origin, forcing, pathways)
- Canada Basin: major mechanisms of halocline formation and variability
- Circulation and fate of fresh water from river runoff (pathways and seasonal transformation due to mixing and freezing)
- Beaufort Gyre: mechanisms of fresh water accumulation and release (origin of the BG freshwater reservoir, sources and sinks, role of sea ice dynamics and seasonal transformations, Ekman pumping)
- Fresh water balance of the Arctic Ocean: seasonal and interannual variability (sources, sinks, pathways)
- Atlantic Water circulation (circulation patterns, variability and heat exchange, model validation based on observations)
- Ecosystem experiments
- Observations, state estimation, and adjoint methods
- Sea-ice drift and changes in drag

ACTION: Strengthen ties between CORE and AOMIP, with a member of WGOMD attending the next AOMIP meeting.

In the Southern Ocean, CORE-II simulations are being applied to study sea ice variability and water mass formation, with plans for simulations investigation lateral restoring of temperature and salinity to incorporate the effects of sub-ice shelf processes and wind perturbation experiments that will look at variability of the Southern Annular Mode (SAM) and the response of the Southern Ocean to climate change.

As already noted, observational programs such as VOCALS and SPICE will be generating data against which CORE-II simulations could be evaluated, and those involved in the observational campaigns may, in turn, be interested in the simulations. Another example is Indonesian Throughflow strength and variability from the INSTANT mooring program being used to tune CORE-II simulations as part of the Australian Community Climate and Earth System Simulator (ACCESS) model development program.

ACTION: Liaise with VOCALS, SPICE and other observational programs with regards to participating in CORE-II.

2.7 Variability of the North Atlantic Sub-Polar Gyre

The sub-polar North Atlantic has seen a freshening ‘trend’ between the late 1960s and mid 1990s; the basin-scale changes in freshwater content appeared tightly anti-correlated with changes in heat content (Boyer et al., 2007; Figure 7a). Observational studies have given various explanations for the variability in freshwater content such as changes in precipitation or as being related to the Great Salinity Anomaly. However, ocean models are able to reproduce the decadal variability in freshwater and heat content and show their linkage to changes in mid-latitude ocean circulation (Scheinert et al., 2009); the fidelity of CORE-II simulations in capturing observed aspects of the circulation variability in the North Atlantic can be assessed by comparing with the index of eastward baroclinic transport (Curry-McCartney index), shown in Figure 7b.

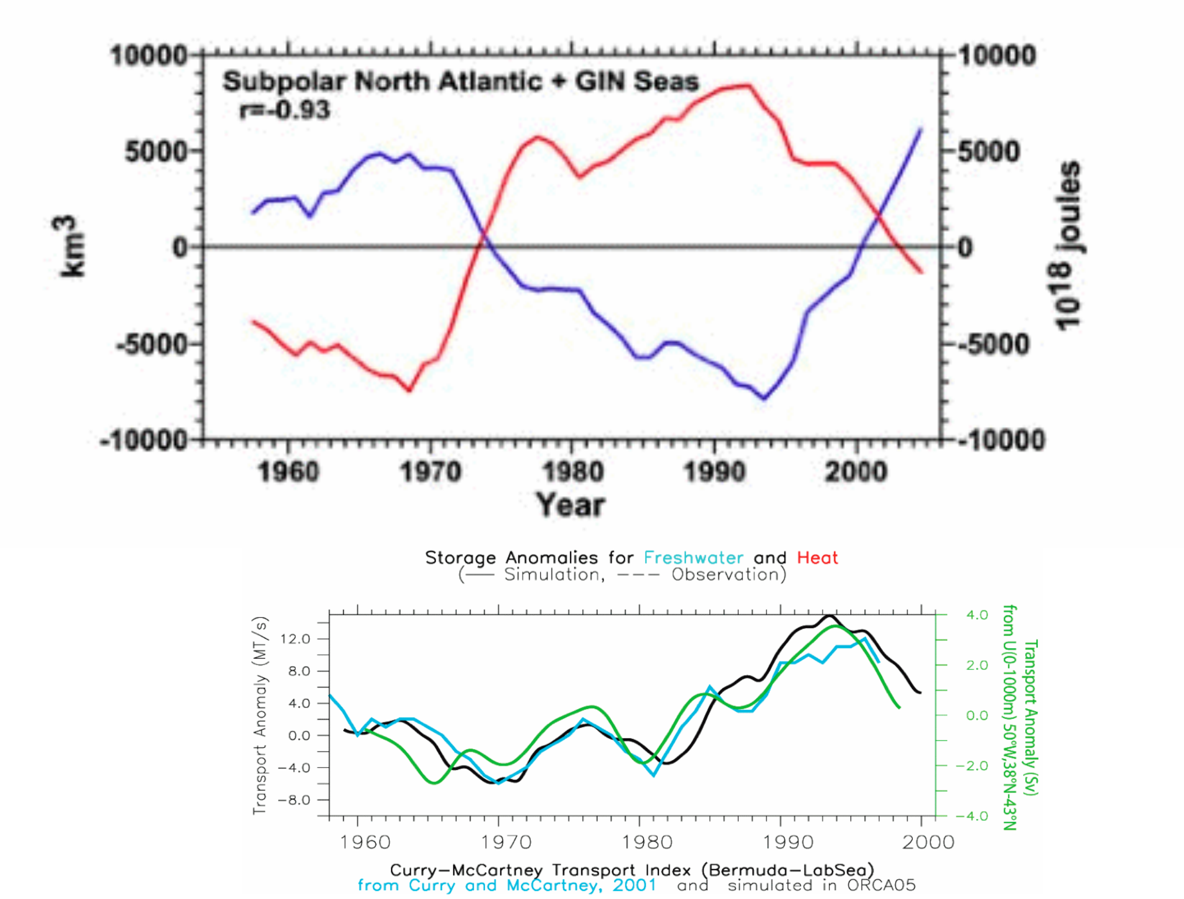

Figure 7: (a) Equivalent freshwater content (red) and heat content (blue) in the subpolar North Atlantic and GIN Seas 0–2000 meters (1955–1959) to (2002–2006) (from Boyer et al.*, 2007), and (b) Bermuda-Labrador Sea transport Curry-McCartney index of eastward baroclinic transport (from C. Böning).*

The strength of the Sub-Polar Gyre (SPG) is governed by the sub-polar (winter) buoyancy forcing that, in general, follows the North Atlantic Oscillation (NAO) wind stress forcing. However, this has not been the case since 1995/96. An assessment of the model system sensitivity to the NAO state has shown that the intensification of the SPG that occurred in the fourteen years since 1980 was associated with the concurrent positive phase of the NAO, while the decline since 1995 was due to internal feedback in the ocean (Lohmann *et al.*, 2008). Heat that was advected to the SPG overrode the NAO winter forcing, balancing the local buoyancy forcing and weakening the gyre. The SPG Index, rather than the NAO, should therefore be used as a proxy for the variability of the marine climate in the North Atlantic region and can be deduced from observations or hindcast model simulations. Sensitivity experiments have confirmed that the rapid post-1995 collapse of the SPG was insensitive to the 1995 atmospheric forcing, but depended crucially on the preconditioning reached by the 1995 ocean state: the SPG was close to maximum strength and approaching a weakening even with unchanged NAO forcing. The importance of the ocean state has implications for the predictability of the North Atlantic climate on decadal timescales.

The reduction in the strength of the SPG since 1995 led to a record inflow of warm surface waters, leading to a marine ecosystem adjustment, with a huge impact on fisheries, see Figure 8 (Hátún *et al.*, 2009). Around twenty new fish species have been observed in this region. A similar record exists in cod-catch records of the 1920-30s. The sub-polar gyre (SPG) is of key importance for the decadal-scale variations in the Atlantic inflow to the Arctic and circulation off the coast of South Greenland. The inflow of warm surface waters contributes to Greenland outlet glacial melting (Holland *et al.*, 2008).

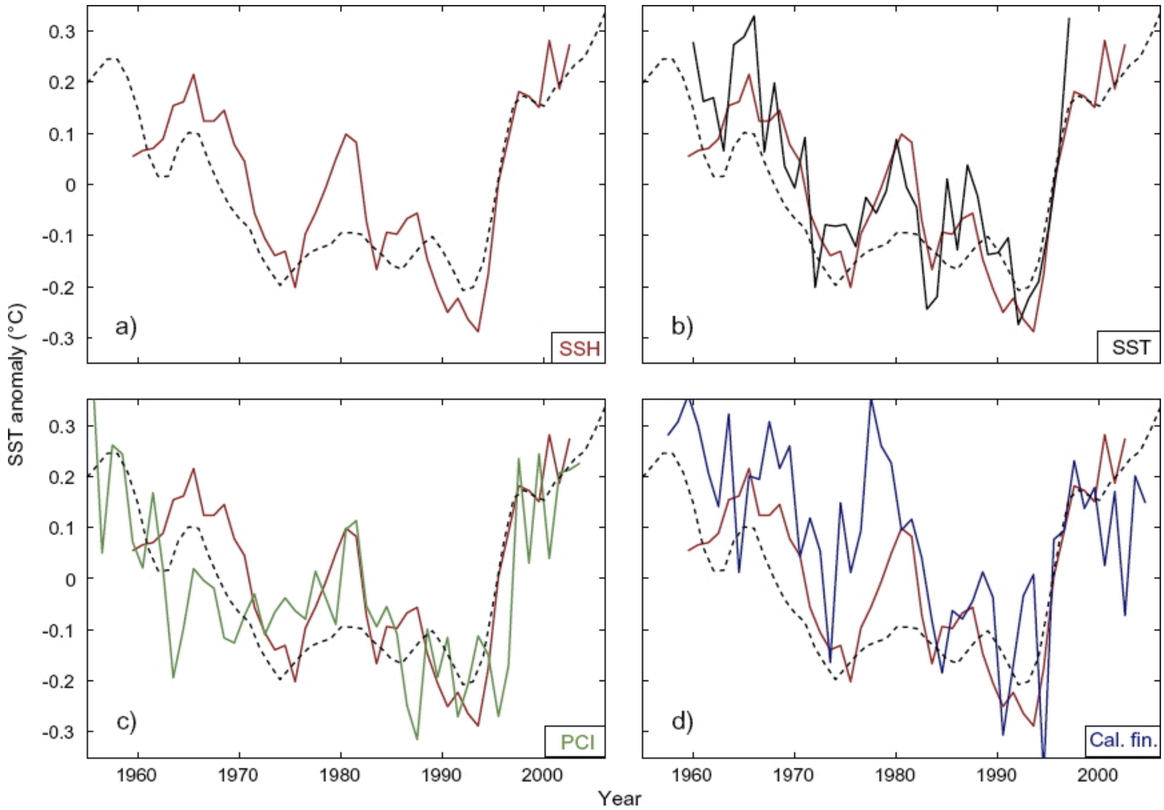

Figure 8: Co-variability of hydrography and phytoplankton/zooplankton abundances in the northern North Atlantic during 1955-2005: (a) The sea surface height (SSH) principal component (inverted gyre index, red) and the north-eastern North Atlantic sea surface temperature (SST) (black dashed) from the Bergen Isopycnic Coordinate OGCM, computed for the northern North Atlantic between approximately 45 and 65 deg N. (b) A previously reported SST principal component (thick black line) based on PCA of observed SST (Beaugrand et al., 2002b). (c) Principal component from PCA of the Phytoplankton Colour Index (PCI) (green; observer phytoplankton biomass) and (d) principal component from PCA of the Calanus finmarchicus (zooplankton) abundance (blue). (From Hátún et al., 2009).

This mechanism appears to be a robust feature of a number of ocean models, regardless of the surface forcing product used or resolution and despite model drift. While the variations observed during the second half of the 20th Century are not necessarily a signature of global warming, a feature of this kind will likely reoccur in the next 40 years or so and its impact may be significantly amplified by a global warming upper ocean temperature trend. WGOMD recommends working towards a multi-model statement demonstrating the robustness of this mechanism.

ACTION: WGOMD recommends the development of a CORE-II multi-model statement explaining the variability of the sub-polar North Atlantic during the second half of the 20th Century (C. Böning, H. Drange, G. Danabasoglu and others).

2.8 Future Directions

A coordinated approach is useful when trying to address hard questions, looking for robust features particularly in the absence of observations, such as for AMOC variability. Understanding the causes of ocean variability and its mechanisms would benefit from a coordinated model effort to see whether there are common features in different models forced by different surface boundary forcings. A question that has not been addressed so far is the impact of changes in overflows that were previously not resolved. Another major area of interest is the Southern Ocean and ACC response to changes in forcing.

Since numerous groups are interested in participating in running or analyzing CORE-II experiments, WGOMD needs to ensure that guidelines for running CORE-II experiments and CORE-II data are made available to the community by means of the CORE website, including, in the absence of a centralized data archive, a list of links to access data from groups' local servers. WGOMD recommends that groups running CORE-II should follow the Griffies *et al*.

(2009a) guidelines on sampling physical ocean fields that were presented to WGCM in the context of the CMIP5 simulations.

WGOMD should define some feasible activities to engage in over the next 1-2 years, as well as some more challenging activities, assigning a representative to each activity. A group activity would be one that involves collaboration between two or more groups. In defining such activities, WGOMD needs to bear in mind the constraints of groups being involved in the CMIP5 simulations as well as how to reach out to groups not directly represented in the working group.

ACTION: Provide the community with recommendations and guidelines on running CORE-II simulations and accessing CORE-II data by means of the WGOMD CORE website (All, A. Pirani).

3. Repository for Evaluating Ocean Simulations (REOS)
Significant progress has been made on the development of the WGOMD Repository for Evaluating Ocean Simulations (REOS), which is a website for cataloguing various ways to analyze ocean model simulations (www.clivar.org/organization/wgomd/reos/reos.php). REOS has recently gone live as part of the WGOMD website. The REOS front page gives an overview of what to expect from the website, as well as some useful related links. The Datasets page lists references and links to data sites (eg SST, altimetry, tracers). The Metrics page has sections for each ocean basin with input from the CLIVAR basin panels, as well as summaries of past activities (e.g. workshops) on ocean model metrics. The page on Model Evaluation has examples of model evaluation practices, e.g. the evaluation of the CORE-I multi-centennial normal year forcing runs. The page on Tools has descriptions and links to tools available to the community e.g. the co-location Google-Earth OceanDiva tool. Finally, the References page has papers arranged according to topic (e.g. datasets, ocean basin, tracers etc) with links to the paper where possible.

The REOS website will continue to evolve to serve as a resource for the ocean modeling community, not only for ocean modelers, but also to bridge the gap between model and observations with suggestions and recommendations for how to best evaluate models against observations. We will continue to solicit input from the modeling, assimilation, observational, and analysis communities to provide guidance and oversight for the contents of this page. As this page matures through usage and input, navigating the content of the REOS website will also improve. The website will continue to be maintained by A. Pirani, who welcomes comments and suggestions, as well as material to include and make available to the wider community.

4. Decadal Variability
CLIVAR has a keen interest in identifying the physical mechanisms associated with decadal variability, and facilitating the modeling tools to develop prediction systems. Many WGOMD panel members are key players in ongoing projects related to decadal variability and prediction. Given the long time scales, decadal variability questions intimately involve the ocean. Many efforts have focused on the Atlantic sector, with the meridional overturning circulation a key player, though the Pacific basin also contains intriguing variability on the decadal time scales. There are significant difficulties with the decadal problem associated with a paucity of observational data, the long time scales involved, and model limitations. Indeed, it is unclear whether there is any predictable signal to be uncovered. Nonetheless, there is variability in the system, and the ocean's role appears to be nontrivial, if only in setting the long time scale via red noise damping processes (e.g., as in Hasselmann, 1976).

The discussion of decadal variability during the panel meeting was somewhat open-ended, largely because the questions remain fundamentally of a research nature, and focused on addressing the following question:

How should the WGOMD, as CLIVAR's primary ocean modeling panel, play a role in guiding rational efforts towards understanding, and possibly predicting, decadal variability?

While there is benefit in initializing seasonal prediction with data assimilation, this has yet to be demonstrated for decadal prediction. In the study by Balmaseda *et al*. (2007) the difference in the estimation of the AMOC with and without data assimilation was the same order of magnitude as the AMOC decadal fluctuations. The reliability of data assimilation in the pre-Argo era is under question. Initializing decadal predictions from CORE-II simulations without data assimilation can be an alternative strategy. Anomalies can be extracted from the CORE-II climatology and then applied to the coupled model decadal simulations.

D. Smith gave a presentation entitled 'The Impact of Initial Conditions on Decadal Climate Predictions', which is available on the panel meeting webpage. The following questions were posed for WGOMD to consider:

- Can CORE II experiments provide reliable estimates of historical ocean changes (T, S, AMOC), together with uncertainties? If so, these could be used to initialise hindcasts, and/or to assess skill.
- CORE II experiments are likely to yield improved understanding of mechanisms of decadal ocean variability and change. This would be very valuable for understanding forecast errors, and for informing where observations are most needed.
- Careful comparison of CORE II results from a variety of resolutions with observations should identify systematic model errors, and their likely impacts on forecasting and prediction.
- Covariances from an ensemble of CORE II experiments could be used for historical ocean analyses. Idealized tests suggest that sub-surface ocean temperature and salinity could be reconstructed reasonably accurately (at least back to 1950) if anomaly covariances are known.

5. WGOMD Business

Membership

As already noted, H. Drange joined S. Griffies as co-Chair. S. Griffies will be standing down at the end of 2009, to be replaced by G. Danabasoglu. M. England has rotated off WGOMD and S. Marsland has been welcomed as a new member. WGOMD is considering expanding its areas of expertise to ocean biogeochemical modelling and coastal modelling. Indeed a topic for a future workshop may be 'coastal impacts of the large scale climate'. The coupling of the ocean to ice shelves is another area that the group wishes to investigate. The view is that it is still premature to have representatives of the sigma and finite element modelling communities.

9th WGOMD Session and Workshop

The 9th WGOMD Session is planned for Fall 2010 and is going to be held in Boulder, USA, hosted by the incoming co-chair G. Danabasoglu. WGOMD will be organising a workshop to coincide with its meeting and the subject is going to be 'Decadal Variability and Predictability: Understanding the role of the Ocean'. The topics that the workshop will cover include the multi-decadal variability in the North Atlantic as depicted in the AMOC in coupled simulations, its dependence on ocean model physics and numerics, exploration of mechanisms, its climate impacts and fingerprints, and associated predictability.

References

Balmaseda M. A., G. C. Smith, K. Haines, D. Anderson, T. N. Palmer, A. Vidard, 2007: Historical reconstruction of the Atlantic Meridional Overturning Circulation from the ECMWF operational ocean reanalysis. *Geophys. Res. Lett.*, **34**, L23615, doi:10.1029/2007GL031645.

Boyer T., S. Levitus, J. Antonov, R. Locarnini, A. Mishonov, H. Garcia, S. A. Josey (2007), Changes in freshwater content in the North Atlantic Ocean 1955–2006, *Geophys. Res. Lett.*, **34**, L16603, doi:10.1029/2007GL030126.

Compo, G.P., J.S. Whitaker, and P.D. Sardeshmukh, 2006: Feasibility of a 100-year reanalysis using only surface pressure data. *Bull. Amer. Met. Soc.*, **87**, 175-190.

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin,B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, S.J. Worley, 2009: The Twentieth Century Reanalysis Project. *Bull. Amer. Met. Soc.*, *in preparation*.

Dai, A., and K. E. Trenberth, 2002: Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. *J. Hydrometeorol.*, **3**, 660-687.

Dai, A., T. Qian, K. E. Trenberth, and J. D Milliman, 2009: Changes in continental freshwater discharge from 1948-2004. *J. Climate*, **22**, 2773-2791.

Doney, S.C., S. Yeager, G. Danabasoglu, W.G. Large, and J.C. McWilliams, 2003: Modeling global oceanic inter-annual variability (1958-1997): Simulation design and model-data evaluation. NCAR/TN-452+STR.

Doney, S.C., S. Yeager, G. Danabasoglu, W.G. Large, and J.C. McWilliams, 2007: Mechanisms governing interannual variability of upper-ocean temperature in a global hindcast simulation. *J. Phys. Oceanogr.*, **37**, 1918-1938.

Gerdes, R, William J Hurlin, and Stephen Griffies, 2006: Sensitivity of a global ocean model to increased run-off from Greenland. *Ocean Modelling*, **12**(3-4), doi:10.1016/j.ocemod.2005.08.003.

Griffies, S. M., 2009: Summary of the CLIVAR WGOMD Workshop on Ocean Mesoscale Eddies: Representations, Parameterizations, and Observations. *CLIVAR Exchanges, July 2009 Issue*.

Griffies, S. M., A. J. Adcroft, H. Aiki, V. Balaji, M. Bentson, F. Bryan, G. Danabasoglu, S. Denvil, H. Drange, M. England, J. Gregory, R. W. Hallberg, S. Legg, T. Martin, T. McDougall, A.Pirani, G. Schmidt, D. Stevens, K. E. Taylor, and H. Tsujino, 2009a: Sampling Physical Ocean Fields in WCRP CMIP5 Simulations. ICPO Publication Series 137, WCRP Informal Report No. 3/2009

Griffies, S. M., A. Biastoch, C. Böning, F. Bryan, G. Danabasoglu, E. P. Chassignet, M. H. England, R. Gerdes, H. Haak, R. W. Hallberg, W. Hazeleger, J. Jungclaus, W. G. Large, G. Madec, A. Pirani, B. L. Samuels, M. Scheinert, A. Sen Gupta, C. A. Severijns, H. L. Simmons, A. M. Treguier, M. Winton, S. Yeager and J. Yin, 2009b: Coordinated Ocean-ice Reference Experiments (COREs). *Ocean Modelling*, **26**, 1–46.

Griffies, S. M., A. Adcroft, A. Gnanadesikan, R. W. Hallberg, M. Harrison, S. Legg, C. Little, M. Nikurashin, A. Pirani, B. L. Samuels, J. Toggweiler, G. Vallis, L. White, H. Banks, C. Böning, E. Chassignet, G. Danabasoglu, S. Danilov, E. Deleersnijder, H. Drange, M. England, B. Fox-Kemper, R. Gerdes, R. Greatbatch, E. Hanert, G. Madec, S. Marsland, H. Simmons, J. Schroter, A. M. Treguier, H. Tsujino, 2009c: Problems and Prospects in Large-Scale Ocean Circulation Models. OceanObs'09 White Paper.

Hasselmann, K., 1976: Stochastic climate models. Part I. Theory. *Tellus*, **28**, 463-485.

Hátún, H., Mark Payne, Gregory Beaugrand, Philip Chris Reid, Annebritt Sandø, Helge Drange, Bogi Hansen, Jan Arge Jacobsenand Dorete Bloch, 2009, Large biogeographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales, *Prog. Oceanogr.*, doi:10.1016/j.pocean.2009.03.001

Holland, D.M., R.H. Thomas, B. deYoung, M.H. Ribergaard, and B. Lyberth, 2008: Acceleration of Jakobshavn Isbrae Triggered by Warm Subsurface Ocean Waters. *Nature Geosci.*, **28**, doi:10.1038/ngeo316.

Hurrell, J. W., Delworth, T., Danabasoglu, G.., Drange, H., Griffies, S., Holbroook, N., Kirtman, B., Keenlyside, N., latif, M., Marotzke, J., Meehl, G. A., Palmer, T., Pohlmann, H., Rosati, T., Seager, R., Smith, D., Suttorn, R., Timmermann, A., Trenberth, K., E., and Tribbia, J., 2009: Decadal Climate Prediction: Opportunities and Challenges, Community White Paper for OceanObs09.

Johannessen, O.M., L. Bengtsson, M.W. Miles, S.I. Kuzmina, V. Semenov, G.V. Alekseev, A.P. Nagurny, V.F. Zakharov, L.P. Bobylev, L.H.Pettersson, K.Hasselmann, H.P. Cattle, 2004: Arctic Climate Change – Observed and Modelled Temperature and Sea Ice. *Tellus*, **56**A, 328-341.

Kauker, F., Köberle, C., Gerdes, R., Karcher, M.(2008).Modeling the 20th century Arctic Ocean/Sea Ice system: Reconstruction of surface forcing, *Journal of Geophysical Research*, **113**, C09027., doi:10.1029/2006JC004023.

Large, W.G. and S.G. Yeager, 2008: The Global Climatology of an Interannually Varying Air Sea Flux Data Set, *Climate Dynamics*, DOI 10.1007/s00382-008-0441-3, 24pp.

Latif, M., T. Delworrth, T., D. Dommenget, H. Drange, W. Hazeleger, J. Hurrell, N. Keenlyside, G. Meehl, and R. Sutton, 2009: Dynamics of Decadal Climate Variability and Implications for its Prediction. OceanObs'09 White Paper.

Lohmann, K., H. Drange, and M. Bentsen, 2008: Response of the North Atlantic subpolar gyre to persistent North Atlantic oscillation like forcing, *Clim. Dyn*., 10.1007/s00382-008-0467-6.
Scheinert et al 2009, *submitted*.

Appendix A

8^{th} Session of WGOMD - Agenda
30 April - 01 May 2009, UK Met Office, Exeter, UK

29April evening: quasi-working dinner together (after completion of mesoscale eddy workshop)

30April
CORE presentations and discussions (bulk of day)
-Goal: develop detailed strawman protocol for CORE-II, and initiate a comparison project amongst panel members and interested others.
REOS website
-Goal: scrutinize the REOS website, anticipating public release soon after Exeter.

01May
Decadal prediction presentations and discussion
-Goal: articulate WGOMD's role in helping to address the research needs of decadal climate prediction.
WGOMD business:
-membership
-member presentations

Appendix B

8th Session of WGOMD – List of Participants
30 April - 01 May 2009, UK Met Office, Exeter, UK

Panel Members

S. Griffies (co-Chair)
H. Drange (co-Chair)
H. Banks
G. Danabasoglu
R. Greatbatch
G. Madec
H. Tsujino

Invitees

C. Böning
M. Alonso Balmaseda
E. Chassignet
R. Gerdes
A.-M. Treguier
M. Roberts
D. Smith
S. Marsland

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CLIVAR WGOMD Workshop on Ocean Mesoscale Eddies:
Representations, Parameterizations, and Observations

Stephen Griffies (NOAA/GFDL)

1 Motivation and Goals for a Workshop on Mesoscale Eddies

The global ocean is a highly turbulent fluid, with scales of motion from the millimetre to global, on time scales from seconds to millenia. One of the most energetic scales is the mesoscale, where variability arises from the chaotic dynamics of geostrophic turbulence. The increasing power of satellite observations has confirmed that mesoscale eddies are a ubiquitous feature of the World Ocean (e.g., Chelton et al., 2007). Mesoscale eddies are critical for establishing ocean tracer properties; they affect the ventilation of heat, carbon, and other tracers; they support rich levels of biological activity; and they interact with smaller and larger scales.

A key weakness of nearly all global climate models used to study climate is the absence of an explicit representation of ocean mesoscale eddies, since their spatial scale is smaller than typical climate model grid meshes can resolve. Hence, the models rely on parameterizations. The most popular parameterizations originate from the tracer diffusion scheme of Solomon (1971) and Redi (1982) (i.e., neutral diffusion, as well as the eddy induced tracer stirring proposed by Gent and McWilliams (1990) and Gent et al. (1995). Many studies have shown that these parameterizations improve simulations relative to models run in their absence, prompting the parameterizations to be used by nearly all IPCC-class ocean climate models. Nonetheless, there remain many unresolved questions, both fundamental and practical, which support a very active research community aimed at providing more robust and flexible parameterizations of mesoscale eddies. In parallel to research aimed at understanding and parameterizing the mesoscale, the modelling community has steadily seen an increase in the numerical integrity of model codes, and the refinement of resolutions available for representing the ocean circulation. This effort has led to a few global, or near global, simulations with vigorous mesoscale eddy variability.

The intense level of research activities related to ocean mesoscale eddies prompted the CLIVAR Working Group for Ocean Model Development (WGOMD) to organize a three-day scientific workshop at the UK Met Office from 27-29 April, 2009. The main goals of the workshop were the following:

- To educate the research community regarding the importance of mesoscale eddies in theWorld Ocean, and correspondingly for establishing features of the ocean climate system;
- To identify best practices for parameterizing ocean mesoscale eddies in coarse resolution climate models, and to discuss various research avenues for improved parameterizations;
- To evaluate the ability of state-of-the-science numerical models to accurately represent the ocean mesoscale in eddying simulations.

In addition to these intellectual aims, the workshop was held to honour the seminal works of Gent and McWilliams (1990) and Greatbatch and Lamb (1990). After nearly 20 years, these works remain the touchstone for studies of mesoscale eddy parameterization and theory. Finally, the workshop represented a memorial to the tireless and intellectually penetrating work of Peter Killworth, who passed away in January 2008. Peter was a leader for more than a generation of physical oceanographers, whose work touched upon many aspects of observations, parameterizations, and modelling. He will be deeply missed.

2 The UK Met Office Workshop

The workshop consisted of six speakers per day, with each speaker presenting, in a pedagogical manner, different views on the state-of-the-science in ocean mesoscale eddies as seen through observations, simulations, and theory. The following workshop speaker list consists of a who's who in oceanography.

Day 1: Observing and simulating the ocean mesoscale
- CarlWunsch (MIT): Observations, simulations, and assimilations
- Dudley Chelton (Oregon State University): Global mesoscale eddy variability from satellite altimeters
- Matthew Hecht (Los Alamos): POP simulations in an eddying regime
- Steve Rintoul (CSIRO): Mesoscale processes in the Southern Ocean
- Malcolm Roberts (UK Met Office Hadley Centre): Impacts of the mesoscale on coupled phenomena
- Frank Bryan (NCAR): Tracer transport in eddy resolving global ocean simulations

Day 2: Parameterizing the mesoscale
- Peter Gent (NCAR): Gent-McWilliams with 20/20 hindsight
- Richard Greatbatch (IFM-GEOMAR): Interpretation of mesoscale eddy mixing
- Carsten Eden (IFM-GEOMAR): Parameterisation of mesoscale eddy mixing
- David Marshall (Oxford University): Parameterisation of geostrophic eddies: energetics, conservation
- and flow stability
- Trevor McDougall (CSIRO): Thermodynamic equation of state of seawater-2010
- John Marshall (MIT): The interplay between baroclinic instability, geostrophic turbulence and
- Rossby waves in the ocean (and routes to parameterisation)
- Raffael Ferrari (MIT): Lateral and vertical variations in eddy mixing

Day 3: At the frontier
- Michael Bell (UK Met Office): Forecasting the ocean mesoscale
- Mike Spall (WHOI): Eddies and deep water formation
- Andreas Oschlies (IFM-GEOMAR): Eddies and ocean biogeochemistry
- Baylor Fox-Kemper (University of Colorado): Submesoscale dynamics and parameterization
- Anne-Marie Treguier (IFREMER): Anisotropy, momentum fluxes: a few remaining challenges for parameterizations
- Jim McWilliams (UCLA): Eddy roles in the general circulation

Each speaker was given 70 minutes to delve in-depth into the chosen subject, and for questions and discussion with the 140 participants. Additionally, there was time during breaks, lunch, and evening socials to view more than 40 posters from students, post-docs, and senior scientists. The presentations and most of the posters are available on the meeting webpage http://www.clivar.org/organization/wgomd/meso/meso.php.

The organizers wish to thank the UK Met Office for hosting the workshop and NOAA, NASA and NSF for

generously awarding us additional funding that enabled us to provide travel support for thirteen young scientists who presented posters at the meeting.

3 Workshop Summary

It is difficult to summarize the content of a workshop such as this, where the variety of ideas discussed extend well beyond the number of speakers. Hence, to help in communicating certain of the workshop topics, the editors of Ocean Modelling, the journal founded by Peter Killworth, are planning a special edition in 2010. We have learned a tremendous amount in the 20 years since Gent and McWilliams (1990) and Greatbatch and Lamb (1990), and it is very satisfying to reflect on this deepening of understanding. It is in turn exciting to imagine how the next generation will continue to expand our knowledge of the ocean garnered from increasingly realistic global eddying simulations, the growing database of observations, and the continuing application of fundamental theoretical principles. The special edition of Ocean Modelling aims to provide a benchmark to document mesoscale eddy research of the past 20 years, and to promote many of the ideas that will be debated into the future.

We are entering an era where climate simulations with an eddying ocean will become common. Many of the assumptions and results arising from the non-eddying simulations will thus be tested. Do we need to resolve the mesoscale to obtain robust simulations of global climate, or can we rely on the parameterized coarsely resolved models? What does it mean to resolve the ocean mesoscale? Perhaps these questions will only be answered after a generation of researchers sufficiently digest eddying models to provide mechanistic interpretations of the huge amounts of information generated by the simulations. How do eddies impact climate variability, predictability, and stability? This question is of fundamental importance as the climate science community aims to realize the goals of CLIVAR by examining the potential for predicting climate phenomena at time scales extending out to the decadal, and to project climate for the 21st Century. These questions, and many more, motivate the science community to continue seeking an intellectual basis for describing the ocean and its role in climate, and to aim for realizing robust simulations of increasing realism. The discussions at this workshop indicate that the ocean mesoscale is at the heart of these goals, thus prompting an ongoing vigorous level of research forming a critical and stimulating area of climate science.

References

Chelton, D. B., Schlax, M., Samelson, R., and DeSzoeke, R.: Global observations of large ocean eddies, Geophysical Research Letters, 34, doi:10.1029/2007GL030 812, 2007.

Gent, P. R. and McWilliams, J. C.: Isopycnal mixing in ocean circulation models, Journal of Physical Oceanography, 20, 150–155, 1990.

Gent, P. R., Willebrand, J., McDougall, T. J., and McWilliams, J. C.: Parameterizing eddy-induced tracer transports in ocean circulation models, Journal of Physical Oceanography, 25, 463–474, 1995.

Greatbatch, R. J. and Lamb, K. G.: On parameterizing vertical mixing of momentum in non-eddy resolving ocean models, Journal of Physical Oceanography, 20, 1634–1637, 1990.

Redi, M. H.: Oceanic isopycnal mixing by coordinate rotation., Journal of Physical Oceanography, 12, 1154–1158, 1982.

Solomon, H.: On the representation of isentropic mixing in ocean models, Journal of Physical Oceanography,1, 233–234, 1971.

Appendix D

Reports

Ocean modeling activities in Japan - Hiroyuki Tsujino (JMA/MRI)

Report to WGOMD of ocean modeling at GFDL Sept2008-May2009 - S. Griffies (GFDL)

UK ocean modelling activities 2008 - Malcolm Roberts (MOHC)

Summary of NCAR Modeling Activities - Gokhan Danabasoglu (NCAR)

Summary of Ocean Modelling Activities in Germany – Richard Greatbatch (IFM-GEOMAR)

Ocean modeling activities in Japan
Report to the CLIVAR Working Group for Ocean Model Development
Submitted by Hiroyuki Tsujino (JMA/MRI), May 2009

Acronyms:
CCSR: Center for Climate System Research, University of Tokyo
ES: Earth Simulator, JAMSTEC
ESC/JAMSTEC: Earth Simulator Center, JAMSTEC
RIGC/JAMSTEC: Research Institute for Global Change, JAMSTEC
JAMSTEC: Japan Agency for Marine-Earth Science and Technology
JMA/MRI: Japan Meteorological Agency Meteorological Research Institute
NIES: National Institute for Environmental Studies
COCO: CCSR Ocean Component Model
MRI.COM: MRI Community Ocean Model

1. Activities related to CMIP5

Most of the efforts made in past years by ocean climate modelers in Japan are devoted to updating OGCMs maintained by their institute or research group in preparation for CMIP5. Two research groups are planning to participate in CMIP5: a group of scientists from CCSR, JAMSTEC/RIGC, and NIES, and a group of scientists from JMA/MRI. Both groups maintain their ocean model (COCO; Hasumi 2006, and MRI.COM; Ishikawa et al. 2005, Tsujino et al. 2009). Some of the recent major developments made in common are:

- Formulation and discretization based on generalized orthogonal curvilinear coordinates and adoption of tri-pole grid arrangement for global model. This is to avoid the singularity at the North Pole and to retain the geographical (latitude-longitude) grids outside the arctic region.
- Use of the second order moment advection scheme (Prather 1986). This is reported to improve representation of the Equatorial thermocline and to alleviate the problem of spurious numerical diffusion that tracer advection schemes exhibit in eddying regimes.
- Thickness distribution of sea ice within a grid cell is represented by partitioning sea ice into several thickness categories. Sea ice in each thickness category is allowed to have heat capacity.
- Inclusion of marine bio-geochemical processes into model source codes so that they might be calculated on-line.

The group of CCSR-JAMSTEC/RIGC-NIES is developing two types of global models. The higher resolution one has a horizontal resolution of 1/4º in zonal and 1/6º in meridional direction and 50 vertical levels. This model is used for near-term (decadal) prediction starting from a state given by data assimilation.

The lower resolution one has a horizontal resolution of 1.4º in zonal and 0.5 ~ 1.4º in meridional direction and 50 vertical levels. The meridional resolution is increased near the Equator. This model is used for long-term projections.

The group of JMA/MRI is also developing two types of global models (Nakano et al. 2008). The lower resolution one has a horizontal resolution of 1º in zonal and 0.5º in meridional directions and 50 vertical levels with one-layer bottom boundary (Nakano and Suginohara 2002). This model is used for long-term simulations. The higher resolution model has a horizontal resolution of 1/8º in the zonal and 1/12º in the meridional direction and 50 vertical levels. This model is basically run as a stand alone ocean-ice model.

These two-groups are planning a comprehensive inter-comparison of CMIP5-class lower-resolution global ocean-ice models after the completion of their models in line with COREs. Results of an inter-comparison activity among high resolution models developed by Japanese modelers are presented by Suzuki et al. (2008).

2. Regional ocean modeling

Efforts of Japanese ocean modelers are also directed to high resolution simulations of the North Pacific Ocean and its western marginal seas.

A group of CCSR-JMA/MRI conducted simulations of the western North Pacific Ocean using high horizontal resolution models. One of them has a horizontal resolution of 1/36º in zonal direction and 1/54º in meridional direction (about 2 km) and 50 vertical levels. Large-scale features of simulated fields are improved with increasing horizontal resolutions while significant improvements are found from the transition from about 20 km to less than 10 km horizontal resolution. On transition from about 10 km to 2 km horizontal resolution, improvements are detected for coastal currents above continental slope.

A group of JAMSTEC/ESC is planning a 1/30º horizontal resolution simulation for the North Pacific Ocean using the updated ES (ES2) focusing on submesoscale features in the Kuroshio and the Oyashio current system (H. Sasaki, personal communication).

Modeling study for the Japan Sea is active in the Kyushu University. They focus on effects of the Japan Sea on climate (e.g., Hirose et al. 2008; Hirose et al. 2009). Modeling study for the Okhotsk Sea is active in the Hokkaido University. They focus on currents along coasts and straits, sea ice processes, and dense water formation (e.g., Uchimoto et al. 2008).

References:

Hasumi, H. (2006): CCSR Ocean Component Model (COCO) version 4.0, *CCSR Report* No. 25, 103pp.

Hirose, N., H. Kawamura, H. J. Lee, and J.-H. Yoon (2007): Sequential Forecasting of the Surface and Subsurface Conditions in the Japan Sea, *Journal of Oceanography*, 63, 3, 467-481.

Hirose, N., K. Nishimura and M. Yamamoto (2009): Observational evidence of a warm ocean current preceding a winter teleconnection pattern in the northwestern Pacific, *Geophysical Research Letters*, 36, L09705, doi:10.1029/2009GL037448.

Ishikawa, I., H. Tsujino, M. Hirabara, H. Nakano, T. Yasuda, and H. Ishizaki (2005): Meteorological Research Institute Community Ocean Model (MRI.COM) Manual, *Technical Reports of the Meteorological Research Institute No.47*, 189pp (in Japanese).

Nakano, H., M. Hirabara, H. Tsujino, and T. Motoi (2008): Development of a global ocean model with the resolution 1ºx1/2º and 1/8º x 1/12º, *CLIVAR Exchanges* No. 44, 11-13

Nakano, H. and N. Suginohara (2002): Effects of bottom boundary layer parameterization on reproducing deep and bottom waters in a world ocean model, *Journal of Physical Oceanography*, 32, 1209-1227.

Suzuki, T., H. Sasaki, N. Nakashiki, and H. Nakano (2008): Common success and failure in simulating the Pacific surface currents shared by four high-resolution ocean models, in "Ocean Modeling in an Eddying Regime", edited by M. W. Hecht and H. Hasumi, Geophysical Monograph 177, pp.165-175, American Geophysical Union, Washington D.C.

Tsujino, H., T. Motoi, I. Ishikawa, M. Hirabara, H. Nakano, G. Yamanaka, T. Yasuda, and H. Ishizaki (2009): Reference Manual for the Meteorological Research Institute Community Ocean Model (MRI.COM) Version 3, (in preparation).

Uchimoto, K., H. Mitsudera, N. Ebuchi and Y. Miyazawa (2007): Anticyclonic eddy caused by the Soya Warm Current in an Okhotsk OGCM, *Journal of Oceanography*, **63,** 379-391.

Report to WGOMD of Ocean Modeling at GFDL: Sept2008-May2009 – S. Griffies

GFDL aims to contribute four coupled climate models to CMIP5 in support of the IPCC AR5. In brief, these found models consist of the following configurations.

EM2M: This coupled model uses the same atmosphere and sea ice model from the AR4 CM2.1 configuration. The ocean is updated to the MOM4p1 code base with modified physical and numerical settings. In addition, this model employs an interactive ocean, land, and atmosphere biogeochemistry.

EM2G: This coupled model is the same as ESM2M, but uses an isopycnal coordinate ocean model.

CM3: This coupled model uses an ocean and sea ice configuration very close to the CM2.1 model from AR4, but with significantly updated atmospheric dynamics, chemistry, and physics. In particular, this model employs interactive aerosols.

CM2.5: This model uses a 1/4 mercator projection of MOM4p1 coupled to a 1/2 degree atmosphere. The main aim for this model is to contribute to the decadal prediction element of AR5.

Model development for these configurations will continue into late 2009, at which point the CMIP5 experiments will start in full.

UK Ocean Modelling Activities 2008-9
Summarised by Malcolm Roberts (MOHC)

Met Office Hadley Centre (MOHC)
The ocean/sea-ice components of HadGEM2-ES (Earth System) model, our model for IPCC AR5, are broadly similar to HadGEM1 (IPCC AR4). Main ocean differences are parameter values for vertical tracer diffusivity (changed vertical profile near surface to reduce mixing), and reducing horizontal viscosity near the equator.

Our new HadGEM3 coupled climate model, which incorporates the NEMO ocean and CICE sea-ice models (on a tri-polar, nominally 1x1° grid with enhancement to 1/3 degree meridionally at the equator) coupled to the atmosphere via OASIS3, is currently being developed, as one of a hierarchy of coupled models at different resolutions. This model is now being used for the operational seasonal forecast, but will not be used for IPCC AR5.
The initial version gave a rather cold SST climatology, so sensitivity studies looking into parameters in the TKE vertical mixing scheme are ongoing.
Contribution to NEMO system developments, including improved Gent-McWilliams implementation (with NOCS).

Met Office Ocean Forecasting (John Siddorn)
The Ocean Forecasting R&D group has been focusing on transitioning their modelling systems from the Unified Model FOAM, for non-tidal modelling applications, and the POLCOMS system, for tidal applications, to use NEMO in all Met Office short-term forecasting systems. At the same time as transitioning to NEMO the opportunity was taken to increase both the horizontal and vertical resolution of our open ocean systems and rationalise the configurations used. This has resulted in a reduction from 10 to 4 operational open ocean configurations. The focus to date has been on validating these systems to give an understanding of the product quality, the results of which have been extremely encouraging. Progress for the tidal applications using has been slower, and the focus has been on updating the NEMO code to ensure suitability of tidal work. It is envisaged that by the end of 2009 a NEMO-Shelf system will be running that will form the basis for future operational runs.

NCAS-Climate, University of Reading, and UKMO
The HiGEM coupled model (incorporating a 1/3 degree ocean model and based on HadGEM1), developed as part of the UK-HiGEM and UK-Japan Climate Collaboration projects, is being used for seasonal-to-decadal integrations which will be submitted to AR5.
An enhanced resolution version of the HadGEM3 model, using the 1/4° NEMO model, is also being developed jointly between MOHC and NCAS-Climate, and may be used as part of a seasonal-to-decadal contribution to AR5 if it is ready in time.

National Oceanography Centre, Southampton (NOCS) (Adrian New)
A number of ORCA025 integrations performed using DFS3/4 forcings (DRAKKAR forcing set) as part of DRAKKAR group. Global 1/12 model planned, and short 1/36 model integrations to study internal tides.
NEMO system developments, including on-the-fly interpolation of forcing fields.
Work on CHIME – HadCM3 model but with hybrid coordinates in the ocean (z at surface, isopycnal beneath mixed layer) – to increase model model diversity – used for freshwater hosing and warming experiments.
Work on AGRIF nesting to enable use in sea-ice covered regions.
NOCS and MOHC have signed an agreement to work together more closely on ocean and sea-ice model development.

Imperial College Ocean Model (ICOM) – unstructured, adaptive mesh **(Matthew Piggott)**
Progress on the development of ICOM is currently focusing strongly on three-dimensional, large-scale, high aspect ratio baroclinic problems. The associated highly-demanding computational issues that result include the accurate representation of balanced dynamics, very ill-conditioned elliptic pressure equations, maintaining sharp interfaces as well as subtle stratification in tracer fields, and high computational cost because of large degree-of-freedom counts and long simulation times. We are addressing these through the following: implementation of a new finite element discretisation type (discontinuous linear representation of velocity and tracer fields, and a continuous quadratic representation of pressure) which allows for accurate and stable representation of balanced dynamics, as well as excellent treatment of advection dominated fields; new algebraic multi-grid (AMG) solvers that have been demonstrated to perform better than off-the-shelf AMG libraries for the uniquely challenging ocean problem; parallelisation of new developments and benchmarking on a number of platforms including a Cray XT4 where preliminary results have shown excellent scaling up to 1024 cores.

Additional developments include a new fully functioning conservative and bounded mesh-to-mesh interpolation method for use with adaptivity; in addition to full 3D adaptivity, the new capability to use 2D adaptivity in the horizontal, and 1D adaptivity in the vertical so that columns can be preserved in certain regions if required; upper mixed layer models implemented via the flexible generic length scale method and validated against lab and real world data; a new NPZD biology module; improved mesh movement algorithms.

Reading ESSC (Keith Haines)
Working on global ocean reanalysis with the NEMO 1 degree and 1/4 degree models forced with ECMWF meteorology. Currently available reanalysis products assimilate all available hydrography for 1960-2007@ 1degree and 1987-2007@1/4 degree. Diagnostics of interest include water mass changes, circulation changes in the Arctic, and thermohaline circulation changes, including the AMOC.
Results show DFS4 performs better than DFS3 (fresh water fluxes more in balance with assimilated salinity data, hence reducing sea level trends in assimilated run). Future work will focus on altimeter assimilation and also the use of assimilation to initialise coupled models for AMOC and climate prediction studies in Rapid-Watch.

Summary of NCAR Modeling Activities
Gokhan Danabasoglu (NCAR)
01 April 2009

We have recently finalized the version of our ocean model to be used in the next generation of the Community Climate System Model, i.e., CCSM4. This will also be the model version that will be utilized in most of the simulations for NCAR's contributions to the IPCC AR5. Some of the major developments that are included in this ocean model since its CCSM3 version are:

- A new base code (POP2) allowing for both micro- and macro-tasking and including many infra-structure changes,
- Modified land-ocean mask and new vertical (60-level) grid with many bottom topography changes - horizontal resolution is still nominally 1^{o},
- Ferrari et al. (2008) near-surface eddy flux parameterization as implemented by Danabasoglu et al. (2008) (CPT),
- Upper-ocean enhancement and deep-ocean reduction of both isopycnal and thickness diffusivity coeffcients as detailed in Danabasoglu and Marshall (2007) (CPT),
- Fox-Kemper et al. (2008a) submesoscale mixing parameterization (Fox-Kemper et al. 2008b) (CPT),
- A parameterization for deep channel and shelf overflows (Danabasoglu et al. 2009 and Briegleb et al. 2009, both in preparation) (CPT),
- Simmons et al. (2004) tidal mixing scheme (Jayne 2009),
- Reformulation of anisotropic horizontal viscosities (Jochum et al. 2008),
- Horizontally-varying internal wave breaking, i.e., background, vertical diffusivity and viscosity (Jochum 2009),
- Zenith angle dependent diurnal cycle of solar forcing,
- Passive tracer infrastructure and prognostic ecosystem model,
- Many additional diagnostics.

We have continued to participate in the two ocean Climate Process Team (CPT) activities. The resulting parameterizations that have been already implemented in the ocean model are denoted by the CPT acronym in the above list. In particular, we have developed a new overflow parameterization for deep channel and shelf overflows,i.e., open-ocean overflows, to represent exchanges through narrow straits / channels, associated entrainment and intrusion of overflow product water into the open ocean. Currently, this parameterization is used for the Denmark Strait, Faroe Bank Channel, Ross Sea, and Weddell Sea overflows.

The CORE version 2 Normal Year and Inter-Annual data sets have been finalized and released through the GFDL web site.

We have been continuing with our investigations of decadal variability and associated predictability in various coupled simulations with CCSM3, CCSM3.5, and CCSM4. In particular, our focus has been the multi-decadal variability in the North Atlantic as depicted by the Atlantic Meridional Overturning Circulation (AMOC). We have been collaborating with colleagues at the GFDL in these activities.

A set of ocean-only, ocean{sea-ice coupled, and fully-coupled integrations have been completed with a global 1=10_ eddy-permitting / resolving ocean model. Analysis of the results is on going.

References

Briegleb, B. P., G. Danabasoglu, and W. G. Large, 2009: An overflow parameterization for the ocean component of the Community Climate System Model. NCAR Tech. Note (in preparation).

Danabasoglu, G., and J. Marshall, 2007: Effects of vertical variations of thickness diffusivity in an ocean general circulation model. Ocean Modelling, 18, 122-141, doi:10.1016/j.ocemod.2007.03.006.

Danabasoglu, G., R. Ferrari, and J. C. McWilliams, 2008: Sensitivity of an ocean general

circulation model to a parameterization of near-surface eddy fuxes. J. Climate, 21, 1192-1208.
Danabasoglu, G., W. G. Large, and B. P. Briegleb, 2009: A parameterization for deep channel and shelf overflows: Application to the Nordic Seas overflows and effects on model solutions. (in preparation).
Ferrari, R., J. C. McWilliams, V. M. Canuto, M. Dubovikov, 2008: Parameterization of eddy fluxes near oceanic boundaries. J. Climate, 21, 2770-2789, doi:10.1175/2007JCLI1510.1.
Fox-Kemper, B., R. Ferrari, and R. Hallberg, 2008a: Parameterization of mixed layer eddies. Part I: Theory and diagnosis. J. Phys. Oceanogr., 38, 1145-1165, doi:10.1175/2007JPO3792.1.
Fox-Kemper, B., G. Danabasoglu, R. Ferrari, and R. W. Hallberg, 2008: Parameterizing submesoscale physics in global climate models. CLIVAR Exchanges, 13, 3-5.
Jayne, S. R., 2009: The impact of abyssal mixing parameterizations in an ocean general circulation model. J. Phys. Oceanogr., doi:10.1175/2009JPO4085.1 (in press).
Jochum, M., 2009: Impact of latitudinal variations in vertical di_usivity on climate simulations. J. Geopyhs. Res., 114, C01010, doi:10.1029/2008JC005030.
Jochum, M., G. Danabasoglu, M. Holland, Y.-O. Kwon, and W. G. Large, 2008: Ocean viscosity and climate. J. Geophys. Res., 113, C06017, doi:10.1029/2007JC004515.
Simmons, H. L., S. R. Jayne, L. C. St. Laurent, and A. J. Waever, 2004: Tidally driven mixing in a numerical model of the ocean general circulation. Ocean Modelling, 6, 245-263, doi:10.1016/S1463-5003(03)00011-8.

Summary of Ocean Modelling Activities in Germany – Richard Greatbatch (IFM-GEOMAR)

Alfred Wegener Institute, Bremerhaven:

1. Finite-element ocean circulation model (FEOM) (Jens Schroeter, Sergey Danilov)

FEOM is a primitive-equation general ocean circulation model developed in the framework of community ocean model (COM) project at the AWI. It works on horizontally unstructured triangular meshes and supports z, sigma or any combination of them as the vertical coordinate. The model is coupled to a finite-element sea ice model which offers both visco-plastic and elastic visco-plastic solvers. The coupled model (FESOM) is commonly integrated for 1948-2008 on a coarse global mesh and is successfully employed at the AWI to study ice and freshwater formation in the Southern Ocean and also to analyze the bottom pressure variability. Several regional version (North Atlantic, Southern Ocean with focus on Weddell and Ross Seas) are also supported. FEOM/FESOM are MPI parallelized.

Current status: Can be downloaded and used (http://aforge.awi.de/gf/project/com/). Current direction of development: New global setups with regional focus and numerical optimization.

2. A set of unstructured-mesh shallow water models (For TsunAWI, Joern Behrens; For the rest, Jens Schroeter, Sergey Danilov)

An original finite-element version (TsunAWI) was developed in support of GITEWS (German-Indonesian Tsunami Early Warning System). It is currently augmented by several other versions (which are more efficient numerically) based on both finite elements and finite volumes. They are applied to tidal modeling on regional (North Sea) and global scales.

Current status: Can be downloaded and used. For TsunAWI, use
http://aforge.awi.de/gf/project/tsunawi/;
for other codes, contact S. Danilov (Sergey.Danilov@awi.de)

Current direction of development: Adjoint models through automatic differentiation.

3. Deep water formation for past, present, and future climates (Gerrit Lohmann, http://www.awi.de/en/go/paleo)

Using an integrated approach of data and model simulations, we will examine the processes in the atmosphere-ocean–sea ice system responsible for the fluctuations in deep water formation rates on interannual to longer time scales. We identify sensitive sites for the ocean circulation changes. These changes are compared to recent salinity anomaly events as well as the 8.2 kyr event which is a distinct example of rapid climate change that occurred in the relatively stable Holocene period. For the more distant past, the mechanisms for deep water formation are studied, where special focus is on the glacial and cenozoic climate with other ocean gateway configurations. To compare the results with data, tracers are introduced and proxy modules are developed. Main tools are the global ocean circulation model MPI-OM by using a horizontal curvilinear grid, as well as FEOM and NAOSIM developed at AWI.

4. Studies using the MITgcm code (Martin Losch)

The MITgcm code is used to study ocean phenomena on regional and global scale at various resolutions. On a global scale, coarse resolution models with a newly developed biogeochemstry component are operated to investigate the cycling and decoupling of silica, nitrogen and carbon and the physical control on biogeochemical activity on interannual to centennial time scales. The same questions are further explored with a global configuration at 18km resolution (Martin Losch, Christoph Völker). Processes at the ice edge and in ice shelf cavities are a particular focus. Further, a data assimilation study aims at estimating trends in Weddell Sea Deep water heat content (Olaf Klatt,
Martin Losch).

An Arctic configuration similar to the NAOSIM system is run on a rotated, quarter-degree resolution grid (Martin Losch and the NAOSIM group).

Somewhat exotic, the development of saltfingers in the ocean are studied in direct numerical simluations (DNS) at a submillimeter resolution with the MITgcm (Thomas Zweigle, Martin Losch).

5. Polar processes in global ocean and climate models (Rüdiger Gerdes)

A focus of modeling work at AWI is the representation of polar processes in global ocean and climate models. We perform hindcasts and process studies with regional ocean-sea ice models and investigate possibilities for seasonal and decadal prediction of the ocean-sea system in the Arctic. Much of the work is embedded in the Arctic Ocean Model Intercomparison Project (AOMIP). An internal comparison of FESOM (finite element sea ice-ocean model), NAOSIM (North Atlantic/Arctic Ocean-Sea Ice Model), and the MITgcm in a configuration for the Arctic Ocean and the subpolar North Atlantic aims at identifying and quantifying the advantages of the finite element model approach.

KlimaCampus, University of Hamburg
Contact: Detlef Stammer

At the KlimaCampus of the University of Hamburg, ocean modeling takes place in several institutions, ranging from the simulation of the physical circulation to the interaction of the physical flow field with bio-geochemistry and ecosystem. In collaboration with the MPI-M, coupled modeling activities take place that include a simulation of the present climate, climate scenario runs of future developments, but also hindcasts of the last 1000 yrs of the climate system. An analysis of the simulating ocean state is a`strong part of those runs. Geographically, activities cover the global ocean, but substantial activity is also ongoing in the Atlantic sector and in the European North Seas and the Arctic. In the latter domain, the simulation of the sea ice cover is also a question of concern. Last but not least, the KlimaCampus has a strong assimilation component that constrains the MITgcm ocean model by most available ocean observations. Those aspects – run under GECCO – again cover the global domain, but also high-resolution Atlantic and Arctic activities and include sea ice assimilation. An important new aspect is the “STORM” experiment that is being performed as a community effort of Germany. It is mainly driven by the KlimaCampus and the MPI-M and targets a very high-resolution global ocean run as well as high-resolution coupled ocean-ice-atmosphere runs.

Substantial efforts are ongoing on the European Shelf Seas, especially in the North Sea. Here interdisciplinary modeling simulations, including nutrients, as ongoing in the context of ecosystem modeling. Increasing efforts are ongoing on the paleo side. Here it is especially the meteorology that is in the process of developing new coupled models, including a spectral ocean model. All other activities are based on Hamburg ocean models (shelf sea from IfM and global models from MPI) and on the MITgcm. However, we are in the process of developing new coupled models for which the adjoint exists. Those models will be used for coupled data assimilation and the initialization for decadal forecasts.

Leibniz Institute for Marine Sciences (IFM-GEOMAR), Kiel
Contact: Richard Greatbatch

1. Eddy-permitting global modelling of decadal ocean variability (Claus Böning)

Investigation of the mechanisms of decadal ocean variability relevant to climate has been a main theme of modelling activities in Kiel using various implementations of NEMO. Research questions included: the spatio-temporal structure and causes of MOC variability in the North Atlantic; the dynamics of the subpolar gyre and its role in decadal changes of freshwater content; the variability of the Subtropical Cells in the Pacific and its impact on equatorial SST; and several aspects of South Pacific and Indian Ocean variability and trends, e.g. of the Indonesian Throughflow, Leeuwin Current, and the subtropical gyres of the south Pacific and Indian Oceans.

Model experiments included a series of hindcasts (under CORE forcing) using global ocean-ice model configurations developed in the DRAKKAR program: a non-eddying 1/2°-model (ORCA05)and an eddy-permitting 0.25°-model (ORCA025). Interpretation of the causes of low-frequency ocean variability in the reference experiments was aided by a host of sensitivity experiments using different combinations of climatological and interannual forcing in individual forcing components (wind stress, heat and freshwater fluxes), or in geographic regions (e.g., interannual forcing in the tropics and climatological elsewhere).

A specific focus of research was the role of the vigorous eddy variability in the Agulhas regime. Using the two-way nesting capabilites of NEMO (involving AGRIF) experiments helped to both clarify the impact of upstream perturbations on the retroflection behavior, as well as the dynamical influence of the regime on the decadal variability of the Atlantic MOC.

2. Mesoscale eddy closures (Carsten Eden)

A mesoscale eddy closure was proposed by Eden and Greatbatch (2008) for the thickness diffusivity of the Gent and McWilliams (1990) parameterisation. The diffusivity is given in that closure by the product between a diagnostic eddy length scale with a eddy velocity scale. The diagnostic length scale was estimated based on eddy-permitting model results and satellite observations as the minimum between Rhines scale and local Rossby radius, while the velocity scale is given by a prognostic eddy kinetic energy (EKE) budget.

The EKE is integrated in a coarse model as an additional model variable, with further parameterisations for EKE production, dissipation, advection and radiation. The closure was tested in regional models of the North Atlantic and the Southern Ocean (FLAME) and a global model (CCSM4) and its performance, in particular the validity of the mixing length assumption for the thickness diffusivity, was successfully evaluated using eddy-resolving regional model versions. The diffusivity implied by the closure agrees well with previous estimates of the thickness diffusivity in the North Atlantic (Eden et al 2007) and the Southern Ocean (Eden, 2006). Furthermore, isopycnal diffusivities have been estimated by Eden and Greatbatch (2009) using eddy fluxes of several different passive tracer in an eddy-permitting biogeochemical model of the North Atlantic, showing strong anisoptropy but similarity amongst each other and, in particular, to the previously estimated thickness diffusivity. This result

supports the usual practise of using
identical thickness and isopycnal diffusivities in ocean models.

References:
Eden, C. and R. J. Greatbatch, 2008: Towards a mesoscale eddy closure. Ocean Modelling, 20, 223-239.
Eden, C., Greatbatch, R. J. and Willebrand, J., (2007): A diagnosis of thickness fluxes in an eddy-resolving model, JPO, 37, 727-742
Eden, C. (2006): Thickness diffusivity in the Antarctic Circumpolar Current, GRL, 33,L11606,doi:10.1029/2006GL026157
Eden, C. and R.J. Greatbatch (2009): A diagnosis of isopycnal mixing by mesoscale eddies. Ocean Modeling 27 (1-2) 98-106

3. Biogeochemical modeling (Andreas Oschlies)

Main topics of the marine biogeochemical modelling group at IFM-GEOMAR include the development of novel adaptive marine ecosystem models, that minimise explicit complexity by introducing property state variables in addition to the traditional material state variables. Simple Earth System models are used to investigate the response of the carbon, nitrogen, and oxygen cycles to changes in climate, atmospheric CO2, and other natural and anthropogenic perturbations (including some geo-engineering approaches). A special focus is on the sensitivity of oxygen minimum zones to environmental change. In close collaboration with mathematicians at the University of Kiel, global biogeochemical models are also used to investigate what complexity of marine ecosystem models is needed to reproduce the distribution of nutrients, carbon, and oxygen in the ocean.

Leibniz Institute for Baltic Sea Research, Warnemuende:
Contact: Martin Schmidt

1. Coastal Ocean Model Development (Hans Burchard).

The model framework within which coastal ocean model development at IOW is mainly carried out is the GOTM/GETM system. IOW scientists are major contributors to these two Public Domain models.

GOTM stands for General Ocean Turbulence Model (www.gotm.net, see Burchard et al. [1999]; Umlauf et al. [2005]) which is a one-dimensional water column model for coupled physical-biogeochemical simulations. For the physical part, a library of state-of-the-art turbulence closure models has been implemented, based on algebraic second-moment closures coupled to two-equation turbulence models (Burchard and Baumert [1995]; Burchard and Bolding [2001]; Umlauf and Burchard [2005]). A biogeochemical module with different biogeochemical models is coupled interactively to the water column model (Burchard et al. [2006]). Both, the turbulence module and the biogeochemical module are written such that they can be coupled into three-dimensional models, see, e.g. Holt and Umlauf [2008] for the turbulence module.

GETM stands for General Estuarine Transport Model (www.getm.eu, see Burchard and Bolding [2002]) which is a three-dimensional finite-volume hydrodynamic model based on general vertical coordinates, structured grids in the horizontal and explicit mode splitting. GETM is paralellised and uses the turbulence and biogeochemistry modules from GOTM. This model system consisting of GOTM and GETM is used at IOW for a large range of studies, envolving realistic costal sea applications (including environmental impact studies), as well as idelaised theroretical studies.

Recent model developments carried out by IOW scientists in the framework of the GOTM/GETM model system are:

• Development of stiff solvers for ordinary differential equations as they are applied for the source and sink terms of biogeochemical models. These solvers are implicit linear solvers of first and second order accuracy which guarantee conservation, monotonicity and positivity, see Burchard et al. [2003, 2005, 2006]; Bruggeman et al. [2006]. Recently, these schemes have been compared to Rosenbrock solvers which are typically used in atmospheric chemistry (Schippmann [2009]).

• For the potential energy anomaly, -, which is a measure of water column stability used in coastal oceanography, Burchard and Hofmeister [2008] derived an exact transport equation and implemented the analysis in GOTM and GETM. This analysis has been used in a GETM application to the Limfjord in Denmark for studying processes of stratification and mixing (Hofmeister et al. [2009b]).

• A method for diagnosing physical and numerical mixing in ocean models has been derived by Burchard and Rennau [2008] and applied to quantify numerical mixing in the Western Baltic Sea by Rennau and Burchard [2008].

• In order to find optimal compromises between geopotential, sigma and isopycnal coordinates, Burchard and Beckers [2004] developed a method for vertically adaptive coordinates and demonstrated the performance for a water column model. This is currently extended to three dimensions by Hofmeister et al.
[2009a] who could show that the numerical mixing in coastal ocean models can be considerably reduced by optimised adaptive coordinates.

• A new method for extending hydrostatic ocean models to represent nonhydrostatic dynamics is suggested by Klingbeil [2009] and implemented into GETM. This new method does not require the solution of a Poisson equation for the pressure and it is shown that dispersive internal waves can be reproduced quite accurately.

• An estuarine circulation analysis tool has recently been developed by Burchard and Hetland [2009] and implemented into GOTM. This allows to quantify contributions from all individual processes to estuarine circulation, such as gravitational circulation, tidal straining, and wind straining.

• Several new biogeochemical models have recently been developed and implemented in to GOTM, such as an iron speciation model (Weber et al. [2005]), a redoxcline chemistry model (Yakushev et al. [2007]), and a bromoform model (Hense and Quack [2009]).

References

Bruggeman, J., H. Burchard, B. Kooi, and B. Sommeijer, A second-order, unconditionally stable, mass-conserving integration scheme for biochemical systems, Appl. Num. Math, 57 , 36–58, 2006.
Burchard, H., and H. Baumert, On the performance of a mixed-layer model based on the k-epsilon turbulence closure, J. Geophys. Res., 100 , 8523–8540, 1995.
Burchard, H., and J.-M. Beckers, Non-uniform adaptive vertical grids in one-dimensional numerical ocean models, Ocean Modelling, 6 , 51–81, 2004.
Burchard, H., and K. Bolding, Comparative analysis of four second-moment turbulence closure models for the oceanic mixed layer, J. Phys. Oceanogr., 31 , 1943– 1968, 2001.
Burchard, H., and K. Bolding, GETM – a general estuarine transport model. Scientific documentation, Tech. Rep. EUR 20253 EN, European Commission, 2002.
Burchard, H., and R. D. Hetland, Quantifying the contributions of tidal straining and gravitational circulation to residual circulation in periodically stratified estuaries, J. Phys. Oceanogr., 2009, submitted.
Burchard, H., and R. Hofmeister, A dynamic equation for the potential energy anomaly for analysing mixing and stratification in estuaries and coastal seas, Estuarine, Coastal and Shelf Science, 77 , 679–687, 2008.
Burchard, H., and H. Rennau, Comparative quantification of physically and numerically induced mixing in ocean models, Ocean Modelling, 20 , 293–311, 2008.
Burchard, H., K. Bolding, and M. R. Villarreal, GOTM – a general ocean turbulence model. Theory, applications and test cases, Tech. Rep. EUR 18745 EN, European Commission, 1999.

Burchard, H., E. Deleersnijder, and A. Meister, A high-order conservative Patankar-type discretisation for stiff systems of production-destruction equations, Appl. Numer. Math., 47, 1–30, 2003.
Burchard, H., E. Deleersnijder, and A. Meister, Application of Modified Patankar schemes to stiff biogeochemical models for the water column, Ocean Dynamics, 55 , 326–337, 2005.
Burchard, H., K. Bolding, W. Kühn, A. Meister, T. Neumann, and L. Umlauf, Description of a flexible and extendable physical-biogeochemical model system for the water column, J. Mar. Sys., 61 , 180–211, 2006.
Hense, I., and B. Quack, Modelling the vertical distribution of bromoform in the upper water column of the tropical Atlantic Ocean, Biogeosciences, 6 , 535–544, 2009.
Hofmeister, R., J.-M. Beckers, and H. Burchard, Non-uniform adaptive vertical grids in a 3D numerical ocean model, Ocean Modelling, 2009a, in preparation.
Hofmeister, R., H. Burchard, and K. Bolding, Realistic modelling of stratification in the Limfjord, Cont. Shelf Res., 2009b, accepted for publication.
Holt, J. T., and L. Umlauf, Modelling the tidal mixing fronts of the northwest European continental shelf, Cont. Shelf Res., 28 , 887–903, 2008.
Klingbeil, K., A feasibility study for implementing an alternative non-hydrostatic pressure formulation into a coastal ocean model, 2009, diploma thesis, University of Rostock, Germany, in preparation.
Rennau, H., and H. Burchard, Quantitative analysis of numerically induced mixing in a coastal model application, Ocean Dynamics, 2008, accepted for publication.

Schippmann, B., Comparison of Rosenbrock methods with modified Patankar schemes used in biogeochemical modelling, 2009, diploma thesis, University of Rostock, Germany.
Umlauf, L., and H. Burchard, Second-order turbulence models for geophysical boundary layers. A review of recent work, Cont. Shelf Res., 25 , 795–827, 2005.
Umlauf, L., H. Burchard, and K. Bolding, General Ocean Turbulence Model. Source code documentation, Tech. Rep. 63 , Baltic Sea Research Institute Warnemünde, Warnemünde, Germany, 2005.
Weber, L., C. Völker, M. Schartau, and D. A. Wolf-Gladrow, Modelling the speciation and biochemistry of iron at the Bermuda Atlantik Time-series Study site, Global Biogeochemical Cycles, 19 , doi:10.1029/2004GB002,340, 2005.
Yakushev, E. V., F. Pollehne, G. Jost, I. Kuznetsov, B. Schneider, and L. Umlauf, Analysis of the water column oxic/anoxic interface in the Black and Baltic seas with a numerical model, Marine Chemistry, pp. 388–410, 2007.

2. Other activities (Martin Schmidt)

The focus of modelling at IOW is the ecosystem of the Baltic Sea. The aim is to understand its major players but also various details. The institute's design is interdisciplinary and project topics range from physical oceanography, biochemical cycle studies over sediment transport studies to special investigations on fish stock dynamics.

Examples of projects are:

Transient simulations for time slices 2000-2100 will be used to assess the impact of different climate change scenarios on the hydrography and biogeochemistry of the Baltic Sea. Historical extreme climate conditions like LIA and MWP will be compared to contemporary and future scenarios. All scenarios are forced by meteorological data sets derived from dynamical downscaling methods for the Baltic Sea region. (INFLOW, ECOSUPPORT)

Spatially highly resolved ecosystem models for lagoons in the Baltic Sea will be used for quantitative estimations of the function of these lagoons for nutrient retention and as nutrient sink. (AMBER)

With the aid of an ecosystem model, path ways, residence times, and final sinks for nutrients from different sources (e.g. rivers, N-fixation) will be estimated. (BEST)

The Baltic Sea ecosystem model will be applied for a tropical region the Beibu Bay. In this study basic knowledge about hydrography and biogeochemistry will be derived. (BEIBU)

A modified version of the Baltic Sea ecosystem model is used for the investigation of the Namibian upwelling ecosystem that has a very special dynamics similary to the Baltic Sea, because it often becomes hypoxic. (GENUS)

A consistent fish population model for the Baltic Sea, including trophic levels from primary production up to fish, will be applied to assess the impact of fisheries, nutrient loads and climate variability on the fish population dynamics. This requires the development of new methods for fish population modelling.

The consequences of building the Fehmarnbelt Bridge for the Baltic Sea ecosystems are investigated in consortium between DHI, B&B and IOW.

Several numerical tools are used to address these topics. They are basically circulation models with optional modules for atmosphere-ice-ocean coupling, biochemical dynamics, sea ice physics, surface waves and sediment transport as well.

Some historical background may be of interest. The water exchange between North Sea and Baltic Sea through the Belt Sea is governed by barotropic and baroclinic waves. Hence, the ocean model should be a free surface model and Baltic Sea modelling at IOW started with the free surface ocean model of Killworth, Stainforth, Webb and Paterson, the only explicit free surface code available in the beginning of the 90ies. Supplemented with Stephens' OBC it was used for short time numerical experiments to hindcast field measurements with the aim to understand the water exchange throught the Belt Sea. The need for more compute performance motivated the migration to a parallel version of MOM, which required the implementaion of the free surface code and OBC code in MOM. From some work together with GFDL this contributed to a new version of MOM with improved tracer conservation and means for correct treatment of fresh water fluxes. For long time experiments the sea ice model of Winton was added (The Baltic Sea has a seasonal ice cover) and a new module for the handling of surface fluxes was developed.

Thomas Neumann develops a special ecosystem model ERGOM that accounts for hypoxic and anoxic conditions in the deep basins of the Baltic Sea. It is a nutrient cycle model that includes nitrogen loss from the ecosystem by denitrification and nitrogen gain by cyanobacteria, which are important processes specific for the Baltic Sea ecosystem. Ecosystem variables undergo the usual tracer dynamics with additional source and sink terms for biochemical processes. A special approach was developed for zooplankton dynamics that allows to include the age of individuals in Eulerian circulation models.

Recently a physical (ice-ocean) Baltic Sea model with high (~1 n.m.) resolution based on mom4p1 could be integrated over several model years. It reveals much better representation of deep basin dynamics than previous less resolved model versions.

Please note the LAS-server that could be used to get examples for model results, data as well as figures: http://www.io-warnemuende.de/live-access-server.1034.html

Max Planck Institute for Meteorology, Hamburg:
Contact: Johann Jungclaus

Ocean model development at MPI-M

Model development at MPI-M has presently two foci:

- Improvement and maintenance of the Max Planck Ocean Model (MPIOM)
- Development of a new genertation of GCMs in the framework of the Icosahedral non-hydrostatic General Circulation Model (ICON)

While it is expected that ICON will become the core model framework at MPI-M over the next years, the current tool for ocean-only, coupled ocean-atmosphere, and ocean-biogeochemistry studies is the primitive equation model MPIOM (Marsland et al., 2003; Griffies et al., 2009; Jungclaus et al., 2006; Wetzel et al., 2006; Raddatz et al., 2007). It is being maintained and improved following both technical and scientific demands.

Recently, a module for ephemeridic tides has been implemented. This model version is used both in global (Müller et al., 2009) and regional modelling studies. Improved parameterizations of vertical mixing, in particular taking into account tidally induced mixing at rough topography are presently implemented. The development of a new sea ice model (to be integrated into MPIOM) is carried out by the new Junior Research Group "Sea Ice in the Earth System). For the CMIP5 simulations, a new grid set-up with a tri-polar grid and a resolution of 0.4° is presently tested and has been coupled to a high-resolution (T159/L100) version of the ECHAM5 model.

ICON is a joint project between MPI-M's atmosphere and ocean departments and the German Weather Service with the goal to develop a new coupled atmosphere-ocean GCM that is capable to operate on a variety of space and time scales. ICON models with different features, but with a generally consistent model philosophy are presently developed as well as atmosphere and ocean general circulation models. The present status of the ocean model development is as follows: A hydrostatic, Boussinesq version of the governing equations has been discretized following the ICON conservation properties both as shallow-water and three-dimensional model. Currently standard physical parameterizations are being implemented. Further ongoing developments in ICON concern a turbulence closure by Lagrangian averaging, a concept for grid refinement, and the implementation of adjoint techniques.

References

Griffies, S.M., and co-authors, 2009: Coordinated ocean-ice reference experiments (CORE's). *Ocean Modelling*, 26, 1-46.

Jungclaus, J.H., M. Botzet, H. Haak, N. Keenlyside, J.-J. Luo, M. Latif, J. Marotzke, U. Mikolajewicz, and E. Roeckner, 2006: Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM. *Journal of Climate*, 19, 3952-3972.

Marsland, S.J., H. Haak, J.H. Jungclaus, M. Latif, and F. Roeske, 2003: The Max- Planck-Institute global ocean/sea-ice model with orthogonal curvilinear coordinates, *Ocean Modelling,* 5, 91-127.

Müller, M., J.H. Jungclaus, J. Sündermann, and M. Thomas: The effect of ocean tides on a climate model simulation. Submitted to *Geophysical Research Letters.*

Raddatz, T.J., C. Reick, W. Knorr, J. Kattge, E. Roeckner, R. Schnur, K.-G. Schnitzler, P. Wetzel, J. H. Jungclaus, 2007: Is the tropical land biosphere dominating the carbon cycle-climate feedback during the 21st century? *Climate Dynamics*, 29, 565-574, doi:10.1007/s00382-007-0247-8.

Wetzel, P., E. Maier-Reimer, M. Botzet, J.H. Jungclaus, N. Keenlyside, and M. Latif, 2006: Effects of ocean biology on the penetrative radiation on a coupled climate model. *Journal of Climate,*19, 3973-3987.

Potsdam Institute for Climate Impact Research

Contact: Anders Levermann

At the Potsdam Institute for Climate Impact Research, Anders Levermann and his group are concerned with the dynamics of tipping elements in the climate system (Lenton et al., PNAS, 2007). The specific systems analyzed are the West Antarctic Ice Sheet, monsoon circulations and the Atlantic meridional overturning circulation. The group runs the coupled climate model of intermediate complexity, CLIMBER-3α which contains the oceanic general circulation model, MOM-3, with a horizontal resolution of 3.75 degrees. Their main interest are processes and mechanisms which determine the large-scale ocean circulation on time scales longer than a decade up to centuries. As an example, Levermann et al. (2005) showed the sea surface anomaly pattern that arises from a collapse of the Atlantic overturning. This pattern is currently explored as a potential measure for monitoring the deep circulation from the ocean surface. In their model Levermann & Born (2007) found two stable state of the North Atlantic subpolar gyre - a feature which has meanwhile been observed in other models and is closely related to Labrador Sea convection. Towards the PIK goal of developing the improved Earth

System Model of Intermediate Complexity (EMIC) CLIMBER-3, the group is co-developing the Parallel Ice Sheet Model (PISM-PIK) for application to the great ice sheets. Currently they investigate the interaction of the Antarctic ice shelves with the Southern Ocean including rapid processes such as grounding line migration and ice berg calving. With PISM-PIK, the group is exploring new territory outside the world of coarse resolution models.

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