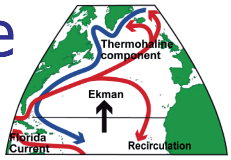
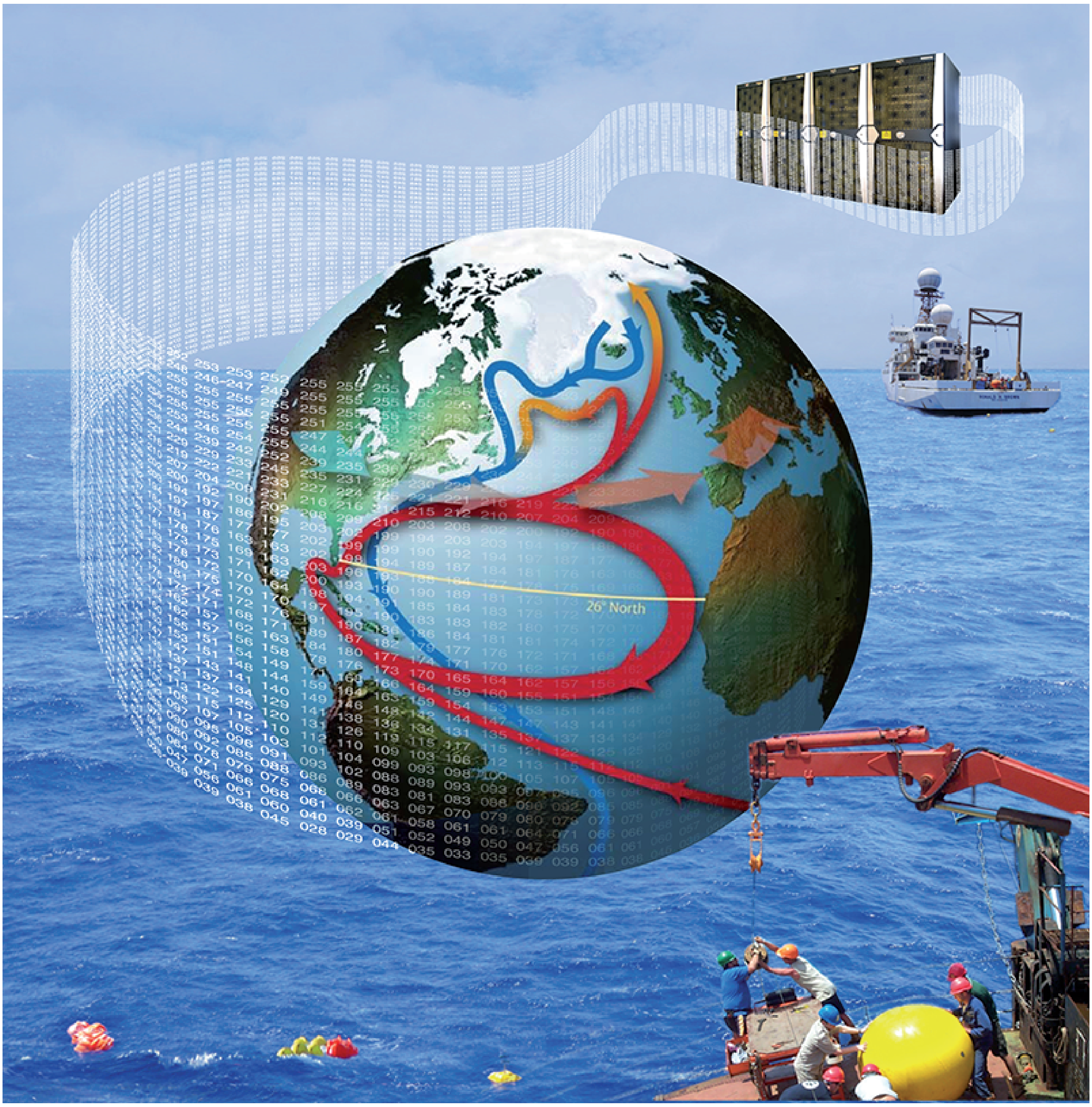
Past, Present and Future Change in the Atlantic Meridional Overturning Circulation



International Science Meeting, 12-15 July 2011, Bristol, U.K.

Programme and Abstracts



Understanding the AMOC through observations and models

The meeting is organised by the UK Natural Environment Research Council's Rapid Climate Change programme (RAPID) and the US CLIVAR AMOC Science Team.

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ACKNOWLEDGEMENTS

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We would also like to thank Institute of Marine Engineering, Science and Technology (IMAREST) for sponsoring the conference bags, and Cape Farewell for providing our after dinner speaker.

Contents

Programme

Tuesday 12 July

11:00 Registration

14:00 Science Meeting Opening
David Anderson Chair, RAPID Programme Advisory Group

14:10 Theme 1: What do we know about present and past changes in the AMOC on seasonal to millennial time scales? Chair: David Anderson

14:10 Stuart Cunningham: Meridional overturning circulation and heat flux array at 26.5°N: Variability observed at periods of minutes to years during the period from April 2004 to April 2009. *Invited talk*.

14:50 Torsten Kanzow: Observed and simulated large-amplitude fluctuations of deep meridional volume transports in the subtropical North Atlantic .

15:10 Matthias Lankhorst: 10 years of continuous observations by the MOVE array

15:30 TEA / COFFEE

16:00 Theme 1 continues. Chair: Bill Johns

16:00 Eleanor Frajka-Williams: Covariability of the Gulf Stream with deep return flow at 26°N in 2009, from the RAPID transatlantic moored array.

16:20 Shane Elipot: Latitudinal coherence of the Atlantic Meridional Overturning Circulation from moored array observations.

16:40 Igor Yashayaev: Variability in the Production and Properties of Deep Western Boundary Flows in the Labrador Sea and Downstream.

17:00 Jonathan Bamber: Recent large increases in freshwater fluxes from Greenland into the North Atlantic.

17:20 Arne Biastoch: The Importance of considering Agulhas Leakage for the Variability of the Atlantic Meridional Overturning Circulation.

18:00 Ice breaker: Wine reception in the poster area

Wednesday 13th July

09:00 Theme 1 continues. Chair: Richard Wood

09:00 Jean Lynch-Stieglitz: Ocean Circulation Response to Glacial Aged Heinrich Events. *Invited talk*

09:40 Claude Hillaire-Marcel: The AMOC slow-down during the Younger Dryas - Deep-sea core evidence from Lomonosov Ridge for a contemporaneous drainage even in the NW Laurentide Ice-sheet area.

10:00 Juliette Mignot: Volcanic impact on the Atlantic ocean circulation over the last millennium.

10:20 Babette Hoogakker: Changes in Holocene North Atlantic Deep Water flow and properties.

10:40 TEA / COFFEE

11:10 Theme 1 continues. Chair: Pascale Lherminier

11:10 Paola Moffa Sanchez: Centennial to decadal-scale ocean changes in the North Atlantic during the Late Holocene.

11:30 James Scourse: AMOC variability during the Last Millennium.

11:50 Martha Buckley: Decadal Variability of the Atlantic Meridional Overturning Circulation.

12:10 Camille Marini: On the links between the Atlantic Multidecadal Oscillation and the Atlantic Meridional Overturning Circulation.

12:30 Claus Böning: Manifestation of multi-decadal AMOC changes in the transport of the Florida Current.

12:50 LUNCH

14:00 Themes 1 and 2 poster presentations
Coffee will be available during the poster session. Posters will remain on display for the duration of the meeting. Poster presenters from themes 1-2 will be on hand to explain their posters during this session.

16:00 Theme 1 continues. Chair: Tong Lee

16:00 Johanna Baehr: Predictability of the meridional heat transport. *Invited talk*

16:40 Will Hobbs: Estimates of 21st century North Atlantic heat transport from satellite and drifter data.

17:00 Herle Mercier: Variability of the circulation and heat transport from six occupations of the A25 Greenland-Portugal OVIDE section between 1997 and 2010.

17:20 Bogi Hansen: Why does the AMOC cross the Greenland-Scotland Ridge?

17:40 Kerstin Jochumsen: Hydrographic and overflow variability in Denmark Strait.

18:00 Day 2 close

20:00 CONFERENCE DINNER
After Dinner Speaker: David Buckland: Art and Climate Change

Thursday 14th July

09:00 Theme 2: How does the AMOC influence ocean, atmosphere and terrestrial climate and ecosystems? Chair: Paul Williams

09:00 Sirpa Häkkinen: Wind stress curl and Atlantic Multi-decadal Ocean Variability. *Invited talk*

09:40 Doug Smith: Decadal predictions of the Atlantic overturning circulation and tropical Atlantic atmosphere.

10:00 Yochanan Kushnir: Atlantic multi-decadal variability in the GFDL CM2.1 model and relevance to the real world.

10:20 Lesley Allison: Mechanisms and impacts of decadal-scale AMOC fluctuation events in unforced AOGCM simulations.

10:40 TEA / COFFEE

11:10 Theme 2 continues. Chair: Kathryn Kelly

11:10 Tim Woollings: Ocean overturning and the Atlantic storm track response to climate change. *Invited talk*

11:50 Julie Deshayes: Model inter-comparison study of variability in AMOC and freshwater content in the North Atlantic.

12:10 Elaine McDonagh: Oceanic Freshwater flux at 26°N in the Atlantic.

12:30 Mojib Latif: Understanding simulated long-term changes in the North Atlantic MOC.

12:50 LUNCH

14:00 Theme 3: How will the AMOC change over the next few decades and over the 21st century? Chair: Chris Meinen

14:00 Tony Rosati: Challenges in Predicting AMOC Variability in the Next Decade. *Invited talk*

14:40 C. Roberto Mechoso: Response of the Sea Level and the MOC in a Coupled Ocean-Atmosphere Model to Greenland Ice Melting.

15:00 Paola Cessi: The adiabatic pole-to-pole overturning circulation.

15:20 Themes 3 - 4 and other poster presentations
Coffee will be available during the poster session..

16:50 Theme 3 continues. Chair: David Marshall

16:50 Henk Dijkstra: Stability of the Atlantic Meridional Overturning Circulation. *Invited talk*

17:30 Harry L. Bryden: The Atlantic Meridional Overturning Circulation exports freshwater southwards.

17:50 Ed Hawkins: Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport.

18:10 Sybren Drijfhout: The stability of the MOC as diagnosed from model projections for pre-industrial, present and future climates.

18:30 Day 3 close

Friday 15th July

09:00 Theme 3 continues. Chair: Meric Srokosz

09:00 Rowan Sutton: Predicting the future of the Atlantic Meridional Overturning Circulation. *Invited talk*

09:40 Gokhan Danabasoglu: AMOC variability and prediction studies in the Community Climate System Model version 4 (CCSM4).

10:00 Holger Pohlmann: Skillful predictions of the mid-latitude Atlantic meridional overturning circulation in a multi-model system

10:20 Rym Msadek: Decadal predictability of the AMOC: model results and challenges.

10:40 TEA / COFFEE

11:10 Theme 4: Outlook and Challenges Chair: Meric Srokosz

11:10 Susan Lozier: Linking deep water formation to AMOC variability: a review, a challenge and a plan. *Invited talk*

11:50 Rong Zhang: Atlantic Meridional Overturning Circulation (AMOC) Adjustment to an Abrupt Change in the Nordic Sea Overflow in a High Resolution Global Coupled Climate Model.

12:10 Thomas Rossby: Monitoring ocean mass and heat transport with ADCPs on commercial vessels.

12:30 Jochem Marotzke: The Next Ten Years of AMOC Observations at 26.5 °N - 2014 to 2024. *Invited talk*

13:10 **Closing notes**

13:20 LUNCH

14:00 **Meeting closes**

Poster Presentations

Posters will be on display for the duration of the Science Meeting. However, presenters will be expected to be available to explain their posters during the two afternoon poster sessions on Wednesday and Thursday afternoons. Lists of posters for each session are given below.

Wednesday 13th July, 14:00 - 16:00

Theme 1

Jin **Ba**: North Atlantic Multi-decadal Variability simulated in CGCMs *Poster A2*

Barbara **Berx**: Variability of physical and biological properties in the Faroe Shetland Channel between 2000-2009: results from a long-term monitoring programme and model data. *Poster A3*

Michael **Brüdgam**: The Ability of the Adjoint Method to recover a decadal AMOC Variability. *Poster A4*

Paul **Butler**: The mollusc Arctica islandica: an annually resolved and precisely dated proxy archive of Atlantic water variability during the past millennium. *Poster A5*

Andrea **Cimatoribus**: Freshwater control of AMOC: collapsing the AMOC by changing evaporation and precipitation in the southern hemisphere. *Poster A6*

Nathalie **Daniault**: Variability of the East Greenland Current-Irminger Current (EGIC) transport at the South east tip of Greenland. *Poster A7*

Entcho **Demirov**: A model study of the Labrador Sea Water production, pathways and transit times. *Poster A8*

Alexey **Fedorov**: Optimal initial perturbations for the Atlantic meridional overturning circulation. *Poster A9*

Geoffrey **Gebbie**: The inter-gyre gyre in ocean data assimilation products. *Poster A10*

Mattias **Green**: The impact of a collapsing ice-sheet on the meridional overturning circulation during Marine Isotope Stage 6. *Poster A11*

Jeremy P. **Grist**: On the Variability of the Surface-Forced Component of the Atlantic Meridional Overturning Circulation (AMOC) from 1958-2010. *Poster A12*

Joel **Hirschi**: Chaotic variability of the meridional overturning circulation on subannual to interannual timescales. *Poster A13*

Alan **Iwi**: Mechanisms linking volcanic aerosols to the Atlantic meridional overturning circulation. *Poster A14*

Laura **Jackson**: Multidecadal variability of the MOC: HadCM3 and a perturbed physics ensemble. *Poster A15*

Young-Heon **Jo**: Sea Level Trends in Different Time and Spatial Scales Associated with AMOC in the North Atlantic. *Poster A16*

Kathryn A. **Kelly**: Estimates of Heat Transport Convergence and Ocean Mass Anomalies from Observations and a Simple Model. *Poster A17*

Anna L. **Kloss**: Vertical distribution of deep and intermediate water masses in the Southeast Atlantic (23°S) during the Last Glacial Maximum. *Poster A19*

Yochanan **Kushnir**: The Dead Sea lake record during the Holocene: evidence of AMOC influence on centennial to millennial time scales. *Poster A20*

Christopher S. **Meinen**: Variability of the Deep Western Boundary Current at 26.5°N. *Poster A21*

Juliette **Mignot**: Seasonal AMOC variability in a climate model. *Poster A22*

Sandrine **Mulet**: A new estimate of the 3D circulation in the Atlantic Ocean from altimetry, SST and in-situ measurements. *Poster A24*

Paul **Myers**: Historical Variability in the Labrador Sea and Baffin Bay, with possible consequences to the MOC. *Poster A25*

Helen **Pillar**: Adjoint Sensitivity of the Atlantic Meridional Overturning Circulation to Surface Fluxes of Buoyancy and Momentum. *Poster A26*

Helen **Pillar**: Momentum Balance of the Atlantic Meridional Overturning Circulation. *Poster A27*

David **Reynolds**: Coherent tree ring and shell increment chronologies reconstruct North Atlantic climate dynamics. *Poster A28*

Peter. **Rhines**: AMOC and Watermass Transformation. *Poster A29*

Patrick **Scholz**: Decadal variability in a new high-resolution model of the North Atlantic ocean. *Poster A30*

Zoltan **Szuts**: Calibrating the Florida Straits submarine cable for salinity transport. *Poster A31*

David **Thornalley**: The deglacial evolution of North Atlantic Convection. *Poster A32*

Rainer **Zantopp**: Toward a synthesis of overflow transports in the Labrador Sea: The Outflow at 53N. *Poster A33*

Dongxiao **Zhang**: Multidecadal Variability of the AMOC in the Tropical Atlantic. *Poster A34*

Erik **van Sebille**: Propagation pathways of classical Labrador Sea Water from its source region to 26ºN. *Poster A35*

Svein **Østerhus**: Long-term variations in the North Atlantic Nordic seas overturning circulation. *Poster A36*

Theme 2

Dan **Hodson**: The impact of Model Resolution on MOC adjustment in a Coupled Climate Model *Poster B1*

Salil **Mahajan**: Impact of the Atlantic Meridional Overturning Circulation (AMOC) on Arctic Surface Air Temperature and Sea-Ice Variability. *Poster B2*

Alex **Megann**: The sensitivity of precipitation changes in the Amazon region under global warming to the choice of ocean component. *Poster B3*

Godhantarman **Nallamuthu**: Implications of climate change on biodiversity of marine plankton communities in tropical marine coastal ecosystems, South India. *Poster B4*

Sumant **Nigam**: Spatiotemporal Evolution of the Atlantic Multidecadal Oscillation and its Continental Hydroclimate Impacts. *Poster B5*

Matt **Palmer**: The importance of oceanic heat re-distribution in estimating Earth's radiation balance. *Poster B6*

Oleg M. **Pokrovsky**: A causal link between the Atlantic Multidecadal Oscillation, Eastern Arctic ice extent andchanges in atmospheric circulation regimes over Northern Eurasia. *Poster B7*

Luke **Sheldon**: Mechanisms of Ocean Heat Content Change in the North Atlantic. *Poster B8*

Craig **Wallace**: Downscaling Precipitation for the United Kingdom in an AMOC-collapse scenario. *Poster B9*

Christoph **Welker**: Decadal-scale variability of extratropical cyclones in the Atlantic basin – a project outline. *Poster B10*

Neil **Wells**: Meridional Overturning circulation at 26N and the North Atlantic heat COntent (MONACO). *Poster B11*

Xiaoming **Zhai**: A Model of Atlantic Heat Content and Sea Level Change in Response to Thermohaline Forcing. *Poster B12*

Thursday 14th July, 15:20 - 17:50

Theme 3

Erik **Behrens**: Can eddies affect the freshwater distribution and the reaction of the MOC in Greenland melting scenarios? *Poster C1*

Peter **Challenor**: Estimating the Risk of the Collapse of the Meridional Overturning Circulation - The RAPIT Project. *Poster C2*

Jürgen **Kröger**: Impact of Different Ocean Reanalyses on Decadal Climate Prediction *Poster C3*

Salil **Mahajan**: Predicting Atlantic Meridional Overturning Circulation (AMOC) Variations Using Subsurface and Surface Fingerprints. *Poster C4*

Daniela **Matei**: Interannual predictions of the Atlantic Meridional Overturning Circulation at 26.5ºN. *Poster C5*

Chris **Roberts**: Detecting changes to the Atlantic meridional overturning circulation in the Hadley Centre climate models. *Poster C6*

Jose **Rodriguez**: A traceable hierarchy of models to identify MOC thresholds. *Poster C7*

Matthew **Thomas**: Impacts of a reduced Meridional Overturning Circulation on the upper ocean circulation in the Atlantic. *Poster C8*

Daniel **Williamson**: Beyond Scenario Analysis: Studying 21st Century AMOC Behaviour Under Infinitely Many Feasible Forcing Futures. *Poster C9*

Bert **Wouters**: Decadal forecast experiments in the North-Atlantic with the EC-EARTH model. *Poster C10*

Theme 4

Chris W. **Hughes**: Drift-free measurements of pressure differences on the continental slope: Demonstration of a method which generalizes hydrostatic balance and thermal wind to sloping boundaries. *Poster D1*

Other posters

Lesley **Allison**: Feedback mechanisms associated with AMOC bistability in an AOGCM. *Poster E1*

Nicolas **Barrier**: A basin-scale statistical-dynamical downscaling to estimate the response of the Atlantic Meridional Overturning Circulation to climate change. *Poster E2*

Michael J. **Bell**: A two-layer planetary geostrophic model of Meridional Overturning Circulations. *Poster E3*

Adam **Blaker**: The impact of inertia-gravity waves on the MOC in a high resolution ocean model. *Poster E4*

Andreas **Born**: Dynamics of decadal variability in the Atlantic subpolar gyre: a stochastically forced oscillator. *Poster E5*

Louis **Clement**: The signature of westward propagating anomalies on the MOC. *Poster E6*

Shenfu **Dong**: Importance of the Argo Float Measurements in Assimilating Meridional Overturning Circulation in the South Atlantic. *Poster E7*

Silvia L. **Garzoli**: Deep Western Boundary Current variability and signal attribution in the North Atlantic. *Poster E8*

Leon **Hermanson**: Indirectly assimilating Atlantic 26°N transport into the UK Met Office Decadal Prediction System. *Poster E9*

Robin **McCandliss**: The RAPID & RAPID-WATCH Data Archive *Poster E10*

Jennifer **Mecking**: North Atlantic Oscillation Forced Ocean Variability Simulated by NEMO. *Poster E11*

Matthew **Menary**: Understanding past and future changes in the AMOC in the state-of-the-art climate model, HadGEM2-ES. *Poster E12*

Darren **Rayner**: The Current Status of the RAPID-MOC 26˚N Mooring Array. *Poster E13*

Monika **Rhein**: Observations of AMOC relevant circulation in the subpolar North Atlantic. *Poster E14*

Jon **Robson**: Causes of the rapid warming of the North Atlantic in the mid 1990s. *Poster E15*

Vassil M. **Roussenov**: North Atlantic gyre-scale property changes and MOC variability over the last 60 years. *Poster E16*

Carl-Friedrich **Schleussner**: Multistability of the Atlantic Subpolar Gyre and its stochastic resonance to Agulhas leakage variance. *Poster E17*

Amrita **Shravat**: Can ocean re-analysis output reproduce the observed overturning circulation near the regions of deep convection in the North Atlantic? *Poster E18*

Vladimir **Stepanov**: RAPID data assimilation experiments and some preliminary analysis of the model results. *Poster E19*

Laure **Zanna**: Low-frequency variability and forecast skill of observed North Atlantic sea surface temperatures. *Poster E20*

Matthijs **den Toom**: Effect of Atmospheric Feedbacks on the Stability of the Atlantic Meridional Overturning Circulation. *Poster E21*

Svein **Østerhus**: Thermohaline Overturning - at Risk? *Poster E22*

Abstracts

All abstracts are provided below in alphabetical order. Presentations are organised by theme, and for posters, by poster number.

Theme 1
Oral presentations: Tuesday – Wednesday.
Posters A1 – A36: Wednesday 14:00 – 16:00.

Theme 2
Oral presentations: Thursday a.m.
Posters B1 – B12: Wednesday 14:00 – 16:00.

Theme 3
Oral presentations: Thursday 16:50 – 18:30; Friday 09:00 – 10:40.
Posters C1 – C10: Thursday 15:20 – 16:50.

Theme 4
Oral presentations: Friday 11:10 – 13:20.
Posters D1: Thursday 15:20 – 16:50.

Other themes
Posters E1 – E22: Thursday 15:20 – 16:50.

Feedback mechanisms associated with AMOC bistability in an AOGCM

Lesley Allison[1,2,*], Robin Smith[1,2], Ed Hawkins[1,2], Tim Woollings[1], Jonathan Gregory[1,3]

* Presenting author

1) NCAS-Climate
2) University of Reading
3) Met Office

While simple box models and climate models of intermediate complexity commonly exhibit multiple equilibria of the Atlantic Meridional Overturning Circulation (AMOC), this phenomenon has not been found in more complex modern atmosphere-ocean general circulation models (AOGCMs). It has been suggested that the presence of a dynamical atmosphere component, with internally-generated atmospheric variability, may allow feedback mechanisms that reduce the stability of the AMOC off-state. This means that although the AMOC can been forced to collapse, coupled feedback mechanisms would allow the circulation to resume once the forcing is removed, preventing the existence of multiple equilibria.
An explicit search for AMOC hysteresis has been carried out using FAMOUS: a lower-resolution version of the HadCM3 coupled AOGCM. This model has the benefit of fast integration speed, whilst retaining a physically detailed atmospheric component capable of producing internally-generated temporal variability over periods from days to millennia. FAMOUS does indeed exhibit AMOC hysteresis under certain conditions, although this behaviour is sensitive to the details of the experimental configuration. We explore the feedbacks and mechanisms that contribute to the existence of hysteresis in FAMOUS and compare them with the responses of other AOGCMs forced by freshwater perturbations.

Other themes - Poster

Mechanisms and impacts of decadal-scale AMOC fluctuation events in unforced AOGCM simulations

Lesley Allison[1,2,*], Ed Hawkins[1,2], Tim Woollings[2]

* Presenting author

1) NCAS-Climate
2) University of Reading

Variations in the strength of the Atlantic Meridional Overturning Circulation (AMOC) have the potential to influence various aspects of climate, particularly in the regions surrounding the Atlantic basin. Understanding the mechanisms behind decadal-scale AMOC variability in atmosphere-ocean general circulation models (AOGCMs) is likely to be important for making future predictions of climate variability, may also help us to understand possible mechanisms for a large abrupt weakening of the circulation, and could help explain the difference in AMOC stability between AOGCMs and lower-complexity models.
As part of the RAPID-WATCH RAPIT (Risk Assessment, Probability and Impacts Team) project, we examine the largest decadal-scale natural fluctuations in AMOC strength within a variety of coupled AOGCM control integrations. The eventual aim is to generate a time-varying fingerprint of precursors to, and climate impacts of, these fluctuation events, which is robust across different climate models. First we wish to identify the characteristics of events that lead to appreciable climatic impacts. To do this we examine the relationships between the magnitude and duration of an event and its associated impacts. We then search within this set of climatically-relevant events to look for common precursors and possible mechanisms. The latest results from this analysis will be presented.

Theme 2 - Oral Presentation

Meridional overturning circulation and heat flux array at 26.5°N: Variability observed at periods of minutes to years during the period from April 2004 to April 2009

C. Atkinson[1], M. Baringer[2], L. Beal[3], H. Bryden[1], M-P. Chidichimo[4], J. Collins[5], S. Cunningham[6*], J. Hirschi[6], W. Johns[3], H. Johnson[7], T. Kanzow[8], J. Marotzke[4], D. Marshall[7], C. Meinen[2], A. Mujahid[9], D. Rayner[6], Z. Szuts[4], E. Frajka-Williams[6]

* Presenting author

1) University of Southampton
2) NOAA-AOML
3) University of Miami
4) Max Planck Institute for Meteorology
5) British Oceanographic Data Centre
6) National Oceanography Centre, UK
7) University of Oxford
8) IFM-GEOMAR
9) University Malaysia Sarawak

Since March 2004 as part of the RAPID-WATCH/MOCHA programme we have been monitoring the strength and structure of the Atlantic meridional overturning circulation and heat flux at 26°N. In this talk I will review the measurements made by the array and

describe what we have learned about the AMOC and heat flux variability at periods of minutes to years from the first six years of observations.

Theme 1 - Invited Talk

North Atlantic Multi-decadal Variability simulated in CGCMs

Jin Ba[1], Noel Keenlyside[1], Wonsun Park[1], Ed Hawkins[2]

1) Leibniz Institute of Marine Sciences (IFM-GEOMAR)
2) University of Reading

Some climate models (CMIP3) indicate that the Atlantic Meridional Overturning Circulation (MOC) varies on Multi-decadal time scale, independent of external forcing. In these models the MOC is key to Atlantic Multi-decadal Variability (AMV), because of its poleward heat transport. However, there is large spread in simulated AMV, with major uncertainty in the roles played by the North Atlantic Oscillation (NAO) and ocean-atmosphere interaction.
In the Kiel Climate Model (KCM), the MOC fluctuates with a 60-years period, driving changes in Atlantic Sea Surface Temperature (SST). The mechanisms for this variability are studied using statistical analysis, including three-dimensional Temperature and Salinity Joint Empirical Orthogonal Functions (EOFs). The NAO plays little role in driving these fluctuations. Wintertime convection in the Greenland-Iceland-Norwegian (GIN), Irminger, and south Greenland Seas play different roles in MOC variability. Irminger Sea convection primarily drives MOC changes, leading them by about 15 year. In this region salinity contribution to density dominates. The Subpolar Gyre (SPG) also plays an important role, also leading MOC changes by about 15 years.

Theme 1 - Poster A2

Predictability of the meridional heat transport

Johanna Baehr

University of Hamburg

I will discuss the timescales of predictability for the meridional heat transport in the North Atlantic - with specific emphasis on how these timescales of predictability compare to the timescales of predictability for the meridional overturning circulation.

Theme 1 - Invited Talk

Recent large increases in freshwater fluxes from Greenland into the North Atlantic

Jonathan Bamber[1], Michiel van den Broeke[2], Janneke Ettema[2], Jan Lenearts[2], Eric Rignot[3]

1) University of Bristol, Bristol Glaciology Centre
2) Utrecht University, Institute for Marine and Atmospheric Research
3) University California, Irvine and Jet Propulsion Laboratory

Freshwater (FW) fluxes from river runoff and precipitation minus evaporation for the pan Arctic seas are relatively well documented and prescribed in ocean GCMs . Fluxes from Greenland on the other hand are generally ignored altogether, despite their potential impact on convection. Here, we present a reconstruction of the spatially distributed FW fluxes from Greenland for 1958-2009. We find that the FW flux into the Arctic Ocean has increased only slightly during this period. Fluxes into the Irminger Sea, however, have increased dramatically during the 1990s at a rate of 6.6±1.4 km^3 yr-2. The cumulative freshwater anomaly since 1995 for this region is equivalent to about 15% of the Great Salinity Anomaly experienced in the 1970s. The FW flux over the last decade is over a factor two higher than previously estimated and accelerating.

Theme 1 - Oral Presentation

A basin-scale statistical-dynamical downscaling to estimate the response of the Atlantic Meridional Overturning Circulation to climate change

Nicolas Barrier[1*], Marie Minvielle[2], Christophe Cassou[2], Anne-Marie Tréguier[1]

* Presenting author

1) Laboratoire de Physique des Océans, CNRS-IFremer-IRD-UBO, IUEM, Brest, France
2) Cerfacs, Toulouse, France

The evolution of the Atlantic Meridional Overturning Circulation (AMOC) is crucial to be estimated in the context of climate change because of its central role in Earth energy equilibrium. Coupled atmosphere-ocean models used so far in CMIPs suffer from large uncertainties associated with, among others, the misrepresentation of oceanic processes (due to coarse resolution) and of air-sea interface processes. Erroneous wind patterns and buoyancy budgets especially alter the representation of the AMOC ; it is thus necessary to find a way to get around these obstacles.
A statistical-dynamical downscaling scheme has been developed in Minvielle et al (2011) to generate unbiased sea-surface atmospheric variables from CMIP models used subsequently as forcing fields for a higher resolution ocean model. A transfer function is first built over a learning period (1958-2002) between air-sea variables and the occurrences of observed (ERA40) atmospheric weather regimes (WR) extracted from daily large-scale pressure fields over the Atlantic. The statistical relationship is then used to reconstruct a modeled set of ocean forcing fields and is validated over the late XXth century before being applied to scenario experiments. Our study is based here on the outputs of the CNRM-CM3 model and on the use of the NEMO ocean model integrated at the 0.5 degree resolution (ORCA05)

Because the transfer function is only based on atmospheric dynamics over 1958-2002, the surface temperature trend associated with greenhouse gazes (GHG) direct effect (that is so far weak but is expected to be very important in the more-or-less near future following scenarios of GHG emissions) is not captured. The respective role of the change in the atmospheric dynamics (through the modification of occurrences and properties of WR) and the increase of surface temperature due to GHGs radiative forcing is assessed here from two sensitivity ORCA05 experiments: one where the sole changes in WR given by CNRM-CM3 A2 scenario is applied (hereafter A2-WR), and a second one in which the surface temperature trend estimated from CNRM-CM3 is superimposed (A2-WR+T2). Those are compared to the original low-resolution CNRM-CM3 coupled model.
We find that the AMOC response is opposite between the two sensitivity ocean-forced experiments and is also very different from the original coupled one. In CNRM-CM3, the AMOC collapses by the end of the XXIth century with a -14Sv decrease. In A2-WR+T2, the AMOC decreases by only -4 Sv (40N, 1500m) while it increases by + 2 Sv (40N, 2500m) in A2-WR. We show that such an increase is associated with greater occurrences of positive North Atlantic Oscillation WR at the end of the XXIth century, leading to enhanced deep convection and acceleration of the subpolar gyre. The latter is dominated in A2-WR+T2 by the overall stabilization of the ocean due to surface temperature warming leading to a clear slackening of the entire ocean dynamics in the Atlantic.

Other themes - Poster E2

Can eddies affect the freshwater distribution and the reaction of the MOC in Greenland melting scenarios?

Erik Behrens[1,*], Claus W. Böning[1,*], Arne Biastoch[1,*]

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What will be the effects of accelerated melting of the Greenland ice sheet on the global ocean circulation, in particular the Atlantic Meridional Overturning Circulation (AMOC)? Since melt water run-off in the subarctic North Atlantic is primarily entrained in the boundary current system along the continental shelves, its impact on deep water formation by open ocean convection, e.g., in the Labrador Sea, may strongly depend on the effectiveness and location of lateral exchanges with the ocean interior. Here we use a set of global ocean-only model experiments differing in horizontal resolution to study the role of mesocale eddy processes in idealised melting scenarios (continuous run-off of 0.1 Sv equally distributed around Greenland). The models are based on different NEMO-ORCA configurations developed in the European Drakkar collaboration with global grid sizes of 0.5° and 0.25°; in addition, a new model version with a 1/20°-nest for the subarctic Atlantic has been set up to explicitly resolve the major part of the eddy spectrum. Atmospheric forcing builds on the bulk formulations and atmospheric data for 1948-2007 developed by Large and Yeager (CORE-forcing), with only a very weak relaxation of sea surface salinity to avoid spurious model drift. Control simulations (hindcasts without additional run-off) show a decadal variability of the MOC of O(2 Sv) associated with NAO-related convection variability. In the melt water runs, the 0.5°-model shows a reduction of the MOC by more than 40% over 40 years, due to a rapid collapse of the deep convection in the Labrador Sea within the first 5 years after the start of the hosing. In the (weakly-eddying) 0.25°-case, the MOC-behaviour is still rather similar;

however, a passive tracer introduced to track the spreading of Greenland melt water gives first hints of the importance of eddies: whereas in the coarse model the convective region in the Labrador Sea is rapidly swamped by the Greenland water, in the the eddy-permitting model much of it is remains in the cyclonic boundary current system, delaying the effect on the convection in the Labrador Sea. The preliminary results thus suggest that the convective area may effectively be shielded in the real ocean, in contrast to the behaviour of current climate models; a more quantitative assessment of this effect is expected from the ongoing experiments with the more realistic 1/20°-model.

Theme 3 - Poster C1

A two-layer planetary geostrophic model of Meridional Overturning Circulations

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State-of-the-art ocean models spinning up from realistic density fields rapidly develop deep western boundary currents and meridional overturning circulations (MOCs). Wajsowicz & Gill (1986) found that the initial spin-up of a flat-bottomed ocean model from a meridionally varying density field is well described by the inviscid shallow water equations for a two-layer fluid and that the initial evolution on a beta-plane could be understood in terms of f - plane dynamics: Kelvin waves propagate rapidly round the ocean boundaries establishing eastern and western boundary currents. The later inviscid evolution on a beta-plane is dominated by westward propagating planetary waves. The time-mean baroclinic solutions for two-layer flat-bottomed fluids on an f-plane which spin up from an initial state of rest with a meridionally sloping interface are used to illustrate the constraints on the MOC imposed by the inviscid boundary conditions of no normal flow. These boundary conditions apply also on a sphere or f-plane. Motivated by the fact that numerical solutions with flat-bottomed oceans support active MOCs, the slow speed of the geostrophic adjustment by the planetary waves at mid- to high-latitudes and the influence of the inviscid boundary conditions, simple, analytical steady state solutions driven by relaxation of the internal interface (representing the thermocline) towards a meridionally varying reference field and closed by dissipative boundary layers are derived using the planetary geostrophic equations for the baroclinic motion in a two-layer flat-bottomed fluid. The solutions can be applied to basins which span the equator and derived using the full non-linear continuity equation for any shape of basin. The depth of the internal interface is constant along the eastern boundaries and the equator but its east-west variations can be a large fraction of the pole to equator difference at high latitudes. The solutions support significant meridional overturning circulations and, when periodic east-west boundary conditions are imposed at the southern boundary, can be shown to have a significant cross-equatorial baroclinic flow in the western boundary layer with greater southward flow in the lower layer than the surface layer. Using reasonable parameter choices, the diapycnal transport across the internal interface and the northward transport in the upper layer are of order 15 Sv.

Reference:

Bell, Michael J. (2011) Ocean circulations driven by meridional density gradients, Geophysical & Astrophysical Fluid Dynamics, 1-31. DOI: 10.1080/03091929.2010.534468

Other themes - Poster E3

Variability of physical and biological properties in the Faroe Shetland Channel between 2000-2009: results from a long-term monitoring programme and model data

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The inflow of Atlantic Water into the Nordic Seas through the Faroe Shetland Channel (FSC) is one of three branches of Atlantic Water crossing the Greenland-Scotland Ridge (GSR). Comparable transports of ~3.8 Sv occur through the FSC and between Iceland and Faroes, with a minor contribution (0.9 Sv) West of Iceland making up the third branch. A Scottish-Faroese-Norwegian collaboration has obtained a long term time series of water mass properties (temperature, salinity, Chlorophyll-a and nutrients) and transports in the FSC. Volume transport is monitored by an array of Acoustic Doppler Current Profilers deployed across the channel. Established in 1994, these observations cover the 2000-2009 decade well. In addition, ship-based observations of water mass properties such as temperature, salinity, Chlorophyll-a and nutrients have also been collected along two standard monitoring lines in the FSC: the Nolso-Flugga and Fair Isle-Munken sections. Two water masses contribute to the circulation of AW in the FSC: North-Atlantic Water (NAW), and Modified North-Atlantic Water (MNAW; water from North of Faroes which recirculates in the FSC).
The seasonal and inter-annual variability in these observational time series over the past decade are presented, and further explored within the context of oceanic and atmospheric drivers. The presentation will also draw on model results of transport through the FSC, to explore our understanding of the observed variability over the past decade, and to demonstrate the need for discussion of uncertainty of simulated and observed time-series, as well as the need for continued, direct observations.

Theme 1 - Poster A3

The Importance of considering Agulhas Leakage for the Variability of the Atlantic Meridional Overturning Circulation

Arne Biastoch[1.], Claus W. Böning[1.], Johann R. E. Lutjeharms[2.]

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Interannual to decadal variability in the AMOC has for some time been attributed mainly to effects of changes in the intensity of deepwater formation in the subarctic North Atlantic and to local forcing. However, important influences on the AMOC are arriving from the south; one of those is by the variability of waters from the Indian to the Atlantic Ocean, the ‘Agulhas Leakage’, that mainly takes place through the shedding of rings from the Agulhas Current retroflection. The exact amount and timing of Agulhas Leakage is largely unknown and depends strongly on the mesoscale circulation in the greater Agulhas system including its sources upstream in the Indian Ocean. To investigate the role of mesoscale variability in the Agulhas system and its influence on the large-scale circulation a set of nested models with effective two-way interaction between the global ocean and the high-resolution local nests has been used. The simulation reproduces all current features of the Agulhas system with great success. By comparing model solutions with and without the high-resolution Agulhas nest it is demonstrated that Agulhas Leakage dynamics affects the decadal variability of the AMOC (Biastoch et al., 2008, Nature). Its signal rapidly propagates meridionally and reaches into the northern hemisphere. In the tropical and subtropical North Atlantic it still has a significant amplitude, comparable to the variations originating from the deepwater formation areas in the subpolar North Atlantic. In addition to this wave propagation an advective signal originates from the Agulhas region that potentially affects the AMOC on longer timescales: in particular, the poleward shift of the Southern Hemisphere westerly winds led to an increased Agulhas Leakage over the last decades, causing a salinity signature that can be traced northward (Biastoch et al., 2009, Nature). The invasion of more saline waters into the North Atlantic could have implications for the future evolution of the AMOC.

Theme 1 - Oral Presentation

The impact of inertia-gravity waves on the MOC in a high resolution ocean model

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Analysis of high temporal resolution output from integrations of the NEMO ORCA025 ocean model reveals a field of inertia-gravity waves (IGWs) which propagate according to the beta dispersion relation. These waves have a significant impact on the Atlantic meridional overturning circulation (MOC) on timescales from a few hours to a few days. Changes in the Atlantic MOC at 26.5N can exceed 50 Sv within one day. The IGW-driven MOC variability is a consequence of temporally variable wind forcing. Applying temporally constant wind forcing leads to removal of the IGW-driven MOC variability within a few weeks. We decompose the Atlantic MOC into Ekman, barotropic and geostrophic components and an ageostrophic residual, and show that the latter contains a dominant high frequency signal, with period constrained by the local inertial period. It is not clear yet whether the IGW-driven MOC variability found in our simulations is realistic. However, our results suggest that the variability would be invisible to observing systems such as the RAPID MOC system at 26.5N in the Atlantic.

Other themes - Poster E4

Dynamics of decadal variability in the Atlantic subpolar gyre: a stochastically forced oscillator

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Internal variability of the Atlantic subpolar gyre is investigated in a 600 year control simulation of a comprehensive coupled climate model. The subpolar gyre shows irregular oscillations of decadal time scale with most spectral power at approximately 20 years. Positive and negative feedbacks mechanisms act successively on the circulation leading to an internal oscillation. This involves periodically enhanced deep convection in the subpolar gyre center and intermittently enhanced air-sea thermal coupling. As a result, anomalies of the large-scale atmospheric circulation can be transferred to the ocean on the ocean's intrinsic time scale, triggering the destabilizing feedbacks and exciting the oscillator stochastically. A detailed understanding of oscillatory mechanisms of the ocean and their sensitivity to atmospheric forcing holds considerable potential for decadal predictions as well as for the interpretation of proxy data records.

Other themes - Poster E5

The Atlantic Meridional Overturning Circulation exports freshwater southwards

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To estimate the size of the meridional overturning circulation and the meridional heat, freshwater and Mov salt transports in the South Atlantic, we made a new transatlantic hydrographic section along 24°S in 2009 and we compare the resulting transports with those estimated for a historical section made in 1983. For the two sections, the overturning is estimated to be 21.5 Sv (2009) or 16.5 Sv (1983), the heat transport is northward at 0.7 PW (2009) or 0.4 PW (1983), and the freshwater transport is small but northward at 0.04 Sv (2009) or 0.17 Sv (1983). The differences in transports are primarily due to the different strengths of the southward Brazil Current transport during the occupation of the sections, 4.9 Sv (2009) or 12.2 Sv (1983). The Mov salinity transport is estimated by two different methods for each of the two sections and is always southward ranging from -0.09 Sv to -0.34 Sv which means that the Atlantic meridional overturning circulation transports freshwater southward at 24°S. On the basis of theoretical studies, such southward Mov salinity transport at the southern boundary of the Atlantic Ocean means that the present Atlantic circulation has multiple equilibrium states, and that the one it occupies at present may be unstable to a sufficiently large freshwater event.

Theme 3 - Oral Presentation

The Ability of the Adjoint Method to recover a decadal AMOC Variability

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The Atlantic Meridional Overturning Circulation (AMOC) has an important influence on today's climate. However, continuous decadal-scale observations of the AMOC are not existing. Therefore, available ocean observations are assimilated into numerical ocean models to estimate the AMOC's mean state and its variability. However, different data assimilation products show rather different AMOC mean states and variability.
To understand these differences, we consider a reversed data assimilation approach. We evaluate the principle ability of the adjoint technique to reproduce a given AMOC from a controlled setup using identical twin experiments. Without observational uncertainties an artificial perturbation producing an AMOC change should in principle be perfectly detectable in space and time. We investigate how far deviations between model and synthetic observations can be minimized in the presence of artificial observational uncertainties and non-linear numerical effects, as e.g. convective adjustment. The results are used to assess error estimates of present assimilation products and AMOC hindcast simulations.

Theme 1 - Poster A4

Decadal Variability of the Atlantic Meridional Overturning Circulation

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In the mean, the Atlantic Ocean transports 1-1.5 PW of heat northward, and estimates suggest that 60% of this heat transport is associated with a circulation that reaches the cold waters of the abyss. Due to the role of the Atlantic Meridional Overturning Circulation (AMOC) in ocean heat transport, numerous studies have suggested that AMOC variability plays a role in climate variability on a wide range of timescales. Our focus is AMOC and ocean buoyancy variability on decadal timescales.
Decadal variability of sea surface temperature (SST) has been observed in the instrumental record and climate proxy data and is thought to be linked to variability in the AMOC. On the other hand, according to the thermal wind relation, buoyancy anomalies on the boundaries lead to anomalies in the MOC, a fact that has been utilized in order to reconstruct the MOC at 26.5 N using data collected by the RAPID array. Here, we study decadal AMOC and buoyancy variability in a coupled and ocean-only GCMs run in idealized geometries. We focus on understanding the mechanisms of decadal variability of the AMOC, both the role of the AMOC in creating decadal buoyancy anomalies and the response of the MOC to buoyancy anomalies.
We find that decadal AMOC variability is driven by buoyancy anomalies near the western boundary of the subpolar gyre. When a buoyancy anomaly hits the western boundary, it is advected southward by the deep western boundary current, leading to AMOC anomalies in accord with the thermal wind relation. Baroclinic Rossby waves excited by the winds

and baroclinic instability internal to the ocean are the dominant sources of decadal buoyancy anomalies on the western boundary. The AMOC responds passively to these buoyancy anomalies. In nature the origin of decadal buoyancy anomalies may be different than in our idealized models, but we expect the response of the AMOC to buoyancy anomalies on the western boundary to be similar.

Theme 1 - Oral Presentation

The mollusc Arctica islandica: an annually resolved and precisely dated proxy archive of Atlantic water variability during the past millennium

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The ability to hindcast AMOC variability with near-annual resolution for the past few centuries would significantly improve our understanding of the rates of change, amplifications and lags in the system, enabling us to better constrain the parameterizations that are incorporated in coupled climate models and to strengthen the regional element in model predictions. Annual growth lines in the shell of the long lived bivalve mollusk Arctica islandica can be used in the same way as tree rings to build crossdated chronologies, thus making available absolutely dated shell material that can be used for geochemical analysis. The results shown here are derived from radiocarbon analysis of material from a 1,350-year A. islandica chronology which uses shells collected from the North Icelandic Shelf (NIS). At the collection site, close to the Polar Front, radiometrically older Arctic waters contend with Atlantic derived waters which are younger with respect to radiocarbon. The ability to carry out radiocarbon analysis on absolutely dated shell material allows the time-varying radiocarbon reservoir age correction (delta R) to be determined. A high value of delta R indicates the dominant presence of the older Arctic water on the NIS, suggesting a weaker influence of Atlantic water and consequently a weakening of the AMOC. In the data presented here, a clear trend of increasing delta R is apparent, suggesting a relatively strong influence of Atlantic water during the Medieval Climate Anomaly(MCA) which weakens into the Little Ice Age(LIA) before an apparent reversal in the late 19th and 20th centuries. These findings are consistent with proxy-based determinations of the northward flow of the Gulf Stream through the Florida Straits (Lund et al 2006 Nature) and of heat transfer in surface waters through the Fram Strait (Spielhagen et al 2011 Science) during the past millennium. Arctica islandica is commonly found in most shelf seas surrounding the North Atlantic, and a number of shorter shell-based chronologies have been built for various sites in the Irish Sea and North Sea. A network of multi-centennial chronologies is now a distinct possibility. Such a network would potentially enable high resolution hindcasting of the temporal and spatial patterns of marine climate transitions, thus allowing hypotheses about the mechanisms of such transitions to be realistically tested.

Theme 1 - Poster A5

Manifestation of multi-decadal AMOC changes in the transport of the Florida Current

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As shown by the RAPID/MOCHA array along 26,5°N, estimation of AMOC transport fluctuations on intraseasonal to interannual time scales requires continuous measurement of contributions across the Atlantic basin. On the other hand, evidence from paleoceanographic studies has led to postulations of a linkage between changes in AMOC on multi-decadal time scales, and the transport of the Florida Current (FC): e.g., benthic foraminiferal data across the Florida Straits suggested a significant decrease in FC transport during the Younger Dryas, consistent with postulations of a reduced AMOC during this period. How does the zonal distribution of velocity anomalies along 26,5°N differ between inter-annual and multi-decadal time scales? Is there a relation between FC and AMOC transports at lower frequencies? Could a gradual decline of the AMOC as projected for the 21st-century be detected in the FC? These questions are addressed here in a modeling study using a sequence of eddy-permitting (1/4°) global ocean model simulations: a reference (hindcast) experiment forced by the atmospheric variability of 1948-2007 according to the CORE (Coordinated Ocean Research Experiments) protocol; and several repetitions of this period with an increasing (decreasing) trend in the AMOC artificially induced by perturbation scenarios in the subarctic freshwater budget.
The salient features of observed transports at 26,5°N, e.g. from RAPID/MOCHA, are reasonably well captured by the reference solution: e.g., a mean AMOC of 16.5 Sv, and a mean FC of 30.3 Sv; an annual cycle (peak-to-peak, 2000-2007) of 5.5 Sv for the AMOC, and 4 Sv for the FC, with maxima in July. Interannual changes in FC and AMOC transports are of O(1-2 Sv). While there is no relation between fluctuations on these timescales, the decadal transport changes give a first hint at a possible linkage between lower-frequency FC and AMOC variability: both transports are decreasing through the 1950s, 60s and early 70s, weakest transports in the 1970s (albeit with a less pronounced minimum in the FC), and a subsequent strengthening through the 1980s and early 90s. The linkage between AMOC and FC transports becomes much stronger for the multi-decadal trends simulated in the perturbation scenarios: increasing and decreasing AMOC trends are reflected in the FC transport; i.e. the AMOC decline simulated in the latter case (~3 Sv in 50 years) is to a large degree manifested in the FC.

Theme 1 - Oral Presentation

The adiabatic pole-to-pole overturning circulation

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The adiabatic pole-to-pole cell of the residual overturning circulation (ROC) in the Atlantic is studied in a two-hemisphere, semi-enclosed basin, with a zonally-reentrant channel occupying the southernmost eighth of the domain. Three different models of increasing complexity are used: a simple, analytically-tractable zonally-averaged model, a coarse-resolution numerical model with parameterized eddies, and an eddy-resolving general

circulation model. Two elements are found to be necessary for the existence of an adiabatic pole-to-pole cell: (1) a thermally-indirect, wind-driven overturning circulation in the zonally-reentrant channel, analogous to the Deacon cell in the Antarctic circumpolar Current (ACC) region, and (2) a set of outcropping isopycnals shared between the channel and the semi-enclosed region of the Northern Hemisphere. These points are supported by several computations varying the domain geometry, the surface buoyancy distribution and the wind-forcing. All three models give results which are qualitatively very similar, indicating that the two requirements above are general and robust.
All three models illustrate how the geometry of the isopycnals is shaped by the interhemispheric ROC, leading to three major thermostads, which we identify with the major water masses of the Atlantic, i.e. North Atlantic Deep Water, Antarctic Intermediate Water and Antarctic Bottom Water. The models also illustrate how changes in buoyancy fluxes in the high latitudes of both hemispheres, as well as the strength of the winds can ccelerate or decelerate the ROC, and what their time-scales are.

Theme 3 - Oral Presentation

Estimating the Risk of the Collapse of the Meridional Overturning Circulation - The RAPIT Project

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If the meridional overturning circulation in the Atlantic Ocean were to collapse or even serious reduce in strength there could be severe consequences for the world's climate. It is therefore important that strategies for the mitigation of greenhouse gas emissions reduce the risk of this happening to an acceptable level. This means that we need a means of estimating the risk as a function of greenhouse gas concentration. This is the focus of the RAPIT project.
Since we are forecasting future climates we are using coupled AOGCM's. However we are not interested in inference about climate models we are interested in inference about the real climate. Currently we are using the Hadley Centre HADCM3 for our simulations but in time we will also use CHIME from NOC and more complex Hadley models. An important part of our work is developing methods to relate climate model output to reality. Our work on inference is based on a statistical emulator for the climate models.
We present an overview of results in two areas: (i) what are the physical characteristics of a rapid slow down in the overturning and (ii) to demonstrate the use of statistical emulators to analyse output from a model as complex as HADCM3. Further details are given in other presentations from the RAPIT team.

Theme 3 - Poster C2

Freshwater control of AMOC: collapsing the AMOC by changing evaporation and precipitation in the southern hemisphere

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It has been suggested that the freshwater transport by the Atlantic meridional overturning circulation (AMOC) at 35S is a key parameter determining the stability of the global thermohaline circulation, as it is a measure of the strength of the salt advection feedback.
We present a systematic method to determine the multiple equilibria regime of the thermohaline circulation in a global Earth System Model of Intermediate Complexity (EMIC). Small freshwater corrections (order of 0.2Sv) are applied only in at the surface of the southern hemisphere, far from the sinking regions of the North Atlantic. In particular, we are able to force a collapse and a recovery of the thermohaline circulation by slowly changing the freshwater budget at the southern border of the Atlantic Ocean. This points to the fundamental role played by the basin-scale salt advection feedback. Time series of AMOC behaviour can be produced with changes in freshwater flux on time scales of thousands of years. The time series have been analysed to detect potential early warning signals (autocorrelation, variance, detrended fluctuation analysis). The collapse and recovery are accompanied by early warning signals, which indicate that these transitions occur due to the occurrence of saddle-node bifurcations. The results from the EMIC are in good agreement with the bifurcation structure computed using a similar control parameter in an ocean only model and demonstrate the fundamental importance of the freshwater budget of the Atlantic Ocean to correctly understand and predict its behaviour in past, present and future climate.

Theme 1 - Poster A6

The signature of westward propagating anomalies on the MOC

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The Meridional Overturning Circulation (MOC) measured at 26.5ºN in the North Atlantic exhibits a mean transport of 18.5 Sv and a standard deviation of 4.7 Sv from April 2004 to April 2009. The subannual variability of the geostrophic transport is believed to be partly caused by Rossby waves and eddies (Hirschi et al., 2007). This hypothesis is tested by studying westward propagating anomalies along the RAPID moorings, which may impact the western boundary dynamic height profile through isopycnal displacements. The characteristics (period, wavelength and speed) of these anomalies are compared to the theoretical dispersion relation and observations of planetary waves from altimetry. The MOC sensitivity to these anomalies can be estimated by prescribing a dynamic height profile at the western boundary with the amplitude and structure of typical anomalies.

Other themes - Poster E6

AMOC variability and prediction studies in the Community Climate System Model version 4 (CCSM4)

Gokhan Danabasoglu[1,*], Steve Yeager[1], Alicia Karspeck[1], Joseph Tribbia[1], Young-Oh Kwon [2], Jeff Anderson[1], Nancy Collins[1], Tim Hoar[1], Kevin Raeder[1], Haiyan Teng[1], James Hurrell[1], Mariana Vertenstein[1]

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We first present an analysis of the AMOC variability from the 1300-year, pre-industrial control simulation of the Community Climate System Model version 4 (CCSM4). The CCSM4 was recently released to the user community, and it contains many physical and numerical improvements in all its component models in comparison with its previous version CCSM3. In its standard configuration, all components use nominal 1 degree horizontal resolution. In general, the CCSM4 control simulation shows much less AMOC variance than was found in CCSM3. An overflow parameterization for the Nordic Sea overflows contributes to this reduction in variance by maintaining stratification in the Labrador Sea. In stark contrast with the 20-year – sometimes oscillatory – AMOC peak variability in CCSM3, CCSM4 AMOC has only weak spectral peaks exceeding red noise at timescales longer than 50 years. Overall, the correlations of various AMOC index time series with other time series for surface temperature, boundary layer depth, etc. are mostly weaker than in CCSM3. Furthermore, the preliminary results indicate that previously proposed mechanisms for AMOC variability in CCSM3 are not applicable to the new control simulation.

We next present some initial results from decadal prediction experiments with CCSM4, focusing on the AMOC behavior. We use two different ocean full-field initialization strategies. The first set of ocean initial conditions is obtained from ocean – sea-ice hindcast simulations forced with the interannually varying Coordinated Ocean-ice Reference Experiments (CORE) atmospheric forcing data sets. In the second approach, the Data Assimilation Research Testbed (DART) ensemble Kalman filter has been combined with the Community Atmosphere Model and the Parallel Ocean Program to create weakly coupled ensemble analyses for the last decade. Both hindcast and data assimilation simulations generate good comparisons with the RAPID observations of AMOC and meridional heat transport at 26.5 N. A suite of prediction ensembles (10-members each) with ocean initial conditions from hindcast simulations and starting in 1960 through 2005 at 5-year intervals are integrated up to year 2030. Another set of prediction ensembles are started at annual intervals from 2000 to 2005 and integrated to 2030. This latter set uses initial conditions from both hindcast and DART approaches. We compare results from these prediction simulations both with the historical record during the overlap periods and with the solutions from uninitialized 20th Century integrations. In all prediction experiments, model drift in the Atlantic Ocean is a dominant decadal signal. Improved initial conditions do not appear to mitigate the drift problem, although they do significantly reduce some model biases relative to observations early on. We also show impacts of some proposed drift – bias correction approaches on the predictive skill for AMOC as well as for upper-ocean heat content.

Other themes - Oral Presentation

Variability of the East Greenland Current-Irminger Current (EGIC) transport at the South east tip of Greenland

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The East Greenland Current-Irminger Current (EGIC) decadal transport variability likely influences deep convection intensity in the Labrador and Irminger Seas but is poorly known yet.
The circulation and related transports at the south east tip of Greenland were first determined from direct current observations of a moored current meter array. The measurements cover a time span from June 2004 to June 2006. The net mean total southwestward transport of the EGIC from the mid-shelf (20 km of the coast at 60^{o}N) to the 2070 m isobath (about 100km offshore) was estimated as 17.3 Sv with an uncertainty of 1 Sv. The transport variability is characterized by a standard deviation of 3.8 Sv with a peak to peak amplitude up to 30 Sv. The seasonal variability has an amplitude of 1.5 Sv. Periods around 10 days dominate the signal, although a variability at periods of about one month also appears in winter.
Given the recently reported spin-down of the surface subpolar gyre, which northern rim is the EGIC, the question arises whether these values are consistent with a transport averaged on a longer period. To infer the EGIC transport from 1992 to 2009, we combined altimetry-derived surface geostrophic velocities with the first Empirical Orthogonal Function (EOF) of the EGIC transport variability computed from mooring observations described above.
The reconstructed 17-year time series of the EGIC transport was then validated against independent estimates confirming that, indeed, the vertical distribution of the EGIC variability has not changed significantly over the last two decades. The 1992–2009 mean transport is 19.5 Sv with a standard error of 0.3 Sv. In 1992– 1996, the EGIC transport was close to the average. Over the following decade (1997– 2005), the EGIC transport declined by 3 Sv (15%) so that the 2004– 2006 mean transport inferred from the moored array is 2.2 Sv (10%) less than the 1992–2009 mean. It was followed by a period of higher transport. Wind stress curl variability over the Irminger Sea, boundary waves, eddies and recirculations likely contribute to the observed variability. However, to better understand the underlying mechanisms, dedicated numerical studies are needed.

Theme 1 - Poster A7

A model study of the Labrador Sea Water production, pathways and transit times

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An ocean general circulation model (OGCM) is used to investigate the Labrador Sea (LSW) variability in the past 50 years and its relation to the properties of water masses and ocean circulation. The OGCM simulations show evolution of the Labrador Sea temperature and salinity in the past 50 years close to observed variability. In particular, the simulated LSW is much colder, fresher and deeper in 1993 (hereafter LSW1993) than that in 2000 (hereafter LSW2000). Two experiments based on a tracer model show that both LSW1993 and LSW2000 spread along the three noted pathways. The derived residence time for LSW1993 in the Labrador basin is longer than that for LSW2000. The arrival times of model LSW in the Irminger Sea, subtropical North Atlantic and the Eastern Basin show strong interannual variability.

Theme 1 - Poster A8

Model inter-comparison study of variability in AMOC and freshwater content in the North Atlantic

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Observations and models altogether suggest that there are times when freshwater content plays an indirect or passive role in the North Atlantic (ie the atmospheric forcing controls the ocean freshwater content and circulation variability such as AMOC) ; while at other times, salinity directly influences the circulation: increased (respectively decreased) high latitude freshwater content weakens (resp. intensifies) the subpolar ocean circulation.
In this talk, we present a model inter-comparison study that investigates the timing, amplitude and variability of freshwater content in the North Atlantic in relation to the full 3-D circulation variability, including AMOC. A suite of analytical indices is developed and consistently applied to each of three coupled model's long control runs to characterize their oceanic FW budget and AMOC variability, and assess underlying mechanisms of interactions.

Theme 2 - Oral Presentation

Stability of the Atlantic Meridional Overturning Circulation in a global eddy-resolving ocean model

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To investigate the global ocean response to enhanced fresh water input due to Greenland Ice Sheet (GrIS) melting, three 45-year simulations have been performed using the strongly eddying global version (0.1 degree horizontal resolution) of the Parallel Ocean Program (POP) without any restoring of salinity. The simulations differ in strength of the freshwater anomaly (0.0, 0.1 and 0.5 Sv). For the 0.5 Sv anomaly, the Atlantic Meridional Overturning Circulation (MOC) decreases by about 50% over a period of 45 years. On the short time scale (years), there is a local response which is mainly restricted to the northern North Atlantic. On the decadal time scale, changes in surface and subsurface quantities have propagated to the South Atlantic. In addition, there is a weaker non-local response which is visible through changes in volume transport through gateways (for example the Indonesian Throughflow). Main focus of the presentation is on understanding the role of eddies in possible future responses of the Atlantic MOC (and global ocean circulation) to the applied freshwater inputs.

Theme 3 - Invited Talk

Importance of the Argo Float Measurements in Assimilating Meridional Overturning Circulation in the South Atlantic

Shenfu Dong[1,2], Molly Baringer[2], Gustavo Goni[2], Silvia Garzoli[2]

1) CIMAS/University of Miami
2) PHOD/NOAA

The meridional overturning circulation (MOC) and meridional heat transport (MHT) from the GFDL coupled models with and without data assimilation are examined and compared with observations at 34°S in the South Atlantic. Both models show similar response of the MHT to the MOC changes as estimated from observations: one sverdrup increase in MOC would give a 0.06 PW increase in MHT. The MOC and MHT, as well as regional contributions, from the GFDL couple data assimilation (CDA) before assimilating Argo data are similar to those from GFDL CM2.1 IPCC simulation, both give weak boundary currents and strong interior overturning transports compared to observations. However, after the Argo float profiles were assimilated, the performance of the data assimilation model is greatly improved in terms of representing the observed MOC and MHT structure at 34°S. The transports of boundary currents are much stronger and deep-reaching, and the overturning flow in the interior region is reduced. Assimilating Argo data also improves the representation of gyre circulation.

Other themes - Poster E7

The stability of the MOC as diagnosed from model projections for pre-industrial, present and future climates

Sybren Drijfhout[1,*], Susanne Weber[1,*], Eric van der Swaluw[1,*]

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The stability of the Atlantic meridional overturning circulation (MOC) is investigated for various climate scenario runs, using data from the CMIP3 archive of coupled atmosphere-ocean models. Apart from atmospheric feedbacks, the sign of the salt flux into the Atlantic basin that is carried by the MOC determines whether the MOC is in the single or multiple equilibria regime. This salt advection feedback is analyzed by diagnosing the freshwater and salt budgets for the combined Atlantic and Arctic basins. Consistent with the finding

that almost all coupled climate models recover from hosing experiments, it is found that most models feature a negative salt advection feedback in their pre-industrial climate: freshwater perturbations are damped by this feedback, excluding the existence of a stable off-state for the MOC. All models feature enhanced evaporation over the Atlantic basin in future climates, but for a moderate increase in radiative forcing (B1 and 2 CO2 scenarios), there is a decrease of the fresh water flux carried by the MOC into the Atlantic (the deficit is made up by increased fresh water transport by the gyre circulation). In this forcing regime the salt advection feedback becomes less negative: for three models from an ensemble of eight it is positive in a 2 CO2 climate, while two models feature a positive feedback in the pre-industrial climate. For even warmer climates (A1B-equilibrium and 4 CO2) the salt feedback becomes more negative (damping) again. It is shown that the decrease in northward fresh water transport at 34°S by the MOC (in B1-equilibrium and 2 CO2) is due to a reduction of the inflow of intermediate waters relative to thermocline waters, associated with a robust shoaling of the MOC in future, warmer climates. In A1B and 4 CO2 climates northward freshwater transport increases again. The MOC keeps shoaling, but both intermediate and thermocline water masses freshen.

Other themes - Oral Presentation

Latitudinal coherence of the Atlantic Meridional Overturning Circulation from moored array observations

Shane Elipot[1], Eleanor Frajka-Williams[1], Chris Hughes[1]

National Oceanography Centre

From three moored arrays in the North Atlantic, we describe the latitudinal coherence of the meridional overturning circulation (MOC) and attempt to identify the mechanisms responsible.

This latitudinal coherence is an important prediction because it is linked to our ability to monitor climate variability on various time scales, and to detect trends from observation arrays. Ocean models show that, while the Atlantic MOC only becomes coherent across latitudes on multidecadal time scales, a coherent component to the circulation exists on shorter time scales. It is generally explained by basin-scale coupling mechanisms with the atmosphere, by gyre-scale adjustments, or by coastally-trapped waves propagating anomalies along the western and eastern boundaries. Our approach is to focus on the lower limb of the Atlantic MOC and to consider the western boundary contributions to the zonally-integrated meridional transport, as model results and observations show that this is thedominant contribution to the total transport.

We form times series of overturning transport below 1000 m, from observations: At 26.5N, we use data from the Rapid/MOCHA array; at 39N we use data from the Woods Hole Line W, and at 42N, data from the Rapid-WAVE array.Preliminary results from cross-spectral analyses between the two northern time series show that the transports are coherent at monthly to seasonal time scales and approximately in phase. Between the northern time series and the time series at 26.5N, there is evidence of coherence at frequenciescorresponding to 10-day time scale to monthly and seasonal time scales, encompassing frequencies associated with boundary waves.

Theme 1 - Oral Presentation

Optimal initial perturbations for the Atlantic meridional overturning circulation

Alexey Fedorov[1*], Florian Sevellec[1]

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Yale University

The main mechanisms of AMOC variability are still being debated. In this study, using a realistic ocean general circulation model (OPA), we find optimal initial perturbations in surface temperature and salinity that would affect the AMOC the strongest after a given time delay. The analysis is conducted within a non-autonomous context for two different measures of the meridional overturning – its volume and heat transports. For each measure the optimal perturbations are computed using a maximization procedure based on Lagrange multipliers. The structure of the optimal initial perturbations is characterized by anomalies in temperature or salinity centered in the northern Atlantic off the east coasts of Greenland and Canada, south of the Denmark Strait. We find only minor differences between optimal perturbations based on the two different measures of the overturning. The most efficient optimal perturbations lead to a strong transient change of the AMOC in about 9 years. This change involves the following mechanism: the initial perturbation of density generates a geostrophic flow that extracts a temperature anomaly (with a zonal gradient) from the mean temperature field (with a strong meridional gradient). The anomalous zonal temperature gradient induces, by thermal wind balance, a northward flow in the upper ocean and a southward flow in the deep ocean, thus strengthening or weakening the AMOC. The optimal perturbations not only generate the transient growth of the AMOC, but also excite a damped oscillatory eigenmode in the system with a period of about 24 years. Simple estimates show that moderate changes in salinity or temperature in the upper ocean (such as changes due to the Great salinity anomaly) can lead to AMOC variations on the order of several Sverdrups, or 10-20% of the mean meridional overturning. This fact emphasizes the role of optimal perturbations for sustaining decadal and longer variability of the AMOC.

Theme 1 - Poster A9

Covariability of the Gulf Stream with deep return flow at 26N in 2009, from the RAPID transatlantic moored array

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In the North Atlantic, the meridional overturning streamfunction reveals a northward-flowing, upper branch (shallower than ~1 km) and a southward-flowing lower branch (from ~1km to 5km). Together, the upper and lower branches comprise the southward deep flow of the Atlantic Meridional Overturning Circulation (MOC). The MOC is estimated by the RAPID array at 26N, a transatlantic array of moored instruments including CTDs and current meters. Past results have shown a distinct annual cycle in the overturning, and that individual components of the MOC have been uncorrelated, meaning that variability

of individual components all contribute to variability of the MOC. However, in 2008, the seasonal cycle of transport in the upper mid-ocean (UMO) changed: the annual cycle was absent, replaced instead by a semi-annual cycle with two peaks and two troughs in transport, with a range of 10 Sv. Furthermore, the character of the relationship between the Gulf Stream and UMO transport changed: From 2004-2007 they were uncorrelated, but in 2008, they were significantly anticorrelated. During the same time period, eddy-kinetic-energy at the western boundary is reduced, suggesting that the anticorrelation between the Gulf Stream and UMO transport is not masked by eddy noise. Separating the UMO transport into variability contributed by density changes at the western boundary only shows that UMO-W has been anticorrelated with Gulf Stream transport since mid-2006, while changes at the eastern boundary (UMO-E) are unrelated to Gulf Stream transport. This changing relationship between the Gulf Stream and mid-ocean transport implies that all of UMO-W, UMO-E, Gulf Stream and Ekman transport are needed to construct an MOC index.

Theme 1 - Oral Presentation

Deep Western Boundary Current variability and signal attribution in the North Atlantic

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The displacement of the core of the Deep Western Boundary Current (DWBC) at 26.5°N in the North Atlantic has been the subject of discussion and interpretation since the first mooring arrays were placed there in the late 1980’s. The observed reversals or off shore shifts of the flow at the mean location of the DWBC core near the western boundary have been attributed alternately to either meandering of the core or pulsations of the current. To further analyze the causes of this variability two additional inverted echo sounders (IES), one including a bottom pressure sensor (PIES), were deployed to augment the permanent Western Boundary Time Series PIES sites for a period of two years (September 2006 to September 2008). This augmented data set, together with the output of the Ocean General Circulation Model for the Earth Simulator (OFES) model, are used to further interpret the observed transport variability. Baroclinic and barotropic signals are uncorrelated at periods larger than 50 days, confirming previous results. The results suggest that the transport variability is decoupled west and east of 75.5°W. Westward propagation is observed at a period of 70 days with energy traveling at 5 to 7 cm/s. The result of the joint analysis of data and model products suggests that neither the meandering nor the pulsation hypotheses is correct regarding the observed DWBC transport variability. These DWBC changes can be attributed to an eastward velocity core displacement due to a westward propagation of eddys or baroclinic waves into the region. The displacement of the core is observed both in the upper layer (0 to 800m) and in deeper ocean at the DWBC core level (800 to 4800 m) indicating that these propagating features are barotropic.

Other themes - Poster E8

The inter-gyre gyre in ocean data assimilation products

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Marshall et al. (2001) hypothesized that the exchange between the North Atlantic subtropical and subpolar gyres in response to the North Atlantic Oscillation (NAO) is described by a so-called inter-gyre gyre that co-varies with the meridional overturning circulation (MOC). Direct in-situ observations are too sparse to diagnose whether the inter-gyre gyre actually exists. Satellite observations and ocean state estimation products that assimilate satellite data offer a potentially useful tool for such an analysis. Here, we analyze the GECCO (German Estimating the Climate and Circulation of the Ocean) product from 1962-2001, and the SODA (Simple Ocean Data Assimilation) product from 1970-2001, and the ECCO2 eddy-permitting solution from 1992-2010. For all products, there is evidence of an inter-gyre gyre associated with NAO forcing that has a signature both in barotropic stream function and sea level. For the eddy-permitting products (SODA and ECCO2), the variability of the inter-gyre gyre is much weaker than the recirculation gyre in the subtropics, which is consistent with the analysis of observed sea level variability. The relationships of the inter-gyre gyre with the subtropical and subpolar gyres and with the strength of the Atlantic MOC at different latitudes are also examined. The results shed light on the utility of observed sea level to infer horizontal and meridional circulations in the Atlantic.

Theme 1 - Poster A10

The impact of a collapsing ice-sheet on the meridional overturning circulation during Marine Isotope Stage 6

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An intermediate complexity climate model is used to simulate the collapse of the Barents Ice Sheet during Marine Isotope Stage 6 (MIS 6; 140 ka BP) with the purpose of investigating whether a mass input of freshwater from the collapse could have affected the convection and deep-water formation in the North Atlantic Ocean. Further experiments used a coupled dynamic and thermodynamic iceberg model to determine the effects of deep-draft icebergs, rather than freshwater alone, on the ocean circulation. The results predict that the collapse of the Barents Ice Sheet has a significant impact on the meridional overturning circulation. Freshwater fluxes have more of an impact on the Atlantic overturning during the actual release period compared to icebergs, but the bergs induce effects over longer time-scales even after the pulse is removed. Freshwater fluxes of 0.15 Sv and iceberg surges of 0.1 Sv trigger significant changes in the global overturning circulation, particularly in the North Pacific Ocean, where there is strengthening of the overturning at the expense of that in the North Atlantic, and increases in air and sea surface temperatures. These results highlight the importance of simulating not only the correct flux but also the form of the freshwater input from ice-sheet collapses appropriately.

Theme 1 - Poster A11

On the Variability of the Surface-Forced Component of the Atlantic Meridional Overturning Circulation (AMOC) from 1958-2010

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Although the RAPID array at 26ºN has proved successful at continuously monitoring the Atlantic overturning, model results indicate the AMOC variability at this latitude is quite poorly correlated to that further north in the sub-polar gyre region. It is in this context that we have been exploring the possibility of estimating mid-latitude overturning variability from estimates of the surface density flux. An earlier analysis of IPCC models indicated that by calculating the Walin water mass transformation diagnostic from the surface density flux, around 40% of the AMOC variability can be accounted for. We are seeking to improve this estimate of the AMOC variability by further investigating the choice of coordinate system and the assumption of steady state used in the Walin method. Considerable improvements are also made by accounting for the variability in the Ekman currents driven by the surface winds. An attractive feature of this approach is that the estimates of AMOC variability are made from surface observations alone. As a consequence we are able to construct a time series of variability over the entire atmospheric reanalysis era (1958-2010). We thus place recent changes in the surface forced component of the overturning circulation in the context of the decadal variability of the previous 50 years.

Theme 1 - Poster A12

Why does the AMOC cross the Greenland-Scotland Ridge ?

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The deep overflows of dense water from north of the Greenland-Scotland Ridge supply more than half the water carried by the deep branch of the AMOC, when including the ambient waters that they entrain after passing the Ridge. The source of the overflows is the inflow of warm and saline waters northwards across the Ridge, which in turn are fed by the upper branch of the AMOC. A feedback loop between these flows has been suggested to cause rapid climate shifts in paleodata and is implicit in suggestions for or against anthropogenic weakening of the AMOC. From continuity, changes in overflow will induce sea level differences across the Ridge, which will act as a forcing mechanism for the Atlantic inflow, but how efficient is this compared to other forcing mechanisms, such as wind stress? Here, we present a decade-long series of measurements from the Iceland-Faroe inflow branch, which carries almost half the total Atlantic inflow. The volume transport of Atlantic inflow in this branch was found to be highly correlated to the sea level difference across the Ridge, which again is mainly controlled by the overflow from the

region north of the Ridge. The thermohaline processes in the Arctic that feed the deep branch of the AMOC, thus, also generate the main forcing of water from its upper branch into the Arctic, at least for the Iceland-Faroe branch of the inflow.

Theme 1 - Oral Presentation

Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport

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The possibility of a rapid collapse in the strength of the Atlantic meridional overturning circulation (AMOC) due to the presence of two bistable regimes has long been recognised. Such bistable behaviour has been identified in a range of simplified climate models. However, up to now, no modern atmosphere-ocean coupled global climate model (AOGCM) has exhibited such behaviour, leading to the interpretation that the AMOC is more stable than simpler models indicate. Here we demonstrate, for the first time, the presence of bistability in the response of an AOGCM to freshwater perturbations in the Atlantic Ocean. The results also support recent suggestions that the direction of the net freshwater transport at the southern boundary of the Atlantic by the AMOC may be a useful physical indicator of the existence of bistability. We also present new estimates for the freshwater transport by the AMOC from four ocean reanalyses which suggest that the Atlantic AMOC is currently in a bistable regime, although with large uncertainties. More accurate observational constraints, and an improved physical understanding of this quantity, could help narrow uncertainty in the future evolution of the AMOC and to assess the risk of a rapid AMOC collapse.

Theme 3 - Oral Presentation

Indirectly assimilating Atlantic 26°N transport into the UK Met Office Decadal Prediction System

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The RAPID array measures the Atlantic Meridional Overturning Circulation (AMOC) at 26°N. Here we develop a method to include these observations in the UK Met Office Decadal Prediction System (DePreSys). The proposed method uses covariances of the transport with temperature and salinity throughout the ocean to create the density

structure necessary to reproduce the observed transport anomaly. Initially, experiments with idealised observations taken from a control run of the model are used to assess the impact of the method in the case where transport is the only observation. It is found to be useful for reproducing the given transport close to and for a few degrees south of 26°N. The method is shown to be better than using temperature and salinity observations and their covariances at the array grid points. Transport is also analysed alongside pseudo-observations of temperature and salinity representative of the 2008 ocean observational network. Finally, the actual RAPID observations are also analysed and found to be reproduced in the assimilation.

Other themes - Poster E9

The AMOC slow-down during the Younger Dryas - Deep-sea core evidence from Lomonosov Ridge for a contemporaneous drainage even in the NW Laurentide Ice-sheet area

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The Younger Dryas climate cooling event and related slowing of the Atlantic Meridional Overturning Circulation (AMOC) has been linked to a large array of processes. If the very recent literature still offers some curious explanations for this event [1-2], the most widely supported causal mechanism involves an influx of freshwater into the North Atlantic Ocean linked to the partial drainage of glacial Lake Agassiz. Initially, an eastward route was suggested for this sudden outburst (via the Great Lakes and St. Lawrence River) [3] but further studies were inconclusive or in disagreement [4-5] with this scenario. Meanwhile, Tarasov and Peltier [6] demonstrated that a Lake Agassiz drainage event through the Arctic Ocean, would have been as efficient in shutting down the AMOC as an eastern route. More recently, some evidence for a northward drainage route, through the Mackenzie River outlet into the Arctic Ocean, has been found from land-based studies in the suspected drainage channel area [7]. At last, investigations on cores raised from the Lomonosov Ridge area yielded relatively robust chronological evidence for the recording of the Younger Dryas interval in the central Arctic [8-9]. The corresponding sedimentary layer (dated ~ 13 to ~12 ka) is marked by a pulse of detrital carbonates in the silt to sand fractions, with approximately equal amounts of calcite and dolomite, indicating an Arctic Canadian sediment source area. This layer also depicts a strong peak in 230Th-excesses, which we link to an enhanced flux of scavenging particles. Sr- and Nd-isotopes also provide further constraints on the sedimentary sediment sources involved. This event followed an interval matching broadly the Marine Isotope Stage 2, when ice-rafting deposition in the central Arctic Ocean was strongly reduced, if any. Our findings support both the scenarios of a glacial Lake Agassiz drainage event northward, with a high sedimentary influx to the central Arctic Ocean, and of an Arctic routing for enhanced freshwater export to the North Atlantic, due to both the drainage event itself and to Arctic sea-ice export when ice-drifting resumed. Thus, the hypothesis of a major drainage event (through the Arctic Ocean) resulting in a slow-down of the AMOC, and likely in the YD cold spell by itself, is in no way disqualified, as suggested in some of the recent papers [2], although its respective role vs that of the re-inception of sea-ice export has still to be deciphered.

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Theme 1 - Oral Presentation

Chaotic variability of the meridional overturning circulation on subannual to interannual timescales

Joel Hirschi[1,*], Adam Blaker[1], Bablu Sinha[1], Steven Alderson[1], Andrew Coward[1], Beverly de Cuevas[1]

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The first 5 years of RAPID observations at 26.5°N have shown that the eridional overturning circulation (MOC) exhibits a large subannual to seasonal variability. The origins of this variability is only partly understood. In particular it is not clear how much of the observed MOC variability is due to chaotic (unpredictable) processes such as eddies (and to a lesser extent external waves). Here we use a 1° and a 1/4° (eddy permitting) global ocean model (NEMO) as well as a simple box-model to illustrate how to isolate the chaotic component of the MOC. The 1° and 1/4° NEMO runs consist of two passes through the surface forcing for the 1958 to 2001 period. After an initial model adjustment with strong drifts during the first pass the model reaches a quasi steady-state. To extract the chaotic MOC component we look at the differences between both passes. Since the surface forcing is the same, the instantaneous differences between passes 1 and 2 are most likely a response to different mesoscale eddy fields. For the 1/4° model, the standard deviation of the differences between passes 1 and 2 is between 5 Sv (equator) and typically 1.5 - 2Sv at mid-latitudes. This corresponds to about 20 to 30% of the total MOC variability. For the coarser resolution of 1° mesoscale eddies are not resolved and the chaotic MOC component is less than 10%. Despite the differences due to eddies and internal waves, the correlation between the MOC values of the two passes of the eddy-

permitting run are high, suggesting that on subannual to interannual timescales the MOC variability is mainly determined by the atmospheric forcing. Interestingly, the ratio between chaotic and total MOC variability does not change much when the subannual and interannual MOC components are considered separately. This suggests that oceanic eddies (with a typical lifetime of a few months) can also trigger intrinsic MOC variability on longer (interannual and maybe even longer) timescales.

Theme 1 - Poster A13

Estimates of 21st century North Atlantic heat transport from satellite and drifter data

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Using temperature, salinity and displacement data from Argo floats combined with satellite sea surface height, a time series of the Atlantic meridional heat transport from 2002-2009 has been calculated for 41oN. The calculation method is validated against hydrographic climatologies and output from the ECCO2 ocean data assimilation model, and the assumptions are shown to be reasonable; the greatest source of error is from the sparse distribution of Argo floats. The mean heat transport is 0.49 ± 0.09 PW, which is consistent with previous estimates made using hydrographic or surface flux data. The heat transport has a significant annual cycle and high degree of sub-annual variability, indicating that uncertainties in previous calculations may have been underestimated. There is little evidence of a trend over the short period of available data. Correlations with sea surface temperature show clear physical relationships between Ekman transport and overturning temperature transport, even on the short time scales of available data.

Theme 1 - Oral Presentation

The impact of Model Resolution on MOC adjustment in a Coupled Climate Model

Dan Hodson[1], Rowan Sutton[1]

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Observed Atlantic Sea Surface Temperatures (SSTs) during the 20th Century exhibit distinct decadal variability. Modelling studies suggest that this variability may be at least partly driven by variations in the Atlantic Meridional Overturning Circulation (AMOC). Decadal ocean variability may be an important source of climate predictability on decadal timescales via the modulation of atmosphere-forcing SST patterns. It is important therefore to attempt to understand the sources and mechanisms involved in generating such decadal variability within the AMOC and the accuracy and limitations of climate models to represent such processes. The ultimate source of AMOC decadal variability is

thought to be high latitude deep ocean convection, predominantly confined to the Labrador and Greenland-Iceland-Norway (GIN) seas. This convection transports cold dense surface water to depth with a consequent downward mass flux in these regions. Complete adjustment of the AMOC requires that such high latitude density changes are communicated throughout the entire Atlantic Basin. Evidence from coupled climate models and idealised ocean models suggest that this adjustment is communicated by the propagation of density signals along the western Atlantic Ocean boundary. The timescale for this ocean adjustment and the subsequent atmosphere response may therefore depend on the speed of propagation of these boundary density signals.
Previous studies have suggested that the propagation speed of these signals may be significantly influenced by model resolution. In this study we the compare the propagation of such boundary density signals, how the AMOC adjusts, and the resulting climatic responses, between a high and a low resolution coupled climate model (HiGEM and HadGEM). We find that the ocean adjustment timescale is dependent on ocean model resolution. However, the SST adjustment timescale in the Tropical Atlantic is not dependent on model resolution, at least for the first decade after a change in the MOC, because the Tropical Atlantic SST changes arise as a response to extra-tropically forced atmospheric changes, rather than the underlying ocean adjustment.

Theme 2 - Poster B1

Changes in Holocene North Atlantic Deep Water flow and properties

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High resolution flow speed reconstructions of two cores located in the North East and North West Atlantic Basins reveal a long-term decrease in flow speed in North East Atlantic Deep Water (NEADW) during the mid- to late Holocene. Benthic foraminiferal oxygen isotopes (δ18O) of sites from the North East and North West Atlantic show similar trends and values during the early Holocene (until 6,500 years) but diverge afterwards, with benthic foraminifera from the North East Atlantic being ~0.27‰ lighter than those from the North West Atlantic basin. Similar benthic δ18O during the early Holocene may be the result of both sites being influenced by a similar water mass, most likely NEADW. After 7,000 years we observe the development of a carbon isotope (δ13C) gradient between Norwegian Sea Deep Waters (source for Iceland Scotland Overflow Water which feeds NEADW) and NEADW itself. We relate these changes in benthic foraminiferal isotopes bathed in NEADW to a shoaling of Lower Deep Water (LDW) whose ultimate source is Antarctic Bottom Water, in combination with a deeper eastward advection of Labrador Sea Water (LSW) in the North East Atlantic Basin. We propose that the absence of a δ13C gradient during the early Holocene indicates that LDW was of only minor importance in the North Atlantic Basin, and that a weakened NEADW flow (as indicated by our flow vigour record) during the mid to late Holocene, allowed the penetration of LDW and LSW into the east Atlantic Basin.

Theme 1 - Oral Presentation

Drift-free measurements of pressure differences on the continental slope: Demonstration of a method which generalizes hydrostatic balance and thermal wind to sloping boundaries

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In an ocean with vertical sidewalls, it would be possible to measure the MOC using just a vertical mooring measuring density at either side of the basin and thermal wind balance. The WAVE array generalizes this concept to the case of sloping sidewalls, using a combination of density and current measurements at the boundary. Using these, and direct bottom pressure measurements (the latter subject to long-term drift), we show how pressure differences can be recovered to subcentimetre accuracy, thus solving the drift problem and allowing the construction of long time series. We also show how knowledge that the pressure field is strongly constrained by topography improves the closure. This method provides a cost-effective way to extend the Global Ocean Observing System to cover the ocean's boundaries.

Theme 4 - Poster D1

Wind stress curl and Atlantic Multi-decadal Ocean Variability

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The warm branch of the AMOC exhibits strong variability over decadal time scales, and these changes form a continuum with the longer-period Atlantic Multidecadal Variability, AMV. We analyze the 20th century atmospheric reanalysis by Compo et al. (2011, 2006) to address why the North Atlantic Oscillation (NAO) cannot explain the particularly strong episode of subpolar warming in the early 2000s. This warming represents a regional part of the AMV warm phase. We show that a wind stress curl mode representing amplitude modulation of the climatological curl pattern, the gyre mode, is closely related to the average SLP over the subpolar gyre such that the gyre is weak when SLP anomaly is positive. This SLP pattern has been identified earlier by Deser and Blackmon (1993) to be associated with the warm phase of the Atlantic multidecadal SST variability. The same gyre mode at its weak phase corresponds to a wide-spread anomalous heating of the North Atlantic Ocean from the Equator to the Nordic Sills. In summary, we have several

potential contributors to AMV, (1) gyre dynamics; weak gyres allow more efficient escape of subtropical waters into the subpolar gyre, (2) surface heat flux favoring heating when the wind stress gyre mode is weak and (3) enhanced AMOC which we could not address here.

Theme 2 - Invited Talk

Mechanisms linking volcanic aerosols to the Atlantic meridional overturning circulation

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This study examines the sensitivity of the climate system to volcanic aerosol forcing in the HadCM3 climate model. We base our main test case on the 1880s, in which there were several volcanic eruptions, the well-known Krakatau being the largest. These eruptions increased atmospheric aerosol concentrations and induced a period of global cooling surface temperatures. However, due to a lack of observations, it is not known what the response of the whole climate system was. In this study, an ensemble of the HadCM3 climate model has been integrated with the usual representation of historical radiative forcings from 1860 to present. A second ensemble removes the volcanic aerosols from 1880 to 1899. The all-forcings ensemble shows an attributable 1.2 Sv increase in the Atlantic Meridional Overturning Circulation (AMOC) at 45°N, a 0.4 PW increase in meridional heat transport at 40°N, and increased northern Atlantic SSTs starting in around 1895, around 15 years from the first eruption, and lasting a further 10 years at least. The mechanisms responsible are traced to the Arctic, with suppression of the global water cycle (high latitude precipitation), which leads to an increase in upper level Arctic and Greenland sea salinities. This then leads to increased convection in the Greenland, Iceland and Norwegian (GIN) seas, enhanced Denmark strait overflows, and AMOC changes with density anomalies traceable all down the western Atlantic boundary. We investigate whether a similar response to the Pinatubo eruption in 1991 could still be ongoing but do not find strong evidence.

Theme 1 - Poster A14

Multidecadal variability of the MOC: HadCM3 and a perturbed physics ensemble

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Met Office, Hadley Centre

Multidecadal to centennial variability of the MOC is examined in HadCM3. Large changes caused by the multidecadal variability are strongly related to salinity anomalies in the sinking regions and hence may help us understand possible mechanisms behind a rapid

shutdown of the MOC. The drivers of the large multidecadal changes and coupled feedbacks associated with the changes are investigated. These involve the propagation of anomalies into the region as well as remote and local feedbacks. A perturbed physics ensemble based on HadCM3 (where physics of the atmosphere, land and sea-ice is perturbed) is also examined. The ensemble members have different MOC strengths and variability due to the different surface forcings caused by the different physics perturbations. The drivers and feedbacks of MOC changes in the ensemble are also analysed, and are compared to those in the control HadCM3 simulation, with the aim of understanding what causes the relative strength of these factors.

Theme 1 - Poster A15

Sea Level Trends in Different Time and Spatial Scales Associated with AMOC in the North Atlantic

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Satellite altimetries have enabled us to map the spatial and temporal characteristics of sea level changes since 1993 continuously. We used the long-term time series of merged monthly mean altimetry from January 1993 to December 2009 and decomposed them into different time and spatial scales based on Ensemble Empirical Mode Decomposition (EEMD). We specifically estimated the contributions of each scale to the sea level trends. Since the trends consist of many different time and spatial scales of forcings in the basin, analyzing interactions between different scales are important to understand the linkage between the shorter variation and the large scale forcing, and we found that the trends are not geographically uniform over the ocean.

In order to understand the effect of teleconnections in sea level trends, we examined the influence of El Nino-Southern Oscillation (ENSO) events and North Atlantic Oscillation (NAO) in the North Atlantic. While the lowering sea levels are closely related to NAO at interannual time scales, the raising trends are closely related to ENSO in annual and interannual time scales. The results suggested that teleconnections play an important role in modulating general ocean circulations in different time scales, and subsequently the sea level trends are not geographically uniform. The mechanisms of negative and positive trends were extensively discussed and based on analysis of the sea level trends. We also investigated the variability of Atlantic Meridional Circulation (AMOC) associated with sea level trends.

Theme 1 - Poster A16

Hydrographic and overflow variability in Denmark Strait

Kerstin Jochumsen[1], Detlef Quadfasel[1]

University of Hamburg

The water exchange across the Greenland-Scotland Ridge plays an eminent role in the dynamics of the Atlantic Meridional Overturning Circulation (AMOC). The dense overflow waters are one of the main sources for the formation of North Atlantic Deep Water (NADW); the densest NADW component is provided by the Denmark Strait overflow.
The hydrographic structure in Denmark Strait consists of three water masses: the overflow water, which fills the deep layer below approx. 200 m depth to the bottom at 630 m, and the two surface water masses transported within the East Greenland Current (EGC) and Irminger Current (IC). The EGC carries cold waters of Arctic origin southward, while the IC transports Atlantic Waters into the Nordic Seas. The horizontal front between these shallow water masses migrates prevalently, resulting in either cold, fresh or warm, salty waters dominating the surface layer of Denmark Strait.
We present an analysis of the hydrographic variability in Denmark Strait, based on CTD measurements repeatedly taken during various ship cruises, and discuss the change between EGC and IC waters in the surface layer. The migration of the horizontal surface front is evident in Sea Surface Temperature (SST) measurements from satellite data as well and found to be highly variable in its position. The subsurface waters exhibit large variability as well: the overflow water layer thickness varies between 20 m and 440 m and corresponding extensive displacements of the isopycnals were noted. Prominent changes occurred during few days. Variations of steric height at Denmark Strait sill were found to be closely connected to the overflow layer thickness. Therefore, the overflow layer variability is expected to give an imprint on satellite measurements of Sea Surface Height Anomaly (SSHA). Time series of SST and SSHA are compared to the point measurements from the cruises.
The transport of the overflow water has been monitored on the sill of Denmark Strait with up to three current profiling moorings since more than ten years (with some gaps due to instrument failures and mooring losses), as well as near-bottom temperatures. While no long term trend is evident in the data, variability is high on short timescales as well.
The results of the study reveal high short-term variability in the surface waters and overflow transport at Denmark Strait, where one important component of the AMOC is monitored. Long term signals in the overflow may be masked by the broad fluctuations and longer time series are needed to detect significant changes in the transport.

Theme 1 - Oral Presentation

Observed and simulated large-amplitude fluctuations of deep meridional volume transports in the subtropical North Atlantic

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Based on simultaneous bottom pressure measurements at different sites along a zonal section in subtropical North Atlantic at 26.5°N from the RAPID/MOCHA array we report on large-amplitude, zonally basin-wide-integrated fluctuations of abyssal northward transports. These transports can be shown to contribute to the compensation for the bulk of upper-ocean basin-wide integrated Gulf Stream, Ekman and upper-mid-ocean transports as part of the Atlantic meridional overturning circulation (MOC). Yet, the

abyssal transport variability exceeds the level of rms fluctuations required to compensate for the upper ocean transport by a factor 3. From an energetics point of view the existence of the sea-floor intensified transport variability is therefore puzzling.
Based on an analysis of bottom pressure records collected between April 2004 and October 2009 we show that the abyssal, zonally-integrated geostrophic transport variations at 5000 m show pronounced seasonal variability, and that the amplitude of the observed fluctuations exceeds those at any other level below 1000 m. This can be explained by intense time-variable flows over the western and eastern continental rises and over other topographic feature in the western basin of the Atlantic.
A simluation relying on a numerical model with a horizontal resolution of 1/12°, driven by daily, high-spatial resolution winds, is shown to capture the observed intensification of the near-bottom, zonally-integrated northward flow successfully. Three-daily snapshots of the zonal and vertical distribution of northward velocities along the 26.5°N section from the model reveal the existence of specific areas of localized, bottom-intensified flow, associated with zonal transitions in the underlying bathymetry. In contrast - but in agreement with the observations – the simulated, deep-ocean, time variable flows over the Mid-Atlantic Ridge exhibit rather small rms variability. Overall, the results suggest that the zonal structure associated with the deep compensating flows - as inferred both from the bottom pressure measurements and the model simulation - has a strong impact on the deep and abyssal part of the time-variable, vertical structure of the MOC of 26.5°N.

Theme 1 - Oral Presentation

Estimates of Heat Transport Convergence and Ocean Mass Anomalies from Observations and a Simple Model

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Changes in sea level in the Atlantic Ocean result from changes in the temperature and salinity of the ocean and from changes in mass. Two observational fields correspond to these components; heat content (from in situ data), and gravity anomalies from the GRACE satellite. Neglecting salinity, which has been estimated to have little effect on sea level in the North Atlantic, the sum of the anomalies of these components should be the observed sea level anomalies. Sea level, arguably, has a relatively small and quantifiable error compared with its components. In the absence of lateral motion and sources (rivers and melting ice sheets), surface heat and freshwater fluxes can be integrated to produce heat content and mass anomalies. Discrepancies between modeled and observed fields are the result of sources or transport convergences combined with errors in the fields. Using a Kalman filter with an unknown control formulation and high-quality surface fluxes, we model the components, constrained by the observations and estimates of all the errors. From the unknown control we infer heat transport convergence in several regions and quantify the contributions of mass to observed changes in sea level. The regional convergences can be integrated to estimate meridional heat transport (MHT), with suitable assumptions in high latitudes. Estimates are made for the Atlantic north of the Southern Ocean for comparisons with RAPID MHT. A more detailed model in the North Atlantic shows that much of the trend in sea level in the subpolar gyre is associated with changes in surface heating, rather than changes in mass or heat transport convergence.

Theme 1 - Poster A17

Vertical distribution of deep and intermediate water masses in the Southeast Atlantic (23°S) during the Last Glacial Maximum

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A leading hypothesis in paleoceanography states that a major reorganisation in the Atlantic Meridional Overturning Circulation (AMOC) occurred between the Last Glacial Maximum (LGM, 19-23 ka) and today. This change is thought to be associated with a vertical redistribution of water masses, whereby during the LGM the core of North Atlantic Deep Water was shifted to a somewhat shallower depth and replaced by bottom water of Southern Ocean origin. Using paleoceanographic reconstructions, we determined the vertical structure of modern and glacial water masses in the southeast Atlantic basin in order to test this hypothesis. In order to intersect the major water masses, we studied a depth transect (600-2730 m water-depth) at 23°S off Namibia, consisting of seven gravity sediment cores and corresponding surface and bottom water samples. To identify the prevailing water masses, we reconstructed the vertical distribution of temperature and salinity (i.e. δ18Oseawater) by combining paired Mg/Ca and oxygen isotope measurements on the benthic foraminiferal species Oridorsalis umbonatus.
The modern vertical temperature and salinity profiles indicate the presence of two distinctive water masses at the site: Antarctic Intermediate Water at around 800 m and North Atlantic Deep Water between 1400 and 3000 m. Our preliminary results for the LGM indicate slightly elevated salinities and temperatures of intermediate waters (700-950 m) relative to today. Deep waters (1400-2500 m) were characterised by similar glacial and modern temperature values, while their salinity was higher during the LGM. At the deepest site (~2700 m), colder and saltier bottom waters during the LGM indicate the presence of a dense glacial bottom water mass of southern origin and thus support the hypothesis of a vertical shift of water masses.

Theme 1 - Poster A19

Impact of Different Ocean Reanalyses on Decadal Climate Prediction

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We study the impact of three ocean state estimates (GECCO, SODA, [ECMWF]-ORA-S3) on decadal predictability in one particular forecast system, the Earth system model from the Max Planck Institute for Meteorology (MPI-M) in Hamburg. The forecast procedure follows two steps. First, anomalies of temperature and salinity of the observational estimates are assimilated into our coupled model. Second, the assimilation runs are then used to initialize 10-year-long hindcasts/forecasts starting from each year between 1960 and 2001.
The impact of the individual ocean state estimates is evaluated both by the extent to which climate variations from the ocean state estimates are adopted by the forecast system ('fidelity') and by the prediction skill of the corresponding hindcast experiments.

We assess prediction skill by computing correlations between hindcasts and direct observations for North Atlantic (NA) sea surface temperature (SST) and upper-levels ocean heat content (OHC). In addition, we compare characteristics of the Atlantic meridional overturning circulation (MOC) in the hindcast experiments with the respective assimilation runs and ocean state estimates. Irrespective of the estimates of MOC predictability that remain inconclusive in our comparison, the ORA-S3 reanalysis gives the best results for our forecast system as measured by both overall fidelity of the assimilation procedure and predictions of upper-levels OHC in the North Atlantic.

Theme 3 - Poster C3

Atlantic multi-decadal variability in the GFDL CM2.1 model and relevance to the real world

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We study the dominant pattern of North Atlantic variability in a long integration of the NOAA/GFDL CM2.1 coupled GCM. The model SST and salinity exhibit regular, damped oscillations with a 15-20 year period. The variability is vertically coherent but surface intensified and takes the form of alternating changes in upper-ocean temperature between the subpolar and subtropical gyre regions. Ocean dynamics governs the pace of the variability primarily through transporting heat between the gyres in time quadrature with the change in ocean temperature. The heat transport variability is linked to anomalies in the meridional overturning. Analysis of the relationship to the atmosphere suggests that the latter provides stochastic forcing to maintain the variability against damping. The main pattern of atmospheric forcing is the North Atlantic Oscillation (NAO), which the simulation depicts quite realistically. The relationship between the NAO and the oceanic variability suggests a possible weak response of the NAO to to the changes in SST. We examine the relevance of this model variability to the real climate system.

Theme 2 - Oral Presentation

The Dead Sea lake record during the Holocene: evidence of AMOC influence on centennial to millennial time scales

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During the Holocene, Dead Sea lake levels exhibited centennial to millennial fluctuations that were in anti- phase with similar timescale fluctuations in the levels of sub-Saharan lakes. In addition, these Dead Sea level fluctuations appear to be in-phase with advances

and retreats of Alpine glaciers. The mechanisms that govern hydroclimatic variability in these regions are different and so is their seasonality. We therefore argue that hydroclimatic variability in these remote regions are synchronized by slowly varying, basin-wide SST anomalies in the North Atlantic. This assertion is supported by instrumental observations and some evidence from marine paleo-proxies. Given that changes in AMOC are perceived to be the prime source of multi-decadal and longer North Atlantic SST variability, the Dead Sea level record adds further evidence to the significant influence of the overturning on the climatic of the Northern Hemisphere.

Theme 1 - Poster A20

10 years of continuous observations by the MOVE array

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The MOVE array (Meridional Overturning Variability Experiment) at 16 N has now measured time series of the Atlantic Meridional Overturning Circulation of sufficient length (2000-present) to discuss decadal-scale variability based on these observations alone. This presentation shows the results up until the most recent deployment and discusses both decadal variability and statistic significance thereof. Comparisons of MOVE results with those from computer simulations and other observatories are shown with the goal of a more comprehensive understanding of the AMOC than a single observatory could achieve.

Theme 1 - Oral Presentation

Understanding simulated long-term changes in the North Atlantic MOC

Mojib Latif[1,*], Thomas Martin, Annika Reintges, Torge Martin, Wonsun Park, Noel Keenlyside

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Future changes in the Atlantic meridional overturning circulation (MOC) will result from processes both internal and external to the climate system. Here, using the CMIP3 database and simulations with the Kiel Climate Model (KCM), three aspects of model-based projections of the Atlantic MOC will be discussed:
First, while most climate models predict a weakening of the North Atlantic meridional overturning circulation (MOC) during the twenty-first century, large uncertainty exists. Quantification of the different sources of uncertainty – external, internal and model – indicates model error is the largest component, internal variability is significant during the first decades, while scenario uncertainty is almost negligible. The different contributions to

model uncertainty – wind and density, salinity versus temperature – will be also discussed.
Second, individual studies suggest that multidecadal changes in the MOC are strongly related to large-scale salinity anomalies and therefore to changes in the surface freshwater fluxes and freshwater transport. Here, the general relationship between the MOC and freshwater budget of the Northern Hemisphere is analyzed for the twentieth and twenty-first centuries. Global warming leads to an amplified hydrological cycle, which affects the vertical salinity and temperature profiles. The meridional changes in the ocean-atmosphere interaction diminish the meridional oceanic density contrast. In the North Atlantic sinking regions, these changes are strongly related to salinity anomalies at the surface. We find in the multi-model mean a strong freshwater export from the Arctic into the northern part of the North Atlantic, stressing the importance of a realistic representation of the hydrological cycle in the models.
Third, experiments with KCM indicate that ocean-sea ice-atmosphere interaction in the Southern Ocean could give rise to significant centennial scale changes in the MOC. The model simulates an internal mode of variability on a multi-centennial time-scale set by the interaction between sea-ice cover, open ocean convection in the Weddell Sea and the global MOC. The multi-centennial mechanism is similar to what has been reported with a standalone ocean model forced with mixed boundary conditions and was thought to be spurious

Other themes - Oral Presentation

Variability in the Production and Properties of Deep Western Boundary Flows in the Labrador Sea and Downstream

John W. Loder[1], Igor Yashayaev[1]*, Kumiko Azetsu-Scott[1], Yuri Geshelin[1], Blair A. Greenan[1], Edward P.W. Horne[1], Miguel A. Morales Maqueda[2], John N. Smith[1]

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Variability in ocean temperature and salinity in the Labrador Sea (LS) deep-convection region over the past half century is described, with focus on the properties of the Deep Western Boundary Current (DWBC) (the lower limb of the Atlantic Meridional Overturning Circulation). Particular attention is given to variability in the production of Labrador Sea Water (LSW), and in the properties of Northeast Atlantic Deep Water (NEADW) and Denmark Strait Overflow Water (DSOW) as they move from the Labrador Sea to the Scotian Slope and Rise (SSR). Hydrographic variability in the Labrador Sea is described from a 21-year time series of properties on the AR7W line obtained from annual surveys by the Bedford Institute of Oceanography, supplemented by earlier weather ship and survey data, and recent Argo float profiles. Variability downstream is described from surveys and recent moored measurements across Orphan Basin (off northeast Newfoundland) and on (or in the vicinity of) the Halifax line across the SSR (in conjunction with the UK Rapid Climate Change program). Complementary observations of chlorofluorocarbon and iodine transient tracers on the AR7W and Halifax lines are used in conjunction with those from Line W farther downstream to describe the distribution of the DWBC branches on the SSR and their transit times from the LS. The analyses indicate that LSW production has continued intermittently over the past decade, but with reduced depth and persistence than in the mid/late 1970s and 1987-1994. Anomalous DSOW

properties originating in the Denmark Strait (e.g. 2004) can be detected on the SSR, but there is only approximate consistency between LS-to-SSR transit times estimated from temperature-salinity anomalies (3-4 years) and transient tracers (5-7 years).

Theme 1 - Oral Presentation

Linking deep water formation to AMOC variability: a review, a challenge and a plan

Susan Lozier

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The relationship between local production of deep water masses and the meridional overturning has been assumed mutually causal for decades. With this causality, the strength of the meridional overturning is believed to depend upon the spread of dense water masses produced via local overturning at high latitudes in the North Atlantic. Likewise, the return of surface waters as part of the upper limb of the overturning has been assumed to impact local overturning at high latitudes by weakening or strengthening the surface stratification, depending upon the salinity and/or temperature of the returning waters. However, observational and modeling studies over the past decade have called this assumed linkage into question. Understanding this linkage is crucial to efforts aimed at predicting the consequences of the warming and freshening of high latitude surface waters to the climate system. The observational basis for linking water mass formation with the ocean’s meridional overturning is reviewed in this talk, the challenge of establishing such a linkage will be discussed and a plan for doing so will be presented.

Theme 4 - Invited Talk

Ocean Circulation Response to Glacial Aged Heinrich Events

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Sediments in the North Atlantic suggest that glacial periods are punctuated by purges of the Northern Hemisphere ice sheets (Heinrich Events). The input of freshwater from the melting icebergs is thought to have interrupted the Atlantic Meridional Overturning Circulation. I will review evidence from various proxies for water mass properties and ocean circulation over the Heinrich Events, and introduce new records of upper ocean properties from the Florida Straits over the most recent Heinrich Events. It appears that not all of the Heinrich Events were associated with changes in large changes ocean circulation. For the two Heinrich Events that occurred during the coldest part of the glacial cycle, many records ocean circulation and water mass properties show a much muted or non-existent response.

Theme 1 - Invited Talk

Impact of the Atlantic Meridional Overturning Circulation (AMOC) on Arctic Surface Air Temperature and Sea-Ice Variability

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The simulated impact of the Atlantic Meridional Overturning Circulation (AMOC) on the low frequency variability of the Arctic Surface Air temperature (SAT) and sea-ice extent is studied with a 1000 year-long segment of a control simulation of GFDL CM2.1 climate model. The simulated AMOC variations in the control simulation are found to be significantly anti-correlated with the Arctic sea-ice extent anomalies and significantly correlated with the Arctic SAT anomalies on decadal timescales in the Atlantic sector of the Arctic. The maximum anti-correlation with the Arctic sea-ice extent and the maximum correlation with the Arctic SAT occur when the AMOC Index leads by one year. An intensification of the AMOC is associated with a sea-ice decline in the Labrador, Greenland and Barents Seas in the control simulation, with the largest change occurring in the winter. The recent declining trend in the satellite observed sea-ice extent also shows a similar pattern in the Atlantic sector of the Arctic in the winter, suggesting the possibility of a role of the AMOC in the recent Arctic sea-ice decline in addition to anthropogenic greenhouse gas induced warming. However, in the summer, the simulated sea-ice response to the AMOC in the Pacific sector of the Arctic is much weaker than the observed declining trend, indicating a stronger role for other climate forcings or variability in the recently observed summer sea-ice decline in the Chukchi, Beaufort, East Siberian and Laptev Seas.

Theme 2 - Poster B2

Predicting Atlantic Meridional Overturning Circulation (AMOC) Variations Using Subsurface and Surface Fingerprints

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Recent studies have suggested that the leading modes of North Atlantic subsurface temperature (T_sub) and sea surface height (SSH) anomalies are induced by Atlantic Meridional Overturning Circulation (AMOC) variations and can be used as fingerprints of AMOC variability. Based on these fingerprints of the AMOC in the GFDL CM2.1 coupled climate model, a linear statistical predictive model of observed fingerprints of AMOC variability is developed in this study. The statistical model predicts a weakening of AMOC strength in a few years after its peak around 2005. Here, we show that in the GFDL coupled climate model assimilated with observed subsurface temperature data, including recent Argo network data (2003-2008), the leading mode of the North Atlantic T_sub anomalies is similar to that found with the objectively analyzed T_sub data and highly

correlated with the leading mode of altimetry SSH anomalies for the period 1993-2008. A statistical auto-regressive (AR) model is fit to the timeseries of the leading mode of objectively analyzed detrended North Atlantic T_sub anomalies (1955-2003) and is applied to assimilated T_sub and altimetry SSH anomalies to make predictions. A similar statistical AR model, fit to the timeseries of the leading mode of modeled T_sub anomalies from the 1000-year GFDL CM2.1 control simulation, is applied to predict modeled T_sub, SSH, and AMOC anomalies. The two AR models show comparable skills in predicting observed T_sub and modeled T_sub, SSH and AMOC variations.

Theme 3 - Poster C4

On the links between the Atlantic Multidecadal Oscillation and the Atlantic Meridional Overturning Circulation

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Although the RAPID project has delivered observations of the Atlantic Meridional Overturning Circulation (AMOC) since 2004, observations remain too sparse to directly study the low frequency variability. A signature of the decadal and multidecadal variability of the AMOC may be the Atlantic Multidecadal Oscillation (AMO). Nevertheless, the AMO is also influenced by other climate modes, such as the El Nino Southern Oscillation, and externally forced variations.
In order to extract the part of the AMO that is related to the AMOC variability, we use a dynamically based filter. Assuming that SST anomalies are well approximated by a linear multivariate Markov process, the Linear Inverse Modelling approach is used to decompose the North Atlantic SST field into a global trend, an ENSO-related part and a residual. Using the latter, a filtered AMO is computed, using HadISST reanalysis. To show that it is an improved proxy of the AMOC variability, we also perform the analysis using the output of several global climate models in control conditions. The correlation between the AMOC and the filtered AMO is slightly improved in all models, and considerably increased in an historical simulation of the IPSLCM5 model. The usefulness of removing other climatic signals in the AMO deconstruction is also discussed.

Theme 1 - Oral Presentation

The Next Ten Years of AMOC Observations at 26.5 ºN – 2014 to 2024

Jochem Marotzke[1,*], Stuart A. Cunningham[2], Johanna Baehr[3], Helmuth Haak[1], Johann H. Jungclaus[1], Daniela Matei[1], Wolfgang A. Müller[1], Zoltan B. Szuts[1]

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We will build the science case for continuing the RAPID/MOCHA AMOC observations at 26.5 ºN into the second decade. The existing time series is the international standard for AMOC strength, structure and variability; its length is such that its time-mean has a standard error of below 1 Sv and a total error that will soon be below 2 Sv, which already puts a powerful constraint on the AMOC simulated in climate models. The second decade of AMOC observations will give us access to evaluating model simulations at the climatically relevant interannual-to-decadal timescale. We have already demonstrated multi-year predictive skill of the AMOC at 26.5 ºN and have shown that this skill arises from internal ocean dynamics. Continuous AMOC observations will be essential for linking the expected multi-year predictive skill of some atmospheric quantities to the processes leading to this predictive skill, among them the AMOC.
In addition to allowing us to perform unparalleled transport calculations for volume and heat, the RAPID/MOCHA hydrography provides duration and vertical resolution unique for Eulerian observations. We will give an example of the prospects this offers, namely the investigation of wave motion near the western boundary. Such exploration of fundamental ocean dynamics is essential for understanding why the AMOC shows the variations it does; continuation of the measurements will be the foundation of all these approaches.
We will explore prospects for optimising both the financial and ship-time resource demands of the AMOC observing system at 26.5 ºN. Moreover we will explore the prospects for establishing the degree of meridional coherence of AMOC fluctuations as well as for constructing validated physical proxies for the AMOC.

Theme 4 - Invited Talk

Interannual predictions of the Atlantic Meridional Overturning Circulation at 26.5ºN

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The Atlantic Meridional Overturning Circulation (AMOC) is an important contributor to European climate, which implies that the future strength of the AMOC is of considerable scientific and societal interest. In the near term (interannual to decadal), AMOC variations are influenced by both anthropogenic forcing and natural variability, and therefore near-term predictions need to be initialized from the current ocean state.

We perform interannual AMOC predictions with the state-of-art coupled climate model ECHAM5/MPI-OM and compare these predictions with the only continuous observations of the AMOC at 26.5ºN, which are provided by the RAPID/MOCHA project over the period April 2004 to March 2009. Our predictions are initialized from an ensemble of ocean-only experiments forced by NCEP-NCAR atmospheric reanalyses. We show that the interannual AMOC variations at 26.5ºN are predictable up to 4 years in advance, with considerably increased skill compared to both non-initialized simulations and persistence forecasts. Investigating the predictability of different AMOC components, we find that the predictive skill arises predominantly from the basin-wide upper-mid-ocean geostrophic transport, which in turn receives its predictive skill through the upper-ocean zonal density gradient. Ensemble forecasts initialized in January 2008 indicate that the AMOC will remain stable over the next five years, with some interannual modulation of the seasonal cycle.

Theme 3 - Poster C5

The RAPID & RAPID-WATCH Data Archive

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The RAPID Data Centre (RDC) manages the large and diverse range of data generated by the RAPID and RAPID-WATCH programmes.
The RAPID programme, which had more than 30 individual projects, ran for 6 years and ended in March 2008. RAPID-WATCH, the follow on programme (2008-2014), is continuing the monitoring efforts of RAPID, maintaining a comprehensive mooring array across the Atlantic. The resulting decade-long time series will provide a valuable data set as a baseline for present day conditions and a test bed for the models. These valuable data sets will be a key source of information for future climate change research.
The RDC is made up of two of NERC's data centres, the British Atmospheric Data Centre (BADC) and the British Oceanographic Data Centre (BODC). Their remit is to provide data management support during the programme and to preserve and make available the data beyond the end of the programme, into the long term.
An overview of the contents and use of the archives is given here.

Other themes - Poster E10

Oceanic Freshwater flux at 26°N in the Atlantic

Elaine McDonagh[1,*], Brian King[1], Harry Bryden[2], Peggy Courtois[2], Stuart Cunningham[1], Zoltan Szuts[3], Chris Atkinson[2], Neil Wells[2], Joel Hirschi[4], Simon Josey[1]

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The oceanic freshwater flux at 26°N in the Atlantic is estimated from six repeat hydrographic sections; -1.11Sv (1957), -0.99Sv (1981), -1.14 Sv (1992), -1.03 Sv (1998), -0.94Sv (2004) and -0.98Sv (2010). These imply an oceanic gain of freshwater of 0.18 to 0.34 Sv between Bering Strait and 26°N. This calculation assumes conservation of salt between Bering Strait and 26°N and a flow of 0.8Sv at a salinity of 32.5 from the Pacific through Bering Strait. The decomposed salinity flux east of Florida Strait at 26°N reveals that the correlated components of the spatially varying salinity and velocity fields contribute between -0.61 and -0.96 Sv (overturning component) and between -0.07 and 0.1 Sv (horizontal component). Thus the overturning and horizontal components vary by 0.35Sv and 0.17Sv respectively between the six occupations.
The MONACO project, funded by RAPID WATCH, has begun to combine Argo data and data from the 26°N monitoring array to calculate the time-varying salinity and freshwater flux. This calculation is informed by the structure of the freshwater and salinity flux from hydrography. Progress on these calculations will be presented.

Theme 2 - Oral Presentation

North Atlantic Oscillation Forced Ocean Variability Simulated by NEMO

Jennifer Mecking[1,*], Noel Keenlyside[1], Richard Greatbatch[1]

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Leibniz Institute of Marine Sciences (IFM-GEOMAR)

Analysis of the sea surface temperature observations in the North Atlantic show clear evidence of a multi-decadal variability. In this study the Nucleus for European Modeling of the Ocean (NEMO) ocean general circulation model with a 0.5° horizontal resolution forced with COREv2 atmospheric data has been used to investigate this variability. Experiments show that key aspects of the Atlantic multi-decadal variability (AMV) can be reproduced by forcing the model using only the observed North Atlantic Oscillation (NAO). The sea surface temperature signal in the observed NAO forced integration is strongest in the subpolar gyre region. To understand whether stochastic NAO forcing plays a key role in driving the AMV, a further experiment with a stochastic NAO index is integrated over several hundred years. Results for different ocean quantities show amplification in different frequency bands. For example, the Atlantic Meridional Overturning Circulation shows amplification in the centennial to multi-centennial band whereas the subpolar gyre strength shows amplification in the decadal to multi-decadal range.

Other themes - Poster E11

The sensitivity of precipitation changes in the Amazon region under global warming to the choice of ocean component

Alex Megann[1], Adam Blaker

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The responses of two IPCC-class coupled climate models to climate perturbations are compared. The first is the HadCM3 model of the UK Meteorological Office's Hadley Centre, while the second, the Coupled Hadley-Isopycnic Model (CHIME), is identical to the first except for the replacement of its ocean model by the Hybrid-Coordinate Ocean Model, HYCOM.
The models are forced by atmospheric CO2 increasing at 1% per year until the concentration is four times that in the control experiment. The reduction in Atlantic meridional overturning circulation (AMOC) is very similar in both of the models. Although similar overall warming results in both models, there are significant regional differences: in particular, the large reduction in precipitation over the Amazon region seen in HadCM3 does not occur in CHIME. We will relate the precipitation changes to differences in the models' representation of ENSO and to changes in the SST and the ITCZ in the tropical Atlantic.

Theme 2 - Poster B3

Variability of the Deep Western Boundary Current at 26.5°N

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Changes in the Atlantic Meridional Overturning Circulation (MOC) have been correlated in numerical climate models with variations in socially important quantities such as precipitation over North America, northern hemisphere surface air temperatures and Atlantic hurricane generation/evolution. The MOC can be thought of as two limbs: a warm upper limb nominally above 800-1000 dbar and a cold lower limb from 1000 dbar down to the bottom. The Deep Western Boundary Current (DWBC) carries the western boundary contribution to the deep cold limb of the MOC at 26.5°N. Variability of the DWBC greatly exceeds that of the total MOC, which is somewhat unsurprising as the current is enmeshed with other flow features such as the well-known recirculation cell in the deep-water layer east of the current. To better understand and attribute observed MOC variations, it is necessary to understand changes to the key components of the overall system such as the DWBC. Five years of data from overlapping lines of pressure-equipped inverted echo sounders from the Western Boundary Time Series project and current meter and dynamic height moorings with bottom pressure landers from the RAPID-MOC/MOCHA programs are now available to study variations in the structure and transport of the DWBC east of the Bahamas. These data are used to present an analysis of the observed variability of this current, to highlight connections to the basin-wide MOC

fluctuations, and to demonstrate the imperative need for continuous time series measurements to advance understanding of this important current.

Theme 1 - Poster A21

Understanding past and future changes in the AMOC in the state-of-the-art climate model, HadGEM2-ES

Matthew Menary[1,*], Paul Halloran[1], Matthew Palmer[1]

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The AMOC in the latest Met Office Hadley Centre model, HadGEM2-ES, is investigated for the period 1860-2010 in a set of ensembles with different forcings. These are an ensemble forced with greenhouse gases, and ensemble forced with land-use changes, an ensemble forced with solar and volcanic changes, and an ensemble forced with all of the above plus anthropogenic aerosols (denoted ALL). The AMOC increases by around 20% over the historical period in the ALL forced ensemble. This is an approximately linear combination of an increase due to land-use changes (2/3rds) and due to anthropogenic aerosols (1/3rd). The increase due to land-use changes appears to be a result of northern hemisphere cooling due to increased albedo. There is also a role for increased dust emissions. The aerosol mechanism involves a strengthening of the subpolar gyre and changes to the Fram Strait export, as well as further Arctic salinity anomalies. A possible increase in AMOC strength over the last 150 years has implications for our understanding of northern hemisphere climate. The model also suggests a reversal from a strengthening to weakening AMOC around the present day, suggesting that we could currently be in an important transition phase.

Other themes - Poster E12

Variability of the circulation and heat transport from six occupations of the A25 Greenland-Portugal OVIDE section between 1997 and 2010

Herle Mercier[1], Pascale Lherminier[1], Claire Gourcuff[1], Artem Sarafanov[2], Anastasia Falina[2], Nathalie Daniault[1], Bruno Ferron[1], Virginie Thierry[1], Thierry Huck[1]

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Six oceanic surveys carried out between the south-east tip of Greenland and Portugal, from 1997 to 2010, revealed remarkable changes in the large scale circulation. The observations showed changes in the whole water column and evidenced large variations (up to 50% of the lowest value) in the Meridional Overturning Circulation (MOC) intensity, computed in density coordinates across the Greenland-Portugal OVIDE section. A significant correlation is found between the MOC intensity, the North Atlantic Current

transport and the net heat flux across the OVIDE section. The time scales of the MOC variability are further evaluated using satellite altimetry and Argo. This is made possible since the North Atlantic Current, which conveys subtropical water northward, is the major current contributing to the MOC upper limb. The results are further analysed in the context of the weakening of the sea-surface circulation in the subpolar gyre observed since the mid-1990's in response to changes in atmospheric forcing linked to the North Atlantic Oscillation.

Theme 1 - Oral Presentation

Seasonal AMOC variability in a climate model

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LOCEAN, IPSL/UPMC/IRS/CNRS/MNHN

The seasonal variability of the AMOC is investigated in a climate model in the light of recent findings from the RAPID program. First, both the coherence in latitude and robustness in time are assessed, using control and externally forced simulations of past and future climate. Second, the physical processes responsible for the seasonal cycle suggested at 26°N are investigated in the model, highlighting model biases regarding both wind stress forcing and oceanic hydrography. Finally, the seasonal cycle of the AMOC in subpolar areas will be characterized. Results will be compared to other recent model studies.

Theme 1 - Poster A22

Volcanic impact on the Atlantic ocean circulation over the last millennium

Juliette Mignot[1,*], Myriam Khodri[1], Marie-Alexandrine Sicre[2], Jérome Servonnat[1], Claude Frankignoul[1]

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The response of the Atlantic Ocean temperatures and circulation to large tropical volcanic eruptions of the last millennium is investigated in the IPSL-CM4 climate model, in a simulation forced by a realistic time series of volcanic eruptions, total solar irradiance variations and atmospheric greenhouse gases concentrations. The thermal response consists in a fast tropical cooling due to the strong volcanic induced radiative forcing, subtropical ventilation of this cooling in the ocean interior one to five years after the eruption, and penetration of anomalies at high latitudes through perturbations of oceanic deep convection. In surface SST, evolutions compare well with recent reconstructions. At interannual time scales, the oceanic circulation first adjusts to low latitude anomalous wind stress due to the strong cooling. The response at decadal timescales seems to depend on specific eruptions. The analysis opens perspective to reconcile earlier studies suggesting different responses of the AMOC to volcanic forcing over the last millennium.

Theme 1 – Oral Presentation

Centennial to decadal-scale ocean changes in the North Atlantic during the Late Holocene

Paola Moffa Sanchez[1,*], Ian R Hall[1], Stephen Barker[1], David JR Thornalley[1]

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The subpolar North Atlantic is a key region for understanding climate variability, as it is one of the world's main localities of deepwater formation. On decadal to multidecadal time-scales two interrelated modes of natural climate variability have been identified that contribute to changes observed in the recent North Atlantic climate system (mostly through their impact on the Atlantic Meridional Overturning Circulation, AMOC): the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). The late Holocene climatic oscillations such as the Medieval Climatic Anomaly (MCA) and the Little Ice Age (LIA) have often been highlighted as a good example of the impact of climate oscillations on society. Although the causality of these oscillations still remains controversial, the most accepted explanation is a weak solar trigger which was amplified and transmitted globally through positive feedbacks, possibly including the NAO and the AMOC. As yet, no clear consensus has emerged as to the relative contribution and interactions of these modes in shaping the North Atlantic climate at 10 100 year time-scales. The limited temporal coverage of instrumental ocean records means that they are currently not sufficient to fully resolve decadal to multidecadal patterns, or to differentiate between natural variability and human-induced changes.

In this study, sediment cores RAPiD-35-COM and RAPiD-17-5P recovered from the Eirik Drift and Iceland Basin, respectively, are used to produce multi-proxy reconstructions of some of the main constituents of the AMOC at subdecadal to multidecadal resolution during the Late Holocene. Near-bottom flow speed reconstructions based on the sortable silt mean grain size proxy show multidecadal variability in both of the Nordic Overflows. In particular, the Iceland Scotland Overflow Water vigour presents a range of decadal to centennial periodicities similar to the AMO (55years) and deVries solar cycles (200years). Additionally, surface water reconstructions from multi-species planktonic foraminiferal δ18O, Mg/Ca and assemblage counts reveal changes in the stratification of the water column with a possible link to changes in the NAO and solar forcing. Further understanding of the processes and mechanisms that govern these oscillations is essential to reduce uncertainty in climate prediction under anthropogenic forcing.

Theme 1 - Oral Presentation

Decadal predictability of the AMOC: model results and challenges

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Numerous modelling and observational studies have shown evidence of decadal variability in the North Atlantic suggesting a potential predictability of the associated climate impacts. The Atlantic Meridional Overturning Circulation (AMOC) is thought to be one driver of this decadal variability and is thus a good candidate to be potentially predictable on decadal time scales. Decadal variations of the AMOC can result from changes in both natural and human-induced perturbations of climate forcing. Decadal predictability of the AMOC and the associated climate impacts should thus be investigated as a joint initial boundary value problem. The upper limit of the AMOC potential predictability will be presented from perfect model results based on the GFDL CM2.1 coupled model. We show that in this model, the AMOC and its oceanic fingerprints are potentially predictable on decadal time scales. We will then present preliminary results of the CMIP5 decadal experiments conducted at GFDL and discuss the impact of using observations and the challenges that remain to provide reliable decadal predictions. Assessing the potential predictability of climate relies on the understanding of the processes governing decadal variability. Analyzing the AMOC decadal variability in different GFDL coupled models suggests that decadal prediction skills will critically depend on model formulation. Understanding past and present changes in the AMOC and predicting its future fluctuations in a changing climate remains a major challenge that requires a better use of available observations to identify models discrepancies and assess the origin of the biases.

Theme 3 - Oral Presentation

A new estimate of the 3D circulation in the Atlantic Ocean from altimetry, SST and in-situ measurements

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Estimating the 3D circulation of the ocean accurately is a key issue for a number of scientific challenges. Complementary to modeling/assimilation approaches, an observation based approach (Surcouf3D) is proposed here to estimate the Atlantic Ocean 3D circulation from the surface down to 1500 meter depth over the 1993-2008 period. It relies on the combination of altimetry and thermohaline field through the thermal wind equation.
Classically, the thermal wind equation is used with a reference level at depth and either assuming a level of no-motion or estimating the current at the reference level but this can be a difficult task. The reference level used here is the surface where geostrophic currents are known thanks to altimetry.

Surcouf3D currents are compared with independent data from in-situ measurements and numerical model reanalyses. We focus on the section at 26.5°N where velocity and T/S profiles are routinely observed by the RAPID-MOCHA array. First, we look at the western boundary current off the Bahamas: in the first 1000 m high correlation (up to 0.9) are found with in-situ velocities measured by the current meters. Then a 1993-2008 long time series of the maximum Atlantic Meridional Overturning Circulation (AMOC) strength at 26.5°N is computed that features a very high variability with no significant trend.
Finally, we investigate the impact on the AMOC strength of the different components that enter the computation of Surcouf3D. Is the geostrophic transport mainly led by the density gradient? What is the impact of the Mean Dynamic Topography used to estimate the surface current?

Theme 1 - Poster A24

Historical Variability in the Labrador Sea and Baffin Bay, with possible consequences to the MOC

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Based on an isopyncal analysis of historical data, 3-year overlapping triad fields of objectively analysed temperature and salinity are produced for the Labrador Sea, covering 1949-1999. These fields are then used to spectrally nudge an eddy-permitting ocean general circulation model of the sub-polar gyre, otherwise forced by inter-annually varying surface forcing based upon the Coordinated Ocean Reference Experiment (CORE). High frequency output from the reanalysis is used to examine Labrador Sea Water formation using an instanteous kinematic approach to calculate the annual rate of water mass subduction at a given density range. Historical transports are computed along a section at 53N for several different water masses. Strong variability but no trend is seen in the Labrador Sea Water layer, but a decline over the 1949-1999 period is observed for the deep western boundary current, mainly in the Iceland-Scotland Overflow layer. The variablity of the meridional overturning circulation in the reconstruction is well correlated between 45N and 55N, and is linked with the variability of Labrador Sea Water formation with a correlation of 0.38 to 0.42, at a lag of 3 years.
Additionally, historical data in the West Greenland Current is examined to show links between variability in sub-polar variability and heat provisions to Greenland glaciers in Disko Bay. A significant change is observed to have occurred in the mid-1990s, not just in the Irminger Water layer (as has previously been observed) but also in the Polar Water layer, suggesting that Arctic/Baffin Bay variability may also impact the oceanic provision of heat to West Greenland Glaciers.

Theme 1 - Poster A25

Implications of climate change on biodiversity of marine plankton communities in tropical marine coastal ecosystems, South India.

Godhantarman Nallamuthu

University of Madras

Global warming and the subsequent events of climate change and variability may have even greater repercussions for marine ecosystems than for terrestrial ecosystems, because temperature influences, water column stability, nutrient enrichment, and changes in the biodiversity of plankton communities and its reproductive cycles. Any change in the plankton diversity and abundance would affect the marine food-web and other trophic levels. In order to understand the impacts of climate change and its variability on the tropical coastal and marine ecosystems, study has been undertaken to investigate the diversity and trophic structure of plankton in the most important tropical estuarine system, a unique coastal marine environment in South India, as it is connected with mangrove ecosystem, brackish water and Bay of Bengal. The long term continuous monitoring survey showed (20 years of intensive study from 1988 to 2008) remarkable variations in environmental parameters, chlorophyll a concentrations and diversity of species, abundance of phytoplankton and zooplankton communities. Besides, it showed seasonal variations also: - being highest in summer (April – June) and lowest during monsoon (October – December). There were wide temperature fluctuations (range: 22.5 – 33.8 oC), salinity gradients (2.9 – 34.5PSU) and chlorophyll a concentrations (1.4 – 18.6 µg l-l). The overall mean abundance of phytoplankton 4.3 fold and zooplankton 3.6 fold were higher in summer than during monsoon. The low diversity and abundance of plankton (both phyto and zooplankton) during monsoon might be due to un-favorable climatological conditions (low temperature and low salinity), disappearance of many species, abundance versus, scarcity of food and high turbidity conditions in the water column. The series of data collected on plankton diversity and abundance over the past 20 years showed interesting observations and these have included changes in species distribution and abundance, the occurrence of neritic/oceanic in estuarine ecosystems and community shifts. Thus, climate change and its variability exert major influence on the diversity of plankton communities and significantly affect the marine food webs and other trophic levels.
Key words: Climate change, tropical ecosystems, monsoon, plankton diversity, seasonal variation, foodweb structure.

Theme 2 - Poster B4

Spatiotemporal Evolution of the Atlantic Multidecadal Oscillation and its Continental Hydroclimate Impacts

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An evolution-centric analysis of Atlantic SSTs yields interesting insights into spatiotemporal evolution of the Atlantic Multidecadal Oscillation (AMO). The Atlantic SSTs were analyzed using the extended-EOF technique after removal of Pacific SSTs'

influence, especially from the western tropical-subtropical basin (Guan and Nigam 2009). The AMO principal component (PC) exhibits decadal pulses along with lower-frequency modulation. A notable pulse in the recent record is the cold state from the late-1960s to early-1980s, one coincident with the Great Salinity Anomaly of the 1970s.

Characteristic pulse evolution consists of a high-latitude SST focus (including the Denmark Strait, Labrador Sea, and Davis Strait) in the genesis phase. Subsequent evolution is characterized by south-eastward development of SST anomalies in the midlatitudes, equatorward development in the central-eastern subtropical basin, and finally, westward development in the tropics - all over decadal time scales. A notable feature of this evolution is the near-quiescence of the tropical-subtropical basin, especially in the nascent and decay pulse phases; in some contrast with conventional AMO description. The smoothed AMO PC exhibits multidecadal timescales (50-80 years) and shows the recent warming of the Atlantic to be not a unique event, given the 1920s-30s warm state.

The AMO exerts considerable influence on the hydroclimate of adjoining continents, with fall dryness over eastern North and South America and wetter conditions across Sahel in the AMO warm phase. Given AMO's multidecadal timescales, such sustained modulation can lead to fall droughts over North America; a drought mechanism will be discussed. The impact on winter surface air temperatures over North America is also impressive, contributing to the recent warming of eastern North America.

Given the AMO timescales and significant impacts, climate models undertaking decadal predictions and multidecadal projections (including GHG-driven century projections) cannot afford to misrepresent this variability component as its impact can both offset and exacerbate (depending on its phase) the GHG-related warming signal over the Northern continents over multidecadal periods. A report on the ongoing evaluation of climate system models (CMIP3, and hopefully CMIP5) in context of AMO variability will be presented.

Guan, B., and S. Nigam, 2009: Analysis of Atlantic SST variability factoring inter-basin links and the secular trend: Clarified structure of the Atlantic Multidecadal Oscillation. J. Climate, 22, 4228-4240.

Theme 2 - Poster B5

The importance of oceanic heat re-distribution in estimating Earth's radiation balance

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We use control run data from three Met Office Hadley Centre climate models to investigate the relationship between: net top-of-atmosphere radiation balance (TOA), globally averaged sea surface temperature (SST); and globally averaged ocean heat content (OHC) on decadal timescales. Decadal trends in SST are found to be only weakly indicative of TOA changes. By integrating OHC over greater depths we are able to more reliably estimate TOA changes and reduce the timescale over which the internal variability tends to zero. Model composites of SST cooling decades are compared to observational analyses of SST over the last century. Finally, we investigate the role of the MOC in vertical re-distribution of heat in the global ocean.

Theme 2 - Poster B6

Adjoint Sensitivity of the Atlantic Meridional Overturning Circulation to Surface Fluxes of Buoyancy and Momentum

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We explore the linear sensitivity of the Atlantic meridional overturning circulation (AMOC) to surface fluxes of buoyancy and momentum. Our tool is a general circulation model (gcm) and its adjoint configured in a realistic global geometry. Traditional sensitivity studies employ an ensemble of forward model integrations. The ensemble comprises one control run and many perturbed members. These are derived from the control run by altering the initial conditions, physical parameterizations and forcing fields. In a gcm the associated degrees of freedom - and therefore possible perturbations - are significant. Consequently, a very large ensemble is required to perform a comprehensive sensitivity study. In contrast, the adjoint simultaneously calculates the linear sensitivities of a single diagnostic (e.g the strength of the AMOC) to all model inputs. It produces time-varying maps of sensitivity. Thus the key variables and regions influencing the AMOC can be easily identified.
In this study we focus on the sensitivity of the meridional volume flux across 26N to wind stress and surface fluxes of heat and freshwater. We identify the key patterns of surface forcing variability and examine the teleconnection mechanisms controlling the seasonal to multidecadal AMOC response. We project the sensitivities onto reanalysis surface flux anomalies to construct timeseries of the volume flux across 26N. These timeseries are compared to recent AMOC variability observed across the RAPID array. Using our results we discuss modifications to the observational array that could improve our potential to forecast variations in the AMOC.

Theme 1 - Poster A26

Momentum Balance of the Atlantic Meridional Overturning Circulation

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When a force is applied to a Boussinesq fluid, such as the ocean, fluid parcels are accelerated both locally by the applied force, and non-locally by the pressure gradient forces established to maintain non-divergence of the resultant motion and to satisfy the kinematic boundary condition. The net acceleration is described by a rotational force which, for 3-dimensional flows, is written in terms of a vector potential. This dynamically important, rotational component can be isolated using a Helmholtz decomposition of the applied force into its rotational and divergent components. A unique solution may be found when we impose the boundary condition that the rotational force must vanish normal to any impermeable boundary.

In this study, we seek to elucidate the 3-dimensional momentum balance governing the strength and structure of the Atlantic meridional overturning circulation (AMOC) in an ocean general circulation model (gcm). We find that the extraction and visualization of the rotational force is greatly simplified in the hydrostatic limit. For a hydrostatic regime, the rotational forces are cleanly separated into components that drive the depth-integrated (mostly wind-driven) circulation and the overturning (mostly buoyancy-driven) circulation. The overturning components are each described by a scalar forcefunction. We show that these scalars represent powerful diagnostics for clearly visualising the 3-dimensional momentum balance governing the modelled AMOC.

Theme 1 - Poster A27

Skillful predictions of the mid-latitude Atlantic meridional overturning circulation in a multi-model system

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Assessing the skill of the Atlantic meridional overturning circulation (AMOC) in historical predictions is hampered by a lack of observations for verification. Models are therefore needed to reconstruct the historical AMOC variability, but different model analyses have previously been inconsistent. Here we show that 10 recent model analyses provide a robust signal of AMOC variability at 45°N, with an increase from the 1960s to the mid-1990s and a decrease thereafter. Importantly, this signal matches observed variations of the North Atlantic Oscillation, sub-polar gyre strength, and Labrador Sea convection which are strongly related to the AMOC. Furthermore, we obtain skillful predictions of this AMOC signal up to 5 years ahead with initialized models. However, models driven only by external radiative changes are not skillful, suggesting a dominant role of natural internal variability during this period.

Theme 3 - Oral Presentation

A causal link between the Atlantic Multidecadal Oscillation, Eastern Arctic ice extent andchanges in atmospheric circulation regimes over Northern Eurasia

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We analyzed a coherence between the oscillations responded to various climate system components. The ocean is a principal climate component as it is the major heat container on the Earth. The climate swings of the Atlantic Multidecadal Oscillation (AMO) are most evident in and around the North Atlantic and take roughly 60 years to complete. The studies of paleoclimate proxies, such as tree rings and ice cores, have shown that oscillations similar to those observed instrumentally have been occurring for at least the last millennium. In the 20th century, the climate swings of the AMO have alternately camouflaged and exaggerated the greenhouse warming, and made attribution of global warming more difficult to ascertain. The data sets of the ice extents in the Russian marginal seas for 1900-1999 have been prepared in the Russian Arctic and Antarctic Research Institute. Our smoothing technique allows us to filter out the high frequency components presented in original time series and to reveal a 60-year AMO cycle in a more transparent mode. The AMO wavelet power spectrum demonstrates very strong anomaly area corresponding to a cycle of about 60 years, confirming the result based on the AMO series smoothing. Moreover, a statistical analysis showed the 60-year cycle to be a significant phenomenon at the 95% probability level. A smoothed ice extent curve for the Barents and Kara Sea September monthly data demonstrates slow multi-decadal oscillations similar to AMO, but opposite in phase. Wavelet analysis exhibits a power spectrum structure similar to those for AMO. Global warming led to an increasing of water temperatures in North Atlantic, which in turn caused a rapid degrading of ice cover in Eastern Arctic. Most dramatic reduction of ice sheet was observed in Russian margin seas: Kara, Laptev and East-Siberian during late summer and early autumn. Absence of ice sheet provides a more intensive energy exchange between air and sea surface while sea surface temperature demonstrates a significant positive trend. Appearance of new phenomenon - the atmospheric convection over ice-free sea surface led to development of low atmospheric pressure anomaly area, which spread over most part of Northern Siberia in Septembers since the beginning of current century. It is only one part of Arctic dipole phenomenon related to appearance of two atmospheric pressure field extreme value domains of opposite signs in Eastern and in Western Arctic. Extremes in anomalies of atmospheric pressure field, which spread over vast territory, prevents a normal zonal atmospheric flow across Siberia from west to east and can cause a flow of opposite direction in Eastern and Western Siberia. Inflow of warm and humid air masses from Pacific Ocean and South-East Asia is a main reason of sudden spring warming in Eastern Siberia. Catastrophic flood in Lena river basin, which was occurred in May 2001, is an example of dangerous consequence of circulation regime development related to a negative pressure anomaly. It is interesting to note that in contrast to a low anomaly the winter positive pressure anomaly can cause a rapid cooling in Eastern Europe and in Western Siberia. Thus, suggested approach permits us to develop a physical background for long-term forecasting model of potentially dangerous weather situations, which might be precedent to catastrophic floods at Siberian rivers and sudden cooling in Eastern Europe.

Theme 2 - Poster B7

The Current Status of the RAPID-MOC 26°N Mooring Array

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The RAPID-MOC mooring array at 26˚N is now into its eighth year of deployment and continues to collect the data necessary for us to calculate the strength and structure of the Meridional Overturning Circulation.
Here we present the current status of the mooring array following the most recent service cruises for the eastern boundary in December 2010 aboard the RRS Discovery, and for the western boundary in Spring 2011 aboard the RV Knorr.
We also demonstrate the effectiveness of our mooring design strategy for tall moorings following the breaking of the mooring MAR1 (measuring from 5200m to 50m depth) caused by longline fishing. Although the top of the mooring was broken off, the whole mooring was recovered and measurements of the density profile were obtained up to a depth of 800m. Data from the project in the form of the MOC component timeseries data and vertical transport profiles are available from the project website at http://www.noc.soton.ac.uk/rapidmoc/.

Other themes - Poster E13

Coherent tree ring and shell increment chronologies reconstruct North Atlantic climate dynamics

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The internal growth increment series contained within the shell valves of long-lived marine bivalve molluscs (sclerochronology) constitute climate series analogous to dendrochronology. We present analysis of two independently-constructed chronologies from northwest Scotland, one derived from the tree-ring widths of coastal Scots Pine (Pinus sylvestris L.) and the first sclerochronology constructed from the internal growth increments of the dog cockle, Glycymeris glycymeris L. The two chronologies correlate significantly over the AD 1870-2006 period ($r=0.418$, $p<0.0005$). Spatial correlation models have been used to assess the correlations between each chronology and sea surface (SST) and air temperatures (data from HadISST1 and CRU TS3 gridded timeseries respectively). Significant positive correlations were identified between the Glycymeris series and mean March-August North Atlantic Current (NAC) SSTs over the period AD 1870 – AD 2006 ($r = 0.391$, $p < 0.0005$) demonstrating a clear linkage between the NAC and Glycymeris growth increments; there is also a significant positive correlation between the Pinus series and mean June-August east Atlantic SST values ($r = 0.288$, $p < 0.0005$). The Glycymeris series correlates significantly with mean November-April north European air temperatures ($r = 0.367$, $p < 0.0005$) for the period AD1902-2006. The Pinus chronology is less strongly correlated yet still demonstrates a significant relationship with mean June air temperatures ($r = 0.201$ $p < 0.03$). Calibration-verification and scaling approaches were then used to reconstruct sea surface and air temperatures based on composite sea surface and air temperature series constructed using data from HAdISST1 and CRU TS3 datasets respectively for geographical areas identified as significant using the spatial correlation techniques. We are therefore able to present the first statistically robust annually resolved marine-terrestrial integrated reconstructions of North Atlantic climate.

Theme 1 - Poster A28

Observations of AMOC relevant circulation in the subpolar North Atlantic

Monika Rhein[1,*], Achim Roessler[1], Dagmar Kieke[1], Christian Mertens[1], Maren Walter[1], Reiner Steinfeldt[1]

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On interannual to decadal times scales, model simulations suggest a strong relationship between anomalies in the deep water formation rate, the strength of the subpolar gyre, and the meridional overturning circulation in the North Atlantic. Whether this is valid, can only be confirmed by continuous, long observational time series. Several measurement components are already in place, but crucial arrays to obtain time series of the meridional volume and heat transport in the subpolar North Atlantic are still missing. Here we summarize the recent developments of the deep water formation rates and the subpolar gyre transports, and present an update of the existing and planned measurement arrays in the subpolar North Atlantic at 47°N, and at the Midatlantic Ridge.

Other themes - Poster E14

AMOC and Watermass Transformation

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Transports of mass, thermal energy and fresh water by the Atlantic meridional circulation are linked to water-mass transformation (‘WMT’) of water masses by internal mixing and air-sea exchange. The modes, locations and rates of WMT vary more between different climate models than does the bulk AMOC transport. Here we describe pieces of this story relating to (i) the variable transit of warm waters from subtropics to subpolar oceans, (ii) upper ocean buoyancy and subpolar mode water production as in the work of Brambilla & Talley (2008), with emphasis on the role of advected low-salinity waters moving south from the Arctic into the subpolar gyre and, (iii), recent analysis by H. Langehaug and T.

Eldevik (2011) of coupled climate models in which multi-century model data produces a rich set of transformations and correlations among the key circulation elements, for example between decade-to-century variability of volume transport at the Greenland-Scotland Ridge and air-sea buoyancy flux. Climate-model transformation sites are compared with observed climatology in the subpolar gyre.
WMT involves temporary accumulation of water masses as well as quasi-steady Wahlin-Speer-Tziperman balance between north-south AMOC transports and air-sea flux of heat and fresh water, as described by Grist, Marsh & Josey (2009), Nurser, Marsh & Williams (1999). Entrainment and suction by dense overflow plumes is a key feature in each of these subproblems, focusing our attention on the fine-scale mixing near the Greenland-Scotland Ridge. This mixing is the focus of intense observations using Seagliders and turbulence probes.

Theme 1 - Poster A29

Detecting changes to the Atlantic meridional overturning circulation in the Hadley Centre climate models

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Observations and coupled climate models have demonstrated that there is significant natural variability in the Atlantic meridional overturning circulation (MOC) on many different timescales. This internal ‘noise’ combined with observational uncertainties means that it may take as long as 50-100 years to detect a significant change in the MOC due to changes in global climate (e.g. Baehr et al., Climatic Change, Volume 91, Numbers 1-2, 11-27, 2008). One way it might be possible to improve detection times is to identify a multi-variate pattern of change that is mechanistically associated with changes in the MOC. A climate signal can then be projected onto this ‘fingerprint’ to derive a detector variable which, in theory, has improved signal-to-noise properties compared to a univariate timeseries of the MOC.
Vellinga and Wood (GRL, Volume 31, doi:10.1029/2004GL020306, 2004) used HadCM3 to identify 16 potentially useful hydrographic variables that could be used to define a 'fingerprint' of MOC change. To test the robustness of this methodology, we apply this fingerprint to results from HadGEM1, HadGEM2 and a 22 member perturbed physics ensemble of HadCM3-like models. We find that the original detector is not immediately transferable to different models and different forcing scenarios. However, with refinement, it is possible to define a detector that behaves consistently across a range of models.

Theme 3 - Poster C6

Causes of the rapid warming of the North Atlantic in the mid 1990s

Jon Robson[1,*], Rowan Sutton[1], Katja Lohmann[2], Doug Smith[3], Matt Palmer[3]

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In the mid-1990s the subpolar gyre of the North Atlantic underwent a rapid warming, with sea surface temperatures increasing by around 1 degC in just 2 years. This rapid warming followed a prolonged positive phase of the NAO, but also coincided with an unusually negative NAO in the winter of 95/96. The anomalous surface heat fluxes associated with the negative NAO undoubtedly favoured warming of the subpolar gyre, but was this the whole story? There is evidence suggesting important changes in the Atlantic Meridional Overturning Circulation (AMOC) at this time; understanding the nature and role of the AMOC is an important challenge, with consequences for the predictability of the warming event.
This paper will present results from new ocean model experiments that have been performed to understand the mechanisms involved in the warming. By separating the time varying buoyancy and wind stress forcing, and analyzing the heat budget of the subpolar gyre, we have demonstrated that changes in the AMOC, and associated northward ocean heat transport, played a critical role in the warming event. Furthermore, we show that warming was primarily a response to the high NAO conditions that prevailed during the early 1990s. The negative NAO of 95/96 amplified this warming and contributed to its rapidity, but was not the most important cause.

Other themes - Poster E15

A traceable hierarchy of models to identify MOC thresholds

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We present results from a hieracrchy of models to evaluate the position of stability thresholds of the Atlantic MOC. The simplest model in the hierarchy is a box model generalised from Stommel's original model to allow for return flow via both warm water and cold water paths. All box model control parameters can be diagnosed from output quantities from any general circulation model, and in principle also from observations. This means that, without any latitude for 'tuning' the box model, we can test the extent to which the simple box model physics controls the physics of MOC hysteresis in more complex models. In particular the importance of the Atlantic MOC fresh water transport across 30°S, which has been proposed as a diagnostic of MOC bistability, can be quantified in more complex models.
We test the box model physics by using it to model the MOC hysteresis structure observed in recent integrations of a low resolution coupled AOGCM (FAMOUS), and use this to develop an error estimate for the box model MOC thresholds. We discuss further

structural sources of error which may distort MOC stability even in low resolution AOGCMs. Taking these sources of error into account, the box model is then used to estimate the sensitivity of the MOC thresholds under a range of climate forcings.

Theme 3 - Poster C7

Challenges in Predicting AMOC Variability in the Next Decade

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Although the mechanisms of Atlantic multidecadal variability are uncertain, AMOC variations are considered to have a significant impact on climate on decadal time scales, as shown by model simulations. AMOC potential predictability due to initial conditions has been investigatedin perfect model studies and has shown predictability on decadal time scales. However, can initial conditions based on observations approach the limits of potential predictability?

The predictability of the AMOC forecasts using observations in a fully coupled ensemble Kalman filter data assimilation system is investigated. The state close to the observed state (analysis) is used to initialize the model introduces a drift towards the models own imperfect climate. This drift may be caused by various imbalances due to imperfect observations, assimilation methods and model systematic error that grow until the model climate is reached. The focus of this presentation will be to look at the effect of the drift on AMOC decadal predictions. In an attempt to understand the source of the bias and the rapid adjustments additional experiments attempting to reduce the model drift through resolution and physics modifications will also be presented. The sensitivity to AMOC decadal predictions to the model changes will be contrasted.

Theme 3 - Invited Talk

Monitoring ocean mass and heat transport with ADCPs on commercial vessels

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The combination of acoustic Doppler current profiler (ADCP) with GPS-based position and heading information permit current measurements to ~ 0.01 m/s accuracy on high-speed commercial vessels. This has opened up a whole new framework for ocean observation: repeat spatially-resolved current measurements build up a context that allows an

understanding of oceanic variability over a wide range of space and time scales. Four ADCP-equipped vessels, the Oleander, Nuka Arctica, the Explorer of the Seas and the Norröna monitor poleward fluxes in the North Atlantic at critical locations, each system highlights different aspects of ocean circulation.
The Oleander ADCP, in operation since Fall 1992, shows that the Gulf Stream has been quite stable yet evinces weak inter-annual variations in transport likely linked to the state of the NAO. It also has found the Sargasso Sea exhibits quite large interannual variations in westward transport south of the Gulf Stream. The Nuka Arctica operated on a three-week schedule between Denmark and Greenland from 1998-2002 and revealed remarkable fine-structure in the mean velocity field over the Reykjanes Ridge pointing to the strong role played by bottom topography. It has also identified quite complex velocity structure in the vicinity of the many banks north and west of the British Isles. The Nuka Arctica recently resumed operation; this will permit a comparative assessment of upper ocean transport a decade apart under quite different atmospheric forcing conditions. The Norröna, operating out of the Faroes to Iceland and Denmark since 2009, is providing a detailed view of inflow into the Nordic Seas, and has already revealed interannual variability in the Faroe-Shetland Channel. Interestingly, the net flow through the Channel is to the south during summer months. The Explorer of the Seas, which operates out of New Jersey in the summer months to Bermuda and the Caribbean, is equipped with a 38 kHz ADCP that routinely (in the absence of bubbles) reaches to 1100-1200 m depth and thus spans the entire upper ocean. This has led to new insights into the structure of the mesoscale eddy field and has confirmed Gulf Stream transport measured by undersea cables.
The above vessels will eventually be equipped with newly developed automatic XBT launchers that can deploy dozens of probes without the need for manual assistance. This will permit profiling of temperature according to some preset schedule, or at user-selectable locations (for example to resolve fronts or specific mesoscale features). The broader application of these technologies will provide a unique contribution toward resolving and understanding the space-time variability of North Atlantic mass and heat transport.

Theme 4 - Oral Presentation

North Atlantic gyre-scale property changes and MOC variability over the last 60 years

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There have been marked gyre-scale property changes over the North Atlantic from 1950 to 2000: the subtropics warmed and became more saline, whereas the subpolar ocean cooled and freshened. The effect of these property changes on the overturning is assessed by initialising the MIT General Circulation model with the hydrographic data and allowing a dynamical adjustment for few years; the uncertainties of the model estimates are assessed by performing Bayesian-type perturbation experiments using the standard errors for the historical data. This procedure reveals a slight strengthening of the overturning at high latitudes by +0.8 ± 0.5 Sv and weakening in the subtropics by −1.5 ±1 Sv from 1950-1970 to 1980-2000. This analysis is repeated using a reconstructed hydrographic data set compiled by the UK Meteorological Office on an annual basis up to the present day. The overturning variability has a similar range of ±2 Sv and shows opposing trends during the last 10 years, strengthening in the subtropics and weakening in the high latitudes. Hence, these gyre-specific changes probably reflect interannual and decadal variations rather than any long-term climate trend. We conclude that gyre dynamics strongly affect temperature and salinity changes that translate into changes in the meridional overturning circulation.

Other themes - Poster E16

Multistability of the Atlantic Subpolar Gyre and its stochastic resonance to Agulhas leakage variance

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The Agulhas leakage is a channel of significant salt and heat export from the Indian to the Southern Atlantic Ocean and has been shown to greatly influence interannual variability of the southern Atlantic meridional overturning circulation. Here we present results of the coarse-resolution climate model Climber-3a proposing that the observed variability of the Agulhas leakage might be enough to trigger substantial circulations changes in the subpolar North Atlantic. Abrupt strengthening of the Subpolar Gyre thereby goes along with an appearance of a southern convection side in the subpolar region. Using NCEP/NCAR reanalysis wind fields we report a stochastic resonance behavior of the Subpolar Gyre in response to changes in the Agulhas leakage well within the range of natural variability.

Other themes - Poster E17

Decadal variability in a new high-resolution model of the North Atlantic ocean

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The climate in the Atlantic region is essentially influenced by the Atlantic meridional overturning circulation (AMOC) which carries warm waters into northern latitudes and returns cold deep water southward across the equator.An important aspect in driving the

AMOC is the deep-water mass formation at northern latitudes, but climate scenarios for the future indicate that deep-water formation rate in the North Atlantic could weaken during the 21stcentury due to global warming. Geological records already indicate that the ocean circulation had almost ceased several times in the geological past due to abrupt changes in the climate. We aim to determine the processes that are responsible for the fluctuations in the deep-water mass formation rates, on interannual to decadal timescales, by using a coupled finite-element sea-ice ocean model approach, that has a special focus on the deep-water mass formation areas in the Atlantic (e.g., Greenland Sea and Labrador Sea) as well as on areas in the Southern Ocean (e.g., Weddell Sea and Ross Sea).
To validate our model setup we made a comparison of the model results with experimental Ocean Weather Ship data (OWS). The comparison of the model and OWS data shows a good agreement for temperature and salinity timeseries in the areas where the model has a high resolution. In the same time, the model tends to overestimate the salinity, by around 0.1-0.3 psu, in the regions where the resolution is coarser. By applying a FFT analysis, we found that the North Atlantic Deep Water (NADW) index, volume transport, temperature and salinity presents a strong decadal variability at 15.6 years and 7.8 years. Using a random forcinrun we show that the 15.6 years peak is related to the atmospheric forcing, while the 7.8 years peak is related to an internal mode of the ocean variability. Additionally, our model captures a salinity anomaly event around 1970, which happened due to an increase of the sea ice export through Denmark Strait.

Theme 1 - Poster A30

AMOC variability during the Last Millennium

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We present a review of Atlantic Meridional Overturning Circulation (AMOC) variability during the last millennium based on published data and new data generated as part of the EU MILLENNIUM project. These data include proxies for sea surface temperature, bottom water temperature, sea ice cover, upwelling intensity and reconstructions of ocean hydrographic variability, including Gulf Stream outflow, North Atlantic Deep Water return flow and the position of the oceanic Polar Front. Palaeoceanographic data indicate that the MCA (Medieval Climate Anomaly) (Little Ice Age, LIA) was characterized by more (less) intense AMOC. This relationship is consistent with the hypothesis, developed from analysis of terrestrial proxy records (speleothem, NW Scotland; tree rings, Morocco), that the MCA was characterized by a pervasive positive phase of the North Atlantic Oscillation (NAO). Changes in pervasive NAO phase result in synoptic shifts in surface pressure, wind fields and precipitation. The marine data support the suggestion that these NAO changes are associated with oceanic responses/feedbacks including upwelling intensity and heat transport via AMOC. Positive (negative) phases of the NAO are associated with enhanced (reduced) AMOC. However, there are multiple datasets, including the Na ion

ice core proxy from the Greenland Ice Sheet, that indicate enhanced storminess across the temperate and high latitude North Atlantic during the LIA. These data conflict with the hypothesis in that enhanced winter storminess (cyclone frequency) should correspond to the NAO positive rather than negative phase. A possible explanation of this problem has been provided by ensemble simulations of the cyclone-resolving Climate Community System Model (CCSM) coupled ocean-atmosphere general circulation model for the Maunder Minimum (LIA). These indicate major mid-latitude blocking anticyclones and reduced cyclone frequency constructions for the LIA consistent with NAO negative phase. However, the intensity of cyclones during the LIA is found to be increased when anticyclones break down. The enhanced storminess during the LIA indicated by the ice core and coastal proxies and archival data may therefore be a product of more intense, rather than more frequent, storms during the LIA.

Theme 1 - Oral Presentation

Mechanisms of Ocean Heat Content Change in the North Atlantic

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A review of in situ observational data has shown that the spatially variable ocean heat content change in the North Atlantic is greatest in the Gulf Stream extension region. Studying reanalysis data, using simple scaling and also as input into the MITgcm, demonstrates that the increased ocean heat content advection from the spinup of the northern subtropical gyre can accommodate for the observed warming. This analysis also shows how changes in the MOC over the past half century do not contribute to the heat budget in this region. The warming is associated with increased surface air temperature and precipitation along the Gulf Stream extension, adding further evidence to a dynamical connection to the upper atmosphere.

Theme 2 - Poster B8

Can ocean re-analysis output reproduce the observed overturning circulation near the regions of deep convection in the North Atlantic?

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The technique of ocean re-analysis provides an objective way of reconstructing recent past changes in the ocean state by combining ocean observations with a general ocean model that is driven by historical estimates of surface winds, heat, and freshwater fluxes.

A transport based metric has been used to compare ocean re-analyses with observations across the Greenland-Scotland Ridge (GSR) and the western boundary current in the Labrador Sea. Labrador Sea outflow and in some cases the Atlantic inflow is unrealistically small in the re-analyses and so we are not confident that hindcasts are able to determine the mean strength of the AMOC, or changes in it.
We, therefore, investigate the time-scale in CMIP5 coupled ocean-atmosphere models to detect any changes in the heat transport across GSR and the overturning transport at 26N. This time-scale can then lead us to recognise what changes, if any, the WAVE and 26N array would have seen, had they been in place since 1960's.

Other themes - Poster E18

Decadal predictions of the Atlantic overturning circulation and tropical Atlantic atmosphere

Doug Smith[1,*], Nick Dunstone[1], Rosie Eade[1], David Fereday[1], James Murphy[1], Holger Pohlmann[1], Adam Scaife[1]

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Met Office Hadley Centre

There is considerable evidence that the Atlantic meridional overturning circulation (AMOC) could be predictable on decadal timescales, and that variations in its strength are associated with important climate impacts in the tropical Atlantic including rainfall and hurricane frequency. We investigate decadal predictions of the AMOC and tropical Atlantic atmosphere both in idealised model experiments and in a comprehensive set of decadal hindcasts covering the period since 1960. Both initialised and uninitialised hindcasts have been performed, enabling the impact of initialisation and the externally forced component of skill to be quantified.
On multi-year timescales, the impact of initialisation on surface temperature predictions is largest in the north Atlantic sub-polar gyre. This is consistent with improved predictions of the AMOC, assessed against a multi-model ensemble of ocean analyses. Initialisation also improves predictions of the tropical Atlantic atmosphere, including wind shear and tropical storm frequency. These results are supported by idealised model experiments which show that the tropical Atlantic is potentially one of the most predictable regions for atmospheric variables including precipitation and wind shear. In both the idealised and hindcast experiments there is a clear link between the tropical Atlantic atmosphere and the sub-polar gyre: a warm sub-polar gyre is associated with an anomalous Hadley circulation and a northward shift of the inter-tropical convergence zone (ITCZ). By withholding data in different parts of the ocean we identify the sub-polar gyre as the key region for driving the skill in the tropical Atlantic. These results provide strong evidence of extra-tropical forcing of the tropical atmosphere, and further highlight the important role of the AMOC and high latitude north Atlantic in the global climate system.

Theme 2 - Oral Presentation

Response of the Sea Level and the MOC in a Coupled Ocean-Atmosphere Model to Greenland Ice Melting

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We investigate the transient response of the sea level and the MOC in a global coupled ocean-atmosphere model to enhanced freshwater forcing representative of melting of the Greenland ice sheets. A 50-year long simulation by a coupled atmosphere-ocean general circulation model (CGCM) is compared with another of the same length in which Greenland melting is prescribed. To highlight the importance of coupled atmosphere-ocean processes, the CGCM results are compared with those of two other experiments carried out with the oceanic component of the coupled model (OGCM). In one of these OGCM experiments the prescribed surface fluxes of heat, momentum and freshwater correspond to the unperturbed simulation by the CGCM; in the other experiment Greenland melting is added to the freshwater flux. The responses by the CGCM and OGCM to the Greenland melting have similar patterns in the Atlantic, albeit the former have five times larger amplitudes in sea level anomalies. The CGCM shows likewise stronger variability in all state variables, including the MOC, in all ocean basins because the impact of Greenland melting is quickly communicated to all ocean basins via atmospheric bridges. We conclude that the response of the global climate to Greenland ice melting is highly dependent on coupled atmosphere-ocean processes. These lead to reduced latent heat flux into the atmosphere and an associated increase in net freshwater flux into the ocean, especially in the subpolar North Atlantic. The combined result is a stronger response of the coupled system to Greenland ice sheet melting.

Theme 3 - Oral Presentation

RAPID data assimilation experiments and some preliminary analysis of the model results

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Experiments with the 1-degree NEMO model demonstrate that direct assimilation of the deep boundary density fields below 1000m can increase the strength of the model MOC for periods of several years. To achieve this temperature and salinity regressions along the deep western boundary observed in the model natural variability are used to project the Rapid array boundary data along the western boundary.
We investigate the assimilation of Rapid array data alone and in conjunction with basin wide profiles mainly from Argo. Rapid data alone has a temporary effect on the overturning which decreases after a few years due to negative feedbacks on water distributions at higher latitudes (the water formation processes are not improved when assimilating into an ocean only model). When Rapid array data are assimilated together

with other basin profile data the strengthening of the overturning can be maintained for longer periods.
These results are then extended to the NEMO ¼-degree model and it is demonstrated that similar improvements in MOC overturning can be obtained. Results are underway to investigate the impact of Rapid array data assimilation in a coupled modelling context. In this case the improved ocean conditions from the assimilation experiments described above are being imported as initial conditions of a coupled model based on NEMO. Preliminary results will be shown.
We also investigate dominant mechanisms of MOC variability at 26N on monthly timescales using analyses of 1o model data. The Ekman component and seasonal cycle were removed and spatial lead-lag correlations and regressions of different hydrodynamic field were calculated. Some results of this analysis will also be discussed.

Other themes - Poster E19

Predicting the future of the Atlantic Meridional Overturning Circulation

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A large body of evidence suggests that substantial changes in the Atlantic Meridional Overturning Circulation (AMOC) would be of major climatic importance, certainly for the North Atlantic region, and quite possibly globally. Significant changes in the AMOC could arise as a facet of natural internal variability, or in response to anthropogenic or natural radiative forcing. These issues raise the obvious question of what is our capability to predict the future of the AMOC over the next years, decades and centuries.
The prediction problem may be separated into two time scales. For the near term, perhaps up to several years ahead, the challenge is primarily an initial value problem, in which the current state of the climate system is an important constraint. Looking further ahead, beyond a decade or so, the challenge is a boundary value problem in which the response to anthropogenic forcing becomes increasingly important. For all lead times, the amplitude and phase of natural variability is an important factor, and the possibility of abrupt change is a particular concern. This talk will partly provide a review of recent progress in understanding the potential for predicting the future of the AMOC, addressing both the initial value problem and the boundary value problem. In addition, a range of new results will be presented, drawing in particular from the VALOR project funded under the UK RAPID-WATCH programme, to investigate the value of the rapid array observations for AMOC prediction. The talk will also provide an assessment of the most important challenges and opportunities for making progress in AMOC prediction.

Theme 3 - Invited Talk

Calibrating the Florida Straits submarine cable for salinity transport

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As part of calculating the freshwater or salinity flux at 26N from the RAPID/MOCHA moorings, we need to calibrate the Florida Straits submarine cable for salinity transport. Frequent CTD/LADCP transects collected by NOAA/AOML across the strait (26 sections from 2001 until 2008) give direct measurements of velocity, temperature and salinity, their variability, and their transports. Regressing transports of volume and temperature yields calibrations that are statistically indistinguishable from earlier calibrations based on separate data sets. Fluctuations in salinity transport, however, are less coherent with volume transport than is temperature transport. When regressed directly against the cable voltages, salinity transport can not be recovered as accurately from the cable as volume or temperature transports. Relative to the average mid-ocean salinity, the rms error of the cable-derived salinity transport is 2.2 Sv psu out of a signal of 32 +/- 2.5 Sv psu (mean +/- standard deviation).

Why is the salinity transport calculation less accurate than that for volume or temperature? Though temperature has a large annual harmonic signal in the upper 100 m, in agreement with a strong seasonal cycle of transport-weighted temperature noted by others, the salinity and velocity fields do not contain significant seasonal signals. Empirical modes of variability show that salinity fluctuations are strongest in mid-depth waters of intermediate salinity, where velocity is neither particularly strong nor variable. In contrast, temperature is highly stratified and warm surface temperatures coincide with strong and variable surface velocities. When combined, these factors help explain the lower correlation of salinity transport with the cable voltage.

Theme 1 - Poster A31

Impacts of a reduced Meridional Overturning Circulation on the upper ocean circulation in the Atlantic

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Climate model predictions detailed in the IPCC fourth assessment report project a slowing down of the Atlantic Meridional Overturning Circulation over the course of the 21st century. Using a high resolution coupled climate model, we here investigate the consequences of this slowing AMOC on the upper layer (<1500m) subtropical Atlantic meridional transport. Specifically, we investigate to what extent the reduction in the deep western boundary flow is balanced by a reduction in the northward flowing surface western boundary current or an increase in the interior southward flow. This is examined using two 100 year model integrations, one a control run and the other forced by an annual 2% increase in CO2 from year 2010 to 2080. In the latter, a 7 Sv reduction in the MOC takes place over the course of the 70 years, a reduction of approximately 30%. The results show that the reducing AMOC is mirrored solely by a reduction in Gulf Stream transport. In addition to this, a further 2 Sv reduction takes place in the interior subtropical gyre, which can be explained by a reduction in the curl of the wind stress. This results in a net 9 Sv reduction in the meridional transport of the Gulf Stream. We suggest that a climate forced weakening of subtropical winds is responsible for the reduced wind stress curl.

Theme 3 - Poster C8

The deglacial evolution of North Atlantic Convection

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Deep water formation in the North Atlantic by open-ocean convection is an essential component of the overturning circulation of the Atlantic Ocean, which helps regulate global climate. Paleoceanographic studies suggest that deep convection within the North Atlantic was altered during the last Ice Age as compared with today. Convection was weaker and/or shallower leading to poorer ventilation of the deep Atlantic and increased storage of dissolved inorganic carbon. Despite the climatic importance of open-ocean deep convection within the North Atlantic, high-resolution evidence for past mode changes has come primarily from stable isotope and nutrient proxy records, yet these proxies are complicated by biological processes and isotopic fractionation during air-sea gas exchange, which may overprint variations caused by water mass changes.
Here we use very high resolution water-column radiocarbon reconstructions to examine changes in Northeast (NE) Atlantic convection since the last glacial maximum. Large and abrupt changes in deep water ventilation (ventilation age shifts of 3-5000 years within 100-200 years) are associated with switching between well-ventilated deep water, formed by convection in the NE Atlantic, and incursions of 14C-depleted water, interpreted to be Antarctic Intermediate Water (AAIW), the latter occurring during cold intervals. Significant differences in the convective activity of the NE versus the Northwest (NW) Atlantic have been revealed. Of particular note is the strong reduction in NE Atlantic convection for a sustained interval (the Intra-Allerød Cold Period) beginning ~600 years prior to the onset of the Younger Dryas (YD) which has important implications for the cause of the YD. Moreover, we suggest that, despite a strong control on Greenland temperature by NE Atlantic convection, reduced open-ocean convection in both the NW and NE Atlantic is necessary to account for contemporaneous perturbations in atmospheric circulation.

Theme 1 - Poster A32

Downscaling Precipitation for the United Kingdom in an AMOC-collapse scenario.

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The UK user community has cited precipitation as a key variable where additional information upon possible changes within an AMOC-collapse scenario is needed in order to better inform adaptive decisions. The broad-scale response of the precipitation field has been identified in 'hosing' type experiments to date but little is known about station-level changes which are of most impact to the local community in many cases. Here, a statistical downscaling model, calibrated by observed station and gridded re-analysis time series, is described and verified -- and preliminary results from the application of the model to gridded GCM data in an AMOC-collapse scenario are presented.

Theme 2 - Poster B9

Decadal-scale variability of extratropical cyclones in the Atlantic basin – a project outline

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The scarce availability of long-term data series has often limited the analysis of decadal-scale variability of synoptic-systems. A novel reanalysis product, the 20th century reanalysis (Compo et al. 2011) extending back to 1870 offers potentially very valuable homogeneous and gridded data for the analysis of decadal-scale variability of cyclones in the Atlantic and European sector.

The 20th century reanalysis data is available on pressure levels with the spatial resolution of 2° and a temporal resolution of 6 hours. Surface pressure information is assimilated into NCEP's climate system model yielding 56 ensemble members consistent with the surface observations. Both individual ensemble members and the ensemble mean are available for analysis.

We plan to apply the cyclone tracking-algorithm of Wernli and Schwierz (2006) to this data set. This tracking-algorithm identifies cyclone object based on close surface pressure contours around local minima in the surface pressure field. In a second step the individual cyclone objects are joined into cyclone tracks. Information on wind maxima within the cyclone objects and integrated energy measures can be extracted as well.

The first step of the analysis will be a rigorous quality control of the data set against historic storm information. This is necessary to decide if the information on the ensemble mean is sufficient in resolution for the analysis of intense cyclones or if the full set of ensemble members needs to be evaluated.

In a second step the decadal-scale variability of cyclone positions, cyclone occurrence frequencies as well as changes in intensity and wind maxima shall be evaluated and links to decadal-scale variability of the Atlantic sea surface temperature fields explored.

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Theme 2 - Poster B1

Meridional Overturning circulation at 26N and the North Atlantic heat COntent (MONACO)

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The main goal of MONACO is to understand the links between the meridional overturning circulation (MOC) and the meridional heat transport (MHT) from the RAPID-WATCH observing system, and the subannual to interannual variability of oceanic heat content (OHC) inferred from Argo floats and sea surface temperatures (SSTs) in the North Atlantic.

We have calculated the OHC and OSC (Ocean salinity content) variability in the North Atlantic for the 1999 to 2009 period, and the MOC observations are available from April 2004 to December 2008. The spatial and temporality of the OHC, and OSC and its relationship with MOC will be discussed.

The largest OHC signal is the seasonal cycle. Its amplitude and phase is similar to the seasonal heat uptake and release through the air-sea heat fluxes. However, North Atlantic MHT changes and air-sea fluxes can differ by more than 1PW (1015W) for periods extending over several months, suggesting that MHT fluctuations may leave a sizable imprint on the OHC.

Lag correlations between deseasoned OHC and MOC variability suggest that the MOC is leading North Atlantic OHC changes by about 8 months. Similarly, we find that MOC leads the development of a tripolar SST pattern in the North Atlantic by 6 months. However, since these correlations are based on the short 2004-2008 period, and it is not clear yet whether the observed MOC – OHC, and MOC - SST links are robust.

Theme 2 - Poster B11

Beyond Scenario Analysis: Studying 21st Century AMOC Behaviour Under Infinitely Many Feasible Forcing Futures

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Studying the way in which the AMOC will change over the 21st Century involves the use of experiments on large scale climate simulators. There are many sources of uncertainty associated with such experiments. From parametric uncertainty, which arises due to the simulators having dozens of parameters with the best choice of each unknown, to structural uncertainty, which arises due to the simulator's dissimilarity from the actual climate. A major source of uncertainty is forcing uncertainty or scenario uncertainty. This arises because only a handful of idealized forcing experiments are ever performed using the models, and because we do not know what the forcing will be in the 21st Century. The analysis of only a handful of forcing scenarios is common practice and will be used by the IPCC through CMIP5.

Modern statistical techniques involving emulators offer a way of extending our study of AMOC from that based on only a handful of forcing scenarios, to a study based on any future forcing within a well defined class of experiments. Using a sufficiently large ensemble of climate simulator runs that varies forcing differently in each experiment, an emulator for features of the AMOC can be built. This emulator is a function of the simulator parameters and the CO2 forcing that can be evaluated in seconds, and returns a distribution for the future behaviour of AMOC in the model for any choice of the inputs. Such an emulator can then be used as part of a statistical model that gives a probabilistic prediction for future AMOC behaviour in the real world for any choice of forcing.

In this presentation I will present some of the techniques being used by RAPIT to build emulators for features of the HadCM3 AMOC as functions of a particular class of CO2 forcing experiments. Once built, we could use these emulators to answer questions such as: Is there a threshold for CO2 concentrations that we must stay below in order to stop rapid, irreversible change to the AMOC?

Theme 3 - Poster C9

Ocean overturning and the Atlantic storm track response to climate change

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It is often asserted that the midlatitude storm tracks shift poleward in response to increased anthropogenic forcing in climate models. While this may be true to some extent in the zonal mean, the regional storm track response can be quite different. In particular, in the CMIP3 climate models the North Atlantic storm track response is if anything a southward shift and an extension downstream into Europe. In this talk it is argued that the spread in the storm track response between different climate models is linked to the weakening of the AMOC in the simulations.

Theme 2 - Invited Talk

Decadal forecast experiments in the North-Atlantic with the EC-EARTH model

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In the EC-Earth model, the North-Atlantic region is characterized by low-frequency variations, implying a certain degree of potential predictability. We have performed a set of hindcast experiments for the period 1960-2005, initializing the model with observation re-analysis data every 5 years. Several regions show a good skill in reproducing observed trends, as well as interannual variations, up to 6-9 years after initialization. In particular, the ENSO region in the Pacific and the subpolar gyre region stand out in the EC-Earth model. We will focus on the latter region and compare the subpolar gyre strength in our hindcast to a 20 year record of satellite altimetry observations.

Theme 3 - Poster C10

Low-frequency variability and forecast skill of observed North Atlantic sea surface temperatures

Laure Zanna

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A statistical model of Atlantic sea surface temperature (SST) anomalies is constructed using an empirical technique, namely linear inverse modeling (LIM), to fit and test a multivariate red noise model to the observed record. LIM is performed on annual averaged SST anomalies from HadSST2 between 1850 and 2009 in the Atlantic basin extending from 30S to 66N. Using the statistical model, different properties of the dynamical system and its forcing component are diagnosed to investigate the forecast skill of different climate indices based on SST anomalies in the Atlantic region, and to explore the error characteristics of the forecasts. Futhermore, a simple dynamical model is introduced to examined the role of the AMOC on the variability and forecast skill of SST anomalies in the Atlantic sector. The development of such regional statistical models, especially in the Atlantic sector, for decadal predictions can serve as a benchmark for current and future decadal climate predictions based on numerical models.

Other themes - Poster E20

Toward a synthesis of overflow transports in the Labrador Sea: The Outflow at 53N

Rainer Zantopp[1], Jürgen Fischer[1], Martin Visbeck[1], Nuno Nunes[1], Torsten Kanzow[1,*]

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Any assessment of changes in the AMOC requires detailed knowledge of the circulation at key locations for the processes to be described. One of the areas of major importance for

the formation and spreading of water masses in the AMOC is the Labrador Sea, characterized by a cyclonic (anticlockwise) boundary current surrounding one of the most active areas of water mass transformation in the world's ocean. Along the Labrador shelf break the three components of North Atlantic Deep Water (NADW) merge into the Deep Western Boundary Current (DWBC) as part of the cold water limb of the Meridional Overturning Circulation (MOC). Therefore, this location at 53°N is well suited to observe - and potentially monitor – the outgoing component of those water masses which enter the North Atlantic from the Arctic Ocean.
For more than a decade, from 1996 to 2010, moored observatories were deployed over varying time intervals and spatial coverage near the western exit region of the Labrador Sea. The most prominent signal during the last decade was a well-documented warming of the water column above 2000m over the entire Labrador Sea, caused primarily by the weakened or absent formation and deep convection of Labrador Sea Water. The ad-hoc assumption that this warming trend in the upper half of the water column should be reflected in a changed intensity of circulation and outflow of the DWBC at 53°N is reviewed through moored and shipboard observations. Outflow characteristics at this key location along the pathway of cold water export are presented primarily on seasonal and interannual time scales, plus an initial estimate of the decadal variability. Transport estimates for the upper and deep limbs of the currents are reviewed for different time periods. The assessment of a monitoring scheme for the cold water export based on strategic instrument placement shows that more than 70% of the NEADW & DSOW variability can be monitored by a single instrument.

Theme 1 - Poster A33

A Model of Atlantic Heat Content and Sea Level Change in Response to Thermohaline Forcing

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The response of ocean heat content in the Atlantic to variability in deep-water formation at high latitudes is investigated using a reduced-gravity model and the MIT ocean circulation model (MITgcm). Consistent with theoretical predictions, the zonal-mean heat content anomalies are confined to low latitudes when the deep water formation rate changes rapidly, but extends to mid and high latitudes when the deep water formation varies on decadal or multi-decadal time scales. This low-pass filtering effect of the mid and high latitudes on zonal-mean heat content anomalies, termed here the ``Rossby buffer'', is shown to be associated with the ratio of Rossby wave basin-crossing time to the deep water formation forcing period. Experiments using the MITgcm also reveal the importance of advective spreading of cold water in the deep ocean, which is absent in the reduced-gravity model.
Implications for monitoring ocean heat content and sea level changes are discussed in the context of both models. It is found that observing global sea level variability and sea level rise using tide gauges can substantially overestimate the global-mean values. Comparing the sea level change and heat content change in the MITgcm also reveals the difficulty of monitoring ocean heat content change from space, since some of the heat content changes do not project well onto the sea surface height.

Theme 2 - Poster B12

Atlantic Meridional Overturning Circulation (AMOC) Adjustment to an Abrupt Change in the Nordic Sea Overflow in a High Resolution Global Coupled Climate Model

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The sensitivity of the North Atlantic Ocean Circulation to an abrupt change in the Nordic Sea overflow is investigated using a high resolution eddy-permitting global coupled ocean-atmosphere model (GFDL CM2.5). The Nordic Sea overflow is perturbed through the change of the bathymetry in GFDL CM2.5. We analyze the adjustment of the Atlantic Meridional Overturning Circulation (AMOC) to such a perturbation. The high resolution global coupled model results suggest that AMOC changes have significant meridional coherence in density space, and AMOC changes at the subpolar region propagate to the subtropics through the slow advection process, instead of the fast Kelvin wave adjustment often suggested by previous studies, resulting in a much longer time lead (several years) between subpolar and subtropical AMOC changes. The longer time lead would provide a more useful predictability. The anomalous barotropic cyclonic gyre associated with changes in the deep flow propagates southwestward with the same tracer advection time scale. When the anomalous cyclonic gyre propagates to south of the Grand Banks, it pushes the Gulf Stream path southward. The AMOC adjustment process in our high resolution coupled model simulation is consistent with that found in the coarse resolution coupled model (GFDL CM2.1). The modeling results also suggest that a stronger and deeper-penetrating Nordic Sea overflow leads to many large scale changes in the North Atlantic ocean circulation that are opposite to the common biases in climate model simulations, such as deeper AMOC, stronger cyclonic Northern Recirculation Gyre (NRG), westward shift of the North Atlantic Current (NAC), southward shift of the Gulf Stream, stronger and deeper NAC and Gulf Stream, warmer SST east of Newfoundland and colder SST south of the Grand Banks, and stronger eddy activities along the NAC and the Gulf Stream paths.

Theme 4 - Oral Presentation

Multidecadal Variability of the AMOC in the Tropical Atlantic

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The North Brazil Current (NBC) connects the North and South Atlantic, and has been viewed as the major pathway for the surface return flow of the Atlantic Meridional Overturning Circulation (AMOC). We will show that the NBC geostrophic transport, calculated from 5 decades of observations near the western boundary off the coast of Brazil, reveals a multidecadal variability. This multidecadal variability lags by a few years Labrador Sea deep convection, commonly regarded as the forcing of AMOC. The NBC

transport time series is coherent with the Atlantic Multidecadal Oscillation (AMO) in sea surface temperature, which also has been widely linked to AMOC fluctuations in previous modeling studies. The results thus suggest that the observed multidecadal NBC transport variability is an useful indicator for AMOC variations. The suggested connection between the NBC and AMOC is assessed in a 700-year control simulation of the GFDL CM2.1 coupled climate model. The model results are in agreement with observations and further demonstrate that the variability of NBC transport is a good index for tracking AMOC variations. We will further explore the relationship between the multidecadal variability of tropical Atlantic AMOC and the subsurface temperature and salinity of subpolar-subtropical North Atlantic, that have been the major constraints on the AMOC in ocean reanalysis. These relationships in different data assimilation products will be investigated to understand the large spread of AMOC low frequency variability in these products.

Theme 1 - Poster A34

Effect of Atmospheric Feedbacks on the Stability of the Atlantic Meridional Overturning Circulation

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The impact of atmospheric feedbacks on the multiple equilibria (ME) regime of the Atlantic meridional overturning circulation (MOC) is investigated using a fully-implicit hybrid coupled model (HCM). The HCM consists of a global ocean general circulation model coupled to an empirical atmosphere model. The latter is based on linear regressions of the momentum, heat and freshwater fluxes generated by a fully-coupled climate model onto local as well as Northern Hemisphere averaged sea surface temperatures. Using numerical continuation techniques bifurcation diagrams are constructed for the HCM with the strength of an anomalous freshwater perturbation as bifurcation parameter. This approach allows for an efficient first-order estimation of the change in MOC stability as a result of the surface fluxes being interactive. The feedbacks in the momentum, heat and freshwater fluxes are first considered individually and then combined. The effect of wind is found to be relatively minor. Heat feedbacks, on the other hand, act to destabilize the present-day state of the MOC and to stabilize the collapsed state, such that the range across which ME are possible is almost unaffected. In contrast, interactive freshwater fluxes cause a destabilization of both the present-day and the collapsed state of the MOC. The joint effect of the three interactive fluxes is to narrow the range of ME. The observed shifts of the saddle-node bifurcations are further explained by analyzing the changes in the solution patterns induced by the feedbacks. Finally, the results are checked for consistency with the original climate model on which the empirical atmosphere model is based.

Other themes - Poster E21

Propagation pathways of classical Labrador Sea Water from its source region to 26ºN

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More than two decades of hydrography on the Abaco line east of the Bahamas reveals decadal variability in the salinity of classical Labrador Sea Water (cLSW), despite the long distance from its source region in the North Atlantic Ocean. Hydrographic time series from the Labrador Sea and from the Abaco line show a pronounced decrease in salinity; between 1985 and 1995 in the Labrador Sea and between 1995 and 2010 near the Bahamas, indicating a time lag between the two locations of approximately 10 years. The amplitude of the anomaly at the Abaco line is about 50% of the amplitude in the Labrador Sea, due to mixing with interior Atlantic waters, particularly with saline Mediterranean Outflow Waters. A similar time lag and decay in amplitude is found in the high-resolution OFES model, in which salinity anomalies can be observed propagating through the Deep Western Boundary Current as well as through a broad interior pathway. Surprisingly, data-assimilative models generally have difficulty reproducing the observed freshening signal at Abaco, despite relatively good reproduction of the decadal changes in the Labrador Sea. In the OFES model, the freshening signal beginning at Abaco in 1995 is seen to result from two distinct freshening pulses in the Labrador Sea that occurred during 1985 to 1995, that merge to form the single broad decadal event observed at Abaco. As yet there is no evidence for an expected reversal to saltier DWBC conditions off Abaco following the trend toward warmer and saltier cLSW in the Labrador Sea since 1995.

Theme 1 - Poster A35

Long-term variations in the North Atlantic Nordic seas overturning circulation

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Observations of volume and heat transport from long term observatories in the North Atlantic Ocean and the Nordic Seas are used to study the poleward oceanic heat and mass transport toward the Arctic. Time-series extending back to the mid 1990's exist for the exchanges across the Greenland Scotland Ridge and in the Atlantic inflow branches in the Nordic Seas. These observations are combined with the long-term measurements of the deep dense mass transport out of Labrador Sea, longer hydrographic time series and model results to study long-term variation.

Observed volume transports shows interannual variability but no trend in the volume transport of Atlantic water toward the Arctic Ocean and in the deep return flow. The observed heat transport shows a shift to higher temperature in the Atlantic Water after 1995. These results are also supported from the model simulation for the whole period from 1948 to 2010.

Theme 1 - Poster A36

Thermohaline Overturning - at Risk?

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The variability of the ocean circulation in the North Atlantic has direct implications for the European climate, and for the global climate through its effects on the meridional overturning circulation (MOC). The new EU-funded THOR project (Thermohaline Overturning – at Risk?) aims to quantify the range and probability of changes associated with MOC variability using palaeoclimate studies, long term observations and numerical models of ocean circulation. Twenty higher education and research institutions from 9 European countries cooperate under THOR. The project is divided into five core themes:

CT1: Quantifying and modeling THC variability using palaeoclimate obser-vations and simulations
CT2: Assessing sources of uncertainty in ocean analyses and forecasts
CT3: Observations of the North Atlantic THC
CT4: Predictability of the THC
CT5: Technological Advancements for Improved near-realtime data transmission and Coupled Ocean-Atmosphere Data Assimilation

Under Core Theme 3, THOR will develop and operate an optimal ocean observing system for the North Atlantic component of the THC. This observation system, consisting of arrays of selfcontained instruments as well as ship- and space-borne measurements, will provide accurate time series of mass, heat and salt fluxes at key locations, allowing for the first time to assess the strength of the Atlantic THC.

Other themes - Poster E22

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