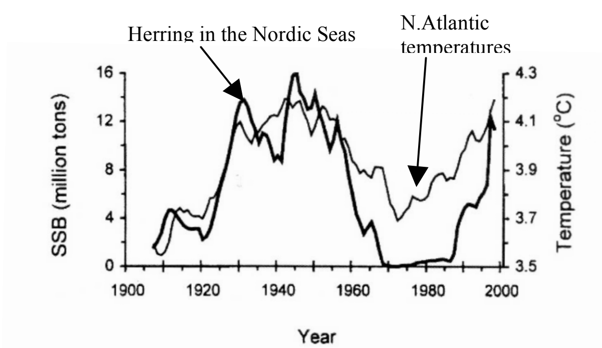
Workshop Report: **Atlantic Decadal Predictability and Plan for Next Steps**

We summarize here the key deliberations of a workshop held at GFDL in June, 2006, in which prospects for Atlantic decadal climate predictability were discussed.[1] We also suggest some next steps to further activities in this area.

Ants Leetmaa (GFDL) and John Marshall (MIT).

1. **Introduction and Background**

Increased Atlantic hurricane activity, persistent droughts, images of enhanced ice stream melting along the margins of Greenland and Antarctic ice sheets, increased rates of sea level rise, and the prospects of an ice free Arctic by the mid-21st Century, have heightened our awareness of the importance and fickleness of climate. Although we have long been aware that the instrumental record reveals the presence of decadal variability, none of these impacts were anticipated. Moreover, paleoclimate research has shown the potential for large, abrupt changes in regional climate on timescales as short as decades. Is rapid climate change taking place now? Considerable progress has been made in understanding climate variability on seasonal to interannual time scales and in the context of global warming. However, a significant gap exists in understanding decadal to multi-decadal[2] climate variability of the present climate and the mechanisms of abrupt changes shown in paleoclimate records.



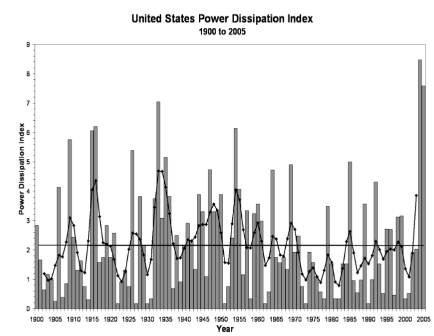


Figure 1. Sea surface temperature and Nordic Sea Herring catches (left) and US power dissipation (right) are dominated by decadal variability during the 20th century; major regimes are the period from 1925 to 1960 and from 1960 to 1990. The transitions from periods of high indices to low indices appear to be 'abrupt', and may have had major impacts on ecosystems and extreme events like landfalls in the U.S. of hurricanes. Courtesy of GLOBEC and NCDC/NOAA.

Although much remains to be learned about the causes of abrupt change in the paleo record, some of the major relevant physical mechanisms have been identified using models (and we must be aware that these are rather difficult to directly test against

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[1] A draft was circulated for comments to workshop participants and to a subset of US Clivar panels. Comments received have been incorporated.

[2] We are using 'decadal' and 'multi-decadal' somewhat interchangeably here: the Atlantic climate record does not suggest that there are spectral peaks which pick out distinct phenomena and forcing mechanisms at decadal vs multi-decadal timescales. Such distinct phenomena may be present, however, and have overlapping timescales.

observations). These include: a) changes in radiative forcing; b) feedbacks between the midlatitudes and the tropics; c) and the interactions of these with the oceanic meridional overturning circulation (MOC[3]) and sea ice cover in the Atlantic and its global manifestations. Modern changes to the MOC have been related to natural decadal variability, e.g. the Atlantic Multidecadal Oscillation (AMO) and in the future to the impacts of human-induced climate change. A consensus result from the models used for the 2007 IPCC assessment is that the MOC will slow down in the 21st Century; GFDL results suggest that this could become significant in the next decades.

Changes in the AMO and MOC are linked with surface temperature changes throughout the Atlantic and the current generation of models shows that these temperature changes play a role in decadal Atlantic hurricane variability and global temperature and precipitation changes. Robust global impacts occur in the Sahel, India, Brazil, Central America, and the Arctic. The AMO also possibly contributes to the major U.S. droughts like the Dust Bowl and the "dirty 50's".

Also implicated in most of the major North American and global droughts are small changes in ocean temperatures of only a few tenths of a degree C. in the tropical Pacific and Indian Oceans. The small temperature changes that may be associated with the initiation of these droughts can occur naturally, can be generated by small changes in radiative forcings, both natural and anthropogenic, and possibly driven from the Atlantic in association with the AMO. In turn Indo-Pacific climate variability can drive changes in the high latitude and subtropical Atlantic. Coupled models suggest that MOC variations, and perhaps the AMO too, are sensitive to high latitude air-sea interactions in the Atlantic. The climate forecasting paradigm for decadal to multi-decadal timescales for the 21st C. requires a prediction system which accounts for each of these major drivers, coupled interaction in the Indo-Pacific, the Atlantic, and impacts of global warming, and the interactions between these.

Atlantic SST is affected by numerous variability mechanisms including ENSO, the NAO, various monsoons systems and their teleconnections, arctic oscillation, PDO, and more. Each of these has been extensively studied, but the interaction between these different systems, and in particular its implications for multi-decadal SST variability needs to be further investigated.

Three significant investments made by the climate community over the past decades make such an effort timely. Firstly, TOGA and post-TOGA research has: refined our understanding the role of coupled interactions in the tropical Pacific in global climate; led to the development of improved coupled climate models; led to the implementation of operational seasonal forecast systems, a climate ocean observing system in the Pacific, and ocean data assimilation systems for the initialization of the forecasts. Secondly, the IPCC process has led to the development of a generation of models which are starting to give information about the regional impacts of global warming and are capable of

[3] By MOC here we do not just mean the 'thermohaline circulation': the MOC has important wind-driven Ekman components, as well as contributions from ocean gyres. All aspects contribute to the overturning circulation of the ocean in the meridional plane.

simulating global climate variability and the regional impacts of this on seasonal to decadal timescales. Thirdly, the basics of a global climate ocean observing and synthesis system are being put in place as a legacy of WOCE. This global observing/analysis system provides the foundation for developing a nowcasting capability for decadal variability (especially the status of the MOC), providing the initial conditions for predictability studies, improvements in the required models, and refinements in the observing capability required for this task.

2. **Workshop at GFDL on June 1-2, 2006**.

A workshop was held at GFDL to explore community interest in the development of an experimental decadal prediction capability with an Atlantic focus. It is recognized that ultimately a decadal prediction system needs to account for global interactions associated with climate variability and change. (Indeed the models and data assimilation systems which will be used are global from the start.) However, recent events such as the onset of a decade of active Atlantic hurricane activity since 1995, which has been linked both to the AMO and to anthropogenic forcing, indicates a need for a special focus on the Atlantic. Moreover, the latest generation of climate models is leading to new insights into both the regional and global impacts of decadal Atlantic temperature changes. The spatial structure of these impacts provides a hypothesis for understanding not only some of the major climate anomalies of the 20^{th} C. but also those observed in the paleo record. Hence, one could argue that the situation now is similar to that in the mid-1980's when the ENSO phenomena provided a key for understanding global seasonal to interannual climate anomalies. Decadal variability in the Atlantic will likely provide the basis for the first successful decadal forecasts. The TOGA program was successful because the scientific mechanisms/hypothesis was well defined; a similar situation is now emerging the Atlantic. A working hypothesis which is consistent with the observations and coupled model results, is that:

> intrinsic variability in the atmosphere associated with the NAO provides a large source of stochastic noise that can excite slower parts of the Atlantic climate system. Ocean processes can provide a memory and, to the extent that they feed back on the atmosphere, color the spectrum of atmospheric variability. The most likely mechanism is what might be called "passive coupling", in which damped oceanic modes (with the MOC as a prime candidate) are excited stochastically impacting SST variability and the AMO, which then feeds back on the atmosphere. If the state of the MOC can be determined from data-assimilative ocean models, then when coupled to atmospheric models, the state of the MOC, and perhaps the AMO, can be projected in to the future.

The 25 participants included researchers actively involved in Atlantic decadal variability and predictability and several US CLIVAR panel members.

3. **Goals of the workshop**:

The agenda for the workshop and the participant list is included in Appendix A. The goals of the workshop were to:

a. Summarize aspects of what is known about decadal Atlantic variability, both in terms of observational analyses and physical mechanisms
b. Discuss and assess what might potentially be predictable
c. Discuss strategies for initializing models for decadal prediction
d. Initiate efforts to catalyze US research on Atlantic predictability and predictions

4. **Workshop presentations**:

The details of the workshop presentations will not be presented here. An overview indicates that the bulk of the workshop presentations could be loosely grouped into the following categories:

a. analyses of the degree to which observed Atlantic decadal and longer fluctuations are anthropogenically forced. The record of northern hemisphere temperatures over the last 120 years can be characterized as consisting of a warming trend on which is superimposed a strong decadal variability. Removal of a linear trend results in a pronounced decadal variability (black curves in figure 2). Simulations of the 20th C. by many IPCC models capture the trend and the decadal variability. This might suggest that the radiative forcing changes (which are not well represented by a linear trend) are solely responsible for the decadal variability. The right panel shows the decadal residual after a linear trend is removed from the ensemble mean of GFDL simulations. Comparisons of this residual with the observations indicates that the radiative forcing runs cause much of the decadal variability. However, an alternative hypothesis is that this is the result of decadal variability in the Atlantic due to variations, for example, in the strength of ocean gyres affecting SST gradients near the Gulf Stream, or other variations in the MOC. At GFDL, simulations for the 20th C in which just the AMO Atlantic ocean temperature signal is imposed (with no changes to the radiative forcing throughout this period), also replicate this northern hemisphere decadal signal (left panel). So a major scientific challenge is to understand in more detail what the contributions of anthropogenic and natural effects are in the northern hemisphere. If there were a link between the anthropogenic forcing and the AMO, that would reconcile these opposing possibilities.

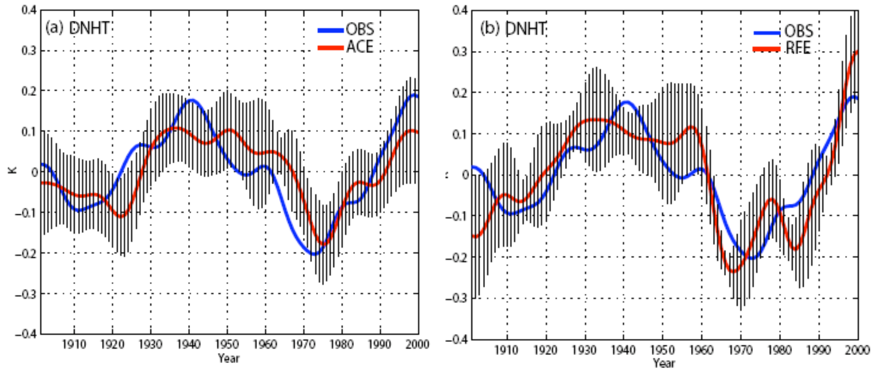

Figure 2. Observed and simulated average northern hemisphere temperatures. Right panel: simulation when model is just forced with radiative forcing changes. Left panel: model is just forced with Atlantic temperature changes (where a trend has been removed) with no changes in radiative forcing. Courtesy of Rong Zhang (GFDL)

b. <u>Analyses of decadal scale fluctuations in Gulf Stream circulation characteristics, and their climatic relevance</u>. Research is showing a strong correlation between excursions of the axis of the Gulf Stream (GS), the stratification on the Sargasso Sea side (PV in figure 3) and the North Atlantic Oscillation (NAO) with possibly a period of around 10 years (left of figure 3). These fluctuations also correlate with ocean shelf temperatures at Woods Hole. The right panel shows a longer time series of sea level fluctuations observed along the east coast of N. America. Fluctuations of about a 10 year period appear in large parts of this record. The sea level record extends the time series back to 1890. Interestingly, the fluctuations are most evident when the AMO phase is negative and absent when the AMO was positive. Are there dynamical reasons for this? These figures (and figure 1) indicate that three time scales are of importance: decadal oscillations, multi-decadal changes (AMO), and the trend. All need to be understood in order to describe Atlantic variability and change.

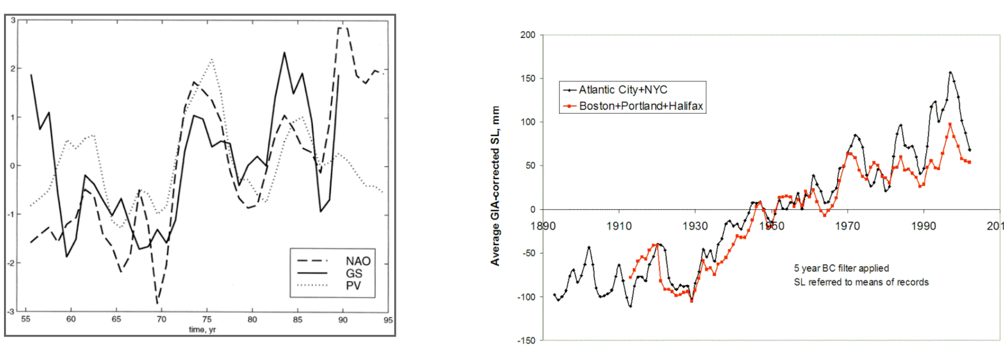

Figure 3. Evidence of regular fluctuations in the northwest Atlantic. Right panel: records from coastal tide gauges – courtesy of Laury Miller (NOAA). Left panel: shift in Gulf Stream axis, an index of the

North Atlantic Oscillation and the potential vorticity seaward of Gulf Stream axis. Courtesy of Terry Joyce (WHOI)

c. Analyses of the influence of the Atlantic SST changes versus remote ocean basins on regional Atlantic and North American climate fluctuations. The impact of Atlantic SST on multidecadal rainfall changes from South America to India was emphasized – see Fig.4. Although Atlantic SST has some impact on North American drought, it was emphasized that the Pacific appears to be the dominant driver.

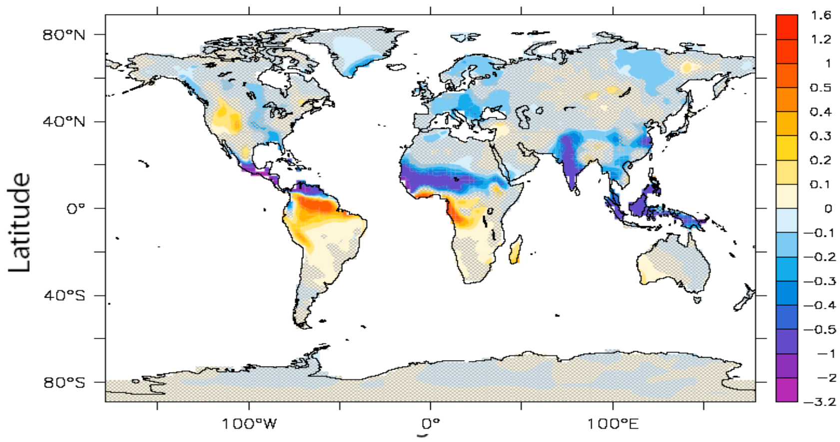

Figure 4. Global rainfall anomalies in mm/yr when the north Atlantic is cooler than normal. (courtesy of Rong Zhang, GFDL)

d. Analyses and models of the tropical Atlantic suggested the possibility of predictability on seasonal timescales and from statistical methods on longer timescales. A number of empirical studies have shown the strong teleconnections from ENSO in the Pacific to the Atlantic which impact SSTs. Recent studies are indicating that a major contributor to Atlantic predictability is this teleconnection. This is shown in the skill score for sea surface temperature anomalies in the subtropical Atlantic (figure 5). Global initial conditions (GIC) for such forecasts give more predictability than just Atlantic initial conditions (AIC)

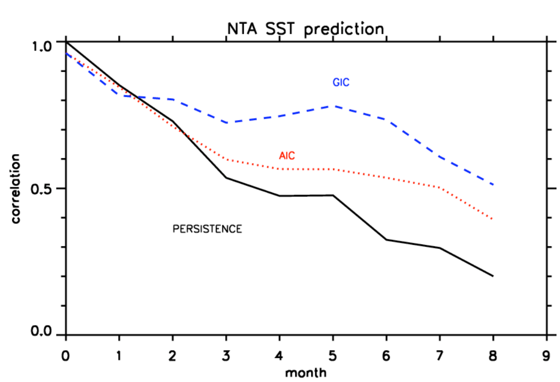

Figure 5. Results from predictability studies for SST anomalies in the subtropical Atlantic. Courtesy of Ping Chang (TAMU)

e. The dynamics and predictability of the thermohaline circulation was emphasized. Both the NCAR and GFDL coupled models have a prominent mode of internal variability involving the MOC with a 20 year time scale (see Fig.6). Preliminary analyses suggest that we are dealing with a possible coupled response and that the structure of the atmospheric component is similar to that of the NAO. It is probably worth noting that the observations suggest the dominance of roughly 10 year and perhaps somewhat longer (40-50) year 'oscillations'. Hence modeling challenges remain and a priority research topic is to understand what is the mechanism and what sets the periodicity of these motions[4]. Substantial decadal predictability of the MOC of this model was shown based on simulations. If this transfers in to predictability of the AMO, then we have the building blocks of a predictability system. However, it should be emphasized that even if the MOC has predictability (quite likely) the 'transfer function' between the MOC and SST, air-temperature and precipitation is not known and is likely to vary between models.

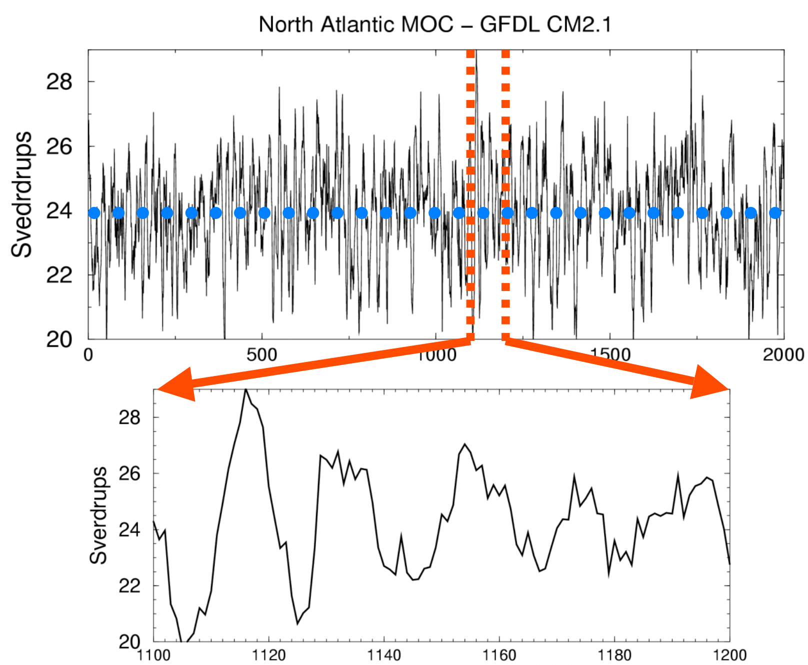

Figure 6. Decadal variability in an index of the meridional overturning circulation (MOC) in a coupled GFDL simulation. Spectral analysis shows the dominant periodicity to be about 20 years. Courtesy of Tom Delworth (GFDL).

[4] It should be noted that AMO-like SST patterns have been found in models that do not invoke MOC changes.

5. **A research program for moving forward**

Observations are showing that major shifts in regional climate have occurred on time scales as short as decades, impacting hurricane activity, droughts, sea ice, rainfall, the Arctic and ecosystems. The investments that NOAA and the U.S. have made in paleoclimate research, climate dynamics, climate modeling, and observing systems are providing the tools needed to better understand and ultimately predict such shifts. The way forward must build on our understanding both of climate predictions and climate projections. The primary components of such a program are: A) a diagnostics program including data-model comparisons; B) predictability studies; C) a program of experimental decadal predictions; D) tools for decadal predictions – ocean/coupled models and ocean/ice state estimations tested against data; E) prototype outlooks.

Outcomes of this program will include: i) an improved understanding of the roles and mechanisms of natural and anthropogenically produced decadal variability in the Atlantic and the global impacts of this; ii) an evaluation of the potential predictability of aspects of this decadal variability; iii) a prototype system for decadal predictions – this would include an ocean nowcasting capability and evaluations of the required observing system; iv) ensemble decadal outlooks for the next decades. These outlooks would be for MOC, SST, heat content, ice, temperature and precipitation over adjacent continents and sea level. A special focus would be on the decadal outlook for Atlantic hurricane activity. Ocean state projections could also be used to drive models of ocean ecosystems with applications to marine conservation and fisheries.

A) **A Diagnostics Program**

Observational and modeling studies indicate pronounced Atlantic variability on a variety of timescales. Specific questions which need to be addressed include:

- What are the physical mechanisms for and morphology of the variability on the 10 year and longer timescales?
- what are the physical mechanisms that drive decadal SST anomalies in the Atlantic. In particular, to what extent can these anomalies be attributed to changes in ocean circulation?
- Do self-sustained coupled modes exist in the Atlantic, ocean modes that are stochastically forced by the atmosphere, or damped coupled modes forced by the atmosphere? This very question is still unresolved for ENSO and may have predictability implications.
- What are the possible impacts of and the links to anthropogenic forcing on decadal timescales?
- What are the regional impacts: in the Atlantic sector and on hurricanes; on the decadal variability of ENSO; on the North Pacific; in the Arctic?
- What are the links to the MOC?
- What are the feedbacks between midlatitudes and the tropics and visa versa?
- What is the influence of global warming on the MOC and its decadal variability?

B) **Predictability studies**

Which components of Atlantic climate variability have predictability?

- Ocean – observations show that long-lived SST anomalies with coherent spatial structures are present in middle latitudes and are likely associated with the variability of the gyre circulations and the MOC on decadal timescales. Are the gyre and MOC variations predictable on decadal timescales? Initial experiments indicate some predictability for the MOC. How this translates to information about gyre variations need to be determined. To the extent this predictability influences SST, it might endow some predictability to atmospheric motions. Will this predictable atmospheric signal stand out from the weather noise, e.g. what is the signal to noise ratio for the atmospheric predictions. If there is too much 'noise', such predictions will be of little use.
- Atmosphere – atmospheric predictability will depend on a coherent response of the atmosphere to predictable SST anomalies and possibly ice cover. To date there is little evidence of coherent atmospheric responses to midlatitude SSTA. Will that continue to be the case as climate models improve? Indications from GFDL and NCAR coupled simulations suggest that the decadal modes in the models are indeed coupled, hence there might be some atmospheric predictability.

Most of the predictability studies will have to be carried out in the framework of idealized model experiments. However a hierarchy of models must be used, culminating in the high-end IPCC-class models that will ultimately provide the framework for decadal projections.

C) **Experimental Decadal Predictions**

The experience from the development of climate prediction systems for the ENSO phenomena indicates that skillful predictions by dynamical systems develop slowly. Hence the long term strategy should include utilization of both statistical (non model-based) and model-based approaches. The statistical ones will serve as a benchmark for model-based predictions.

<u>Statistical forecast systems</u>:
These will require knowledge of the physical timescale and space-scales of the key "decadal modes" and the manner in which they vary, one with respect to the other.

- Credible analyses of the system state will be required to build statistical connections guided by our understanding of the key mechanisms
- A variety of approaches are available (POPs, other techniques used for ENSO and intraseasonal predictions).

- It could be argued that statistical prediction may be more difficult to apply to decadal prediction than to seasonal prediction, simply because the observed record is too short to allow for a reliable "training" of the statistical models.

Model-based forecast systems: these will ultimately spring from fully coupled global models because the MOC, which is the special aspect of Atlantic climate variability, is a global-scale process with important inter-basin and inter-hemispheric aspects. The phenomena reach from pole to pole, fluxes of heat and fresh water in high latitudes are likely important, interactions with ice probably matter, and the timescales are long. However, this same modeling system would be used for both short range climate predictions (ENSO) as well as making predictions of decadal variations resulting from natural and anthropogenic effects. Experience from ENSO forecasting shows that the system can be run in two modes:

- The ocean and ice components are not initialized by observations. Initialization is provided by spinning up the system from a past to the current state by specification of variables such as the history of SST anomalies or the atmospheric forcings.
- The ocean and ice components are initialized. This requires estimates of the ocean's state and hence can leverage community efforts in ocean and ice state estimation. Although the premise is that initialization will be most important in the Atlantic, the impacts of initializations of the global state will also be explored.

One particular challenge will be how to deal with the "noise" influence. This problem can be particularly relevant to decadal prediction because the stochastic component may be more dominant than the deterministic component. It may be important to explore some unconventional modeling approach, such as interactive ensemble approaches.

Utilization of multiple models : experience in weather and short range climate forecasting has shown that multi-model ensemble forecasts are more skillful on average than those from any individual model. Hence the program should aim for utilization of as many models as feasible from the U.S. and internationally

Tests of Atlantic predictability: Unlike the situation for ENSO forecasting, far fewer cases based on observations will be available to test these decadal prediction systems. Hence establishment of appropriate signal/noise measures will be far more difficult than for ENSO. Depending on the timescale of the decadal variability, two approaches seem feasible:

- For decadal variations, as shown in figure 3, three cases are available since about 1960. Perhaps, as techniques and historical analyses improve, the turn of the century cases might also become accessible. Except for the more recent of these, ocean analyses for initializations will not be available and only statistical/empirical techniques and un-initialized coupled models can be utilized.
- For the multi-decadal variability, e.g. the AMO, fewer realizations are available. The primary focus for the initialized forecasting experiments has to be on the era when ocean altimetric satellites were available giving us information about ocean circulation – from 1993 up until the present. Fortunately the Atlantic underwent significant variations during this period.

Predictability studies using ocean state estimation systems: Existing uncoupled ocean circulation models and state estimation systems are driven by atmospheric surface boundary conditions obtained from analyzed fields. These are used as control parameters which are adjusted to bring the model in to consistency with the observations. The resulting constrained model then yields the time-evolving meridional heat flux, heat content, MOC, etc. The system can readily be used to study the predictability of, for example, the MOC, by comparing the trajectory of the MOC obtained by, for example, by perturbing the surface fluxes.

Global atmospheric imbalances in fresh water, energy, and surface stress translate in ocean models to incorrect heating/cooling, sea level rise or fall, and circulation errors. How do these translate in to loss of predictability of the MOC?

Ultimately these ocean state estimation systems will be coupled to the atmosphere to yield the systems that will be sued to make projections in to the future.

Research on predictability loss on decadal time scales via transient growth of optimal initial conditions
'Transient amplification' by non-normal mode growth is the mechanism by which predictability is lost in the atmosphere and in ENSO. It can be expected that the same is true of, for example, the MOC. Methodologies and tools exist - for example tangent linear and adjoint models – to identify which initial conditions will lead to maximum amplification of the MOC and hence likely patterns of error growth. A research program involving NOAA labs and academia is required to address these issues.

D) **Tools for Decadal Predictions and Analyses**

Overall questions, which need to be addressed, include:

1) How good are the present Atlantic ocean observing and synthesis systems for understanding of Atlantic decadal variability, for testing of models, and the identification of key mechanisms?
2) What are the key observational/synthesis elements of an oceanic 'nowcasting' capability for the Atlantic with emphasis on decadal signals, i.e. is something missing?
3) How could we use such ocean nowcasts to initialize global coupled models and so project the ocean and coupled states into the future?

Some specific activities to address these follow.

Improved and tested ocean and coupled models.
The existing observational and synthesized data sets give clues as to the range and types of observed decadal variability in the Atlantic. These include description of Gulf Stream path variability with links to NAO variability and coastal SST signals, propagating SST features, and changes to GS recirculation patterns. Further synthesis studies will provide a more coherent picture of the morphology of long term variations in the Atlantic.

- Forced and unforced models need to be compared to these observations and syntheses.
- The physics of what processes lead to the timescale of variability in the models needs to be understood (current models exhibit an order 20 year period for the variability which is not observed). This will require study of simpler models in the light of high-end models and the observations.
- The CLIVAR Climate process teams can be harnessed to improve weaknesses of the critical modeling components.

<u>Ocean state estimation</u>

Just knowing what the state of the MOC and related important parameters are, and the reasons for this, will be a major step forward in assessing the potential for changes. For the hurricane problem this information by itself will help in the current debate. Is the AMO entering a positive phase which means it might persist, or not (the observations suggest northward heat transport in the Atlantic is decreasing). Or perhaps the current warming has little to do with the AMO. Better nowcasts for the Atlantic have the potential to totally change the national debate and NOAA's decadal outlook for hurricane activity.

An extensive global ocean observing system, consisting of altimeters, ARGO floats, and other in situ measurements, some of which are specifically designed to monitor the MOC, is currently in place. Prototype ocean state estimation activities are also underway at a number of institutions. Although the ocean observing system has demonstrated its utility for seasonal forecasting, we don't know if it is adequate for the problem of decadal forecasting.

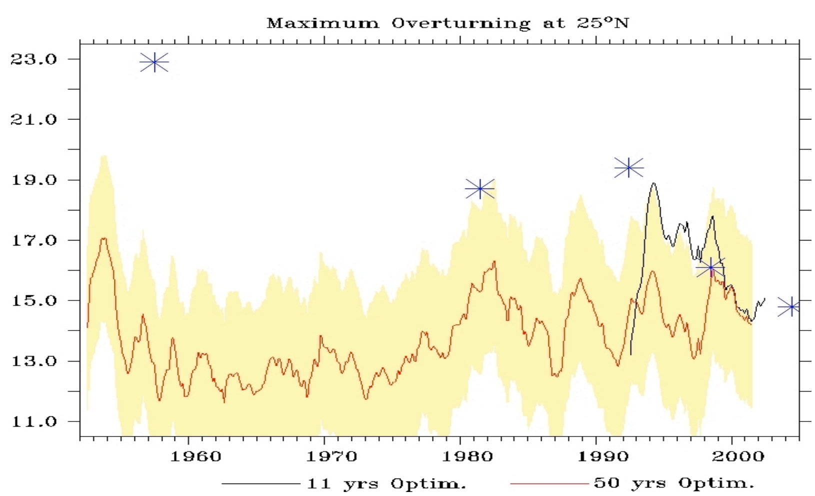

Figure 7 Preliminary estimates of Atlantic MOC strength from the GECCO (German ECCO) project in which an ocean model is constrained by observations. The stars represent estimates carried out directly from *in- situ* measurements. The set of analyses using the 11 year optimization and the in-situ based ones both seem to suggest a slowdown of the overturning circulation at 25 deg. N over the last 10 years. Courtesy of Detlef Stammer

The preliminary analyses shown above are courtesy of Detlef Stammer and are from the GECCO (the German ECCO) project. The stars represent estimates carried out directly from in situ measurements. The set of analyses using the 11 year optimization and the in-situ based ones both seem to suggest a slowdown of the overturning circulation at 25 deg. N over the last 10 years; however, there are large discrepancies between these and the analyses based on the 50 year optimization and one should be concerned that the observed values are often outside the range (yellow) of the 50-year optimal. This latter analysis – which, however, is constrained by much less data than during the last 11 year WOCE period – shows little signs of a slowdown and is dominated by sub-decadal variability. It is important to realize, however, that the estimates shown in Figure 7 may be sensitive to initialization shocks which could compromise the 11-year estimate. Another important factor is the relative weight given to the various data sets.

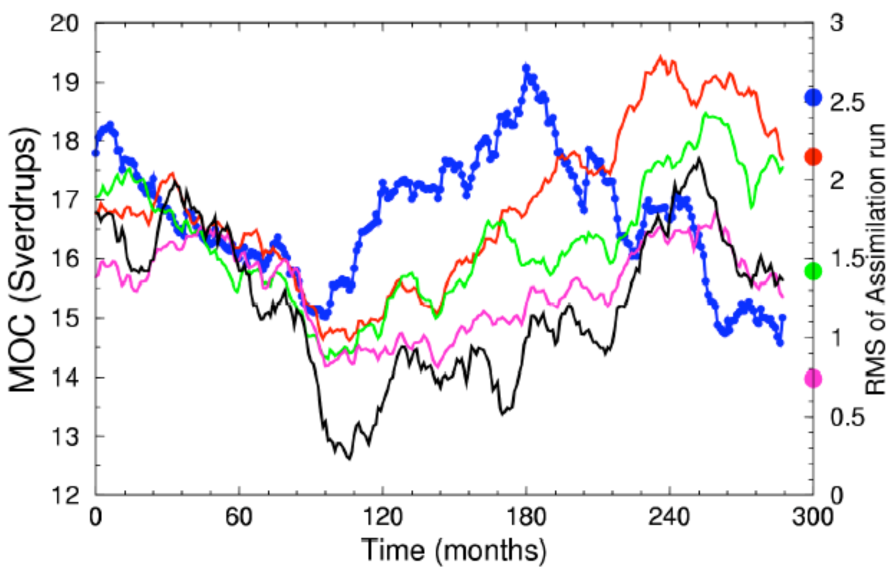

Figure 8. Studies of the capability of current assimilation techniques and observing systems to analyze the MOC being carried out at GFDL. The black curve represents a solution from a model simulation. The blue curve represents an independent simulation. The red curve uses only temperature observations in the top 500 meters; the green curve temperature and salinity in the top 500 meters; the magenta curve T and S observations from the top 2000 meters (e.g. ARGO). Courtesy of Shaoquing Zhang (GFDL).

Preliminary work on assessing the capability of current assimilation techniques and observing systems to analyze the MOC has also started at GFDL, as shown in Figure 8. This has been done in the context of 'perfect' model date sets where the answer is known. The black curve represents a solution from a model simulation. The blue curve represents and independent simulation. The question being addressed is 'can the current spatial, vertical, and temporal distribution of observations (utilizing data from the target simulation) 'correct' the blue simulation to the black one?'. The red curve uses only temperature observations in the top 500 meters; the green curve temperature and salinity in the top 500 meters; the magenta curve T and S observations from the top 2000 meters (e.g. ARGO). This idealized study suggests that ARGO like information will be critical for developing a nowcasting capability for the MOC. Clearly more work will be needed even in these idealized cases. As the assimilation is tried on real observations, inter-comparisons between independent data sets, such as the specialized observations being put out to monitor the MOC at 24N in the Rapid project, will be a critical part of assessing the veracity of the analyses.

Detailed tasks which need to be accomplished are:

a. comparison studies of analyses from various ocean state estimation systems: Two of the ODA systems to be used for these studies are the ECCO system and GFDL's coupled ensemble data assimilation system. Others should also be considered. A systematic program of intercomparisons between these is needed.

b. Further improvements to ODA systems and analyses: A number of studies will most likely be undertaken. These will include: the impacts of atmospheric observations; the impacts of model drifts and biases on assimilation skill; the impacts of the various observational systems on our ability to monitor critical aspects of the decadal variability and on initialization of the forecasts.

c. Evaluation and design of observing systems: What kind of observing system does one require to nail down the MOC and its ability to transport heat meridionally? What is missing from the current observational network? Ocean state estimation systems can and should be used to design an optimal system so that, for example, the ARGO array can be best deployed, in combination with satellite systems, to measure the state of the MOC. The trade-off between a well-observed Atlantic basin and a reduced global deployment can be addressed with models. The resulting estimates can be compared to direct measurements along particular zonal sections as in, for example, the Rapid project…..

E) **Prototype Ensemble Outlooks for the Future**

Depending of progress in the above program components, an experimental system will be established at GFDL.

Appendix 1

Atlantic Decadal Predictability
Thursday, June 1st

8:30 a.m.
Introductory Remarks
Ants Leetmaa, Tom Delworth

8:40 a.m.
1. What are the modes of decadal climate variability in the Atlantic and what is known of their underlying mechanisms?
Introduction and context: John Marshall
Chair: John Marshall
Reporter: Ants Leetmaa

Bob Molinari:
Decadal variability of the NAO, propagating SST signals, Gulf Stream position, Gulf Stream transport and the recirculation gyre south of the Gulf Stream, are they coupled signals?

Terry Joyce:
Mid-latitude interannual-decadal variability and Gulf Stream path

Mingfang Ting:
Detection of Forced and Naturally Occurring Atlantic Multi-Decadal Variability in Coupled Models and Observations

Ben Kirtman:
The Role of Internal Atmospheric and Oceanic Dynamics in Decadal Variability in the Atlantic

10:15 a.m. - 10:30
Break

10:30 a.m.

2. What are the associations between decadal Atlantic variability and hemispheric climate?
Chair: Vikram Mehta
Reporter: Bob Molinari

Marty Hoerling:
North Atlantic-European Climate Change Since 1950

Rong Zhang/Tom Delworth:
Impact of Observed Atlantic Multidecadal SST Fluctuations on India/Sahel Rainfall and Atlantic Hurricanes

Richard Seager:
Tropical Atlantic influences on North American precipitation

11:30 a.m.
3. What components of the Atlantic climate system might be predictable?

Introduction and context: Saravanan, Delworth
Chair: Lisa Goddard
Reporter: David Legler

Vikram Mehta:
Hybrid prediction system for decadal variability of the tropical Atlantic SSTs and associated atmospheric climate

Ping Chang:
Destructive Ocean-Atmosphere Interference -- Why is Atlantic Nino so difficult to predict?

Saravanan:
SST predictability in the north tropical Atlantic region

12:15 pm - 1:00 pm
Lunch

3. (Continuation) What components of the Atlantic climate system might be predictable?

1:00 p.m.

Eli Tziperman:
Transient amplification of thermohaline circulation anomalies

Ghokan Danabasoglu:
Multi-decadal oscillations of the North Atlantic meridional overturning circulation in CCSM3

Tom Delworth:
Decadal variability of the MOC in GFDL's CM2.1 model

Keith Dixon:
Decadal predictability of the MOC in GFDL's CM2.1 model

2:30 p.m.

4. What form would prototype predictability systems take? How would we test Atlantic predictability systems? What observations are required to initialize and test coupled predictability systems? Hindcasts, forecasts...

Introduction and context: Ants Leetmaa
Chair: Jim Todd
Reporter: John Marshall

Ben Kirtman:
Prediction and Predictability from Days to Decades: The TFSP Experiment.

Tony Rosati, Matt Harrison:
Strategies and plans for initializing the MOC

3:15-3:30 pm
Break

Shaoqing Zhang:
Estimation and Initialization of Atlantic MOC using GFDL's CDA System Based on Perfect Model Argo Network

4:30 pm-5:00 pm
Begin discussion of draft implementation plan

Overarching questions to discuss:

(1) How can we push forward work on decadal Atlantic predictability?

(2) How can we better evaluate the potential predictability of the Atlantic system, and its relative importance to continental climate?
(3) What are the characteristics of the prediction systems that would be required to realize such potential predictability?
(4) What observations are required to realize such predictability?
(5) What would be the key products of such a prediction system?
(6) What predictability systems exist now and what can one realistically build? Who might do this?
(7) What might be some partnership programs we could start in the near future?

Atlantic Decadal Predictability
Friday June 2

8:30 am
Continue discussion of draft implementation plan

10:15 am - 10:30 am
Break

10:30 am
Continue discussion of draft implementation plan

12:00 pm
Summary

12:30 pm
Lunch

Appendix 2

Workshop Participants

Ping Chang	Texas A&M University
Ghokan Danabasoglu	National Center For Atmospheric Research
Tom Delworth*	Geophysical Fluid Dynamics Laboratory, NOAA
Keith Dixon	Geophysical Fluid Dynamics Laboratory, NOAA
Lisa Goddard	International Research Institute for Climate and Society, Columbia
Matthew Harrison	Geophysical Fluid Dynamics Laboratory
Martin Hoerling	Earth System Research Laboratory, NOAA
Terry Joyce	Woods Hole Oceanographic Institution
Ben Kirtman	Center for Ocean-Land-Atmosphere Studies
Ants Leetmaa*	Geophysical Fluid Dynamics Laboratory, NOAA
David Legler	U.S. CLIVAR office
John Marshall*	Massachusetts Institute of Technology
Vikram M. Mehta	Center for Research on the Changing Earth System
Robert Molinari	Atlantic Meteorological and Oceanographic Institution, NOAA
Tony Rosati*	Geophysical Fluid Dynamics Laboratory, NOAA
R. Saravanan	Texas A&M University
Richard Seager	Lamont-Doherty Earth Observatory, Columbia University
Mingfang Ting	Lamont-Doherty Earth Observatory, Columbia University
Eli Tziperman	Harvard University
James Todd	Climate Program Office, NOAA
Rong Zhang	Geophysical Fluid Dynamics Laboratory, NOAA
Shaoquing Zhang	GFDL/UCAR

*Organizing Committee