Atlantic Oceanographic
& Meteorological Laboratory
National Oceanic & Atmospheric Administration

Workshop report

Atlantic Decadal Variability: Combining observations and models to investigate predictability

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January 10-12, 2007

Workshop Executive Summary: **Atlantic Decadal Variability: Combining observations and models to investigate predictability**

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Decadal and longer time-scale variability of droughts, hurricanes, floods, etc., has gained increased attention over the past few years not only because of the immense societal relevance but also because such weather and climate extremes may also be affected by anthropogenic forcing (e.g. through increased frequency and/or intensity). A variety of decadal and longer time-scale signals in the Atlantic region have been identified in observations and numerical modeling experiments, and global connections have been suggested although causal relationships are more difficult to define. These results are the motivation for the development of a prediction system for Atlantic decadal variability. They also highlight the direct relevance of such a prediction system to NOAA's climate mission and to the goals of the US and International CLIVAR and IOOS programs. In recognition of this importance a pair of workshops on Atlantic Decadal Predictability have been held involving scientists from US government laboratories, universities, and international institutions as well as representatives from the US science funding agencies. The first workshop focused on the modeling aspects of the problem (held at GFDL on June 1-2, 2006), while the second workshop focused on the observing system and combining models with observations (held at AOML on January 10-12, 2007). The results of the second workshop are summarized here.

The workshop participants agreed that extensive observations of the ocean will be required globally for the foreseeable future, and probably indefinitely. They are required to initialize models, to test their forecast skill, and to reveal unsuspected elements of oceanic change. This includes observational systems that are already in place and new observational systems that are needed. Interagency and international coordination is required to weigh tradeoffs between research needs, potential longevity and costs of observing system elements and to find additional funding resources. The participants also stressed the need for research focus to shift toward the attribution of signals rather than just the identification of signals. It was agreed that progress was needed in the following specific areas:

- Sustain the current observing system to preserve the continuity of long-term observations and expand it to capture decadal signals throughout the whole Atlantic Basin.

- Analysis and synthesis of presently available observations and model-data comparison studies are needed to characterize observed variability and to evaluate existing datasets and models for their suitability in determining predictability and generating nowcasts.

- Model development in this area needs to focus on initialization by the observed state, simulation of observed signals, and the evaluation of predictability. This includes study of the effects of projected changes in the external forcing of the system, and also includes the development and testing of statistical prediction systems.

- Better hypotheses and diagnostics need to be developed to understand and characterize observed decadal variation in the MOC and other major signals. Studies of how these major signals impact hurricanes, ecosystems, the carbon cycle, monsoons, droughts, etc. are also needed.

Workshop Report: **Atlantic Decadal Variability: Combining observations and models to investigate predictability**

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Background

Decadal and longer time-scale variability of droughts, hurricanes, floods, etc., has gained increased attention over the past few years not only because of the immense societal relevance but also because such weather and climate extremes may also be affected by anthropogenic forcing (e.g. through increased frequency and/or intensity). Studies with coupled IPCC-class climate models suggest that the Atlantic Ocean may be playing an important role at these time scales. For example, several models have shown that changes in the meridional overturning circulation (MOC) and/or sea surface temperature (SST) could lead to significant changes in precipitation over the neighboring continents (e.g. Figure 1). A variety of decadal and longer time-scale signals in the Atlantic region, including the adjacent continents, have been identified in observations and numerical modeling experiments. Correlations between oceanic signals and atmospheric anomalies have been identified, although causal relationships are more difficult to define. Modeling studies have suggested that variability in Atlantic Ocean circulation, including not only the MOC[1] but also variability in the tropical Atlantic Ocean (TAV) and wind-driven gyres may all be playing a role in climate impacts both over the US and indeed globally. In fact these circulation features are all interrelated and variations in each are thought to affect and be affected by the others. The same modeling studies have also found some degree of predictability in oceanic components of the coupled system, such as ocean gyres and the MOC, which could possibly lead to predictability in air-temperatures, precipitation and extreme weather events over the adjacent continents. These results are the motivation for the development of a

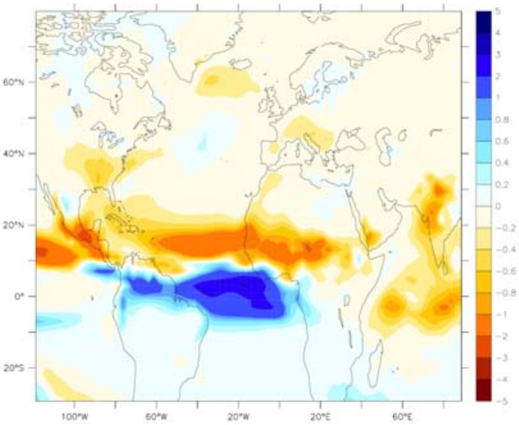

Figure 1: Change in precipitation (mm/day) simulated in response to Atlantic sea surface temperature (SST) differences between the period 1971-1990 and 1941-1960 (adapted from Zhang and Delworth, 2006). Negative values denote a reduction in rainfall for the 1971-1990 period relative to the 1941-1960 period. The 1971-1990 period had significantly colder SSTs for the North Atlantic relative to the earlier 1941-1960 period.

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[1] The term MOC has more than one definition in the literature of ocean-atmosphere-climate research. For the context of this report, MOC is defined as the total vertical circulation cell that involves vertical exchange between the surface layer and the deep (not intermediate) ocean. It is clear, however, that this circulation is interconnected with shallower overturning cells and the horizontal wind-driven gyres in an integral way.

prediction system for Atlantic decadal variability and they highlight the direct relevance of such a prediction system to NOAA's climate mission and to the goals of the US and International CLIVAR and IOOS programs.

The prediction system envisioned herein should be capable of providing 'nowcasts' of the present phase of climatically important decadal signals as well as 'forecasts' of the evolution of these signals. The initial goal in the development of a nowcast system must be the evaluation of the ability of existing observational datasets and models to replicate the characteristics of oceanographic and atmospheric decadal signals. A first step in the establishment of a prediction system must be the evaluation of the extent to which decadal time-scale variability can be predicted.

In recognition of the importance of decadal and longer time scale climate variability, as well as of the potential role of Atlantic Ocean circulation in this variability, a pair of workshops on Atlantic Decadal Predictability have been held involving scientists from US government labs, universities, and international institutions as well as representatives from the US science funding agencies. The first workshop was held at the Geophysical Fluid Dynamics Laboratory (GFDL) on June 1-2, 2006. The 2006 workshop focused primarily on the modeling aspects of the problem, with the goal of developing an implementation plan to (1) improve our understanding of ongoing decadal scale changes in the Atlantic, (2) evaluate decadal scale predictability in the Atlantic, and (3) to map out a plan of action to develop a prototype decadal prediction system for the basin which would include observations, assimilation schemes and forecast models. A series of presentations were made at the meeting addressing these issues, and a workshop report was prepared and reviewed by participants and by selected US CLIVAR panel members. The first report sets out some of the key components of a prototype decadal prediction system. These components include potential decadal signals to be predicted, model initialization schemes for coupled projections, and theoretical-diagnostic studies enquiring into underlying mechanisms of coupled variability and limitations on predictability of the coupled system. Additional details on the GFDL workshop can be found in the final report written by Ants Leetmaa and John Marshall. The report is available at www.aoml.noaa.gov/phod/ADV/.

A second workshop was held at the Atlantic Oceanographic and Meteorological Laboratory (AOML) on January 10-12, 2007. The focus of this second workshop on decadal predictability was on the observation system and combining models with observations. Specific topics included: (1) the existing components of the ocean observing system in the Atlantic Ocean and its ability to generate datasets needed for nowcasts and for monitoring the signals important to understanding decadal variability; (2) the skill of models in capturing the observed oceanic and atmospheric variability in the Atlantic region; and (3) a review the status of ocean state estimation and the initialization methodologies required to obtain a 'nowcast' of the current state of the Atlantic climate, a prerequisite for projections of the coupled climate into the future. This white paper presents the results of the second workshop including the recommendations of the organizing committee for achieving these goals. Combined, these two reports represent both the motivation behind decadal prediction in the Atlantic sector and the roadmap that the workshop organizers and participants recommend to the US funding agencies for future progress in research into decadal predictability and prediction.

Second workshop objectives

The agenda for the workshop is listed in Appendix 1, while a list of the participants is provided in Appendix 2. The overarching goal of the second workshop was to continue the development of a 'road-map' to address the question of what signals might be predictable and to identify the key issues for a prototype decadal prediction system for the Atlantic. Discussion at the workshop was broken into two principle areas relating to decadal predictability, with each topic having an observational and a modeling component: 1) Signal identification, and 2) Tests of models. Discussion of the third planned topic, model initialization, was postponed to a future workshop by common agreement amongst the participants because that area was more of a future goal that depended upon the success of study in the first two areas.

Workshop presentations

The presentations that were given during the workshop are available on the web at: www.aoml.noaa.gov/phod/ADV/. What follows is an overview of the key points of the discussions.

a) Observing and characterizing the signals needed to evaluate predictability and understand decadal variability in the Atlantic sector:

Presentations in this session focused on the decadal signals that have been identified by different parts of the international observing system in the Atlantic and on the datasets that are available for future work in this area. The obvious importance of the Atlantic component of global datasets such as satellite altimetry, the global surface drifter program, and the ARGO float network, were stressed by many of the speakers. The need to study the paleo record to better understand the present climate was discussed, as was the importance of monitoring not only the physical parameters of the system (mass, heat, salt) but also the other property-tracer and biogeochemical components (nutrients, nitrates, iron, oxygen, CFCs and carbon). Characterization of the distribution of these properties will aid in discriminating between the variety of oceanic pathways of the main components of the MOC and will lead to better understanding of the impacts of circulation changes on the global carbon system and the climate system. Potential 'choke-point' observations of the upper and lower limbs of the MOC were also discussed, with much conversation centered on observing arrays along the length of the path of the Deep Western Boundary Current (DWBC) and the international program that is measuring the complete circulation across the North Atlantic Basin at 26ºN, the RAPID/MOCHA array.

The length of time that various observations are available for study was also addressed. The length of the historical records, whether the 25+ years of observations of transport fluctuations in the Florida Current or the 40+ years of upper ocean temperature data available along the long-term repeat bathythermograph lines, was acknowledged to be too short to address certain important questions. This deficiency demonstrates the importance of both the paleo observations and the modeling approaches to the problems. However, the length of the record was shown to be sufficient to approach some important questions that have not yet been addressed.

A critical requirement that was discussed is how to define/quantify changes to basin-wide and global circulation systems without ignoring important details of the variability. The primary example discussed was the Atlantic MOC, which is often reduced to a simple zonally-integrated profile of transport across a meridional transect. Such a definition is of limited use when it comes to understanding the observed variability. Thus, the participants stressed the need for ancillary observations and more detailed definitions of the components of the MOC system. The need for ancillary information will most certainly necessitate future expansions of the observing system into new areas and using new technologies.

The requirement for research to focus on the attribution of the signals that are observed was also stressed. One example that was given was the need to determine whether the physical forcing behind changes in the mean Gulf Stream position as it comes off the shelf is due to changes in the winds stress field (curl field) or due to changes in the water-mass and transport of the shelf-slope current flowing down from the Labrador Sea. It was stressed that attribution of the signals needs to be a critical element of any predictability study.

b) <u>Testing the models and the prospects for predictability of decadal variability</u>

Presentations on the second day of the workshop focused on the use of models for assessing the impact of Atlantic variability on climate, understanding observed changes in the Atlantic, how assimilation systems and model validation systems were currently being tested with the available data, and on efforts at predictability and predictions. One point that was made several times was that the impacts of Atlantic multi-decadal SST fluctuations are quite large. Effects that were discussed include (a) modulation of Indian and African monsoonal rainfall, (b) alteration of vertical wind shear in the tropical Atlantic, which is of particular relevance for hurricanes, (c) influence on summer climate over North America and Western Europe, and (d) possible influences on the nature of ENSO variability. Additionally with regards to ENSO, a suite of modeling results were presented demonstrating the impact of sustained changes to the Atlantic MOC on the mean state of the tropical Pacific, with impacts on ENSO. It was agreed that this is an important emerging area of research.

The predictability of Atlantic variability was also emphasized by several speakers, including analyses of optimal methods for evaluating predictability. A suite of assimilation analyses was presented showing various estimates of Atlantic changes over the past 50 years. Significant issues were discussed in terms of the ability of observing systems to adequately capture variability, which has important implications for initializing prediction models. One issue in this regard is the lack of widespread salinity data, particularly at depth, prior to the ARGO period. This has important consequences for estimates of past changes in the overturning circulation.

Analyses of key regions were also presented. The potential importance of water-mass conversion processes in the South Atlantic was emphasized. An ongoing decadal scale weakening of the subpolar gyre in the North Atlantic was demonstrated via a combination of observational and model based analyses. Analyses of Gulf Stream variations and their potential relationship to Labrador Sea processes were presented, as derived from decadal scale ship-borne measurements. There was also some discussion of decadal scale changes in Atlantic ecosystems and biogeochemical processes, and their interactions with the physical climate system.

The participants agreed that observation systems will never be fully complete nor can they provide perfect measurements (although significant improvements are possible with proper funding). In particular, while ocean models are still not reproducing many observed ocean signals well, these models have reached a level of realism sufficient that serious experiment design and optimization studies may be usefully started. The costs of such design studies, while not trivial, are likely a minuscule fraction of the total implied investment for any particular element. It is clear from the discussion among the participants that we need to develop a better physical understanding of the causes of observed decadal variations in the Atlantic, with particular emphasis on the MOC which may have atmospheric relevance on decadal timescales. This must involve a synthesis of models constrained by observations along with experimentation to probe the physical mechanisms of change.

Concluding discussion and recommendations from the workshop

On the final day of the workshop the participants separated into two subgroups, one to discuss signal identification and the other to discuss tests of models. The subgroups then rejoined and the participants worked together to provide recommendations for future research and analyses. Their recommendations include:

- To study predictability and to develop nowcasts of the Atlantic MOC it is crucial to be able to characterize the pathways of the upper and lower limbs of this feature. Existing observations are most likely not sufficient to characterize the decadal variability of cross-gyre, inter-hemisphere, and inter-ocean exchanges of properties (mass, heat, salt, nutrients, nitrates, iron, oxygen, CFCs and carbon). Expansion of the observing system, analysis and synthesis of the presently available observations and modeling studies are all needed to characterize existing datasets and models for their suitability in determining predictability and generating nowcasts.

- New hypotheses need to be developed and tested to explain how water mass properties move around the system when the MOC changes in order to estimate predictability and generate nowcasts. (e.g. to explain the differences between property flux time scales and volume transport time scales)

- Integrated datasets and models need to be used to determine if there are significant coupled air-sea interactions in the mid-latitudes (e.g. are there lag or lead relationships, a requirement for predictability) on decadal time scales.

- New diagnostics (in addition to the zonal-integral) need to be developed and tested both with observational data sets and within models to define variability of the MOC and interpret observed changes.

- Additional studies are needed using existing observations and model nowcasts to characterize the impacts of decadal variability on hurricanes, ecosystems, carbon cycle, monsoons, drought, fisheries and decadal ENSO variability.

For all of these issues in order to establish predictability a key focus needs to be not only the characterization of the signals themselves but also the attribution of the signals to physical forcing dynamics.

Road-Map: Moving forward

The first workshop in 2006 addressed many of the tasks required for moving forward on the modeling aspects of the decadal predictability and prediction problem. The conclusions of the first workshop lists four areas of research that are needed to move the modeling side of the problem forward: 1) a diagnostics program; 2) predictability studies; 3) experimental decadal predictions; and 4) tools for decadal predictions and analyses. Some of the recommendations in that first report have parallel components in observations and model-data comparison. Many other recommendations from the second workshop are unique, and they add to the list from the first workshop. In what follows the specific recommendations of the workshop participants are presented in the context of a "road-map" for moving research forward in this area. The same four areas given in the first report are used to illustrate the overlap and complementary nature of the recommendations of the two workshops.

1. The Diagnostic Program

The Atlantic experiences variability on a wide range of timescales, some of which exists merely as 'noise' that will interfere with studies of decadal variability and some of which is dynamically related to the signals of interest. In addition to the questions posed in the first workshop report, specific questions that will need to be addressed in order to diagnose and attribute the signals that are observed include:

- What timescales describe the variability of the key inter-ocean and inter-basin exchanges, and how do variations at periods other than decadal/multi-decadal alias the observations presently available?
- How does one describe the variability of the MOC when the use of a simple zonal-integral of the stream-function is too simplistic?
- What are the physical mechanisms that control decadal variability of the major ocean circulation systems? For example, does the Latif gyre

hypothesis correctly describe decadal changes in the North Atlantic subtropical gyre, and if so can predictability be found in planetary waves?
- Which, if any, mid-latitude decadal upper-layer signals are coupled to atmospheric signals?

The workshop participants agreed that extensive observations of the ocean will be required globally for the foreseeable future, and probably indefinitely. They are required to initialize models, to test their forecast skill, and to reveal unsuspected elements of oceanic change. This includes observational systems that are already in place and are likely to be maintained due to community consensus (i.e. ARGO, repeat VOS/hydrographic sections across key locations, Jason-class altimetry, Quickscat-class scatterometry, surface drifters, high-quality tide gauges, chokepoint transport observations), systems that are likely to be available in the next 5-10 years if a modest level of resources are made available for them (i.e. long-lived mooring systems with near-real-time data transmission, full-depth ARGO, wide-swath altimetry, improved scatterometry, autonomous gliders, gravity gradiometry, laser altimetry for sea ice, satellite sea surface salinity, coastal radars, improved observing systems for the VOS), and systems that should be developed for the long-term and for which there is both greater risk and greater potential payoff (i.e. very-long-life gliders, ARGO/glider measurements beyond temperature and salinity such as oxygen and nutrients, and perhaps acoustic tomography).

Resources are always finite, and inevitably there are tradeoffs in available dollars and in manpower. These tradeoffs can be quite complex, as decisions e.g., to fly satellites are made by different agencies and by different means than funding e.g., for surface drifters. Some elements may be more directly competitive within single agencies (e.g., surface drifters and ARGO floats). In the context of a national, global observation system, some interagency coordination is required to weigh tradeoffs between research needs, potential longevity and costs of any system element, complementary international initiatives, and impact. Such interagency cooperation is also needed to identify and expand new resources to put additional observation platforms in the water where needed.

2. Predictability Studies

One of the most fundamental questions that must be addressed in attempting to build a decadal prediction system is "Which components of Atlantic climate variability have any predictability?" This question was addressed in the report of the first workshop in terms of both oceanic and atmospheric predictability. With respect to the ocean, it was suggested that a framework of idealized model experiments could be tailored to evaluate the predictability of long-lived, large spatial scale, SST anomalies and changes in the gyre circulations, for example. In addition to the techniques suggested in the first report, combined model-observation studies can also be used to address the predictability question.

The majority of the observational studies that show decadal signals in the North Atlantic mid-latitudes have found correlations with the decadal atmospheric signal of the NAO. However the phase lag relationships between the NAO and these North Atlantic mid-latitude signals are not all consistent, possibly due to dynamical differences or due to analytical-methodological differences in the various studies. In the South Atlantic studies have found decadal signals that are correlated to a decadal modulation of the El Niño-Southern Oscillation signal in the Pacific sector, however again the dynamical underpinnings of this relationship are unclear. Model-observational studies with the following steps could overcome these problems:

- Comprehensive analyses of the existing datasets are required to determine the characteristics of the observed ocean decadal signals.
- Model-data comparisons are needed to ensure that the model includes the specific ocean decadal signal to be studied and this signal is correlated with the appropriate atmospheric signals (e.g. the NAO).
- Once the model has been validated, process studies using model results (e.g., heat balances, vorticity balances, etc.) should be performed to attribute the ocean signals (i.e., internal oceanic variability, coupled air-sea interactions).

The suggested model-data studies are not only relevant for the mid-latitude North Atlantic but also should be performed in the subtropical and tropical North and South Atlantic where decadal ocean signals have also been identified. Ascertaining if decadal ocean signals are forced, force or are coupled to atmospheric signals is also a critical step in determining predictability.

Once the decadal signals in coupled models have been validated as discussed previously, results from these models can be used to determine if present observing systems are effective in capturing MOC variability signals and suggest refinements if warranted. For example, once the efficacy of coupled models has been demonstrated for simulating key MOC signals such as water mass fluxes around South Africa, and cross-equatorial and cross-gyre exchanges of mass due to North Brazil Current rings, the models can then help to define sampling requirements (i.e., accuracies, spatial and temporal resolutions) needed in future observational systems.

3. Experimental Decadal Predictions

Development of a decadal prediction system will require testing and comparisons of both numerical and statistical prediction systems. The choice of numerical modeling systems for any prediction system will depend on the validation and testing described earlier to demonstrate the ability of the models to reproduce the key decadal signals and generate nowcasts.

For modelers, the climate time-scale is particularly challenging as compared to, for example, weather forecasting. Models tend to accumulate errors as computation time is extended, and certain errors of no consequence for weather time scales can dominate the calculation of the climate state. The Atlantic nowcasting and predictability problem can provide a focused science goal that, in the Atlantic at least, can help prioritize resources and methodologies needed to advance study of the climate system. However, the need to maintain a global observing and modeling system cannot be stressed too strongly.

Over the long-term, the ocean cannot be understood in isolation from the other elements with which it interacts. The most obvious ones are the atmosphere and the cryosphere, but ultimately one must account for the entire biogeochemical universe of ocean and land, including the global water cycle. Already, for example, interpretation of the ocean gravity data from the GRACE mission hinges on having adequate estimates of time-varying ground water content. One can assert that none of the model or state estimation elements of this coupled system is currently adequate. Once the subcomponents are regarded as mature, serious attention must turn toward gaining experience with the coupled state estimation problem. Although the principle of such estimates is identical to that as applied to the sub-components (e.g., the ocean alone), there is almost no experience with estimation with coupled systems in which radically different time scales exist (ocean and atmosphere), or in which one component may be in a chaotic regime while the other remains predictable. Gaining that experience must be a high priority for the next 5+ years.

This leads to the question; “What form would prototype predictability systems take?” Decadal predictability systems must be based on fully coupled global models of the atmosphere, ocean and ice, particularly when the Atlantic sector is considered. This is because the MOC is the special aspect of Atlantic climate variability – very different from the Pacific ENSO. The phenomena reach from pole to pole, interaction with ice is important, and the timescales are long. With such a single coupled system, one would envisage running ENSO forecasts as well as making projections of decadal Atlantic variability such as the MOC, SST, and heat content.

Such projections would require the ocean's state and so can leverage community efforts in ocean state estimation. Are the projections sensitive to the initial state of the ocean local to the Atlantic, or are they sensitive to the global state? The main ‘products’ of these activities would be probabilistic projections of the evolution of the Atlantic ocean circulation and associated ocean temperature changes, as well as any associated atmospheric changes, possibly extending over continental regions. Such projections could have many applications but would be of particular use in assessing the likelihood of abrupt climate change, the IPCC process and studies of the importance of anthropogenic forcing of climate change. It would also motivate further predictability research in the MOC etc.

The ultimate goal being sought here is the development of the capability to make both nowcasts of the current state of the Atlantic, and credible decadal scale predictions of the Atlantic, with particular emphasis on the MOC. In order to develop such capabilities, several different pathways need to be pursued. The specific recommendations for progress in this area are;

- As previously discussed, models need to be developed that are of sufficiently high fidelity that they can adequately simulate the primary aspects of observed variability in the Atlantic, particularly on the interannual to decadal scale. The development of ever improving models is an ongoing, iterative process – models are developed, evaluated against observations, and refined based upon an improved understanding of the physics of the system, improved numerical formulations, and increased computational resources.

- A system must be developed by which models can be accurately initialized to the observed state of the climate system. This involves both a sufficiently complete observational system, and an assimilation system capable of utilizing the direct observations to constrain the model solution.

- Predictability studies need to be undertaken to evaluate what components of the Atlantic system have meaningful predictability on interannual to decadal time scales. Note that such studies use models to estimate the predictability of the true system, and these predictability estimates are model dependent. Hence, it is possible that estimates of the true predictability of the climate system will evolve as models evolve.

- Any decadal scale predictions must utilize information both from the initial value of the climate system, and from projected changes in external forcing of the system. For example, changing aerosol or greenhouse gas concentrations may have a significant influence on the evolution of the Atlantic on a decadal time scale, and need to be taken into account in any decadal predictions.

- As a complement to the dynamical systems described above, statistical prediction systems need to be developed and evaluated.

4. Tools for Decadal Predictions and Analyses

Data available for tests of Atlantic predictability include gridded and non-gridded observations.

- Gridded SST fields are available from the 1860s to the present, providing more than 10 realizations of any observed decadal signals. There are several SST datasets available, each using somewhat different assumptions to project the data back in time. These data have been used to study mid-latitude propagating SST signals in the North Atlantic, north-south migrations in the position of the Gulf Stream and other SST features. The ability of models to simulate such phenomena must be assessed in order to have confidence in using the models for studying predictability and generating nowcasts. For instance, a recent comparison of a GFDL model with observations indicates that the model can replicate the meridional motions of the Gulf Stream but does not include propagating SST signals.

- The available subsurface temperature data are more limited than SST data. Realistically it is only possible to generate coarsely resolved Atlantic wide subsurface fields from the late 1960s to the present, which limits the number of events available for study. Considering transect data rather than basin-wide gridded data, however, allows for the combination of mechanical and expendable bathythermograph datasets in the Atlantic to generate time series along many transects that extend back to the early 1950s. Subsampling of model results along these lines provides a method to validate the subsurface model simulations for almost 60 years. There are sufficient data from these historical records to identify decadal signals from the southern tropics to the subpolar North Atlantic. Analyses of these data have shown, for example, the presence of decadal signals in components of the MOC (e.g., meridional migration of the Gulf Stream). Repeat CTD sections, such as the 20+ years of roughly annual sections across the DWBC east of Abaco Island in the Bahamas can also be used in model comparisons.

- Actual time series observations of velocity and transport are not generally available over a long enough period to be of use to study decadal variability in the ocean. One exception to this rule is the 25+ years of nearly continuous observations for the Florida Current transport. As the Florida Current carries the bulk of the upper limb of the MOC at this latitude it represents a useful tool that can be used for comparison to models. For example, do models reproduce the observed phase-lag between the NAO and the Florida Current transport? Including snapshot section estimates of the transport and earlier experiments in the Florida Straits it may be possible to extend this record back to nearly 40 years. Other observations such as the 10+ years of Gulf Stream location and velocity observations from the Oleander project and the time series observations in the GIN sea overflow passages should be used to validate both nowcast estimates from models and seasonal to interannual variability to understand how those signals can alias other observations being used to validate the model simulations. Furthermore, new programs that are underway intended to become long-term transport time series, such as the DWBC monitoring east of Abaco Island in the Bahamas, need to be maintained so that they can provide the long records needed for climate model validations/comparisons in the coming years. New sites for such observations should be identified and instrumented so that the records that will be needed in the future will be available.

- Profiling float and satellite altimetry data are available for about 10 years in Atlantic, with more limited float coverage in the South Atlantic. While these records cannot be used directly to study decadal variability, by comparing these records to longer-term data sets it should be possible to evaluate how well these observing systems can reproduce key decadal signals. Some work has begun in the North Atlantic and demonstrates that the float data can reproduce annual and interannual signals in the properties of the recirculation gyre south of the Gulf Stream (a potential component of coupled air-sea interaction).

Appendix 1: Workshop agenda

Miami observation-model Atlantic decadal workshop
January 10 – 12, 2007

Wednesday, January 10th, 2007

Theme: Observing and characterizing the past and present state of the Atlantic Ocean

9:00am-9:15am: Welcome and introduction to the meeting

9:15am-9:45am: Molly Baringer, AOML

> **"What aspects of the Atlantic MOC can we observe directly?"**

9:45am-10:15am: John Toole, WHOI

> **"Recent measurements of the North Atlantic's deep western boundary current"**

10:15am-10:45am: Rick Lumpkin, AOML

> **"Gridded surface current fields for model validation"**

10:45am-11:00am: BREAK

11:00am-11:30am: Bob Molinari, AOML

> **"A sampler of *in situ* observations available for interactive model-data studies"**

11:30am-12:00pm: Larry Peterson, RSMAS

> **"Modeling and Observations of the Atlantic Meridional Overturning Circulation in the Paleo Record"**

12:00pm-12:30pm: Jorge Sarmiento, Princeton

> **"Predicting decadal variability of biogeochemistry."**

12:30pm-2:00pm: LUNCH

2:00pm-5:30pm: General discussion – Input from the participants
Facilitator: Chris Meinen
Reporter: Rick Lumpkin
Specific topics:

- Other observations that are needed
- New or modified methodologies that are needed
- Integration issues and needs (in situ & remote sensing)
- Resolution issues and needs
- Other topics

Thursday, January 11th, 2007

Theme: Prospects for predictability of oceanic (and atmospheric) variability in the Atlantic

9:00am-9:15am: Welcome and overview for day 2

9:15am-9:45am: Eli Tziperman, Harvard

"Procedures for ocean predictability studies"

9:45am-10:15am: Tom Delworth, GFDL

"Impact of Atlantic Multidecadal Variability on Regional and Hemispheric Climate"

10:15am-10:45am: Martin Visbeck, IFM-GEOMAR

"What components of the Atlantic Ocean variability might have some predictability?"

10:45am-11:00am: BREAK

11:15am-11:45am: Tony Rosati, GFDL

"How well are ocean data assimilation systems capturing the meridional heat transport and its variability"

11:45am-12:15pm: Axel Timmerman, U. Hawaii

"Decadal predictability, ENSO regime predictability"

12:15pm-2:00pm: LUNCH

2:00pm-5:30pm: General discussion – Input from the participants
Facilitator: Ants Leetmaa
Reporter: Tom Delworth
Specific topics:

- Signal identification
- Tests of models
- Model initialization
- Other topics

Friday, January 12th, 2006

9:00am-12:30pm: Discussion
Facilitator: Chris Meinen
Reporter: Bob Molinari
Specific topics:

- Breakup into panels to discuss subgoals
- Discussion of future plans
- Wrap-up, designation of tasks, close of workshop

Appendix 2: List of workshop participants

Molly Baringer	Atlantic Oceanographic and Meteorological Laboratory, NOAA
Jim Carton	University of Maryland
Tom Delworth*	Geophysical Fluid Dynamics Laboratory, NOAA
David Enfield	Atlantic Oceanographic and Meteorological Laboratory, NOAA
Rana Fine	University of Miami
Mick Follows	Massachusetts Institute of Technology
Zulema Garraffo	University of Miami
Silvia Garzoli*	Atlantic Oceanographic and Meteorological Laboratory, NOAA
Gustavo Goni	Atlantic Oceanographic and Meteorological Laboratory, NOAA
Sirpa Hakkinen	Goddard Space Flight Center, NASA
Bill Johns	University of Miami
Chet Koblinsky	Climate Office, NOAA
Ants Leetmaa*	Geophysical Fluid Dynamics Laboratory, NOAA
David Legler	US CLIVAR Office
Eric Lindstrom	Office of Earth Observations, NASA
Rick Lumpkin	Atlantic Oceanographic and Meteorological Laboratory, NOAA
Chris Meinen*	Atlantic Oceanographic and Meteorological Laboratory, NOAA
John Marshall*	Massachusetts Institute of Technology
Bob Molinari	Atlantic Oceanographic and Meteorological Laboratory, NOAA
Chris Mooers	University of Miami
Breck Owens	Woods Hole Oceanographic Institution
Larry Peterson	University of Miami
Tony Rosati	Geophysical Fluid Dynamics Laboratory, NOAA
Tom Rossby	University of Rhode Island
Jorge Sarmiento	Princeton University
Carlisle Thacker	Atlantic Oceanographic and Meteorological Laboratory, NOAA
Axel Timmerman	University of Hawaii at Manoa
Jim Todd	Climate Program Office, NOAA
John Toole	Woods Hole Oceanographic Institution
Eli Tziperman	Harvard University
Martin Visbeck	Leibniz Institute for Marine Science (IFM-GEOMAR)
Rik Wanninkhof	Atlantic Oceanographic and Meteorological Laboratory, NOAA

*Workshop organizing committee