Decadal forecast skill in the North Atlantic sector: the role of the ocean

A project proposal to The Research Council of Norway

P r o j e c t   d e s c r i p t i o n[1]

Project manager:	Dr. Arne Melsom, Norwegian Meteorological Institute (*met.no*) (*arne.melsom@met.no*)
Co-investigator:	Dr. Anne Britt Sandø, Institute of Marine Research (*IMR*)
Duration of project:	2014-01 – 2016-12

Primary objective

To explore the limits of predictability that is due to the large variability on (multi-)decadal time scales in the North Atlantic Ocean

A set of secondary objectives is listed in the Application form, and in section 4 below.

1 Relevance

The Research Council's call for proposals has explicit focuses on *(i)* understanding climate variability and its uncertainties, *(ii)* the relations between natural variability and changes resulting from human activities, and *(iii)* the limitations to the predictability of the climate system. This is further emphasized by the five research questions that are listed in the call.

Prediction of decadal to multi-decadal variability involves all of these science issues. Decadal prediction is a novel branch of forecasting where the slowly evolving effects of anthropogenic climate forcing converges with changes on time scales of the climate system's natural variability.

The scientific investigations we propose for this project will aim at quantifying the skill and uncertainties of decadal forecasts, based on examinations of observational records and relevant IPCC CMIP5 integrations which are now becoming available. Furthermore, our research will focus on the ability of the models to reproduce aspects of the ocean circulation that have been shown to be pivotal for decadal forecasting to succeed.

2 Background and motivation

2.1 Climate modeling and decadal variability

Traditionally, the aim of modeling Earth's climate of past centuries and the future has been to quantify the impact on climate from changes in radiative forcing on time scales from

[1]This document contains hyper-links that are active when using properly enabled software. An electronic copy of this document is available from http://projects.met.no/DecCast/documents/DecCast.pdf

multiple decades to centuries and beyond. The radiative forcings that give rise to climate change in such simulations are the direct and indirect manifestations of recent and projected anthropogenic release of greenhouse gases and aerosols, and land use.

These model simulations have been initialized in the mid-19th century and integrated up to the present applying the best estimate of the climate forcing for the historical period. Simulations have subsequently been continued into the future, usually adopting prescribed emission scenarios (Meehl *et al.*, 2007).

The approach outlined above is not suited for decadal forecasting since there is no synchronization with the modes of natural internal variability. Such modes, which include the North Atlantic Oscillation (NAO), the Atlantic Multi-decadal Oscillation (AMO), and the Pacific Decadal Oscillation (PDO), are due to processes which occur on inter-annual to multi-decadal time scales.

In order to produce decadal forecast it is essential that the initial state can be described accurately. While the "memory" of the atmosphere is of the order of a few weeks, other compartments of the climate system vary more slowly. Although other parts of Earth's climate, such as the cryosphere, have a much longer "memory" than the atmosphere, it is particularly important to capture the initial state of the inert ocean (Smith *et al.*, 2007).

In many ways, decadal prediction is a union between climate projections which are integrations using prescribed anthropogenic forcing, and seasonal forecasts that are produced by applying an analysis of the present state which is integrated forward in time. Thus, the main discrepancies of the two approaches can be attended to: While traditional climate simulations ignore the state of internal variability at the time of initialization, seasonal forecasts disregard variability of the external forcing (with the obvious exception of the deterministic forcing due to Earth's orbital motion).

2.2 CMIP5

The Coupled Model Intercomparison Project Phase 5 (CMIP5) provides a framework for coordinated climate change experiments that are prepared for IPCC's 5th assessment report (IPCC AR5), as well as for experiments that extend beyond the AR5. The CMIP5 experiment design defines three main suites of experiments. In the present project, the focus is on results from experimental suite *I. Decadal Hindcasts and Predictions simulations.*

Experiment design details are given by Taylor*et al.* (2012). Suite *I* ensemble experiments are labelled "decadalXXXX" were XXXX should be substituted by the simulation initialization year. These experiments are divided into 10-year simulations which are intitialized every 5th year from 1960 to 2005, and 30-year simulations which are initialized in 1960, 1980 and 2005. Thus, almost all of these simulations are for the historical period. Below, we refer to such experiments as hindcasts, decadal hindcasts or retrospective predictions.

2.3 Motivation

The motivation for the particular attention being given to the North Atlantic Ocean in this proposal, is that the North Atlantic is a region were some early efforts in decadal forecasting give encouraging results. It is also a region where the amplitude of the decadal variability is very large, and where the variability can be linked to changes in the ocean circulation (Keenlyside *et al.*, 2008; Pohlmann *et al.*, 2009; Bellucci *et al.*, 2013).

3 Scientific issues and methods

3.1 The North Atlantic oscillation

Variability in the North Atlantic region on various time scales is manifested by various indices. The NAO index (*e.g.* Hurrell et al., 2003) is the index that is most frequently used to describe changes in the regional atmospheric circulation, particularly during the winter season. Hence, a successful decadal forecast for the present region must, as a minimum, reliably describe any systematic NAO anomaly during the forecast period.

The winter NAO index exhibits a range of time scales. The fluctuations can be quasi-biennial during some periods, while decadal variability dominates in other periods. A decadal character has been a notable feature of the NAO for the past decades, with negative values during the 1960s and positive values during the late 1980s through the 1990s (Hurrell et al., 2003).

3.2 SST anomalies in the North Atlantic Ocean

Changes in the regional atmospheric circulation are correlated with North Atlantic SST anomalies, which propagate along the pathway of the North Atlantic Current (Visbeck *et al.*, 2003; Sutton and Allen, 1997). These SST anomalies can persist for many years, so their effect on the air-sea heat flux is potentially important for decadal forecasting.

However, the correlation values from observations reveal that only up to 10-20% of the variance in winter-time SSTs can be explained by the NAO variability. So in order to investigate the CMIP5 SST patterns and time scales in more detail, a spectrum analysis of the leading EOFs of the SSTs can be performed. This was done in an analysis of CMIP3 control results by Jamison and Kravtsov (2010), who found that while the spatial patterns of the observations were captured in only some models, the models generally were capable of reproducing the behaviour within at least one of three selected frequency bands.

Visbeck *et al.* (2003) also considered the low-pass filtered SST *vs.* NAO correlations, for SSTs that lagged NAO. When a lag of 6 years was considered, they found high correlation values downstream of one of the hot-spots in the original (no lag) analysis. This suggests that the anomalies may follow the large-scale circulation fields. Thus, SST anomalies may provide predictability on inter-annual to decadal time scales by having systematic effects on the air-sea heat flux many years after they formed. A similar propagation of SST anomalies was found by Sutton and Allen (1997). An analysis of model results along the lines of these observational based investigations should give valuable information with relevance for the model's predicitive skill on interannual and decadal time scales.

3.3 North Atlantic multi-decadal variability

The Atlantic Multidecadal Oscillation (AMO) is a quasi-periodic index which can *e.g.* be constructed from a time series of area integrated North Atlantic SST values. This was done by Sutton and Hodson (2005), who demonstrated a significant effect of AMO variability on summertime precipitation and surface air temperatures in North America, Europe and the Sahel region.

Due to the multi-decadal time scale of the AMO signal, the zero crossing of the lagged autocorrelation occurs after 15–20 years. This was exploited by Ting *et al.* (2011) in their examination of the AMO index from CMIP3 results. They found that while the SST anomaly patterns were similar between models and observations, the persistence of the AMO signal was generally weaker in the CMIP3 models. This discrepancy may potentially limit the predictive skill on time scales of 1–2 decades and beyond.

In an assessment of AMO predictability in hindcasts from one of the CMIP5 models (GFDL), Yang *et al.* (2013) found that SST and T2m may be predictable for lead times up to 10 years at a 90% significance level. Kim *et al.* (2012) examined hindcast results from the first CMIP5 ensembles, and found that while changes in the global surface temperature trends were not reproduced accurately, AMO was modeled with significant skill.

AMO is the lowest frequency signal that is discussed in the present project. The CMIP5 decadal hindcasts cover a 50 year period, which includes one AMO episode only, and this limitation needs to be recognized when CMIP5 results are evaluated. The obvious remedy would be to extend hindcasts to initialization dates prior to 1960. However, prior to 1960, the quality of the initial conditions for the three-dimensional ocean state based on synoptic observations may be inadequate for retrospective prediction.

3.4 The impact of NAO on ocean transport variability

Curry and McCartney (2001) defined an index for the intensity of the gyre circulation in the North Atlantic Ocean, which they refer to as "an oceanic NAO index". They apply this index, which is computed from the difference in the potential energy anomaly between Bermuda and the Labrador Basin, to describe inter-annual to inter-decadal variability of the mass transport.

The oceanic response to changes in the NAO includes local effects on the properties of the mixed layer due to heat fluxes and Ekman transports, and remote effects by means of propagation of internal waves. Curry and McCartney found that when the NAO signal is filtered with an appropriately chosen weighing function (backward in time), the correlation between the transport index and the NAO index exceeds 0.75.

Using hydrographic data from two WOCE sections in the North Atlantic Ocean, Bersch (2002) found that the intermittent reversal from a regime with positive NAO index numbers to a large, negative NAO index in 1996 led to changes in the circulation of the upper layer. The shape of the subpolar gyre changed as the subarctic front shifted westward in the Irminger Basin, and eastward in the region off the Grand Banks. The subtropical gyre was found to expand northwards. Bersch suggests that the corresponding shifts in the air-sea heat flux could subsequently become a forcing mechanism for the NAO.

This episode was recently examined by Robson *et al.* (2012a,b), who showed that the warming event in the upper layer of the subpolar gyre in the mid-1990s was predictable. Moreover, they found that the warming was associated with an anomalously strong circulation in the North Atlantic Ocean which was found to be primarily a delayed response to the preceding persistent positive phase of NAO.

3.5 NAO and the deep-water of the North Atlantic Ocean

Lozier et al. (2008) examined the response in the deep North Atlantic Ocean to the differences between the regime with low NAO index values in the 1950s and 1960s, and the high NAO regime of the 1980s and 1990s. They found that this shift gave rise to a warming in the subtropics at 1000 m and 2000 m, while the subpolar gyre underwent a cooling at these depths. The northern cooling was attributed mainly to changes in water mass properties, while the warming in the subtropics was found to be significantly influenced by a deepening of isotherms. At the 1000 m level, changes in water mass properties also contributed to the subtropical warming.

In a recent study, Mauritzen, Melsom and Sutton (2012) examined observations in isopycnal space. The analysis of the circulation in the deep North Atlantic Ocean was performed separately for the Upper North Atlantic Deep Water (UNADW, formed in the subpolar gyre) and the Lower NADW (LNADW, originating from the Greenland–Scotland deep overflow). The boundary between these two water masses are generally at depths between 1500 m and 3000 m.

We found that the water mass properties in the UNADW propagate southward on decadal time scales. A warm, salty signal which emerged in the north in the 1960s could be traced during the following 20 years as the anomaly propagated. Similar results were found for a cold, fresh anomaly that emerged in the 1980s and 1990s. These anomalous events peak in the subpolar gyre about 5 years after the corresponding peaks in the inter-annual NAO index. The LNADW evolved differently from the UNADW, with a general cooling from the late 1950s onward. The southward propagation of a cold LNADW anomaly during the 1990s is most notable along the western rim of the North Atlantic Ocean, in contrast to the UNADW anomalies which are found to propagate into the central basin.

In an investigation using data from the mid-1980s to 2010, van Sebill *et al.* (2011) found that salinity anomalies in the Labrador Sea appeared at the "Abaco line" off Bermuda with a delay of about 9 years.

3.6 Analyses of ensemble decadal hindcasts

Due to non-linear interactions, small differences in the initialization will lead to solutions in the subsequent integrations that diverge. Such a stochastic system must be investigated by ensemble simulations, and evaluated by the probability distributions of its results.

A number of techniques are available for the purpose of such investigations. Such techniques have been applied in evaluations of the quality and precision of results from ensemble simulations for weather forecasting. Relevant validation tools include multi-category reliability diagrams and rank histograms (Talagrand diagrams) for evaluation of model *vs.* observed variability (Hamill, 1997; Hamill, 2001), and Brier score, reliability diagrams and ROC analysis to diagnose probability of events (Palmer *et al.*, 2000; Bröcker and Smith, 2007; Fawcett, 2006).

While most of these techniques were developed primarily for validation of station (point) data in the form of time series, their application may be extended to integral properties, *e.g.* circulation indices. Kim *et al.* (2012) used anomaly correlation coefficients in their evaluation of the decadal predictability of surface temperatures based on seven CMIP5 ensembles.

Further, more advanced techniques exist for validation of patterns, such as the average predictability time analyses (DelSole and Tippett, 2009a,b).

4 Work plan

Our aim is to evaluate the quality of the IPCC CMIP5 decadal retrospective predictions. As pointed out in section 2, the key to decadal forecasting is a reliable description of the compartments of the physical climate system that has a "memory" of months and years. The main compartment in this context is the ocean.

We also noted in section 2 that the amplitude of decadal variability is large in the North Atlantic Ocean. Recent studies of decadal predictability also indicate that predictability on the time scales in question is larger in this region than elsewhere.

Next, in section 3 processes that are native to the North Atlantic, and which vary on relevant time scales, were described. In order to produce reliable decadal forecasts, it is essential that the forecast model can capitalize on these processes. It is very unlikely that a model that is without skill when it comes to describing the distribution and evolution of SST and air-sea heat fluxes on a decadal time scale, can produce useful predictions for the same time scales.

Hence, analyses of the processes that are described in section 3 are at the heart of this project.

The work packages that are listed below have been designed in order to address four topics:

- Has the models' description of the relevant processes improved from CMIP3 to CMIP5? (section 4.2)
- Are the processes that give rise to the observed decadal variability in the North Atlantic Ocean captured in the CMIP5 decadal hindcasts? (section 4.3)
- Is the decadal variability described with any skill in these hindcasts? (section 4.4)
- Which process(es) must the model describe more accurately in order to improve predictability? (section 4.5)

4.1 WP0: Preparations

In order to perform the scientific investigations efficiently, we will start by acquiring the relevant sets of model results, model code and observational data sets:

- Results from selected CMIP5 and CMIP3 control simulations
- Results from selected CMIP5 decadal hindcast simulations
- Code for calculation of the equation of state from the selected models
- Hydrobase3[2] quality controlled profile data and software (Curry, 2013)
- Quality controlled observations from profiling buoys (ARGO data)
- The Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST)
- The winter-time NAO index and the AMO index

The production of gridded fields as in Mauritzen *et al.* will be repeated, but with an updated data set and application of the new version of the Hydrobase software, which includes a new optimal interpolation routine (R. Curry, pers. comm.). The resulting fields will be available with a pentadal resolution in time, a horizontal resolution of 1° and up to 84 z levels.

[2] At the time of writing, Hydrobase3 is not yet available. It will however become available later in 2013 (R. Curry, *pers. comm.*).

4.2 WP1: Analysis of control-climate variability

The focus here is on the quality of the representation of relations between NAO variability and its effect in the North Atlantic Ocean, as presented in sections 3.2–3.5 above.

The objectives of this work package are firstly to examine if these relations are qualitatively similar in the model results and in the observations, and secondly to investigate if there has been an improvement from the CMIP3 to CMIP5 sets of model results.

A motivation for including latter issue is that since CMIP3, much work has been invested in reproducing the carbon cycle in the models. Still, we anticipate that changes in the model physics and numerics since CMIP3 will lead to an improved quality in the CMIP5 simulations.

4.3 WP2: Analysis of decadal variability in the North Atlantic Ocean

Here, analyses similar to those in WP1 will be performed for results from the CMIP5 decadal hindcast simulations. The aim of this work is to examine how the pace at which the results from these simulations diverge from observations.

A key question in this context is whether or not anomalies of the initial fields that can be attributed to decadal NAO variability evolve according to the observational record: Does the history of anomalies unfold as expected, or are they lost *e.g.* due to shortcomings of the models' numerical representations of the relevant processes?

4.4 WP3: Analysis of the predictability based on CMIP5 decadal hindcasts

Due to the stochastic nature of both the atmospheric and oceanic circulation, the forecast skill on inter-annual time scales and beyond must be evaluated by probabilistic analyses of results from ensemble simulations, rather than from the traditional deterministic approach.

Fortunately, as outlined in section 3.6, many techniques for evaluation of predictability from ensemble simulations are available. Here, a selection of these tools will be applied to results from the CMIP5 ensemble decadal simulations in order to quantify how well processes related to NAO forcing in the North Atlantic can be predicted.

We will also include an examination of probabilistics of decadal forecasting of events that are attributed to persistent anomalies in the atmosphere, such as warm spells and droughts.

4.5 WP4: Analysis of CMIP5 hindcasts using ARGO data

In WP2 and WP3, the observational record that will be used, is the Hydrobase3 product which covers hydrographic observations from the past 60 years. The resolution of this product is limited by the uneven distribution of observations in space and time. In contrast, the amount of profiling hydrographic data has increased significantly during the past decade, mainly due to the autonomous floats that constitute the Argo project.

Since more details are available from observations, an examination of retrospective predictions for the Argo period may add valuable insight into the models' ability to reproduce variability in the North Atlantic Ocean on inter-annual time scales.

4.6 Deliverables

The deliverables in the project will be the publications and web site as listed under *Dissemination of project results* in the Application form.

5 Project management

5.1 [3] Personnel

The research will be lead by Dr. Arne Melsom. He has experience in coordinating research and managing projects, relevant projects include ocean ensemble modeling in *Ensemble forecasting and the ocean's mesoscale* and variability and signal propagation in the *Norwegian Ocean Climate Project*. Dr. Melsom is presently the Arctic Centre's representative in the working group for quality, calibration and validation in the EU project *MyOcean*.

His relevant scientific experience includes analysis of signal propagation in model results (*e.g.* Melsom *et al.*, 2003), analysis in isopycnal space of hydrographic observations from the North Atlantic (Mauritzen, Melsom and Sutton, 2012), regional downscaling of ocean circulation results from a climate model (Melsom *et al.*, 2009), work with ocean ensemble simulations (Melsom, 2005), examination of predictability of ocean forecasts (Melsom *et al.*, 2012), and analysis of seasonal forecasts (*e.g.* Orsolini *et al.*, 2012).

Dr. Anne Britt Sandø has experience from numerical modelling with emphasis on the North Atlantic Ocean, Nordic Seas and Arctic Ocean. Her main research interests are mechanisms for variability on inter-annual to decadal time scales, *e. g.* an analysis of the subpolar gyre and its influence on the thermohaline circulation (Hàtùn *et al.*, 2005b), and a tracer and dynamics analysis in the North Atlantic (Mauritzen *et al.*, 2006). Both of these studies involved the use of the isopycnal model MICOM, from which is the ocean component in the Norwegian climate model NorESM is built. Results from relevant CMIP5 simulations with NorESM will be included in the analyses of the present project.

Dr. Sandø has broad experience from evaluating models (Hàtùn *et al.*, 2005a; Eldevik et al. *et al.*, 2005; Sandø and Furevik, 2008; Eldevik *et al.*, 2009; Sandø *et al.*, 2010; Sandø *et al.*, 2012) including results from CMIP3 simulations.

Dr.s Melsom and Sandø are presently collaborating on an analysis of ocean circulation results for the Barents Sea region from two of the CMIP3 models (GISS-AOM and NCAR-CCSM3). The control climate simulations (20C3M) and climate projection (A1B) are examined, along with regional downscalings which apply results from the CMIP3 models as boundary conditions.

5.2 International collaboration

Work in this project will be performed in close collaboration with Dr.s Rowan Sutton and Jon Robson at the UK National Centre for Atmospheric Science (NCAS), Department of Meteorology, University of Reading. The prediction of climate on decadal timescales, and understanding the mechanisms that give rise to this predictability, is a core research issue. At the heart of this topic is ocean processes in the North Atlantic sector, which is paid particular attention to at NCAS. Annual project meetings with NCAS are planned.

Dr. Sutton has collaborated successfully with the project leader (Dr. Melsom) in the past, resulting in a publication in Nature Geoscience (Mauritzen, Melsom and Sutton, 2012).

5.3 Budget

The budget is given in the Application form.

[3] References in section 5.1 are *not* listed in section 8, but are found on the *c.v.*s of Dr. Melsom and Dr. Sandø that are included in the present proposal.

6 Perspectives and strategic significance

6.1 Strategic significance

The statutes of the Norwegian Meteorological Institute (*met.no*) state that the institute shall perform work that contributes to planning and protection of the environment. The statutes explicitly states that *met.no* shall provide relevant climate information. The Institute of Marine Research (*IMR*) has made a priority of understanding climate change and its implications for marine life. Both *met.no* and *IMR* are national institutes with an obligation to provide informed scientific advice to public sector decision makers.

6.2 Relevance for society

Decadal predictions provide forecasts on a time horizon which is highly relevant for decision makers. Furthermore, such predictions are also for lead times that the public at large can relate to. Environmental management that would particularly benefit from reliable decadal forecasts includes disaster preparation and management (*e.g.* in relation to heat waves, droughts and flooding), management of freshwater resources, and resource management for agriculture, forestry and fisheries (Hurrell *et al.*, 2010). Nevertheless, when applying decadal predictions for such purposes, it is essential that their quality is known.

7 Communication

We anticipate that the results from this project will be of interest to fellow scientist, and also for decision makers who must relate to changes on inter-annual and decadal time scales.

Communication with the science community will be facilitated by publications in peer-review journals and oral presentations in relevant forums. Moreover, we will seek to inform non-science groups in Norway by publishing popular science accounts through appropriate channels such as the periodical *Klima* and/or web sites like *yr.no* and *forskning.no*.

All presentations will be made available from a project web site.

8 [4] References

Bellucci A. *et al.*, 2013: Decadal climate predictions with a coupled OAGCM initialized with oceanic reanalyses. *Clim. Dyn.*, **40**, 1483-1497. doi:10.1007/s00382-012-1468-z

Bersch, M., 2002: North Atlantic Oscillationinduced changes of the upper layer circulation in the northern North Atlantic Ocean. *J. Geophys. Res.*, **107**, 3156, 11 pp. doi:10.1029/2001JC000901

Bröcker, J., and L.A. Smith, 2007: Increasing the Reliability of Reliability Diagrams. *Wea. Forecasting*, **22**, 651-661. doi:10.1175/WAF993.1

Curry, R., 2013: Hydrobase3: a tool for climatological analysis of oceanographic properties. Data, software and documentation is available from `http://www.whoi.edu/hydrobase` [5]

Curry, R.G., and M.S. McCartney, 2001: Ocean gyre circulation changes associated with the North Atlantic Oscillation. *J. Phys. Oceanograph.*, **31**, 3374-3400. doi:10.1175/1520-0485(2001)031<3374:OGCCAW>2.0.CO;2

DelSole, T., and M.K. Tippett, 2009a: Average predictability time. Part I: Theory. *J. Atmos. Sci.*, **66**, 11721187. doi:10.1175/2008JAS2868.1

[4]References in section 5.1 are *not* listed in section 8, but are found on the *c.v.*s of Dr. Melsom and Dr. Sandø that are included in the present proposal.

[5]At the time of writing, Hydrobase3 is not yet available. It will however become available later in 2013 (R. Curry, *pers. comm.*).

DelSole, T., and M.K. Tippett, 2009b: Average predictability time. Part II: Seamless diagnosis of predictability on multiple time scales. *J. Atmos. Sci.*, **66**, 11881204. doi10.1175/2008JAS2869.1
Fawcett, T., 2006: An introduction to ROC analysis. *Pattern Recogn. Lett.*, **27**, 861-874. doi:10.1016/j.patrec.2005.10.010
Hamill, T.M., 1997: Reliability Diagrams for Multicategory Probabilistic Forecasts. *Wea. Forecasting*, **12**, 736-741. doi:10.1175/1520-0434(1997)012<0736:RDFMPF>2.0.CO;2
Hamill, T.M., 2001: Interpretation of Rank Histograms for Verifying Ensemble Forecasts. *Mon. Wea. Rev.*, **129**, 550-560. doi:10.1175/1520-0493(2001)129<0550:IORHFV>2.0.CO;2
Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, 2003: An Overview of the North Atlantic Oscillation. In: *The North Atlantic Oscillation: Climatic Significance and Environmental Impacts.* Eds.: Hurrell, Kushnir, Ottersen, Visbeck. *Geophys. monogr.* **134**, AGU, 1-35. doi:10.1029/GM134
Hurrell, J.W. *et al.*, 2010: Decadal Climate Prediction: Opportunities and Challenges. In *Proceedings of OceanObs09: Sustained Ocean Observations and Information for Society.* Ed.s: Hall, Harrison, Stammer. *ESA Publication* WPP-306, 13 pp. doi:10.5270/OceanObs09.cwp.45
Jamison, N., and S. Kravtsov, 2010: Decadal variations of North Atlantic sea surface temperature in observations and CMIP3 simulations. *J. Clim.*, **23**, 4619-4636. doi:10.1175/2010JCLI3598.1
Keenlyside, N., M. Latif, J. Jungclaus, L. Kornblueh, and E. Roeckner, 2008: Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature*, **453**, 8488. doi:10.1038/nature06921
Kim, H.-M., P.J. Webster, and J.A. Curry, 2012: Evaluation of short-term climate change prediction in multi-model CMIP5 decadal hindcasts. *Geophys. Res. Lett.*, **39**, L10701, 7 pp. doi:10.1029/2012GL051644
Mauritzen, C., A. Melsom, and R.T. Sutton, 2012: Importance of density-compensated temperature change for deep North Atlantic Ocean heat uptake. *Nature Geo.*, **5**, 905-910. doi:10.1038/ngeo1639 (Supplementary information)
Meehl, G.A. *et al.*, 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis.* Ed.s: Solomon *et al.*]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Meehl, G.A. *et al.*, 2009: Decadal prediction: Can It Be Skillful? *Bull. Am. Met. Soc.*, **90**, 14671485. doi:10.1175/2009BAMS2778.1
Palmer, T.N., Č Branković, and D.S. Richardson 2000: A probability and decision-model analysis of PROVOST seasonal multi-model ensemble integrations. *Q. J. R. Met.Soc.*, **126**, 20132033. doi:10.1002/qj.49712656703
Pohlmann, H., J.H. Jungclaus, A. Köhl, D. Stammer, and J. Marotzke, 2009: Initializing decadal climate predictions with the GECCO oceanic synthesis: Effects on the North Atlantic. *J. Clim.*, **22**, 39263938. doi:10.1175/2009JCLI2535.1
Robson, J., R. Sutton, K. Lohmann, D. Smith, and M.D. Palmer, 2012a: Causes of the Rapid Warming of the North Atlantic in the 1990s. *J. Clim.*, **25**, 41164134. doi:10.1175/jcli-d-11-00443.1
Robson, J.I., R.T. Sutton, and D.M. Smith, 2012b: Initialized decadal predictions of the rapid warming of the North Atlantic ocean in the mid 1990s. *Geophys. Res. Lett.*, **39**, L19713, 6 pp. doi:10.1029/2012GL053370
van Sebille, E. *et al.*, 2011: Propagation pathways of classical Labrador Sea water from its source region to 26°N. *J. Geophys. Res.*, **116**, C12027, 18 pp. doi:10.1029/2011JC007171
Smith, D. *et al.*, 2007: Improved surface temperature prediction for the coming decade from a global circulation model. *Science*, **317**, 796799. doi:10.1126/science.1139540
Sutton, R.T., and M.R. Allen, 1997: Decadal predictability of North Atlantic sea surface temperature and climate. *Nature*, **388**, 563-567.
Sutton, R.T., and D.L.R. Hodson, 2005: Atlantic Ocean forcing of North American and European Summer climate. *Science*, **309**, 115-118. doi:10.1126/science.1109496
Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An Overview of CMIP5 and the Experiment Design. *Bull. Am. Met. Soc.*, **93**, 485498. doi:10.1175/BAMS-D-11-00094.1
Ting, M., Y. Kushnir, R. Seager, and C. Li, 2011: Robust features of Atlantic multidecadal variability and its climate impacts. *Geophys. Res. Lett.*, **38**, L17705, 6 pp. doi:10.1029/2011GL048712
Visbeck, M. *et al.*, 2003: The ocean's response to North Atlantic Oscillation variability. In: *The North Atlantic Oscillation: Climatic Significance and Environmental Impacts.* Eds.: Hurrell, Kushnir, Ottersen, Visbeck. *Geophys. monogr.* **134**, AGU, 113-145. doi:10.1029/GM134
Yang, X. *et al.*, 2013: A Predictable AMO-Like Pattern in the GFDL Fully Coupled Ensemble Initialization and Decadal Forecasting System. *J. Clim.*, **26**, 650661. doi:10.1175/JCLI-D-12-00231.1