CHAPTER 9

NORTH ATLANTIC MULTI-DECADAL VARIABILITY - MECHANISMS AND PREDICTABILITY

Noel S. Keenlyside

Geophysical Institute, University of Bergen and Bjerknes Centre,
Bergen, 5007, Norway
E-mail: noel.keenlyside@gfi.uib.no
www.uib.no/gfi/en

Jin Ba, Jennifer Mecking, Nour-Eddine Omrani, Mojib Latif

GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel
Düsternbrooker Weg 20, 24105 Kiel, Germany

Rong Zhang, Rym Msadek

GFDL, NOAA
Princeton NJ, 08540, USA

The North Atlantic Ocean undergoes pronounced basin-wide, multi-decadal variations. The corresponding fluctuations in sea surface temperature (SST) have become known as the Atlantic Multi-decadal Oscillation (AMO) or Atlantic multi-decadal variability (AMV). AMV is receiving increasing attention for three key reasons: (1) it has been linked to climate impacts of major socio-economic importance, such as Sahel rainfall; (2) it may temporarily mask anthropogenic global warming not only in the North Atlantic Sector, but over the Northern Hemisphere (NH); and (3) it appears to be predictable on decadal timescales. This chapter provides an overview of current understanding of AMV, summarizing proposed mechanisms, our ability to simulate and predict it, as well as challenges for future research.

1. Introduction

The existence of AMV has been long known (Bjerknes, 1964; Deser and Blackmon, 1993; Kushnir, 1994). During the instrumental record, AMV exhibited a periodicity of 70-80 years (Fig. 1a). There were two cold periods (1900-1920 and 1970-1990), and three warm periods: one at the start of the record, another in the middle of last century (1930-1960), and an ongoing one that began around 1990. These variations had major socio-economic impacts, including large ecosystem shifts and the collapse of major fish stocks in the North Atlantic, such as herring in the English Channel (Edwards et al., 2013). AMV was also linked to precipitation and temperature changes, over Northern Africa (Fig 1c), North

America, Europe, and India, as well as to North Atlantic Hurricane activity (See Ch. 8 & 18 this book and references therein). The large multi-decadal fluctuations in summertime Sahel rainfall had profound consequence for people living in the region. For example, the 1970-80s drought caused the death of at least 100,000 people, and displaced many more (Ch. 2, UNEP, 2002).

AMV was also linked to multi-decadal fluctuations in observed global mean surface air temperature (SAT), which showed enhanced warming from 1920-1940 and 1970-2000, and weak cooling from 1950-1970s. (Schlesinger and Ramankutty, 1994). These SAT variations superimposed on centennial scale global warming (Keenlyside and Ba, 2010) and could have resulted from either external factors or internal unforced climate dynamics (Ch. 9, IPCC, 2007). AMV may play a role in the second case, as models show that it may have driven NH multi-decadal SAT changes (Zhang et al., 2007) and likely results from internal dynamics (Ting et al., 2009). However, the possible contribution of external factors in AMV is also debated (Booth et al., 2012; Zhang et al., 2013).

This chapter reviews the understanding of AMV. We describe the observed AMV (Sec. 2) and its potential causes (Sec.3). Relevant studies from climate models, which are an essential tool given limited observations, are summarized (Sec. 4), along with the leading mechanisms for AMV (Sec. 5). Section 6 reviews the predictability of AMV and discusses future research challenges. A summary concludes the chapter.

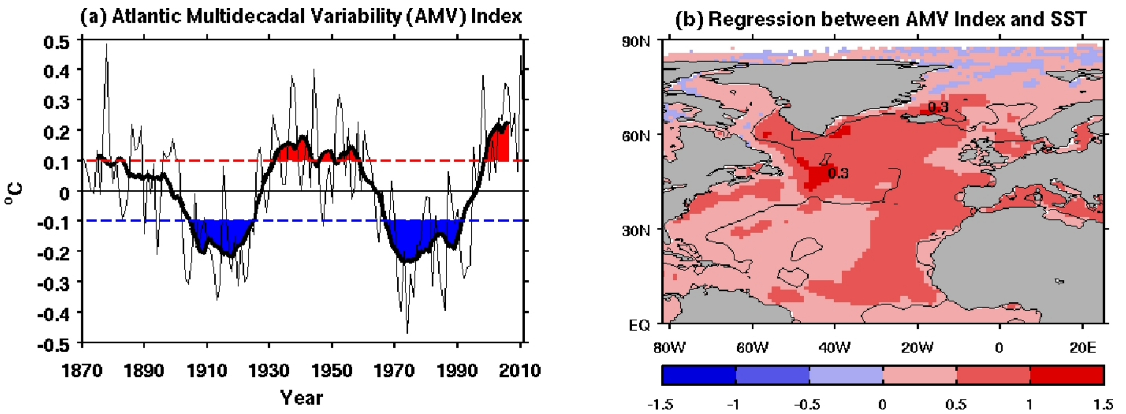

Fig. 1. Observed AMV (a) index and (b) pattern, computed by regressing the index on to SST in North Atlantic (Rayner et al., 2003). Explained variance is contoured (Contour Interval=0.3). See section 2 for definition of index.

2. Observed Atlantic multi-decadal variability

A common AMV index is the low-pass (e.g., 11 year moving average) filtered, North Atlantic (0°-60°N, 7.5°-75°W) average of linearly detrended SST (Sutton and Hodson, 2005) (Fig. 1a). The linear trend is removed because of the persistent warming that was observed in the north Tropical Atlantic and may be related to global warming. While other methods may better exclude global warming, the basic characteristics of AMV remain the same (Ting et al., 2009). In particular, North Atlantic SST differ by around 0.4°C on average between warm and cold phases (Fig. 1a). The changes are of same sign across the entire basin, but are largest over the subpolar North Atlantic (40°-60°N), Gulf Stream region, and the eastern subtropics/tropical North Atlantic (Fig. 1b). Furthermore, the SST variations persist throughout the year.

Boreal winter is a season of particular relevance for AMV as several processes are active that may be key to ocean-atmosphere interaction; these include formation of deep water and stratosphere-troposphere interaction (Sec. 6). Monte Carlo Singular Spectrum Analysis (MC-SSA) (Ghil et al., 2002) identifies the leading mode of the winter AMV index as multi-decadal. This variability differs significantly (P=0.05) from a first order auto-regressive (AR-1) process and explains 48% (69%) of the raw (3-year running mean) variance (Fig. 2a). The strong multi-decadal signal is clearly visible in both winter and annual mean SST variations (Fig 1a & 2a, blue curve).

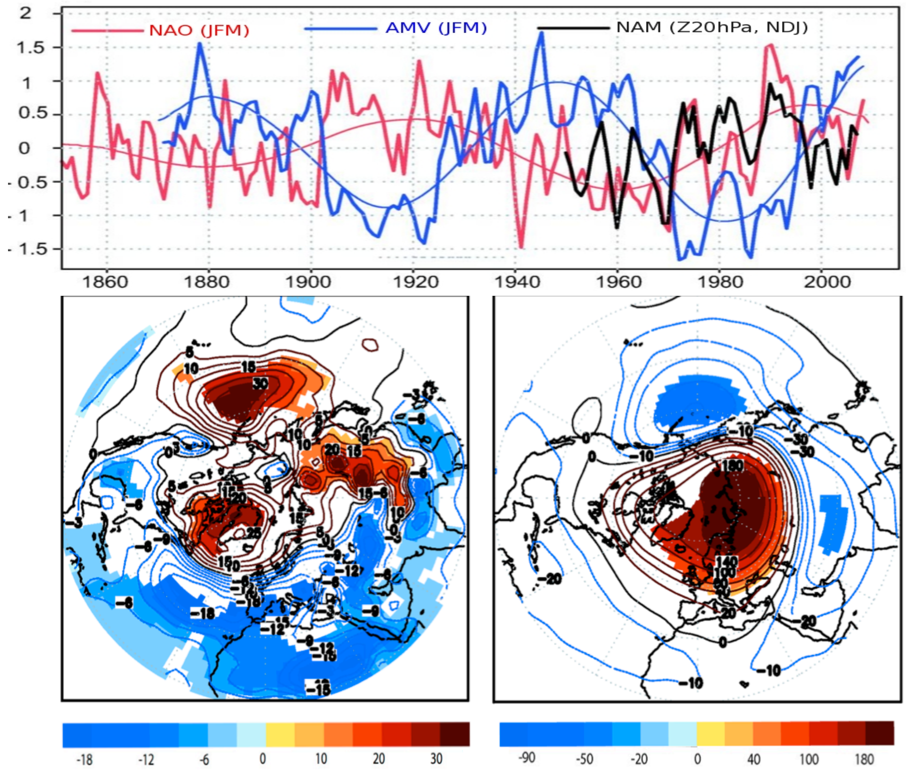

Fig. 2. Observed multi-decadal atmospheric variability associated with AMV. (Upper) The 3-year running mean winter (JFM) NAO (red) and AMV (blue) indices, and their multi-decadal MC-SSA reconstructions (thin blue and red) and the 3-year running mean early winter (NDJ) Northern Annular Mode (NAM) index (black) at 20hPa level. A typical warm phase is depicted by anomalies for 1951-1960 relative to 1961-1990 for (lower left) winter (JFM) 1000hPa geopotential height (gpm), and (lower right) early winter (NDJ) 20hPa geopotential height; only significant values at the 90% level are shaded. Figure adapted from Omrani et al. (2013).

The large-scale atmospheric circulation, and in particular, the North Atlantic Oscillation (NAO) also exhibited multi-decadal variations (Fig. 2a). The NAO is the dominant large-scale pattern of NH winter atmospheric variability, explaining up to 31% of the NH winter-mean SAT variability (Hurrell et al., 2003). A negative (positive) NAO phase is associated with anomalous weak (strong) high latitude westerlies and a southward (northward) shift of subpolar jet, storm track and weather systems in the North Atlantic Sector (Hurrell et al., 2003). Although many alternative NAO indices exist, they are all designed to capture sea level pressure (SLP) difference between the Azores High and Icelandic Low.

The multi-decadal variability of the winter NAO index explains 14% (36%) of the raw (3-year running mean) variance (Omrani et al., 2013) and gives the NAO a weakly red spectrum (Wunsch, 1999). (In a red spectrum amplitude decreases with frequency.) The multi-decadal variations in the winter NAO and AMV indices tend to occur out of phase: a warm (cold) AMV phase is associated with a negative (positive) NAO. Composite analysis using historical SLP observations confirm this relation (Omrani et al., 2013), which we illustrate with the winter surface geopotential height anomalies for the 1950-60's warm period (Fig. 2b). Atmospheric reanalysis (Kalnay et al., 1996) suggest that associated changes in the zonal winds extend deep into the stratosphere, where they occur in early winter (Fig. 2a). In particular, the stratospheric polar vortex was anomalously weak in early winter during 1950-60's (Fig. 2c).

Oceanic circulation is thought key to AMV. The North Atlantic horizontal oceanic circulation consists of the anti-cyclonic subtropical gyre, the cyclonic subpolar oceanic gyre (SPG), and the Gulf Stream and North Atlantic Current (NAC) that separates the two gyres. The Gulf Stream and NAC transport warm and salty subtropical water northward in the upper ocean. Through surface cooling and vertical mixing the water becomes denser and eventually sinks in the high-latitudes, returning southward at intermediate (~1000-2500m) levels (Kuhlbrodt et al., 2007). Much of the sinking occurs in the Greenland, Iceland and Norwegian Seas (GIN), and in the Labrador and Irminger Seas (Marshall and Schott, 1999). The upper-level northward and intermediate-level southward flows form the Atlantic Meridional Overturning Circulation (AMOC), which transports vast amounts of heat poleward (Kuhlbrodt et al., 2007).

Although salinity, subsurface temperature, and ocean circulation data are more limited than SST, they also show evidence for multi-decadal changes. In particular, sea surface salinity (SSS), for which observations extend back till 1895, show multi-decadal variations over the subpolar North Atlantic that slightly lagged the SST variations there (Reverdin, 2010). Hydrographic observations during the last 100 years provide evidence for decadal variations in temperature and salinity that extend over the upper 3000m (Polyakov et al., 2005). The subsurface changes have been related to variations in deep convection over the Labrador Sea, driven by changes in the NAO (Curry et al., 1998; Dickson et al., 1996): Labrador Sea Water (LSW) thickness decreased from the 1930's to the 1970's, then increased until the mid-1990's, and then decreased sharply; these changes lagged the winter NAO by a few years (Fig. 3).

LSW is one of the main water masses of the AMOC return flow. Thus, the observed LSW thickness changes suggest the AMOC may have undergone pronounced multi-decadal changes. It is not possible to confirm the AMOC changes, as direct observations of the AMOC only exist since 2004 at 26.5^{o}N (Cunningham et al., 2007). However, fingerprint techniques, which link observable patterns to AMOC variability, suggest the AMOC underwent multi-decadal changes

(Latif et al., 2004)(Ch. 9). For example, the SST difference between the North and South Atlantic is linked to AMOC driven changes in northward heat transport in models (Latif et al., 2004); it suggests multi-decadal AMOC changes lagged those in the NAO and LSW by around a decade (Fig. 3). In addition, hydrographic data and satellite measurements of sea surface height show that the SPG, Gulf Stream and NAC strengthened from the 1960's to the 1990's, and then weakened, likely related to the NAO changes (Häkkinen and Rhines, 2004). The link to AMOC, however, remains unclear.

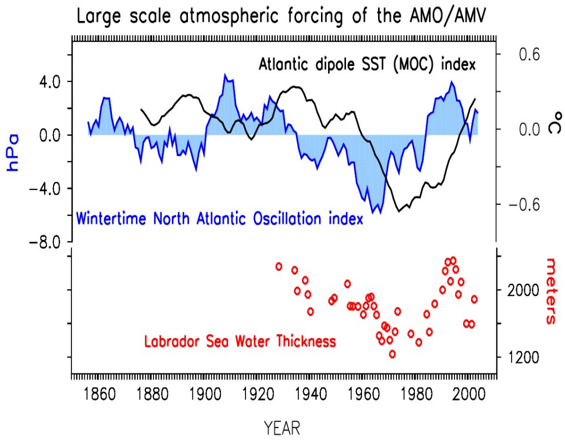

Fig. 3: Time series of winter NAO index (shading blue curve), the Atlantic dipole-SST anomaly index (black curve) and annual data of LSW thickness (red). The dipole index is a measure of the AMOC strength and defined as the difference in SST between the North (40°–60°N, 50°–10°W) and South (40°–60°S, 50°W–0°) Atlantic. The NAO and dipole indices are smoothed with an 11-year running mean. Multi-decadal changes of AMOC as indicated by the dipole index lag those of the NAO by about one decade. Figure from Latif and Keenlyside (2011).

3. What drove the observed AMV?

On short (interannual) timescales extra-tropical SST variations result primarily from anomalous turbulent heat flux, particularly in winter (Cayan, 1992). Extra-tropical atmospheric variability, including the NAO, is often considered as a stochastic, white noise process (i.e., spectral amplitude is frequency independent) (Wunsch, 1999). The direct thermodynamic response of the ocean mixed-layer to such variability describes a red noise AR-1 process – the simplest stochastic climate model in the Hasselmann (1976) paradigm. AMV, however, is not consistent with an AR-1 process (Sec. 2) and thus not with this simplest model (Sec. 5).

There is evidence that the observed AMV was driven by the multi-decadal variations in the winter NAO. On these timescales the two phenomena tended to vary out of phase with each other (Fig. 2a). The turbulent fluxes associated with the negative (positive) NAO drive a tripolar SST pattern: warming (cooling) over higher latitudes and in the tropics, and cooling (warming) around the Gulf Stream and NAC (Visbeck et al., 2003). Thus, the direct thermodynamic forcing associated with the NAO may explain changes in the high latitudes and sub-tropics (Fig. 1b). It cannot explain the temperature changes in the Gulf Stream and NAC (Bjerknes, 1964; Gulev et al., 2013; Kushnir, 1994), suggesting a role for ocean dynamics there.

Observations are presently insufficient to assess the upper ocean heat budget on these timescales. Forced ocean model experiments, however, indicate that ocean circulation changes, associated with the AMOC and SPG, drove the recent decadal changes in upper ocean heat content over the SPG (Robson et al., 2012; Yeager et al., 2012). The winter NAO variations were shown to play a dominant role in the ocean circulation changes, which in turn were related to ocean deep convection and LSW formation with a few years lag (Böning et al., 2006; Eden and Willebrand, 2001; Hatun et al., 2005). Furthermore, idealized experiments show that the NAO variations can explain the observed AMV, through thermodynamic forcing and advection of heat (Eden and Jung, 2001; Klöwer et al., 2013; Visbeck et al., 1998).

The NAO forced picture, however, has problems explaining several aspects of AMV: Firstly, the coherent tropical SST anomalies are not fully explained in all seasons, and may result from local ocean circulation changes (Wang and Zhang, 2013). Climate models also largely reproduce the pattern, despite simulating little relation between the NAO and AMV (Sec. 4). Secondly, decadal variations in ocean circulation may also be influenced by non-linearity (Lohmann et al., 2009) other large-scale patterns of atmospheric circulation (Langehaug et al., 2012; Msadek and Frankignoul, 2009), and salinity anomalies (Zhang and Vallis, 2006). Thirdly, the origin of the multi-decadal variations in the winter NAO is unclear, and they may be partly forced by SST fluctuations. Lastly, external factors may also be important.

4. AMV in climate models

Due to the lack of instrumental data on these timescales, climate models become a useful tool to investigate AMV. In these models the North Atlantic is also a region of pronounced decadal variability (Boer and Lambert, 2008). Furthermore, this variability can be simulated in the absence of time varying external forcing (i.e., it is a mode of unforced, internal climate variability) and shares many similarities to observations (Delworth et al., 1993; Knight et al., 2005). Here the key features of unforced AMV will be described; Ba et al. (2013b) present a similar but more detailed analysis. Sec. 7 discusses the issue of external forcing.

The analysis here is based on eight climate model preindustrial control simulations from the third coupled model intercomparison project (CMIP3). The simulation lengths vary from 340 to 500 years, and horizontal model resolutions from 2-4 degree (see Ch2, Ba, 2013). We note that caution is required when interpreting the model results as they suffer from large biases, with SST errors of several degrees in the North Atlantic. The AMV index is defined as in Sec. 2, and the AMOC index as the maximum overturning streamfunction at 30°N. In all correlation (regression) analysis we filter the indices with an 11-year running mean. A Student's T-test that accounts for serial correlation is used to assess significance.

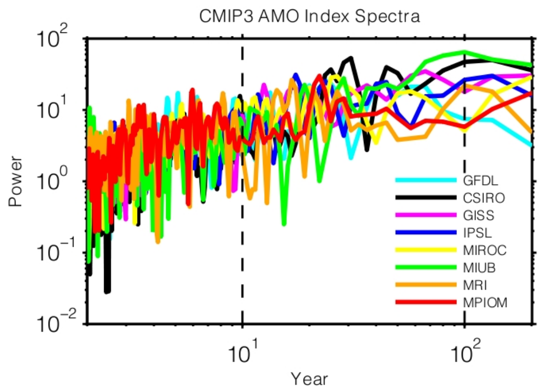

Fig. 4: Spectra of AMV indices in eight CMIP3 CGCMs. Due to the varying autocorrelation for the models, the individual AR-1 red-noise spectra are not shown.

The power spectra of simulated AMV indices in the eight CMIP3 preindustrial control runs show a red noise character (Fig. 4). The models all simulate some multi-decadal variability, but provide little evidence for a preferred 70-80 year periodicity suggested by observations. The spectra are consistent with past studies that have shown many models simulate variability in the North Atlantic on multi-decadal time scales, but with little agreement on preferred time scales (Ba et al., 2013a; Delworth et al., 1993; Jungclaus et al., 2005; Knight et al., 2005).

The AMV SST anomaly patterns from the eight CMIP3 models (Fig. 5) show the largest loadings in mid-latitudes, as observed (Fig. 1b). To varying degrees, all models show a positive relation in the tropical and subtropical North Atlantic and a tendency for weaker values to the west as observed (Fig 1b). The relation with SST north of 60°N differs significantly among models.

As indicated above, AMOC fluctuations are thought to drive AMV. This hypothesis is based mostly on ocean model and CGCM experiments that have shown a close relation between variations in the AMOC and northward oceanic heat transport (Delworth et al., 1993; Knight et al., 2005; Latif et al., 2004). Consistently, the lead-lag relationship between the AMV and AMOC indices in the eight CMIP3 models strongly suggests that the AMOC impacts SST variability on multi-decadal time scales (Fig. 6a). In most models, AMOC variations tend to lead AMV changes by 4-6 years, with correlations above 0.5. Cross-correlation analysis of AMV indices and North Atlantic SST averaged over 0-30°N and over 30-60°N further indicates that the decadal AMOC changes mainly impact SST variability in the mid-latitude North Atlantic (not shown). This is consistent with the larger loadings in mid-latitudes seen in the AMV SST anomaly patterns (Fig. 5).

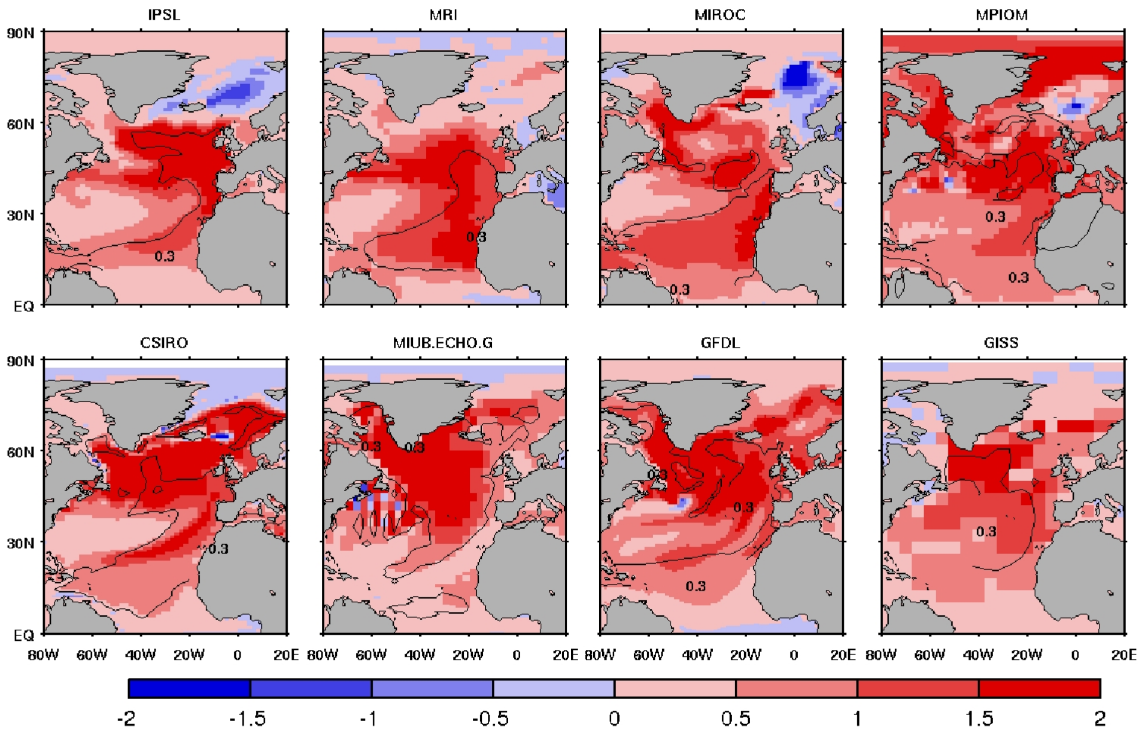

Fig. 5: The regression (shade) of AMV Indices on the SST in 8 CMIP3 models. Explained variance is shown by contours (Contour Interval=0.3).

The power spectra of the AMOC indices have a red character, with all models exhibiting enhanced power on multi-decadal timescales, but with no preferred periodicity (Fig. 6b). Some models show quite strong variability with 20-30 year periodicity (GFDL, CSIRO), some with 40-50 years (MIUB-ECHO-G, ECHAM5/MPIOM, GISS), and others depict even longer-timescale variability (MIROC, MIUB-ECHO-G). For the models with a strong AMOC and AMV relation (e.g., CSIRO, MPIOM, MIUB), the AMV and AMOC spectra show correspondence in the respective decadal band (Fig. 4 & 6b).

A number of studies based on observations and models have argued that the NAO may drive multi-decadal variations in the AMOC (Sec. 2&3). The NAO simulated by the eight CMIP3 models all exhibit spectra consistent with a white noise, stochastic process (Fig. 6c). This is largely in agreement with the observed NAO spectrum, which is weakly red (Wunsch, 1999). The reddening may simply represent a single realisation of a white noise process in the short instrumental record, and/or a weak response to either external forcing or surface variability.

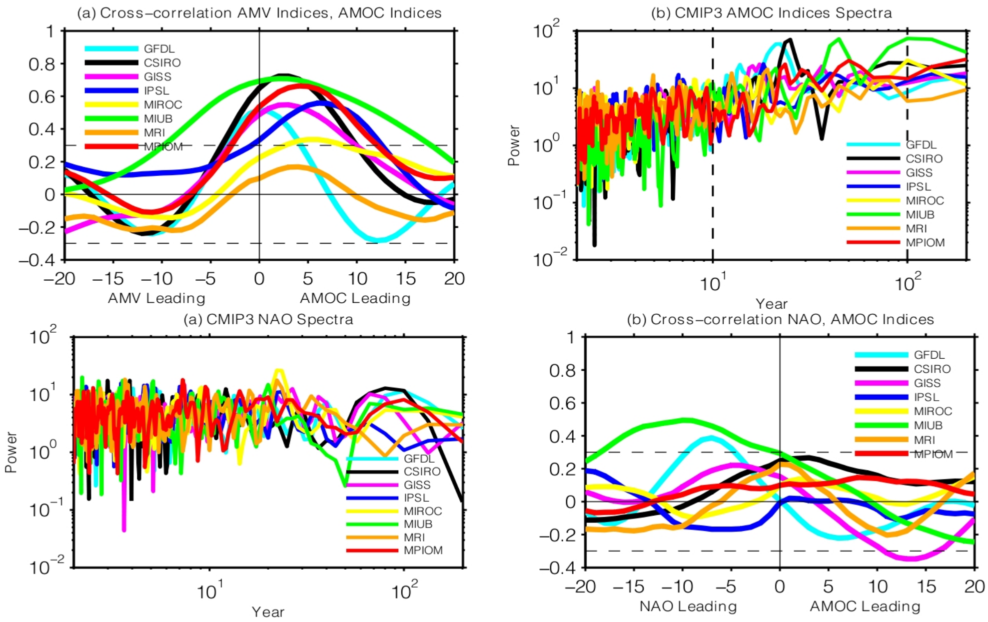

Fig. 6: (a) Cross-correlation among AMV and AMOC indices, power spectra of both (b) AMOC and (c) NAO indices, and (d) cross-correlation among NAO and AMOC indices, as simulated in 8 CMIP3 models. For the correlations an 11-year running mean is applied to the indices, and the 95% confidence level is around 0.3 (dashed line) in each model.

Cross-correlation between decadal variations in NAO and AMOC indices shows little agreement among models (Fig. 8d). There are indications in two models (MIUB, GFDL) that the NAO may drive decadal variations in AMOC, and indications in another model (GISS) that the AMOC may lead to a negative NAO phase 10-15 year later. In contrast, Gastineau and Frankignoul (2012) analyse six CGCMs using more complex statistical methods and show that in five of the models, positive NAO variations precede a stronger AMOC by 2-3 years. However, the explained variances are generally low, similar to the cross-correlation analysis results here. Thus, the climate models seem to provide little support for the hypothesis that NAO variations precede those in the AMOC, by about a decade. This may reflect the importance of other processes, such as other modes of atmospheric variability (Medhaug et al., 2012; Msadek and Frankignoul, 2009). However, it could be also due to model error (Sec. 5&6). In particular, partially coupled model experiments support a strong NAO influence on the AMOC, while the relation is absent in the fully coupled model (Klöwer et al., 2013).

5. Mechanisms for simulated AMV

The stochastic climate model paradigm is a powerful framework for understanding and interpreting climate variability (Hasselmann, 1976). It may explain much of the observed AMV, and provides a null hypothesis for more complex mechanisms, such as coupled ocean-atmosphere dynamics and externally forced variability. Relevant aspects of the paradigm are summarised here; see Latif and Keenlyside (2011) for more discussion.

The paradigm recognises that climate is composed of phenomena with very different timescales. In particular, weather has typical lifetimes of hours to days, while the deep ocean has timescales of many centuries. The paradigm separates these timescales. Weather is considered a fast and chaotic process, and modelled as a stochastic variable that drives the slow, deterministic part of the climate system. The resulting models for the slow variables are collectively known as stochastic climate models.

A hierarchy of such models exists depending on the complexity of the equations used to represent the slow variables. The simplest consists of a slab ocean model for upper-ocean temperature that is forced thermodynamically by stochastic atmospheric variability. The slab ocean integrates the weather noise, which is treated as a white noise process (implicitly including decadal timescales). The resulting SST variations exhibit an AR-1 red spectrum (Hasselmann, 1976). Observed SST variability is consistent with this model over parts of the mid-latitudes, away from coasts, fronts, and other regions where ocean dynamics are important (Frankignoul and Hasselmann, 1977).

As discussed above, while observed and simulated NAO spectra are to first order white, the slab ocean response to such forcing cannot entirely explain the observed AMV pattern. Furthermore, there is evidence that ocean circulation changes drive multi-decadal variations in extra-tropical SST (Sec. 3 & 4). Stochastic climate models that account for mean oceanic advection (Saravanan and McWilliams, 1997) and long baroclinic Rossby waves (Schneider et al., 2002) may explain variations in the North Atlantic on the order of a decade. Model studies have also shown that stochastic atmospheric variability can excite decadal (Weisse et al., 1994), multi-decadal (Delworth and Greatbatch, 2000; Frankcombe et al., 2009), and centennial (Mikolajewicz and Maier-Reimer, 1990) AMOC variability.

To what extent can AMV be described as the oceanic response to stochastic NAO variability? Mecking et al. (2013) address this question by driving an ocean general circulation model (OGCM) with a 2000 year long white noise forcing associated with the NAO (Fig. 10a). The forcing patterns are computed by linearly regressing observed NAO index against ocean model forcing fields. The AMOC at 30°N (Fig. 7b) and SPG (not shown) strength both have enhanced power at low frequencies. However, neither provides evidence for an oscillatory mode of ocean-only variability. Rather, both indices respond linearly to the NAO forcing, as is seen by comparing AMOC and NAO wavelet spectra (Fig. 7a,b). Thus, in this picture the observed AMV may result from a particular realization of stochastic NAO variability.

The variability of the AMOC at 30°N is strongly enhanced on timescales longer than 90 years (Fig. 7b), while that of the SPG on timescales longer than 15 years (not shown). These different response times are linked to the different "memory" of these two indices to past atmospheric forcing. Furthermore, neither index follows the AR-1 spectra of the simplest stochastic climate model; rather the AMOC and SPG spectra are consistent with AR-7 and AR-5 processes, respectively. The simulated AMV SST index exhibits characteristics (Fig. 7c) of both AMOC and SPG variability. On timescales longer than 90 years it shows correspondence to the AMOC at 30°N, while on decadal timescales to the SPG strength. The spectrum of simulated AMV is also not consistent with an AR-1 process. These results show that even though AMV may not be consistent with an AR-1 process, it may still fit the stochastic model paradigm. While the experiments here are limited to the NAO pattern, similar results are likely for other extra-tropical atmospheric circulation patterns.

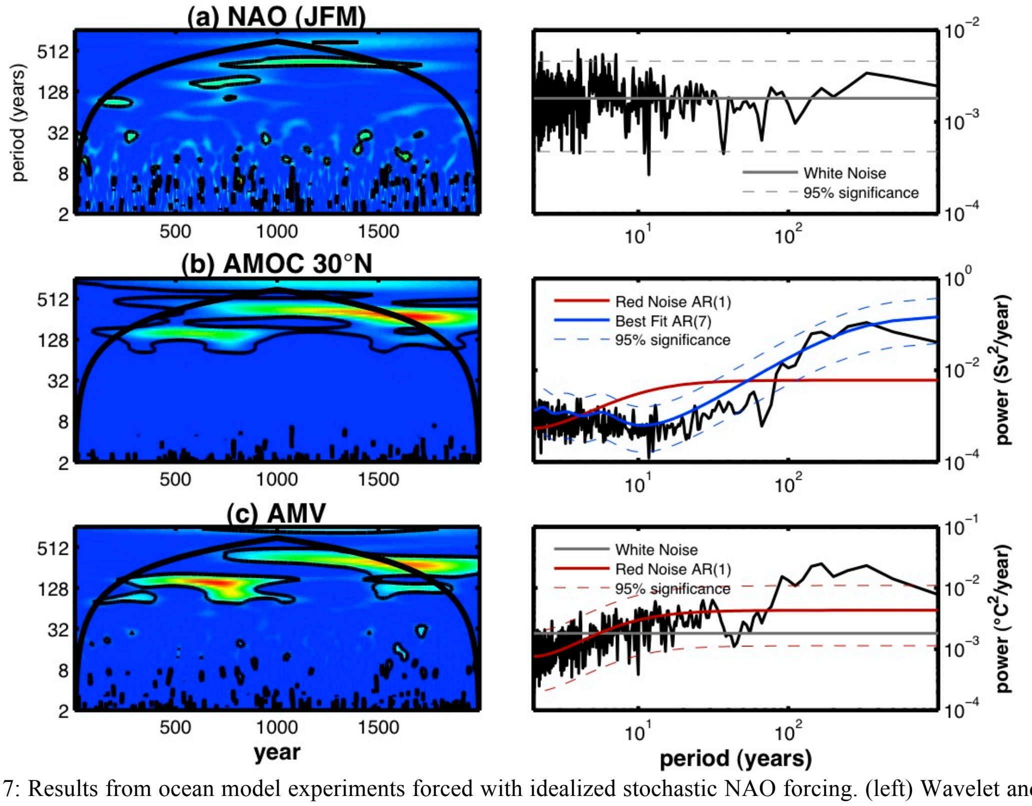

Fig. 7: Results from ocean model experiments forced with idealized stochastic NAO forcing. (left) Wavelet and (right) power spectra of (a) the stochastic NAO index used to drive the model, and simulated (b) AMOC at 30°N, and (c) AMV SST indices. Solid line demarcates the cone of influence on the wavelet spectra, and contour lines regions significant at the 95% level. Confidence intervals for theoretical spectra are shown on right panels.

The response time of the ocean is dictated by the exact set of processes controlling the variability. The inconsistencies seen among CGCMs (Sec. 4) indicate that different processes control variability in these models. Oceanic deep convection, which is often related to deep-water formation, is likely a major source of uncertainty in the mechanisms for AMV. Although atmospheric variability dominates heat loss and drives oceanic deep convection, a cap of surface freshwater anomalies can inhibit wintertime convection (Marshall and Schott, 1999). The relative importance of these processes on longer timescales is not clear, and differs among CGCMs (Ba et al., 2013b); in some models salinity variations are key to AMV (Ba et al., 2013a), while others suggest AMV is purely temperature driven (Dijkstra et al., 2006). Furthermore, the impact of salinity is likely timescale dependent (Deshayes et al., 2013). This sensitivity may arise because temperature and salinity anomalies affect density in opposite ways – salinity increasing density, temperature decreasing it – with temperature controlling their relative importance. In particular, as the freezing point of water is approached, salinity anomalies dominate variations in density. Thus, differences in model mean states and source waters to convection sites may lead to different timescales. Salinity variations arising from the tropics (Vellinga and Wu, 2004), SPG strength changes (Ba et al., 2013a; Delworth et al., 1993), and the high-latitudes (Jungclaus et al., 2005) could all play a role.

The locations of deep-water formation introduce more uncertainty. CGCMs often do not simulate the three sites of observed convection (GIN, Labrador, and Irminger Seas) well in terms of location and strength (Ba et al., 2013b); convection is commonly used as an index of deep water formation. The contribution of the different convection sites to AMOC decadal variability differs among models, some giving greater importance to the Labrador Sea (Delworth et al., 1993), others to the Irminger Sea (Ba et al., 2013a), while the role of GIN Seas is less clear (Medhaug et al., 2012). A related issue is the different contribution of interior and western boundary transport feeding the lower branch of the AMOC (Zhang, 2010). Furthermore, different large-scale patterns of atmospheric variability may excite convection at different sites. While the NAO may be important for Labrador Sea convection (Delworth et al., 1993), the East Atlantic Pattern may be important for Irminger Sea convection (Msadek and Frankignoul, 2009).

Lastly, multiple timescales may exist in a single model, excited by different processes. For example, detailed analysis of the CMIP3 GFDL model simulation (Sec. 4) identifies two timescales: a 20–30-yr periodicity that results from an internal mode of AMOC, and a 50–70-yr periodicity that results from interactions with high-latitudes (Frankcombe et al., 2010). Also as discussed next, coupled ocean-atmosphere interaction (Timmermann et al., 1998; Vellinga and Wu, 2004) and external factors could also contribute to AMV.

6. Decadal prediction and future challenges

There is growing interest in predicting AMV and its climatic impacts. This is part of the greater goal of predicting climate on decadal timescales (Smith et al., 2007), an area of research that features in the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) (Keenlyside and Ba, 2010; Meehl et al., 2013). External forcing and internal dynamics contribute to variability on these timescales, with internal dynamics contributing more at regional scales (Hawkins and Sutton, 2009). Thus, decadal (or near-term) prediction must account for both (Branstator and Teng, 2010).

Extensive experimentation during the last five years indicate that there are two regions where decadal prediction is skillful: the Indian Ocean, where external forcing dominates (Guemas et al., 2012) and the extra-tropical North Atlantic, where internal dynamics dominate and initialization is critical (Keenlyside et al., 2008; Matei et al., 2012; Msadek et al., 2013; Yeager et al., 2012).

Skill in predicting AMV has been shown to be of the order 5-10 years (Doblas-Reyes et al., 2013; Kim et al., 2012), which is short in comparison to the observed periodicity. Detailed analysis shows that skill in predicting extra-tropical North Atlantic SST arises from ocean dynamics (Robson et al., 2012; Yeager et al., 2012). Despite this initial success significant challenges exist. One is the development of techniques to initialize predictions from observations (Meehl et al., 2013). This topic is beyond the scope of this chapter. Instead we cover several issues related to understanding and simulating AMV.

A key issue is the poor representation of the mean climate by CGCMs. In addition to errors in high-latitude processes, models exhibit significant SST and SSS biases in the extra-tropics (Ba et al., 2013b). These are mostly associated with an incorrect Gulf Stream separation and too zonal NAC, both of which may be related to insufficient oceanic resolution (Scaife et al., 2011). The errors in the ocean circulation influence the exchange of water masses between tropical and subtropical gyres, and with the high-latitudes; while errors in SST can impact the atmospheric circulation and variability (Scaife et al., 2011). Poor representation of the mean state can also lead to significant forecast drift (Yeager et al., 2012), which is found in most decadal prediction systems and is of major concern. The method of Klöwer et al. (2013) avoids such a "coupling shock" and could serve as an intermediate approach to decadal AMV forecasting.

Secondly, the view that the extra-tropical ocean only weakly influences the atmosphere (Kushnir et al., 2002) is being challenged. High-resolution observations and models indicate that the sharp SST front associated with the Gulf Stream drives a deep atmospheric circulation (Minobe et al., 2008). However, whether SST variations in this region are of climatic significance remains unclear (Hand et al., 2013). In addition, recent studies show that changes in the stratospheric circulation may drive multi-decadal changes in the winter NAO (Scaife et al., 2005). Atmospheric models show observed warm SST conditions associated with AMV can drive a weakening of the polar vortex in the early winter that propagates back into the troposphere, leading to a negative NAO in late winter as observed (Fig. 8) (Omrani et al., 2013). Atmospheric models that poorly resolve the stratosphere cannot reproduce this link (Hodson et al., 2010; Omrani et al., 2013) (Fig. 8). Thus, the ocean may have driven part of the observed multi-decadal NAO variations. Better resolving the stratosphere improves simulated variability of the extra-tropics (Charlton-Perez et al., 2013), and this in turn may improve simulation (Manzini et al., 2012; Schimanke et al., 2011) and prediction of AMV and its impacts.

A third issue is the role of external forcing. Anthropogenic and natural (volcanic) aerosol loading and solar forcing also showed decadal variations (IPCC, 2007). Statistical analysis (Mann and Emanuel, 2006) and coupled model experiments (Booth et al., 2012) suggest cooling from tropospheric aerosols together with anthropogenic driven global warming can explain AMV during the 20th century. However, aerosol forcing has large uncertainty (IPCC, 2007). Furthermore, while Booth et al. (2012) argue that most climate models underestimate indirect aerosol effects, their simulations fail to reproduce other observed variations, including Atlantic ocean heat content (Zhang et al., 2013). Alternatively, weaker external forcing could synchronize internal dynamics to produce observed AMV (Cheng et al., 2013; Otterå et al., 2010). Thus, while most models indicate AMV is primarily internal in origin (Ting et al., 2009), external factors could have a large contribution.

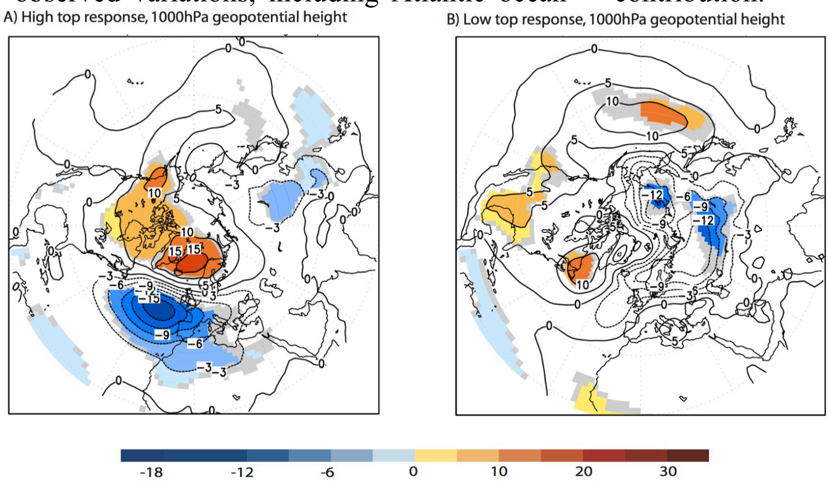

Fig. 8: The winter (JFM) 1000 hPa geopotential height simulated in response to the 1951-1960 warm conditions in the Atlantic with a model (A) including the whole stratosphere (high-top, until ~80km) and (B) the one only partly resolving it (low-top, until ~30km). Values significant at the 90% (95%) level are shaded in grey (colour). Results can be compared to Fig. 2b. Figure from Omrani et al. (2013).

New data is key to advance understanding, and paleo-proxy data provides an alternative to the short instrumental record. Studies based on marine and terrestrial proxy data have shown the existence of AMV beyond the instrumental record (e.g., Gray et al., 2004). However, disagreement exists among records. Thus more data, particularly from the marine environment are required, and methods to combine multiple proxy records should be explored (Svendsen et al., 2013).

7. Summary

Historical data indicate pronounced multi-decadal variations in North Atlantic SST with a 70-80 year periodicity. These basin-wide changes in SST were largest in the subpolar region. They were associated with multi-decadal variations in the atmosphere that extended deep into the stratosphere: the warm (cold) phase of the AMV is associated with a negative (positive) NAO structure in the late winter, and weakening (strengthening) of the stratospheric polar vortex in the early winter. Hydrographic data indicate that the AMV encompassed the upper 3000m of North Atlantic Ocean, with evidence that the NAO drove multi-decadal changes in the formation of LSW and in turn the AMOC. Forced ocean model simulations support these findings, and indicate ocean dynamics drove the observed SST changes in the SPG.

CGCMs simulate AMV in the absence of varying external forcing. Simulated indices of North Atlantic oceanic variability exhibit red spectra, but provide little evidence for a preferred timescale. The simulated SST patterns resemble those observed, and are generally consistent with being driven by variations in the AMOC. There is, however, little evidence from CGCMs of a consistent

NAO and AMOC relationship; and simulated NAO indices exhibit white spectra, similar to observations. Despite this climate models largely reproduce the observed AMV pattern, and thus the role of the NAO in AMV may not be as important as observations may suggest.

The leading hypothesis among CGCMs is that AMV represents the response of the ocean to stochastic atmospheric variability. Idealized ocean model experiments demonstrate the applicability of the stochastic climate model: simulated spectra are consistent with high-order AR processes, indicative of ocean dynamics. In this picture, the observed AMV may result from a particular realization of stochastic atmospheric variability. There is, however, disagreement among CGCMs on the exact mechanisms for the oceanic response to atmospheric variability. Mean state errors, which are particularly large in the North Atlantic, could explain much of this uncertainty and need consideration when interpreting model results. Although controversial, recent results indicate external factors may largely explain AMV.

A key issue raised here is that while the comparatively short observations suggest an anti-phase relation between AMV and NAO indices, no consistent relation exists in CGCMs. This implies that models may underestimate the role of ocean-atmosphere interaction for AMV. Experiments showing stratosphere-troposphere interaction is key to capturing the wintertime atmospheric response to AMV support this notion, but further research is required.

CMIP3 preindustrial control experiments were used here to illustrate performance in simulating AMV. Several recent studies based on the newer generation of CGCMs used for the IPCC AR5 present similar findings: the key aspects of the SST pattern and its relation to the AMOC are reproduced; the associated winter atmospheric circulation is poorly simulated and large uncertainties exist in the role of salinity variations; and in addition simulated variability generally has a timescale less than 70-80 years (Kavvada et al., 2013; Marini and Frankignoul, 2013; Zhang and Wang, 2013). No major improvement was found in simulating AMV in the newer models (Ruiz-Barradas et al., 2013).

Despite our limited understanding, models demonstrate skill in predicting AMV on 5-10 year timescales, and operational prediction systems are being developed (Smith et al., 2012). This is generating a new research area that aims to predict the socio-economic impacts of decadal climate variations.

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