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Decadal climate variability and potential predictability in the Nordic region: a review

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This paper reviews decadal climate variability and predictability and its potential implications for adaptation decisions with emphasis on the Nordic region. In the North Atlantic sector, there is strong decadal to multi-decadal climate variability. The most prominent internal mechanisms explaining the variability are the North Atlantic oscillation (NAO) and the Atlantic meridional overturning circulation (AMOC). These affect also the climate variability in the Nordic region, but their impacts vary depending on local and regional conditions. The published studies also indicate that there appears to be potential for predictability of the decadal climate variations in the North Atlantic sector, mainly due to the AMOC variations. This also contributes to the predictability in the Nordic region, especially in the coastal areas adjacent to North Atlantic. The conclusions are uncertain at the moment, despite the fact that new knowledge is rapidly accumulating. Potential decadal predictability may generally be reduced due to global warming which is the largest over the high latitude oceans. For instance, weakening of the AMOC is generally noted in warmer world simulations. This may have consequences also on climate in the Nordic region, although the response is still uncertain.

Introduction

Adaptation to anthropogenic climate change has a typical time perspective of 10 to 30 years into the future. This is too far considering the current capabilities of weather centres regarding seasonal to inter-annual forecasting. At the same time, it is too close for the long-term climate change projections of climate service centres. An entirely new field of Earth science — decadal climate prediction — is thus emerging to bridge this gap and to provide guidance for planning and decision making.

Worldwide climate records contain plenty of evidence of climate variations at decadal time-scales. Of direct relevance to society, decadal to inter-decadal fluctuations are found in atmospheric circulation patterns, precipitation, and climate extremes (Keenlyside and Ba 2010). One extreme example is the Sahel drought in the 1980s which had profound effects on ecosystems and societies. In fact, the 1980s drought is just the latest one in a sequence of recurring events. It seems plausible that past and future drought events in the Sahel region are linked with the atmosphere–ocean–biosphere coupling at multi-decadal time-scales, driven by the low-frequency ocean fluctuations (Held *et al*. 2005, Zhang and

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Delworth 2006, Shanahan *et al*. 2009). Another example is the inter-decadal variation associated with North Atlantic oscillation such as strong changes in wintertime storminess, and European and North American surface temperature and precipitation (Hurrell *et al*. 2003). European temperature extremes also exhibit multi-decadal variations (Beniston and Stephenson 2004). Consequently, these events could in principle be predicted if the ocean state was known and the coupled Earth system models were initialized with faithful representations of the true Earth system state (Keenlyside *et al*. 2008). This is in sharp contrast to the common practice in long-term climate simulations which are initialized without sophisticated Earth system initial states. In these simulations, decadal scale climate variations appear somewhat realistic but are not in close correspondence with the actual variations.

Extensive resources are currently used to build decadal climate prediction capabilities in U.S., Europe and elsewhere. These aim at using climate observations in the context of Earth system models to explore the limits of predictability, formulated as initial value problems (Meehl *et al*. 2009). The initialization methodologies bear close resemblance to the data assimilation techniques used in numerical weather prediction. These industrial-scale research and development lines are beyond capacities of individual small nations. By clever networking we can however take full advantage of these international efforts, and feedback meaningful contributions in selected areas.

Decadal climate prediction technology is still in its infancy. While worldwide developments are taking place in key areas of predictive capabilities, basic research is needed to assess the level decadal predictability in the Nordic region, and its possible implications for preparation of adaptation decision. This article will review the current knowledge on decadal climate variability and potential predictability. The emphasis will be on how to interpret this knowledge from Nordic region's viewpoint.

Decadal climate variability

Climate variability can be described with anomalies, which are differences between momentary states of the climate system and the longer-term climatology. Climatology is the mean state computed over months, years, decades or centuries (Hurrell and Deser 2009). Climate variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural (volcanic eruptions, solar activity) or anthropogenic external forcing.

Climate variations occur at practically all conceivable time-scales. Oceans play a crucial role in decadal and longer-term climate variability because the effect of the annual cycle and month-to-month variability in the atmospheric circulation decays rapidly with depth (Hurrell and Deser 2009). The mechanisms behind the decadal-to-multi-decadal variability are not well understood, but there is some consensus that the longer-term variability is driven by internal climate variations like the North Atlantic Oscillation (NAO), the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Variability (PDV), the Atlantic Multi-decadal Variability (AMV) and the Atlantic Meridional Overturning Circulation (AMOC).

Decadal climate variability can be studied based on observations and climate model simulations. Since direct observational records are relatively short and sparse, especially over the oceans, modelling studies are often used for studying decadal-scale climate fluctuations.

Observed mechanisms of decadal climate variability

Changes in naturally-occurring patterns of atmospheric and oceanic climate variability affect large-scale variations in weather and climate globally at inter-annual and longer time-scales (Hurrell and Deser 2009). The Atlantic multi-decadal variability (AMV) or oscillation (AMO) is a mode of variability which occurs in the Atlantic Ocean and is mainly manifested as sea surface temperature (SST) anomalies (Fig. 1a). AMO has been linked to changes in Sahel, North American and European precipitation (Sutton and Hodson 2005), Atlantic hurricane activity and northern hemisphere (NH) surface temperature (Zhang *et al*. 2007). AMV has some support in historical

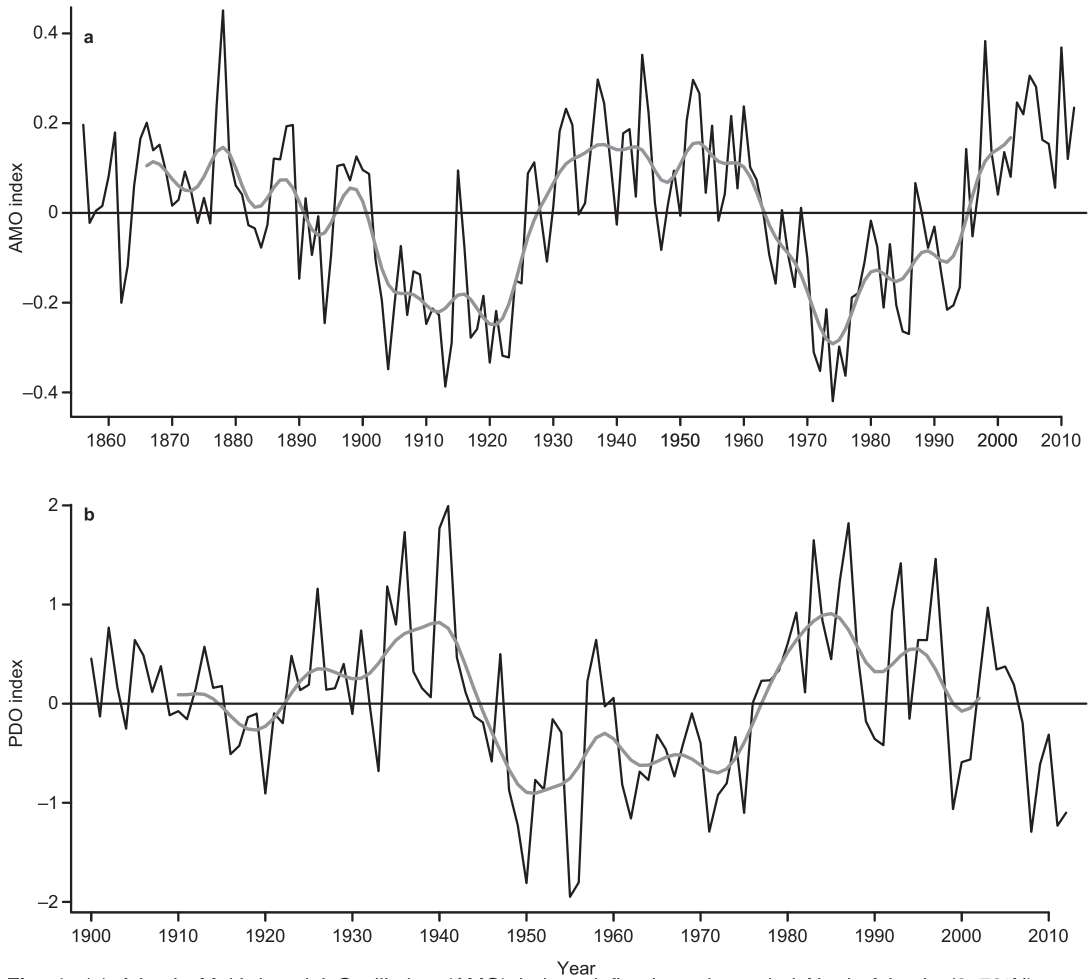

Fig. 1. (**a**) Atlantic Multi-decadal Oscillation (AMO) index, defined as detrended North Atlantic (0–70°N) area weighted average SST anomalies, and (**b**) Pacific Decadal Oscillation (PDO) index, derived as the leading PC of monthly detrended SST anomalies in the North Pacific Ocean, poleward of 20°N. Thin lines indicate annual mean and thick grey lines give smoothed annual values (smoothed with 21-point binomial filter). The AMO index data were obtained from http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data and PDO index data from http://jisao.washington.edu/pdo/PDO.latest.

observations but there is controversy regarding its amplitude and it is estimated to have periods of about 40–70 years (e.g. Kushnir 1994, Delworth and Mann 2000).

The most prominent mechanism associated with AMV is the Atlantic Meridional Overturning Circulation (AMOC). It is a giant conveyor belt that brings warm water northwards into the North Atlantic, releases its heat to the atmosphere, and returns the cooled water to the south (Wood 2008). It consists of a wind-driven part and the thermohaline circulation (THC) (Pohlmann *et al*. 2006). There is evidence that the strength of this circulation can fluctuate naturally over periods of decades and it has the potential to influence North Atlantic and European climate (e.g. Pohlmann *et al*. 2006, Shaffrey and Sutton 2006). Since AMOC can affect the climate at multiple time-scales, there has been increasing interest in understanding the mechanisms behind the AMOC variability.

The North Atlantic Oscillation (NAO) is a leading pattern of weather and climate variability over the northern hemisphere. NAO is measured by an index which is defined as a difference in sea-level pressure between the Azores high and the Iceland low (Hurrell 1995). NAO fluctuates from one phase to other producing large changes in surface air temperature, winds, storminess and precipitation over the Atlantic as well as the surrounding continents (Hurrell and Deser 2009). A positive phase of NAO is associated with anomalous low pressure in the subarctic and high pressure in subtropics with stronger westerly winds and enhanced flow of warm and moist air across the North Atlantic and Europe (Hurrel 1995).

According to Hurrel (1995), NAO exhibits quite strong inter-annual variability, but also some considerable decadal to multi-decadal variability. It has been shown that decadal to multi-decadal variations coherent with those in NAO can be also observed in the ocean (Curry *et al.* 1998), which indicates that there exists some kind of atmosphere–ocean interaction. However, Hurrel and Deser (2009) argued that there is little evidence for NAO to vary at any preferred time-scale: large changes can occur from one winter to the next, as well as from one decade to the next. In some studies decadal to multi-decadal changes in NAO have been linked to SSTs in the tropical Atlantic (Okumura *et al.* 2001) and Indo-Pacific region (e.g. Hoerling *et al.* 2001). Rodwell *et al.* (1999) suggested that NAO variability is mainly dependent on North Atlantic SST.

It is not clear which parts of the World Ocean drive the low frequency variations of NAO. Therefore it is important to take a global view on patterns of climate variability when considering the possible mechanisms of decadal climate variability in the North Atlantic sector. Similar decadal to multi-decadal variability as in the North Atlantic sector is seen in the North Pacific. Pacific Decadal Variability (PDV) or Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability that is manifested as positive or negative SST anomalies in the tropical Pacific and opposite anomalies in the western extra-tropical North and South Pacific. The PDO index is derived from the monthly detrended SST anomalies in the North Pacific (Fig. 1b). PDO has been associated with variations in surface temperature and precipitation in the land areas at the rim of the Pacific, the Pacific marine ecosystem, and the Indian monsoon (Keenlyside and Ba 2010).

It has also been shown by Fraedrich and Müller (1992) and by Merkel and Latif (2002) that there is a significant response of the atmosphere over the North Atlantic to ENSO-related variations in tropical Pacific SST. ENSO is a climate pattern that is related to coupled atmosphere–ocean variations: warming (cooling) of eastern tropical Pacific SST and high (low) surface pressure in the western tropical Pacific (Trenberth *et al.* 2007). ENSO has an average period of five years but since it can influence the global circulation patterns far away from the tropical Pacific through the atmospheric bridge (Liu and Alexander 2007), it is also interesting from decadal climate variation point of view.

Inter-decadal climate variations may partly result from processes that are external to the climate system. These are variations in solar activity, volcanic eruptions and anthropogenically forced changes in greenhouse gas concentrations and aerosols. The amplitude of past variations in solar forcing is much debated but the irradiance variations over the 11-year sunspot cycles are quite well known, as they can be calibrated against satellite measurements since 1979 (Gouirand *et al.* 2007). The climate effects of strong volcanic eruptions can persist for about a decade (Latif and Keenlyside 2011). However, volcanic eruptions cannot be predicted but because of strong effects, they should be considered in decadal predictions. Anthropogenic changes in greenhouse gases and aerosols are an important forcing for climate at longer time-scales and should be taken into account when analysing multi-decadal variability. The role of uncertainties in forcing of anthropogenic emissions is anyhow likely to be relatively small at decadal time-scales (Meehl *et al.* 2009).

There is a controversy on how internal variability and external forcing affect the decadal variability. According to some studies natural decadal to multi-decadal climate variability has a potential to mask or enhance anthropogenic climate change, particularly at a regional level (e.g. Meehl *et al.* 2009, Keenlyside and Ba 2010). On the other hand, unpredictable external forcing through explosive volcanic eruptions and anomalous solar radiation may offset the internal variations (Latif and Keenlyside 2011). The relative roles of internal and external processes in driving decadal and multi-decadal climate variations are not well understood and more precise quantification is needed. In addition, apart from separating the effects of external forcing and internal variability on inter-decadal variability, nonlinear interaction between these mechanisms should also be considered.

Decadal climate variability in modelling studies

Climate models can produce climate variability to some extent and therefore decadal climate variability can also be estimated based on climate model simulations. There are several studies that have investigated the contribution of AMOC to climate variability. For example, Latif *et al*. (2006a) investigated AMOC by analysing relationship between AMOC and SST found in global climate models. The strength of AMOC was defined as the SST difference between North and South Atlantic. Their results indicate that the AMOC variations are driven by the low-frequency variations of NAO through changes in the Labrador Sea convection and lag the corresponding variations of NAO by about a decade. In a more recent study, Ortega *et al*. (2012) analysed the AMOC variability in an unforced present-day control run, two forced runs for the last millennium, and two IPCC scenarios with ECHO-G atmosphere–ocean general circulation model. They suggest that at low frequencies (decadal to multi-decadal time-scales) AMOC is largely controlled by convection activity south of Greenland (Labrador and Irminger Seas) and the influence of NAO on AMOC through convection changes in this area is also identified. These results are in line with the findings in Latif *et al*. (2006a). In addition to Latif *et al*. (2006a) and Ortega *et al*. (2012), several other modelling studies suggest that AMOC may contribute to climate variability at inter-annual and decadal to multi-decadal time-scales (e.g. Delworth *et al*. 1993, Delworth and Mann 2000, Sutton and Hodson 2005). However, some observation-based studies indicate that the NAO–AMO/AMOC relation calls for further research. For example Walter and Graf (2002) identified a non-stationary relation between NAO and AMO: during the negative phase of AMO, North Atlantic SST is strongly correlated with the NAO index, but during the positive phase the correlation is weak. Vukcevic (2011) also showed the complexity of AMO–NAO multi-decadal relationship.

Modelling studies also indicate that external forcing has considerable effect on climate variations at multiple time-scales. For example Bauer *et al*. (2003) estimated the effects of natural and anthropogenic external forcing on climate variability for the past millennium. Their results indicate that the pre-industrial variations in the northern hemisphere (NH) temperature at annual to multi-centennial scales are predominantly caused by solar and volcanic activity. In the industrial period, increasing greenhouse gases and deforestation additionally affect temperature variability. However, Bauer *et al*. (2003) did not take any stand on what is the role of natural internal processes on NH temperature variations.

Ineson *et al*. (2011) investigated solar forcing of winter climate variability in NH. An ocean–atmosphere climate model was driven with ultraviolet variations estimated from satellite observations of solar variability. Their modelling results show that the solar minimum is connected to pressure and surface temperature patterns that resemble the negative phase of NAO and Arctic Oscillation (AO). Ineson *et al*. (2011) suggested that this result could have important implications in decadal prediction of the NAO.

Nonlinear interaction between external forcing and internal variability and its effect on inter-decadal variability is also estimated in modelling studies: e.g., in Dunstone *et al*. (2013) it is shown that decadal variability in tropical storm frequency is well reproduced through aerosol-induced north–south shifts in the Hadley circulation and only after incorporating aerosol effects in the model. In addition, the sensitivity of AMOC to external forcing was investigated by Ortega *et al*. (2012). Their results show that starting from the industrial era, increasing greenhouse gases have a major impact on AMOC weakening. There is also a weak but significant signal of AMOC strengthening because of major volcanic eruptions. This is due to the fact that volcanic eruptions produce colder and saltier surface conditions over the main convection

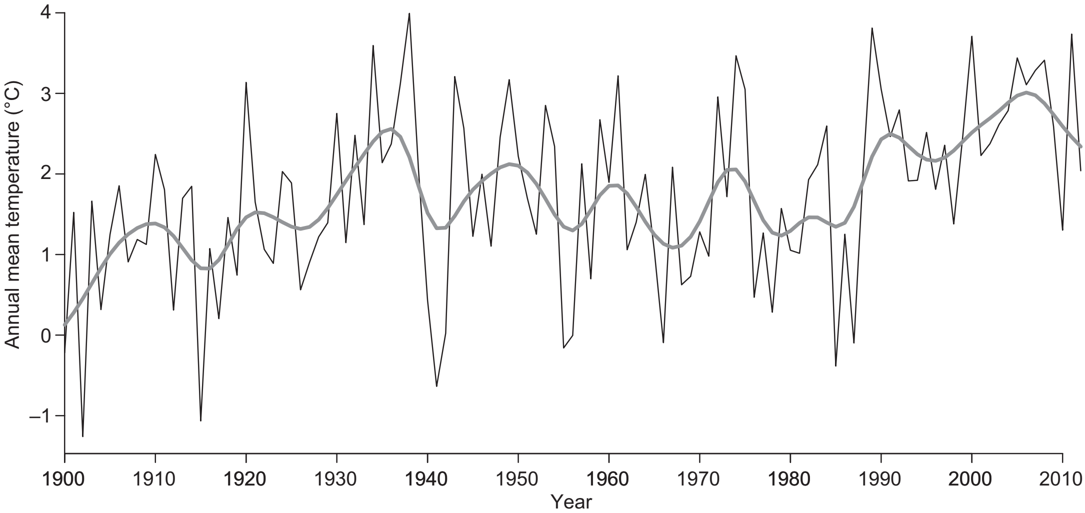

Fig. 2. Annual mean temperature (°C) of Finland 1900–2012 based on spatially interpolated monthly mean temperature records. Black line indicates annual values and grey line gives smoothed annual values (smoothed with 21-point binomial filter). Time series was extended at the end points before filtering to make the filtered time series cover the whole time range. After Tietäväinen *et al.* (2010).

regions driving AMOC. The impact of solar forcing on AMOC is deemed small.

Decadal climate variability in the Nordic region

At northern high latitudes, climate is characterized by large inter-annual and inter-decadal variability. For example, Tietäväinen *et al*. (2010) studied the annual and seasonal mean temperature climatology in 1847–2008 in Finland and showed that there is a distinct division into periods of cold and warm years with decadal-scale fluctuations (Fig. 2). Long-term climate variability in the Nordic region can be estimated based on observational data and simulations. However, the observational record is relatively short for estimating decadal-scale variability. According to Gouirand *et al*. (2007) there are few proxy-based temperature reconstructions for Scandinavia available for the entire millennium but they reflect only a fraction of the true climate variations and only for certain parts of the year.

The most prominent internal mechanisms affecting the climate variability in the Nordic region are NAO and AMOC. NAO has a significant influence on wintertime temperatures and precipitation in the Nordic region. Winters with positive the NAO index are associated with warmer than normal surface air temperatures and wetter than normal conditions over northern Europe (e.g. Hurrell and van Loon 1997, Serreze *et al*. 1997, Alexandersson *et al*. 1998, Visbeck *et al*. 2003). However, impacts of atmospheric circulation pattern depend crucially on local or regional details (Hurrell and Deser 2009) and according to Blenckner *et al*. (2004) it appears as if the influence of NAO on the local climate is less pronounced north of 65°N.

Modelling studies show that AMOC fluctuations have also the potential to influence the climate in the Nordic region. Persechino *et al*. (2013) studied the regional impact of AMOC variability at the decadal time-scale with the IPSL-CM5A-LR model. Their study results show that the AMOC impact on surface temperature at the decadal time-scale is dominant over the North Atlantic. Impact is much weaker over land but some marine influenced regions of western Europe show weak signal including parts of Scandinavia. The signal of the impact of AMOC variability on precipitation at the decadal time-scale largely resembles the corresponding signal of surface temperature. As for temperature, the impact over land can be seen in areas close to the ocean.

For the Nordic region, the study indicates that in the case of strong AMOC there might be drier in Norway and wetter in northern Finland. An earlier study by Pohlmann *et al*. (2006) investigated the influence of AMOC on European surface air temperature (SAT) by calculating the probability density functions (PDFs) of European SAT for strong and weak overturning conditions and using Atmosphere–Ocean General Circulation Model (AOGCM) ECHAM5/MPI-OM. In the case of weak AMOC conditions, SAT averaged over Europe is colder than in the case of strong AMOC conditions, and vice versa. The difference of mean SAT between years with strong and weak AMOC conditions increases from southern to northern Europe. According to Pohlmann *et al*. (2006) the difference of the mean precipitation between strong and weak AMOC displays also an enhancement over northern Europe.

In addition to internal variability, the external mechanisms, such as changes in radiative forcing caused by variations in greenhouse gases, solar irradiation and volcanic aerosols can affect the climate in the Nordic region. According to simulations of Gouirand *et al*. (2007), decadal and multi-decadal deviations from the centennial cooling–warming pattern in Scandinavia are the result of different causes. Some cold intervals can be explained with temporary decreases in solar radiation and sequences with strong volcanic eruption events. Negative phase in NAO can also explain especially low winter temperatures through a weakened westerly flow, but also cold summer temperature because of the large heat capacity of the nearby ocean.

Decadal potential predictability

Decadal predictability has been estimated based mainly on modelling studies. Most of the predictability studies are concentrated at the global scale and decadal predictability is found predominately over the mid- to high-latitude oceans (e.g. Boer 2004, Pohlmann *et al*. 2004, Boer and Lambert 2008). In addition to North Atlantic, the Southern Ocean has been identified to be the most prominent region in decadal predictability studies (e.g. Boer and Lambert 2008, Koenigk *et al*. 2011). Climate model studies indicate that in these regions the potential predictability of decadal variations is due to variations in the ocean circulation and heat storage (Pohlmann *et al*. 2004). Several studies agree with the idea that predictability at decadal time-scales resides in the ocean, where information can be stored and later transferred to the atmosphere (Latif *et al*. 2006a). According to Boer (2010) internal and externally forced variability are both important sources of potential predictability in global-scale projections. However, at regional level, relative importance of these factors varies substantially.

Methods for measuring decadal predictability

In the literature usually two types of predictability studies are described: potential and classical. Decadal potential predictability can be defined as the ratio of the variance at decadal time-scales to the total variance (Latif *et al*. 2009).

Potential or diagnostic predictability studies (e.g. Boer 2004, Boer and Lambert 2008, Boer 2010, Persechino *et al*. 2013) try to quantify the fraction of long-term variability from the internally generated natural variability, which is not predictable at long time-scales and considered noise. The long-term variability signal that may be distinguished from this noise is thought to arise from potentially predictable processes in the physical system (Latif and Keenlyside 2011).

In classical or prognostic predictability studies (e.g. Pohlmann *et al*. 2004, Koenigk *et al*. 2011, Branstator *et al*. 2012, Persechino *et al*. 2013) ensemble experiments are performed with a single coupled model by perturbing the initial conditions. Predictability of a variable is given by the ratio of the actual signal variance to the ensemble variance. This method assumes a perfect model and often near-perfect initial conditions that usually gives an upper limit of predictability (Latif and Keenlyside 2011).

A method called 'ocean dynamics approach' (Park and Latif 2005) has also been used. This method compares the variability simulated with and without the ocean–sea ice dynamics and identifies those regions in which ocean dynamics are important in generating the decadal-scale variability. Those regions are believed to be the regions of high decadal predictability potential.

Persechino *et al*. (2013) studied decadal predictability of AMOC with the IPSL-CM5A-LR model using both diagnostic and prognostic potential predictability measures. Their results showed that both diagnostic and prognostic approaches generally brought out the same main features concerning both temperature and precipitation predictability. According to Latif *et al*. (2006b), all the three methods (diagnostic, prognostic and ocean dynamics approach) yield similar patterns of decadal predictability.

Decadal potential predictability in the North Atlantic and Nordic Region

Decadal predictability studies done so far were mostly concentrated at the global scale. The aim was to point out the areas that have most potential for decadal predictions. Decadal predictability studies concentrated especially on the Nordic region were not found during this review study, but there are several studies that present regional information on predictability over ocean and land areas in the North Atlantic sector (e.g. Collins *et al*. 2006, Boer 2009, Boer 2010, Hermanson and Sutton 2010, Koenigk *et al*. 2011, Persechino *et al*. 2013). A summary of the studies is presented in Table 1, with emphasis on the Nordic region.

Potential of decadal predictability appears to be quite large in the North Atlantic sector. The most prominent mechanism driving some of the decadal-scale variability seems to be AMOC which is a focus of many recent predictability studies (e.g. Msadek *et al*. 2010, Ortega *et al*. 2011, Tulloch and Marshall 2012, Persechino *et al*. 2013). Early analysis of Delworth *et al*. (1993) showed that there is a broad resemblance between simulated and observed multi-decadal SST variability patterns in the North Atlantic and that is usually associated with AMOC. Based on these results variability of AMOC may be predictable at decadal or longer time-scales. A multi-model-ensemble study of Collins *et al*. (2006) indicated potential predictability of inter-annual–decadal AMOC variations for one to two decades into the future. Persechino *et al*. (2013) showed that modelled AMOC has an average predictive skill of eight years. Studies of Collins and Sinha (2003), Sutton and Hodson (2005) and Pohlmann *et al*. (2006) showed that multi-decadal AMOC predictability in the HadCM3 and ECHAM5/MPI-OM models leads to some predictability of European climate. More recently Ortega *et al*. (2011) studied the processes that influence predictability of decadal variability in AMOC with the ECHO-G coupled climate model. They identified two predictors of AMOC variability: the anomalous heat flux averaged over a region in the Eastern Labrador Sea and an anomalous ocean density in a region of the Western Irminger Sea. These predictors together account for over 80% of the inter-annual variance of AMOC (Ortega *et al*. 2011). Thus, most state-of-the-art climate models seem to indicate that AMOC variations are predictable at decadal scales although there are still major uncertainties regarding the level and extent of predictability of different oceanic and atmospheric variables (Latif *et al*. 2006b).

Boer (2010) estimated the potential predictability of temperature and precipitation and its forced and internal components for the first part of the 21st century based on simulation data from a collection of coupled climate model results in the CMIP3 data archive. He used two measures of potential predictability. First, the multi-decadal view considered the forced component to be the difference from the beginning of the century. Second, the next-decade view considered the change in the forced component from the previous decade, thus putting emphasis on the change from the present rather than from an earlier period. Results of Boer (2010) show that in case of temperature, the forced component of potential predictability is generally largest over tropical oceans and declines with latitude being relatively low over mid- to high-latitude land. In contrast, internally-generated decadal potential predictability for temperature is largest over mid- to high-latitude oceans. It seems that internally-generated decadal potential predictability in the Nordic region is quite weak (2%–10%), but it is still slightly higher as compared with that for other land areas (2%–5%) (Table 1). However, it should be kept in mind that over land, the long time-scale internally-generated variability in temperature (the "signal") is masked by the rela-

Table 1. Summary of decadal predictability studies and implications for the Nordic region. The notation: ppvf stands for potential predictability variance fraction.

Study	Aim of the study	Model/Data	Method	Results in the Nordic region
Boer 2009	Internally generated variability of the unforced climate was compared with simulations with the B1 and A1B climate change scenarios	Multimodel simulation data from the CMIP3 archive	Diagnostic	Temperature: decadal potential predictability 0%–10% (unforced preindustrial control simulation) Precipitation: no predictability
Boer 2010	Potential predictability of temperature and precipitation and its forced and internal components were estimated for the first part of the 21st century	Multimodel simulation data from the CMIP3 archive, SRES B1 scenario	Diagnostic	Temperature: internally generated potential predictability 2%–10% (ppvf), forced ppvfs comparatively small in middle to high latitude areas Precipitation: internally generated and forced potential predictability very weak
Hermanson and Sutton 2010	The predictability of ocean and climate variables were investigated using a perfect model-based case study approach	Model: HadCM3	Prognostic	No significant longer time-scale predictability for temperature or precipitation
Koenigk *et al.* 2011	Study analyzed the upper limit of climate predictability on decadal time scales and its dependency on sea ice albedo parameterization	Model: EC-Earth, two perfect ensemble experiments	Prognostic	Temperature: significant prognostic potential predictability 0.5–0.8 (on a scale from 0 to 1) over Nordic region, close to high predictability over the sea Precipitation: no clear signal for predictability
Persechino *et al.* 2012	The decadal potential predictability of the AMOC and the predictability of associated oceanic and atmospheric fields were explored	Model: IPSL-CM5A-LR	Diagnostic/ prognostic	Temperature: internally generated decadal potential predictability 10%–20% in the coastal areas close to North Atlantic and 5%–10% elsewhere Precipitation: potential decadal predictability weak

tively strong short time-scale climate variability (the "noise"). Decadal potential predictability for precipitation for the unforced control climate is very weak. There is some, although relatively small potential predictability for precipitation due to the forced component mainly at middle to high latitude land areas (Boer 2010).

In line with previous studies, Persechino *et al*. (2013) found that potential predictability of surface temperature over land is less significant than over the ocean. Predictability over the coastal areas is found to be close to that of some of the potentially predictable oceanic regions and it is linked with AMOC fluctuations. In the Nordic region, internally-generated decadal potential predictability of surface temperature is 10%–20% in the coastal areas close to North Atlantic, and 5%–10% elsewhere (Table 1). These results are somewhat more positive than those of Boer (2010). Potential decadal predictability of precipitation is clearly smaller than for surface temperature and link to decadal AMOC fluctuations is less clear. However, the Nordic Seas are the most prominent regions where precipitation seems predictable at decadal time-scales. Persechino *et al*. (2013) also found convincing evidence that extreme changes in AMOC might be potentially predictable up to two decades ahead from the monitoring of its high-latitude Atlantic precursors (Sea Surface Salinity in the Labrador sea and the East Greenland Current (EGC) index). In line with the earlier study of Collins *et al*. (2006), results of Persechino *et al*. (2013) also show that the initial state corresponding to an anomalously strong AMOC is more predictable than those corresponding to weak AMOC.

A study of Koenigk *et al*. (2011) used prognostic methods for analysing the upper limit of climate predictability at decadal time-scales and its dependency on sea ice albedo parameterization with two perfect ensemble experiments with the global coupled climate model EC-Earth. Compared with experiment 1, in experiment 2, the sea-ice albedo was reduced by 0.03. Their results show that AMOC is highly predictable in both experiments and governs most of decadal climate predictability in the northern hemisphere. They found highest potential predictability for 2-m air temperature (T2m) over the northern North Atlantic and the southern South Atlantic. Also sea surface salinity and sea surface temperature show high predictability in these regions. Over most land regions, prognostic potential predictability of T2m is quite small and not significant. However, both experiments show a significant predictability of air temperature over northwestern Europe and most of the high potential predictability areas over land are located close to high predictability over sea (Table 1). In both experiments, precipitation shows largest decadal potential predictability in the northeastern North Atlantic and in the Barents Sea region as well as in the Labrador Sea. Compared with previous studies, results of Koenigk *et al*. (2011) indicate higher decadal predictability over land regions. The authors hypothesize that this might be due to higher resolution in EC-Earth as compared with that in the models used in most of the previous studies.

Hermanson and Sutton (2010) took a perfect model-based case study approach to investigate predictability of ocean and climate variables. They used the Hadley Centre HadCM3 coupled atmosphere–ocean model. Their results indicate that large-scale ocean variables such as volume-integrated ocean heat content, salinity or AMOC generally show significant predictability for several years or more. On the other hand, predictability of surface annual-mean climate variables is generally limited to two years at the most. Their results also indicate that there is no significant longer time-scale predictability for temperature or precipitation in the Nordic region. However, Hermanson and Sutton (2010) admitted that a single climate model of modest resolution they used and a small number of cases is the limitation of their study.

As mentioned before, some studies have identified connections between NAO and AMOC. According to Latif *et al*. (2006b) there is some evidence from observations of the last century and from forced ocean model simulations that the future state of AMOC may be predictable from past low-frequency variations of NAO. However, when considering predictability in the Atlantic sector, a global approach is needed because forcing from the other climate patterns in the tropics and extra tropics should also be considered.

Apart from potential predictability, actual near-term prediction skill is estimated for example in a recent study of Doblas-Reyes *et al.* (2013). Their study illustrates the forecast skill of initialized regional near-term climate predictions conducted as a part of the Fifth Coupled Model Intercomparison Project (CMIP5). The main result is that the climate forecast systems have a substantial skill in predicting multi-annual near-surface temperature anomalies at regional scales and most of the skill is due to changes in atmospheric composition, but also partly due to the initialization of predictions. In more detail, their results show significant skill in the North Atlantic for near-surface temperature predictions up to 6–9 years. In the Nordic region there is also some positive forecast skill but it is not statistically significant. The skill for land precipitation is much lower than for near-surface temperature, but there is some positive, although not statistically significant skill for predictions up to 6–9 years especially in the northern hemisphere and also in the Nordic region.

In summary it can be concluded that a potential for decadal predictability appears to be quite large in the North Atlantic sector and predictability is based on the variations of AMOC. This potential decadal-scale predictability of AMOC might also contribute to predictability in the Nordic region, especially the coastal areas close to North Atlantic, but any definite conclusions cannot be made yet. State-of-the-art climate prediction systems also show a substantial skill in predicting near-surface temperature up to 6–9 years in the North Atlantic. However, it should be kept in mind that the models used, the initial states employed and the measures of predictability differ among studies.

Decadal predictability under global warming

There are some studies that consider decadal climate variability and predictability under global warming (e.g. Parker *et al.* 2007, Boer 2009, Boer 2010). For example Parker *et al.* (2007) reviewed the most prominent modes of climate variability (e.g. PDO, ENSO, NAO, AMO) in the instrumental record and compared these with background signal of global warming. Their results show that regional climate variations result from these natural modes of decadal to inter-decadal variability as well as from anthropogenically-induced climate change in these modes. For example, the increase in NAO during 1965–1995 was partly naturally-induced but simulations also indicate that anthropogenic forcing was affecting the increase (Parker *et al.* 2007). According to Hurrell and Deser (2009) significant part of global warming in recent decades is attributed to decadal changes in two dominant climate patterns, NAO and ENSO. In addition, Corti *et al.* (1999) argued that the spatial pattern of the response to anthropogenic forcing may project principally onto these dominant modes of natural climate variability. Natural decadal to multi-decadal climate variability may also mask anthropogenic climate change (Latif *et al.* 2006b). Distinguishing the roles of natural internal and anthropogenically-forced variability is actually one of the major challenges in assessing decadal predictability and making regional decadal predictions (e.g. Solomon *et al.* 2011).

Boer (2009) compared the internally generated variability of the unforced climate with that of the warmer conditions for simulations with the B1 and A1B climate change scenarios. He investigated the changes in the variability of annual mean temperature and precipitation and in the variability of decadal potential predictability based on the collection of coupled climate model simulations in the Coupled Model Intercomparison Project phase 3 (CMIP3) data archive. According to the results of Boer (2009), global warming may induce a general decrease in decadal potential predictability for temperature and the decrease seems to be largest over the high-latitude oceans. Potential predictability of precipitation also decreases although it is already small in the beginning. In the Nordic region, decadal potential predictability of annual mean temperature is 0%–10% and there is no predictability for precipitation (unforced preindustrial control simulation). In a warmer world (B1 and A1B scenarios) decadal potential predictability of temperature and precipitation does not change or decreases slightly in the Nordic region (Table 1). According to Boer (2009) the overall decrease in decadal potential predictability in future, warmer climate indicates that decadal potential predictability of the internally generated component might decrease. Results of Boer (2009) also show that long-term variability indices (e.g. AMOC, AMO, ENSO and NAO) may change because of global warming.

Weakening of AMOC and associated changes in heat transports are noted as a general result in warmer world simulations. For example, the simulations of Ortega *et al*. (2012), covering the Industrial Era and continuing in the future scenarios, show AMOC decreasing finally up to 40% when compared with the pre-industrial average. This final weakening is associated with a reduced meridional density gradient and with decreased convection in the North Atlantic. Therefore, the anthropogenic climate change may influence especially the Atlantic sector by inducing strong changes in the strength of the AMOC which in turn has direct consequences to North American and European climates (Latif *et al*. 2006b). However, there are still large uncertainties concerning the response of AMOC to global warming.

Decay of ice sheets and associated freshwater flux should also be considered in decadal predictability studies. According to Vizcaíno *et al*. (2010), ice sheets can modify atmospheric conditions via changes in e.g. albedo and orography, and indirectly via changes in ocean circulation. For example, Vizcaíno *et al*. (2010) studied the future evolution of global ice sheets under anthropogenic greenhouse forcing and its impact on the climate system with an Earth system model consisting of a coupled atmosphere–ocean general circulation model, a dynamic vegetation model and an ice sheet model. In their study, the North Atlantic meridional overturning circulation (NAMOC) weakens substantially in just 100 years in all the simulations. Their results show that the freshwater fluxes are dominated by increased precipitation over the ocean and increased river runoff. The freshwater flux from the Greenland ice sheet has a minor role. However, the modification of ocean density by the increased freshwater flux from the Greenland ice sheet seems to play an important role in hindering the recovery of the ocean circulation (Vizcaino *et al*. 2010). The experiments of Koenigk *et al*. (2011) also show that decadal variations are substantially smaller in the simulations with reduced ice albedo, which can be explained by reduced sea-ice thickness in these simulations. Koenig *et al*. (2011) hypothesized that reduced decadal-scale variations in the Arctic sea-ice volume reduces sea surface temperature and salinity variations in the Labrador Sea which in turn reduces the decadal variability of AMOC. This reduces temperature variations in mid- and high-latitude northern hemisphere regions. According to Latif and Keenlyside (2011) virtually all climate models considerably underestimate the observed Arctic sea-ice decline during the recent decades in the so-called 20th century integrations with prescribed (known natural and anthropogenic) observed forcing. This indicates that the simulations of future changes in ice sheets are still uncertain.

Decadal prediction

Seasonal prediction is considered an initial value problem (the evolution of the atmosphere-ocean system is largely determined by the initial condition) unlike centennial projection, which is a boundary value problem (the system evolution depends on the external forcing and formulation of boundary condition) (e.g. Palmer *et al*. 2004, IPCC 2007). Prediction of climate on decadal time-scales is somewhere between seasonal and centennial scales and produces both an initial and boundary value problems (Fig. 3).

In decadal prediction, initialization of climate models offers the potential to make predictions of internal variability in addition to external forcing. One of the major issues is the initialization technique used in predictions. The two main approaches are full-field initialization (in which an estimate of the observed climate state is used to initialize the model), and anomaly initialization (which uses estimates of observed ocean and sea ice anomalies on top of the model climatology) (e.g. Hazeleger *et al*. 2013). A comparison of the two methods shows that full-field initialization provides more skilful predictions at the seasonal time-scale (e.g. Smith *et al*. 2013a) but at the decadal time-scales the two methods show similar prediction skill (e.g. Hazeleger *et al*. 2013, Smith *et al*. 2013a). However, accord-

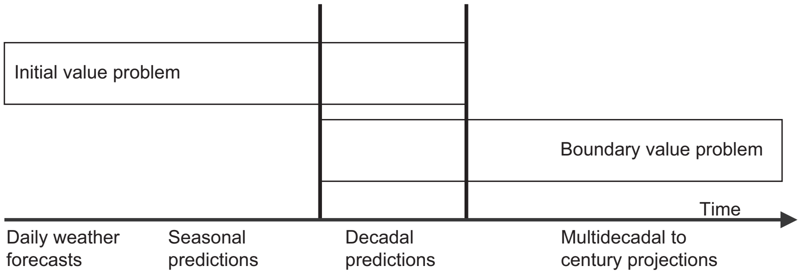

Fig. 3. Illustration of initial value problems with daily weather forecasts at one end, and multi-decadal to century projections as a boundary value problem at the other, with seasonal and decadal predictions in between. Adapted from Meehl *et al.* (2009).

ing to Hazeleger *et al*. (2013), anomaly initialization shows poorer skill in some regions (e.g. North Atlantic).

Initialized predictions should better quantify the uncertainty range in the near future by taking into account internal variability and the mean forced response. However, climate models are not perfect and when initialized with observations, they tend to drift towards their own and biased climatology (Meehl *et al*. 2009). Pioneering studies of Smith *et al*. (2007), Keenlyside *et al*. (2008) and Pohlmann *et al*. (2009) examined the impact of initial conditions on decadal the prediction skill with a coupled GCM. In general, these studies indicate that initialization improves the decadal prediction skill of climate variables. Results of Keenlyside *et al*. (2008) even indicate that initialization leads to a significant enhancement in the skill in the Nordic region. In contrast, Smith *et al*. (2007) does not suggest significant impact of initialization on the prediction skill for annual mean temperature in the Nordic region and results even show that in some regions initialization can lead to a decrease in the skill. Hermanson and Sutton (2010) showed that based on knowledge of initial conditions, climate variables are generally not predictable more than two years ahead, and only rarely predictable more than one year ahead. This discrepancy suggests that an improved skill in initialized predictions and hindcasts may arise from removing biases that exist in uninitialized climate models (e.g. Hermanson and Sutton 2010, Solomon *et al*. 2011).

In a recent study, Matei *et al*. (2012) investigated how two different ocean initializations (GECCO ocean reanalysis and an ensemble of ocean-forced experiments) impact the quality of decadal hindcasts performed with the ECHAM5/MPI-OM coupled model. Results show that initialization considerably increases the predictive skill of SST up to a decade ahead over the North Atlantic, central North Pacific, and the Mediterranean region. They found also a predictive skill of land surface air temperature at a decadal timescale in several land areas including northwestern Europe. Branstator *et al*. (2012) also quantified the initial-value predictability properties of six AOGCMs to help determine the benefit from initializing decadal predictions with the observed state of the climate system. Their results show that with a typical model and typical initial conditions predictability in upper-ocean conditions resulting from initialization lasts for about a decade in the North Atlantic, and somewhat less in the North Pacific. In line with many other studies, their study indicates that resources should be devoted to development of initialization of decadal predictions. On the other hand, it is highly uncertain to quantify the added value of these investments since the modelling results vary substantially (Branstator *et al*. 2012).

There are still many open questions concerning initialization. For example, impact of many processes in decadal predictions is still unsolved (such as sea ice and ocean conditions under the sea ice, snow cover and its modeling, frozen soil, soil moisture, stratospheric processes, land surface and vegetation). Initialization of these factors may have potential to contribute to the predictive skill. It has also been suggested that the skill of decadal prediction may depend on the initial state (e.g. Collins *et al*. 2006, Koenigk *et al*. 2011, Persechino *et al*. 2013). For example, AMOC seems to be more predictable if initialized from anomalously strong *versus* weak phase. Initialization is also substantially hampered by the lack of subsurface ocean observations and imperfect initialisation may lead to degradation of the forecast skill (e.g. Solomon *et al.* 2011). Furthermore, it is not entirely clear which is the best method for initialization.

In decadal prediction it is important to construct ensemble forecasts to sample the possible outcomes consistent with uncertainties in initial states and the model (Meehl *et al.* 2009). Constructing ensembles from different available GCMs has been shown to provide improved estimates of uncertainty as compared with single-model ensembles using only perturbed initial conditions (Hagedorn *et al.* 2005). Stochastic-dynamic parameterization schemes have also been proposed in this context to provide uncertainty estimates in decadal climate predictions (Palmer *et al.* 2009). Stochastic-dynamic methods are based on the fact that the climate system has components with different internal time-scales: fast components are treated as stochastic processes and the slow ones evolve following dynamical equations with stochastic forcing (Hasselmann 1976). There are also some statistical methods (such as lagged correlations, linear inverse modelling, and constructed analogues) that are found to have significant skill in predicting the internal variability of Atlantic SSTs for a decade ahead (Hawkins *et al.* 2011).

There is a broad set of decadal experiments conducted as part of CMIP5 (Coupled Model Intercomparison project) (Table 2). There are two core experiments, 10 and 30 year hindcasts (i.e., a "prediction" of the observed climate history of the recent past), or predictions. Ten-year simulations are initialized at least in every five years starting from 1960 and these experiments are meant for assessing the model skill in forecasting climate change at time-scales when the initial conditions drive the future evolution (Taylor *et al.* 2009). These experiments also try to increase the knowledge on decadal predictability and the best ways to initialize models in decadal predictions. The other core experiments extend the simulations initialized in years 1960, 1980 and 2005 to 30 years. These 30-year simulations explore the predictability and prediction in a longer time-scale when the external forcing from increasing greenhouse gas concentrations should become more important (Taylor *et al.* 2009). In these core experiments, volcanic

Table 2. CMIP5 decadal experiments. Information is mainly based on the ESGF-data portal (pcmdi9.llnl.gov/esgf-web-fe/live) and few other references that are noted as a superscript after the name of each model. The sources are: [1] bcc.cma.gov.cn/bcccsm/web/channel-34.htm, [2] www.cesm.ucar.edu/events/ws.2012/Presentations/CVC1/teng.pdf, [3] pcmdi9.llnl.gov/esgf-web-fe/live, [4] www.cccma.ec.gc.ca/data/cgcm4/CanCM4/index.shtml, and [5] gmao.gsfc.nasa.gov/research/climate/decadal_pred_GEOS-5.

Model	10-year hindcasts/predictions	30-year hindcasts/predictions	Ensemble members	Other experiments	Time frequency
BCC-CSM1.1[1]	initialized in years 1960– 2005 (except years for 30 year runs)	initialized every 5 years 1960–2005	4	Hindcasts without volcanoes (noVolc) initialized 1960, 75, 80, 85, 90 Prediction with 2010 Pinatubo-like eruption (volcIn2010)	3 hr, 6 hr, daily, monthly
CCSM4[2]	initialized 1966, 71, 75, 76, 85, 86, 90, 91, 95, 96, 2000, 01, 02, 03, 04, 05	initialized 1961, 80, 81, 2006	10	–	monthly
CFSv2-2011[3]	initialized 1980, 81, 83, 85, 90, 93, 95, 96, 98, 2000, 03, 05, 06, 09, 10	–	4	–	3 hr, monthly

continued

Table 2. Continued.

Model	10-year hindcasts/predictions	30-year hindcasts/predictions	Ensemble members	Other experiments	Time frequency
CMCC-CM[3]	initialized 1965, 70, 75, 85, 90, 95	initialized 1960, 1980, 2005	3	–	3 hr, 6 hr, daily, monthly
CNRM-CM5[3]	initialized 1964, 65, 69, 70, 74, 75, 84, 85, 89, 90, 94, 95, 99, 2000	initialized 1959, 60,79, 80, 2004, 05	10	volcIn2010	daily, monthly
CanCM4[4]	initialized 1961–2011 (except years for 30 year runs)	initialized 1960, 80, 2005	10	–	6 hr, daily, monthly
EC-EARTH[3]	initialized 1965, 70, 85, 90, 95, 2000, 05	initialized 1960, 80	10	–	3 hr, 6 hr, daily, monthly
FGOALS-g2[3]	initialized 1965, 70, 75, 85, 90, 95, 2000	initialized 1960, 80, 2005	3	–	3 hr, 6 hr, daily, monthly
FGOALS-s2[3]	initialized 1965, 70, 75, 80, 85, 95, 2000	initialized 1960, 90, 2005	3	–	monthly
GEOS-5[5]	initialized 1960–2009 (except years 1981–1984)	–	3	–	monthly
GFDL-CM2.1[3]	initialized 1961–2012	–	10	–	monthly
HadCM3[3]	initialized 1961–2009 (except years for 30 year runs)	initialized 1960, 80, 2005	10	–	daily, monthly
IPSL-CM5A-LR[3]	initialized 1965, 70, 75, 85, 90, 95, 2000	initialized 1960, 80, 2005	6	–	3 hr, 6 hr, daily, monthly, yearly
MIROC4h[3]	initialized 1965, 70, 75, 85, 90, 95, 2000	initialized 1960, 80, 2005	6	–	3 hr, 6 hr, daily, monthly
MIROC5[3]	initialized 1959–2010 (except years for 30 year runs)	initialized 1960, 80, 2005	6	–	3 hr, 6 hr, daily, monthly
MPI-ESM-LR[3]	initialized 1960–2010	–	10	noVolc: 1960, 75, 80, 85, 90 volcIn2010	6 hr, daily, monthly
MPI-ESM-MR[3]	initialized 1960, 65, 70, 75, 80, 85, 90, 95, 2000, 01, 02, 03, 04, 05, 06, 07, 08, 09, 10	–	3	–	6 hr, daily, monthly
MRI-CGCM3[3]	initialized 1965, 70, 75, 85, 90, 95, 2000, 10, 11	initialized 1960, 80, 2005	9	–	3 hr, 6 hr, daily, monthly

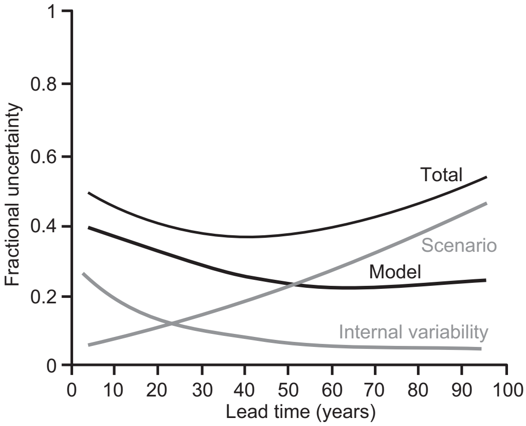

Fig. 4. The relative importance of different sources of uncertainty in decadal global mean surface temperature projections. Fractional uncertainty is the prediction uncertainty divided by the expected mean change of variable relative to 1971–2000. Adapted from Hawkins and Sutton (2009).

aerosol and solar cycle variability is prescribed using actual values for the past and assuming a climatological 11-year solar cycle and no volcanic eruptions in the future (Meehl *et al*. 2009). There are also few additional experiments that are hindcasts without volcanoes and predictions with the 2010 Pinatubo-like eruption.

Many of the forecasting centres that have produced decadal hindcasts for CMIP5 have also made experimental decadal predictions in real-time. There has been international activity to collect the predictions in a multi-model data set and results of these experimental decadal predictions are presented in Smith *et al*. (2013b). Predictions comprise 9 dynamical climate models and 3 empirical techniques. They are initialized in the year 2011 and made for 5-year periods 2012–2016 and 2016–2020. Predictions of AMV and PDV show no signal beyond climatology after the year 2015, but the Niño3 region is predicted to warm 0.5 °C during the coming decade. Results also show that initialized forecasts of globally averaged temperature are significantly cooler than uninitialized projections, consistent with the results of Meehl and Teng (2012). However, the global mean temperature is predicted to continue to rise with a 50% chance of every year after 2013 to exceed the current record. Uncertainties are still large for individual years and in most regions initialization has little impact after 4 years.

Challenges in decadal predictability and predictions

There are still many challenges and unsolved issues in decadal climate predictions and predictability. The uncertainties that are affecting climate projections for the 21st century are also affecting decadal climate predictions and predictability studies. These uncertainties arise from three sources: internal variability, model uncertainty and scenario uncertainty (Fig. 4). According to Hawkins and Sutton (2009), for lead times of the next few decades the main sources of uncertainty are internal variability and model uncertainty. For decadal time-scales and regional spatial scales the model uncertainty is more important. At longer lead times (more than 50 years) the emissions scenario uncertainty generally becomes dominant.

The main challenges have been already summed up in several studies and are now presented here following Meehl *et al*. (2009), Keenlyside and Ba (2010), Latif and Keenlyside (2011), Mehta *et al*. (2011) and Solomon *et al*. (2012):

i. Mechanisms of decadal climate variability are not well understood and the coherence among the climate models is limited. Interaction between natural and externally forced variability and sources of potential predictability should be identified.
ii. There are systematic errors in models that affect predictions and these errors should be identified, understood and corrected. Higher resolution is needed and parameterizations and coupling of additional climate subsystems should be improved.
iii. Lack of observations, especially in the ocean, are limiting forecast verification as well as development and testing of initialization and prediction systems. The instrumental record is short and properly covers only a few full cycles of decadal variability. It is crucial to maintain and enhance the existing observation systems.

iv. Long-lasting effects of solar and volcanic activity should be considered in decadal prediction models although they cannot be predicted.
v. Societal usefulness of decadal climate predictions should be elevated.

Despite all the challenges, some improvements have also occurred during the last decade such as the availability of enhanced ocean observations with the Argo array (www.argo.ucsd.edu). It is a global array of over 3000 free-drifting profiling floats that measure the temperature and salinity of the upper 2000 m of the ocean. This allows continuous *in situ* monitoring of temperature, salinity, and velocity of the upper ocean. It is likely that decadal climate predictions will benefit from the Argo data. On the other hand, the Argo data have only been available for approximately 10 years and it will take time until they can be used for verification of decadal predictions. However, there are already some results showing the benefits of the Argo data: for example in Zhang *et al*. (2007) AMOC is successfully reproduced only when the Argo observations are included in the simulations.

Summary and discussion

Decadal prediction is a new field of Earth science that is trying to bridge the gap between seasonal to inter-annual forecasting and climate change projections. Decadal predictions have a time perspective of 10–30 years into the future, which is a time-scale important for making societal adaptation decisions. This paper has reviewed the level of decadal predictability with emphasis on the Nordic region.

Understanding the mechanisms behind climate variability is important in making decadal predictions and assessing decadal predictability potential. Climate variability may be due to natural internal processes within the climate system, or to variations in natural or anthropogenic external forcing. The relative roles of internal and external processes in driving decadal and multi-decadal climate variations are not well understood and more precise quantification is needed. In addition to observations, modelling studies are often used for studying decadal scale climate fluctuations.

In the North Atlantic, there is strong decadal to multi-decadal variability. The most prominent internal mechanisms associated with this variability are the North Atlantic Oscillation and the Atlantic Meridional Overturning Circulation (AMOC). These internal mechanisms also affect climate variability in the Nordic region: a positive NAO index in winter and strong AMOC conditions are associated with higher surface temperatures and more precipitation than average. However, impacts of atmospheric circulation pattern may depend crucially on the local or regional details.

There is evidence that climate is predictable at decadal time-scales. Internal and externally forced variability are both important sources of potential predictability, but at a regional level, relative importance of these factors varies substantially (Boer 2010). Most of the decadal-predictability studies were carried out at the global scale, but decadal predictability is found predominately over mid- to high-latitude oceans (e.g. Boer and Lambert 2008). Over land predictability is usually low. The studies reviewed in this article indicate that potential of decadal predictability appears to be quite large in the North Atlantic sector and predictability is mainly based on the variations of AMOC. Some studies also indicate that AMOC predictability leads to some predictability of European climate (Collins and Sinha 2003, Sutton and Hodson 2005, Pohlmann *et al*. 2006). This potential decadal-scale predictability of AMOC might also contribute to predictability in the Nordic region, especially the coastal areas close to the North Atlantic (e.g. Koenigk *et al*. 2011, Persechino *et al*. 2013), but any robust conclusions cannot be made based on the current knowledge.

The prediction of climate at decadal time-scales is somewhere between seasonal and centennial scales and presents both an initial and boundary value problem. Initialization of climate models has been suggested to significantly increase the decadal prediction skill over the North Atlantic (e.g. Smith *et al*. 2007, Keenlyside *et al*. 2008). For example, a recent study of Doblas-Reyes *et al*. (2013) shows a significant skill in the North Atlantic for near-surface temperature predictions up to 6–9 years. It has also been suggested that the skill of decadal prediction may depend on the initial state (e.g. Persechino *et al*. 2013) and AMOC seems to be more predictable if initialized from anomalously strong phase rather than from a weak phase. Based on the study results, it is not clear how initialisation affects the prediction skill in the Nordic region and there are still many open questions concerning initialization.

The main challenges associated with decadal predictions and predictability studies are poor understanding of mechanisms of decadal climate variability, systematic errors and need for improvements in models, lack of observations (especially in the ocean) and how to take into account the long-lasting effects of solar and volcanic activities. The societal usefulness of decadal predictions should also be elevated. Interactions between natural internal variability and anthropogenically-induced global warming are also important in assessing decadal predictability and making regional decadal predictions. According to Boer (2009) global warming may induce a general decrease in decadal potential predictability and the decrease seems to be largest over high latitude oceans. For example, weakening of AMOC is noted as a general result in warmer world simulations and this may have consequences also for climate in the Nordic region, although the response is still uncertain. Weakening of AMOC may result from decay of ice sheets and associated fresh-water flux (Vizcaíno *et al*. 2010) as well as reduced variations in sea surface temperature and salinity in Labrador sea (Koenigk *et al*. 2011). Natural decadal to multi-decadal climate variability can also mask anthropogenic climate change (Latif *et al*. 2006b).

Based on the current knowledge, there are still large uncertainties concerning decadal predictability in the Nordic region. However, closeness to the North Atlantic sector, which is the area of high potential decadal predictability, indicates that there might be some potential for making decadal predictions in this region.

Decadal predictions would offer valuable information for the society in making adaptation decisions. For example, the energy sector would benefit of guidance on climate variations in the following decades when making decisions on investments in energy production capacities. Climate conditions will also determine the usage of the carbon-intensive capacity, and therefore the decadal climate predictions are needed to produce the emission predictions from this sector.

As decadal predictability information in the Nordic region does not really exist or it is highly uncertain, there is a need for basic research in this field. For example data mining of the atmospheric data of the past millennium (CMIP5 and the COSMOS millennial-scale ESM simulations) could be conducted to find the predictable decadal climate signals for the Nordic region and to search for factors that are potentially related to predictable events. The topics for further research would also cover for example analysis of decadal climate variability and its relation to boreal biosphere as well as energy production and demand conditions.

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