Prospects for decadal climate prediction

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Prospects for decadal climate prediction

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Keywords

Atlantic multi-decadal variability, Pacific decadal variability, Meridional overturning circulation, Climate models, Climate change

Abstract

During the last decade global surface temperatures did not increase as rapidly as in the preceding decades. Although relatively small compared to the observed centennial scale global warming, it has renewed interest in understanding and even predicting climate on time scales of decades, and sparked a community initiative on near-term prediction that will feature in the fifth intergovernmental panel on climate change (IPCC) assessment report. Decadal prediction, however, is in its infancy, with only a few publications existing. This article has three aims. The first is to make the case for decadal prediction. Decadal fluctuations in global climate similar to that of recent decades were observed during the past century. Associated with large regional changes in precipitation and climate extremes, they are of socio-economic importance. Climate models, which capture some aspects of observed decadal variability, indicate such variations might be partly predictable. The second aim is to describe the major challenges to skilful decadal climate prediction. One is poor understanding of mechanisms of decadal climate variability, with climate models showing little agreement. Sparse observations in the past, particularly in the ocean, are also a limiting factor to

developing and testing of initialization and prediction systems. The third aim is to stress that despite promising initial results, decadal prediction is in a highly experimental stage, and care is needed in interpreting results and utilizing data from such experiments. In the long-term, decadal prediction has the potential to improve models, reduce uncertainties in climate change projections, and be of socio-economic benefit.

Introduction

Although defined as the prevailing weather conditions in a region, climate varies over a wide range of space and time scales. At the global scale, surface temperature increased by almost one degree Celsius during the last century (Fig. 1). The increase is attributed largely to anthropogenic greenhouse gas emissions(1 [Ch 9]). Although these rose monotonically, global surface temperature did not, exhibiting clear interdecadal fluctuations: pronounced warming occurred during 1910-1940 and 1970-2000, and weak cooling from 1940-1970. Decadal-to-interdecadal fluctuations are also prominent in many regions. North Atlantic sea surface temperature (SST), for example, exhibited warming and cooling periods coherent with global surface temperature(2) (Fig. 1). Eastern Tropical Pacific SST also exhibited decadal fluctuations (3)(Fig. 1). These show some correspondence to global changes, but have a shorter timescale and are less prominent compared to interannual variability.

Of direct relevance to society, decadal-to-interdecadal fluctuations are also found in atmospheric circulation patterns, precipitation, and climate extremes. For example, the North Atlantic Oscillation (NAO), a vacillation in sea level pressure between Iceland and the subtropical North Atlantic, underwent pronounced interdecadal variations (4)(Fig. 1). These were associated with strong changes in wintertime storminess, and European and North American surface temperature and precipitation, and thus had major economic impacts (4). Large inter-decadal fluctuations were also seen in summertime Sahel rainfall (5)(Fig. 1), with profound consequence for people living in the region. For example, the drought of the 1970s-80’s caused the death of at least 100,000 people, and displaced many more (6 [Ch 2]). North America too suffered from persistent droughts, the 1930’s ‘dust bowl’ is an example (7). North Atlantic Hurricane activity (8) (Fig. 1) and European temperature extremes (9) also exhibit multi-decadal variations.

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Causes of observed interdecadal climate variations

Climate variations result from process external to the Earths climate system, internal to it, or a combination of both. The first category of variability, often referred to as *externally forced,* covers variations caused by factors considered external to the climate system, such as variations in solar forcing, and anthropogenic changes in greenhouse gas concentrations and aerosol loadings. The seasonal cycle and anthropogenic global warming are familiar examples. The second category, referred to as *internal climate variability,* encompasses variations that arise naturally from interactions within the atmosphere itself and with other components of the climate system, such as the ocean. Weather is a good example, arising from the atmosphere's inherent non-linearity, it can be essentially treated as stochastic on timescales longer than fourteen days, and hence can produce variability on all timescales. Another example is the El Niño phenomenon, arising from ocean-atmosphere interaction in the Tropical Pacific. It has global impacts, and explains much of the interannual variations in global surface temperature. It contributed to 1998 being one of the warmest years on record (Fig. 1).

Although external forcing may have contributed (10-12), observed decadal-to-interdecadal SST variations in the Atlantic and Pacific (Fig. 1) are thought to be largely expressions of internal climate variability (1 [Ch 9], 13), and are termed Atlantic Multidecadal Variability (AMV)(2) and Pacific Decadal Variability (PDV)(3), respectively. The internal nature of both is supported by climate models, which simulate similar decadal-to-interdecadal variability (14, 15) independently of external forcing. Furthermore, paleo-observations indicate AMV(16) and PDV(17) existed prior to the instrumental era. AMV is characterized by basin-wide fluctuations in North Atlantic SST that exhibited a 70-80 year timescale during the instrumental record (Fig. 2). It has been linked to changes in Sahel (5), North American(7) and European(18) precipitation, Atlantic hurricane activity(8), and Northern Hemisphere surface temperature(19). PDV exhibits a v-shaped pattern of SST anomalies in the Tropical Pacific and opposite signed anomalies in the western extra-tropical North and South Pacific (Fig. 2). It is associated with variations in surface temperature and precipitation of Pacific-rim countries, the Pacific marine ecosystem and the Indian Monsoon(15, 20). Many impacts of AMV and PDV can be simulated by atmospheric models forced with observed SST(18, 21), but discrepancies exist among models

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(22). Also, many observed interdecadal changes, particularly in the extra-tropics, cannot be simulated even when accounting for external forcing (23).

How have external and internal variability contributed to observed interdecadal fluctuations in climate? The spatial pattern and temporal evolution of changes in climate can provide insight on this. Detailed observations of global climate are limited during the 20th century; surface temperature arguably provides the best record. The observed patterns of surface warming associated with interdecadal fluctuations in global temperature are far from uniform (Fig. 3): Warming during the period 1910-1940 was most pronounced in the North Atlantic and eastern North Pacific; whereas cooling from 1940-1970 exhibited a similar pattern but with opposite sign; in contrast, warming during the last three decades was most pronounced in the North Atlantic, while the eastern Pacific cooled weakly. The resemblance of these patterns with AMV and PDV suggests that internal variability contributed to observed interdecadal fluctuations in global temperature.

The pattern of surface warming from 1910-2008 (Fig. 3) is distinct to those of the observed interdecadal fluctuations: warming over land is greater than over ocean, where it is relatively homogenous, except for a weak cooling in the North Atlantic and enhanced warming in the Southern Ocean. Note the rate of warming is approximately one third of that of the interdecadal changes. The pattern, however, is not similar to any known modes of internal climate variability (1 [Ch. 9]). Climate model simulations that include changes in known external forcing – natural and anthropogenic – are able to reproduce the global mean warming over this period (Fig. 1). On this timescale, they simulate broad scale warming over ocean and enhanced warming over land and in high-latitudes (Fig. 3), similar to observations (1 [Ch. 9]).

In contrast, climate models driven with only external forcing are not able to reproduce the spatial patterns of interdecadal variations in surface warming (Fig. 3), further indicating that these fluctuations result from internal variability. (Simulated trends for 1910-1940 and 1940-1970 are weak and not shown.) Discrepancies are particularly obvious in the Pacific and North Atlantic (Fig. 1). Errors in representing externally forced variability, particularly aerosols(24), may partly explain this discrepancy. Nevertheless, at the global scale climate model simulations indicate external forcing – particularly solar, greenhouse gases, and aerosol – were important throughout the 20th century (Fig. 1); for more details see Ch. 9, IPCC 2007(1). Hence, although internal variability is prominent on

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interdecadal timescales, externally forced variations are currently likely of equal importance, even on regional scales (Fig. 3).

Prediction of inter-decadal climate variations

Climate prediction has previously considered external and internal factors separately: centennial scale projections(1), which attempt to predict external forced variability by prescribing a scenario for future changes in external forcing – anthropogenic and natural; and seasonal predictions(25), which endeavour to predict internal climate variability by prescribing only the initial climate state. On decadal timescales both factors contribute similarly. External forced variability alone provides some prediction skill on these timescales (26), and approaches to best calibrate forecasts and represent uncertainty have been proposed (27, 28). Skilful decadal climate prediction, however, can be only achieved by also predicting internal climate variability. The latter requires that variability on these timescales is predictable, realistically represented by the prediction model, and can be accurately initialized.

Significant evidence exists that climate is predictable on decadal timescales(29). First, observations and models indicate four regions where internal variability on inter-decadal timescales is predominant, suggestive of underlying and potentially predictable dynamical interactions: North Atlantic, North Pacific, Southern Ocean, and Tropical Pacific. Second, theoretical studies with climate models indicate that decadal variations in the North Atlantic, Southern Ocean and, to lesser extent, North Pacific are predictable due to variations in the ocean circulation and heat storage(30). However, the level of predictability and extension over land vary among models and is low(29).

Differences in predictability among models arise because mechanisms responsible for simulated variability differ. A hierarchy of mechanisms were proposed: in the simplest, decadal fluctuations result from weather's stochastic impact on the ocean, which due to its thermal inertia suppresses high and enhances low frequencies (31); while in the most complex, two-way ocean-atmosphere interaction is essential(29). Identifying which mechanisms are important in reality is difficult as instrumental observations are comparatively short. Uncertainty in mechanisms is a major challenge for decadal prediction. The simulated variability of the Atlantic Meridional Overturning Circulation (AMOC) by climate models highlights the problem (Fig. 4). The AMOC, which transports a significant amount of heat northward from the Tropics, is prominent in most proposed mechanisms for AMV (29), through driving basin wide SST fluctuations (Fig. 2). Models, however, disagree on the nature of

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AMOC variability: in some it appears consistent with the stochastic (red-noise) null hypothesis, suggesting a minor role for ocean-dynamics, while others exhibit distinct variability on decadal-to-interdecadal timescales (Fig. 4). Thus, estimates of AMOC predictability remain highly uncertain.

Predictability on decadal timescales resides in the ocean, where information can be stored and later transferred to the atmosphere. Thus, precise knowledge of the ocean state and suitable data assimilation schemes for initialising models are key to decadal prediction. During the last decade, detailed observations of ocean upper 2 km heat storage and density have become available from the ARGO array of profiling floats (www.argo.ucsd.edu/). Idealised experiments indicate that this data sampling should yield skilful decadal predictions, particularly in the North Atlantic and Southern Ocean(32). Prior to the ARGO period, subsurface ocean data are sparse and some appear to have significant errors(33). Nevertheless, these data may be adequate to initialize upper-ocean heat storage on large spatial scales, but appear insufficient to constrain AMOC fluctuations, either in strength or phase (Fig. 5). This poses a significant problem for retrospective prediction of AMV. Forecast verification is essential to the development of any prediction system, and thus a major challenge to decadal prediction.

Despite these challenges, several recent attempts at decadal prediction show much promise. In these, climate models were initialised from observations, as in seasonal forecasting, and changes (natural and anthropogenic) in radiatively active gases were prescribed following observations (or scenarios), as in climate change experiments. Enhanced skill compared to only external forced simulations was demonstrated in predicting decadal fluctuations in surface temperature, globally averaged(34) and over the North Atlantic(35, 36) and North Pacific(37).

Despite their promise, these initial studies raise several important issues, illustrated here with results from three of them(34-36). First, although following similar strategies, the level of skill and regions where it is enhanced appear to differ among these studies, and only one(34) demonstrated improved predictions for global surface temperature. However, a multi-model mean of only externally forced simulations apparently agrees better with observations (Fig. 6a). Thus, decadal predictions must account for modelling uncertainties. Second, predictions for regions where internal variability is thought to predominate show most gain from initialisation. In particular, for AMV initialized predictions agree better with observations than do only externally forced simulations (Fig. 6b), which indicate a long-term downward trend that is likely associated with the weakening of the AMOC(1). Third, little

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skill enhancement was demonstrated over land and for variables other than surface temperature, nor beyond a decade. Although consistent with theoretical studies(29), this raise questions about the usefulness to society. Also, initialized predictions may not yield reduced uncertainty compared to only externally forced simulations, as inter-model spread appears larger, with future ten-year projections from these systems giving somewhat different outcomes (Fig. 6).

Conclusion

Pronounced interdecadal fluctuations in climate – global and regional – are observed with major socio-economic impacts. While caused by both factors internal and external to the climate system, internal variability appears prominent and has the potential to temporarily mask or enhance anthropogenic climate change on interdecadal timescales. Theoretical modeling studies indicate that such internal climate variations may be anticipated a decade in advance with knowledge of the ocean state(30). Several recent studies show that when accounting for internal variability in addition to external factors, part of this potential predictability may be realizable, globally and regionally (34-37). This has generated much excitement in the climate research community to better understand interdecadal variability and predict it to the extent possible.

Significant challenges, however, remain before decadal climate prediction can be useful to society. The mechanisms of interdecadal climate variability must be better understood and represented in climate models. High-resolution paleo-proxies of climate and improving important physical processes in climate models provide two ways to achieve this. Another challenge is forecast verification and initialization. Limited subsurface ocean data in the past makes retrospective predictions difficult, and novel approaches are needed to test forecast systems, through alternative(36) and better use of limited data, or *twin model* experiments(32). The importance of reducing model systematic error cannot be stressed enough. It causes forecast uncertainty(38) and produces forecast drift, which can mask the predicted signal and lead to poor simulation of impacts. Finally, decadal climate prediction is in a highly experimental stage and model data should be treated accordingly. This includes data from the near-term prediction experiments planned for the next IPCC assessment report. Nevertheless, decadal prediction promises significant socio-economic benefits and the potential to reduce uncertainty in future climate change projections, through separating better internal and external caused climate variability.

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Further Reading

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Figure captions

Figure 1: Observed (blue) indices of climate variability, and the ensemble mean of 21 climate-model simulations (black) that account only for external factors. Shown are global, North Atlantic (0-60N) and Eastern Tropical Pacific (150-90W, 20S-20N) average surface temperature(1, 39); December-February NAO index(40); June-October precipitation averaged over the Sahel (http://jisao.washington.edu/); and June-November accumulated cyclone energy index of Atlantic hurricane activity (http://www.aoml.noaa.gov). Thick (thin) lines show eleven year running (annual/seasonal) means, and grey shading the 90% confidence interval computed from model spread. Model data are from Coupled Model Intercomparison Project-3 (CMIP3) database (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) used for the IPCC fourth assessment report.

Figure 2: Observed decadal variability indices and sea surface temperature (SST) patterns(41). (A) Atlantic multi-decadal variability index, defined as linearly detrended North Atlantic (0-60N) average SST and (B) SST pattern, computed as the composite difference between positive and negative phases (shading in A). (C) Pacific decadal variability index, first EOF of North Pacific (20-60N) SST, and (D) SST pattern (computed as in B). Thick (thin) lines indicate eleven year running (annual) mean.

Figure 3: Interdecadal and centennial surface temperature linear trend patterns, as observed (39) and the ensemble mean of 21 climate-model simulations that account only for external factors(1). Regions with insufficient observations (less than 70%) over the period considered are hashed. CMIP3 data are as in Fig. 1. Note different units used for centennial trends.

Figure 4: Spectra of the maximum Meridional Overturning Circulation (MOC) stream function (at 30N) simulated by four state-of-the-art climate models. The fitted theoretical red-noise (i.e., order one auto-regressive process) spectra are also shown, along with 5 and 95% confidence intervals. All simulations are 500 yrs long and assume preindustrial conditions. Data are from the CMIP3 data base (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) used for the IPCC fourth assessment report(1).

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Figure 5: Maximum Atlantic meridional overturning stream function at 30N from five different data assimilations systems used for initialising decadal predictions. Data are from the EU-ENSEMBLES project (http://www.ensembles-eu.org/).

Figure 6: Retrospectively predicted and forecast ten year mean (top) global surface temperature and (bottom) Atlantic SST dipole indices from three decadal prediction systems(34-36). The dipole index, a proxy for MOC fluctuations, is the north (60-10W, 40-60N) minus south (30W-10E, 10-40S) averaged SST difference. Corresponding 10-year running mean values from (red) observations(39, 41) and (pink) the ensemble mean of 24 climate-model simulations that account only for external factors(1) (90% confidence interval pink shaded). Predictions for Smith et al. (2007) begin in 1982, with one per season and four ensemble members (spread grey shaded); Keenlyside et al. (2008) begin in 1955, with one every five years and three ensemble members (vertical bars); and Pohlmann et al. (2009) begin in 1953, with one per year, and one (seven) member per retrospective (future) predictions. The individual predictions of each system are centered on the corresponding prediction periods (i.e., five years after the initial date), and are joined by a continuous line. Separate vertical bars show future forecasts, centered on the forecast period. Smith et al. (2007), Keenlyside et al. (2008), and Pohlmann et al. (2009) predictions have been adjusted to have the observed means over the 1979-2001, 1955-2005, and 1953-2001 periods, respectively. Figure from Murphy et al. 2009(42).

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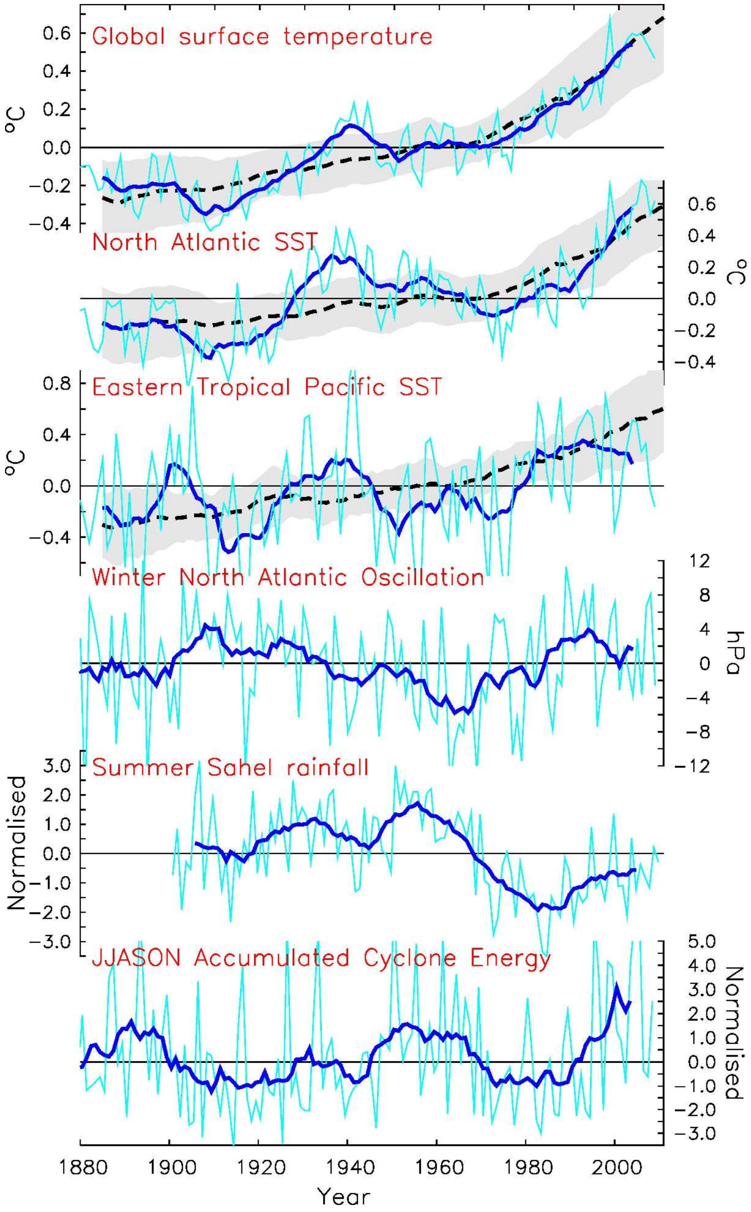

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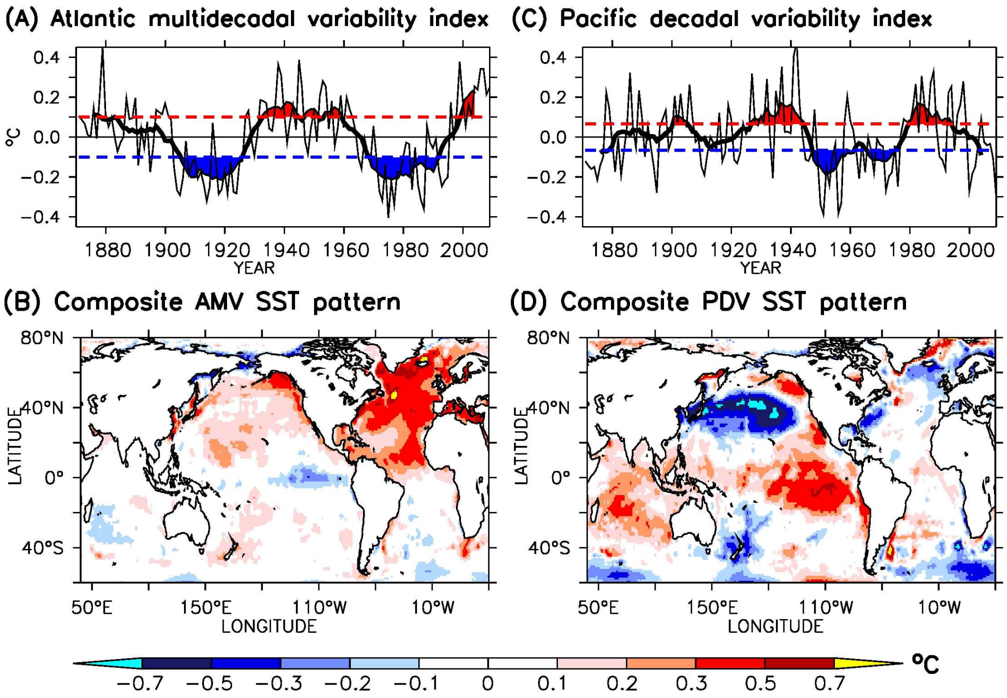

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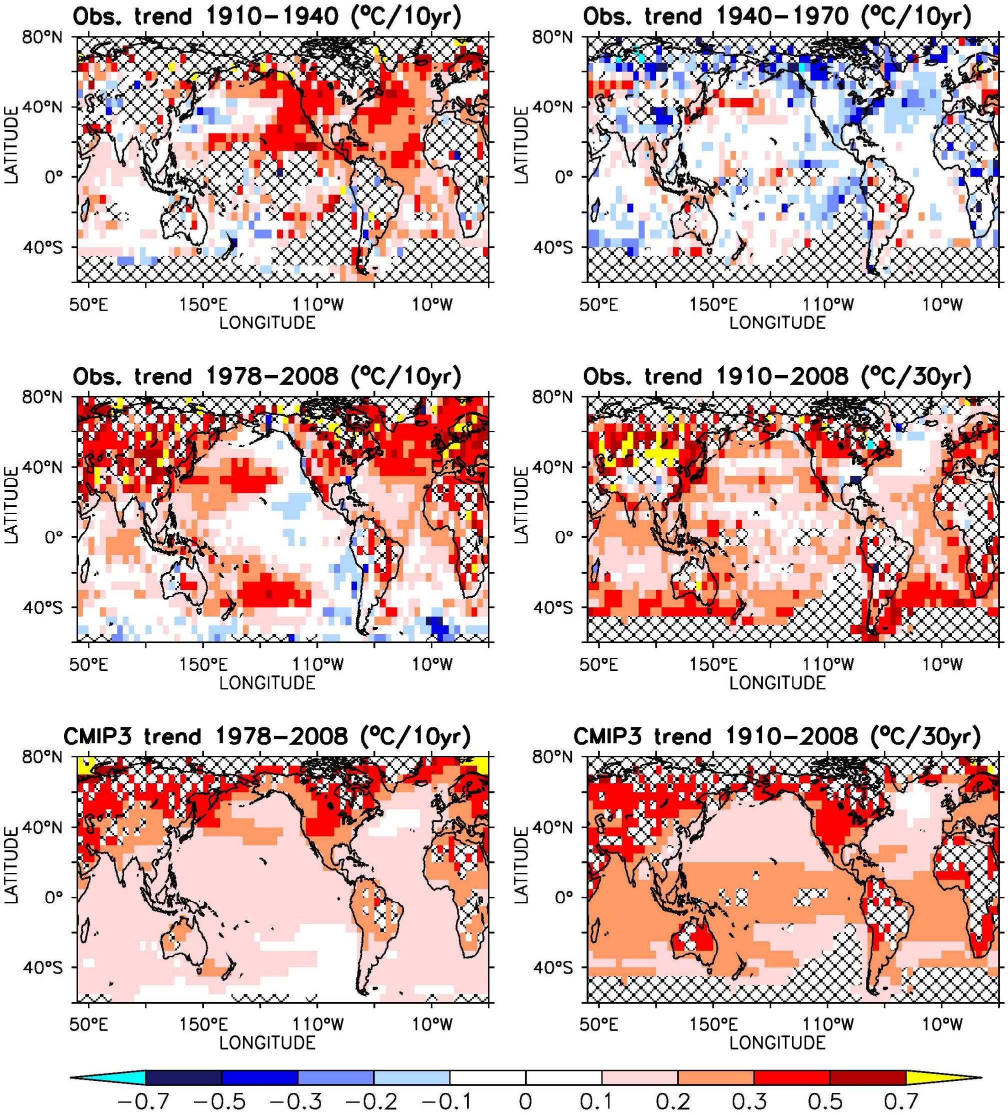

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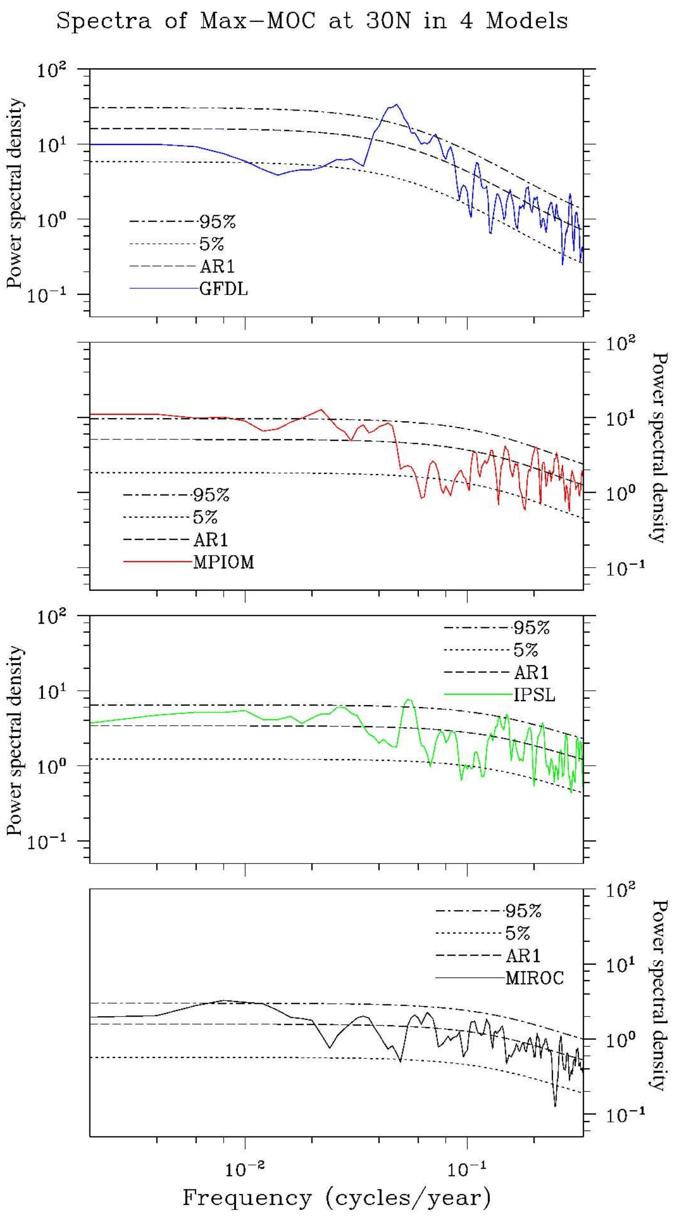

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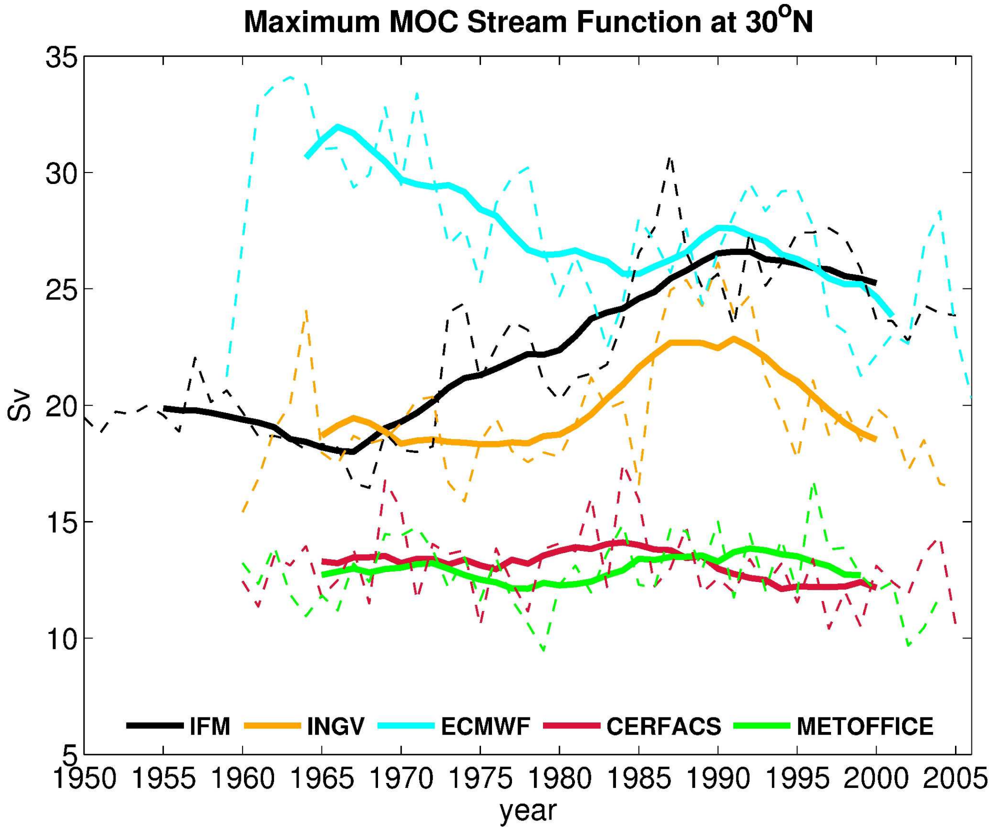

Figure 5: Maximum Atlantic meridional overturning stream function at 30N from five different data assimilations systems used for initialising decadal predictions. Data are from the EU-ENSEMBLES project (http://www.ensembles-eu.org/).
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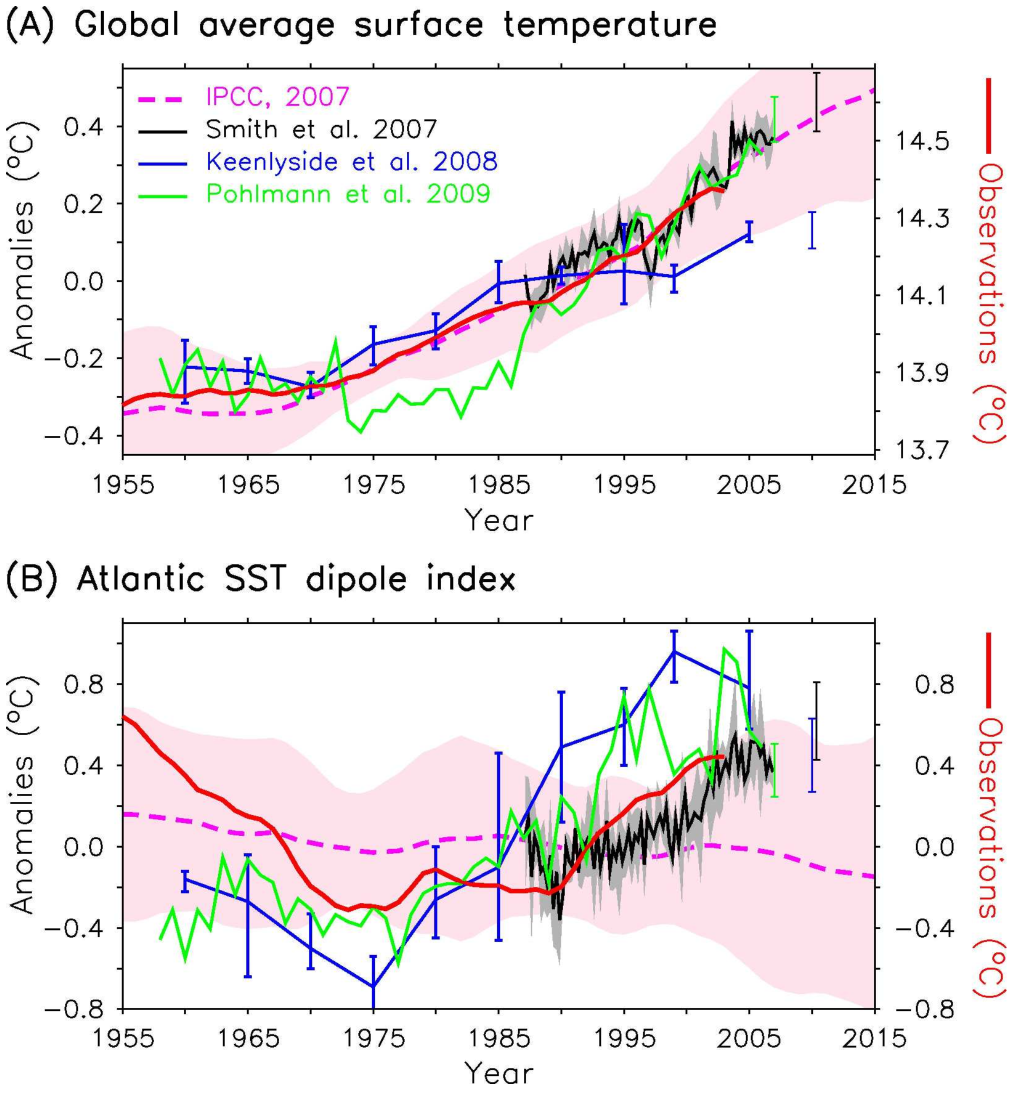

(A) Global average surface temperature

(B) Atlantic SST dipole index

Figure 6: Retrospectively predicted and forecast ten year mean (top) global surface temperature and (bottom) Atlantic SST dipole indices from three decadal prediction systems(34-36). The dipole index, a proxy for MOC fluctuations, is the north (60-10W, 40-60N) minus south (30W-10E, 10-40S) averaged SST difference. Corresponding 10-year running mean values from (red) observations(39, 41) and (pink) the ensemble mean of 24 climate-model simulations that account only for external factors(1) (90% confidence interval pink shaded). Predictions for Smith et al. (2007) begin in 1982, with one per season and four ensemble members (spread grey shaded); Keenlyside et al. (2008) begin in 1955, with one every five years and three ensemble members (vertical bars); and Pohlmann et al. (2009) begin in 1953, with one per year, and one (seven) member per retrospective (future) predictions. The individual predictions of each system are centered on the corresponding prediction periods (i.e., five years after the initial date), and are joined by a continuous line. Separate vertical bars show future forecasts, centered on the forecast period. Smith et al. (2007), Keenlyside et al. (2008), and Pohlmann et al. (2009) predictions have been adjusted to have the observed means over the 1979-2001, 1955-2005, and 1953-2001 periods, respectively. Figur
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