producing diagnostics based on multi-level annular mode indices. To do this, daily, zonal-mean geopotential is required at all model (or pressure) levels. If these zonal-mean geopotential data are available, then diagnostics such as variance of the annular modes, and time scale of the annular modes can be examined and compared to observations. Such analyses are necessary to know if the model's representation of stratosphere-troposphere coupling is realistic.

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Acronyms:

CliC: Climate Cryosphere
CLIVAR: Climate Variability
GEWEX: Global Energy Water Experiment
NWP: Numerical Weather Prediction
WCASP/CLIPS: World Climate Applications and Services Programme /Climate Information and Prediction Services
WCP: World Climate Programme
WCRP: World Climate Research Programme

♦

Decadal predictability: How might the stratosphere be involved?

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How warm, wet, and stormy will the next decade be? This question and how to answer it – decadal climate prediction – is currently generating a large amount of interest in the research community. The interest stems from the growing awareness that climate varies naturally on decadal time scales, both regionally and globally, with large socio-economic consequences, and has the potential to temporarily offset or exacerbate anthropogenic global warming. The aim here is to discuss the current status of decadal prediction and highlight areas where the stratosphere may play an important role.

Natural decadal variability

Where does natural decadal variability occur? What are the mechanisms? Is it predictable? These are important questions in the context of decadal prediction. Only a few key points are discussed here; Latif *et al.,* (2006a) give a recent review of some of these issues.

During the last century, there was an increase in global mean temperature of around 1°C (**Figure 1**). Superimposed on the slow increase, there were also fluctuations on multi-decadal time scales. A good example is the warming early last century, which peaked around 1940. Multi-decadal climate variations are not only seen at a global scale, but occur regionally. For example, the early century warming had a strong expression in the North Atlantic Sector (**Figure 2**), which was associated with Atlantic Multi-decadal Variability (AMV, Delworth and Knutson, 2000). AMV is an internal mode of the climate system involving large-scale air-sea interaction in the Atlantic (Bjerknes, 1964; Kushnir, 1994; Schlesinger and Ramankutty, 1994; Knight *et al.,* 2005). Its impacts include hurricane activity (Figure 2 from Goldenberg *et al.*, 2001), and surface temperature and rainfall variations in Northern Africa (Figure 2 from Folland *et al.,* 2001), and Europe (Sutton and Hodson, 2005). Modelling studies indicate that AMV also influences global mean temperature (Knight *et al.,* 2006; Zhang *et al.,* 2007).

In addition to the North Atlantic, pronounced decadal variability is observed in the North Pacific, the Tropical Pacific and the Southern Ocean. Modelling studies suggest that these four regions have high potential decadal predictability, with the North Atlantic and Southern Ocean showing the highest levels (**Figure 3**, colour plate III). Interestingly, both are regions with a possibly strong stratospheric influence (*e.g*. Thompson and Wallace, 2000). The mechanisms for decadal variability remain largely controversial, due to lack of observations and disagreement among models. Despite this, perfect model predictability studies show that the North Atlantic and Southern Ocean variability is predictable on decadal time scales. The level of predictability and extension over land, however, vary among models.

Although there have been several mechanisms proposed for AMV, the importance of the Atlantic Meridional Overturning Circulation (MOC) is common to most. The MOC transports a significant amount of heat from the equator to the Northern Hemisphere, contributing to the relatively mild climates of Europe and eastern North America. Results from coupled models and

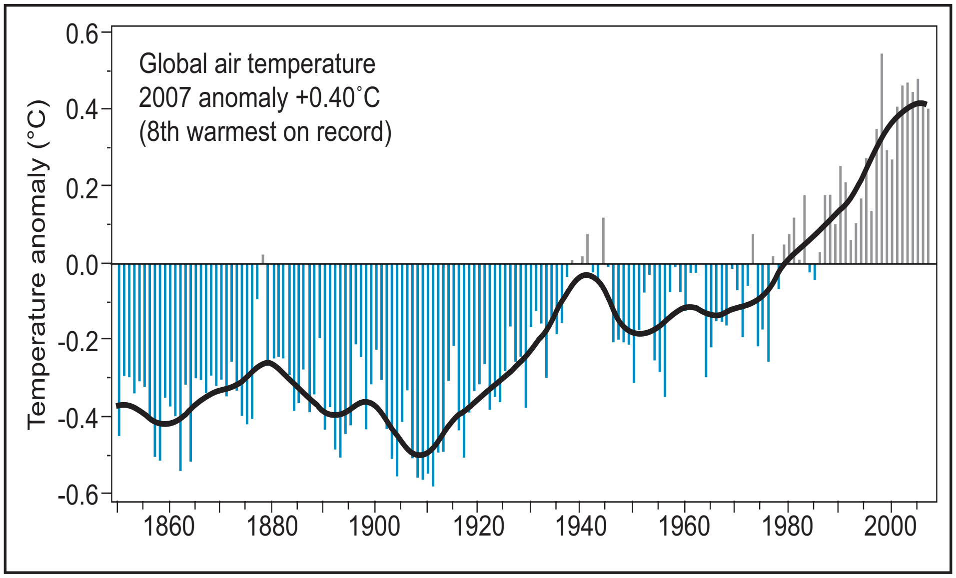

Figure 1: Observed temperature anomalies (Brohan et al., 2006), from the Climate Research Unit, University of East Anglia, UK.

uncoupled ocean models show a close relationship between multi-decadal fluctuations of the MOC and Atlantic sea surface temperature (SST). Although the origin of the multi-decadal fluctuations of the MOC remains controversial, there is evidence that the North Atlantic Oscillation (NAO) plays an important role. Specifically, variations in the NAO drive changes in the Labrador Sea convection, and in this way influence the amount of dense water formed and the strength of the MOC (Eden and Jung, 2001; Latif *et al.,* 2006b). Similarly, variations in the Southern Annular Mode may drive changes in the Southern Ocean circulation (Cai *et al.,* 2005), and possibly the Atlantic MOC (*e.g.* Vallis, 2006).

A joint initial value/boundary value problem

Climate prediction has been mostly considered on two different time scales: seasonal and centennial. Seasonal prediction is primarily an initial value problem, *i.e*. the evolution of the system depends on the initial state (Palmer *et al.,* 2004). Whereas centennial scale prediction is normally considered a boundary value problem, *i.e.* the evolution of climate depends on external changes in radiative forcing, such as anthropogenic changes in atmospheric composition or solar forcing (IPCC, 2007). What class of problem is decadal prediction: initial value or boundary value?

As described above, observations and models indicate that decadal climate variations – global and regional – may arise from internal modes of the climate system and be potentially predictable (*i.e.* an initial value problem). On the other hand, climate predictions indicate a rise in global mean temperature of between 2 and 4°C by 2100, dependant on emission scenario and model (**Figure 4**, colour plate III). This translates to an average rise in global mean temperature of order 0.3°C per decade. This is large compared with observed increase of around 1°C during the last century (Figure 1), and argues that decadal prediction is also a boundary value problem. Twentieth century climate simulations that include both natural and anthropogenic forcing further support this picture, as they reproduce the observed increase in global mean temperature (IPCC, 2007). Consistent with decadal prediction also being an initial value problem, these simulations poorly reproduce the early century warming, with the largest discrepancy over the ocean (Figure 5 from Summary for Policy Makers, IPCC, 2007)). Two other reasons for this discrepancy are the impact of external forcing in the models is too weak and the observed time series is partly erroneous (David Thompson, private communication).

Initial efforts at decadal prediction

There have been two recent efforts at decadal prediction, and both follow a similar strategy: a global climate model is initialised from observations and run forward ten years, at the same time accounting for changes in external forcing (natural and anthropogenic). In the first work (Smith *et al.,* 2007), the Hadley Centre model was initialised using surface and subsurface ocean observations and the ECMWF atmospheric reanalysis. The results showed that global mean temperature could be predicted out to a decade in advance, with more skill than that obtained by only accounting for external radiative forcing (boundary condition) changes (**Figure 5**). This skill enhance-

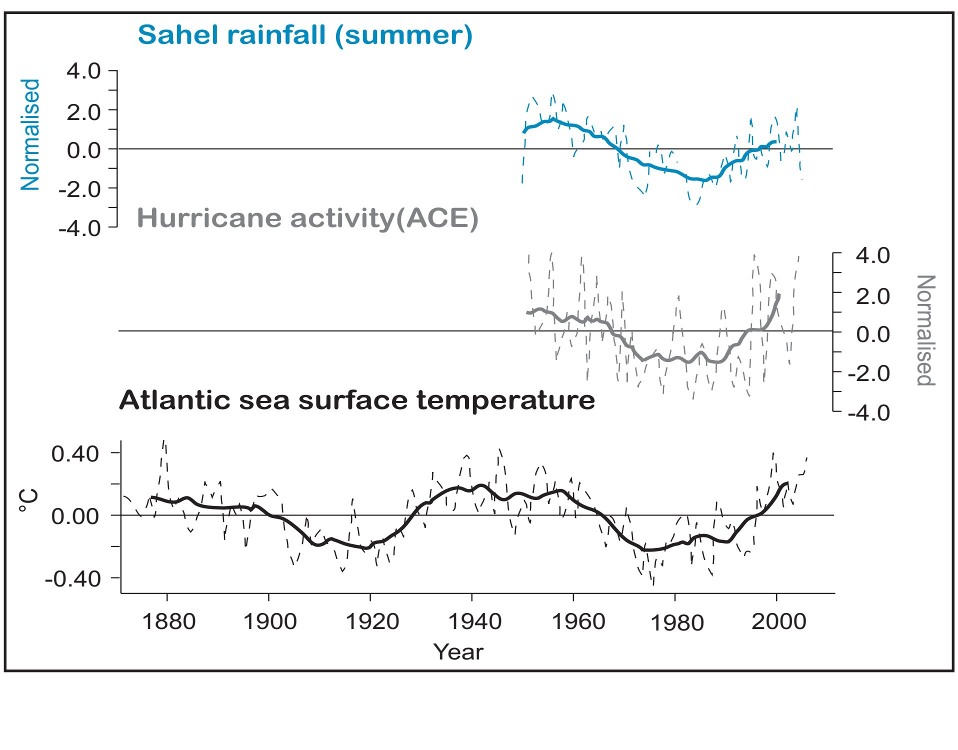

Figure 2: Time series of Atlantic (0-60ºN) averaged seas surface temperature (Rayner et al., 2003), hurricane activity (Accumulated Cyclone Energy (ACE); http://www.aoml.noaa.gov/hrd/tcfaq/E11.html), and June-October averaged Sahel rainfall (http://jisao.washington.edu/data_sets/sahel/). The mean trend is removed from all time series. Eleven year running mean and annual values are shown by solid and dashed lines, respectively.

ment resulted from initialisation of the upper ocean heat content. There was skill enhancement also in particular regions, including the Indian Ocean and parts of the Southern Ocean.

In the second study (Keenlyside *et al.,* 2008), the Max-Planck-Institute for Meteorology climate model was initialised using only SST observations, by simply restoring coupled model SST anomalies towards observations. Although simple, the scheme was able to initialise low frequency variations in the ocean circulation, particularly the Atlantic MOC. This forecast system showed skill in predicting ten year mean surface temperature variations a decade in advance over parts of the North Atlantic Sector, including Europe and North America, and the Tropical Pacific (**Figure 6**, colour plate IV). In these regions, skill was again greater than that obtained from only external radiative (boundary condition) forcing. Ten year averaged global surface temperature variations were also predictable, but with marginally less skill than obtained from radiative forcing only.

In both studies forecasts were made for the next ten years, and in both cases, natural internal variability was found to temporarily offset anthropogenic global warming. The offset was largest in Keenlyside *et al.,* (2008), whose results suggest a temporary lull in global warming for the next decade. Keeping in mind the simplicity of the scheme employed by Keenlyside *et al.*, (2008), the results nevertheless highlight the impact of internal variability on the evolution of surface temperature, globally and regionally, over the next decade and warrant further investigation.

How might the stratosphere be involved?

Stratospheric and tropospheric variability are linked on seasonal time scales, as shown by observational (*e.g.* Kodera *et al.,* 1990; Baldwin and Dunkerton, 1999) and modelling studies (*e.g.* Boville, 1984; Christiansen, 2001; Polvani and Kushner, 2002). It follows that low-frequency stratospheric change, of either natural or anthropogenic origin, can influence tropospheric circulation. This was recently highlighted in experiments that showed that the observed strengthening of the stratospheric jet from 1965-1995 could reproduce the observed changes in the NAO and North Atlantic Sector climate (Scaife *et al.,*2005). Both the pattern and amplitude of the winter land surface temperature and precipitation over this multidecadal period were well reproduced once the stratospheric change was imposed in the model (**Figure 7**, colour plate IV). It is thus important to understand the nature of low-frequency stratospheric variability and to simulate it correctly.

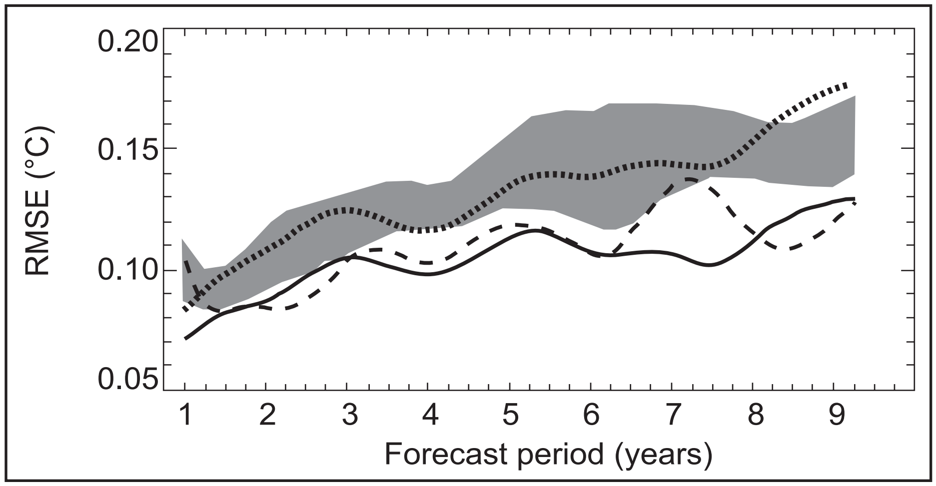

Figure 5: Hindcast skill (root mean square error) in predicting globally averaged annual mean surface temperature anomalies as a function of forecast lead-time of initialised (solid) and uninitialised radiative forcing only (shaded region) forecasts. Shading shows the 5 to 95% confidence interval. Figure from Smith et al., (2007); see article for description of other curves.

Boundary condition forcing from anthropogenic ozone depletion and greenhouse gas increases are an important source of low-frequency stratospheric variations. Both have cooled the polar stratosphere (*e.g.* Ramaswamy *et al.,* 2001). Given the link between stratospheric and tropospheric changes, the response to the continuing expected increase in greenhouse gases may also be modulated by the stratosphere (*e.g.* Huebener *et al.,* 2007). The depletion of ozone in the polar stratosphere is associated with both dynamical and radiative cooling that enhances the polar vortex and makes the ozone depletion even stronger. Because of this feedback, the simulation of the ozone impact on the climate requires a coupled chemistry climate model (CCM) that includes both a troposphere and a stratosphere. The ozone depletion is associated with Annular-Mode-like structures in both hemispheres, which can penetrate into the troposphere (*e.g.* Volodin and Galin, 1998; Kindem and Christiansen, 2001; Thompson and Solomon, 2002; Gillett and Thompson, 2003). In this respect, the recovery of ozone, which is expected to occur over the next 40-50 years (*e.g.* WMO, 2007), may give rise to predictable changes at the surface on decadal time scales.

Solar variations are another potential source of low-frequency stratospheric variability. Depending on the Quasi Biennial Oscillation (QBO) phase, the extra-tropical stratospheric circulation appears to be strongly affected by the 11-year solar cycle (*e.g.* Labitzke, 2005). The signature of the solar cycle appears to be present not only in the stratosphere, but also in the troposphere (*e.g.* Labitzke and van Loon, 1988; Kodera, 2002), and possibly also in the upper ocean temperatures (*e.g.* White *et al.,* 1997). The three most common methods to simulate solar cycle variations are to vary (1) total solar irradiance (as typically done in IPCC class 'low top' models), (2) UV radiation by prescribing ozone climatologies, and (3) to use a CCM, which explicitly captures the ozone feedbacks. All reproduce a significant response at the surface (Matthes *et al.,* 2007, SPARC Newsletter No. 28). However, it needs to be clarified how much of this effect comes from tropical dynamics and the QBO, spectrally resolving short wave radiation, the role played by fully representing the stratosphere, and a good representation of the ozone feedbacks to the solar cycle.

A third way that the stratosphere may play an important role in low-frequency tropospheric variability is by providing teleconnection pathways. In particular, the stratosphere bridges the tropics with the extra-tropics on seasonal time scales (*e.g.* Brönnimann, 2007). A stratospheric bridge between the North Pacific and Atlantic has also been identified (*e.g.* Castanheira and Graf, 2003). Finally, in addition to the ocean circulation, the natural internal variability of the stratosphere itself could lead to decadal time scale variations (*e.g.*

Butchart *et al.,* 2000; Taguchi and Yoden, 2002).

Summary

Decadal climate prediction is of socio-economic importance and has a potentially important role to play in policy making. In contrast to seasonal prediction and centennial climate projections, it is a joint initial value/boundary value problem. Thus, both accurate projections of changes in radiative forcing and initialisation of the climate state, particularly the ocean, are required. Although the first promising steps towards decadal prediction have been made, much more work is required. Understanding of the mechanisms and predictability of decadal-to-multidecadal variability is lacking, and is a key area where stratospheric research should contribute. In particular, the stratosphere may have an important role in correctly capturing the response of climate to changes (natural and anthropogenic) in external radiative forcing, and also by providing a teleconnection pathway to the annular modes and extratropical storm tracks.

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Announcement

A workshop on "The Role of Halogen Chemistry in Polar Stratospheric Ozone Depletion" was held at the University of Cambridge from June 15-17, 2008. A detailed workshop report is in preparation and information regarding its availability will be posted on the SPARC web site. Publications in each of the focus areas Laboratory/Theory, Atmospheric Measurements and Modelling/Analysis will be assembled in one or two special journal issues on a time scale suitable for use in the 2010 UNEP/WMO Ozone Assessment. A workshop summary will follow in the January 2009 issue of the SPARC Newsletter (no. 32).

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