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Review Article
The potential for skill across the range of the seamless weather-climate prediction problem: a stimulus for our science*

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*This article is based on the 2011 IMO Lecture given under the title ‘Predictability beyond the deterministic limit’.

Predictability is considered in the context of the seamless weather-climate prediction problem, and the notion is developed that there can be predictive power on all time-scales. On all scales there are phenomena that occur as well as longer time-scales and external conditions that should combine to give some predictability. To what extent this theoretical predictability may actually be realised and, further, to what extent it may be useful is not clear. However the potential should provide a stimulus to, and high profile for, our science and its application for many years. Copyright © 2012 Royal Meteorological Society

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1. Introduction

The purpose of this article is to highlight the necessity and advantages of considering forecasting on all time-scales in the context of the seamless weather–climate prediction problem, and the fact that there is potential predictive skill of the atmospheric state on all time-scales. This may seem unlikely given that chaos and turbulence abound in the atmosphere. Since the research of Lorenz, we all know that the flapping of the wings of a butterfly can be expected to change the atmospheric state on all scales within the next few weeks. Lorenz (1969) was also the first to raise the notion of unpredictable small-scale eddies influencing just-larger spatial scales, and these in turn influencing larger scales, and so on, leading to an upscale transfer of this uncertainty, and that in any range in which the energy spectrum is sufficiently shallow (for example decaying as $k^{-5/3}$ as later observed by Nastrom and Gage, 1985, for scales below about 100 km), this transfer of uncertainty occurs from the smallest to the largest scale in the range in a finite time. Global weather forecast models exhibit errors in for example 500 hPa height that double in 1–2 days. This leads to a loss of useful skill which has now been pushed back beyond the first week, but beyond week 2 the error saturates as the state becomes little different from any found in the climatology of the model.

In the midst of this gloom that the dynamics of the atmosphere and climate system lead inexorably to lack of predictability, a glimmer of hope is provided by the Quasi-Biennial Oscillation (QBO). This change in the equatorial zonal winds in the lowest 15 km of the stratosphere from westerly to easterly and back again on a time-scale close to 26 months is clearly quite predictable, as long as the smaller-scale details in space and time are not required. However, according to our understanding, it is the dynamics of the atmosphere, in the form of wave–mean flow interaction, that lead to the QBO, and therefore to this predictable behaviour. The dynamics also lead to cases in which the turbulence arguments (i.e. each scale affecting just-bigger scales up to the largest scale) fail. Indeed, in semi-geostrophic frontogenesis (Hoskins and Bretherton, 1972), it is the synoptic scales that directly determine the growth of the small scales.

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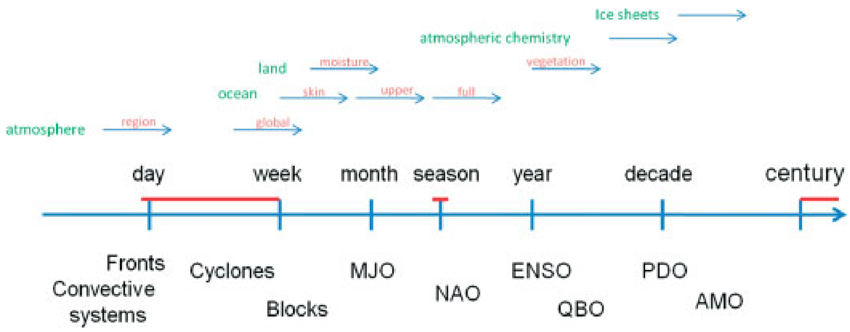

Figure 1. The seamless weather–climate prediction problem. The time-scales are shown along the axis in the middle. The focus for prediction in the years 1980–2005 is indicated by the red lines below this. Some phenomena on the different time-scales are shown at the bottom (acronyms are given in the text). At the top are indicated the components of the Earth system that need to be represented.

In an El Niño–Southern Oscillation (ENSO) event, the warm waters of the equatorial west Pacific and the associated region of deep convection in the atmosphere spread eastwards. ENSO events generally evolve in similar ways on seasonal time-scales, and during this time they influence the weather around much of the Earth. In this case it is a coupling of the dynamics of the ocean and the dynamics and physics of the atmosphere that underlie the evolution of the phenomenon.

These examples introduce a theme of this article: the phenomena in the Earth system that occur on all time-scales imply potential predictive power for the atmosphere on that time-scale. This predictability is associated with the inertia or predictable evolution of the phenomena. If we can understand, identify and model these phenomena, then we can hope to be able to determine the difference between weather and climate behaviour that has some pattern to it and behaviour that is random: we will be able to discriminate better between the music and the noise*. The notion of considering 'what is music and what is noise' again runs through this article.

In section 2, the general weather–climate problem will be considered. In section 3, aspects of prediction on specific time-scales increasing from the first day up to a century will be discussed. Given the huge range of time-scales, the discussion on each will necessarily be partial and will be done using specific examples or ideas. The author apologises for the consequent lack of references to the huge bodies of work on the various time-scales. Finally some concluding comments will be made in section 4.

2. The weather–climate problem

As illustrated in Figure 1, the focus for prediction in the 25-year period 1980–2005 could be considered to be broadly on three discrete ranges of time-scale within the spectrum from within the first day to a century. The weather forecast focus was on a day and upwards to one week. There was also much activity on seasonal prediction. The focus for climate prediction (or more correctly projection) was mainly on the long-term change to a new equilibrium climate or more latterly on the end of the twenty-first century.

However, phenomena occur on all time-scales. Examples of these are indicated in the lower part of Figure 1. Taking one of these, a block, this interruption to the westerly flow in middle latitudes can be initiated on synoptic time-scales by large north–south excursions of air associated with a slow-moving midlatitude depression. It then often persists beyond the synoptic time-scale, characteristically bringing extreme heat in summer and cold in winter. (Examples of both of these extremes will be discussed later.) It is clear that the weather–climate prediction problem is seamless (WCRP, 2005): the atmosphere knows no barriers in time-scales. This provided the basis for the WCRP 2005–2015 strategic framework for its research programme, and the weather–climate strategy in Shapiro *et al.* (2009) and Brunet *et al.* (2010)†. It is also clear that phenomena which may have potential predictability cover the range. These ideas pervade the whole discussion in this article.

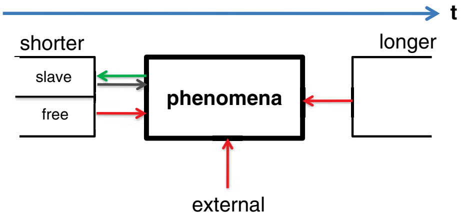

Figure 2. The prediction problem for a particular time-scale. External forcing and longer time-scales influence the behaviour. The evolution of phenomena on the time-scale of interest is central to the prediction. The smaller scales that are slave to these phenomena can be expected to feed back on them in a manner that can be represented in a deterministic fashion. Other variability on these scales (denoted 'free') will introduce a stochastic element to the parametrisation problem.

However the extent and complexity of the weather–climate system that is required in the prediction model depends on the time-scale range considered. For 1 day, a regional atmospheric model suffices. Moving beyond this, a global atmospheric model is required. Perhaps for diurnal tropical convection, but certainly on the one-month time-scale, it is necessary to represent the evolving skin temperature of the tropical ocean. At this time-scale and longer, an interactive upper ocean is required. For one season and beyond, the deep ocean and also sea-ice need to be simulated. The land surfaces, and in particular the variation of soil moisture and snow cover, need to interact at 1 month; beyond the annual time-scale, interactive vegetation on the surface must also be represented. Of course

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*It was John Green of Imperial College whom I first heard some 30 years ago make the comment 'that's not noise; it's music!' when someone talked to him about climate noise.

†Earlier, Palmer and Webster (1995) had put forward the advantages of a unified approach to weather and climate modelling on a wide range of time-scales.

the atmospheric model must now include a more detailed radiative transfer scheme. The evolving chemistry of the atmosphere is of major interest itself, but it is also needed to interact with the physics on decadal time-scales. Beyond this, there should be interaction with the carbon cycle and with evolving ice sheets. The weather–climate prediction problem is seamless, but the modelling system required can be unified in the sense of having common core elements and modelling infrastructure (e.g. Hurrell *et al.*, 2009). For efficiency in the use of scarce human resources and for simplicity in forecasting infrastructure, this 'unified' model may be used with, for example, a full 3D ocean, even though only the upper tropical ocean is required for the time-scale of interest.

The nature of the prediction problem on any particular time-scale is indicated in Figure 2. There will be external forcing and wider system/longer time-scales that influence the development that occurs. In terms of the Earth system, the only real external forcing is from possibly varying solar radiation, though geological processes such as volcanism are practically viewed as external. Variations in greenhouse gases would be part of the wider Earth system. On the time-scale of interest, playing centre stage, there will be phenomena whose potentially predictable evolution will need to be modelled. A few of these, such as ENSO, may be sufficiently dominant and regular to give a local peak in the power spectrum of energy, though most will not. Skilful prediction of phenomena depends both on the representation of the necessary processes in the model and on initial data provided through observations and an analysis–initialisation procedure.

Rowntree (1972) showed that sea-surface temperature (SST) anomalies in the tropical Pacific could influence extratropical latitudes through a stationary train of waves. The notion that the long waves may have a predictable evolution from their initial state even up to one month was pioneered by Shukla (1981), and was termed by him dynamical predictability. Charney and Shukla (1981) then introduced the idea that some predictability of the atmosphere on this time-scale may also be present because of the slow evolution of influential boundary conditions such as tropical SSTs and soil and vegetation conditions. Another important plank on which to build was the study of Miyakoda *et al.* (1983) who showed evidence of some predictive skill in the best available models for the evolution of 5–10-day means throughout January 1977, a month with major blocking and extreme cold in North America. Shukla (1998) showed that the large-scale winter mean flows in a Northern Hemisphere East Pacific/America sector predicted over a six-month period by an atmospheric model with imposed tropical Pacific SSTs from opposite strong phases of ENSO were remarkably independent of atmospheric initial conditions. They were also remarkably accurate. The notion of 'predictability in the midst of chaos' which Shukla (1998) used in this context is one that is developed here for more general weather–climate prediction problems.

Returning to the general prediction problem in Figure 2, there will be influence also from time-scales shorter than those explicitly considered. Some of these may be slave to, i.e. strongly constrained by the behaviour of, the scale of interest. For example, the nature and evolution of fronts are largely determined by the midlatitude depressions in which they occur, and a front itself provides organisation for the convective structures which occur in it. In principle, therefore, it should be possible to parametrise a significant part of the feedback onto the synoptic scale using variables on that scale. However some aspects of these slaved features and all aspects of other smaller-scale processes and phenomena will be free to develop so that their feedback onto the scale of interest can be expected to have a strong random behaviour. Palmer (2012) has persuasively argued that their representation should have a stochastic nature.

As reviewed recently in Slingo and Palmer (2011), uncertainty in initial conditions, in parametrisations and the parameters in them, and the stochastic behaviour of shorter time-scales, along with the sensitivity encapsulated in chaos, mean that predictions on all time-scales will have uncertainties that need to be characterised. This is increasingly handled on many time-scales by means of an ensemble of runs of the forecast system. These may have a range of initial conditions determined by possible analysis error and differences in state that are designed to lead to the best possible exploration of the space of possible forecast states. They may have choices from a range of possible parameter values (e.g. Murphy *et al.*, 2004) or different parametrisation schemes, such as those for convection. They may be different runs of the same model which includes stochastic parametrisation (Palmer, 2012). They may be runs of different model systems (e.g. Vitart *et al.*, 2007, on seasonal time-scales; IPCC, 2007, on decadal to century time-scales). Analysing and communicating the forecast to users of the information from such ensembles, not underplaying the uncertainty but also not obscuring potentially useful information, is a challenge that has been taken up, but which will continue for many years.

3. Prediction on a range of time-scales

3.1. Day one

There is good progress on developing forecast systems for the first day using kilometre-scale models embedded in regional or global models. The example chosen here is from the UK Met Office (N. Roberts, personal communication) and is for hindcasts of an extreme local rainfall event near the south coast of southwest England on 29–30 October 2008. Here 24 members of an ensemble of runs of a 24 km grid regional model have been used to provide boundary conditions for runs of a 1.5 km grid model. Figures 3(a,b,c) show the lower-troposphere temperatures in the three regional model runs with the highest rainfall values, one of them being the control run, and Figures 3(d,e,f) the 6 h accumulated precipitation in the corresponding fine-resolution model runs. In each of them, localised very heavy rainfall is predicted somewhere inside the frontal region as dictated by the larger-scale model. In none of the cases was the actual location of the heavy rainfall correct, but the likelihood of such an event within the envelope of the larger-scale front is potentially very useful information. As the actual position of the front became clearer on the day, so the possible location of very heavy rainfall would also become clearer.

3.2. Week one

The improvement on this time-scale has been dramatic. According to ECMWF (personal communication), for 500 hPa height the average day on which the skill has ceased to be useful has increased from about day 3.5 in 1972/73 to

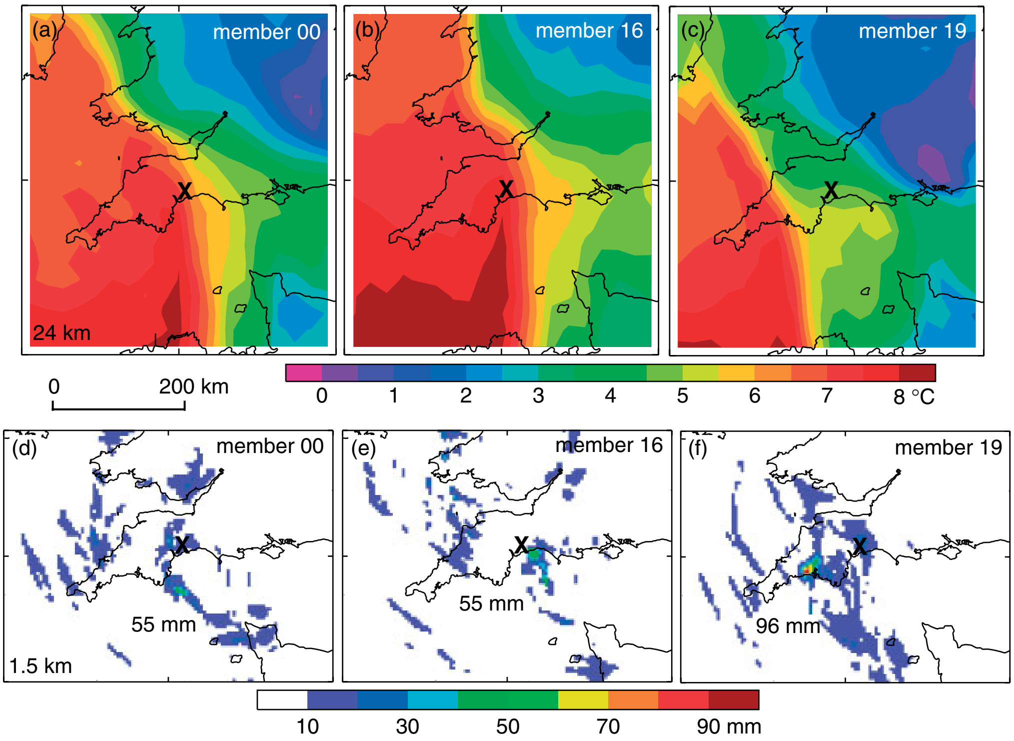

Figure 3. Hindcasts by the UK Met Office for an extreme rainfall event in southwest England on 29–30 October 2008. (a, b, c) show the lower-tropospheric thermal structure (T_{850}) in the three members of a 24-member ensemble of 24 km regional model runs that have the highest rainfall values. (d, e, f) show the 6 h accumulated rainfall in corresponding 1.5 km model runs using boundary conditions from these; the position of the actual event is shown by a cross (N. Roberts, personal communication).

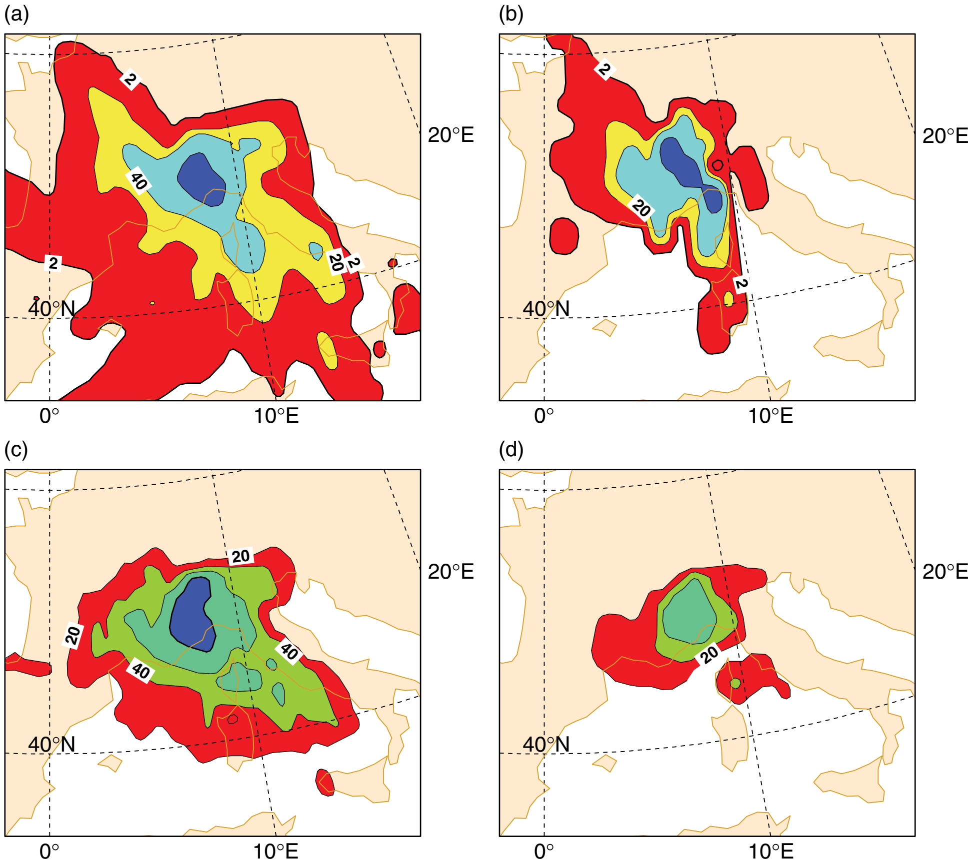

Figure 4. Rainfall which gave rise to an extreme flood event on 5–6 November 1994 in southern France. (b) shows the observed 24 h accumulated rainfall (mm), and (a) that given by the ECMWF deterministic 5-day forecast. (c) and (d) show probabilities (%) produced using the Ensemble Prediction System of 24 h accumulations greater than 20 mm and 40 mm respectively (Buizza, 2001).

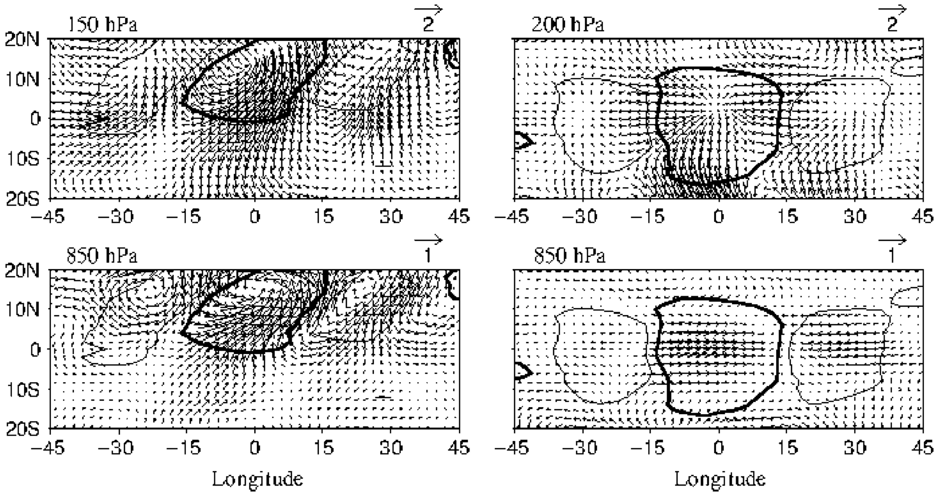

Figure 5. Composite convectively coupled equatorial wave structures determined from ECMWF analyses and convective activity deduced from satellite data. (Yang *et al.*, 2007). The upper and lower panels show velocity vectors at 150 hPa and 850 hPa, respectively, and on each the region of enhanced (reduced) convective activity is indicated by a heavy (light) solid contour. The structure in the left panels moves westwards and has some characteristics of Rossby and mixed Rossby–gravity waves. That on the right moves eastwards and has both Kelvin wave and mixed Rossby–gravity wave characteristics. These structures typically remain coherent for up to a week.

day 5.5 in 1979/80 and to almost day 9 today. The increase in skill is a sign that midlatitude weather systems such as the mobile lows and highs and now even blocking highs are well represented by the 20–50 km resolution global models currently employed. For some other fields such as rainfall, even in midlatitudes the progress is less dramatic, but still substantial. Figure 4 from ECMWF (Buizza, 2001) shows an example in which the ECMWF Ensemble Prediction System was able to give excellent warning of an extreme rainfall event in southern France some 5 days before the event. Again this was possible because the rainfall event was slave to the larger-scale system that was itself quite predictable on this time-scale.

However there are still prospects for significant improvements in this time-range, particularly in the Tropics, and perhaps inspired by considering the phenomena that may give enhanced predictive power. Research has recently shown the prevalence of both eastward and westward convectively coupled equatorial wave structures (e.g. Wheeler and Kiladis, 1999) that typically retain their coherence for up to a week. The wave structure acts to organise the convective rainfall and this rainfall is an integral component of the wave. Examples from Yang *et al.* (2007) of the vertical and horizontal structure of a westward-moving wave with embedded Northern Hemisphere convection and an eastward-moving wave with equatorial convection are given in Figure 5. Current modelling systems are not able to capture the interaction of convection and dynamics that is essential for these waves, but this should be possible as our understanding develops. Then enhanced predictive capability of convective regions on time-scales up to 7 days should be possible.

3.3. *One week to one month*

Predictive capability beyond the first week is sometimes striking. An example is provided by the Japanese Meteorological Agency ensemble of predictions for the following period from 16 and 17 December in which a very cold two-week spell started on 26 December (JMA, personal communication). The actual 850 hPa temperatures for western Japan and the individual forecasts for it are given in Figure 6. The overwhelming predominance of ensemble members exhibiting the occurrence of the cold spell indicates the 2–4 week predictability of this event.

The origin of this predictability can be traced back to two phenomena. The first is the presence in the initial analysed state of a strong disturbance on the westerly winds upstream of Japan. These westerly winds act as a wave-guide for the Rossby waves that develop in a predictable manner downstream of the initial disturbance, as described by Yeh (1945), Hoskins and Karoly (1981) and Hoskins and Ambrizzi (1993), and consistent with Rossby wave group velocity. As this downstream Rossby wave reached the Japanese region, it amplified and broke, leading to the formation of the blocking high that brought the cold weather to Japan. The 1–2 week persistence of this blocking high is not unusual. Again there is predictable behaviour because of phenomena whose evolution is not easily disrupted by smaller-scale processes.

Another very different example which actually has similar ingredients is the Russian heat wave and Pakistan floods in summer 2010. The upper tropospheric winds for the last week in July 2010 are shown in Figure 7(a). There are strong winds on the northern periphery of the blocking high over Russia. This very persistent block brought the heat-wave to Russia. On its eastern flank, the air moves southward towards northwest Pakistan. The Rossby waves along the region of westerly winds from the western North Atlantic eastwards to Japan include a sharp trough near northwest Pakistan and then large acceleration to a jet maximum. The colder air moving towards northwest Pakistan from both features, along with the forcing of ascent in that region by the strong trough and jet entrance structure in the westerlies, created the right conditions for strong convection there, given the warm, moist monsoon air in the lower troposphere (also Hong *et al.*, 2011). Figure 7(b) (ECMWF, personal communication) shows that there was a sequence of major rainfall events in the region, and that each of these was predicted by ECMWF some 1–2 weeks previously. Again there is a suggestion that Rossby wave propagation enabled this predictability. Each rainfall event

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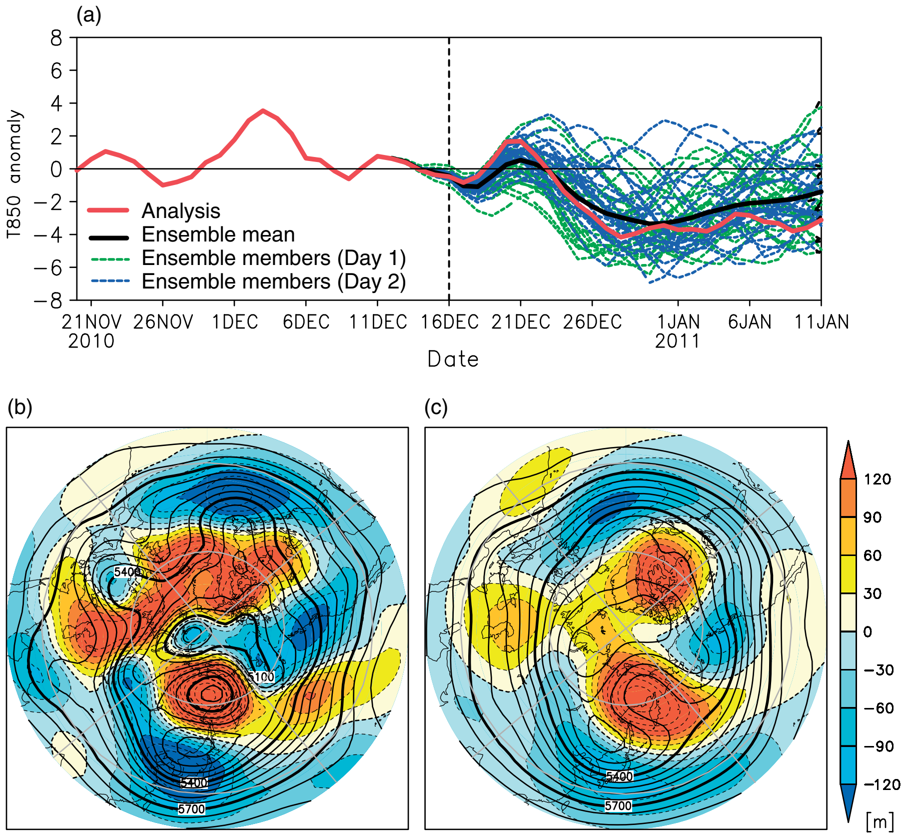

Figure 6. Forecast by the Japanese Meteorological Agency (personal communication) of an extreme cold spell in western Japan in late December 2010 to mid-January 2011. (a) 850 hPa temperature anomalies in western Japan over the period 21 November 2010 to 11 January 2011. Most ensemble members from 16 and 17 December predicted the cold spell, and the ensemble mean temperature is close to that observed throughout the period. (b) analysis and (c) ensemble mean forecast 500 hPa height (solid contours, m) and anomalies (dashed contours and colour shading, m) for the period 26 December to 11 January.

was preceded by an intensification of the northwest flow over the UK and an eastward propagation of the amplification in the wave pattern, moving with the Rossby wave group velocity. Each triggered a rainfall event when it reached the northwest Pakistan region.

Again there is evidence that there is predictive power that is not yet being realised because the interaction between the dynamics and physics of the Tropics is not yet sufficiently well represented by models. As shown by, for example, Matthews *et al.* (2004), the Madden–Julian Oscillation (MJO) or Intra-Seasonal Oscillation exhibits a sufficiently regular life-cycle that a composite structure from many events is well-defined. It shows that, associated with propagation of a region of enhanced convection from the western tropical Indian Ocean to the west Pacific, followed by a region of reduced convection, there is a pair of tropical upper-tropospheric anticyclones and then a pair of cyclones. When each of these reaches the Indonesian region, they trigger Rossby wave-trains that propagate into the higher latitudes, particularly in the winter hemisphere. Consistent with this, Cassou (2008) has shown that certain phases of the MJO tend to have an association with the two signs of the North Atlantic Oscillation (NAO). Generally, two weeks has been found to be the limit of the predictive power for forecasting the evolution of MJOs that are present in initial conditions. (e.g. Hendon *et al.*, 2000). However very recently, predictive power up to 3 weeks has been reported using coupled ocean–atmosphere forecasting systems (Vitart and Molteni, 2010; Rashid *et al.*, 2011). The hope now is that there may in future be some predictive power globally for up to a month or so associated with the MJO.

3.4. *One month to seasons*

The biggest source of predictive power on time-scales up to a year has been ENSO, the coupled evolution of the upper layer of the tropical Pacific Ocean (the El Niño) and the tropical atmosphere (the Southern Oscillation). The evolution of ENSO is slow on the monthly time-scale. As indicated in Figure 8 from the European Seasonal to Interannual Prediction (EuroSIP) project (e.g. Vitart *et al.*, 2007), on some occasions its behaviour on seasonal time-scales is now quite predictable and on others there is currently little predictive power. The impact of ENSO on regional weather is quite predictable (e.g. Arribas *et al.*, 2011), and globally it produces a greater or lesser bias in the probability distribution of likely weather. However there can be a temptation for a forecaster seeking to communicate a simple message and also to demonstrate usefulness to over-simplify the probability information and turn it into a deterministic statement.

There is still research discussion over to what extent the NAO, a measure of the fluctuating westerly winds in the North Atlantic region, is really a phenomenon in its own right. It certainly describes an important variation in the structure of the flow, in particular the storm-track location, in the North Atlantic and European regions. The 1960s was a decade with mostly negative NAO and cold west European winters, and the 1990s was the opposite. Whether the seasonal to decadal signal is really a residual of

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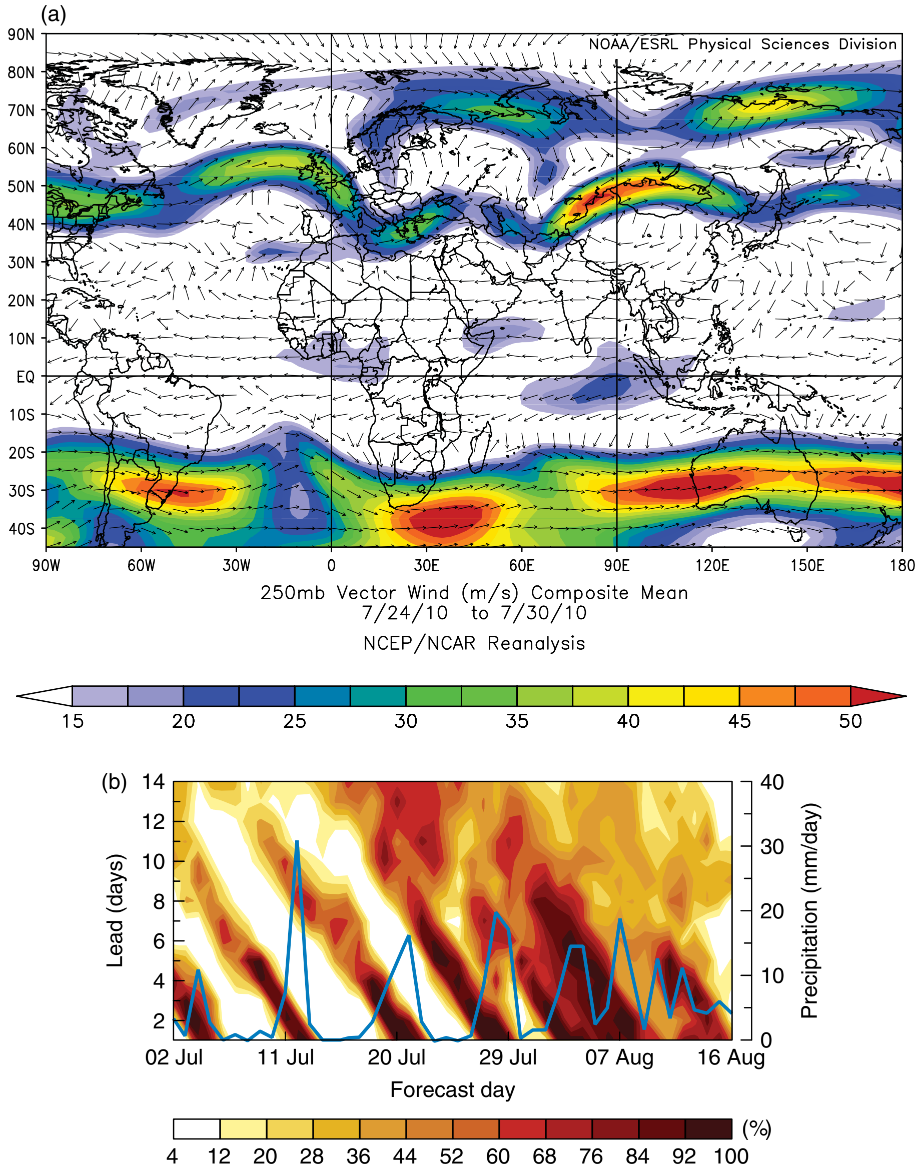

Figure 7. Russian heat wave and Pakistan floods, summer 2010. (a) mean 250 hPa winds for 24–30 July (direction denoted by arrows and speed by colour shading) determined from NCEP data. (b) Time series of the rainfall in northwest Pakistan (blue curve) and the rainfall forecast (red shading) for the region by ECMWF deterministic 14-day forecasts. The initial time for the forecast is on the abscissa and the time into the forecast is on the ordinate. The forecast of a particular rainfall event appears as a region sloping into the *x*-axis. For example, for the event of 12 July this region should slope from a 10-day lead on 2 July to a 0-day lead on 12 July. The evolution of the forecast intensity as the actual date is approached is shown by the colours (courtesy of ECMWF).

synoptic 'noise' or whether there is music in the form of a phenomenon whose evolution is on the longer time-scale and therefore potentially predictable, is not yet clear (e.g. Feldstein, 2000). Closely related to the NAO is the Arctic Oscillation (AO) and also the concept of annular modes (Thompson and Wallace, 2000; Ambaum *et al.*, 2001; Wallace and Thompson, 2002), in which the longitudinal variation is not a crucial aspect. In the Southern Hemisphere the Southern Annular Mode (SAM) appears to be a good description but in the Northern Hemisphere with its longitudinal asymmetries it is less clear in the troposphere. In general, models currently show little predictive power for the NAO on seasonal time-scales (e.g. Arribas *et al.*, 2011). However Baldwin and Dunkerton (2001) have given strong evidence that annular behaviour associated with a strong or weak winter polar vortex appears to propagate downwards and to bias the westerly flow in the troposphere over the next 2 months. Also, forecasts initialised just before stratospheric sudden warmings have shown some skill in the troposphere over the following 2 months (Kuroda, 2008).

Very recently Cohen and Jones (2011) have shown remarkably high negative correlations between indices of October snow cover over Eurasia south of 60°N and the AO index for the following winter. For the 28-year period up to the winter 2010/11, the correlation was −0.5 with snow cover extent and −0.6 with a measure of snow advance. Such empirical results based on a limited number of years must be viewed with caution, but it will be of great interest to see if this potential predictability is confirmed in climate models when their representation of processes related to snow cover is improved.

The predictable nature of ENSO is intimately related to equatorial waves in the Pacific Ocean and, very recently, Webber *et al.* (2011) have shown that there may also be predictive power for the initiation of an MJO event some months ahead, associated with the slow westward

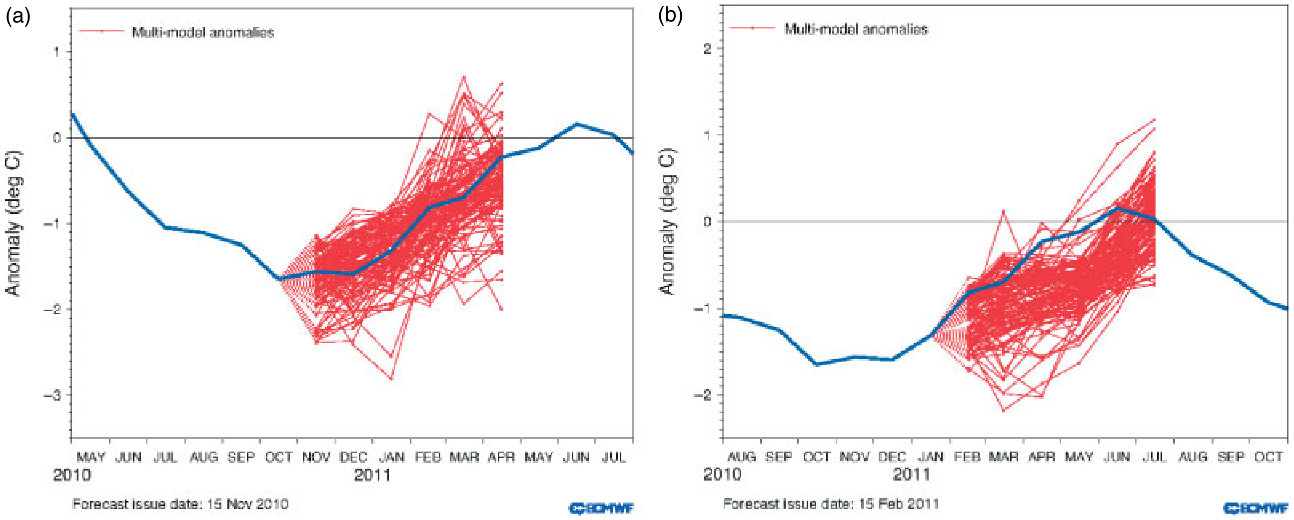

Figure 8. The actual (blue) and EuroSIP ensemble members forecast (red) evolution of the anomaly of the Niño-3.4 SST index, a measure of ENSO, for starting dates on (a) 1 November 2010 and (b) 1 February 2011 (courtesy of ECMWF).

propagation of an equatorial Rossby wave in the Indian Ocean. The origin of the wave can be the reflection at Sumatra of an oceanic Kelvin wave, itself forced by anomalous westerlies in the Indian Ocean. The impact of this Rossby wave when it reaches the coast of Africa is to raise the SSTs, perhaps enough to stimulate an MJO.

In middle latitudes, there has been no clear message about whether SST anomalies in the western North Atlantic and North Pacific may influence the individual storms in the storm-track sufficiently to give promise of predictive power on monthly to seasonal time-scales (e.g. Kushnir *et al.*, 2002). However, recent studies by Minobe *et al.* (2008), Nakamura *et al.* (2008) and Czaja and Blunt (2011) give evidence that smaller-scale atmospheric processes not represented explicitly or implicitly in current global models may lead to a strong ocean–atmosphere coupling in the neighbourhood of the Gulf Stream and Kuroshio. Therefore there is the potential for some future predictive power.

Each season provides a new experiment to test our understanding and predictive capability. Summer 2002 provided an example in which anomalous behaviour in regions remote from one another may have been linked. The Indian summer monsoon had a major break in rainfall lasting the month of July. This caused major problems for agriculture in India. Summer 2002 also brought rainfall to usually dry Mediterranean regions and flooding in central Europe. This was associated with Atlantic weather systems entering the Mediterranean and taking very moist air into Europe. The fact that such behaviour does not normally occur in the summer is due to the ambient descending air there, and this descent has been shown by Rodwell and Hoskins (1996) to be associated with the ascent that occurs in the region of the deep convection of the Indian Monsoon. Therefore the two anomalous events may be connected. Given more understanding of the interaction of dynamics and physics in the Tropics, there may be more skill in prediction of the likely occurrence of such a break in the Indian monsoon. This would have great benefit for agriculture in that region and may give some predictive power for summer in southern Europe.

The study of the summer 2003 heatwave in Europe by Weisheimer *et al.* (2011) showed that this did not appear to be predictable with an earlier version of the model, but with a new version there seemed to be significant predictability. A detailed diagnosis demonstrated that this improvement in skill came from a set of model parametrisation changes rather than from any single change. Such a result means that in some cases it can be difficult to plan the development of individual model parametrisations with the aim of improving the simulations of particular phenomena.

Winter 2009/10 was one with extreme cold in a band from Northern Russia through Europe and continuing, though weaker, through to the southeast USA. Warmth elsewhere was particularly extreme in the Greenland region. Persistent blocking was again the cause in Eurasia. Whether this was in any way predictable is not yet known. However there are recent indications from the Met Office (A.Scaife, personal communication) that in hindcast mode there are hints of some skill for this event. According to the recent studies of Lockwood *et al.* (2010) and Woollings *et al.* (2010), such frequent winter blocking in Europe and a cold season is more likely when a certain measure of solar activity indicates that it is low (Figure 9), an example of external conditions providing some predictability. The extent of this predictability is not yet known because of the shortness of the record. There is also very recent evidence from Ineson *et al.* (2011) that models with sufficient stratospheric resolution may be able to capture some of this behaviour.

3.5. *One year to ten years*

A number of the phenomena that are almost stationary on seasonal time-scales and give potential predictability on that time-scale may also do this on longer time-scales because of their slow, potentially predictable evolution. The NAO appears to have some decadal persistence; the stratosphere has longer time-scale behaviour associated with changes in composition, particularly of ozone but also water vapour; solar activity fluctuates with an approximate 11-year period. Arctic sea-ice variability and change may influence the NAO and the occurrence of storms in the Northern Hemisphere (e.g. Badre *et al.*, 2011).There may be also some predictive power in the cycle between El Niño and the opposite state, La Niña.

When the ocean is initialised, there are indications of skill in predicting upper-ocean heat content in the northern

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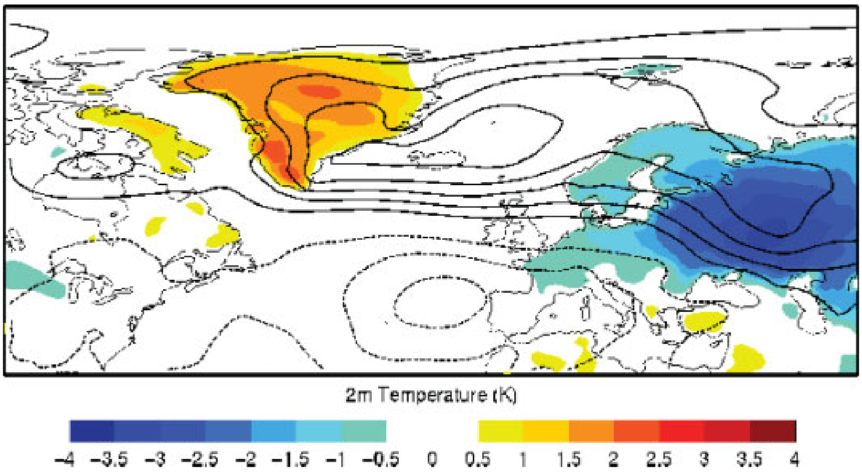

Figure 9. The difference in mean sea level pressure (contours) and surface temperatures (colours) between composite winters with low and high solar activity (low minus high). (Lockwood *et al.*, 2010).

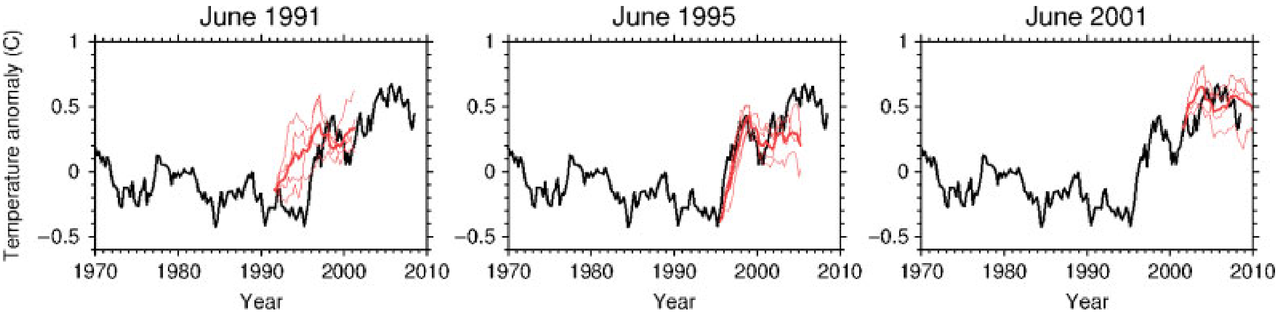

Figure 10. Anomalies of analysed heat content (black) in the upper 500 m in the region of the North Atlantic subpolar gyre for the period 1975–2010, and ensembles of hindcast predictions of it (red) using the Met Office decadal prediction system (DePreSys) starting from the three different dates shown (J. Holden, personal communication).

North Atlantic out to 5 years. Pohlmann *et al.* (2009) indicate skill in predictions of the midlatitude Atlantic Multi-decadal Oscillation in the ocean up to 5 years ahead. Figure 10 (J Holden, personal communication) shows ensembles of hindcasts for the upper-ocean heat content in the North Atlantic polar gyre starting at different times in a period when there was observed to be a large increase in this heat content. The model appears to capture some aspect of the initial state that leads to a tendency for the heat content to increase to a new level, but there is some difficulty with the timing of this transition.

Of course there is still the question of the extent to which predictability of such upper-ocean heat content changes can be translated into predictability of regional weather and climate. In one case, this translation to atmospheric predictability is clear. Tropical cyclones are dependent on the warmth of the ocean, and this underlies the impressive predictive power shown in Figure 11 from Smith *et al.* (2010) for both the 1-year and 5-year average numbers of tropical storms in the North Atlantic. Figure 11(b) also contains (blue) hindcasts made without an ocean data assimilation. It is clear that having a more realistic ocean initial state (red) improves the predictions. However it is also clear that there is skill on multi-decadal time-scales even without data assimilation. This indicates predictability on such longer time-scales associated with the imposed external conditions of solar irradiance and volcanic aerosol, and the imposed human-related factors of greenhouse gases, stratospheric ozone and aerosols. This leads on to consideration of these longer time-scales.

3.6. *One decade to one century*

The Atlantic Multi-decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) have been analysed as two patterns of behaviour of the climate system on this time-scale. Freely running models exhibit somewhat similar structures and behaviours (Knight *et al.*, 2005; Parker *et al.*, 2007). With improvement in the models and their initialisation, there is hope that there may be some predictive power. Slowly changing stratospheric composition and longer-term behaviour in the solar flux could also contribute.

Interpretation of the past climate record struggles with the problem of disentangling the trend from the natural variability. Recently Wu *et al.* (2011) and DelSole *et al.* (2011), using different techniques, have produced similar results for such a partition for global surface temperature, indicating that the two components are currently of similar magnitude, so that global warming can be stalled or amplified on the multi-decadal time-scale. In climate projections up to the end of the century for scenarios with increased greenhouse gases, it is necessary to cope with the obscuring of the signal by climate 'noise' (e.g. Deser *et al.*, 2012). Hawkins and Sutton (2009, 2011) have used models to estimate the amount of the uncertainty that is due to the scenario, the model structure and the natural variability. However, as stressed by Meehl *et al.* (2009) and Solomon *et al.* (2011), some of the latter may in fact be predictable, given the past record and initial state. In addition, one of the major impacts of the increasing greenhouse gases

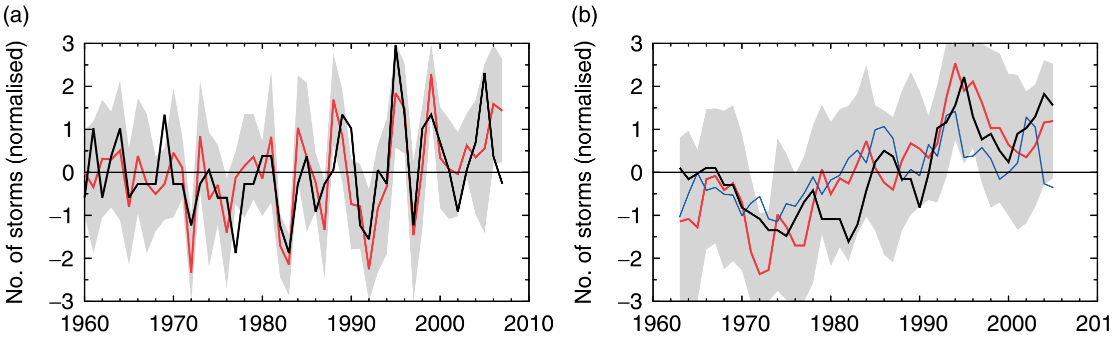

Figure 11. The observed (a) 1-year and (b) 5-year averaged numbers of North Atlantic tropical cyclones (black lines) and ensembles of hindcasts using DePreSys showing ensemble means (red lines) and the 5% to 95% range (shading). Five-year average number predictions are also given (blue) for a model with no data assimilation (Smith *et al.*, 2010).

may be through the changing of the natural patterns of variability such as the NAO, and these changes through the century may well be predictable to some extent. However the predictability on different time-scales could itself be affected by global warming (Boer, 2009).

4. Concluding comments

Before making some summary comments, three ideas that apply across time-scales will be briefly mentioned. The first is the chain of predictability[‡]. An example is that (as discussed above in section 3.4) a large anomaly in the winter stratospheric vortex gives some predictive power for the troposphere in the following month. However the stratospheric anomaly itself was probably forced in the previous weeks by anomalous long-wave tropospheric flow, such as a large blocking event, and consequent change in upward propagating waves. If the response to the upward propagating waves could be predicted, and beyond this if the tropospheric long-wave anomaly itself could be, then the period showing predictive power could be extended. Depending on the current forecast system skill, at some point going backwards along the chain of predictability the useful skill will shrink to zero. However the potential is there and more skill may be realised as model skill increases.

Secondly, the methods for exploitation of ensembles of predictions need to be considered. It is widely recognised that the ensemble mean gives a good summary, but there is much more information that can be available in the ensemble. Splitting the different trajectories of the members into different categories using a variety of techniques is valuable and can be used to produce scenarios for future behaviour. One method for using the ensemble that could be useful on all time-scales is to compare the individual members of the categories of members with data that have become available after the initialisation of the forecast system, and then concentrating on the subsequent evolution of those which match best. This technique is often employed by the weather forecaster, and might be caricatured as checking by looking out of the window! For longer time-scales, the diagnosis of the actual and the individual ensemble member behaviour may need to involve detailed analysis based on latest theoretical ideas. For example, a week after a seasonal forecast has been produced, it may become clear that the real world has moved into a blocking region of parameter space which is inhabited by only a portion of the ensemble members. The focus should then be on their evolution.

Thirdly, there are major benefits for the longer time-scale predictions in the seamless weather–climate context. The verification and improvement of shorter-term prediction of individual realisations of phenomena such as blocking, which are important both in their statistics and in their feedback onto the longer time-scales, provide support for the longer-term predictions themselves.

Returning to the article as a whole, despite the prevalence of chaos and turbulence in weather and climate, the optimistic notion has been developed that there could be predictive power on all time-scales. The discussion given here could be extended to century and millennial time-scales and beyond. The argument has been made in the context of the seamless weather–climate prediction problem. On all scales, there are phenomena and external conditions that may give predictability. To what extent this theoretical predictability may actually be realised and then to what extent it may be useful is at present unknown. However the potential, for example for useful prediction of the Asian summer monsoon at least a season ahead, is immense, and will provide a stimulus to our science and its application for many years. We will need to observe, model and understand the phenomena on all time-scales. One guide to future research suggested by the above discussion is that there should be a greater focus on the phenomena and structures that provide the potential predictability. We will need to recognise the music in what may seem like noise. The music may initially seem like that of a modern composer. However, with more familiarity some of it may become so readily accessible (and enjoyable) that it will seem more like Mozart to us!

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[‡] The suggestion for the explicit mention of this concept was made by David Strauss.

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