The development of seasonal forecasting

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1 Introduction

I'm going to start my discussion of the history of seasonal forecasting in the mid 70's, which is about when I got involved in oceanography. One of the interesting topics at that time was whether short-term climate fluctuations (especially over North America) were predictable. Jerome Namias (1972) had presented some evidence that there was some predictability, using as predictor, Sea Surface Temperature (SST) in the mid-latitude Pacific Ocean with the idea that the ocean variability was diving the atmospheric variability. Russ Davis, an oceanographer from Scripps tried to reproduce Namias's results but found no evidence to support this. The strategies used by the two researchers were different, however. Davis (1976) felt Namias's approach was too intuitive making it difficult to quantify the skill objectively. He wanted to put the predictions on a more secure footing and so he developed a more rigorous statistical approach but found that while there was some evidence for a connection between the atmosphere and ocean, it was contrary to what Namias proposed. He found the correlations of SST and Sea Level Pressure (SLP) over the North Pacific to be in the sense of the atmospheric anomalies driving the ocean SST anomalies.

Namias correctly pointed out that Davis was using annual mean values and this was inappropriate if the SST/SLP connection was seasonal, but Namias strongly supported continuation of Davis's work, even though it would have threatened or destroyed much of his life's work if Davis was proved right. I've included a quote from Davis acknowledging Namias's generosity in the pursuit of truth[1]. Davis did take up Namias's point about the seasonality, however, and showed (Davis 1978) that, when analysed seasonally, his EOF-based approach was consistent with Namias's results. He found that SLP could be related to SST, to some degree; in particular that July SST could be related to Autumn (SON) SLP, and October SST to winter SLP.

He then developed a statistical model to be used for prediction. Fig 1 gives the forecast of anomalous winter (D,J) SLP for the winters 1967-76. At that time, Davis only had data maps of SLP for the period 1947-76. (I imagine the pressure data over the Pacific were considerably less good than would be possible for these years now from reanalyses such as ERA-40 or its successors. Recall there were no atmospheric reanalyses in the 70's when Namias and Davis were doing their pioneering work.) He used the years 1947-66 to develop the statistical model linking Nov SST to Dec Jan SLP

[1] What is remarkable is that Namias regarded the study, which might have been thought to threaten a major element of his life's work, with objectivity and supported continuation of similar work. In a field where charlatanry is the rule rather than the exception, this attitude stands out as an important commentary on the man.

and then used it to make predictions for the years 1967 to 76. He considered his predictions for the years 68, 69, 71 to be successes, with 67 and 75 failures because the signs of the forecast anomalies were wrong. The forecast for 1976 had the right sign but no indication was given of the severity of the record breaking anomaly. Davis pointed out that it is quite possible that SST and SLP were only indicators of a climatic development in which they play no active role i.e. there is not a causal link between the two. This might be a clue to the importance of ENSO, for 1976/7 was an El Nino year. On the other hand so was 1972 but fig 1 shows no great north Pacific SLP anomaly in that year.

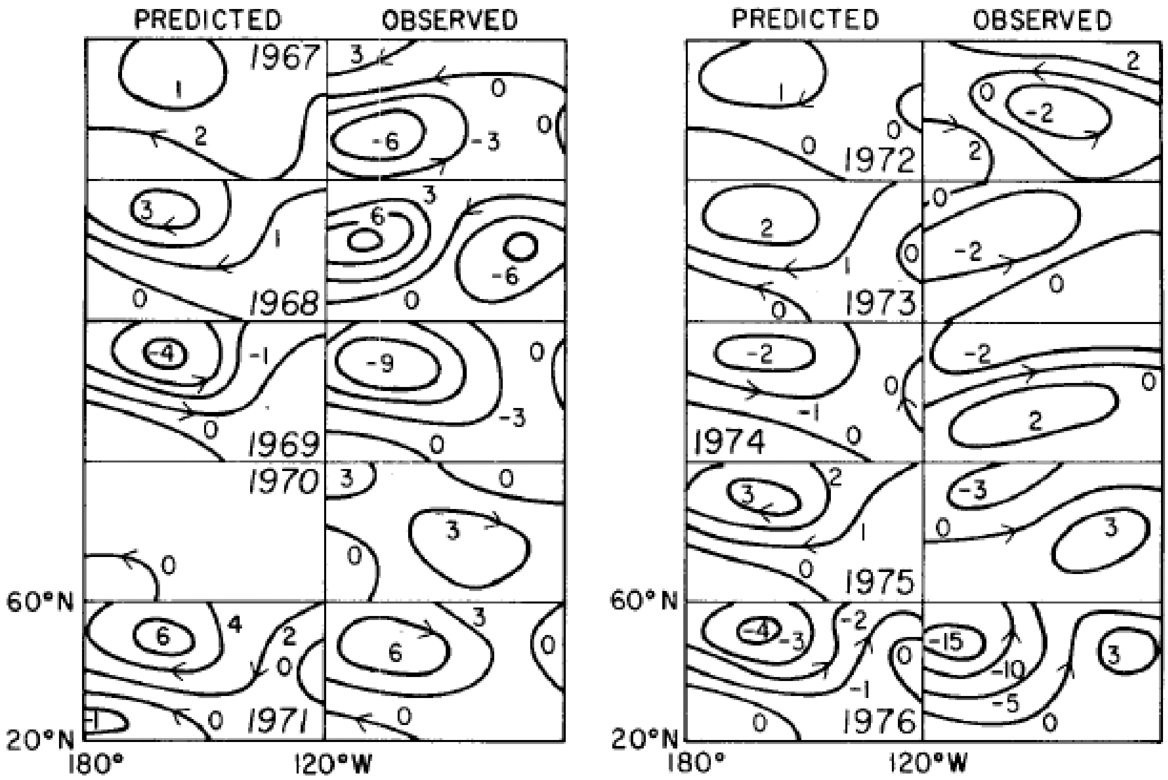

Figure 1: Forecast and observed SLP anomalies (HPa) for winters of 1967-76 (Dec-Jan average) for the mid latitude Pacific. Forecasts are based on the November SST. The statistical model is trained on the period 1947-66. From Davis (1976).

There have been many subsequent studies of the role of the mid latitude ocean in climate variability, including studies in which the higher latitudes influence ENSO as well as those in which ENSO leads to midlatitude anomalies. Arnaud Czaja is scheduled to talk more about the importance of mid-latitude anomalies and I hope will expand on the early work described here. I want to shift the focus of this talk now towards sources of predictability originating in the tropics.

2 The importance of the tropics

2.1 Early understanding of tropical atmosphere-ocean interaction

The largest, coherent interannual signal in the world is undoubtedly El Nino (or ENSO as it is sometimes referred to). Although the existence of the El Nino current was known for a long time, and even that it was from time to time interrupted, it appears that it was not until the International Geophysical Year (IGY) in 1957/8 that it was realised that local disruption to a coastal current along the Gulf of Guayaquil was really of much larger significance[2]. The IGY year was fortunately an El Nino year and Bjerknes (1966,1969) realised the significance of the large scale sea surface temperature changes in the equatorial Pacific and that these were linked to changes in the atmosphere, (represented by the Southern Oscillation)[3]. The link between the atmosphere and ocean was thus established and Bjerknes put forward a positive feedback mechanism for the development of El Nino (or for the reverse phase sometimes called La Nina). Fig 2 gives plots of various atmospheric and oceanic parameters from the equatorial Pacific, showing the various strong correlations and anti-correlations that exist between atmospheric and oceanic parameters.

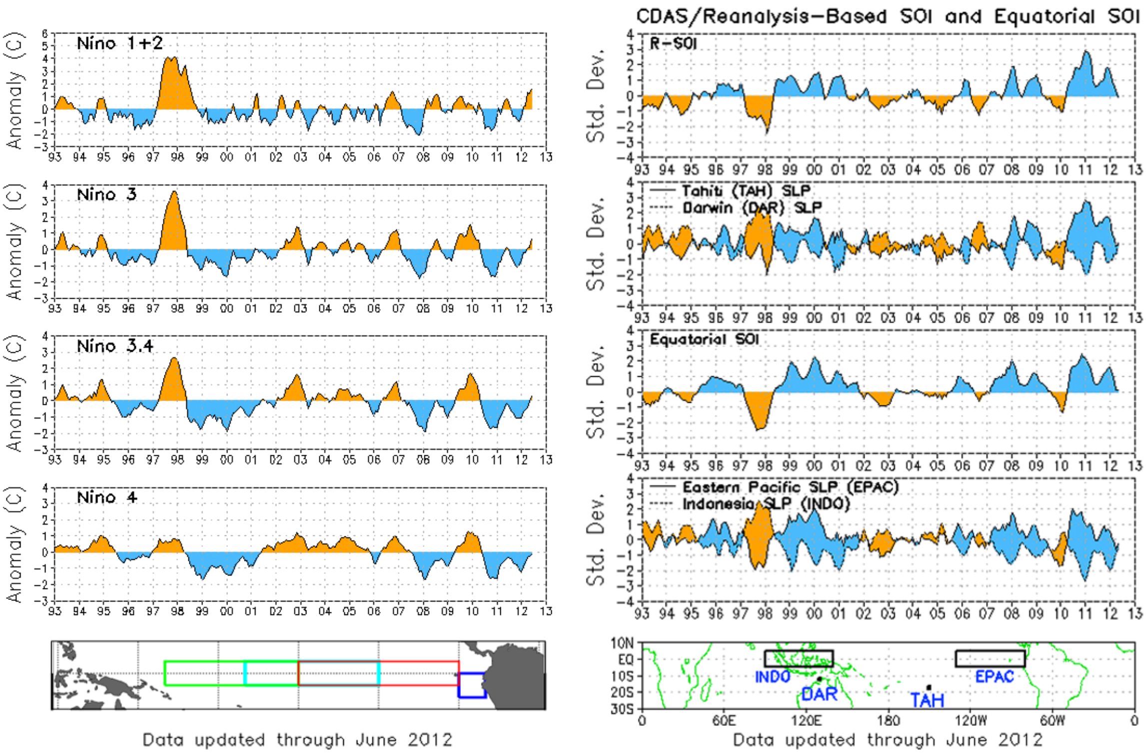

Figure 2: SST in various regions in the equatorial Pacific (left panels), and sea level pressure (right panels). Note the various correlations and anticorrelations. From Climate Diagnostics Bulletin (NOAA).

The surface equatorial winds depended on the East-West sea surface temperature gradient along the equator. Weaker winds would not support as strong an east west temperature gradient, which would lead to weaker winds and a further weakening of the temperature gradient, i.e. warmer water in the eastern part of the basin and the development of El Nino. Conversely stronger winds would generate a stronger temperature gradient leading to stronger winds, further cooling in the east and La Nina. Bjerknes did not provide a negative feedback mechanism, i.e. what leads to an

[2] The El Nino current, a warm current which flows southward against the cold Humboldt current around Christmas was well known to local fishermen. Its name originally referred to a fairly insignificant coastal current, but now is applied to an almost global phenomenon.

[3] The Southern Oscillation was originally a measure of pressure fluctuations between Darwin and Tahiti. The more recent EQSOI may be a better representation of pressure swings between the west and east equatorial Pacific as Tahiti is almost mid Pacific and quite far from the equator, but was used, presumably because there was a longish pressure record there.

end to El Nino or La Nina. [Mechanisms were later proposed by Suarez and Schopf (1988) involving large-scales waves with wavelengths of thousands of kilometres, notably Kelvin and Rossby waves through the so-called delayed oscillator mechanism. See the various papers in the special issue of JGR (1998) or McCreary and Anderson (1991) for some review articles.]

In 1982 Rasmusson and Carpenter proposed a composite development pattern of El Nino. They averaged several El Nino events to deduce that in terms of SST, El Nino started in the east Pacific and then 'propagated' westward. Klaus Wyrtki (1975) had developed an ocean observing system for the tropical Pacific by installing tide gauges on various islands in the tropical Pacific (mainly in the western half, since that is where the islands are mainly located). He was able to examine the development of the 1976/7 El Nino and noted that there was a build-up of warm water in the west Pacific ahead of the El Nino.

2.2 Confusion and the birth of TOGA

To gain some impression of the progress made over the last 25 years or so, it is useful to go back to the early eighties. 1982/3 saw one of the largest El Nino events ever recorded, surpassed in only some respects by the El Nino of 1997/8. There was a marked difference in our awareness of El Nino and how to monitor its progress between these two events, however. It is often recorded that not only was the 1982/3 El Nino not forecast, scientists weren't even aware it was happening until it was well developed. That lack of awareness lead key scientists to plan an experiment to observe and understand tropical phenomena so that uncertainty surrounding the 82/3 El Nino would not happen again. That endeavour resulted in a major ten-year experiment, TOGA, which kicked off in January 1985. TOGA was one of the most successful international experiments in climate understanding, but, as we will see, it certainly did not solve all the problems. Although the ocean observing system performed well in 1997/8, keeping the world well informed of changes in the Pacific ocean, including the 1997/8 El Nino, predictions of the severity of this event were generally poor, but see 2.5 later.

El Nino is a coupled phenomenon; it involves knowledge of both what is happening in the ocean as well as in the atmosphere. The atmospheric observing system, (which was developed to permit numerical weather prediction, rather than climate prediction) has advanced substantially since the early eighties but more importantly the upper ocean observing system has improved from an opportunistic system to a more mature 'pseudo-operational' system. Measurements of the interface between the atmosphere and ocean have also improved. In the early eighties, it was possible to measure sea surface temperature (SST) from Advanced Very High Resolution Radiometer (AVHRR) satellites and so changes in SST in the equatorial Pacific should have been detected. Unfortunately it seems the satellite was largely blinded because of aerosol; in late March, early April 1982 there was a series of major eruptions from El Chichon, a volcano located in Mexico at about 17N. The erupted gasses spread westward, circling the earth in a few weeks. This lead to radiative measurements being outside the acceptable range, and the default setting of climatological sea surface temperature being invoked; no evolving El Nino was seen from space[4].

This was not the only reason for not being aware of what was going on, however. At the time, the conceptual model of El Nino was that SST anomalies started in the east, along the South American coast and spread westwards (Rasmusson and Carpenter 1982). In 1982, there was no strong sign of coastal warming, so no El Nino was anticipated. Secondly, sea level was not evolving as expected. One reason was that there had been no "buildup" of sea level in the western Pacific by stronger than normal trade winds prior winds prior to 1982, presumed to be a necessary precursor of El Niño (Wyrtki, 1975). Klaus Wyrtki had played a major role in establishing a network of island tide gauge stations. He observed that strong equatorial trade winds in 1975 increased sea level in the western Pacific. The relaxation of the wind in January 1976 allowed an internal equatorial Kelvin wave to form and propagate eastward, raising sea level along the eastern side of the ocean (Wyrtki 1979). But this didn't happen according to plan in 1982/3. So the failure to alert the world to an impending El Nino was really a combination of factors: a major volcanic eruption blinding the satellite observation, El Nino evolving differently to our then understanding of how it should evolve and effectively no real-time observations of the subsurface ocean, and no models of predicting an El Nino.

A key observation leading to an El Nino alert was that made by Toole on board the research ship Conrad. The ship happened to be on the equator and observed that the thermocline was 60m-150m deeper than normal; this set the alarm bells ringing. See Toole and Borges 1984 and Toole 1985 for a later analysis of the data.

2.3 TOGA and an improved ocean observing system

Regardless of the cause, the failure to recognise in a timely fashion what was evolving in the tropical Pacific, lead some important scientists to meet and ponder what should be done. A major observing, understanding and prediction programme was proposed through the CCCO (Committee for Climate Change in the Ocean) and WCRP (World Climate Research Programme) channels, which was formalised in the Tropical Atmosphere Global Ocean (TOGA) programme. Key objectives of TOGA were:

(1) To gain a description of the tropical oceans and global atmosphere as a time-dependent system in order to determine the extent to which this system is predictable on the timescales of months to years and to understand the mechanisms and processes underlying its predictability.

(2) To study the feasibility of modelling the coupled ocean-atmosphere system for the purpose of predicting its variations on time scales of months to years.

(3) To provide the scientific background for designing an observing and data transmission system for operational prediction if this capability is demonstrated by coupled-atmosphere-ocean models.

[4] There was evidence (see the Climate Diagnostics Bulletin for October and November 1982) of at least some awareness that something was going on, but it took time to analyse and produce these SST charts (Anderson 2010).

One of the great visionaries of TOGA and the first Chairman of the Scientific Steering Committee was Adrian Gill, author of that excellent book, Atmosphere-Ocean Dynamics (Gill, 1982). It is very sad that he died so soon after TOGA started and never saw what a wonderful experiment he had helped to conceive and initiate. TOGA was innovative not just in developing the observation array but also in the change it brought in data exchange. All data collected through TOGA funding had to be made freely and rapidly available. This was similar to the meteorological approach but very different to the then current oceanographic practice whereby data were only released after the collector had finished analysing and publishing on them.

To put the development of the observing system in perspective, fig 3 shows a snapshot of observations in 1979 and at 10-year intervals. In the late seventies, early eighties, the observations were mainly from XBTs. There were odd research cruises such as that described above but they were not designed to detect changes in a systematic way. XBTs measured only temperature as a function of depth. The data were recorded on ship but only made available after someone met the ship at port, collected the data and then put it on the GTS or sent it to a data archive. This usually took a few months. Technology to record the data and transmit it electronically grew slowly in the eighties and nineties to the extent that nowadays, such XBTs as are made would be transmitted rapidly. When viewing fig 3, recall that, especially in the early years, much of the data illustrated would not have been available in real-time

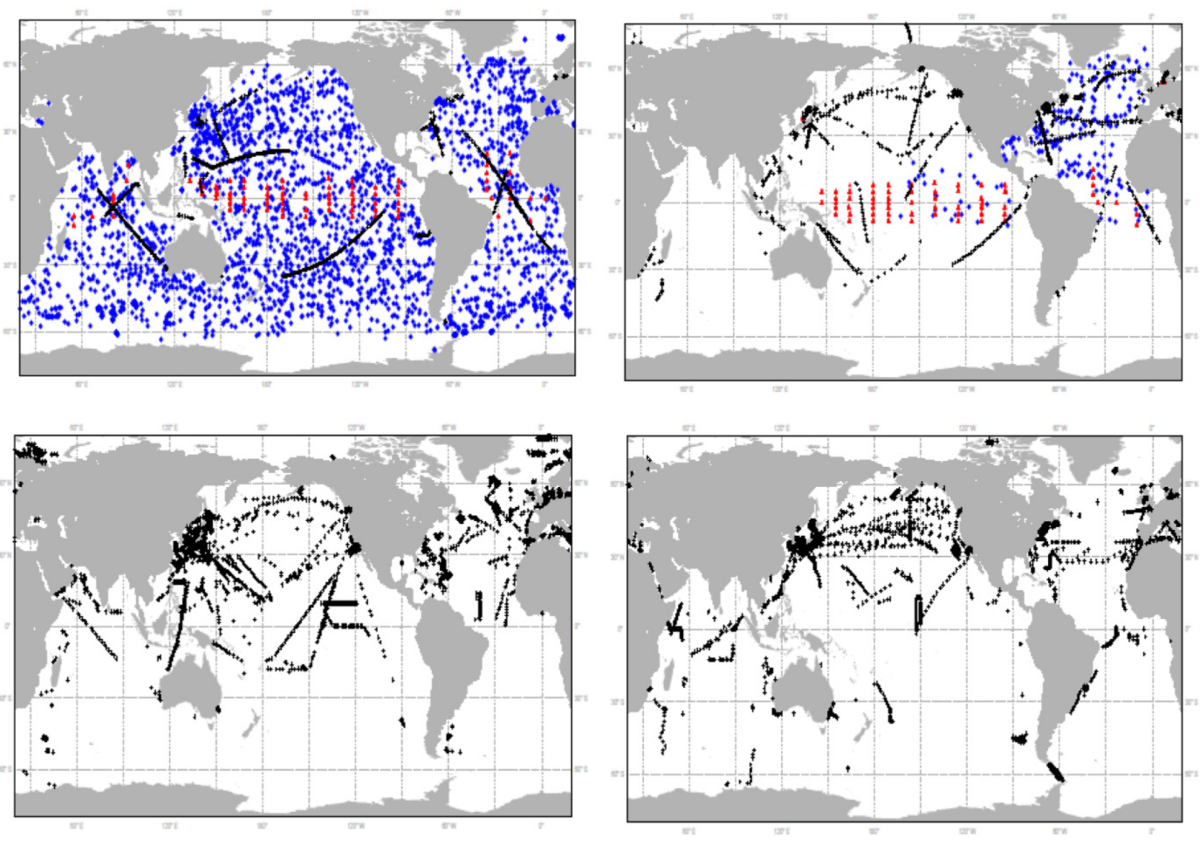

Figure 3: Coverage at 10 year intervals from 1979 (bottom right), 1989, 1999 and 2009 (top left) for 10 day intervals. Note the vast improvement in coverage of the equatorial Pacific when the TAO array was developed (red dots), and the improved mid-latitude coverage when the ARGO system was developed (blue dots). Ten days is a typical data window used in ocean analysis systems.

The first task of TOGA was to develop the XBT network in the Pacific. This had already begun prior to the formal start of TOGA through the Pacific Panel of the CCCO. The technology existed; what was required was an expanded network of ships of opportunity (largely merchant ships). This relied on a network of volunteers, to apply for funding to set up arrangements with ship operators, to train ship crew to load and fire the XBT, to make and record the data. While this was fine as an interim measure, it was not the way of the future, not least because the ships were merchant ships which took the most efficient route between ports. The coverage therefore reflected the major shipping routes, not necessarily the important oceanographic areas.

Fortunately, technology to deploy fixed moorings, to leave them in the water for months and later recover them was also evolving, largely as a result of David Halpern and Stan Hayes at PMEL (Pacific Marine Environmental Laboratory). Halpern had developed the technology to deploy moorings in the high velocity regions of the equatorial ocean in up to 6000m depths (Halpern 1987). These taught-wire surface moorings could remain in the water for many months making both thermal and current measurements. Hayes was heavily involved in the TOGA programme which called for the collection and rapid delivery of measurements of the thermal and near-surface winds across the whole Pacific within a few degrees of the equator. The mooring system had to be relatively low cost so they could be deployed in relatively large numbers across the vast expanse of the Pacific basin. Hayes, in collaboration with Ed Harrison proposed a network of ~70 moorings. One of his last papers before his untimely death in 1992 (Taft and Wallace 1996), gives an excellent description of the state of the array in 1990 when some 19 buoys had been deployed and many more planned (Hayes et al 1991). This paper also describes the proposed final array. Although Hayes did not see the completion of his dream, responsibility for the array fell to Mike McPhaden who brought the array to maturity by the end of TOGA (McPhaden et al, 1998). The ATLAS moorings (Autonomous Temperature Line Acquisition System) typically record temperatures at 10 depths in the upper 500m, as well as surface temperature at 1m and surface wind, air temperature and humidity at a height of 4 m. This has been a wonderful example of how to measure key variables in the upper 500m of the ocean. It is amazing that you can see, on a more or less real-time basis, what is happening in the equatorial Pacific, one of the remotest places on earth.

The scientific community argued successfully for sustaining the TOGA observing system after the end of TOGA. The TAO array for example was not completed until the last month of the program (December 1994) and the full benefit of this and other observing system components had not been fully realized by then; ten years was simply too short to critically determine the value of the TOGA observing system for understanding and predicting seasonal-to-interannual climate variability. Thus, the observing system was continued and later adopted as an initial contribution to the Global Ocean Observing System for climate.

One of the objectives of TOGA was to provide prediction capability if it proved possible. Early studies using simplified coupled atmosphere-ocean models such as those of Cane and Zebiak, Philander, McCreary and Anderson had shown some skill in representing low frequency variability reminiscent of El Nino. In fact the Anderson and McCreary (1986) study had also indicated eastward progression of SST in contrast to the canonical El Nino of Rasmussen and Carpenter which indicated westward progression. However, Cane et al (1986) were the first to attempt prediction using a dynamical model. Their Nature paper showed a successful prediction of the 1982/3 El Nino, initiated TWO years ahead. They went on to make a prediction for the years 1986/7, initiated at monthly intervals from Aug 1985 to Jan 1986. Their model predicted a significant El Nino, although at the time of going to press (end of May 1986) there was no sign of an El Nino developing. However, a late-developing El Nino did occur (see fig 4). The model was largely built on the Bjerknes hypothesis, but included important equatorial ocean wave dynamics. In the early days, only one forecast was made per month. The models were largely deterministic, with the atmosphere slave to the ocean; once the SST was known there was only one large-scale atmospheric state linked to that SST pattern. Whether their success had an element of beginners luck, or not, it had a major positive impact as it generated interest in ENSO prediction and gave the impression that ENSO was predictable up to two years ahead. This had the positive effect of kick starting seasonal (ENSO) prediction and lead to the development of more sophisticated forecast systems, of which the ECMWF was one of the first to develop an operational forecast system based on fully coupled general circulation models of the atmosphere and ocean. Of course, as is so often the case, the initial euphoria was not really justified. Prediction of ENSO to two years ahead is a major challenge, and is generally accepted to be beyond the usual bounds of predictability. There has been considerable progress, however.

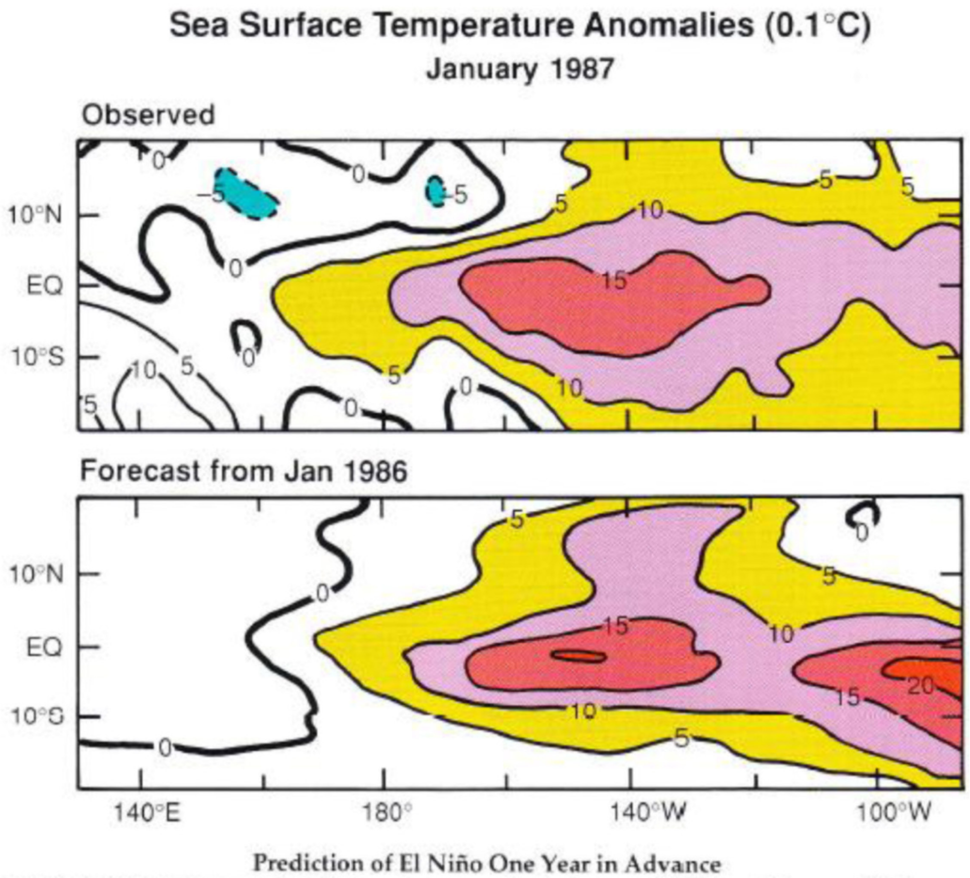

Figure 4: One of the earliest forecasts. This one was influential in the development of TOGA since it seemed to indicate considerable predictability for El Nino events. See Cane et al 1986, for a description of their forecast methodology and of a forecast for the 1986 El Nino.

2.4 Development of seasonal and monthly forecasting at ECMWF

The first seasonal forecast system at ECMWF (called System 1 or S1) was developed in 1996. This was running routinely in late 1976, (though not as part of the operational system) and showed that a significant El Nino was likely to develop in 1997. Fig 5, drafted by CLIVAR but based on the ECMWF results, shows forecasts from various starting months. Several different starting conditions were generated by perturbing the SST (Stockdale et al 1998). Different start months are shown in different colours. The solid black line indicates the subsequently observed SST. The overall impression is that seasonal forecasting is a great success. The good-looking results for the 1997/8 El Nino were probably another bit of 'beginners-luck' for subsequent development systems did not show this level of skill, especially with respect to the large amplitude. Further, if you look carefully you will see that the forecasts initiated in the spring of 1997 seriously underpredict the intensity of the El Nino. This is more obvious if you consider additional start months to those shown as illustrated in Vitart et al (2003).

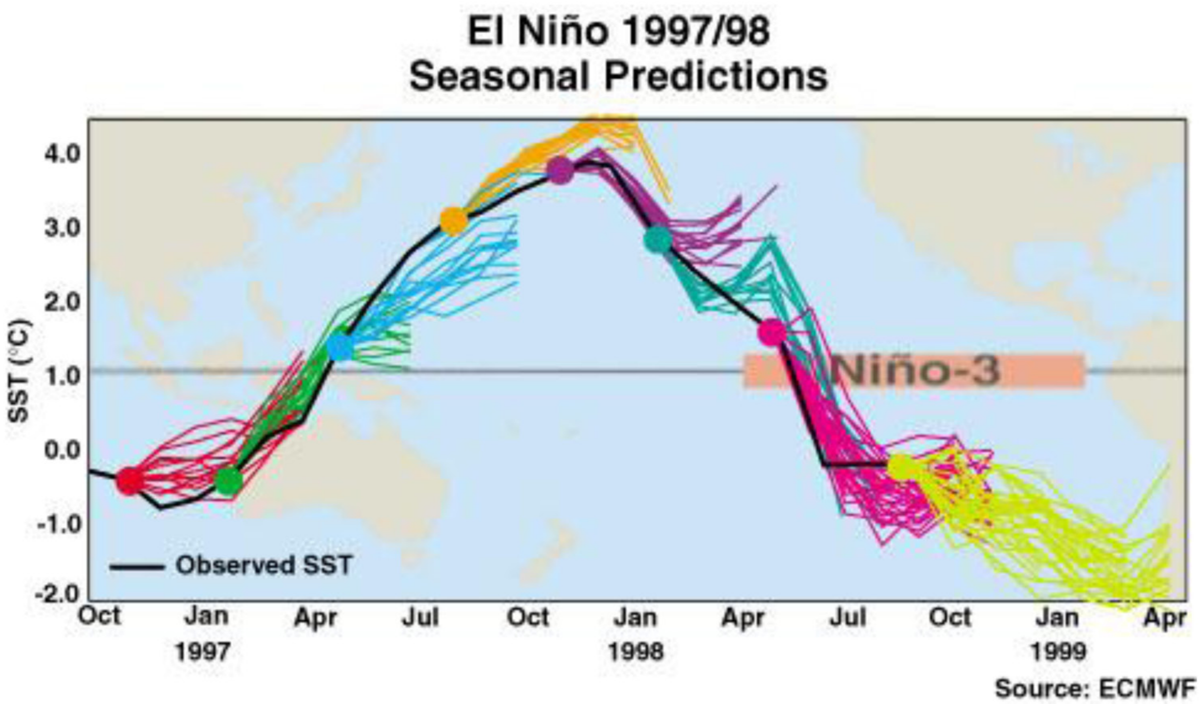

Figure 5: Realtime forecasts for the 1997/8 El Nino made with the very first seasonal forecast system at ECMWF.

In the mid-nineties, it was only possible to run a few ensemble members and even more serious, the system could only be tested on a few past cases, partly because of computer limitations and partly to the lack of appropriate reanalyses. In the Nino regions it is usually only necessary to run a few ensemble members but one would like to span as many years as possible. Although it is possible to generate many forecast realisations (i.e. ensemble members), there is only ever one realisation of truth, and so one needs to span as many years as possible to get a good assessment of how well one can predict 'truth'. If one wants to assess the skill in predicting events away from the equatorial region, the ensemble size needs to be larger as the width of the forecast probability distribution function (pdf) is wider and the shift smaller.

Anderson (2010) shows an interesting example of two forecasts of the 1997 El Nino from two different initial conditions, differing only in small perturbations to the SST-smaller than any likely measurement error. Yet after a few months, largely through the chaotic nature of the atmosphere and by association the ocean, the differences are larger than you might think. Both ensemble members predicted El Nino but the details differ significantly, especially in the mid-latitudes. If the level of variability in this model is correct, this figure shows that we will never be able to predict the details of El Nino; there will always be a substantial uncertainty resulting from chaotic processes over which we have no control. Of course this figure could exaggerate the extent of chaotic processes if the model is too active but it could also underestimate their role if the model is not sufficiently active. We do not know how active S1 really is. On the one hand it appears to be over-active when we compare the range of ENSO variability it predicts while, on the other hand, it under-represents the MJO or intraseasonal variability.

2.5 Progress over the years

It is 16 years since the development of the first ECMWF seasonal forecast system. Currently forecasts are made with the fourth system (S4) introduced operationally in 2012. Has there been progress over this time? The first thing to note is that with only four systems in 16 years, the typical lifetime of a system is about 4 to 5 years. This is in marked contrast to operational weather forecasts where model updates are made every few months. Why the different philosophy? Until relatively recently, model error was not seen as a major issue in weather forecasting. All models have systematic errors, but whereas model error can be sidestepped/ignored to some degree for weather forecasting this is not possible in extended range forecasting such as seasonal forecasting as the errors are comparable to the signal one is trying to detect and predict. One strategy for reducing model error/drift, initially proposed by Klaus Hasselmann and used extensively in long climate integrations for a number of years, is flux correction. It was seen as progress when models improved to the extent that they could be run without flux correction (Gordon et al 2000), but in recent times the use of flux correction has reappeared as the perturbed physics strategy of developing an ensemble of climate integrations has been developed (Stainforth et al 2005).

At ECMWF, in 1996 we decided not to go down the flux-correction route; part of the rational for developing seasonal forecasts was to expose model weaknesses and so lead, hopefully, to model improvements and better medium range forecasts. The strategy to deal with model error that was adopted was to run many realisations of the model over past events in order to define the model climatology. Forecast anomalies could then be obtained by comparing a forecast ensemble against the model climatology. This requires the model forecast errors to be evaluated for each start month for every month of the forecast. Initially forecasts were for 6 months, subsequently increased to 7 months and recently (in S3), the forecast range was increased further to 13 months. The correction strategy makes only a linear correction; where the correction is really nonlinear then the strategy might not work well. Experience is that is has worked rather better than was expected (Stockdale 1997, Stockdale et al 2010). An interesting spin-off is that this strategy is now being used in medium range and monthly forecasting (Hamill and Hagedorm 2007, Vitart 2004).

Most operational analysis/forecast systems make a posteriori corrections for model error. There are differences in the way skill is assessed. Atmospheric analysis systems used for reanalysis differ from those used for real-time, even at Centres producing the reanalyses. This difference may be larger at other Centres where the model used for real-time forecasting will be different, potentially substantially different, from that used for the reanalyses/reforecasts e.g. the reforecast initial conditions for the atmosphere could come from the ERA interim reanalysis, but the real-time forecasts could use initial conditions from the local (in house) analysis system. The atmospheric analyses have a wider role than just providing atmospheric initial conditions for the forecasts; they are used in driving the ocean during the ocean analysis cycle and therefore also influence the ocean initial conditions. They also influence soil initial conditions. To deal with the latter potential inconsistency, the strategy used at the Australian Bureau of Meteorology, called ALI seems to be a good compromise (Hudson et al 2010). The strategy for dealing with skill assessment at the UK Met Office is to use really high resolution for the ocean (1/4 deg) and moderately high resolution for the atmosphere. The coupled model is therefore expensive. Added to that, the UK updates its seasonal forecast system quite frequently. So to limit cost, a smaller number of hindcast years is used. This has the advantage that the observing system may be more stable, but has the disadvantage that skill assessment may be limited since fewer events are sampled.

To assess the improvement in skill over the three systems S1, S2, S3 we will consider the growth of error in the forecast period. This is shown in fig 6 for the NINO3.4 region. For comparison, the skill of using persistence is also shown. The results span the period 1987-2002. This is considerably less than the period spanned by S3 (1982-2009), but is the longest common period for the three systems. This figure, from Stockdale et al 2011, clearly shows the reduction in error in S3 compared with S2 which in turn was considerably better than S1 in terms of growth of forecast error. Also shown in the lower three curves is the spread of the ensemble. This can be considered as a measure of predictability, the best we can achieve, if the model and initial conditions were essentially perfect. One can think of this as the error one would obtain if one took an ensemble member as truth and measured the difference of other ensemble members from this truth as error. The difference or growth of error is that which results from chaotic i.e. unpredictable processes. Clearly there is a marked difference between the three estimates of perfect forecast error and that which is currently achieved. This is good news since it implies that as the models get better and we can create improved initial conditions, primarily ocean initial conditions the error in the forecasts will be much smaller than it is currently. There is a smaller difference in the predictability limits of the three systems. Some difference is to be expected since they are model estimates and as the properties of the model change, so too can the estimates of predictability. On the other hand, the estimates do not differ very much which suggests the estimates may be fairly stable and realistic. A figure such as this does not tell the whole story, however. S1 was much more active i.e. it forecast larger SST anomalies than S2 or S3.

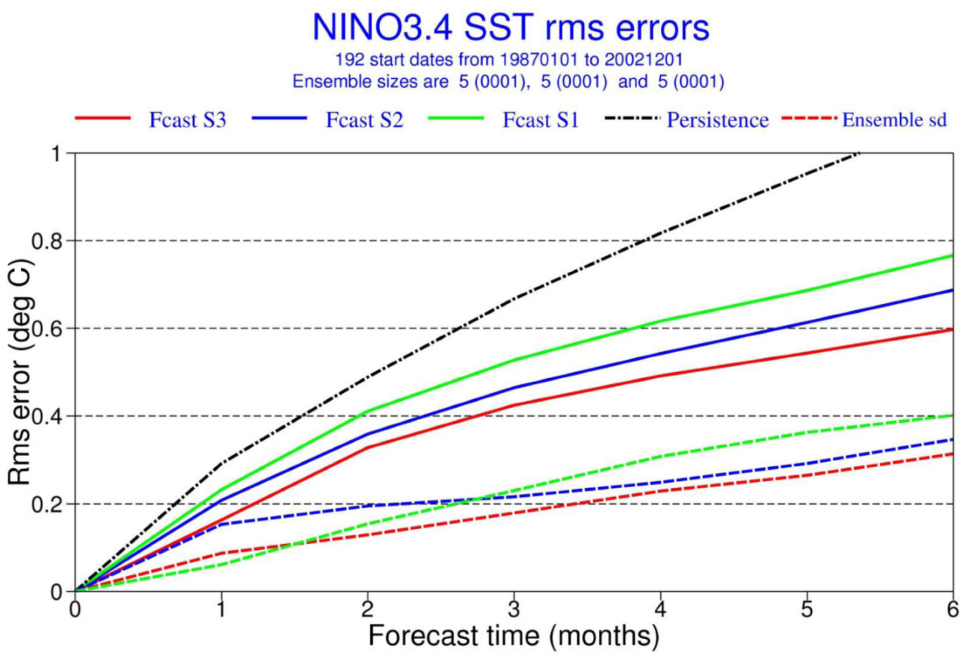

Figure 6: Plot of the growth of error as a function of leadtime for the first three ECMWF seasonal forecast systems. This plot shows a steady reduction in the growth of error with developing systems. The dashed lines show the ensemble spread. This does not show much difference as the forecast systems develop, indicating that this might give a measure of the growth of error in a perfect system.

In fact it was overactive in that the anomalies on average were larger than observed anomalies whereas S2 was underactive. S3 is also on the underactive side though not as strongly so as S2 (Anderson et al 2007). This figure has another interpretation, however; that the forecast system is too confident. The growth of error in reality is larger than it is estimated to be i.e. the system is too confident in its forecast probabilities. This can be offset to some degree by the use of multimodel forecasts or calibration of the forecasts. See EUROSIP, ECMWF web site, or Palmer 2006 and other papers in that book.

In summary, there has also been significant progress in seasonal climate prediction since the end of TOGA. As a direct result of the research advances during TOGA, operational seasonal forecasting has been established at the major numerical weather prediction (NWP) centers around the globe such as NCEP, ECMWF, the UK Met Office, the Japan Meteorological Agency, Meteo-France, the Australian Bureau of Meteorology, and others. There have also been significant refinements in seasonal forecasting techniques, with improved model resolution, physical parameterizations, and initialization systems. Ensemble forecasting methods have been introduced to improve reliability, provide probabilistic forecasting information, and to quantify forecast uncertainties. These improvements have led to steady improvements in ENSO forecasting.

2.6 The post-TOGA era and the development of CLIVAR

The 1997-98 El Niño provided one measure of TOGA's success. This El Niño was by some measures stronger than even the 1982-83 El Niño (McPhaden, 1999). In stark contrast to the confusion that surrounded events 15 years earlier, evolution of the 1997-98 El Niño was tracked day by day with dramatic clarity via space-borne and in situ sensors of the TOGA observing system. High temporal resolution real-time data from the TAO array highlighted the role of episodic westerly wind burst forcing associated with the MJO on the onset, and amplification (see fig 7). Development of oceanic anomalies was mediated by wind-forced downwelling intraseasonal time scale equatorial Kelvin waves as strikingly illustrated in both TAO data and TOPEX/Poseidon altimeter data. Once underway, data from the TOGA observing system provided the observational underpinning for seasonal forecasts in different parts of the globe that, with a few notable exceptions, proved to be surprisingly accurate. Among the exceptions were near normal seasonal rainfall totals in India, Australia and South Africa where extreme drought had been anticipated. Forecasting successes were also tempered by the possibility that there was little skill in predicting the explosive onset of this El Niño 1-2 seasons in advance (Barnston et al, 1999a).

It was clear even before TOGA ended that, despite its great successes, it would fall short of expectations in several areas. In the tropical Indian and Atlantic Oceans, ocean-atmosphere variability was not as thoroughly studied, ocean observing systems were not as well developed, and not all sources of predictability on seasonal-to-interannual time scales were identified. Predictability of the higher latitudes under the influence of the tropics, though a strong motivation for TOGA, was also less fully explored than expected. In addition, there were unanswered questions with regard to the ultimate limits of ENSO predictability and what determined them.

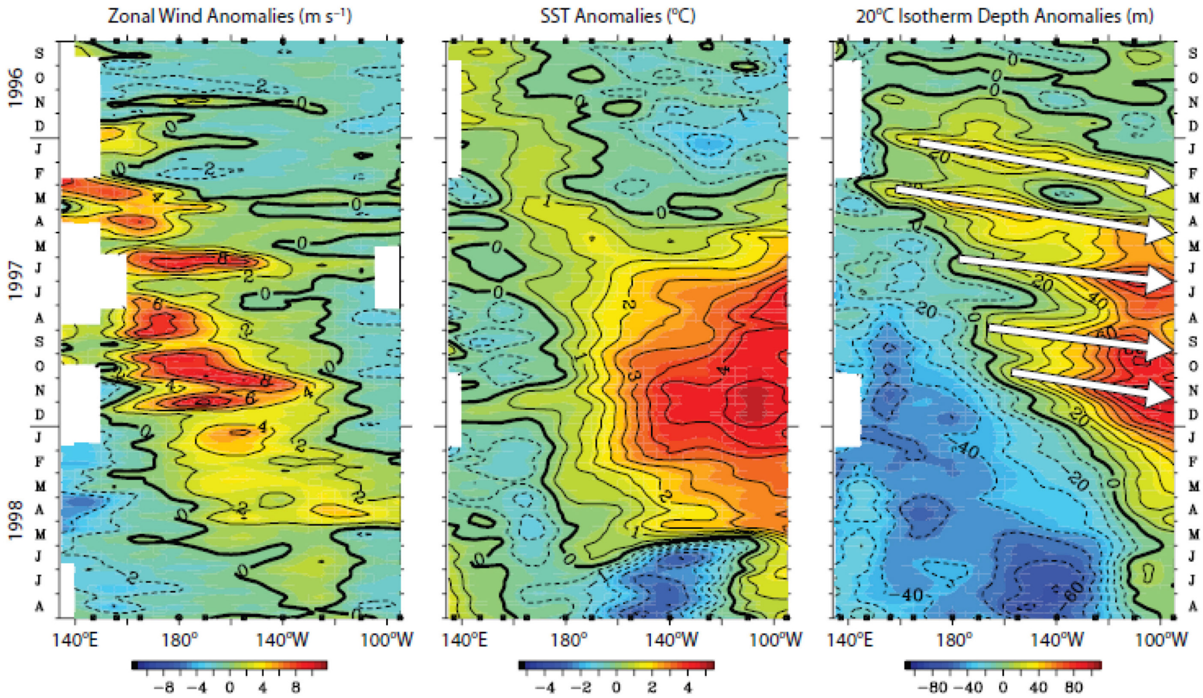

Figure 7Time versus longitude sections of anomalies in surface zonal wind (left), SST (middle), and 20°C isotherm depth (right) from September 1996 to August 1998. Analysis is based on 5-day averages of moored time-series data from the TAO array between 2°N and 2°S. Anomalies are relative to monthly climatologies that were cubic spline fit to 5-day intervals. The 20°C isotherm is an indicator of thermocline depth along the equator. Black squares on the abscissas indicate longitudes where data were available at the start (top) and end (bottom) of the time series. Arrows indicate the eastward propagation of downwelling equatorial Kelvin waves in response to the episodic westerly wind burst forcing. (After McPhaden et al 2010).

Thus, the WCRP initiated the Climate Variability and Predictability (CLIVAR) Program in 1998 to carry on the work of TOGA and its sister program WOCE which ended in 1997. Under CLIVAR, many new threads of research developed, some of which were initiated or anticipated by TOGA, and others of which were new. CLIVAR stimulated further efforts to define the different flavours of El Nino i.e. eastern v central Pacific (or modoki) El Nino events (Larkin and Harrison 2005, Ashok et al (2007)). The role of heat content variations along the equator as a precondition for El Niño and La Niña development through both theory and observation (Balmaseda 1995, Jin, 1997; Meinen and McPhaden, 2000) was further investigated. The mechanisms by which intraseasonal atmospheric forcing can initiate El Niño development were also more clearly identified (e.g., Kessler et al, 1997). Moore and Kleeman (1999) among others found that intraseasonal wind fluctuations, because they occur on time scales short compared to a season, represent stochastic forcing of the ENSO cycle and therefore potentially a significant limitation on its predictability.

The Indian Ocean Dipole (IOD), the dynamics of which share similarities with ENSO (Murtugudde et al, 2000), was discovered during CLIVAR (Webster et al, 1999, Saji et al, 1999). Regional ocean-atmosphere interactions associated with the 1997-98 IOD event were viewed as a possible cause for mitigating expected El Niño droughts in India, Australia and South Africa during the 1997-98 El Niño. Further discussion of the predictability of the IOD is presented in the next section. Tropical Atlantic climate variability and its regional climatic impacts also emerged as an important CLIVAR research theme (Chang et al, 2006).

CLIVAR also spearheaded efforts to understand the connection between ocean conditions and extreme mid-latitude droughts and pluvials (Schubert et al, 2009). Numerous studies have identified changes in atmospheric circulation associated with tropical SST anomalies, in particular those in the Pacific associated with ENSO and longer term decadal fluctuations, as a principal driver of extended dry and wet periods over North America and elsewhere. Unusually cold SST anomalies in the eastern and central equatorial Pacific for example have been identified as a primary forcing for the extended U.S. “Dust Bowl” drought of the 1930s and the 1998-2004 drought in the western U.S. (Hoerling and Kumar, 2003; Seager et al, 2005).

Ocean and atmosphere reanalysis efforts have expanded in recent years to encompass more data over longer periods of time. Compared to the first 5-15 year reanalyses undertaken during TOGA, 40-100 year ocean and atmospheric reanalyses now exist (Kalnay et al, 1996; Kistler et al, 2001; Uppala et al, 2005; Compo et al, 2006; Carton and Geise, 2008; Balmaseda et al 2008; Wunsch et al, 2009). In addition, the latest generation of model-based analysis systems is better at extracting information from the data through refinements in assimilation techniques and through the inclusion of a more diverse set of observations.

Although much of the emphasis so far in this paper has been on ENSO and the Pacific, there are promising indications that climate variability in the tropical Atlantic and Indian Oceans may be predictable at lead times of 1-3 seasons based on both external ENSO influences and ocean-atmosphere interactions internal to these basins (Barreiro

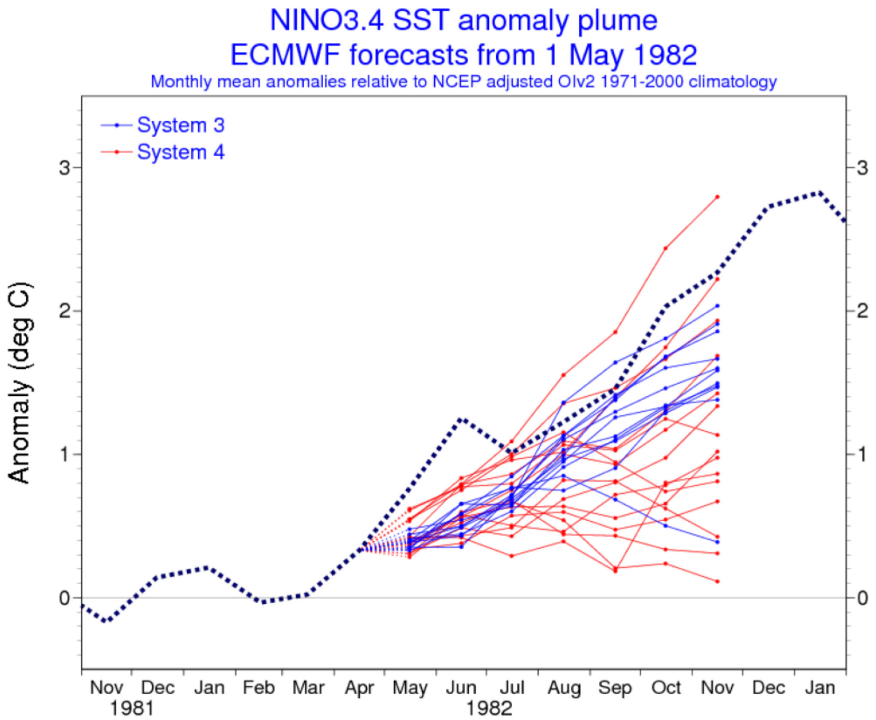

Figure 8: Forecasts for the 1982/3 El Nino made from the latest and second latest forecast systems at ECMWF. Forecasting the large amplitude of the 1982/3 El Nino has not been so easy.

et al, 2005, Wajsowicz, 2005; Li et al, 2012). However, seasonal forecasting efforts are not as advanced and forecast skill is in general not as high for, say, the Indian Ocean Dipole or tropical Atlantic climate variability as for ENSO. Compared to the Pacific, year-to-year climate variations in the other basins are weaker, shorter-lived, and therefore more difficult to accurately predict. The source of predictability in these regions appears to involve variations in upper ocean heat content and land surface processes on adjacent continents. Systematic errors in coupled ocean-atmosphere-land models and, for the Indian Ocean, an incomplete ocean observing system are among the major hurdles to improved forecast skill in these basins (Balmaseda and Anderson, 2009). In the next section, the Indian Ocean will be considered in more detail. However, before doing so, I want to return to prediction of the 1982/3 El Nino, and to end this section on a cautionary note, pointing out that although there has been progress over the years, forecasting the 1982/3 El Nino remains a challenge. Fig 8 shows forecasts from S3 and S4 for Nino 3.4. In both cases the observed SST lies almost outside the forecast ensemble, and the impression is given that the amplitude of the event was underpredicted.

3 Predicting the Indian Ocean dipole

In the years preceding TOGA, there had been considerable interest in the oceanography of the Indian ocean but mainly for the interesting dynamics of the Somali current and its rapid reversal each year, and of the Low level or Somali jet in the atmosphere, both of which are western boundary phenomena. In the early years of TOGA there was an attempt (not very successfully) to establish an observing system for the Indian ocean although there was no clear indication at that time that the Indian Ocean played a major role in interannual climate variability. Over the years however, there has been an increasing awareness that the Indian Ocean is potentially an important player, and so some aspects of the skill in predicting its variability will be considered.

In light of the growing recognition of the role of surface temperature variations in the Indian Ocean for driving global climate variability, Li et al (2012) have made a recent assessment of the predictive skill of SST anomalies associated with the Indian Ocean Dipole (IOD) using ensembles of seasonal forecasts from a selection of contemporary coupled climate models that are routinely used to make seasonal climate predictions. It is now better appreciated how SST variations in the tropical Indian Ocean are a primary source of seasonal climate variability throughout the adjoining land masses of eastern Africa (e.g., Black et al. 2003; Clark et al. 2003), Asia (e.g., Saji and Yamagata 2003), the Maritime Continent (e.g., Hendon 2003) and Australia (e.g., Nicholls 1989; Ansell et al. 2000; Cai et al. 2011).

The Indian Ocean Dipole (IOD; e.g., Webster et al. 1999, Saji et al. 1999) is a zonal mode of variability in the tropical Indian Ocean, tightly tied to the seasonal cycle, with events tending to develop in boreal summer, peak in fall and decay rapidly in winter. It is also tied to ENSO, with peak negative phases (warm eastern Indian Ocean) tending to occur during La Niña (e.g., Shinoda et al. 2004b). See fig 9. The variations of tropical rainfall in the Indian Ocean during an IOD event not only affect the immediate local climate in the tropical Indian Ocean but also act to excite atmospheric Rossby wave trains giving rise to extratropical climate variability.

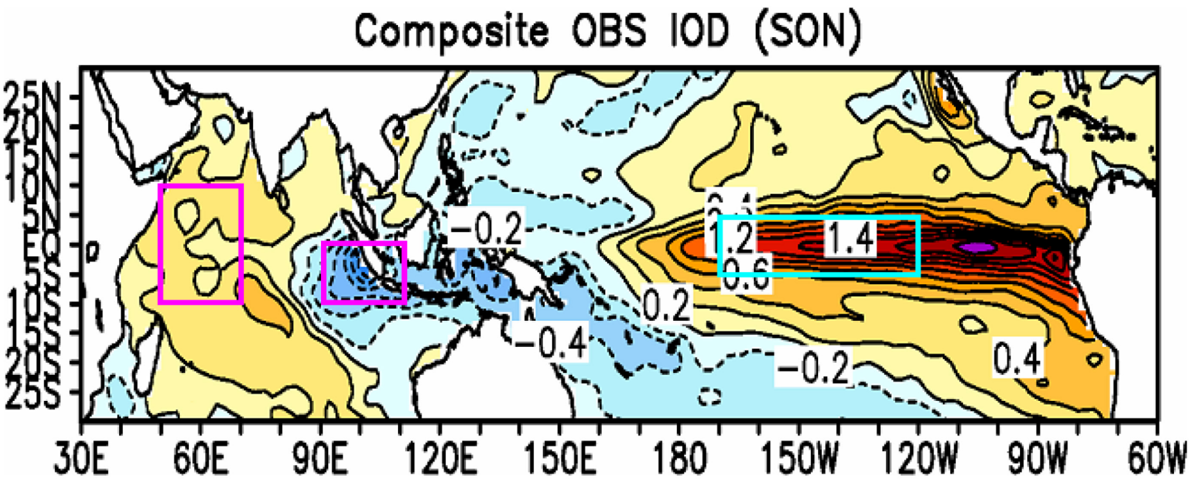

Figure 9: Composite seasonal mean (September-November) SST anomaly for positive IOD events. Contour and shading interval is 0.2°C. Boxes indicate area means for WIO, EIO and NINO3.4 SST indices as used in Li et al 2012.

The role of SST variations due to the IOD for driving rainfall variations across southern Australia during ENSO is especially important (e.g., Cai et al. 2011). Hence, predictability of rainfall across southern Australia during ENSO is limited by the ability to predict the IOD. Furthermore, although IOD events tend to co-occur with El Niño, this is not always the case and so it is important to be able to predict variations of the IOD and, more generally, SST throughout the tropical Indian Ocean that are independent of ENSO in order to progress the capability to make seasonal climate forecasts.

Forecast skill of the IOD has previously been assessed using a range of coupled climate models and verification approaches (e.g. Wajsowicz 2005, 2007; Zhao and Hendon 2009; Kug et al. 2012). These suggested that the lead time for skillful prediction of the IOD was only about 3-4 months because there was a strong boreal spring "predictability barrier". On the other hand, some strong individual IOD events (i.e. 2003, 2006) have been reported to be predictable at long lead times which may stem from their association with El Niño (e.g., Song et al. 2008; Zhao et al. 2010).

Because of the importance of climate variations linked to the IOD, it is important to know what the current capability of predicting the IOD is and how it varies between models. Li et al (2012) find the lead time for skilful prediction of SST in the western Indian Ocean to be about 5-6 months while in the eastern Indian Ocean it is only 3-4 months when all start months are considered. For the IOD events, which have maximum amplitude in the September-October-November (SON) season, skilful prediction is limited to a lead time of about one season. Li et al went on to consider whether there was enhanced skill for large IOD events, as had been suggested by Luo. Indeed they do find that large events can be predicted further ahead, and that in that sense there is enhanced skill. However, this has to be interpreted cautiously as they also find a tendency for the models to over-predict the occurrence of large events limits so limiting confidence in the predictions of these large events.

4 Higher frequency events

So far I have discussed El Nino/ La Nina or ENSO, and the role of the Indian Ocean Dipole. Although there is much further work to be done in model development and initialisation to improve forecast skill, including the teleconnections within the tropics and to and from midlatitudes, there are other potential limits to forecast skill. One of these, the intraseasonal oscillation, or Madden Julian Oscillation (MJO) has already been mentioned. I want to end discussing another, which involves not only ENSO and the MJO, but extends even to Antarctica. As highlighted by Hendon et al (2012), Austral spring and summer 2010/11 saw some of the heaviest rainfall and extensive flooding in Australia ever recorded. They concentrate on spring, rather than summer, because spring rainfall is important for water resources and farming, but may also be more predictable than summer rainfall.

A primary cause of the heavy rains over Australia was undoubtedly the strong La Nina which developed in the latter half of 2010 (Nicholls 2011). Australia usually experiences above average rainfall during La Nina. The IOD can also contribute. The third contender is the Southern Angular Mode or SAM. Hendon et al show that the SAM contributed to the higher than normal surface pressure in higher latitudes. Indeed the SAM index had its highest value for at least 50 years. Hendon et al (2007) have shown that rainfall in Austral spring is increased in east central Australia during high SAM and indeed the combination of La Nina and high SAM results in the wettest conditions.

Hendon et al 2012 estimate that SAM contributed up to 40% of the excess rainfall in central east Australia in the spring of 2010. The impact of SAM and other contributors, viz ENSO and IOD, vary geographically. So while SAM may play a more important role than the IOD in some regions, the IOD may be more important than SAM in others. One of their key results is that the record rainfall in central east Australia resulted from the co-occurrence of a very strong La Nina and a record SAM.

This work is retrospective. The occurrence of SAM is generally thought not to be predictable on seasonal timescales, but is this necessarily so. Could there have been some underlying reason why SAM was so strong for so long, perhaps the existence of a strong La Nina? If this is not so, and SAM is indeed unpredictable, then accurate (precise) prediction of a significant part of the rainfall across large portions of Australia would not be predictable.

The role of usually higher frequency events such as SAM, MJO, NAO is unknown. If their distribution is influenced by ENSO then they might be on occasion more predictable. On the other hand they might also influence ENSO. Although the role of higher frequency events is currently unclear, as models improve to represent these processes better, biases are reduced and teleconnections improved, the ability to represent these events will get better and some answers may be forthcoming.

5 Outstanding issues

It is apparent that in the 25 years since TOGA began, there has been great progress in our ability to observe, understand, and predict climate variability and change. In a real sense though, TOGA's work is still not complete. Except for the regular progression of the seasons, ENSO is the most predictable climate fluctuation on the planet. Yet, despite the advances in seasonal forecasting, predicting the onset, demise, and ultimate amplitude of ENSO events remains a challenge. The 2006-07 El Niño, which started late and ended early, is typical of how important details in the evolution of the ENSO events continue to be missed by forecasters (McPhaden, 2008). Stochastic forcing related to westerly wind bursts and the MJO, chaos in the climate system, model biases, errors in initial conditions all affect ENSO forecast error growth. Model bias in particular is still a major problem in all climate models, many of which fail to realistically simulate the mean state, the mean seasonal cycle, and ENSO (Latif and Keenlyside, 2009).

Ongoing research may reduce bias and other errors in coupled models, extending the limits of predictability. For example, operational seasonal forecasting using dynamical models for example is presently based on uncoupled initialization of the oceanic and atmospheric components of coupled systems. Hence it may be possible to improve model forecast skill a bit through development of coupled-ocean atmosphere assimilation schemes to reduce initialization shock. We can also anticipate improvements from more careful use of multi-model approaches and through mining additional sources of predictability, such as land-surface processes and stratosphere-troposphere interaction (Kirtman and Pirani, 2009). Improvements in observing systems, especially in the Indian Ocean, may also help to reduce errors in initial conditions. In addition, large-scale evolving ENSO SST patterns have been shown to organize the seasonal statistics of atmospheric noise forcing (Eisenman et al, 2005) and it may be possible to exploit this feedback to improve seasonal forecasting techniques.

Predicting climate impacts on seasonal-to-interannual time scales is also still a challenge. For example, the unexpected drought in western South America during the 2002-03 El Niño resulted in serious hardship for farmers and others who acted on forecasts for unusually wet conditions typical of most El Niño events. The 2002-03 El Niño however, was a central Pacific or "modoki" El Niño that did not involve significant anomalous warming or rainfall in the eastern Pacific. Normal Indian summer monsoon rainfall in 1997 during the intense 1997-98 El Niño was also unexpected. Drought was mitigated possibly because of the co-occurrence of an Indian Ocean Dipole that year or because of a changing relationship between ENSO and the monsoons on decadal time scales (Kumar et al, 1999). Predicting climate impacts associated with ENSO outside the tropics is likewise problematic because weather noise can obscure teleconnections from the tropics, especially for weaker El Niños and La Niñas.

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