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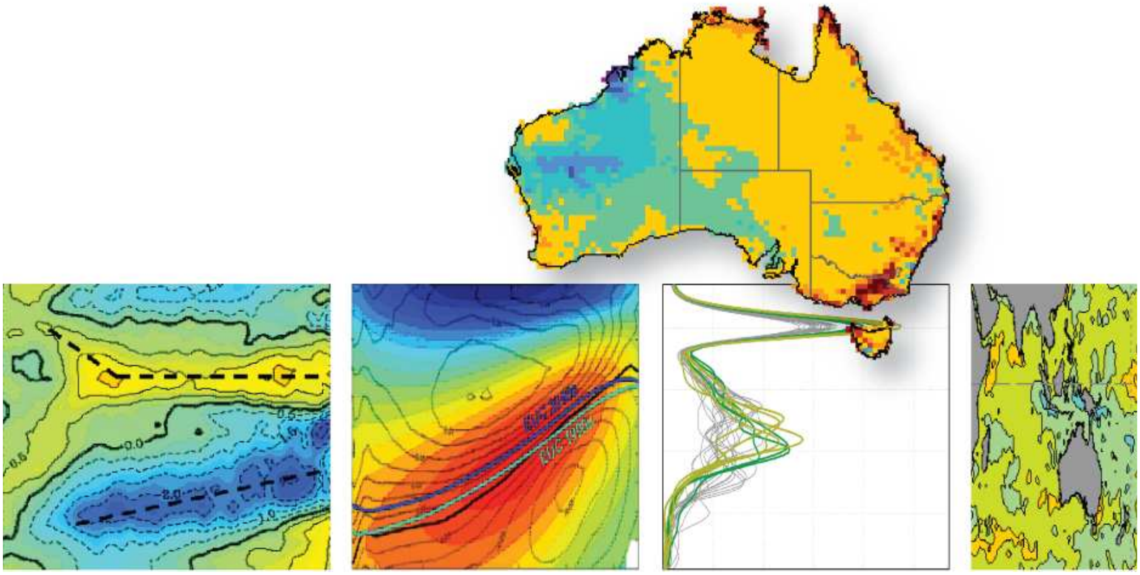

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A CSIRO Office of the Chief Executive Science Team Cutting Edge Science Symposium

International ENSO Workshop: El Niño and Climate Change

25-27 March 2009
Burswood Convention Centre, Perth

Australian Government
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WCRP
World Climate Research Programme

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PREFACE

Due to the great global impacts of the El Niño-Southern Oscillation (ENSO) phenomenon, and widespread concern over climate change, a critical question is “how will ENSO respond to global warming?”. To address this issue, an international World Climate Research Program (WCRP) Workshop “El Niño and Climate Change" was held in conjunction with a wider conference called Greenhouse 2009, in Perth, Australia, March 25-26. The workshop was attended by over 60 participants, including at least 25 from overseas. The workshop focused on the dynamics and predictability of ENSO and interactions between ENSO and global warming. The research has become a profound area of mathematical physics. There are only a few people in the world who have the skills to do this research and the workshop was successful in bringing many of them to Australia. They presented their latest findings at the conference and the workshop. This report provides a summary of these findings.

SUMMARY

Given that ENSO and climate change has had an enormous impact on humanity in the past, and will continue to do so in the future, the mathematical physics of ENSO is a topic that has widespread and profound global repercussions. Unravelling how ENSO works and how it will respond to global warming will in time lead to more accurate predictions and help to underpin large social and environmental benefits. Most of the results presented at this Workshop are at the forefront of the science. The results provide advances on what was reported on in the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007).

The workshop included much discussion of a new direction in ENSO research: recognition that the so-called "flavours" or “vintages” of ENSO events are the consequence of a complex, highly non-linear and dynamical system that can have very different impacts on climate in many parts of the world – including Australia. In addition, recent results from GFDL, the UKMO and a research group based in Hawaii were presented that support the view that El Niño might become more frequent and more intense under global warming. While there is still no consensus on this issue (IPCC 2007), the emergence of these 3 independent but corroborating studies post IPCC 2007 is noteworthy, concerning, and deserving of further investigation.

The workshop programme was organised so that it began with a basic definition of ENSO and ENSO indices, followed by discussion of ENSO properties in palaeo-climate records, the skill of current prediction methods, ENSO triggers and their interaction with other climate drivers, and ENSO’s response to global warming.

The workshop also saw an intensification of efforts to document and understand past variability and change in ENSO. For example, there have been modelling studies aimed at improving our understanding of how ENSO and the tropical Pacific changed during epochs in our paleo-climatic past, and meticulous observational studies aimed at increasing the accuracy of indices used to track variability linked to ENSO over the past 150 years.

Sometimes the term ‘El Niño-like’ is used to characterize global warming. While the maximum in precipitation response is east of the warm pool, there is a reduction in the SST gradient in the equatorial Pacific. There is also a reduction in thermocline tilt; however, there are many other changes under global warming that do not resemble El Niño at all. Furthermore the changes evident in the tropical Pacific arise from different reasons to the counterpart changes that occur during El Niño. Given these and other important differences the characterisation of global warming as “El Niño-like” is not appropriate and best avoided.

Changes under global warming may be better characterised by stating that:

- wet places tend to get wetter;
- dry places tend to get drier;
- there is a poleward expansion of dry zones; and
- the atmospheric circualtion in the tropics tends to weaken – especially the Walker circulation.

Research has highlighted that the weakening of the trade winds, the strengthening of air pressure over northern Australia and the apparent increase in the frequency of El Niño have reached record levels in recent decades and a good deal of research is being conducted to clarify the extent to which these and other associated changes are driven by global warming and natural variability.

A good deal of attention is being given to documenting, improving and understanding the imperfections that climate models have in simulating ENSO and its teleconnections. This includes work that is looking in great detail at the 1918/19 El Niño event.

Other work presented here illustrates that while we still have a lot to learn, we now have a clearer understanding of the interesting differences in the evolution of large and moderate El Niño events; the importance of linkages between ENSO and the Indian Ocean Dipole (IOD); the importance of the Madden–Julian oscillation (MJO) to ENSO prediction; the character, dynamics and impacts of Modoki El Niño events; and the interplay between the mean-state, the annual cycle and the amplitude of ENSO.

EVIDENCE OF CHANGING AND ROBUST ENSO

ENSO exists in our remote past, even when the climatic conditions were rather different from the present-day climate. However, El Niño events have become more frequent in recent decades (IPCC 2007), at the same time global temperatures have risen sharply to levels not seen for thousands of years. Modelling studies indicate that ENSO will continue to operate into the future as global warming intensifies, but the impact of global warming on the frequency of El Niño in recent decades and on the frequency and intensity into the future remains unclear. Certainly large generational changes can occur in ENSO properties through complex spontaneously generated variability in the coupled atmosphere-ocean system without the need for human intervention or human-induced changes (e.g., Power et al. 2006).

ENSO dynamics through the exploration of past climates

Historical reconstructions from across the Pacific Basin show that significant changes in ENSO characteristics took place during the Holocene Epoch, which spans the past 12,000 years (e.g. Rodbell et al., 1999; Moy et al., 2002). Weak decadal-scale events occurred during the early Holocene, with 'modern' El Niño variability beginning around 5,000-7,000 years ago. Thereafter, there was a gradual strengthening of ENSO, with a possible peak in variability around 1,000-2,000 years ago. One record which clearly illustrates these changes is the sedimentary evidence from Laguna Pallcacoha in southern Ecuador (Moy et al., 2002; Figure 2). Exploring past changes in ENSO, using both data and models, provides a means of understanding ENSO dynamics. It can also provide insights into the mechanisms that drive changes in ENSO behaviour, allowing us to anticipate how ENSO might evolve in a warming world. This was the topic of the presentation by Dr Steven Phipps, of the University of New South Wales.

Dr Steven Phipps reviewed previous modelling work showing that orbitally-driven changes in insolation can alter ENSO behaviour. The weaker mid-Holocene ENSO is consistent with a mechanism whereby insolation changes resulted in an enhanced seasonal cycle, intensifying the Asian monsoon system. This enhanced the Walker circulation, resulting in stronger easterly trade winds in the central and western Pacific. In turn, this caused the thermocline to become steeper, increasing upwelling in the central and eastern Pacific, and hence suppressing the development of El Niño events. During the late Holocene, decreasing summer insolation over the Asian landmass resulted in a weakening of the Asian monsoon system and therefore a weakening of the easterly trade winds in the western Pacific, making it easier for El Niño events to develop. Such a mechanism has recently been tested by Dr Steven Phipps using the CSIRO Mk3L climate system model, who conducted a suite of simulations of the climate of the past 8,000 years.

The model reproduces the historical trends in ENSO variability, and therefore provides a useful tool with which to explore changes in ENSO dynamics. Consistent with the changes in insolation, the mean state of the tropical Pacific remains essentially unchanged over the Holocene, while there are large changes in the seasonal cycle. In the early Holocene, the easterly trade winds are amplified in the western Pacific during the northern autumn, consistent with an enhanced Asian monsoon. The stronger trade winds represent a barrier to the eastward propagation of westerly wind bursts, therefore inhibiting the onset of El Niño events. However, the fundamental behaviour of ENSO remains unchanged, highlighting the robustness of ENSO in the past, and suggesting that ENSO may be robust in the future.

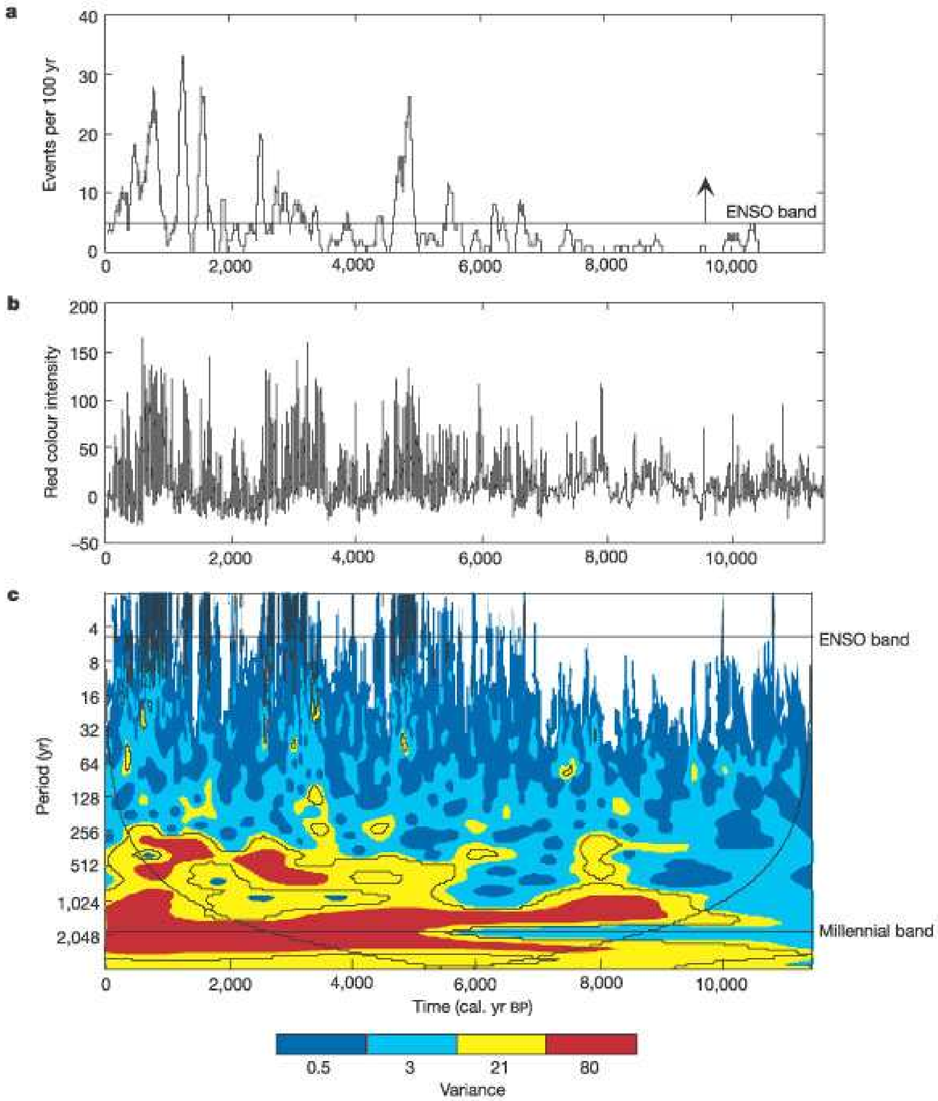

Figure 2: a), Event time series created using the event model (see Methods), illustrating the number of events in 100-yr overlapping windows. The solid line denotes the minimum number of events in a 100-yr window needed to produce ENSO-band variance (~5). b), Most recent 11,500 yr of the time series of red colour intensity. The absolute red colour intensity and the width of the individual laminae do not correspond to the intensity of the ENSO event. c), Wavelet power spectrum calculated using the Morlet wavelet on the time series of red colour intensity (b). Variance in the wavelet power spectrum (colour scale) is plotted as a function of both time and period. Yellow and red regions indicate higher degrees of variance, and the black line surrounds regions of variance that exceed the 99.98% confidence level for a red noise process (at 4–8-yr period, the regions of significant variance are shown black rather than outlined). Variance below the dashed line has been reduced owing to the wavelet approaching the end of the finite time series. Horizontal lines indicate average timescale for the ENSO and millennial band, from Moy et al. (2002).

ENSO during the Pliocene times

The Pliocene epoch is of particular interest to the climate research community because the concentration of greenhouse gases during that time is similar to what we can expect by the end of this century. The paleo record suggests that 3-5 million years (Mya) ago the tropical Pacific zonal (i.e. east-west) sea surface temperature (SST) gradient was negligible and this is sometimes referred to in some quarters as a ‘Permanent El Niño’, because the same gradient is also weakened during El Niño events in modern climate (see Figure 3). At this time there were only very small ice sheets in the Northern Hemisphere. For reasons still debated, this changed drastically. The earth went on to exhibit intermittent ice ages, and there is now a strong zonal SST gradient in the tropical Pacific. The connection between ice ages and the tropical Pacific SST gradient could be coincidental, or it could be due to atmospheric super-rotation (Tziperman et al. 2009), aliasing (Wunsch 2009), or changes in the tropical ocean (e.g., changes in the geometry of the Indonesian archipelago could force the high latitudes (Cane & Molnar 2001), or high latitude changes (e.g., the onset of glaciation, could lead to changes in tropical SST and ENSO (Fedorov et al. 2006).

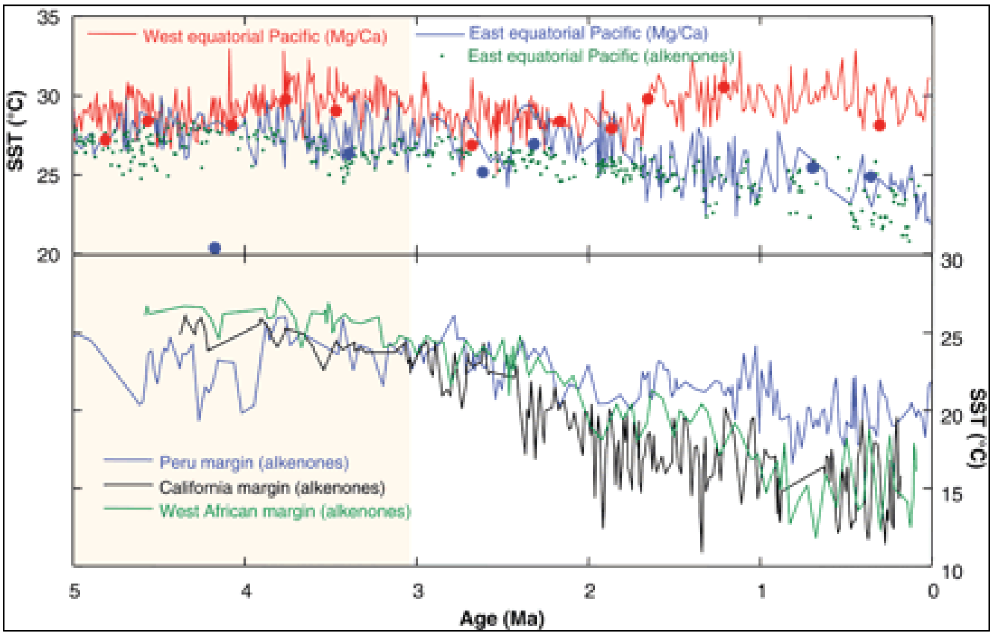

Figure 3: Time series of SST in the western equatorial (red, upper) and eastern equatotoal (blue and green, upper), and in other Pacific regions. Source: Fedorov et al. (2006).

The last two hypotheses were recently tested by Dr Marcus Jochum of NCAR with the latest version of the NCAR climate model (CCSM3.5). This version of the model is similar to CCSM3 but with the Neale et al. (2008) convection scheme included. Within the framework of this model, they reject the tropical forcing hypothesis. The hypothesis of high latitude forcing is rather vague and could not be rejected. It appears, however, unlikely that this hypothesis can explain the observed changes in the SST gradient.

The key result of their work is as follows (Jochum et al. 2009). Firstly, assumptions about the effect of the Indonesian islands on the equatorial thermocline, and about the connection between equatorial thermocline and ENSO, do not hold in climates like the Pliocene or our future. They found that the bigger the throughflow passage, the less water is transported because of other factors, and climate changes induced by the changes of throughflow are minor and too small to cause large global or even basin scale changes. Further, compared to the control experiment, ENSO in the Pliocene is more stochastic and less deterministic. Finally, the future of ENSO may depend less on the structure of the equatorial thermocline, but more on the structure of the off-equatorial SST. Even in a much warmer world ENSO with similar magnitude and frequency can exist, albeit with a weaker Bjerknes and a stronger latent heat flux feedback.

Verified estimation of the El Niño index NINO3.4 since 1877

Professor Allan Clarke of the Florida University made the point that decadal and longer time scale variability of our best known ENSO SST indices are poorly correlated before 1950 and so our knowledge of ENSO and its interdecadal variability and trend before 1950 is restricted. How does decadal and longer term variability affect ENSO? Can we tell whether Niño3.4 has even warmed? Are conditions becoming more El Niño or La Niña like?

These issues are addressed by Prof. Allan Clark and colleagues by constructing and comparing physically related monthly ENSO indices. The constructed indices include a base index, NINO3.4 (the SST anomaly averaged over the equatorial box bounded by 5°N, 5°S, 170°W and 120°W), indices based on the night-time marine air temperature over the NINO3.4 region (NMAT3.4) and an Equatorial Southern Oscillation Index (ESOI). The NINO3.4 index used the HadSST2 monthly dataset (Rayner *et al*. 2006), a dataset with smaller uncertainty and better geographical coverage than others.

In constructing the index, data at each point for a given month were weighted to take into account the typical considerable spatial variation of the SST anomaly over the NINO3.4 box as well as the number of observations at that point for that month. Missing monthly data were interpolated and 'noise' was reduced by using the result that NINO3.4 has essentially the same calendar month amplitude structure every year. This 12-point calendar month structure from April to March was obtained by an empirical orthogonal function (EOF) analysis over the last 58 years, and then was fitted to the entire monthly time series using a least squares approach. Equivalent procedures were followed for NMAT3.4 and ESOI. The new ESOI index uses Darwin atmospheric pressure in the west and is based on theory that allows for variations of the atmospheric boundary layer depth across the Pacific. The new NINO3.4 index was compared with NMAT3.4, the new ESOI and with a record of $\delta^{18}O$ from a coral at Palmyra, an atoll inside the region NINO3.4 (Cobb *et al*. 2003).

Correlation coefficients between NINO3.4 and the three monthly indices mentioned above before 1950 on interannual and decadal time scales are 0.84, 0.87, 0.73 and 0.93, 0.86, 0.73, respectively. These relatively high correlation coefficients between physically related but independent monthly time series suggest that Professor Clarke and his colleagues have improved our knowledge of low-frequency variability in ENSO. All four indices are consistent with a rise in NINO3.4 SST since the beginning of the record and are accompanied by the weakening of the equatorial trade winds, especially since about 1970 when anthropogenic global warming seems to have accelerated (Figure 4).

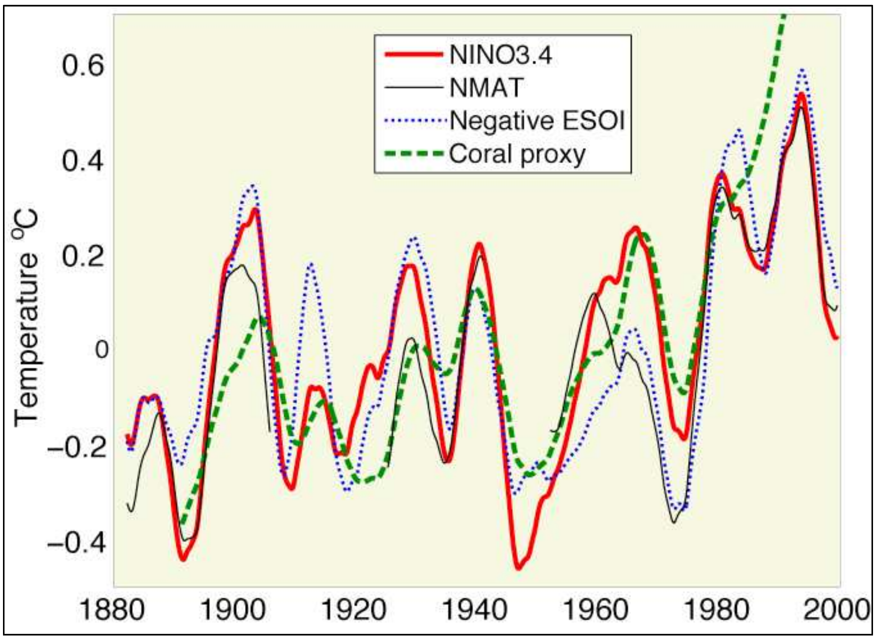

Figure 4: Time series of verified ENSO indices. See text for details regarding their definition.

Professor Clarke showed that all indices agree well on decadal and longer time scales. In particular, since about 1970, there has been an upward trend in SST, air temperature and negative ESOI. The strong consistency in these indices suggests that there is a global warming signature in the Pacific, where the warming pattern is "El Niño-like." This is consistent with recent model results that suggest that the Walker Circulation has been weakening since 1970. This work has been published since the workhop (Bunge and Clarke 2009).

Has ENSO become stronger? Lessons from the 1918 El Niño

Continuing the theme of determining the strength of El Niño events, Prof. Ben Giese highlighted the need to examine ENSO behaviour in the first part of 20th century to understand global warming, but with a focus on the 1918/19 event. In many respects, the impact of 1918/19 event was extraordinary. It coincided with failure of the Indian monsoon, and is associated with one of the most severe droughts of the 20th century. During this time, 25 million people died from a flu pandemic. Available data would suggest that it was a mild event although before World War II there were very few observations to rely on. If 1918 El Niño was weak, why were the effects so extreme?

Because of limited ocean observations from the early part of the 20th century, little is known about El Niño events prior to the 1950s. Yet, it is essential to know the strength of El Niño events in the first part of 20th century to understand global warming. The SODA (Simple Ocean Data Assimilation) Group is working toward the completion of an ocean reanalysis of the 20th century. In preparation for the extended reanalysis, the group conducted an ocean simulation (SIMU 3.0.2) using winds that extend back to 1908 (C20r), and an ocean reanalysis (SODA 2.1.2/2.1.3) for the period from 1958-2007. The ocean model for both runs is based on the Parallel Ocean Program (POP) software. The ocean model has a global average 0.4° (longitude) × 0.25° (latitude) × 40-level eddy-permitting resolution with 10 m spacing near the surface.

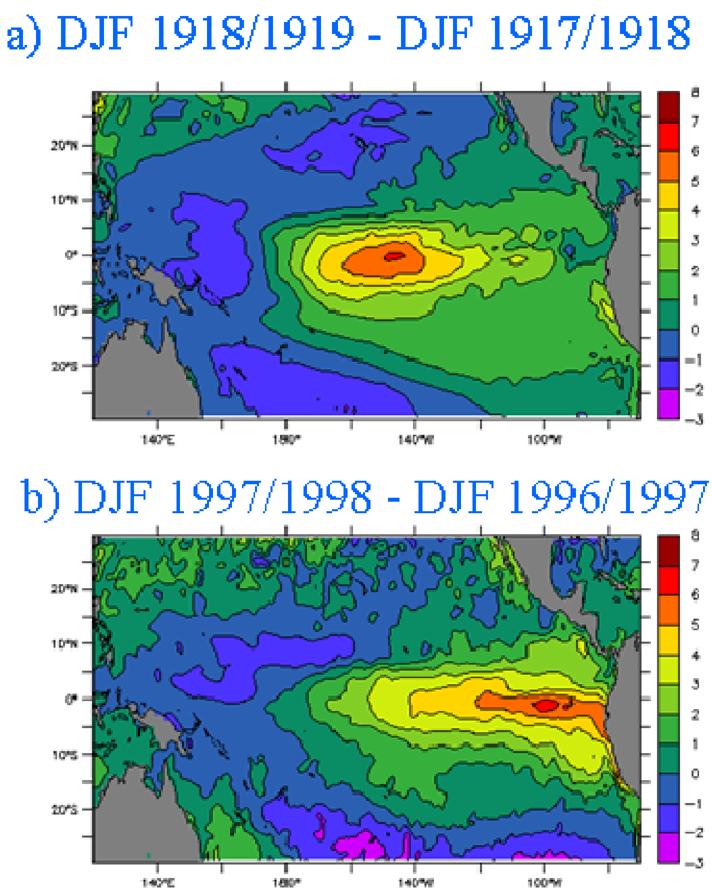

Figure 5: SST changes from those of the previous year for the two largest El Niño, a) the 1918/19, and b) the 1997/1998. Source: Dr B. Giese (SODA group).

The outputs from these runs are used to explore the structure and evolution of ENSO during the 20th century. The model shows that the NINO3.4 SST anomaly of the 1918 El Niño is as strong as those in the latter half of the century. However, the results also suggest that the structure of the 1918 El Niño is considerably different from that of the powerful El Niño events of 1982 and 1997 (Figure 5). The pattern in Figure 5a is recently referred as the El Niño Modoki (Ashok et al. 2007), and will be discussed later. It was found that very powerful westerly wind events in 1918, twice as large as those prior to the 1982 and 1997 El Niño events, played a significant part, and those westerly events were associated with two of Australia's worst tropical cyclones (in Innisfail and Mackay).

Although a lack of high density SST observations presents a challenge, the large SST anomalies were corroborated by the Urban et al. (2000) study, in which corals were used as a proxy for climate variability in the tropical Pacific. The large impact is consistent with the explanation of Kumar et al. (2006), which suggests that El Niños with maximum warming in the central Pacific are more likely to provoke drought in India. Thus, it is important not to assume a single canonical structure of ENSO when trying to understand the past or understand the impact of global warming on ENSO.

1.5 Recent changes in ENSO activity

Changes in ENSO and the Walker Circulation can be routinely monitored using the Southern Oscillation Index (SOI). Work described by Dr Scott Power showed that the lowest 30-year average value of the June-December SOI occurred in recent decades (i.e. 1977-2006), and that this coincided with the highest recorded value in mean sea-level pressure at Darwin and the weakest equatorial surface wind-stresses on record (Power & Smith 2007). A concurrent period of unprecedented El Niño dominance is also apparent. The extent to which global warming may be responsible for some of the recent changes is addressed in several studies described in section 5.

UNDERSTANDING AND PREDICTING RECENT ENSO EVENTS

The ENSO phenomenon has been the subject of thousands of studies since the early 1980's. Most of the studies have been concerned with theoretical and statistical descriptions of the phenomenon, understanding its underlying causes and its global climate impacts, identification of ocean atmosphere interactions, and the development, performance and use of prediction systems. The studies so far have shown that moderately accurate predictions are possible, even though the complex nature of ENSO is not well understood. This section describes the characteristics of recent ENSO events and recent advances in seasonal prediction.

Evolution of the 2006-2008 ENSO cycle

To address the issue of whether characteristics of the recent Indo-Pacific variability are consistent with climate change, examination is carried out on the recent ENSO events. ENSO properties: period, intensity, spatial structure, and *direction of propagation*, have been known to depend on the background climatic state, i.e., the mean state (Fedorov & Philander, 2001). This theory has been invoked to explain westward propagation of El Niño anomalies in the 1960s and 1970s but eastward propagation for El Niño anomalies in 1982-83 and 1997-98. However, observations of the 2006-2008 ENSO cycle (for which the mean state is constant by definition) indicate both eastward (El Niño) and westward (La Niña) propagation (Figure 6).

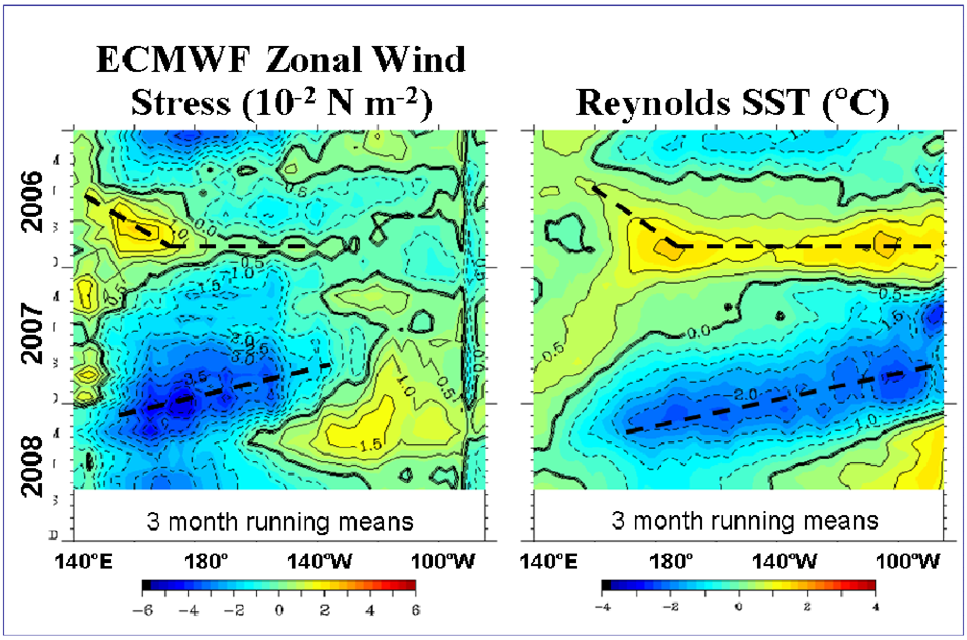

Figure 6. Anomalies of zonal wind and SST of the 2006-2008 ENSO cycle, showing a notable asymmetry in propagation between the warm (eastward) and cold (westward) phases of the ENSO cycle. Source: Dr McPhaden (PMEL, NOAA). An extended version of this result has been published since the work shop (McPhaden & Zhang 2009).

Dr Mike McPhaden and colleagues from the Pacific Marine Environmental Laboratory, NOAA, USA, described research aimed at unraveling the dynamics of the notable asymmetry between the warm (El Niño) and cold (La Niña) phases of the ENSO cycle. Using wind forced ocean models (McPhaden & Yu 1999) to understand the oceanographic factors that control SST, they interpreted the results in terms of prevailing ENSO theory. They found that wind forced equatorial waves contribute to the evolution of these ENSO events with SST controlled strongly by “Remote Mode” dynamics, in which wind anomalies away from the eastern Pacific play an essential role in the evolution. However, they found no simple theoretical explanation for the asymmetry between the warm and cold phase ENSO anomaly zonal propagation of SST anomalies. The issue of whether the notable asymmetry is a manifestation of global warming is therefore not resolved.

Interactive predictability between El Niño and the Indian Ocean Dipole

Climate variability in the tropical Indian and Pacific oceans is closely interlinked via the atmospheric Walker circulation and oceanic pathways. However, how the inter-basin coupling may influence the trigger and predictability of El Niño and the IOD - the two principal interannual climate signals with great global impacts - remains an important issue that is poorly understood.

Dr Jing Jia Luo of the Frontier Research Center for Global Change, Japan, conducted various forecast experiments using a fully coupled ocean-atmosphere model with demonstrated predictive capability and revealed that the inter-basin coupling is crucial to both extreme positive IOD and El Niño predictions. In particular, accurate predictions of the IOD (El Niño) signal greatly enhance the El Niño (IOD) onset forecast. The result indicates that progress in predicting either El Niño or IOD can mutually improve the forecast of the other, providing hope for enhanced predictive skill of both in the future.

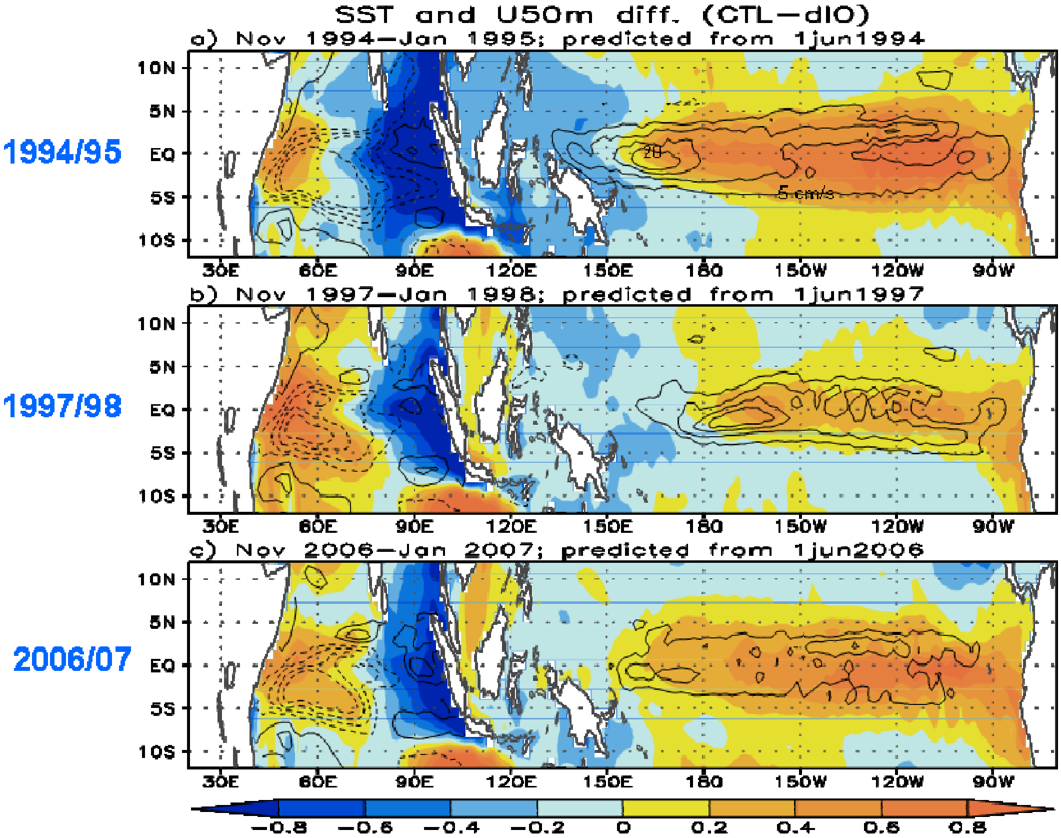

Figure 7: Impacts of the IOD-induced ENSO signal as seen in the differences in a prediction model between a case in which air-sea coupling in the tropical Pacific and Indian Ocean is allowed (CTL), and a case in which no coupling is allowed in the Indian Ocean (dIO). The difference indicates the effect of the IOD's impact on the Pacific. Shown are oceanic 50 m zonal velocities (contour) and SSTs. Source: Dr J. Luo (JAMSTEC).

Further, it was shown that the IOD can be very important for El Niño development, and can drive the signal in the Pacific via the atmospheric Walker circulation. This is illustrated in Figure 6, in which the influence of the IOD in the Pacific is able to instigate the development of an El Niño event. Dr Luo also concluded that the influence of the Indian Ocean on the Pacific also needs to be considered in order to understand the possible changes to ENSO under global warming.

The MJO and prediction of El Niño

The MJO is regarded as relevant to the timing, initial growth and strength of El Niño. There is indeed a strong observational basis for a modulation of MJO activity preceding the mature phase of El Niño events, although the cause and effect are uncertain. Observations, models, and theory support a coupled feedback: MJO activity advects warm pool water eastward and cools the far west Pacific. This reduces the east-west SST gradient, weakens the trades, and generates downwelling Kelvin waves. Together, these changes promote El Niño. The initial eastward expansion of the warm pool in turn feeds back into MJO activity.

To understand how the role of the MJO in tropical variability affects ENSO in a warming climate, the impact of the MJO on ENSO development must be explored. This can be conducted in the seasonal forecast framework to examine a series of issues. Can the coupled feedback be simulated? How important it is to realistically include the MJO in ENSO forecast systems? What role does the MJO play in generating spread/uncertainty? Is the MJO nothing more than a source of noise or are MJO effects unique and are they predictable? What is implication for limiting/promoting predictability?

Some of these issues were explored by Dr Harry Hendon and his colleagues at the Centre for Australian Weather and Climate Research, in two sets of model forecast experiments. In the first set, the impact of internally generated MJO variability on the onset of the 1997-98 El Niño was examined using a large ensemble of forecasts starting on 1 December 1996, using the Australian Bureau of Meteorology POAMA seasonal forecast coupled model. The experiment was designed so that the ensemble spread was simply due to internal stochastic variability that is generated during the forecast. In the second set, the impact of the initial state of the MJO was explored by initialising the forecasts from the identical ocean state but with the MJO in different phases. The forecasts that had developed MJOs extending further into the central Pacific early in the forecast, tended to lead to a stronger El Niño (see Figure 8). There was a clear separation of cause and effect, with the westerly winds in the western Pacific associated with the MJO leading the development of SST and thermocline anomalies in the central and eastern Pacific. These results imply a limit to the accuracy with which the strength of El Niño can be predicted, since the detail of individual MJO events matter and such detail is not easy to predict. To represent realistic uncertainty, coupled models should be able to represent the MJO including its propagation into the central Pacific in order that forecasts produce sufficient ensemble spread.

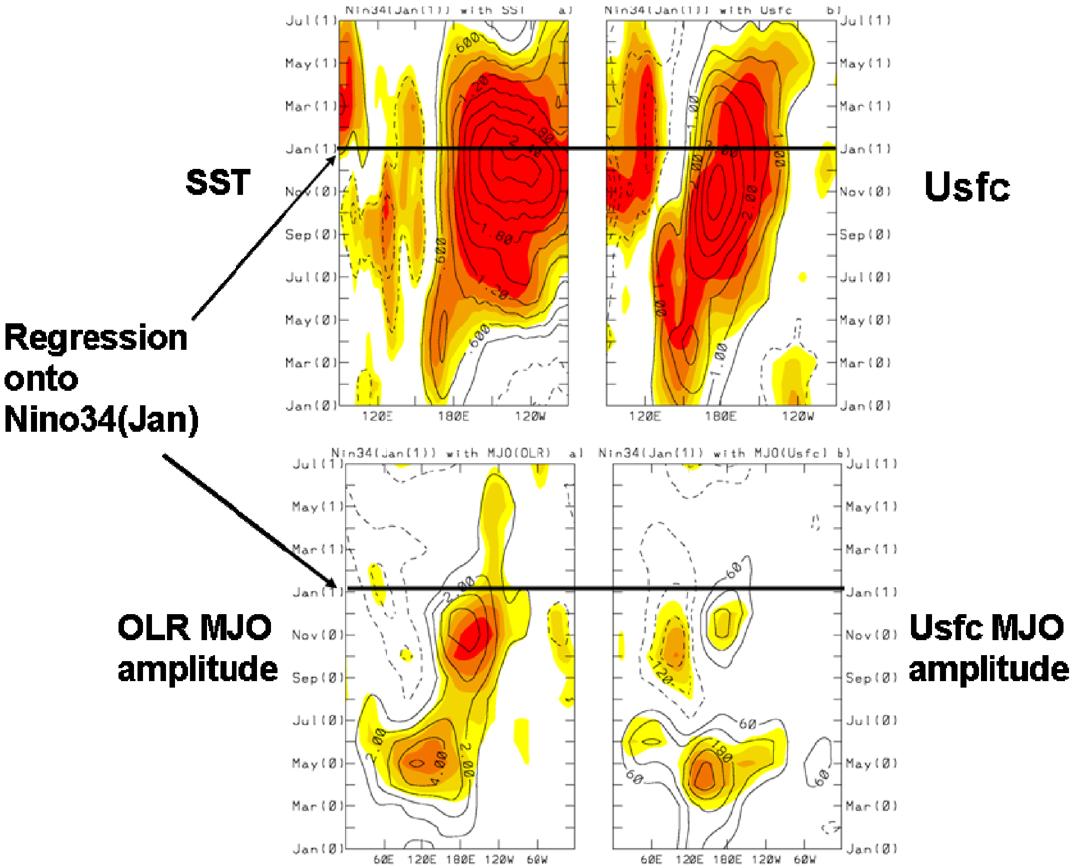

Figure 8: MJO-ENSO behaviour 1979-2006. The anomaly pattern (contours) is obtained by regressing anomalies onto NINO3.4 (Nin34, in the plot). The corresponding correlation is shown in colour shading. Source: Dr H. Hendon (BoM).

Role of the IOD in the Indo-Pacific climate variation

Dr Swadhin Behera pointed out that the IOD has a large impact on Indian Ocean rim countries (Behera et al. 1999; Ashok et al. 2003; Saji & Yamagata 2003; Behera et al. 2005; Cai et al. 2009b; Ummenhofer et al. 2009). Through changes in the Walker circulation and associated moisture transports, a positive IOD event causes floods over eastern Africa with suppressed convection over Indonesia and Australia. By affecting the mean sea level pressure variability at Darwin - one pole of the SOI - the IOD has the potential to influence ENSO intensity (Figure 9). Moreover, through the mutual interactions between ENSO and the IOD the two phenomena may influence each other’s periodicity (Behera et al. 2006). From coupled model experiments conducted with SNTEX-F, Dr Behera presented evidence indicating that ENSO variability is indeed affected by IOD variability. In the non-IOD case, when the tropical Indian Ocean is decoupled from the atmosphere, ENSO variability was predominantly pentadal as compared to a higher frequency (3-4 years) mode of variability in the control experiment. He also found that the concurrent evolution of the IOD shortens the average lifespan of ENSO; ENSO events are more likely to prolong until the boreal summer of the following year in the non-IOD case.

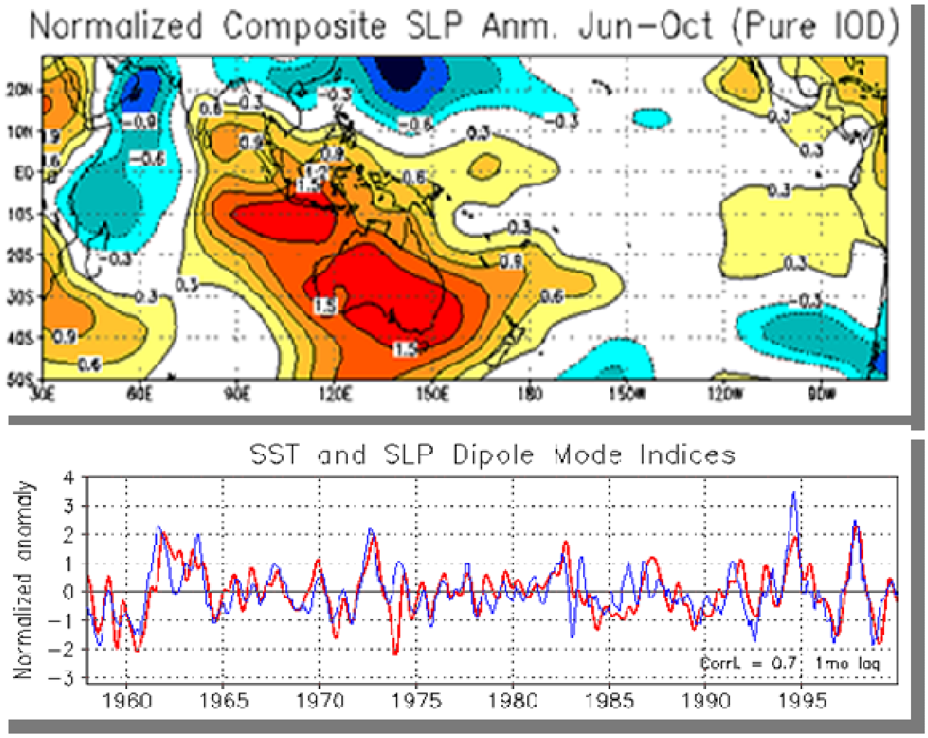

Figure 9: Anomaly pattern in sea level pressure during June – October in pure IOD cases (a), and IOD SST (red) and sea level pressure (blue) indices, which show SST leading by month. Source: Dr S. Behera (JAMSTEC).

The SINTEX-F model experiments (Behera et al. 2006) also suggest that the IOD periodicity is dominantly biennial in the absence of ENSO. This biennial nature of IOD was also found in the past records of observed data. However, Dr Wenju Cai reported on a rare turn of the history of Indian Ocean climate variability: three positive dipole events developed during 2006, 2007 and 2008 (Cai et al. 2009a). Dr Cai explained that this rare incidence could be related to recent changes in the background conditions. Coupled model experiment results examined by Dr Cai and his colleagues that adopted the IPCC SRES A2 scenario suggest that a positive dipole-like mean state could prevail in the latter half of the 21st century. Therefore, Dr Cai suggested that in coming years it is expected that the background conditions under global warming will favour more positive IOD developments in the Indian Ocean.

ENSO IMPACTS: CASE STUDIES

With the opening of a new direction in ENSO research, a recognition that the so-called "flavours" of ENSO is the consequence of a complex, highly non-linear, dynamical system, comes the realization of the strong inter-event variations in impacts. This section covers the associated global pattern as well as local manifestations. It is worth recognising that much of this type of analyses will appear in the upcoming years.

The impact ENSO Modoki on the Southern Hemisphere storm tracks during boreal winter

ENSO anomaly patterns can vary a great deal from one event to another. Events of different flavours, e.g., with different SST patterns, appear to have different spatial pattern of impacts. New research has identified a pattern, with its centre of action near the dateline region. This type of ENSO is similar to, but not the same as, the traditional ENSO pattern, and is sometimes called the ENSO Modoki (Ashok et al. 2007). The warm phase of ENSO Modoki, El Niño Modoki, has a distinct tripolar SST structure with the largest anomalies occurring in central tropical Pacific. This maximum is flanked by negative SST anomalies to the north and south. These distinct conditions are accompanied by anomalous double Walker circulation cells with a common ascending limb in the central tropical Pacific, leading to a teleconnection pattern distinctly different from that of the canonical El Niño. A recent study suggests that the 1997 El Niño event, which has a rather weak influence on Australian rainfall, belonged to the traditional type, whereas the 2002 El Niño, associated with a severe Australian drought, was an El Niño Modoki event (Wang & Hendon 2007).

Dr Karumuri Ashok of APEC Climate Center, South Korea, presented a description of the distinct morphology, evolution of the ENSO Modoki. He also discussed underlying causes, including the mecahsnisms underlying its tropical teleconnections. Using observational data, Dr Ashok showed that El Niño Modoki events are associated with anomalous blocking over central-eastern Australia, which suppresses the austral winter storm track activity from south-west to central-east Australia. On the other hand, the storm track activity in central Argentina is enhanced owing to the strengthened upper air westerlies in this region. Dr Ashok presented evidence supporting the view that the impacts of ENSO Modoki events are apparently stronger than the individual impacts from the traditional ENSO or the IOD (Figure 10). The impact from the ENSO Modoki on Australian rainfall in autumn is also very significant as discussed in Cai & Cowan (2009).

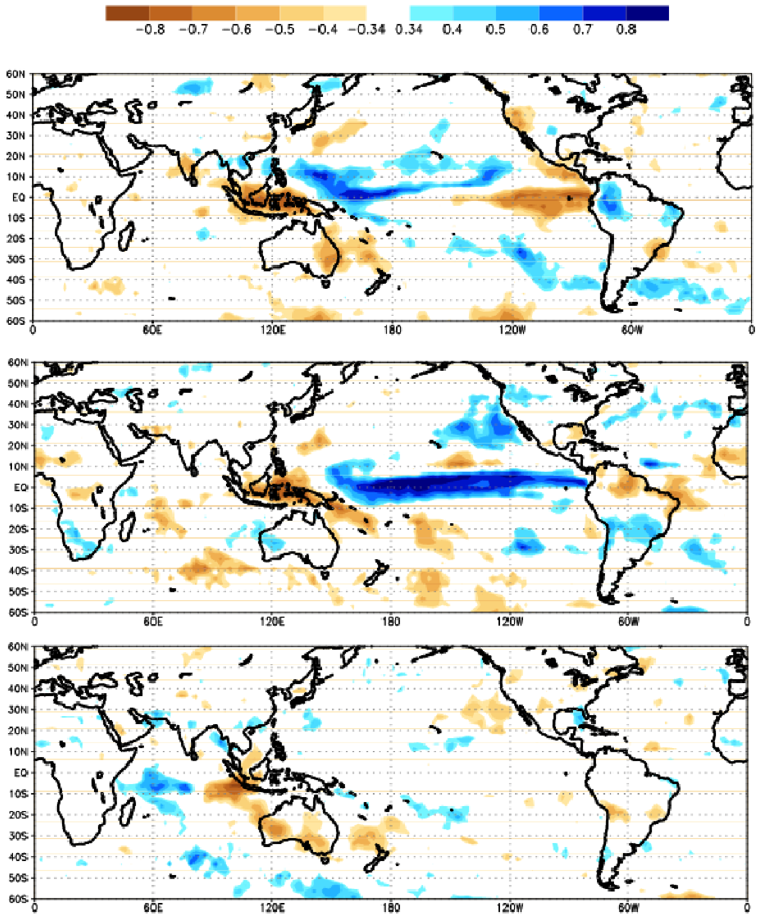

Figure 10: Maps of boreal summer (June, July, August, and September) correlation between grid-point rainfall and ENSO-Modoki (upper), traditional ENSO (NINO3) (middle), and IOD index (lower), using data over the period since 1978. Source: Dr K. Ashok (APEC).

Attribution of causes of current decadal droughts

Satellite observations of global rainfall over the past 30 years have enabled a new perspective on the factors that affect long-term Australian rainfall variability. When combined with observations of SST and reanalysis data of the motion of the atmosphere, these observations are beginning to enable an understanding of the mechanics of the decadal variability of the climate of Australia and elsewhere. An analysis based on EOFs of several variables that include SST and rainfall, conducted by Prof. Peter Baines, of the Department of Earth Sciences, Bristol, UK suggests that the current drought of southern Australia may be a part of a global pattern that includes rainfall decrease in the continental United States and equatorial Africa, with concomitant rainfall increases in other equatorial regions, mostly over the oceans (Figure 11). These changes are correlated with changes in SST, and indicate that they may be associated with a combination of global warming and fluctuations in the 'global conveyor belt.' Dr Baines believe that these relationships are mostly independent of ENSO, as the ENSO and ENSO-Modoki modes appear in separate modes, and do not display any trends.

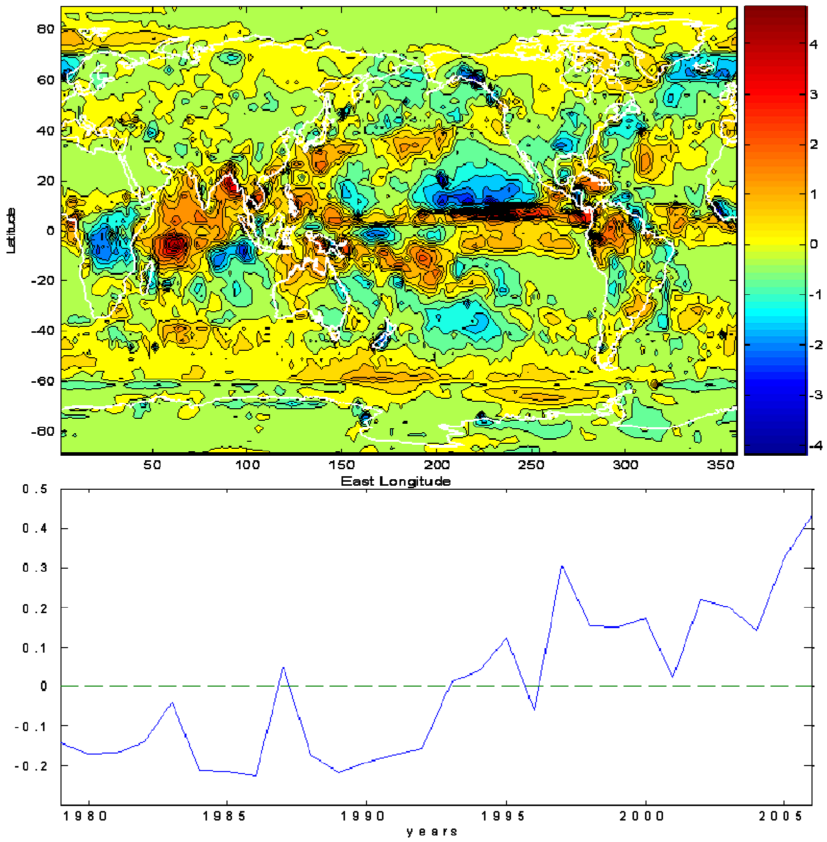

Figure 11: Trend pattern of global rainfall as manifested in an empirical orthogonal function (EOF1) analysis on rainfall anomalies, accounting for 6.4% of total variance. Source: Dr P. Baines.

Linking global climate change to local rainfall

Global climate change cascades through a number of space- and time-scales to influence local rainfall. Global warming may alter large-scale climate drivers such as ENSO, which may in turn impact on synoptic weather systems and hence local rainfall. While global climate models are effective at reproducing many large-scale climate features, they vary enormously in the way they transfer these changes to local rainfall (Smith & Chandler, 2009). Dr Jaclyn Brown and colleagues explored the mechanisms behind the impact of climate drivers on local rainfall changes. They focussed on the south-eastern Australian region, where cut-off low pressure systems are responsible for about half of all growing season rainfall, and nearly all of the important high rainfall events (above 25 mm/day) (Pook et al. 2006). The same study also showed that the drying trend observed in this region in the last decade is not related to a decrease in the number of cut-off lows, but rather a decrease in the amount of rain per cut-off.

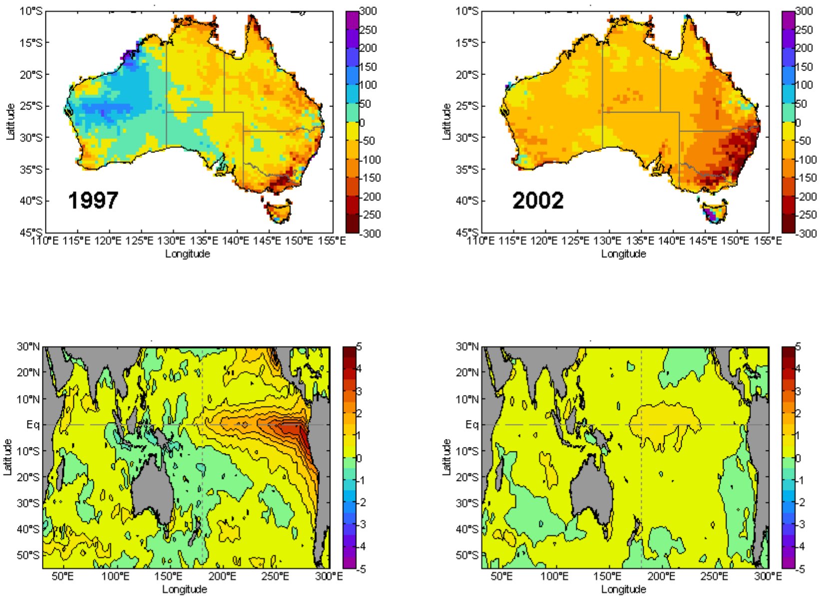

Figure 12: Anomalous rainfall for April – October (mm, from SILO) in 1997 and 2002. Source: Dr J. Brown (CSIRO).

Case studies of cut-off-related rainfall in the Mallee region in southeast Australia in a number of key El Niño years reveal that variations in the amount of Mallee rainfall do not clearly correlate with any single climate driver. For example, 1997 rainfall totals were only just below average despite the occurrence of one of the strongest El Niños on record (Figure 11, left panels). On the other hand, in 2002 a weak El Niño SST anomaly resulted in one of the lowest rainfall tallies on record (Figure 11, right panels). These two years had roughly similar numbers of cut-off lows, but in 2002 there was half as much rain per cut-off day. An air-parcel back-tracking algorithm (McIntosh et al. 2007) was then used to determine the origin of the moisture supplying the cut-off low rainfall. Their case studies demonstrate that a critical feature is the position of the high pressure ridge near Queensland. In years when this ridge contracts eastward (such as 1982 and 2002), the moisture pathway is reduced or absent, and cut-off lows are ineffective at providing rainfall to the Mallee region. This provides a new perspective, that complements the ENSO and ENSO Modoki paradigm, to explain the different impacts of the 1997 and 2002 El Niño events. The study described by Dr Brown suggests that it is important to ensure that climate change models represent the important dynamical connections between different space- and time-scales before they are used to predict long term changes to rainfall for the Mallee and the wider Murray-Darling Basin with more confidence.

ENSO and ecosystems of the north-east Pacific

Many climate simulations indicate that increasing westerly winds in both Southern and Northern Hemispheres at mid-to-high latitudes accompany global climate warming. To assess the impacts of climate change on the subarctic north-east Pacific, Prof. Crawford and colleagues examined simulated changes of 20th and 21st century climate in boreal winter, when the North Pacific is most strongly influenced by the Aleutian Low and ENSO.

Their analysis of an ensemble of six IPCC models exhibiting relatively realistic 20th century North Pacific climate variability finds a deepening and northward shift of the climatological Aleutian Low, accompanied by rising ocean temperatures that lag global rates of warming in the north-east Pacific. The amplitude of interannual variability in the strength of the Aleutian Low is found generally to increase, particularly over the Gulf of Alaska (Figure 13).

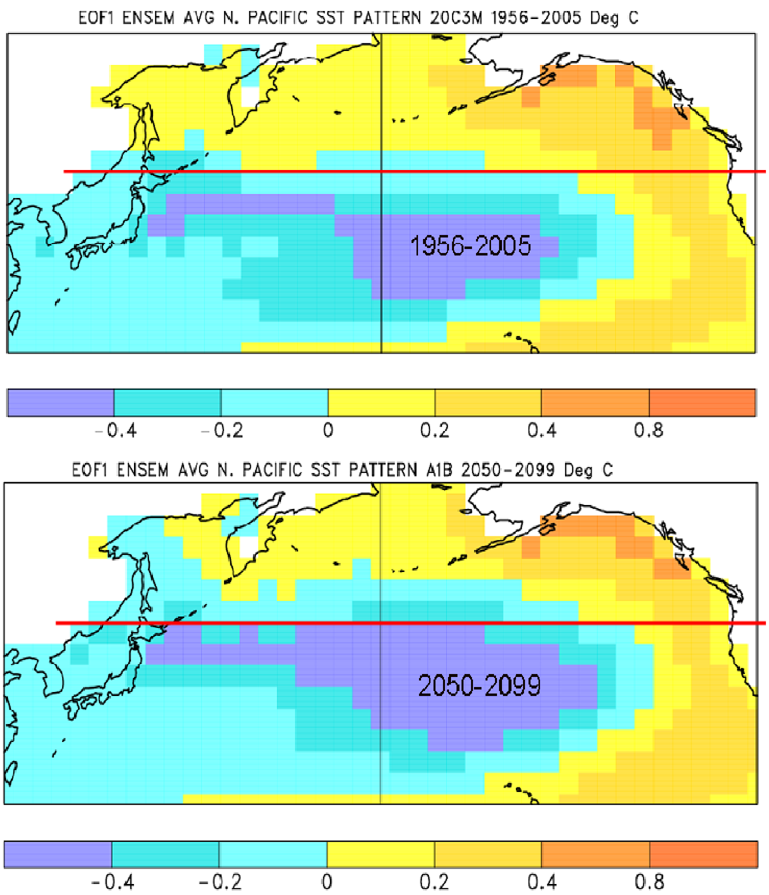

Figure 13: Dominant variability pattern of SST for the past and future climate. A northward shift in the mid-Pacific modal structure suggests stronger variability in westerly winds. Source: Dr Crawford.from Canada.

Strong variability of winter temperatures in the region has driven major ecosystem changes along the continental shelf in the past decade. Boreal zooplankton, herring, sockeye salmon, and many sea birds declined in numbers after warmer winters, usually associated with El Niño, whereas squid, tuna and sardine numbers increased. Yet a return of cooler waters rought back the warmer species. The rate of ecosystem shift varied with the lifetime of each species. Zooplankton populations responded in several months; sockeye salmon began to respond after several years; some shifts are slow and others are surprisingly swift. Although these ecosystem shifts provide insight into future ecosystems, we need to be prepared for surprises.

In about 30-50 years the climate variability will be overpowered by global warming under a mid range greenhouse gas emissions scenario. IPCC models indicate a stronger Aleutian Low Pressure System and slightly stronger North Pacific High pressure system in winter, with stronger westerly winds in mid-North Pacific. Their analysis suggests an increase in interannual variability of winter SST. The North East Pacific has experienced strong decadal and interannual changes in temperatures and currents in the past few decades, with major changes in the marine ecosystem. We can expect swift changes in this ecosystem during future warm episodes. Some cold-water species will fail to recover during the ensuing cool episodes; some warm-water species will remain during warm-water episodes. Although we may think of climate change as a slow process, it can irreversibly change our species composition rapidly during warm episodes and it some cases species this has already occurred.

UNDERSTANDING EL NIÑO IN OCEAN-ATMOSPHERE GENERAL CIRCULATION MODELS

Ocean-atmosphere coupled general circulation models (CGCMs) are routinely used to analyse El Niño mechanisms and teleconnections and to predict the evolution of the climate system on a broad range of timescales, from seasonal to interannual time-scales, and to provide projections of changes in the statistics of climate from decadal to centennial time-scales. The ability to simulate El Niño using these models has been greatly improved over the last few years. Nevertheless, the diversity of model simulations of present-day El Niño indicate current limitations in our ability to model this climate phenomenon and to anticipate changes in its characteristics. Prof. Eric Guilyardi of LOCEAN/IPSL, France, provided a review of the several factors that contribute to this diversity, and the potential that exists to improve the simulation of El Niño in CGCMs. His talk was followed by more focused studies, as detailed below.

The inverse relationship between the amplitude of both ENSO and the annual-cycle

The influence of the tropical Pacific annual mean state on the amplitude of both the annual cycle and ENSO variability, is an important area of research because global warming has changed and will further change the mean state. This is a subject that Prof. Soon-Il An of Yonsei University, Korea, is exploring using CGCMs. In most of the CGCMs he examined, an intensified annual cycle of SST in the eastern tropical Pacific is associated with reduced ENSO variability, and vice versa. The intermediate coupled model experiments show that the amplitude of ENSO is more sensitive to the change in annual mean than in annual cycle (Figure 14). Using a hybrid coupled model in which the annual-mean background states have been prescribed, Professor Soon-Il An further demonstrated that an annual-mean background state diagnosed during a reduced annual cycle period, suppresses the development of the annual cycle of SST in the eastern equatorial Pacific, and vice versa. Thus, these results support the idea that annual-mean background state changes control both ENSO and the annual cycle amplitude, although in opposing ways. Further studies are required to address the mechanisms behind the relationships identified.

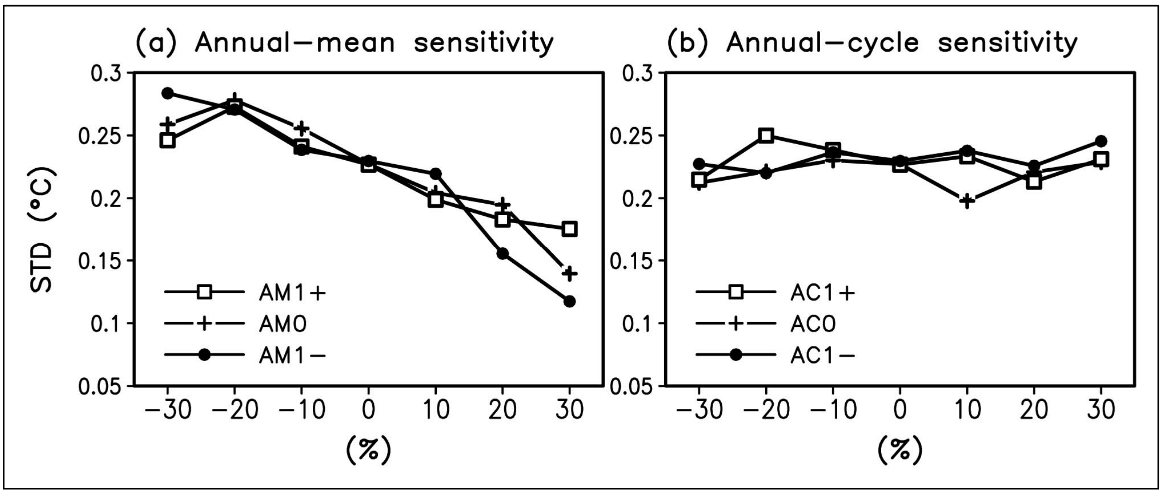

Figure 14: Sensitivities of ENSO amplitude to annual mean (a) and annual cycle (b). The slope is far greater in (a) than in (b), suggesting that annual mean has a stronger control. Source: Professor Soon-Il An.

Atmospheric properties and the ENSO cycle

Significant differences exist in the main feedbacks and atmospheric properties associated with ENSO between reanalyses and models, and between models. The implications for diagnosing future ENSO behaviours has been investigated by a team led by Dr Geer-Jan. van Oldenborgh of KNMI, The Netherlands. This study looked at: the amplitude of atmospheric “noise” (i.e. the component of the surface wind-stress not driven by SST anomalies), ENSO SST skewness (the magnitude of SST anomalies during El Niño events tend to be larger in amplitude than SST anomalies during La Niña events), and the impact of skewness back on the atmospheric noise. Most models are deficient in the amount of non-ENSO atmospheric noise they simulate, and they tend to underestimate the SST response to wind stress anomalies. This deficiency tends to to be compensated by a damping term that is weaker than observed. The models also have problems simulating skewness (Figure 15), and they tend to underestimate the wind variability and the nonlinear response of wind stress to a given SST anomaly. At this stage it is not clear though how these defficiencies impact on the modelled response of ENSO to global warming.

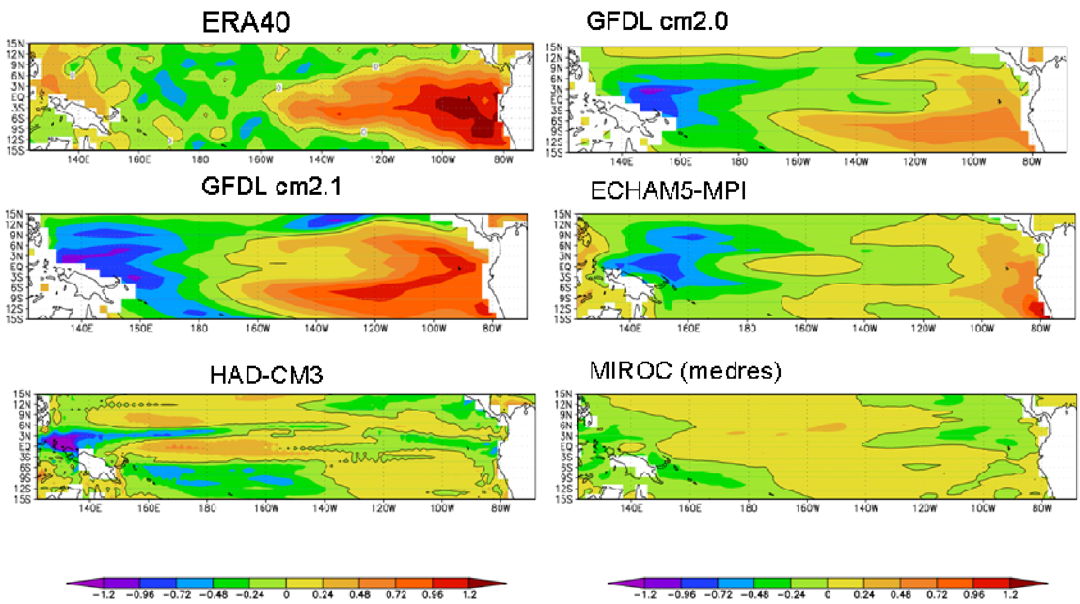

Figure 15: Skewness in a reanalysis product (ERA-40) and in various climate models. The skewness refers to the feature that El Niño events are larger in amplitude than La Niña events. Source: Dr Geert-Jan van Oldenborgh.

Contrasting the termination of moderate and extreme El Niño events in coupled general circulation models

There is large diversity in observed El Niño events and it is important to identify and understand differences between El Niño events (e.g. differences between extremely large and moderate events during the termination phase). The extreme 1982-83 and 1997-98 El Niño events both terminated unusually in the eastern Pacific in contrast to moderate El Niño events. These extreme events display a prolonged positive SST anomaly (SSTA) in the eastern equatorial Pacific in boreal winter (DJF) and boreal spring (MAM) with a late termination in early boreal summer (JJA). In contrast, moderate events tend to last for a shorter period. They display a decay of SSTAs in the eastern Pacific in boreal winter and a return to normal conditions in boreal spring. Dr Matthieu Lengaigne and colleagues have shown that a suite of state-of-the-art CGCMs are able to simulate both types of events (moderate and extreme) with characteristics similar to what is observed. In addition, the physical mechanisms controlling the peculiar termination of extreme events agrees qualitatively well between models and observations. The distinctive termination observed in 1983 and 1998 is to be expected for extreme El Niño events in general.

The prolonged eastern equatorial Pacific warm anomalies during the termination of extreme El Niño events lead to an apparent eastward propagation of SSTAs during these events in models and observations, in contrast with the more westward propagation evident in moderate El Niño events. The eastward SST propagating periods in models and observations can, however, be largely attributed to the peculiar termination of only a few extreme El Niño events.

RESPONSE OF TROPICAL PACIFIC CIRCULATION AND VARIABILITY TO CLIMATE CHANGE

This session began with a description of the mean circulation changes in the tropical Pacific, using IPCC multi-model ensemble averages. The issue of whether it is appropriate to describe the mean circulation using an ENSO analogy was discussed. This was followed by a theoretical analysis and results from targeted model experiments on ENSO's response to global warming. The convergence of these results is obtained after the IPCC AR4, and represents the latest, which if confirmed by more models will have important implications.

Projected ocean circulation changes to the tropical Pacific over the 21st century

Physical and chemical changes to the tropical Pacific Ocean will play a vital role in controlling future shifts in the biology of the region. Changes in water properties and circulation will impact on nutrient supply, larval dispersal and the distribution of habitable zones. Reliable future projections of these changes are of particular importance for the management of the economically valuable fisheries of the region. This is the subject of a recently initiated, cross-disciplinary project headed by AusAid that will investigate the future of regional fisheries in light of projected changes to the environment. Principal investigator Dr Alexandre Ganachaud and colleagues from the Institut de Recherche pour le Developpement, New Caledonia focus on the physical system. Fidelity and projected changes in the climate models, used for the IPCC AR4, are assessed with regard to biologically important physical features of the tropical Pacific. Three 20-year periods were investigated centred on 1990, 2035 and 2090 under both low emission (SRES B1) and high emission (SRES A2) scenarios.

The multi-model mean of selected simulations based on ENSO variability suggest over time as CO_2 emissions increase, some changes in the circulation are expected, partly derived from wind changes. Although there are no major changes in subtropical North Equatorial Current (NEC) or in South Equatorial Current (SEC) (but the northern edge of the SEC shifts north), the Equatorial Undercurrent Current shoals (Figure 16a), while the North Equatorial Counter Current (NECC) decreases, the South Equatorial Counter Current (SECC) decreases strongly and shifts north, and the equatorial SEC decreases, as summarized in Figure 16b.

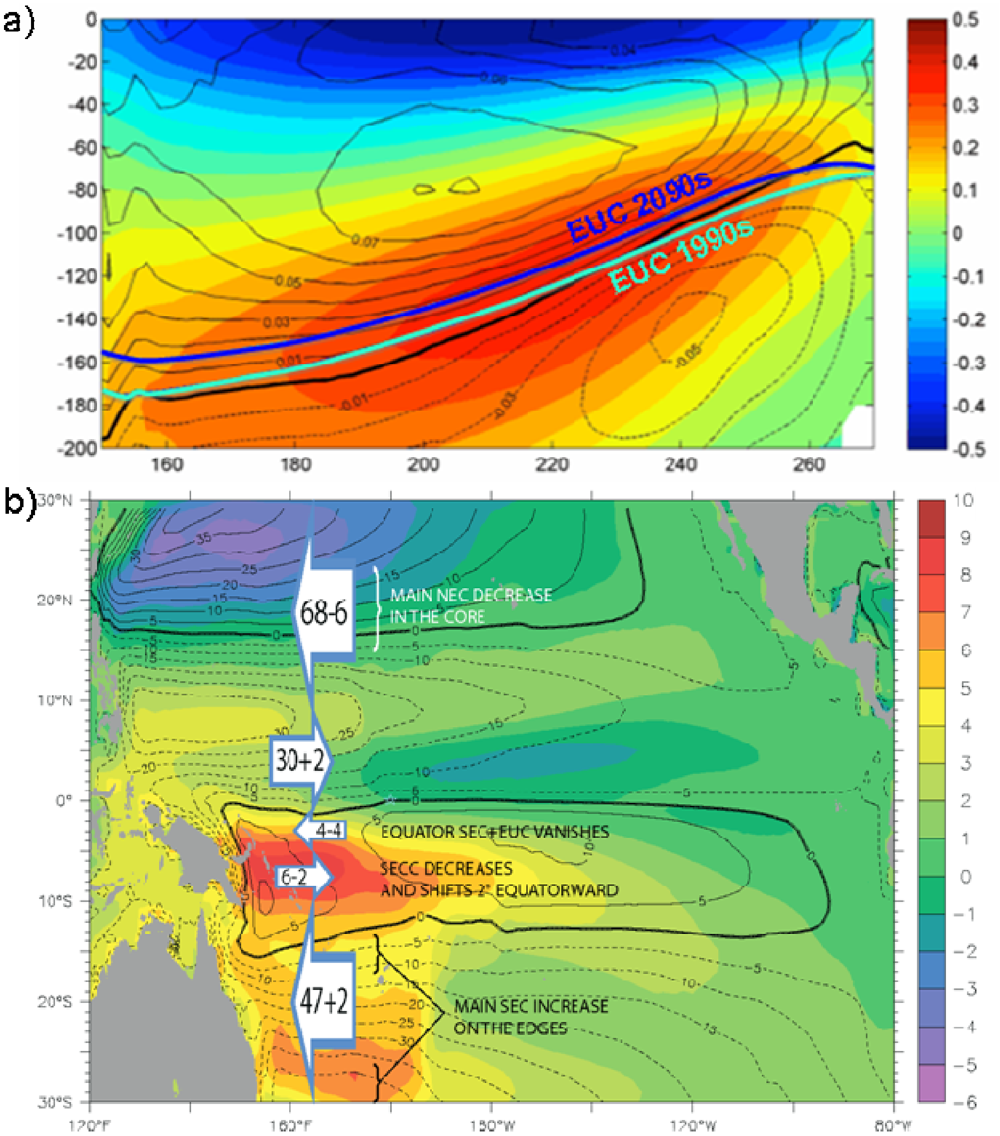

Figure 16: Multi-model mean changes by 2090 following A2 emission scenario, a) zonal current, showing a decrease in the equatorial SEC (30% transport), and an upward shift of 20m of the EUC, b) streamfunction (colour) superimposed on climatological mean. Source: Dr Alex Ganachaud (IRD).

Tropical response to greenhouse forcing: oceanic and atmospheric contribution

Mean changes in the oceanic and atmospheric circulation, thermal structure, and precipitation patterns - including changes in the Hadley and Walker circulations are the focus of the recent work by Dr Gabriel Vecchi of the Geophysical Fluid Dynamics Laboratory, USA. The change to the tropical Pacific mean state is complex, controlled by both oceanic and atmospheric processes (Vecchi et al. 2006; Vecchi and Soden 2007; Vecchi et al. 2008). In models with a simplified representation of atmospheric physics, feedbacks originating in the ocean drive the system to a 'La Niña-like' state. In models with atmospheric general circulation components, thermodynamic constraints result in a reduction of the strength of the atmospheric overturning circulation – manifest primarily in the zonally-asymmetric (Walker) rather than zonal-mean

(Hadley) component. In these models changes over the tropical Pacific Ocean that are, in some respects, 'El Niño-like' conditions, although the mechanisms are fundamentally different from those of El Niño, as are many of the impacts. Observations of sea level pressure indicate that over the 20th century, the Pacific Walker circulation has weakened; however, differing reconstructions of SST are inadequate to distinguish between an increase or decrease in east-west SST gradient across the Pacific.

To what extent is El Niño a good analogue for drivers of societal impacts (e.g. precipitation, tropical cyclones) in a warming climate? The aspects that bear some "El Niño-like" patterns include an eastward shift of precipitation, a reduction in SST gradient, and a reduction in thermocline tilt. However, the physical process is not the same as that associated with El Niño, and many aspects are not "El Niño-like." These include that the ocean mean state change is opposing the atmospheric mean state change (because Bjerkne's feedback is not effective in long time scales), and rainfall teleconnection is not "El Niño-like" (Lu et al. 2007). In fact the differences are so large, that the use of this term to describe global warming is misleading and best avoided.

Instead, changes may be better characterised by the following features. Firstly, "wet regions get wetter", "dry regions get drier" and there is a "poleward expansion of dry zones," as illustrated in Figure 17. Secondly, tropical circulation gets weaker, in particular the Walker circulation, in association with an increase in surface radiative imbalance.

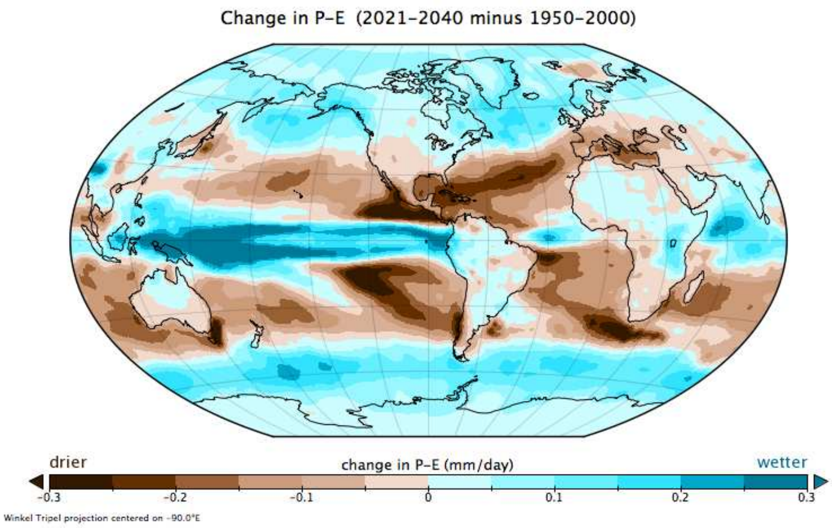

Figure 17: Changes in precipitation minus evaporation averaged over 2021-2040 from that averaged over 1950-2000 based on multi-model ensemble average. Source: Dr. G. Vecchi (GFDL).

ENSO intensities in the global warming simulations

In an attempt to address how ENSO activity responds to global warming, Prof. Fei-Fei Jin of the University of Hawaii and colleagues analysed IPCC AR4/CMIP3 simulations. The 20th century simulations of the AR4 models exhibit great variations in simulating ENSO activity (measured by NINO3 variance for instance). Variability in some models is half the observed level, while in other models it is twice as large as the corresponding observed value. While there can be very large naturally ocurring variability in ENSO, such differences are large enough to indicate model deficiency.

The great variations of ENSO amplitude in these different models are closely related to the differences in the coupled instability of ENSO. The latter is measured by the so-called Bjerknes (BJ) instability index (Jin *et al*. 2006). There is a clear and strongly nonlinear relationship between the BJ index and ENSO variance. They developed a theory, which demonstrates that the non-linear relationship is an expected behavior near criticality where ENSO is either marginally damped or unstable. The diverse results from the IPCC models fit well with the theoretical formula relating ENSO amplitude to growth rate. An implication of this theory is that when the thermocline becomes shallower (narrower), as simulated in the majority of models, the tropical Pacific climate becomes more sensitive and would make ENSO actively stronger.

Has ENSO already been influenced by human activities?

Dr Matthew Collins from the UKMO discussed the results of a set of targeted experiments with the HadCM3 model to investigate the impact of anthropogenic greenhouse gas forcing on ENSO. HadCM3 performed consistently well in studies which evaluate present-day ENSO fidelity. The set of the targeted experiments contains 33 ensemble members, and is forced with anthropogenic and natural forcings.

An increase in the amplitude of ENSO events over the 20th century is detectable in the ensemble mean above the level of natural variability. The change is consistent with both observations of an increase in ENSO variability toward the end of the 20th century (IPCC 2007) and with theoretical considerations of a shift from a weaker, surface-mode-type ENSO (similar to the pre-1975 period) to a stronger thermocline-mode-type (similar to that after 1975) ENSO. Both the ensemble mean ENSO amplitude (Figure 18 and Figure 19) and ENSO frequency continue to increase in the future under SRES A1B forcing in the simulations, with individual members showing the possibility of rapid shifts in ENSO behaviour on decadal time scales.

The increase in amplitude is consistent with the further dominance of the thermocline-type mode as greenhouse gases increase. In this mode, ENSO signals propagate from west to east, and are driven more by off-equatorial winds–thermocline feedbacks involving the west Pacific with a 4- to 5-year period. The increase in frequency is brought about by an increase in the surface-shortwave-flux feedback which terminates the larger ENSO events earlier, because this feedback is a negative one in that an increase in amplitude leads to increased cloud and negative radiation anomalies.

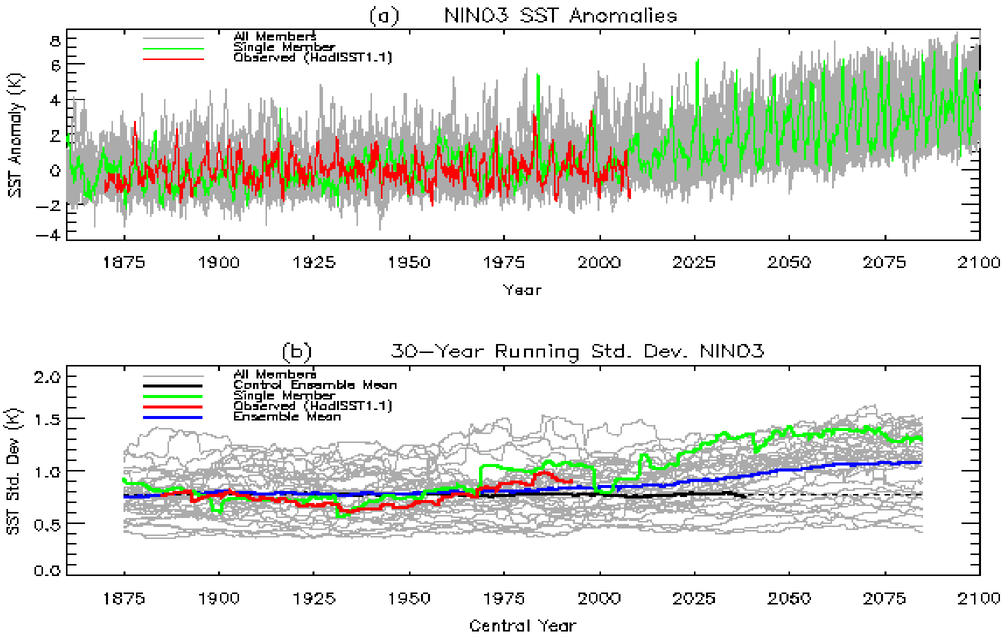

Figure 18: Time series of (a) NINO3 SST anomalies of all ensemble members (grey), a single ensemble member (green) and observed (red); and (b) 30-year running window of standard deviation of NINO3. In (b), control ensemble mean (black), and ensemble mean of all forced experiments are also shown. Source: Dr M. Collins (UKMO).

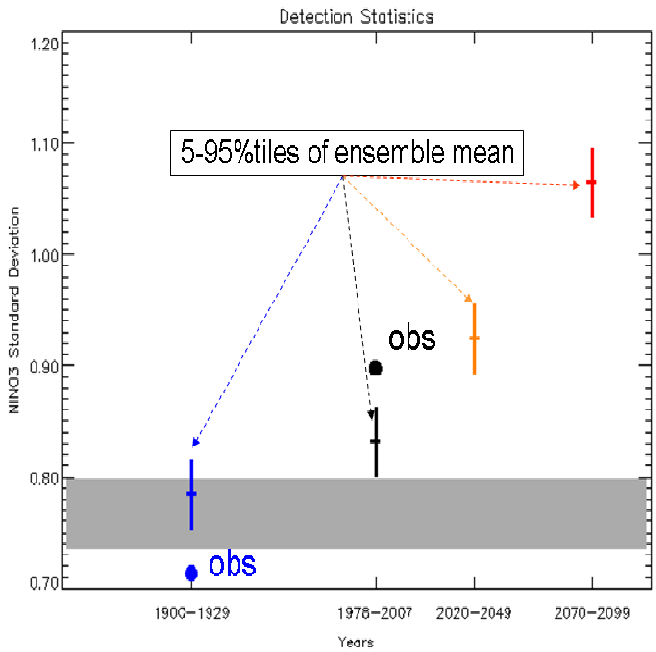

Figure 19: Detection statistics showing ENSO amplitude changes going into future in the targeted experiments. The colour displays the 5-95 percentile range. Source: Dr M. Collins (UKMO).

CO_2-induced changes in tropical climate and variability as simulated by a GFDL CGCM

Another set of experiments to examine impacts of increased CO_2 on tropical climate and variability using simulations from the NOAA/GFDL CM2.1 global CGCM was described by Dr Andrew Wittenberg of the Geophysical Fluid Dynamics Laboratory, USA. Dr Wittenberg first characterised the unforced behavior of the models, using multicentury control simulations with their atmospheric composition, solar irradiance, and land cover held fixed at pre-industrial values. He then compared these control simulations with runs under doubled and quadrupled atmospheric CO_2.

In terms of mean state changes, the $4{\times}CO_2$ simulations show a fairly uniform 3-4°C warming of the annual-mean tropical SST, with reduced SST contrasts between the equator/off-equator and east/west Pacific; stronger rainfall and weaker easterly trade winds which are both more symmetric about the equator; a sharper and shallower equatorial oceanic thermocline and halocline; and weaker surface currents. Thus the tropical mean climate change differs from El Niño. The simulated annual cycle of SST and rainfall strengthens along the equator (Figure 20, period at one year), due to increased seasonal ocean-dynamical cooling (Figure 20).

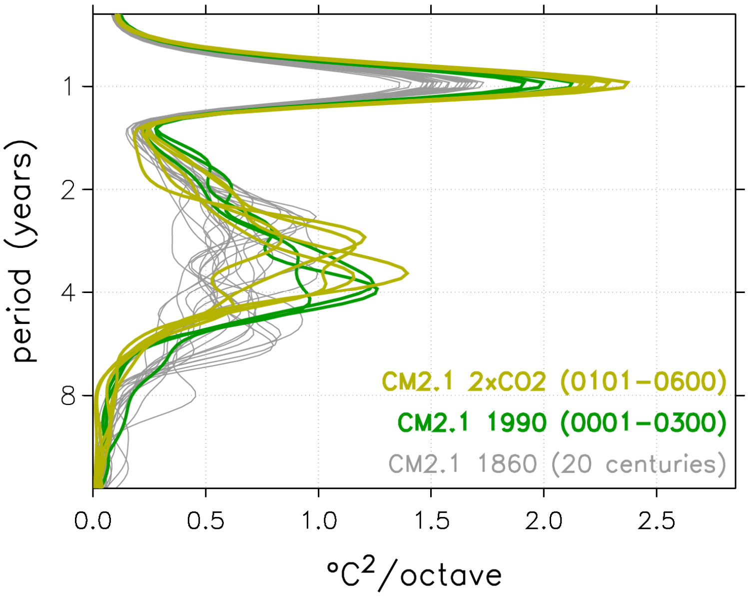

Figure 20: ENSO amplitude (x axis) and frequency at pre-industrial, current, and future CO_2 levels. Each distribution curve is obtained using 100 years of model output. Source: Dr Wittenberg (GFDL). The result has been published since the workshop (Wittenberg, 2009).

Because of a centennial-scale modulation of ENSO, increasing CO_2-induced changes are barely detectable with 100 years of data. From the set of targeted experiments with multi-century integration, he was able to show larger ENSO amplitude at a $2{\times}CO_2$ level, and a higher ENSO frequency, although the amplitude does not grow towards a $4{\times}CO_2$ level. It is shown that at $2{\times}CO_2$, a stronger wind coupling, stronger noise, and a shallower thermocline all contribute to the stronger amplitude, and with more eastward SSTA propagation as CO_2 increases. An increase in the surface-shortwave-flux feedback is similarly generated as in the UK's targeted experiments.

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