Global responses of terrestrial productivity to contemporary climatic oscillations

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The terrestrial biosphere is subjected to a wide range of natural climatic oscillations. Best known is the El Niño–southern oscillation (ENSO) that exerts globally extensive impacts on crops and natural vegetation. A 50-year time series of ENSO events has been analysed to determine those geographical areas that are reliably impacted by ENSO events. Most areas are impacted by changes in precipitation; however, the Pacific Northwest is warmed by El Niño events. Vegetation gross primary production (GPP) has been simulated for these areas, and tests well against independent satellite observations of the normalized difference vegetation index. Analyses of selected geographical areas indicate that changes in GPP often lead to significant changes in ecosystem structure and dynamics. The Pacific decadal oscillation (PDO) is another climatic oscillation that originates from the Pacific and exerts global impacts that are rather similar to ENSO events. However, the longer period of the PDO provided two phases in the time series with a cool phase from 1951 to 1976 and a warm phase from 1977 to 2002. It was notable that the cool phase of the PDO acted additively with cool ENSO phases to exacerbate drought in the earlier period for the southwest USA. By contrast in India, the cool phase of the PDO appears to reduce the negative impacts of warm ENSO events on crop production.

Keywords: advanced very high resolution radiometer; El Niño–southern oscillation; Pacific decadal oscillation; gross primary production; normalized difference vegetation index

1. INTRODUCTION

The composition of the atmosphere changes on a very broad range of time scales due to both extraterrestrial and terrestrial causes (Beerling & Woodward 2001; Berner 2006). In terms of the *ca* 400 Myr of the Phanerozoic era of terrestrial exploitation, these changes, in particular carbon dioxide and oxygen, are strongly influenced by very large changes in photosynthetic activity (Beerling & Woodward 2001). These changes are probably little due to evolutionary changes in the photosynthetic process itself; rather it is in the way plants evolve to package and display their photosynthetic units in a wide array of structures combined with a diversity of mechanisms for capturing other limiting resources.

Atmospheric changes in carbon dioxide concentration directly integrate the net exchanges of carbon dioxide by the living biosphere on century to millennial time scales (Beerling & Woodward 2001). On geological time scales, the mineralogical exchange and sequestration of carbon are key drivers of change (Berner 2006). Since the onset of the industrial revolution, atmospheric carbon dioxide concentration has been increasing by reversing geological carbon

sequestration and by fires associated with changes in terrestrial land cover (Houghton 2003). The current release of carbon dioxide through these activities is more than 4 ppm yr^{−1} (Patra *et al.* 2005). However, the increase in atmospheric carbon dioxide concentration is only 1.5 ppm yr^{−1}, a measure of the joint capacities of the terrestrial and oceanic carbon dioxide sinks.

Continuous measurements of atmospheric carbon dioxide concentration since 1958 (Keeling *et al.* 1995) have not only demonstrated the monotonic increase in carbon dioxide concentration since measurements began, but they have also indicated the impact of seasonal changes in photosynthetic activity by the Northern Hemisphere temperate and boreal forests. This information-rich time series of carbon dioxide concentration shows further interannual dynamics, independently of both seasonal vegetation activity and human activities (Patra *et al.* 2005). Well researched is the impact of the El Niño–southern oscillation (ENSO; e.g. Jones *et al.* 2001). During warm ENSO (El Niño) events, the terrestrial biosphere increases its source of carbon dioxide at rates just less than that of human-derived emissions (Patra *et al.* 2005). During the converse, cool ENSO (La Niña) event, the terrestrial sink capacity increases, reducing the rate of carbon dioxide accumulation in the atmosphere.

The ENSO has an average time period of *ca* 4 years between warming (El Niño) and cooling (La Niña) of the tropical eastern Pacific Ocean. There are global climatic consequences, although with quite discontinuous

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Electronic supplementary material is available at <http://dx.doi.org/10.1098/rstb.2008.0017> or via <http://journals.royalsociety.org>.

One contribution of 15 to a Discussion Meeting Issue ‘Photosynthetic and atmospheric evolution’.

geographical distributions (Glantz 2001) and with variable differences between each event. The impacts of ENSO on climate and marine ecosystems have attracted much attention, but the effects on terrestrial ecosystems have received rather less attention (Holmgren *et al.* 2001). The objective here is to first define those areas that with high probability have had climatic teleconnections with ENSO over the last 50 years of the twentieth century, when climatic data have been relatively extensive and reliable globally. Photosynthetic productivity of these areas will then be simulated using a dynamic global vegetation model (Woodward & Lomas 2004), in order to identify whether the selected areas are significantly sensitive to ENSO events. These observations will then be tested against independent satellite observations of the normalized difference vegetation index (NDVI, DeFries *et al.* 1995), to test the reliability of the simulations. Finally, the ecosystem impacts of the ENSO events will be assessed from published research in different geographical locations. This final objective will therefore address the question of whether ENSO events can control ecosystem structure and behaviour.

ENSO is not the only global climatic oscillation and Viles & Goudie (2003) outline 14 different oscillations on the century to millennial time scales. One additional oscillation will be considered here and that is the Pacific decadal oscillation (PDO). The PDO is like ENSO in character (Viles & Goudie 2003) and in the warm phase the central and eastern Pacific are warm and the southwest and northwest Pacific are cold (Gedalof *et al.* 2002). The reverse occurs during the cool phase. The PDO has a decadal scale oscillation period and, broadly, it was in the cool phase from 1950 to 1976 and the warm phase from 1977 to 2005 (Schneider & Cornuelle 2005). The PDO has been selected for investigation because the change in its phase, at approximately 1976 to 1977, was at a time when the frequency of ENSO events appeared to change, potentially due to direct effects of climatic change (Power & Smith 2007). It is therefore of interest to determine whether the changes in the PDO might account for the ENSO changes. These two different phases then provide a method of investigating the sensitivity of ENSO events to additional climatic drivers, at a time when there is concern that global warming may increase the frequency and strength of ENSO events (Power & Smith 2007).

2. MATERIAL AND METHODS

Spatially independent correlation analyses were performed between ENSO (Wolter & Timlin 1998; <http://www.cdc.noaa.gov>) and PDO (Mantua *et al.* 1997; <http://www.atmos.washington.edu/~mantua/abst.PDO.html>) climatic indices (figure 1a,b) and ground-based data on a $1^\circ \times 1^\circ$ global land grid. The ground-based data were temperature and precipitation (New *et al.* 2000; CRU TS 2.1, Mitchell & Jones 2005), simulated gross primary productivity by the Sheffield dynamic global vegetation model (Woodward & Lomas 2004) and a satellite product of NDVI (Tucker 1979) from the advanced very high resolution radiometer (AVHRR) family of satellite-borne sensors. The NDVI dataset used has been processed to compensate for the effects of solar elevation

and noise (e.g. clouds) in the data (Los *et al.* 1994; Sellers *et al.* 1994). The correlations were determined from 1950 to 2002, 1950 to 1976, and 1977 to 2002 for climate and gross primary productivity and from 1982 to 1999 for the NDVI.

Monthly index and ground-based data were converted into quarterly (seasonal) averages. Each seasonal series was independently normalized to both remove any long-term climatic effects and make each series comparable. The normalization was composed of detrending (using a polynomial with degree determined by the length of the series 1, 2 or 3) and division by the standard deviation. The reassembled seasonal series is then comparable with the seasonal climatic indices and a correlation analysis can be performed. From the analysis, the significance, in the form of a probability, and the gradient of the regression were extracted. The gradient is mapped globally for all the locations where the correlation between the two metrics was at least 95% significant.

3. RESULTS

Warm ENSO events lead to extensive and repeatable warming in the tropics and the Pacific Northwest and Alaska (figure 2a), with the reverse occurring during cool events. The ENSO impact on precipitation is less geographically extensive than temperature (figure 2b) with significant reductions of precipitation during warm events in Australia, Southeast Asia, southern Africa and northern Amazonia. Significant increases in precipitation occur in southwest USA, Peru and central Asia. The simulated responses of gross primary production (GPP, figure 2c) closely follow the patterns of precipitation (sites 2–7 on figure 2b). However, the Pacific Northwest and west Canada show increased GPP during warm ENSO, a response due primarily to high temperatures during warm ENSO events.

NDVI, a satellite product, has only been observed for a shorter period from 1982 to 1999 but provides an independent test of the GPP simulations (figure 2d). The data tend to show less extensive areas of ENSO impacts than GPP, but there are general similarities in areas 1, 2, 3, 6 and 7. Chile (area 5) shows positive and negative responses to ENSO, while the GPP simulations only indicate positive responses. Little change is observed over northern Amazonia (area 4). Changes in NDVI indicate differences in the amount and greenness of vegetation and in some areas changes in GPP during ENSO events may not be due to changes in these factors. A closer agreement between simulated GPP and NDVI is shown by comparing the GPP simulations for the later time period (figure 3d), with the NDVI observations (figure 2d), owing to a closer match of the observation time periods.

The PDO has relatively long periods of more or less uniform cool or warm conditions (figure 1b). There is a transition in 1976 from cool to warm PDO conditions and this change impacts on ENSO-related events, in particular precipitation and GPP (figure 3). Southwest USA, India and Australia show much stronger responses in the earlier period, while the response is greater in the later period in southern Africa, suggesting interactions between the phases of PDO and ENSO. The time scale of the PDO is longer than the existing satellite data record and so it is unlikely that its effects will be evident in the NDVI signal.

Figure 1. (a) ENSO climatic index from 1950 to 2006. Positive values of the index indicate warm (El Niño) events and negative values indicate cool (La Niña) events. (b) PDO from 1950 to 2006; positive values of the index indicate warm events and negative values cool events.

4. DISCUSSION

An early response by plants and vegetation to the teleconnected climatic changes resulting from ENSO and PDO events will be a response of GPP (figures 2 and 3). However, other, perhaps contingent, changes in vegetation or ecosystems may also occur and this aspect is addressed by considering the areas identified in figures 2 and 3.

Warmer springs occur in western Canada and the Pacific Northwest during warm ENSO events (figure 2a, area 1) and this leads to enhanced GPP as a consequence of earlier leaf emergence in spring (Black *et al.* 2000). However, changes in weather and precipitation patterns associated with the PDO lead to enhanced fires when the PDO is in the cool phase (Duffy *et al.* 2005).

The southwest USA (figures 2b,c and 3) shows significant impacts of ENSO events (figure 2c, site 2) and many studies have investigated impacts of the events on different ecosystems in the area (Holmgren *et al.* 2001). In semi-arid areas, enhanced rainfall

during warm ENSO events leads to extensive germination and growth of short-lived annual plants. Longer term changes have also been seen with, for example, significant expansion of creosote bush in the Mojave Desert (Hereford *et al.* 2006) but over a defined and wet period between 1976 and 1998. An extreme drought in the area between 1989 and 1991 led to significant mortality of perennial grasses and herbs. ENSO has a weaker impact on precipitation and GPP in this region from 1977 to 2002 (figure 3a,c, area 1), compared with the period from 1951 to 1976. This is associated with the dominantly cool phase of the PDO in the earlier period, which acts additively with the higher frequency of cool ENSO events to reduce precipitation. In the later period, the PDO is in the warm phase with a weak impact on precipitation, while warm ENSO events dominate with enhanced precipitation, except during 1989 and 1991 when a return to cool PDO and ENSO conditions reduces precipitation. In this region, ENSO and PDO events

Figure 2. ENSO responses shown as regression gradients between climatic index (figure 1) and selected variables. Positive values indicate increases during the warm ENSO phase and the reverse during the cool phase. Only geographical areas where there is equal to or greater than a 95% probability of repeat occurrence in ENSO events are shown. Gradient responses are shown for yearly (a) temperature, (b) precipitation, (c) gross primary production (GPP) and (d) NDVI. Circles with numbers indicate areas considered in the discussion.

exert substantial impacts on vegetation structure and activity. Longer term palaeoclimatic studies indicate that the joint coincidence of warm and cool ENSO and PDO events occurred for at least four centuries in the past (Verdon & Franks 2006).

Ecosystem and lag effects of ENSO events have been well described on Barro Colorado Island, Panama (Wright *et al.* 1999). Two features characterize the ENSO response. Warm ENSO events stimulate fruit production by the trees of the tropical forest. It has also been noted that frugivorous and granivorous mammals suffer famine in the year after a warm ENSO event (the response of birds is not known). One potential explanation for the ecosystem level effect of a warm ENSO event is that when fruit production is stimulated 1 year, then the following year is most likely to have inadequate fruit production to support the current mammalian population.

A strong ENSO signal is seen for northern Amazonia (figure 2b, area 4) with significant reductions in precipitation and GPP (figure 2c). A consequence of the dry conditions is an enhanced fire risk and this interacts with human activities to the extent that 90% of recent forest burning (natural plus human induced) occurs during dry warm ENSO events (Cochrane *et al.* 1999). Fewer significant correlations are shown in the

NDVI signal for this region (figure 2d). Areas with perpetually dense vegetation will exhibit low variability in NDVI and are consequently unlikely to exhibit strong relationships with the ENSO index. However, fine scale satellite imagery plus ground-based data indicate significant increases in understorey fires during warm ENSO phases (Alencar *et al.* 2006). These fine scale observations would be overlooked in the coarser scale of the AVHRR NDVI product and during signal processing.

GPP of vegetation in Chile is stimulated by the enhanced rainfall associated with warm ENSO events (figure 2b,c, area 5). This simulated GPP enhancement is also seen on the ground with increased biomass and seed production (Lima *et al.* 1999). A further ecosystem-level consequence is a stimulation of rodent outbreaks, including the leaf-eared mouse. These herbivores may prove to be economic pests of crops, during periods of high population densities. The absence of a strong NDVI response (figure 2d) implies that although GPP may change there is a rather limited impact on the degree of vegetation leafiness that can be detected by satellite observation.

Major impacts of ENSO events occur in the Southern Hemisphere, in particular for both southern Africa and Australia, where precipitation reductions

Figure 3. The impact of ENSO events on geographical patterns of (a,c) precipitation and (b,d) GPP for 1951–1976 (a,b) and for 1977–2002 (c,d) and determined as for figure 2. Circles with numbers indicate areas considered in the discussion.

are a major feature of warm ENSO events (figures 2 and 3, areas 6 and 7). In southern Africa, the mean ground area affected by drought is approximately 1 million km² (Rouault & Richard 2005). This area is greatly reduced in extent during wetter cold ENSO events and greatly increased in extent during warm ENSO events (Rouault & Richard 2005). Since the late 1970s, the extent of the droughted area has been increasing, due to stronger reductions in precipitation during warm ENSO events (figure 3) but also apparently exacerbated by interactions with the warm phase of the PDO, which appears to increase the drought effect originating from warm ENSO events. The effects of the ENSO events on the GPP are mirrored to an extent in the NDVI (figure 2d, areas 6 and 7). In these areas, the variability of the NDVI due to fluctuations in the amount of green biomass will be more pronounced than areas such as the Amazon. The response of NDVI to sea surface temperature (from which the ENSO index is derived) in these areas has been noted by Myneni *et al.* (1996).

Australia is strongly affected by ENSO events, with marked ranges from floods during cool ENSO events to droughts, and consequent fires during warm ENSO events (Nicholls 1992). Just like in Chile, this wide range of rainfall events exerts significant impacts on ecosystems. In the Simpson Desert of Australia, wet cool ENSO events lead to increased rainfall, followed by enhanced vegetation productivity. This in turn leads

to irruptions of rodents and their associated predators. Following the end of the rains, the vegetation dies back and the risk of wildfires increases markedly (Letnic & Dickman 2006).

Australian crop production is reduced during warm ENSO events (Nicholls 1997) and such events tend to have higher profile than native ecosystem effects, owing to the direct impacts on food production. Long-term analyses of food grain production in India (Selvaraju 2003) also demonstrate large impacts of ENSO on production, like Australia with stimulated productivity during cool ENSO events, and the reverse in warm events. The data from India also indicate a period of average stability in cereal production (after detrending the productivity data) from 1950 to 1978. After that period, there was a steep reduction in productivity that continued to 1999. The analysis of ENSO events into the two time periods (figure 3) indicates that the responses of precipitation and GPP to ENSO events were greater (increases with cool phase and the reverse for the warm phase) in the period from 1951 to 1976 than the subsequent period, while productivity was greater during this time. This has probably occurred because the predominantly cool PDO period of the earlier time period has enhanced precipitation and productivity in this period.

ENSO events occur with relatively high frequency and with climatic effects that exert significant impacts on terrestrial ecosystems. It is interesting to note that

these are not always represented in the satellite data: events that do not directly impact on leaf material go undetected. The most geographically extensive effects occur through changes in precipitation. However, the warmer conditions in the Pacific Northwest and Alaska are likely to be key in maintaining the extensive temperate, rather than boreal evergreen, needleleaf forests in this region. As for a number of the putative impacts of ENSO and PDO events, there are interesting and at times very strong correlations between events and ecosystem responses; but this does not mean of necessity that the events are the primary originators of the responses.

We are grateful to the Natural Environment Research Council for funding the NERC Centre for Terrestrial Carbon Dynamics.

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