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Discussions

Indigenous vegetation burning practices and their impact on the climate of the northern Australian monsoon region

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Abstract

Here we pose the question: was there a downturn in summer monsoon precipitation over northern Australia due to Aboriginal vegetation practices over prehistoric time scales? In answering this question we consider the results from a global climate model incorporating ocean, land, ice, atmosphere and vegetation interactions, reducing the total vegetation cover over northern Australia by 20 % to simulate the effects of burning. The results suggest that burning forests and woodlands in the monsoon region of Australia led to a shift in the regional climate, with a delayed monsoon onset and reduced precipitation in the months preceding the "full" monsoon. We place these results in a global context, drawing on model results from five other monsoon regions, and note that although the precipitation response is highly varied, there is a general but region specific climate response to reduced vegetation cover in all cases. Our findings lead us to conclude that large-scale vegetation modification over millennial time-scales due to indigenous burning practices, would have had significant impacts on regional climates. With this conclusion comes the need to recognise that the Anthropocene saw the impact of humans on regional-scale climates and hydrologies at much earlier times than generally recognized.

1 Introduction

It is now evident that changes in atmospheric composition have had, and will continue to have, a profound impact on the global climate system (e.g. Intergovernmental Panel on Climate Change, 2007). In much of this work, the emphasis has been on industrial and post-industrial time scales, with some claims that earlier land-use changes had already impacted atmospheric composition prior to the industrial era (Ruddiman, 2007). While the degree to which early agricultural activity may have led to changes in atmospheric composition remains somewhat of an open question (Brook, 2009), what cannot be questioned is that land-surface modifications through human activity have a millennial-scale history, well evidenced by the archaeological record. These changes have left a strong imprint on vegetation, and given the growing realisation of the degree of vegetation–climate interactions, the expectation is that they may well have led to a climate–hydrology response, albeit at a more regional scale. Here we introduce this topic in the specific context of the possible impact that vegetation changes, brought about by the burning-practices of indigenous Australians, may have had on the summer monsoon precipitation-hydrology regimes of northern Australia. While focussing on this question, we place aspects of the discussion into a wider global perspective, and provide an introduction to the interplay of vegetation and climate in other monsoon regions. We address these questions from a palaeoclimate-palaeoenvironment perspective and use this to stress the long-history of human impact on atmosphere-land surface interactions.

2 Land-surface changes and their climate impacts: time scales

The influence of vegetation change on regional climate is now a central theme of climate change and paleoclimate studies, and one that can be readily explored through global- and regional-scale climate models (e.g. Washington and Parkinson, 2005; Bonan, 2008; Claussen, 2009). While likely changes can be inferred from basic atmospheric physics with the recognition that changing vegetation types alter climate-controlling parameters, such as surface roughness, evaporation and radiation characteristics (McPherson, 2007), the full climate implications of vegetation changes could only be explored with the advent of climate models and the more recent and more comprehensive Earth System models. These models have allowed a change in scale from local, in part, instrumented studies to regional- to global-scale climate simulations. One consequence of the application of these models is that they make it possible to explore the role that vegetation changes have played as a control of past climates and hydrology. With these advances, a door was opened for questions of possible climate impacts that may be linked with vegetation modifications over prehistoric and historic

time scales. In turn, these then allow such issues to be addressed as the climate impact of vegetation burning and “creation” of grasslands of North and South America, the early forest clearing in China and the clearing of medieval European woodlands.

The environmental literature dating back to the middle of the last century contains two benchmark volumes: J. C. Glacken’s (1967), “Traces on the Rhodian Shore” and W. L. Thomas’ (1956) “Man’s Role in Changing the Face of the Earth”. With differences in emphasis and aims, both volumes draw attention to the magnitude of the environmental changes that have taken place as the result of human activity, and place these into their cultural and intellectual context and emphasising the long-time scales that are involved when considering this question. In the Thomas volume, the relevance of the immediate historical-time scale is highlighted by H. C. Darby’s (1956) essay, in which he outlines his work on the clearing of European forests. This theme of forest clearing-modification was extended, and placed in a more global context by Williams (e.g. 1990, 2000), with both Darby and Williams drawing on historical data which allowed them to confidently trace the history of forest clearing. China, with its long-history of detailed “written” records, provides even more striking insight into the extensive nature of forest clearing and the veracity with which land-use changes and specifically the destruction of the forest was undertaken over many thousands of years (Elvin, 2004).

While the extensive nature of land-use changes are evident from historical records and/or the application of proxy palaeoenvironmental indicators (Mackay et al., 2005), the likely climate impact of these changes can only be anticipated at a local physical-level based on an understanding of boundary layer meteorology (e.g. Geiger, 1966; Bonan, 2008). Although the necessary basis for such an understanding has been available for some time (the first edition of Geiger’s book was published in 1927), for many, the realisations of the strength and regional importance of likely land-surface changes – climate interactions were prompted by Jules Charney’s (1975, 1977) recognition that land-surface changes, such as vegetation clearing, grazing, and burning may have played a central role in the devastating drought experiences of semi-arid areas such as the Sahel region of West Africa over the past century.

For the palaeoclimatologist the findings of Charney opened wider questions of the controls of the Saharan palaeoclimate history, and with it the recognition of the important feedback relationships. This topic was pursued in a number of global circulation model based palaeoclimate studies (e.g. Kutzbach et al., 1996; Claussen, 1997; Ganopolski et al., 1997; Claussen et al., 2004) that found a positive vegetation feedback through changes in surface albedo and evapotranspiration such that changes in land cover could translate to changes in rainfall (see Claussen, 2005 for an overview). A more complex response was advocated by Notaro et al. (2008) and Liu et al. (2010), in which details of vegetation types, soil moisture and climate variability play a role. The proposed strong biogeophysical response associated with vegetation feedbacks on the climate system, advocated by a number of studies, are taken to account for the details of "drying" of the North African region following the Holocene "African Humid Period". This "drying" has been interpreted as an abrupt event completed within a few hundred years. Although a recent proxy palaeoclimate record has questioned this claim (Kröpelin et al., 2008), a strong argument that the Saharan vegetation-related biogeophysical feedback triggered a threshold response remains (Brovkin and Claussen, 2008).

These claims of North African strong vegetation feedback relationships provoke the question of the likely climate and hydrological impact that extensive forest clearing and vegetation modification over historical time scales, as outlined for instance by Darby (1956), Williams (1999, 2000), and Elvin (2004) (see above), may have had and whether this could be captured through global or regional scale climate model studies. On the basis of an atmospheric general circulation model and historical land-use data Takata et al. (2009) proposed that changes in the Asian monsoon can be related to preindustrial cultivation. More recently, Lee at al. (2011) were able to demonstrate that the East Asian summer monsoon is weakened when natural vegetation is "converted" to bare ground or irrigated cropland. Their model study simulated sensible heat flux during March–May and latent heat flux in June–September, with significant decrease with irrigated crop and bare ground, respectively, impacting on summer mon-

soon strength. From this it would seem likely that the vegetation changes outlined by Elvin (op. cit.) may well have impacted on the East Asian summer monsoon.

Seen more globally, the evidence of extensive vegetation modifications extends much further back in time (e.g. Bush, 2005; Pinter et al., 2011), raising questions of whether there may be evidence of a climate response to anthropogenic land cover change in prehistory. The indigenous people of Australia have a history extending back some 50 000 yr (O'Connell and Allen, 2004) and fire is generally recognised as an important component of their land management toolkit (e.g. Russell-Smith et al., 1997). With such a long history of occupation, the question of how "effective" their modification of vegetation and through this regional climate may have been, should figure prominently in any discussion of the environmental-climatic history of the Australian continent.

3 Indigenous vegetation burning in Australia and its impact on the summer monsoon regime

Fire is an integral component of the Australian environment, tied both to human activity and the climate regime (see, for example, Lynch et al., 2007). The modification of vegetation over prehistoric time scales has been a pervasive theme in Australian archaeology, linked to claims of fire-stick farming (Jones, 1969). Such "farming" would have had a dramatic impact on the vegetation of Australia, as fire is generally recognised as an important element in "shaping" global biome distributions (Bond and Keeley, 2005; Bond et al., 2005). Gammage (2011, p. 167) details how, at the time of European arrival, the Australian landscape had been shaped by carefully managed fires: "Particular animal and plant communities needed and got very precise fire timings and intensity. . . When to burn grass might hinge on its varying growth from year to year, or on associated tubers or annuals, some killed by fire, others needing it to flower, seed or compete. . . Yet plant communities embracing different fire responses thrived in 1788.

Multiply this by Australia's 25 000 species, and a management regime of breathtaking complexity emerges".

However, there are limitations to the strength of claims of extensive Aboriginal burning practices stretching back into prehistory. A recent compilation of Australian late Quaternary charcoal records concluded that there is no evidence of increased human activity in the history of biomass burning, other than that associated with European impact (Mooney et al., 2011). It is however noteworthy to draw attention to Pinter et al.'s (2011) retort who note: (i) that Tasmania was colonised later than mainland Australia and the likely environmental impact of human activity occurred correspondingly later; and (ii) that the evidence of fire and de-vegetation closely followed the colonisation of New Zealand during the late Holocene.

It has been proposed that a large scale shift in the vegetation cover of northern Australia, from a closed woodland to a more open grassland type environment, due to burning practices, led to a decline in the strength of the early Holocene north Australian summer monsoon (Miller et al., 2005), while other model results have suggested a much less enthusiastic response of the Australian monsoon system to vegetation change (Pitman and Hesse, 2007; Wyrwoll et al., 2007; Marshall and Lynch, 2008). Given these results, questions of human impacts on the summer monsoon climate of northern Australia through vegetation change remains open and pose an important issue for a rounded understanding of environmental/palaeoenvironmental controls and events for this part of the Australian continent.

A vegetation change-driven monsoon response in Australia was first advocated by Johnson et al. (1999), following work on the carbon isotope composition of eggshell calcite from the Lake Eyre Basin in central Australia. This inference was adopted to explain apparent differences between the strength of the Australian summer monsoon of the Last Interglacial and Holocene (Magee et al., 2004). The claim is based on the lacustrine stratigraphy of Lake Eyre, with the suggestion that the low lake levels, dated to around 10 ka, cannot be explained by the key drivers of monsoon strength (Magee et al., 2004; Miller et al., 2005 – but see Wyrwoll et al., 2007), and represent the cli-

mate response to vegetation burning land management practices, implemented on the arrival of Aboriginal people during the late Pleistocene. Given the strength and scale of the northern Australian-Indonesian summer monsoon, its dynamic/thermodynamic controls and global-scale impact (McBride, 1987, 1999), that burning vegetation practices can result in a down-turn of the full summer monsoon regime is surprising.

Following on from Magee et al. (2004), Miller et al. (2005) used the general circulation model GENESIS Version 2 with a coupled land-surface model to investigate the importance of vegetation on the Australian monsoon under differing Milankovitch insolation states. Simulated output at 10 ka indicated a significant reduction in precipitation across northern Australia, when the region was depicted as desert, and significantly increased precipitation when the region was covered with broadleaf deciduous forest. The desert land-surface changes are extreme and unrealistic. In comparison, embedding more realistic vegetation changes in a regional climate model (Regional Atmospheric Modelling System), and running it for January (using present day boundary conditions: insolation, sea surface temperatures and land extent) showed a clear response in latent heat flux and wind velocity following vegetation change, but a much smaller change in simulated precipitation (Pitman and Hesse, 2007). This difference in results was addressed by Miller et al. (2007), who claimed that vegetation is a significant control on monsoon precipitation only during periods when external forcing mechanisms are acting to enhance the monsoon regime, as was the case at 10 ka.

A different approach was adopted by Marshall and Lynch (2008) who, using the Fast Ocean Atmosphere Model Version 1.5 (FOAM) at selected time-slices, varied insolation, surface roughness length, global ocean cover and radiative forcing, and then fitted a multivariate reduced form model, in order to explain the relative importance of each forcing mechanism. This study aligned with Pitman and Hesse (2007), finding that vegetation plays a minor role relative to the dominant controls of insolation and sea level – land extensions, and provided an alternative theory regarding lower-than-expected Lake Eyre levels in the early Holocene, countering Miller et al. (2005) by proposing reduced Southern Hemisphere solar insolation stopped the monsoon from penetrating inland. It is worth highlighting that as this experiment only incorporated variation in the aerodynamic properties of vegetation (surface roughness length) it is perhaps not best equipped to fully answer questions regarding vegetative feedbacks.

In order to better understand the impact of early human land management practices on the climate of the monsoon region, distinct from large-scale drivers, we used a global atmosphere–ocean–land–ice model, the Community Climate System Model Version 3.5 (CCSM3.5; Gent et al., 2010), incorporating vegetation dynamics and the Lund–Potsdam–Jena model for annual vegetation processes (Notaro et al., 2011a). A comprehensive initial value ensemble approach was employed, with a multi-century, modern-day simulation run for November through to March, encompassing the full monsoon season, along with pre- and post-monsoon circulation. The effects of burning were accounted for by a 20 % reduction of the total vegetation cover across northern Australia, based roughly on estimated pre-European burning patterns as outlined in Russell-Smith (2002).

The results of this study indicated a significant climate response to reduced vegetation cover during the pre-monsoon period of November and December (Fig. 1a). Noteworthy is the delayed onset of the monsoon. Other prominent changes were decreases in total rainfall of more than 30 mm, higher surface and ground temperatures and enhanced atmospheric stability. However, no difference was seen in peak precipitation, nor were the changes in precipitation during the monsoon period of January and February statistically significant. These results demonstrate that no significant response is observed in monsoon precipitation following vegetation change, but feedbacks are evident in the pre-monsoon period. This seasonal response pattern is not unique to vegetation. Other studies have shown that, despite its proximity and size, there is essentially no monsoon response to the El Nino-Southern Oscillation (ENSO) over much of the summer monsoon region of northern Australia (BOM, http://www.bom.gov.au/climate/enso/; McBride and Nicholls, 1983). Instead, there is a reduction in precipitation in El Nino years during the months preceding the monsoon, with a delayed onset of the monsoon also evident (Nicholls et al., 1982). This being

the case, it is possible that feedback relationships between El Nino events and vegetation changes due to fire use may well have occurred, further augmenting the reduced precipitation signal. A link between ENSO and vegetation burning in north eastern Queensland was suggested by Haberle et al. (2010) who noted a coinciding peak in charcoal quantities and El Nino activity at 2 ka, but this is likely to be simply ENSO-driven droughts leading to increased fire frequency, rather than a vegetation–climate feedback.

From our findings, we present a model of vegetation-climate interactions in the monsoon region of Australia in which these interactions play a significant role in the regional climate, but where the impact on the "full" monsoon regime is minor. These inferences find agreement with studies indicating no response to vegetation change in January precipitation (Pitman and Hesse, 2007) or arguing that vegetation plays a marginal role relative to dominant, global-scale controls (Marshall and Lynch, 2008). Nevertheless, we can conclude that through burning practices resulting in biome changes in northern Australia, indigenous people altered not only the ecology but also the climate of the region, effectively extending the dry season and delaying the onset of the "full" monsoon. A question that follows on from these findings is whether similar climate responses to vegetation change are evident in other monsoon regions?

4 Global monsoon comparison

With additional model experiments (Notaro et al., 2011b) it has become now clear that the conclusions that have come out of the northern Australian work do not necessarily apply to other monsoon regions. Previous work has already provided the expectation that vegetation changes need not necessarily provoke the same climate response in the various monsoon regions (e.g. Hoffmann and Jackson, 2000). Our recent extensive set of model experiments (Notaro et al., 2011b) considered, in addition to northern Australia, five other monsoon regions: North America, South America, North Africa, India and China. A summary of the response to a 20 % reduction in vegetation cover is provided in Fig. 1b. The results show a consistent response of a number of variables, including diminished turbulent fluxes, surface warming and a dampened hydrological cycle. Precipitation shows a different story, with differences much more prominent. In general, the largest precipitation response to reduced vegetation cover occurs in spring (prior to the monsoon season) or autumn (following) and little response is evident during the full monsoon. In this, northern Australia stands out as the only region that shows a statistically significant change in annual precipitation due to vegetation changes. This reflects similar results from Hoffmann and Jackson (2000) who found, using CCSM Version 3 to simulate the response to a shift from savannah to grassland, that northern Australia saw the strongest reduction in precipitation, compared with South America and Africa.

The differences between the climate parameters is also mirrored in the dynamics (Fig. 2), with tropospheric response to reduced vegetation cover being less over North Africa, South America and India than over the other monsoon regions. Nevertheless, increased tropospheric subsidence is a consistent feature in response to reduced vegetation cover, but differences emerge when it is considered season-by-season. Although the evidence in northern Australia of increased subsidence throughout October to January indicates a delayed and weakened monsoon, the Chinese response appears to be an earlier monsoon, with anomalies of ascent in May and descent in September. Besides northern Australia, the other monsoon region that appears to trigger a widespread response in velocity potential is over North America. Likewise, during January–March, anomalous subsidence over North America corresponds to anomalous divergence at 850–700 hPa and convergence at 250 hPa. The upper level convergence into North America extracts air from the South American monsoon region during its corresponding wet season.

The varied response to vegetation change is to be expected for a number of reasons. The monsoon regions of China and North America, for example, are located in the subtropics, while the others have a tropical location. This is reflected in the responses to reduced vegetation, whereby the Bowen ratio increases in the wetter, more tropical

regions of North Africa, northern Australia and India, due to significant decreases in evapotranspiration and thus latent heat flux. In the drier, subtropical regions of North America and China, latent heat flux does not reduce more than sensible heat flux, and so we observe a decrease in the Bowen ratio. This indicates that while some monsoon regions react to vegetation change primarily through a thermal response (subtropical regions), while others react with a more moisture-driven response (in the tropics). Similarly, different biomes have been shown to lead to different climate feedbacks (Synder et al., 2004), and thus removing vegetation from a region dominated by grasslands (say, South America), would lead to a different climate response than a region dominated by evergreen and deciduous trees such as China.

5 Conclusions

The overall conclusion that emerges from this model study is that changes in vegetation through Aboriginal burning practices could have impacted on the regional hydrological cycle of northern Australia, since the occupation of the continent some 50 000 yr ago. The climate changes evident in the model results point to particularly pronounced changes during the early/pre-monsoon months. During the peak monsoon, the large scale hemispheric-interhemispheric land/ocean thermodynamic-dynamic controls overwhelmed the more regional scale biophysical changes. From the results it is also clear that the northern Australian hydroclimate responses to vegetation are not directly mirrored by other monsoon regions, prompting a clear need for further explorations of the reasons for the monsoon region-specific response to vegetation changes. In this it may be worthwhile to remember that modeling studies are model-dependent and there is a clear need for more observed vegetation feedback benchmark studies, in which palaeoecological work can play a major role. Given projected changes in climate of the low latitude monsoon regions our findings carry implications for future climates. With a changing climate over the monsoon regions provoking a vegetation response, feedbacks will be set-up which may project the regional climates into other climate trajectories. In closing, we draw attention to the wider implications of our findings, emphasising the long term history of vegetation clearing, as evidenced by the archaeological record. And draw attention to the likelihood that vegetation modifications over historical-prehistoric time scales, may well have brought about stronger regional to continental scale climate-hydrology changes than are commonly recognised, changes which are clearly embraced by the concept of the Anthropocene.

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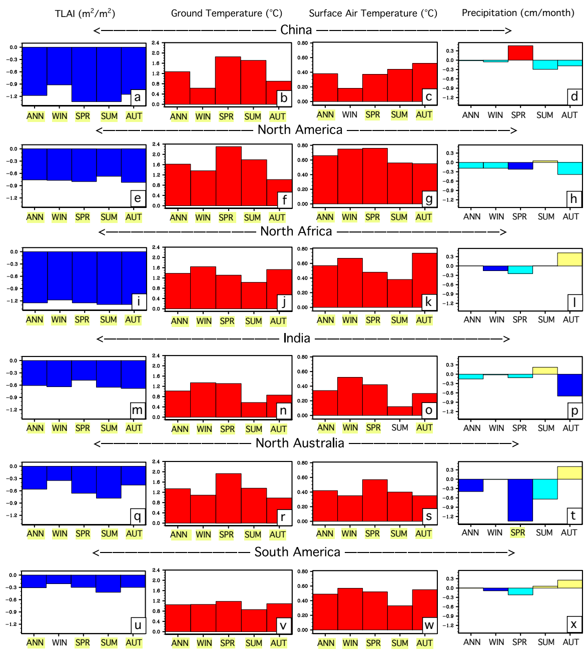

Fig. 1a. Mean changes (ENSEMBLE–CONTROL), both annually (ANN) and seasonally (January–March – JFM, April–June – AMJ, July–September – JAS, and October–December – OND), in leaf area index (m^2 m^{-2}), ground and surface air temperature (°C), and precipitation (cm month^{-1}) for the six monsoon regions. Red and yellow bars indicate increases, with the former achieving 90 % significance with *t* tests. Dark and light blue bars indicate decreases, with the former achieving 90 % significance. Changes with a robustness index of at least 70 % are highlighted in yellow.

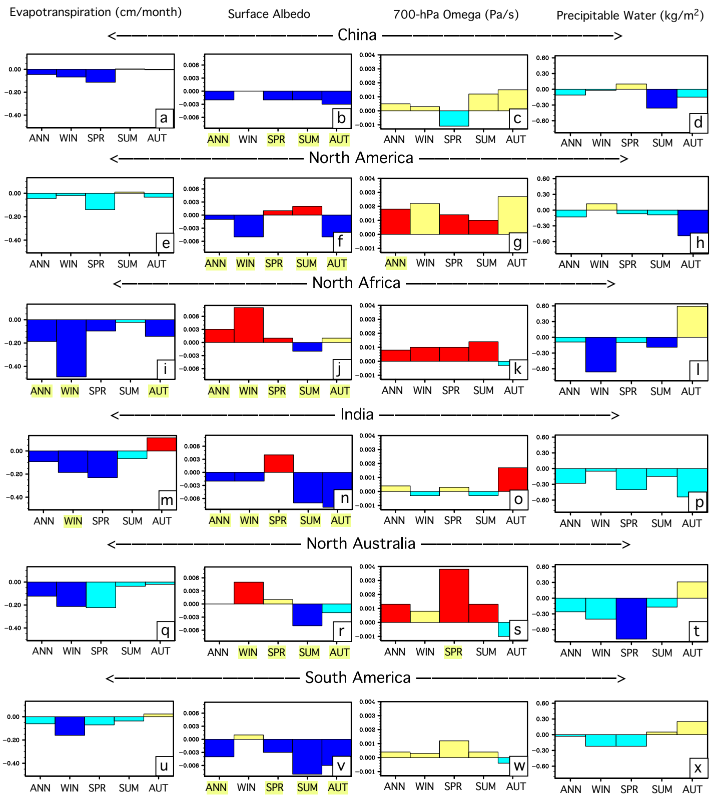

Fig. 1b. As in Fig. 1a but for evapotranspiration (cm month^{-1}), surface albedo, 700-hPa vertical motion (Pa s^{-1}), and precipitable water (kg m^{-2}).

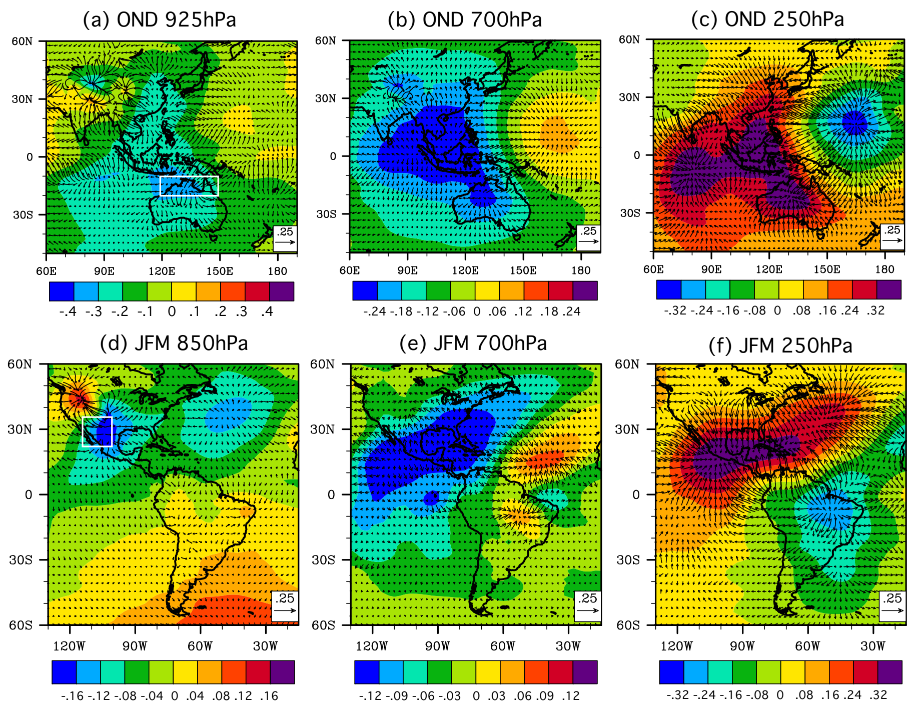

Fig. 2. Mean changes (ENSEMBLE–CONTROL) in velocity potential(m^2 s^{-1} scaled by 10^6) for **(a)** 925 hPa, **(b)** 700 hPa, and **(c)** 250 hPa during OND, shown for the area around the north Australian monsoon region. Mean changes in velocity potential for **(d)** 850 hPa, **(e)** 700 hPa, and **(f)** 250 hPa during JFM for the area around the North American monsoon region. Red (blue) indicates anomalous convergence (divergence).