

Influence of savanna fire on Australian monsoon season precipitation and circulation as simulated using a distributed computing environment

Amanda H. Lynch,¹ David Abramson,² Klaus G6rgen,³ Jason Beringer,¹ and Petteri Uotila¹

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[1] Fires in the Australian savanna have been hypothesized to affect monsoon evolution, but the hypothesis is controversial and the effects have not been quantified. A distributed computing approach allows the development of a challenging experimental design that permits simultaneous variation of all fire attributes. The climate model simulations are distributed around multiple independent computer clusters in six countries, an approach that has potential for a range of other large simulation applications in the earth sciences. The experiment clarifies that savanna burning can shape the monsoon through two mechanisms. Boundary-layer circulation and large-scale convergence is intensified monotonically through increasing fire intensity and area burned. However, thresholds of fire timing and area are evident in the consequent influence on monsoon rainfall. In the optimal band of late, high intensity fires with a somewhat limited extent, it is possible for the wet season to be significantly enhanced. **Citation:** Lynch, A. H., D. Abramson, K. G6rgen, J. Beringer, and P. Uotila (2007), Influence of savanna fire on Australian monsoon season precipitation and circulation as simulated using a distributed computing environment, *Geophys. Res. Lett.*, 34, L20801, doi:10.1029/2007GL030879.

1. Introduction

[2] Dry season fires are one of the largest natural and anthropogenic disturbances in the tropical savannas. Between 40 to 75% of global savannas were burned annually between 1975 and 1980 [Hao *et al.*, 1990]. Savanna fires consume three times as much dry matter annually as the burning of tropical forests (e.g., 3690 Tg dm yr⁻¹ for savanna versus 1260 Tg dm yr⁻¹ for tropical forests [Andreae, 1991]) although recovery of the biomass is an order of magnitude more rapid. The Australian tropical savanna is one of the world's largest, with vast tracts affected by fire each year, particularly in deliberate burning by pastoralists, Aboriginal land holders and conservation managers – an estimated 244,000 km² of the total area of

northern Australia was affected in 1997 [Russell-Smith *et al.*, 2000].

[3] Fires across this landscape have impacts on the regional water, energy and carbon dioxide exchanges [Beringer *et al.*, 2003] through altered vegetation composition and reduced surface albedo, increased available energy for partitioning into the convective fluxes, and increased substrate heat flux into the soil. In addition, the aerodynamic and biological properties of the ecosystem can change, affecting surface-atmosphere interaction [Beringer *et al.*, 2007]. Local tethered balloon profile measurements [Wendt *et al.*, 2007] and idealized computer sensitivity studies [G6rgen *et al.*, 2006; Pitman and Hesse, 2006] have demonstrated intensified boundary layer processes in fire-affected areas and have led some to suggest impacts extending to the regional scale [Miller *et al.*, 2005]. However, these impacts, and their potential for the modification of the Australian monsoon regime, have not been systematically quantified. Here we address that quantification using a comprehensive experimental design made possible through the use of software that allows the implementation of legacy code on a global computational grid.

2. Methods

[4] Quantifying the impacts of fire in savanna regions is challenging because fire and its effects span many temporal and spatial scales. Moreover, there is high interannual variability. Hence, this question requires the application of a high resolution climate model which allows the representation of the effects of savanna fire across a range of manifestations through multiple realizations of the model.

[5] We represented savanna fires in the Conformal-Cubic Atmospheric Model (C-CAM) from the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), which is a global hydrostatic atmospheric model coupled to a land surface model with a variable-resolution conformal-cubic grid [McGregor and Dix, 2001]. This grid provides a resolution of approximately 65 km over Australia extending to about 800 km on the far side of the globe. Far-field atmospheric nudging is achieved using the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data [Kalnay *et al.*, 1996] with an e-folding time of 96 hours, resulting in relatively weak constraints on the high-resolution part of the model domain [G6rgen *et al.*, 2006].

[6] A fire/re-growth scheme has been implemented in the existing C-CAM land surface model. The surface properties modified by fire and the subsequent vegetation re-growth

¹Climate Program, Monash Sustainability Institute and School of Geography and Environmental Science, Monash University, Clayton, Victoria, Australia.

²Clayton School of Information Technology, Monash University, Clayton, Victoria, Australia.

³D6partement Environnement et Agro-Biotechnologies, Centre de Recherche Public–Gabriel Lippmann, Belvaux, Luxembourg.

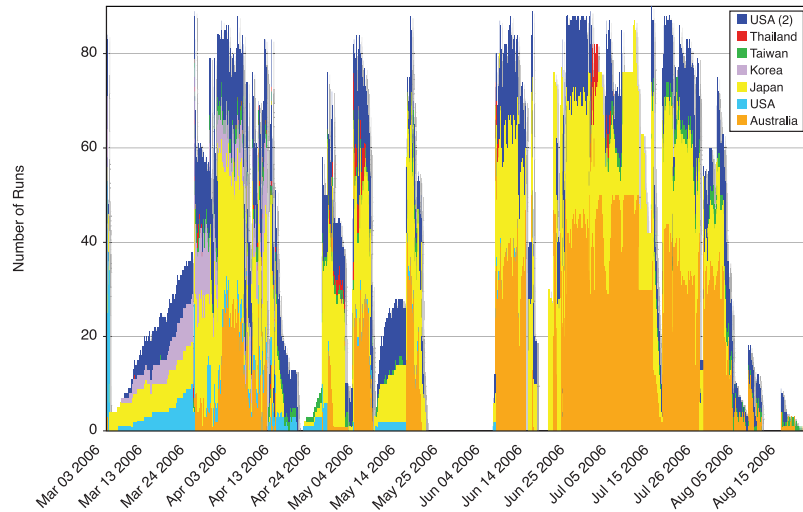


Figure 1. Number of jobs executed by computational resources in each country participating in the experiment over the PRAGMA grid (www.pragma-grid.org).

are defined in the model by four parameters which are based on the observed fire regime [Russell-Smith *et al.*, 2003]. First, the intensity of the fire in any one grid cell ranges from 10% to 100% of the maximum possible biomass that can be destroyed, on the basis of fire intensities associated with an energy release between 10^3 and 10^4 kWm^{-1} [Chaffer *et al.*, 2004]. Secondly, the spatial distribution of fire-affected grid cells is defined within a range from 10% to 100% of the maximum possible area, based on the observed area burnt between 1997 and 2001. Thirdly, the temporal range for the timing of the fire event lies between 1 May and 30 November, which is followed a few weeks after by the average monsoon onset date. Finally, the length of the regrowth period is allowed to vary between 35 and 140 days.

[7] In order to quantify the relative importance of each of the four forcing parameters (area, intensity, timing and length of regrowth), a multifactorial approach that allows the analysis of both the impacts of individual forcings and the interactions between forcings is required. Rivers and Lynch [2004] developed just such a method using a factorial experimental strategy based on the work of Henderson-Sellers [1993] for assessing the effects of the changing land surface on early Holocene climate in Beringia using a series of multi-year ensemble perturbation experiments that varied all forcing parameters simultaneously. This approach has been adopted here by varying all four forcing parameters simultaneously using a Latin hypercube sampling to define 90 individual experiments, each of 21 years duration (1979–1999) and each having a 5 year fire-free spin up period.

[8] Using a single sequential high end workstation would require more than 10 years of wall clock time to complete this experiment. Clearly this is unacceptable. However, the individual realizations can be executed in parallel and it is possible to reduce the execution time substantially using this technique. Rather than using a single 90 processor cluster (which was not available), we distributed the computations across multiple independent clusters located in Australia, Japan, Korea, Taiwan, Thailand and US. These have been provided as part of a multi-country Grid com-

puting initiative called PRAGMA (the Pacific Rim Grid and Middleware Assembly).

[9] Running such a large scale experiment over distributed resources is very time consuming and error prone without adequate software support. In response, Abramson *et al.* [2000] have developed a software tool called Nimrod/G, which automates the execution of parameter sweep and search applications, such as the design developed here, over global computational Grids. Nimrod/G manages the complexity of running the experiment, handles network and resource failures, and gives the appearance of a single supercomputer.

[10] Our experiment ran for an elapsed time of 170 days – significantly less than 10 years – with an average of 37 processors in use across that period (Figure 1). Of the 90 original experiments, 85 executed successfully, and 5 were terminated due to instabilities in the model.

3. Response of the Monsoon

[11] The area-total monsoon precipitation over northern Australia responds, with a statistically significant increase, to increases in the fire intensity, the lateness of the timing and the area burned in the preceding dry season. The maximum increase of the simulations performed, due to the combination of all four parameters, is 1.6 mm day^{-1} over an average precipitation rate of 5.1 mm day^{-1} (a 31% increase in average monsoon season precipitation) (Figure 2a). This maximal response occurs in the simulation that specifies a fire intensity of 72%, a fire area of 90%, and a date of fire of the 5th November, around 6 weeks before typical monsoon onset [Hendon and Liebmann, 1990]. The length of the regrowth period has a limited impact on monsoon precipitation, accounting for only around 9% of the total variance in monsoon precipitation. In contrast, the fire intensity accounts for around 15% of the variance, the fire area accounts for almost 18% of the variance, and the fire timing accounts for almost 58% of the variance in monsoon precipitation.

[12] Results from the 85 multiple realizations allowed the development of a statistical model [Lynch *et al.*, 2001] of the response metrics (such as monsoon onset and intensity) to variations in the four driving parameters. The statistical

model allows inter- and extra-polation from the simulations that were successfully performed to postulate the maximal response. This model suggests that the largest increase in monsoon rainfall in response to previous dry season fires is dependent upon a maximum possible fire intensity occurring as late as possible during the dry season, but does not support the largest possible fire area. This is due to the need for sufficient vegetated area to remain to boost the moisture available for convective activity. This limit occurs at around 90% of the total possible burned area.

[13] The interaction between monsoon season precipitation, fire intensity and the timing of the fire is of particular interest to decision-makers. High intensity fires that burn both the over-storey and the undergrowth in the early dry season (up to around mid-July) have limited impact on monsoon precipitation because atmospheric moisture is limited (Figure 2a). Conversely, late dry season fires have a small influence on precipitation unless the fire is also very intense. Fire area and timing also interact such that a large fire area has effectively no impact during early dry season fires, but fires of any area between around 40% and 90% had a strong influence on monsoon precipitation if they occurred during the late dry season. The relationship between monsoon precipitation and fire area shows less variability than that between monsoon precipitation and fire intensity. The variability in monsoon rainfall is due specifically to variations in uplift intensity (see Figure 2b, discussed below) rather than moisture availability.

[14] The impact of dry season fire intensity on monsoon season precipitation is due to the interaction between the generation of uplift due to surface heating and the availability of moisture. Fires result in decreased albedo, increased net radiation, increased Bowen ratio (surface heating) and enhanced vertical uplift. The area over which enhanced vertical motion exceeds a threshold value of 1.5 Pa s^{-1} (accumulated over three model levels in the upper boundary layer) increases with both intensity (Figure 2b) and area of fire. The influence of the timing of the fire on vertical motion is rather small, as the intensification of boundary layer processes is not driven by moist processes. However, the timing of the fire becomes important in the simulation of moist parameters, including latent heat fluxes, precipitable water in the tropospheric column, and convective cloud (Figure 2c). There is insufficient available moisture for fires to influence these variables in the early dry season, but during monsoon buildup a combination of

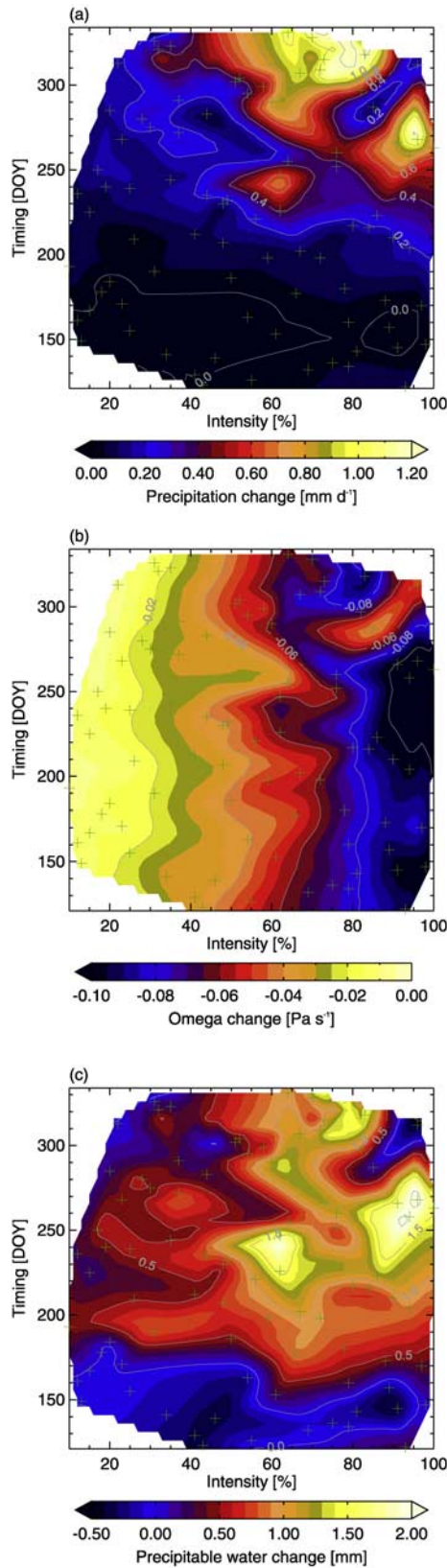


Figure 2. Simulated differences (scenario minus reference simulation) in response to variation in fire intensity and the date of fire onset. Shown are differences in (a) average precipitation [mm d^{-1}], (b) vertically averaged boundary layer uplift [Pa s^{-1}], spatially averaged over those grid elements that satisfy a threshold criterion (below 1.5 Pa s^{-1}), and (c) vertically integrated precipitable water [mm]. The differences of the spatial averages over Australia's land area north of Tropic of Capricorn are averaged over the first 60% of the regrowth period over the 20 years of each experiment. The crosses indicate the population of the simulation space. The contoured response metric is then Gaussian low pass filtered linear interpolations based on Delauney triangulations.

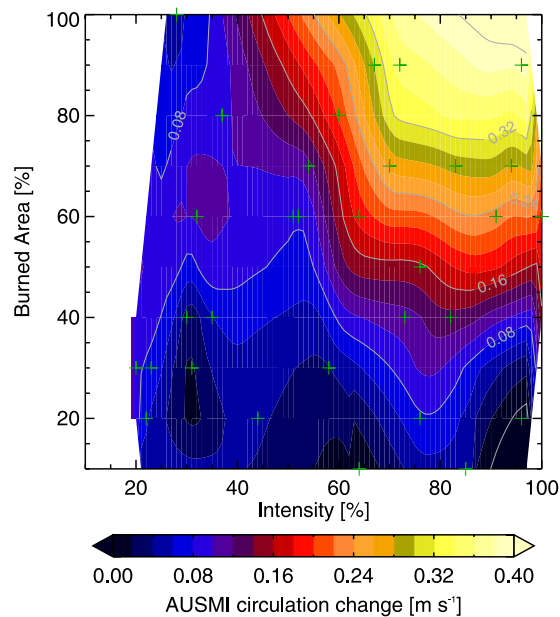


Figure 3. Simulated differences (scenario minus reference simulation) in response to variation in fire intensity and burned area. Shown are differences in the mean zonal wind speed [m s^{-1}] at 850 hPa. Spatial averages of zonal winds are calculated from 0° to 10°S and 120°E to 150°E , the zone of monsoonal reversal of the flow in and out of Australia. Only experiments with a timing of the fire-event later than the Julian day 250 (7 September) are considered, as indicated by crosses.

enhanced convective activity with increased atmospheric moisture leads to both an advancement of monsoon onset and increased precipitation intensity, and hence an increase in total monsoon season precipitation.

[15] Given the large scale influence of fire on surface energy balance, albedo, vertical motion and moist processes, we hypothesized that the simulated changes may have an impact on regional scale monsoon circulation patterns such as that postulated by Johnson *et al.* [1999]. To test this we used an indicator of large-scale circulation changes called the Australian Monsoon Index (AUSMI) [Wang *et al.*, 2004], which is obtained by averaging the daily mean 850 hPa zonal wind speed from the equator to 10°S and from 120°E to 150°E . Earlier studies [Görgen *et al.*, 2006] using single fire realizations have found that fires have a limited impact, if any, on the large scale development of the monsoon regime, with responses that are temporally and spatially restricted to fire-affected areas. However, in this more complete experimental design, we have found a significant influence of fire intensity and area on the AUSMI when consideration is restricted to late dry season fires (Figure 3). For example, the maximum value of AUSMI is 0.43 ms^{-1} for a high intensity, late dry season fire, compared to the average of all scenarios of 0.03 ms^{-1} . As for the local impacts, the moisture availability later in the year is a requirement for a statistically significant perturbation to the monsoon circulation. In contrast, fires that occur before September have no discernable influence on the large scale monsoon circulation. Thus, across the experiments performed, fire timing accounts for almost 85% of the

variance in AUSMI. Nevertheless, changes in both fire intensity and area burned account for 6% of the variance respectively, and statistical modeling indicates that the area threshold noted for maximum monsoon rainfall impact is not evident in the influence on circulation.

[16] These responses are certainly model dependent, due to variations in sensitivity amongst climate models, the impacts of grid resolution and parameterization choice, and the possible constraining effect of far field nudging. However, the technical innovation that supports this experimental design is highly scalable, and hence an extension of this work will be to consider multi-model ensembles. In this context, these experiments suggest that savanna burning can shape monsoon response through two mechanisms. The first, and primary, mechanism is the influence on the intensity of surface heating, which has a direct effect on the boundary layer circulation and thence large scale convergence. The secondary mechanism is the influence of these changes on convection and monsoon precipitation – evident is a threshold of fire timing on the one hand and fire area on the other. Under the appropriate condition of sufficient available moisture combined with enhanced convergence and uplift, the subsequent wet season is indeed significantly enhanced.

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- D. Abramson, Clayton School of Information Technology, Monash University, Clayton, VIC 3800, Australia.
- J. Beringer, A. H. Lynch, and P. Uotila, Climate Program, Monash Sustainability Institute and School of Geography and Environmental Science, Monash University, Clayton, VIC 3800, Australia. (amanda.lynch@arts.monash.edu.au)
- K. Görgen, Département Environnement et Agro-Biotechnologies, Centre de Recherche Public–Gabriel Lippmann, L-4422 Belvaux, Luxembourg.