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Near-global impact of the Madden-Julian Oscillation on rainfall

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[1] The accuracy of synoptic-based weather forecasting deteriorates rapidly after five days and is not routinely available beyond 10 days. Conversely, climate forecasts are generally not feasible for periods of less than 3 months, resulting in a weather-climate gap. The tropical atmospheric phenomenon known as the Madden-Julian Oscillation (MJO) has a return interval of 30 to 80 days that might partly fill this gap. Our near-global analysis demonstrates that the MJO is a significant phenomenon that can influence daily rainfall patterns, even at higher latitudes, via teleconnections with broadscale mean sea level pressure (MSLP) patterns. These weather states provide a mechanistic basis for an MJO-based forecasting capacity that bridges the weather-climate divide. Knowledge of these tropical and extra-tropical MJO-associated weather states can significantly improve the tactical management of climate-sensitive systems such as agriculture. **Citation:** Donald, A., H. Meinke, B. Power, A. de H. N. Maia, M. C. Wheeler, N. White, R. C. Stone, and J. Ribbe (2006), Near-global impact of the Madden-Julian Oscillation on rainfall, *Geophys. Res. Lett.*, *33*, L09704, doi:10.1029/2005GL025155.

1. Introduction

[2] The Madden-Julian Oscillation (MJO) is an atmospheric, large scale, eastward propagating circulation anomaly that originates over the Western Indian Ocean, is confined to the tropics, moves at around 5–10 ms^{-1} and has a recurrence interval of around 30 to 80 days [*Madden and Julian*, 1972, 1994]. Evidence suggests that the MJO is responsible for much of the observed intraseasonal climate variance not only in the tropics, but also in higher latitudes [*Bond and Vecchi*, 2003, *Chen and Murakami*, 1988; *Barlow et al.*, 2006]. Analysis has been restricted by the ability to accurately identify, forecast and/or model the MJO, however, the use of the Real-Time Multivariate MJO (RMM) Index [*Wheeler and Hendon*, 2004] overcomes many of these restrictions. In farming, many tactical decisions could benefit from a better quantification of intraseasonal climate variability. We sought to provide such quantification, in a manner accessible primarily to rural tacticians.

[3] Considering the global importance of rainfall variability for climate sensitive industries [*Meinke and Stone*, 2005] we investigated (a) whether and where the active and break periods of the MJO might influence rainfall and (b) how these regional rainfall anomalies might be explained via synoptic patterns as evident in global mean sea level pressure anomalies. Such investigation of possible teleconnections between the passage of the MJO and other, extra-tropical atmospheric phenomena might provide the scientific basis for the development of more rigorous MJO-based forecast systems.

2. Methods

[4] The methods were initially developed and refined using Australian data sets [*Donald*, 2005] and then applied to a global set of daily rainfall records [*Kistler et al.*, 2000]. The RMM Index [*Wheeler and Hendon*, 2004] was used as an MJO proxy (Figure 1). All references to 'phase' in this paper refer to RMM Index phase. For this analysis, we used daily phase data for a period 1 June 1974 to 27 April 2004 (excluding 17th March 1978 to 31st December 1978 due to lack of satellite coverage).

[5] Comparing Australian results based on the Australian and global data sets we observed some differences due to variations in data quality and station density. However, similar regional patterns for each phase emerge regardless of data source. This provides corroborating evidence that the global trends observed in our analysis are valid. Seasonal differences between the paths of the convective centre of the MJO have been reported [*Wang and Rui*, 1990; *von Storch and Xu*, 1990] and need to be accounted for. Although a more detailed seasonal analysis would be desirable, data scarcity only permitted us to consider two 'seasons', namely austral summer (1 November to 30 April) and austral winter (1 May to 31 October).

[6] MSLP is a reliable indicator of the state of the atmosphere and the associated weather experienced at the surface, allowing the investigation of potential teleconnections by which the MJO might influence precipitation. Any systemic changes in synoptic patterns exert influence on local rainfall and impacts will be evident in historical rainfall records [*Hughes and Guttorp*, 1994]. To quantify evidence of causality between the passage of the MJO and observed standardised MSLP anomaly patterns, we defined a cell around the active centre of convection (ACC; approximately 3000 by 2000 km) for each MJO phase and season based on OLR measurements (similar to definitions by *Wheeler and Hendon* [2004] and *Wheeler and Weickmann* [2001]).

[7] For each ACC cell we calculated the observed, aggregated standardised MSLP anomalies and constructed stochastically generated null distributions of such anomalies by sampling from synthetic time series represented by Markov Chain Models (MCM; 2000 runs), which maintain the observed frequencies for phase transitions between

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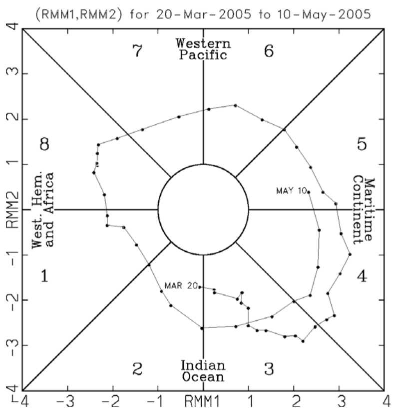

Figure 1. RMM Index Phase Space Diagram: example March–May 2005. The RMM Index [*Wheeler and Hendon*, 2004] consists of the pair of normalized projection time series of the leading empirical orthogonal functions (EOFs) of the combined fields of near-equatorially-averaged 850-hPa zonal wind, 200-hPa zonal wind and satellite-observed outgoing longwave radiation (OLR) data. The index provides MJO information without the need for time filtering. When the MJO is active, points in this phase space trace anticlockwise circles around the origin, which signifies the systematic eastward propagation of the MJO. Large-amplitude circles signify strong cycles of the MJO, while weak MJO activity appears as rather random motions near the origin (i.e., within the inner circle), when the signal can be obscured beyond the focus of the RMM tool.

consecutive days. P-values associated with the observed MSLP anomalies were derived from the MCM-generated null-distributions. Low p-values indicate strong empirical evidence of causal relationships between MSLP patterns and the passage of the MJO (Figure 2).

[8] As physical connections between MSLP patterns and rainfall are self-evident, we use inferential procedures (Monte Carlo based statistical tests) to investigate the influence of MJO phases on MSLP and only a descriptive approach to quantify MSLP (and hence MJO) influence on rainfall. Such a quantification approach is not only more informative, it also overcomes issues associated with the presence of autocorrelations patterns in daily rainfall time series (represented by their respective CDFs). Some commonly used statistical tests for comparing CDFs (e.g., Kolmogorov-Smirnov), means (e.g., t-tests) or medians (e.g., Kruskal-Wallis) rely on independence assumptions and are therefore not appropriate when autocorrelations are present. Although complex and time consuming inferential procedures could be applied (e.g., by fitting time series models and checking for distributional assumptions for each rainfall station), this is unlikely to yield much, if any additional information in regards to the underlying mechanisms that are responsible for such rainfall differences.

[9] MJO impacts on daily rainfall were quantified for each location by calculating the maximum absolute vertical distance between unconditional and respective conditional daily rainfall CDFs for each MJO phase. Those distances (in units of percent difference at the point of largest divergence) were mapped to display spatial patterns of MJO impacts for each phase. The colour (red or blue) (Figures 3 and 4) is based on the sign of the signal (+ or −) at the point of maximum divergence, while the colour intensity indicates the magnitude of the MJO-related divergence.

3. Results

[10] Maps show the occurrence of suppressed or enhanced rainfall and corresponding standardised MSLP anomalies for all seasons and phases. Here we only present results for austral winter Phases 2, 4, 6 and 8 (Figures 3 and 4, respectively). All other results including analyses based on high quality Australian rainfall data are available via the auxiliary material[1]. A shift from negative MSLP anomalies (Phases 1–6) to positive MSLP anomalies (Phases 7–8) reflects the breakdown of MJO related active convection and the 'drying out' of the MJO over mid-Pacific (Figure 2), a result that is fully consistent with our physical understanding of MJO-based convection [*Jones et al.*, 2004].

4. Discussion

[11] Many scientists have already alerted to the extra-tropical impacts of the MJO [*Chen and Murakami*, 1988; *Goswami et al.*, 2003]. Anecdotal evidence provided by the Australian farming community suggests that probabilistic rainfall forecasts based on the MJO are useful for intra-

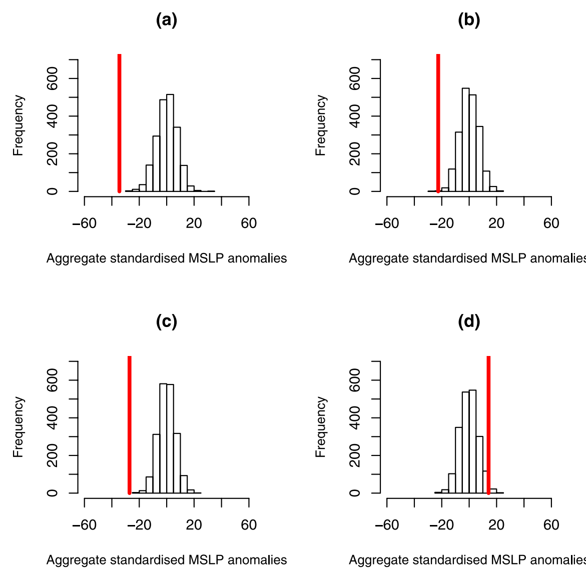

Figure 2. Null distributions of aggregated MSLP anomalies generated using a first order Markov Chain Model (MCM) for Phases 2, 4, 6 and 8 during austral winter. Corresponding p values are <0.001 for phases 2, 4 and 6 and 0.03 for phase 8. The red vertical line indicates the relative location of observed MJO-associated MSLP anomalies in respect to the null distributions (histogram). MCM-generated null distributions are expected to have a central tendency near zero, as shown in our examples. Strong negative or positive MSLP anomalies associated with MJO phases suggest causal relationships between the passage of the MJO and MSLP. As the MJO travels east and dries out we see a shift from strongly negative (a-c) to strongly positive (d) MSLP anomalies.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005gl025155.

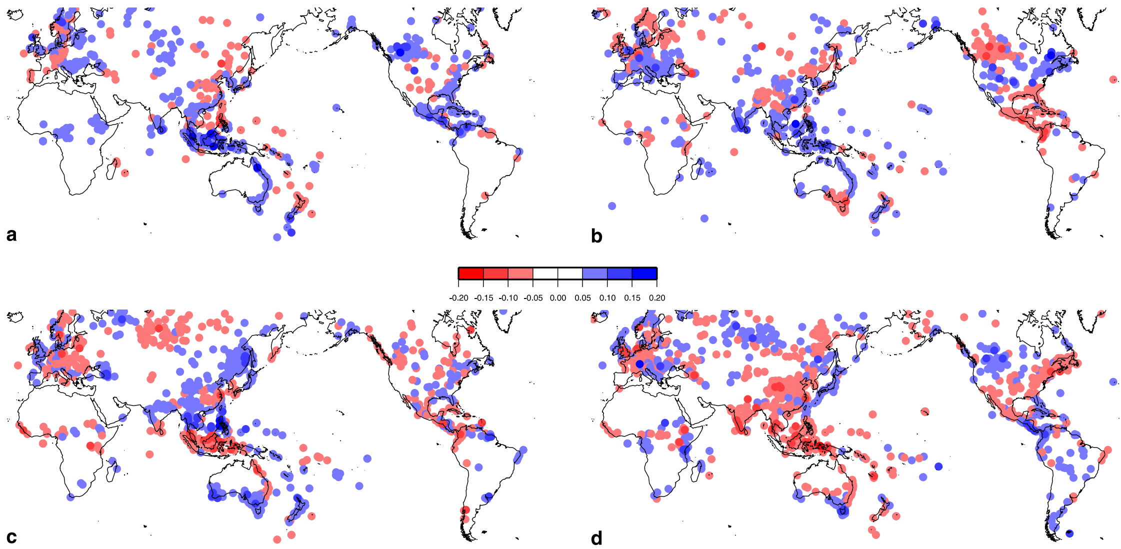

Figure 3. Rainfall anomalies associated with MJO phases. Rainfall anomalies associated with the location of the active centre of convection during MJO Phases (a) 2, (b) 4, (c) 6 and (d) 8 for austral winter. Differences are expressed as maximum vertical distance between the unconditional CDF and the corresponding conditional CDF for a particular phase (vertical differences are measured at the point of maximum divergence in dimensionless units of 'percent change in probability'). Positive (negative) distances indicate evidence of enhanced (suppressed) rainfall during the respective phase.

seasonal, tactical decision making - a timescale that sits at the interface between weather and climate and has so far proven difficult in terms of forecast provision. Here we report significant, global MJO impacts on seasonal rainfall as far as 50°N and S. Concentrating on the Austral-Asian region, we have identified a clear link between the MJO ACC, MSLP and rainfall patterns.

[12] The MSLP results show expected links between (air) pressure and rainfall (e.g., coastal rains associated with onshore winds evident from MSLP anomalies as during phase 4 in eastern Australia) and demonstrate the equatorial eastward movement of MSLP anomalies at MJO timescales. We do not suggest that all rainfall and MSLP anomalies identified are direct consequences of MJO activity. However, as our results show, the MJO is a very significant phenomenon that can influence global weather patterns even in higher latitudes via teleconnections. Our analysis represents a tactical tool that is already proving valuable for operational climate risk management in many (rural) industries. We have qualified MJO impacts on global rainfall and provide synoptic explanations for the observed patterns.

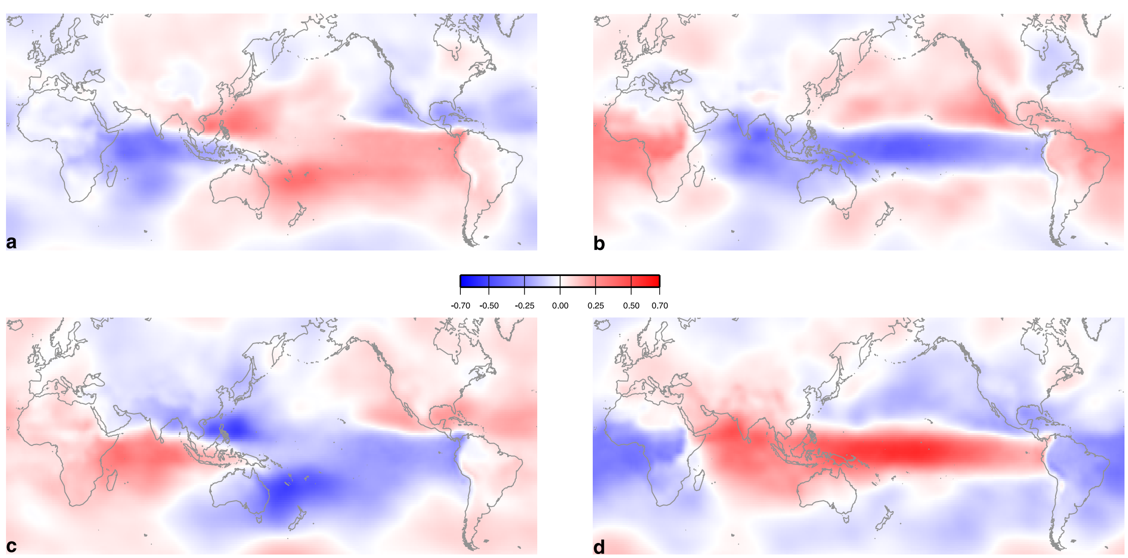

Figure 4. Standardised MSLP anomalies associated with MJO Phases (a) 2, (b) 4, (c) 6 and (d) 8 during the austral winter. MSLP anomalies were calculated as $(M_P - M_A)/S_A$, where M_P is the mean SLP for the phase, M_A is the mean SLP for all phases and S_A is the standard deviation of SLP for all phases). Dark blue (red): −0.70 to −0.50 (0.70 to 0.50); mid blue (mid red): −0.50 to −0.25 (0.50 to 0.25); light blue (light red): −0.25 to −0.05 (0.25 to 0.05); white −0.05 to 0.05. Daily MSLP data is from the NCEP/NCAR reanalysis II [*Kistler et al.*, 2000] in 2.5° × 2.5° interval grids.

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