**THE IMPACT OF THE MJO ON WEATHER REGIMES IN THE NEW ZEALAND REGION AND RELATIONSHIP WITH THE SAM DURING THE SOUTHERN HEMISPHERE SUMMER**

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ABSTRACT

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1. INTRODUCTION

The MJO is the dominant mode of atmospheric variability at the intra- seasonal time scale, with a periodicity typically comprised between 30 and 60 days. Its core signal is associated with a mean eastward propagation of large-scale convective loci (~10000 km across) from the Indian Ocean across to the Maritime Continent and then to the west Pacific basin at tropical latitudes. Convective anomalies decay east of the Indo-Pacific warm pool, but the associated atmospheric dynamics (zonal wind, sea level pressure, and geopotential height in all layers of the troposphere) are consistent and highly significant at the near-global scale (Zhang 2005). The impacts of the MJO inside the tropics include but are not limited to rainfall and convection, tropical cyclone initiation () and characteristic and sea surface temperatures; a comprehensive review of the climatic impacts of the MJO can be found in e.g. (Zhang, 2013).

Outside the tropics, towards the mid and high latitudes of both hemispheres, distinct signatures of the MJO have been shown, and can be interpreted in terms of patterns of extratropical responses to tropical diabatic heating anomalies (Ferranti & Palmer, 1990) (Wallace & Gutzler, 1981) in the framework of Rossby waves dispersion theory (Hoskins & Karoly, 1981).

For the Northern Hemisphere, the impact of the MJO on atmospheric variability has been clearly documented (). A series of studies have refined the picture of MJO activity using the paradigm of atmospheric weather regimes, leading to new insights on the potential predictability of extra-tropical atmospheric circulation based on the MJO. Cassou (2008) has shown that weather regimes over the North Atlantic / European sector related to the North Atlantic Oscillation (NAO) are significantly affected by the MJO, leading to a potential predictability on climatic scales. Similarly (Riddle et al., 2012) have shown that over the North American region, several weather regimes resembling linear combinations of the Arctic Oscillation (AO) and the Pacific/North American (PNA) are significantly modulated by the MJO. The reader is also referred to e.g. Ferranti & Palmer, 1990 and Matthews, 2004*.*

In the Southern Hemisphere (SH), the counterpart of the AO, and leading mode of atmospheric variability, is the Southern Annular Mode (also called the Antarctic Oscillation of AAO, or high latitude mode). It basically consists of an atmospheric mass transfer from the Antarctic region to the southern middle latitudes, with those two regions experiencing out-of-phase surface pressure and geopotential height anomalies. The SAM positive (negative) phase translates into a poleward (equatorward) shift and a strengthening (weakening) of the mid latitude westerly wind belt. SAM variability occurs throughout the year, with a possible seasonal peak in December (Gong and Wang 1999). Its most obvious effects are mainly restricted to the lower and middle layers of the troposphere, although they were noted to extend to the upper levels and the stratosphere during the late austral spring season (Thompson and Wallace 2000). Attempts to investigate how SAM is modulated by the MJO - a summary of which is given hereafter - have lead to somewhat conflicting conclusions:

(Carvalho, Jones, & Ambrizzi, 2005) indicate that the onset of negative phases of the SAM is related to the propagation of the MJO. Suppression of intra-seasonal convective activity over Indonesia is observed in positive SAM phases.

(Matthews & Meredith, 2004) indicate that the Antarctic Circumpolar Current could respond to the MJO, through changes in wind forcing (related to the SAM) in the high latitudes of the Southern Hemisphere. They indicate that approximately 7 days after anomalous MJO convection in the equatorial Indian Ocean peaks, an atmospheric extra-tropical response is set up with anomalous surface westerlies at about 60oS.

(Flatau & Kim, 2012) on the other hand have indicated that strong MJOs in the Indian Ocean are related decreasing SAM index values.

Pohl and Fauchereau (2012) adopt a more nuanced view and argue that the SAM is not unambiguously related to MJO activity. Their argument is motivated by the absence of coherent phase relationship between the SAM and the MJO index and the lack of zonally symmetric extratropical response to the MJO (i.e. no ‘annular’ pattern).

Before proceeding further, we note that:

1. the SAM is defined statistically as an index, usually derived from an EOF analysis of geopotential or SLP anomalies south of 20S. As such, some non-zonally symmetric events can project strongly into the SAM index, resulting into large amplitudes of the index in the absence of zonally homogeneous anomalies.
2. Lead-lag relationships between the SAM / SH extratropical circulation and the MJO seem to exist, however these relationships are not necessarily consistent amongst previous studies. It is unclear whether these lags can be related unambiguously to the time-scales predicted by Rossby wave dispersion theory.

In contrast to the Northern Hemisphere, no reports have been made that have examined the potential MJO signal, including relationships with extratropical modes such as the SAM, in the Southern Hemisphere circulation and regional climate within a framework of atmospheric weather regimes (as in Cassou 2008 or Riddle et al 2012.).

In this paper we choose the New Zealand region (see figure 1) to undertake this investigation for a range of reasons: *i)* its position from the subtropical to the westerly wind belt, *ii)* its known sensitivity to the SAM (references here), *iii)* the availability of a high quality, high resolution climate dataset (Tait et al., 2006), and *iv)* the existence of foundational studies (Kidson 2000; Renwick, 2011, Jiang et al., 2013) having established already the recurrent atmospheric weather regimes over the region and demonstrated its relevance for studies ranging from examining extreme events (references here) to paleo-climate reconstructions (Lorrey et al., 2007; 2008; 2013).

We evaluate the extra-tropical response to the MJO through i) its potential regional climate anomalies ii) modulation of weather regimes iii) a more detailed investigation of the relationships (including possible lead / lags and non-linearities) between the MJO and the SAM index. The paper is organized as follows: In the first section we briefly present the data and the methods used, with a notable focus on the non-parametric approach adopted to test the significance of weather frequency changes in response to the MJO and overview the weather typology used here and developed originally by Kidson (2000). This is followed (Section 2) by results that document the impact of the MJO on the rainfall field in NZ. The section 2 presents an examination of mean atmospheric circulation changes over the NZ region by putting them in context with the rainfall anomalies previously identified. We then use the paradigm of weather regimes to investigate how the occupation statistics of the regimes are modulated by the MJO and then expose relationships between the MJO and the SAM and how they drive national-scale rainfall anomalies. A discussion of the significance of the findings for NZ and more generally for the problem of the extra-tropical signal of the MJO follows.

The Southern Hemisphere summer (November to February, NDJFM in the following) has been chosen as the focus of this study as it has been shown that during the austral summer season, MJO signals extend into the southern sub- tropical latitudes [e.g., Australia (Wheeler and Hendon 2004, hereafter WH04) or South Africa (Pohl et al. 2007)]. It is therefore assumed here that MJO teleconnections are also stronger over the NZ sector during this time. It is also the time of the year when the SAM pattern is the most prominent (contains more variance) and is more zonally symmetric. A companion paper is currently in preparation

1. DATA AND METHODS

2.1 Data

The MJO signal is captured by the real-time multivariate MJO indices developed by WH04. The indices are the principal component (PC) time series of the two leading EOFs of combined daily mean tropical (averaged 15oN– 15oS) 850- and 200-hPa zonal wind and outgoing longwave radiation (OLR) anomalies. WH04 subtracted the annual cycle and the low-frequency variability associated with ENSO before calculating the EOF. The indices, denoted real-time multivariate MJO 1 and 2 (RMM1 and RMM2), were designed to capture both the northern winter and summer MJO. RMM1 and RMM2 are approximately in quadrature and describe the average large-scale, eastward-propagating convective and circulation anomalies associated with the MJO. The evolution of the MJO can be concisely visualized in a two-dimensional phase–space diagram, with RMM1 (RMM2) as the horizontal (vertical) Cartesian axes. WH04 divide the MJO pseudocycle into eight distinct phases, which depict the average eastward propagation of the convective and dynamic anomalies. Figure 2 presents a reminder of the convective activity anomalies associated with each phase of the MJO during the NDJFM season (November – March), the focus of this study. Enhanced Intra-seasonal (IS) convective activity starts over the Indian Ocean at phase 1. Large-scale convective clusters develop and extend over the Indian basin during phases 2 and 3 and reach the Maritime Continent during phases 4 and 5. In phases 6 and 7, they propagate over the west Pacific basin and are finally located in the Western Hemisphere and Africa during phase 8.

The daily SAM index is provided by the Climate Prediction Center at (URl here) and is calculated constructed by projecting the daily (00Z) 700hPa geopotential height anomalies poleward of 20°S onto the loading EOF (#1) obtained on monthly anomalies of Z700 over the same region.

Rainfall data for NZ comes from the Virtual Climate Station Network (VCSN) available from 1972 to 2010. The NZ VCSN (Tait et al. 2006, 2012) includes 13 daily climate variables interpolated on a regular (~5km) grid covering the whole of NZ. A thin-plate smoothing spline model is used for the spatial interpolations: this model incorporates two location variables (latitude and longitude) and a third "pattern" variable. For temperature elevation is included in the model, while for rainfall the 1951–80 mean annual rainfall digitised from an expert-guided contour map is used. This Dataset has been used in numerous studies (references here).

NCEP / NCAR reanalysed fields (zonal and meridional wind component and geopotential at 700 hPa) have been used to document large scale atmospheric circulation anomalies.

2.2 Testing for changes in the occupation statistics of atmospheric weather regimes.

We investigate if and how the occupation statistics of the weather regimes (Kidson types) are modulated as a function of the MJO phase. To test the significance of these changes, a Monte-Carlo approach essentially following the one exposed e.g. in Cassou, (2008) and Riddle et al (2012) was employed. Artificial realizations of the time-sequence of the 12 Kidson types can be generated using a 12 states discrete Markov chain constrained entirely by: i) the observed probability of occurrence of each type (calculated over the NDJFM 1972/73 – 2009/10 period) and ii) a matrix describing the probability of transitions from day n-1 to day n from type i to type j. (*see supplementary figure XXX ??).*

10000 simulations were performed independently for each of the 38 NDJFM seasons , leading to 380000 seasons whose properties (types distribution and transitions) are identical to the observed sequence of Kidson types, but with randomized temporal sequences.

The change in probability of observing the type k for the days falling into each phase of the MJO is calculated for each of the 10000 synthetic realizations, and the 90th and 95 % confidence limit is drawn from this null distribution, so that the observed anomaly in the frequency of type k is considered significant at the 95% confidence level if it is below the corresponding 5th percentile for negative anomalies (above the 95th percentile for positive anomalies).

1. IMPACT OF THE MJO ON NEW ZEALAND RAINFALL

The rainfall anomalies composites (in mm/day) from the VCSN during the summer (NDJFM) are shown in figure 3.

We make two observations: i) It appears that interactions between the topography (see Figure 1) and the circulation are at least partly responsible for NZ’s detailed spatial distribution of mean rainfall anomalies during some phases of the MJO pseudolife-cycle. Particularly striking are the role of the Southern Alps in the South Island. *i.e.* during phases 2, 3 and 8, large (> + 2.5 mm/day) anomalies are experienced on the eastern flank of the alps, while during phases 4, 6 and to a lesser extent 7, dry conditions are prevalent over the same part of the South Island. ii) spatial patterns are generally (but not systematically nor exactly) opposite to each other between MJO phases that are in quadrature, for example phase 2 of the MJO (when intra-seasonal convective activity is active over the eastern Indian Ocean) is related to enhanced rainfall on the eastern flank of the Southern Alps and decreased rainfall over the eastern facing regions of the North Island. The phase 6 of the MJO (decreased convective activity in the eastern Indian Ocean) is associated with the opposite pattern. The same can be said of phases 3 and 7 and 4 and 8, while phases 1 and 5 present weak and inconsistent anomalies. In the next section we will briefly review the mean circulation response and how it can be related to the rainfall response presented above.

*More detailed analysis of the relationship between the MJO and rainfall in NZ are then carried out by deriving regional rainfall indices. Two regions of interest are selected: the western flank of the South Island Southern alps (figure 4, region 1), and the coromandel / bay of plenty area in the North Island (region 2, figure 4)*

1. MEAN CIRCULATION RESPONSE

The Figure 6a present the long term climatological circulation (geopotential at 700 hPa and vector winds) for NDJFM 1979 – 2010 (from NCEP). In average over the SH summer, westerly winds dominate the NZ region. The Figure 6b to 6i presents the composite anomalies related to each phase of the MJO. One must note that not all phases of the MJO are (in average over the NDJFM season) related to significant anomalies over the NZ region. In particular, phase 1 and 8 are not related to circulation anomalies of noticeable amplitude interacting with NZ’s landmass. On the other hand, phase 6 for example is related to significant north-easterly anomalies over NZ, a pattern consistent with enhanced rainfall over the north / northeast facing regions of NZ (Northland, Bay of Plenty and north of the South Island) and decreased rainfall to the west of the Southern Alps in the South Island (see figure 3f). Phase 4 of the MJO is associated with south to south-easterly anomalies, bringing cool air from the Southern Ocean, a pattern again consistent with mainly reduced rainfall over the western side of the Southern Alps and western North Island (Figure 3c).

1. WEATHER REGIMES RESPONSE

In this section, we re-assess the implication of changes in regional circulation for the NZ rainfall anomalies by adopting a regime view, using the typology developed by Kidson (2000, see section 2.2), and investigate the atmospheric circulation impacts of the MJO in terms of changes in the occupation statistics of these regimes. In the first part of this section we present a brief overview of the main characteristics of the so-called ‘Kidson types’.

* 1. Characteristics of the Kidson types

We refer the reader to Kidson (2000) for the details of the synoptic type classification method. The archetypes (centroids) associated with each Kidson type are presented in Figure 7a. Their climatological distribution over the period 1972-2010 is presented in Figure 7b (mean seasonal cycle) and 7c (NDJFM). During the summer, the ‘HSE’ type (within a larger ‘blocking’ regime) is greatly enhanced compared to winter (give figures here) while the zonal regime types (notably ‘H’ type) are less frequent. *Other diagnostics to be shown and discussed are possibly their transitions, persistence, and the correlation between the seasonal anomalies in frequency ??? if So that makes figure 8*

* 1. Changes in frequency in response to the MJO

The Figure 9 presents the change in the frequency (compared to the NDJFM climatology) of the 12 Kidson types as a function of the MJO phase. The significance of the frequency changes are assessed via a Monte-Carlo approach based on artificial realizations of the time-sequences of the Kidson types (using Markov-chains generators) as described in section 2.X. First it must be noted that few of the anomalies in frequency of the regimes emerge as significant according to our test.

*In the following, we investigate the delayed response of the Kidson types (in terms of changes in frequency) to the MJO phase.*

1. RELATIONSHIP BETWEEN THE MJO AND THE SAM

Synchroneous response

The synchronous response of the SAM to the MJO phase is shown in Figure 11. Both the filtered (20 – 120 days) and unfiltered version of the SAM index are shown.

Delayed response to strong MJO initiation

Strong (i.e. compared to these displayed in Figure XXX showing the composite SAM anomalies for ALL days falling in each phase) negative SAM anomalies are observed around 15-20 days after the initiation of phase 1, 10 days after phase 2, 6 days after phase 3. Conversely, significant positive anomalies are triggered around 34 days after the onset of strong phase 3, 28 days after phase 4, 25 days after phase 5

1. DISCUSSION

This study demonstrates that regional scales anomalies over the NZ region in response to the MJO signal are evident, can be related partly to (mediated by) changes in the occupation statistics of regionally recurrent weather regimes (the Kidson types), and that interactions between topography and circulation plays a large part in dictating the spatial distribution of the observed rainfall anomalies. We have also shown that the large scale SH extratropical atmospheric variability, encapsulated by the SAM index, shows a response to the MJO, both in terms of tendencies of the SAM index to be either negative or positive during certain phases of the MJO (Figure XXX) or in terms of the response of the index to the initiation of strong events, with time-scales consistent with the propagation of Rossby waves (??).

*I think there is a need to discuss the implications of these various results in terms of mid-range prediction for NZ*. As noted in (Matthews & Meredith, 2004), The tropical part of the MJO can be predicted skillfully up to 20 days ahead [see e.g.(M Wheeler & Weickmann, 2001)] and the skill of extratropical forecasts improves when the tropical MJO is well represented in an NWP model [see Ferranti et al., 1990].

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