Extratropical Impacts of the Madden–Julian Oscillation over New Zealand from a Weather Regime Perspective

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ABSTRACT

The Madden–Julian oscillation (MJO) signal in the Southern Hemisphere (SH) extratropics during the austral summer (November–March) is investigated over the New Zealand (NZ) sector, using the paradigm of atmospheric weather regimes (WRs), following a classification initially established by Kidson. The MJO is first demonstrated to have significant impacts on daily rainfall anomalies in NZ. It is suggested that orographic effects arising from the interaction between regional atmospheric circulation anomalies and NZ’s topography can explain the spatially heterogeneous precipitation anomalies that are related to MJO activity. These local impacts and circulation anomalies are shown to be better understood as resulting from changes in the occupation statistics of regional WRs (the Kidson types) through the MJO life cycle, although both constructive and destructive effects are demonstrated. The hypothesis of a significant forcing of the MJO over the NZ sector is further supported by lagged composite analyses, which reveal timing characteristics of the delayed regional circulation response compatible with the average propagation speed of the MJO. While the southern annular mode (SAM) has been previously shown to be statistically related to the MJO and is known to be a significant driver of NZ’s climate, no evidence is found that the impact of the MJO over the NZ sector is mediated by the SAM. It is therefore suggested that the MJO directly impacts regional circulation and climate in the NZ region, potentially through extratropical Rossby wave response to tropical diabatic heating. These findings suggest a new potential for predictability for some aspects of NZ’s weather and climate deriving from the MJO beyond the meteorological time scales.

1. Introduction

The Madden–Julian oscillation (MJO: Madden and Julian 1971; Zhang 2005) is the dominant mode of atmospheric variability at the intraseasonal time scale in the tropics, with a periodicity typically comprising between 30 and 60 days. Its core signal is associated with a west-to-east propagation of large-scale convective clusters (~10,000 km across). These convective events are initiated in the western Indian Ocean basin, they migrate across the Maritime Continent, and then they terminate in the tropical western Pacific basin along the equator (see Fig. 2). 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 in the tropics include, but are not limited to, rainfall and convection, tropical cyclone initiation (see, e.g., Hall et al. 2001) and sea surface temperatures (Matthews et al. 2010). Comprehensive reviews of the climatic impacts of the MJO can be found in Zhang (2005, 2013).

Outside the tropics, toward the middle and high latitudes of both hemispheres, distinct signatures of the MJO have been highlighted and can be interpreted in terms of extratropical responses to tropical diabatic heating anomalies (Ferranti and Palmer 1990; Wallace and Gutzler 1981) in the framework of Rossby wave dispersion theory (Hoskins and Karoly 1981).
The impact of the MJO on atmospheric variability has been clearly established especially for the Northern Hemisphere (NH; Ferranti and Palmer 1990; Donald et al. 2006; Matthews 2004). Recently, a series of studies (Cassou 2008; Riddle et al. 2012) have refined the picture of MJO activity using the paradigm of atmospheric weather regimes (WRs), which can be defined as equilibrium points—or attractor basins—in the phase space of the atmospheric circulation and are usually extracted using hierarchical or nonhierarchical clustering procedures (see, e.g., Molteni et al. 2006; Vautard 1990; Michelangeli et al. 1995).

These studies led to new insights on the potential predictability of extratropical atmospheric patterns in the NH arising from the MJO. For instance, Cassou (2008) showed that the probability of North Atlantic Oscillation (NAO) WRs over the North Atlantic–European sector were significantly modulated by the MJO with an approximate 10-day lag, leading to potential predictability of regional climate anomalies (temperature and precipitation) beyond meteorological time scales. Similarly, Riddle et al. (2012) showed that, over the North American region, several WRs resembled linear combinations of the Arctic Oscillation (AO) and the Pacific–North American (PNA) pattern, and these were significantly modulated by the MJO.

In the Southern Hemisphere (SH), several studies have demonstrated that the MJO is related to significant regional impacts from the subtropics to the extratropics: for instance, Pohl et al. (2007, 2010) have shown that the MJO modulates rainfall and convection in South Africa. In South America, Shimizu and Ambrizzi (2016) have shown that regional precipitation and convection responds to the MJO life cycle. At higher latitudes, Matthews and Meredith (2004) suggest a delayed response to the MJO of surface westerly winds at 60°S, which triggers acceleration of the transport by the Antarctic Circumpolar Current. The MJO has even been implicated in the decadal temperature trends in Antarctica (Yoo et al. 2012).

However, the framework of WRs has not yet been employed to investigate the extratropical signal of the MJO in the SH. For instance, Pohl et al. (2007, 2010) have shown that the MJO modulates rainfall and convection in South Africa. In South America, Shimizu and Ambrizzi (2016) have shown that regional precipitation and convection respond to the MJO life cycle. At higher latitudes, Matthews and Meredith (2004) suggest a delayed response to the MJO of surface westerly winds at 60°S, which triggers acceleration of the transport by the Antarctic Circumpolar Current. The MJO has even been implicated in the decadal temperature trends in Antarctica (Yoo et al. 2012).

However, the framework of WRs has not yet been employed to investigate the extratropical signal of the MJO in the Southern Hemisphere. One reason might be that, contrary to, for example, the North Atlantic–European sector, where numerous robust regional WR decompositions have led to the well-known typology (NAO+/-, blocking, and Atlantic ridge), few robust and tested regional WR decompositions exist in the Southern Hemisphere midlatitudes.

One exception is, however, the New Zealand (NZ) region (Fig. 1). Foundational studies (Kidson 2000; Renwick 2011; Jiang et al. 2013) have established recurrent daily weather regimes over the NZ region (see sections 2 and 3c), and this framework has been used extensively for studies ranging from attributing modern extreme meteorological events (Lorrey et al. 2014a) to paleoclimate reconstructions (Lorrey et al. 2007, 2008; Ackerley et al. 2011; Lorrey et al. 2012, 2014b).

In addition to the existence of a well-tested WR decomposition, NZ presents the advantage that it extends from the subtropics to the midlatitudes astride the Southern Hemisphere westerly wind belt. As such, this is an ideal domain to assess the potential extratropical signal of the MJO in the SH. Moreover, a high-quality, high-resolution gridded climate dataset (Tait et al. 2006) is also available for the country to enable connecting WR occurrences to local hydroclimatic impacts.

NZ climate has been shown to be sensitive to several climate modes that influence WR occurrence (Jiang et al. 2013). At interannual time scales, the dominant drivers are the ENSO (Gordon 1986; Mullan 1995) and the southern annular mode (SAM; see, e.g., Ummenhofer and England 2007; Thompson et al. 2011).

The SAM is the leading mode of SH atmospheric variability poleward of 20°S (Rogers and van Loon 1982; Thompson and Wallace 2000) and is the antipodal counterpart of the AO. The positive phase of the SAM is schematically associated with lower (higher) pressures...
than normal over the Antarctic continent (the mid-latitudes), while the negative phase is associated with the opposite anomalies. SAM variability occurs throughout the year, with a seasonal peak in December (Gong and Wang 1999). The SAM arises as a purely atmospheric phenomenon linked to the interaction between the mean flow and transients (Lorenz and Hartmann 2001; Codron 2005), and, contrary to ENSO, it is also distinguishable at synoptic and intraseasonal time scales (Pohl et al. 2010). Previous work that has investigated how SAM is modulated by the MJO, a summary of which follows, has led to somewhat conflicting conclusions:

- Carvalho et al. (2005) indicate that the negative SAM phase onset is related to the propagation of the MJO. Suppression of intraseasonal convective activity over Indonesia is observed in positive SAM phases.
- Matthews and Meredith (2004) indicate that the Antarctic Circumpolar Current could respond to the MJO through changes in wind forcing (related to the SAM) in the SH high latitudes during the Southern Hemisphere winter. They indicate that approximately seven days after anomalous MJO convection in the equatorial Indian Ocean peaks, an atmospheric extratropical response is set up with anomalous surface westerlies at about 60°S.
- Flatau and Kim (2013) indicate that strong MJO events in the Indian Ocean are related to decreasing SAM index values and argue that the MJO influence on the SAM may vary with the season.
- Pohl et al. (2010) argue that the SAM is not unambiguously related to the 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 (i.e., annular) extratropical response to the MJO.

In investigating the response of NZ’s climate and circulation to the MJO, there is thus the potential that these signals might be mediated by the SAM. Our aim, in the present paper, is therefore to answer the following main questions, in succession:

(i) Is there a discernible—and significant—signal of the MJO over the NZ sector?
(ii) Do the occupation statistics of regional WRs for NZ change in response to the MJO?
(iii) Do lag relationships exist, and if so, are the temporal characteristics of these consistent with the hypothesis of a forcing by the MJO?
(iv) Is the SAM involved in mediating any MJO signal over the NZ region?

The paper is organized as follows: the data and the methods used are presented (section 2), focusing notably as well as on the nonparametric approach adopted to test the significance of frequency changes of WRs. Then the influence of the MJO on NZ’s daily rainfall is documented (section 3a), together with mean regional atmospheric circulation anomalies (section 3b). The occupation statistics of a predetermined set of NZ-region WRs (Kidson 2000, hereafter K2K) are then investigated through the MJO life cycle (section 3c). Lagged relationships are then presented and discussed (section 3d) before a consideration of the potential interactions with the SAM (section 3e). Finally, a summary of the results and discussion is given (section 4).

2. Data and methods

a. Data

1) NEW ZEALAND RAINFALL

Daily rainfall data for NZ come from the Virtual Climate Station Network (VCSN) available from 1972 to 2011. The NZ VCSN (Tait et al. 2006, 2012) includes 13 daily climate variables interpolated onto an approximate 5 km² grid covering the country. A thin-plate smoothing spline model is used for the spatial interpolations between station data: this model incorporates two location variables (latitude and longitude) and a third “pattern” variable. For temperature, elevation is included in the model, whereas, for rainfall, the 1951–80 mean annual rainfall digitized from an expert-guided contour map was used.

2) GLOBAL-SCALE ATMOSPHERIC FIELDS

NCEP–NCAR reanalyzed fields (zonal and meridional wind components, geopotential height at 700 and 500 hPa) have been used to document large-scale atmospheric circulation anomalies (see Kalnay et al. 1996). We chose the NCEP–NCAR reanalysis product rather than more recent products, in order to be consistent with the dataset used in K2K.

3) MJO INDEX

The MJO signal is captured by the real-time multivariate MJO indices developed by Wheeler and Hendon (2004, hereafter WH04). The indices are the principal component (PC) time series of the two leading EOFs of combined daily mean tropical (averaged 15°N–15°S) 850- and 200-hPa zonal wind and outgoing longwave radiation (OLR) anomalies. These so-called Real-Time Multivariate MJO (RMM) indices (RMM1 and RMM2) time series are approximately in quadrature and describe the average large-scale, west-to-east propagation of convective circulation anomalies associated with the
MJO. WH04 divide the MJO pseudocycle into eight distinct phases, which depict the average geographic position and strength of the convective and dynamic anomalies. We restrict the analyses to the post-1979, high-quality satellite coverage period in this paper. For the composite analyses, only MJO events with amplitude greater than 1 standard deviation (std dev) were selected. Note that we conducted supplementary analyses by adopting a further restriction based on a criterion or persistence (i.e., selecting sequence lasting more than five days), and the results were qualitatively unchanged. Figure 2 presents the spatiotemporal progression of convective activity anomalies (depicted by outgoing longwave radiation anomalies) associated with each MJO phase (amplitude $\geq$1 std dev) during the austral warm season [November–March (NDJFM)]. Enhanced intraseasonal convective activity starts over the Indian Ocean in MJO phase 1. Large-scale convective clusters develop and extend over the Indian Ocean 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 western Pacific basin and finally reach the Western Hemisphere and Africa during phase 8.

4) REGIONAL WEATHER REGIMES OVER NEW ZEALAND

In the present study, we make use of a regional WR classification (weather typing) established by K2K. This classification is based on an EOF decomposition of the NCEP–NCAR (Kalnay et al. 1996) daily 1000-hPa geopotential field followed by a $k$-means clustering procedure (see, e.g., Michelangeli et al. 1995) over the domain 25°–55°S, 160°E–175°W, yielding 12 WRs. For the sake of making our results comparable to earlier studies, the 12 WRs obtained will be referred to as Kidson types (KTs) in the rest of the document and labeled according to the original K2K study (see Fig. 4) The 12 KTss were also grouped into three basic groups in K2K (termed regimes in K2K) that were determined based on outcomes for six homogenous climate districts that show coherent responses for precipitation and temperature. The trough group (types T, SW, TNW, and TSW) describes predominantly unsettled conditions, the zonal group (types H, HNW, and W) is mainly related to enhanced westerly flow over New Zealand, and the blocking group (types HSE, HE, NE, HW, and R) describes predominantly settled, anticyclonic conditions over all or part of the country. Initially established over the January 1958–June 1997 period, the K2K classification is updated on a regular basis for operational purposes (Renwick 2011).

5) THE SAM

The daily SAM index for 1979–present is provided by the Climate Prediction Center (CPC; ftp://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.aao.index.b790101.current.ascii) and is calculated by projecting the daily 700-hPa geopotential height ($Z_{700}$) anomalies poleward of 20°S onto the loading EOF obtained on monthly anomalies of $Z_{700}$ over the same domain (see the CPC website for the details of the method).
6) SEASON OF INTEREST AND PERIOD OF ANALYSIS

The austral warm season (NDJFM) was chosen as the focus of this study because MJO signals reach their southernmost extent at this time of the year, reaching into the southern subtropical latitudes [e.g., Australia (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 season. It is also the time of the year when the SAM contains more variance and is more zonally symmetric (Fogt et al. 2012). For all the datasets except the VCSN (available until December 2011), the period of analysis is NDJFM 1979/80–2013/14 and the climatological period for the calculation of anomalies is 1981–2010.

b. Testing for changes in the occupation statistics of WRs

We essentially use a Monte Carlo approach to assess whether the observed WR frequency anomalies could arise by chance at a given level of confidence. Artificial realizations of the time sequence of the KTs can be generated using a 12-states discrete-time Markov Chain constrained by (i) the observed probability of occurrence of each KT (calculated over the NDJFM 1979/80–2013/14 period) and (ii) a transition matrix describing the transition probabilities between the KTs. The resulting artificial time series have statistical properties (frequency, persistence, preferred transitions, etc.) similar to the observed time series, albeit with randomized time sequences.

For each of the 35 NDJFM seasons, 10 000 realizations were performed independently. The change in the probability of observing a given KT K for the days falling into each phase of the MJO is then calculated for each of the 10 000 synthetic realizations. The confidence limits are drawn from this null distribution so that the observed anomaly in the frequency of K is considered significant at the 95% confidence level if it is above the 95th percentile for positive anomalies (below the corresponding 5th percentile for negative anomalies). The same methodology was used in Riddle et al. (2012) and has been applied recently in Lorrey et al. (2014b).

3. Results

a. The MJO signal in New Zealand daily rainfall

Composite rainfall anomalies (in mm day $^{-1}$) associated with each phase of the MJO (amplitudes $>$1 std dev only) during the summer season are shown in Figs. 3a–d. With the exception of phase 5 (when intraseasonal convection associated with the MJO is active over the Maritime Continent), all phases of the MJO are associated with locally significant daily rainfall anomalies. Two observations can be made from the detailed spatial distribution of the composite anomalies. First, it appears that interactions between the topography (see Fig. 1) and the incident atmospheric circulation are at least partly responsible for the spatial distribution of mean rainfall anomalies during some phases of the MJO. Particularly striking is the role of the Southern Alps in the South Island (SI): for example, during phases 2, 3, and 8, relatively large ($>$+2.5 mm day $^{-1}$) positive anomalies occur on the western flank of the range, while during phases 4, 7, and to a lesser extent 6, dry conditions are prevalent over the same area. Second (with the exception of phases 1 and 5), the spatial patterns are generally opposite between opposite phases of the MJO. For example, phase 4 of the MJO (when intraseasonal convective activity is enhanced over the eastern Indian Ocean) is notably characterized by decreased rainfall on the western flank of the Southern Alps, while phase 8 of the MJO (decreased convective activity over the eastern Indian Ocean) is associated with increased rainfall in the western SI. The same observation can be made to some extent between the phases 3 and 7, as well as 2 and 6 of the MJO. The latter fact is suggestive of a physical relationship between the MJO and NZ rainfall.

b. Mean regional atmospheric circulation response to the MJO

Figures 3a–d presents the regional-scale atmospheric circulation anomalies related to each MJO phase. The MJO is associated with strong and significant geopotential height and atmospheric mass flux anomalies in the lower troposphere in the subtropical latitudes. It shows the succession of positive geopotential height anomalies (during phases $\sim$1–4, when intraseasonal convection is reduced over the Australasian region; Fig. 2) and negative geopotential anomalies (during phases $\sim$5–8, when convection is enhanced over the same region). Farther south, significant extratropical responses are also observed for some (but not all) of the MJO phases.

There are also clear interactions between anomalous flow and parts (or all) of NZ’s landmass, particularly during MJO phases that set up strong pressure gradients between the subtropics and the midlatitudes. Phase 6, for example, shows significant northeasterly flow anomalies over the whole of NZ, a pattern that is consistent with the observed enhanced rainfall over regions east of the main axial ranges (including Northland, Bay of Plenty, and north of the SI), coinciding with decreased rainfall to the west of the Southern Alps in the SI during the same phase (Fig. 3f). Phase 4 of the MJO is
associated with south to southeasterly wind anomalies over the country, drawing in cool air from the Southern Ocean. That atmospheric circulation pattern is consistent with reduced rainfall over the western side of the Southern Alps and western North Island (NI; Fig. 3d). In general, regions on the exposed side of the main axial ranges that face into the anomalous flow tend to be wetter than normal, while the opposite is true for locations on the leeward side of mountain ranges. The origin of the anomalous flow and the characteristics of the associated air masses are also of importance for the interaction with the topography and the resulting rainfall anomalies. Schematically, westerly anomalies and anomalous flow with a northerly origin are characterized by moist and warm air, which, interacting with the local relief, is associated with enhanced rainfall (see, e.g., phase 6 of the MJO for the north of the North Island or phases 2 and 8 for the west of the Southern Alps in the SI). Southeasterly wind anomalies (see phase 4) are often connected to dry and cool air, resulting in anomalously low precipitation particularly downstream on the leeward side of the axial ranges, but with diminished or insignificant precipitation anomalies on the upstream side of the mountains.

c. Modulation of the KT by the MJO

Figure 4 illustrates the 12 WRs (KTs), as defined in K2K, and the daily composite rainfall anomalies over NZ associated with each KT. The austral warm season
(NDJFM) is notably characterized by a large contribution (17%) of the KT HSE, which is related to mostly anticyclonic conditions over and to the southeast of NZ and is associated with dry conditions over most of the country. As is the case with the MJO, the spatial distribution of the rainfall anomalies associated with most KTs reveals the importance of the interactions between incident atmospheric circulation and NZ’s peculiar topography (K2K; Renwick 2011; Jiang et al. 2013).

The frequency (or probability of occurrence) of the KTs appears to be modulated along the eight MJO phases (Fig. 5). Note that the anomalies are expressed in percentage frequency change: for example, a 100% value would indicate that the number of occurrence of this KT is twice the climatological mean, while a 100% decrease (−100%) indicates no occurrence of this KT. These results indicate that the MJO life cycle is associated with significant modulation of several of the KTs frequencies. From a perspective of KT groups, the zonal KTs (H, HNW, and W; see Fig. 4) are more frequent (≈40%–60% increase) during the first half of the MJO life cycle (phases 2 and 3), while their probability of occurrence is reduced by about the same percentage during the second half of the MJO life cycle during phases 6 and 7 (Fig. 5). In contrast, the KT TSW (in the trough group; Fig. 5) is significantly less likely than
normal during phase 3 (−41%), while its probability is increased compared to climatology during phases 6–8. The KTs in the blocking group show a less consistent response to the MJO, but it is worth noting the strong increase (±95%; i.e., almost a doubling in occurrence) in probability of the NE type during phase 6 of the MJO.

Generally, opposite phases of the MJO (e.g., 2 and 6, 3 and 7, and 4 and 8) are related to opposite changes in the KTs’ occurrence. For example, during phase 3 of the MJO, the KTs H, HNW, and W are more frequent than normal, while the KTs TSW and R are less frequent. Opposite anomalies (i.e., reduction in frequency of KTs H, HNW, and W, increased frequency of TSW and R) are observed during phase 7 of the MJO. This relation (i.e., response of opposite sign between opposite MJO phases) holds in general, particularly for the KTs presenting a strong response to the MJO (Fig. 5).

We examined the combination of KTs’ changes in occurrences for each MJO phase in relation to the corresponding rainfall anomalies, as shown in Fig. 3. An important observation is that KTs are generally associated with very heterogeneous rainfall anomalies over NZ (Fig. 4), and this finding reflects the strong role of the interaction between incident flow and topography in NZ. Because of the southwest–northeast orientation of both the NZ landmass and the main axial ranges (primarily the Southern Alps in the SI) and the near-perpendicular climatological westerly circulation, even very subtle changes in the direction of the flow can lead to dramatic changes in the resulting spatial distribution of rainfall amounts at daily time scales. It is therefore not surprising that KTs, which are associated with opposite local rainfall responses, can occur more frequently for the same MJO phase, leading to weak rainfall anomalies when aggregating all days in the corresponding MJO phase. On the other hand, some KTs induce locally similar precipitation anomalies, but exhibit opposite responses in terms of occurrence to the MJO. In other words, the observed changes in the frequency of KTs in response to the MJO can lead to either additive (constructive) or subtractive (destructive) effects. Below are some specific examples.

- During phase 4 of the MJO, a large decrease in daily rainfall is observed over most of the SI, especially to the west of the Southern Alps, as well as over the southern NI (Fig. 3d). This phase is related to a
significant increase in the frequency of the KTs HSE (+28%) and the HW (+52%) (Fig. 5), which are both associated (Fig. 4) with decreased rainfall in the SI. Meanwhile, the T type is less frequent than normal (−46%), and that WR usually increases rainfall over the SI and the south of the NI (Fig. 4). The latter is an example of clear constructive interference, where the signs of KTs’ frequency change (more or less) for a given MJO phase are related to a similar spatial distribution of rainfall anomalies.

- Another example of constructive interference is shown for phase 7 of the MJO, which is characterized by decreased rainfall to the west of the Southern Alps and increased rainfall east of the NI main ranges. This phase is associated with significant increases in the KTs TSW and R, both related to decreased rainfall in the western South Island and increased rainfall in the eastern North Island.

- On the other hand, an example of destructive interference is present for phase 3 of the MJO. During this MJO phase, relatively limited positive rainfall anomalies are observed toward the center of the SI west of the Southern Alps. During this phase, the occurrences of both the H and W types are significantly increased (respectively 42% and 62% more frequent than normal): these KTs, however, are associated with opposite rainfall anomalies in the west of the SI (respectively dry and wet). The resulting limited positive rainfall anomalies can be attributed to the comparatively larger increase in the W types, as well as decreases in the frequency of the KTs TSW, HW, and R (all related to drier-than-normal west SI).

The local rainfall impacts of the MJO (Fig. 3) can then be understood (and reconciled) as arising from the changes in the occupation statistics of the KTs in response to the MJO. These combinations can lead to compound effects that result in a positive, a negative, or no significant precipitation anomaly when several KTs related to an MJO phase are simultaneously modulated.

d. Lagged relationships

The results presented above are suggestive of a locally significant MJO forcing on NZ regional rainfall patterns that are mediated by changes in the occupation statistics of the KTs. Of particular importance is that (i) opposite phases of the MJO are generally associated with locally opposite rainfall anomalies and (ii) opposite phases of the MJO appear generally to generate opposite anomalies in KT occurrences.

To further support the hypothesis of a physical forcing of the MJO over NZ’s climate and atmospheric circulation, we examined the potential lagged relationships between the MJO signal and extratropical circulation over the NZ sector. An MJO forcing should hypothetically result in lead–lagged relationships compatible with the average propagation speed of the MJO envelope in the tropical waveguide.

Following Cassou (2008), we first present the longitude–time diagram of daily 500-hPa geopotential height (Z500) anomalies averaged between 35° and 45°S (spanning the latitudinal extent of NZ). Note again that only MJO events exceeding amplitudes of one std dev during the NDJFM season have been selected, and lagged composites are calculated up to 30 days after the corresponding phase is observed. Eastward propagation of Z500 anomalies should translate in diagonally elongated regions of positive or negative Z500 anomalies, with a slope corresponding to the average propagation speed of the MJO of approximately 6°–12° of longitude per day (for an average MJO life cycle of 30–60 days). Note, however, that the propagation speed of the MJO envelope varies from one longitude sector to another (as a result of the coupling with atmospheric convection notably over the warm pool), but also from event to event, and appears to be modulated by, for example, ENSO (Pohl and Matthews 2007). While there is a considerable amount of noise in the composite anomalies, leading to a signal not as clear as in previous work (Cassou 2008, their Fig. 4), the west–east propagations of geopotential anomalies with phase speeds that are broadly consistent with the MJO propagation are evident.

For example, following phase 1 of the MJO, positive geopotential anomalies propagate from lag 0 to about 10 days later from around 100°E to just west of New Zealand. Phase 4 of the MJO is associated with a positive geopotential anomaly wave train propagating from west of NZ (∼150°E) to east of the international date line in about 10 days. Following phase 8 of the MJO, a region of positive geopotential anomalies propagates from the eastern Indian Ocean (∼100°E) toward NZ, reaching 175°W about 15 days later.

Figure 6 therefore suggests that the lagged impact of the MJO over the NZ sector results, at least partly, from the eastward propagation of circulation anomalies at midlatitudes, with phase speed consistent with the MJO life cycle.

We repeated the analysis presented in Fig. 5, but including lags up to 30 days after a given MJO phase is observed (Fig. 7). An MJO forcing on the KTs’ occurrences can be suggested if (i) there is presence of a slope with lag and (ii) the difference (in days) between the timing of the approximate maximum lagged response of a given KT between successive MJO phases is again compatible with the average propagation speed of the MJO.
Figure 7 shows that these two criteria are met in several instances and that several KTs show significant responses (anomalies in occurrence) up to approximately 30 days after a given MJO phase. Of particular interest are the characteristics of the lagged response of the KTs TSW, H, HNW, and W to the MJO. For example, at lag 0 for phase 3 of the MJO, TSW is less frequent than climatology, while H and W are both more frequent (see also Fig. 5). At about 17–23-day lags, a strong opposite response is observed, with large increase in the occurrences of TSW and decrease in the occurrences of H, W, and HNW. The following MJO phase (4), the maximum response is found at lags of about 12–18 days, while it is present to some extent about 7–12 days after phase 5, around 3–5 days after phase 6, and finally a near-synchronous response is observed during phase 7 (see also Fig. 5). The difference in timing of the approximate maximum lagged

Fig. 6. Longitude–time diagrams of zonally averaged (35°–45°S) daily Z500 lagged composite anomalies for the MJO phases. The y axis shows the lag (in days), and the x axis shows the longitude (negative east of the international date line). The longitude bounds encompassing New Zealand’s landmass (170°E and 180°) are indicated by the two vertical lines toward the middle of each plot. Anomalies significant at the 95% confidence level (standard Student’s t test) are contoured.
response of these KTs to successive MJO phases is thus about 5 days. This is consistent with the average propagation speed of the MJO signal itself around the equatorial waveguide, and thus the average life cycle of an MJO event (30–60 days). This finding suggests that MJO effects on NZ regional circulation are not only through synchronous modulations of atmospheric fluxes that interact with the topography and act to modulate associated rainfall patterns, but also through delayed responses of the atmosphere that result in changes in KTs’ frequencies.

e. Potential interactions with the SAM

The preceding results have demonstrated that the MJO life cycle produces significant changes in the occupation statistics of the KTs. These changes can explain, to some extent, NZ precipitation patterns in response to the MJO. The characteristic propagation properties of anomalous daily Z500 in response to the MJO over the NZ zone, and the lagged relationships between the MJO and KT frequency changes strongly suggest a forcing of the MJO onto the region.
However, as exposed in the introduction, another mode of variability operating at the subseasonal time scale, and known to be related to local climate anomalies over NZ is the SAM, whose relationship with the MJO is not fully understood (see, e.g., Pohl et al. 2010; Flatau and Kim 2013). In the following section we briefly investigate the SAM’s response to the MJO on one hand, the response of the KTs to the SAM on the other hand, and discuss whether the results are supportive of a significant role of the SAM in mediating the regional circulation response to the MJO exposed in the preceding sections.

Figure 8 presents the CPC SAM index composite anomalies as a function of the MJO phase. The SAM index tends to be negative during phase 3 of the MJO (i.e., when convection is active over the central Indian Ocean; see Fig. 2c) and positive during phases 5–7 [i.e., when the region of enhanced intraseasonal activity reaches into the Maritime Continent and western Pacific Ocean (Figs. 2e–g)]. Note that these results are broadly consistent with previous work (see Fig. 2a in Pohl et al. 2010), with the discrepancies likely a result of the analyses of Pohl et al. (2010) spanning the entire year, while the present study is restricted to November–March. The SAM—as defined by the CPC index—is therefore not statistically independent from the MJO; however, it is noted that the amplitude of the anomalies is relatively low (±0.4 std dev).

Figure 9 presents the frequency changes of KTs occurrences as a function of the SAM index, the latter being discretized into five categories according to sign and amplitude as a mean of diagnosing potential nonlinearities. This analysis extends the study of Renwick (2011), who considered the changes in the monthly frequency of the three main Kidson groups (trough, zonal, and blocking; see K2K) in relation to the SAM. We show here that the largest changes are observed for the KTs T and SW (in the trough group) as well as for the KTs HSE and HE (belonging to the blocking group). Both the T and SW types are significantly more (less) frequent during the negative (positive) phase of the SAM (as defined by the CPC index). For the HSE, and to some extent the HE type, the response is opposite; that is, their probability is increased (decreased)
during the positive (negative) phase of the SAM. Other KTs show more ambiguous relationships to the SAM; for example, the KT HW (blocking) is less frequent during both the positive and negative phase of the SAM (~48% and ~59%, respectively).

Echoing results presented above for the MJO, some KTs have associations with locally opposite rainfall anomalies in NZ and align similarly to the SAM phase. The clearest example is for KTs T and SW, which are both significantly more (less) frequent than normal during negative (positive) phases of the SAM but are associated with opposite rainfall anomalies over the western half of the SI (see Figs. 4a,b).

Of importance, the KTs that show the most consistent response to the SAM (T, SW, and HSE) only show moderate response to the MJO, which suggests that the impact of the MJO on the NZ sector is likely not to be primarily mediated by the SAM. Further support is given when investigating the lagged relationships between the MJO and the SAM (Fig. 10). While the delayed response of the SAM index to the MJO meet the criteria defined above (presence of a slope with lag and time difference of approximate location of the maximum response to successive MJO phases compatible with the MJO propagation), the position of the maximum lagged response is markedly different from the one shown in Fig. 7. The maximum lagged response (decreasing values) of the SAM to the phases 1–3 of the MJO are found between 15 and 20 days (phase 1), then 5 and 10 days (phase 2), and 0 and 5 days (phase 4). The maximum lagged response of the KTs to the same phases of the MJO (Fig. 7) is markedly different (e.g., ~20 days after phase 3). During phases 4 and 5, the maximum response (increased SAM values) is found between 25 and 30 days (phase 4), then about 20 days (phase 5) and between 13 and 15 days (phase 6). The maximum lagged response of the KTs during the same phases of the MJO is also markedly different (~15 days for phase 4, between 5 and 10 days for phase 5, and between 0 and 5 days for phase 6).

In other words, while the MJO can be seen as a precursor of both the negative and positive phases of the SAM, the time scales of the lagged SAM response are markedly different from those displayed for the KTs. This strongly suggests that the regional response of NZ atmospheric circulation to the MJO is not primarily mediated by the SAM.

4. Summary and discussion

This study demonstrates that the Madden–Julian oscillation (MJO) signal is associated with locally significant rainfall anomalies across New Zealand.
(Fig. 3). The spatial distribution of these anomalies strongly suggests prominent orographic effects that result from interactions between the anomalous flow (direction and airmass origin) that are initiated during the MJO life cycle and the dominant relief presented by the axial ranges in NZ. Local precipitation and regional circulation anomalies can be further interpreted as resulting from changes in the occupation statistics of regional weather regimes (the Kidson types) in response to the MJO, although both constructive and destructive interferences can be demonstrated (Figs. 4 and 5).

The lagged relationships between the MJO and regional circulation were then investigated. It was first shown that the lagged response of zonally averaged geopotential anomalies at the latitudes of NZ present characteristics supporting a physical forcing of the MJO over the region, with propagation of positive or negative geopotential anomalies with phase speeds compatible with the average duration of a MJO cycle. Moreover, lagged response of the KTs’ occurrences also showed a clear delayed response, with the time difference between the timing of the maximum lagged response being compatible with the average phase speed of the MJO.

The potential implication of the southern annular mode (SAM) in the relationship between the MJO and regional circulation and climate anomalies was next investigated, and it was confirmed that the SAM is not independent from the MJO. However, the KTs that show the strongest and most consistent response to the SAM are distinct from the KTs modulated by the SAM (Fig. 9). Moreover, the timing of the delayed response of the SAM to the MJO is markedly different. These results suggest that the MJO signal over the NZ sector is not primarily mediated by the SAM: that is, the SAM is probably not the preferred pathway by which the tropical MJO signal is transmitted over the NZ sector at midlatitudes.

Given the existence of strong (+40%–70% in some cases) responses of KTs’ occurrences to MJO phases out to 15–20-days lag times, we suggest that the results presented in this paper bear the potential for predictability for some aspects of NZ weather and climate that arise from the MJO at time scales exceeding the meteorological time scales.

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