The Tropical Madden–Julian Oscillation and the Global Wind Oscillation

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ABSTRACT

The global wind oscillation (GWO) is a subseasonal phenomenon encompassing the tropical Madden–Julian oscillation (MJO) and midlatitude processes like meridional momentum transports and mountain torques. A phase space is defined for the GWO following the approach of Wheeler and Hendon for the MJO. In contrast to the oscillatory behavior of the MJO, two red noise processes define the GWO. The red noise spectra have variance at periods that bracket 30–60 or 30–80 days, which are bands used to define the MJO. The correlation between the MJO and GWO is $\rho = 0.5$ and cross spectra show well-defined, coherent phase relations in similar frequency bands. However, considerable independent variance exists in the GWO. A basic dynamical distinction occurs in the direction of midlatitude wave energy dispersion, being predominantly meridional during a MJO and zonal during the GWO. This is primarily a winter season feature centered over the Pacific Ocean. A case study during April–May 2007 focuses on the GWO and two 30-day duration orbits with extreme anomalies in GWO phase space. The MJO phase space projections for the same time were irregular and, it is argued, partially driven by mountain torques and meridional transports. The case study reveals that multiple physical processes and time scales act to create slowly evolving planetary-scale circulation and tropical convection anomalies.

1. Introduction

Subseasonal, 10–90-day events in the atmosphere’s circulation evolve in the frequency band that connects synoptic weather variations and interannual climate behavior. These atmospheric fluctuations influence the statistics of extreme weather events and can initiate rapid changes in the interannual climate. Such abrupt or extreme developments are at the frontier of weather and climate prediction. Moreover, interactions within this band between internal (e.g., jet stream) atmospheric dynamics and “external” boundary forcing (e.g., sea surface temperature) influence the evolution of the coupled ocean–atmosphere system. Understanding the time and space scales of the band, and its interaction with adjacent time bands, is a scientific challenge with applications to global weather–climate modeling and extended-range prediction.

The tropical Madden–Julian oscillation (MJO; Madden and Julian 1972) and the extratropical teleconnection patterns (Wallace and Gutzler 1981) are phenomena that bridge weather and climate. They have inherent lifetimes between 10 and 90 days and are linked with variations in the global or near-global circulation. Additional global teleconnection patterns have been proposed by Branstator (2002) and Weickmann and Berry (2007, hereafter WB07). Such phenomena can be used to monitor the time-evolving large-scale atmospheric circulation, the pattern of large-scale tropical convection, and the ongoing influence of coherent tropical–extratropical interactions.

Atmospheric angular momentum (AAM) provides a convenient framework (Peixoto and Oort 1992, chapter 11) to track these subseasonal weather–climate phenomena, and is a starting point for monitoring their regional impacts. Nearly 30 yr ago Langley et al. (1981) documented the presence of $\sim$50-day variations in length of day and global AAM. Anderson and Rosen (1983) linked these variations to the MJO and analyzed a coherent poleward and downward propagation of zonal
mean zonal wind anomalies. Global AAM anomalies peaked as the zonal mean zonal wind anomalies moved into the subtropics. The AAM link to the MJO was further explored by Madden (1987) who showed that global AAM is largest when MJO convection anomalies are weakening near the date line. Madden (1987, 1988) proposed that frictional torque anomalies over the Pacific Ocean basin to the east of convection anomalies were responsible for the exchange of angular momentum between the atmosphere and the earth. Although the mountain torque appeared to be small, subsequent investigations (Weickmann et al. 1992; Madden and Speth 1995; Hendon 1995; Weickmann et al. 1997, hereafter WKS) proposed approximately equal roles for the friction and mountain torque in forcing the global AAM changes.

In contrast to the focus on the MJO, several studies (Ghil and Childress 1987; Dickey et al. 1991; Ghil and Robertson 2002) argued for a separate ~40-day AAM oscillation in the extratropical atmosphere forced primarily by the mountains and their interaction with zonally asymmetric circulation anomalies (Marcus et al. 1996). Oscillatory forcing by the extratropical mountain torque in the 20–30-day band was also proposed (e.g., Lott et al. 2004; Lott and D’Andrea 2005 ). The idea of independent intraseasonal global AAM oscillations, one forced by mountain torques in the extratropics and the other by convection in the tropics was postulated and the former process was studied by Marcus et al. (1994) and Jin and Ghil (1990).

Weickmann et al. (2000, hereafter WRP) also argued for a separate mode of subseasonal global AAM variation but rather than a nonlinear oscillation they assumed it was a linear stochastically forced mode (Sardeshmukh and Sura 2009). The underlying physics and time scale was linked to the atmosphere’s attempt to maintain global AAM balance in the presence of large or clustered mountain torque events. Composites show atmospheric wave patterns over the major mountain ranges that produce either easterly or westerly wind anomalies over the topography. These patterns disperse downstream and can flux AAM meridionally. A zonal mean analysis confirms impulsive momentum fluxes, especially across ~30°–40°N, play a dual role of exciting the mountain torque and transporting the resulting momentum from mountainous source regions to frictional sink regions via midlatitude eddies. A characteristic feature of this adjustment process is a quadrature relation in the global time series of the friction and mountain torque with the frictional torque leading. Coherent variations of the circulation that accompany the process include the well-known Pacific–North America (PNA) teleconnection pattern and zonal index variations (Weickmann 2003, hereafter W03).

The slow time scale governing the global evolution of this separate extratropical mode is assumed to be the ~6-day decay time of the global frictional torque (WRP). A red noise spectrum (Wilks 1995) with a 6-day decay time would show broadband variance centered at 2π × 6 days ~40 days, and thereby the frictional torque would force AAM variations with power concentrated around 40 days. The MJO produces variance in a similar frequency band and the interaction between it and the midlatitude-dominated frictional red noise process is viewed as a prototype for tropical–extratropical interaction.

Using AAM as a framework, WB07 advocated a global-to-regional approach to monitoring short-term climate variations and evaluating subseasonal predictions by GCMs. This includes evaluation of zonal mean anomalies and the interaction of multiple time–space–scale physical processes within a dynamical weather–climate linkage framework. Global indices provide the big picture on the atmosphere’s state and are linked to the zonal mean and then regional behavior of the circulation, including teleconnection patterns. WB07 chose three indices to represent multiple subseasonal time scales. Daily indices of the MJO (Madden and Julian 1972), the global frictional torque, and the global mountain torque were combined to construct four distinct phases of a global synoptic dynamic model (GSDM) of the atmosphere.

In this study, an objective definition of the GSDM is derived for monitoring and prediction applications. This will involve combining the MJO, as defined by Wheeler and Hendon (2004, hereafter WH04), with the global wind oscillation (GWO) as defined by the global relative AAM and its time tendency. Although both “oscillations” produce signals in AAM, the MJO signal develops through tropical convective forcing and meridional wave energy dispersion while the GWO signal is dominated by midlatitude mountain forcing and zonal wave energy dispersion. Additionally, the GWO life cycle includes phases that resemble the circumpolar teleconnection pattern studied by Branstator (2002).

A case study is used to introduce the GWO. The main purpose of the case study is to illustrate a subseasonal event with a large signal in the GWO phase space but a small and irregular one in the MJO’s space. Observations of lead and lag suggest brief episodes of projection on the MJO may actually be forced by circulation anomaly fields linked to global mountain torques and zonal mean momentum transports.

In section 3, we examine the relationship between the MJO and the GWO and contrast their spectra and cross spectra. We show that while the MJO is embedded within the GWO, independent midlatitude processes are
important in the latter along with tropical convective forcing. In section 4 the phase–space plots for both oscillations are introduced and a summary of the MJO and GWO features is presented. The phase plots are then used to study the period from April to May 2007. The results show tropical convective forcing, while important, had weak projection on the MJO, while the GWO projections were large and primarily forced by extreme mountain torque events. The case study relationship between the global indices and the zonal mean flow anomalies is also examined. Finally, a successful week 2 prediction of a western U.S. trough in late May 2007 is related to a particular portion of the GWO phase space, one where prediction models often struggle and have low predictability in the 1–3-week forecast range. The summary and conclusions are presented in section 5.

2. Datasets and calculations

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis 1 (Kalnay et al. 1996) is the primary dataset used in the study. The global integral of relative AAM ($M_R$) and its time tendency are computed as described by Weickmann and Sardeshmukh (1994, hereafter WS) using daily average data. It is defined as

$$M_R = \int_{-\pi/2}^{\pi/2} a \cos \phi d\phi \int_0^{2\pi} a d\lambda \int_0^{p_s} m_r dp/g,$$

where $m_r = u\cos\phi$, $a$ is the earth’s radius, $u$ is zonal velocity, $\phi$ is latitude, $p_s$ is surface pressure, and $g$ is gravity. The global tendency ($dM_R/dt$) is estimated from the $M_R$ time series using a fourth-order finite-difference scheme. The anomalies are computed relative to a 1968–96 climatology and are standardized using 5-day-average data from 1968 to 2006. The standard deviations based on the entire record are shown in Table 1. Tests using the 365-day computed annual cycle of standard deviations versus one value for the entire year did not substantially change the results.

Since the $M_R$ units are unfamiliar to some readers a conversion to zonal wind units is provided in Table 1, where the global mean (uniform) zonal wind corresponding to a global relative AAM value is given by

$$\bar{u} = M_R g/\pi^2 a^2 p_s.$$

An application example is the seasonal cycle where $M_R$ is characterized by an annual mean of $1.4 \times 10^{28}$ kg m$^2$ s$^{-1}$ and an average annual range from $1.4 \times 10^{26}$ to $1.7 \times 10^{26}$ kg m$^2$ s$^{-1}$. The equivalent values from (2) are 5.4, 4.6 and 6.5 m s$^{-1}$, respectively. (One could also define a global mean of $u\cos\phi$, which would imply a meridional profile of the zonal mean zonal wind.)

Similarly, for a latitude band one can define (see WS)

$$\{\{m_r\}_v\}_\phi = \int_0^{\pi} a \cos \phi d\phi \int_0^{2\pi} a d\lambda \int_0^{p_r} m_r dp/g,$$

and relate the value to a zonal and vertical mean zonal wind

$$\{\{u\}_v\}_\phi = \{\{m_r\}_v\}_\phi g/2\pi \cos^2 \phi \Delta \phi a^3 p_s.$$

Thus, an $\{\{m_r\}_v\}_\phi$ anomaly of $1.0 \times 10^{24}$ kg m$^2$ s$^{-1}$ corresponds to a vertical and zonal mean zonal wind anomaly of $2.8$ m s$^{-1}$ at $30^\circ$ and $8.4$ m s$^{-1}$ at $60^\circ$, where $\Delta \phi$ is $\sim 1.9^\circ$ for a $192 \times 94$ Gaussian grid. For $\{[\partial m_r/\partial t]\}_\phi$, an integrated anomaly of $1.0 \times 10^{18}$ kg m$^2$ s$^{-2}$ corresponds to a vertical and zonal mean zonal wind tendency of $\sim 0.2$ m s$^{-1}$ day$^{-1}$ at $30^\circ$.

Finally, the extreme GWO events during the case study had equivalent anomalies of $\pm 1$ m s$^{-1}$ for the global mean zonal wind and $\pm 5.6$ m s$^{-1}$ for $\{\{u\}_v\}_\phi$ at $30^\circ$. For the tendency, equivalent anomalies are $\pm 0.15$ m s$^{-1}$ day$^{-1}$ for the global mean and $\pm 0.8$ m s$^{-1}$ day$^{-1}$ for $\{[\partial u/\partial t]\}_\phi$. The mountain torque from individual mountain ranges like the Rockies, the Tibetan Plateau, and the Andes can contribute $>50\%$ of the tendency.

3. The Madden–Julian oscillation versus the global wind oscillation: Cross-spectral and spectral analysis

WH04 defined an empirical measure of the MJO from the first two EOFs of a multivariate field consisting of a $15^\circ$N–$15^\circ$S average of the 200-mb zonal wind, the 850-mb zonal wind, and OLR. They refer to the two EOF time series as RMM1 and RMM2. Using an analogous approach, the GWO is defined by two dynamically related quantities: $M_R$ and $dM_R/dt$, which will be referred to as GWO1 and GWO2, respectively. Figure 1 shows sample 120-day time series for the MJO and the GWO

<table>
<thead>
<tr>
<th></th>
<th>GWO1 ($M_R$)</th>
<th>GWO2 ($dM_R/dt$)</th>
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<tbody>
<tr>
<td>Daily data</td>
<td>$1.25 \times 10^{25}$ kg m$^2$ s$^{-1}$</td>
<td>$1.84 \times 10^{19}$ kg m$^2$ s$^{-2}$</td>
</tr>
<tr>
<td>0.5 m s$^{-1}$</td>
<td>$0.07$ m s$^{-1}$ day$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Pentad data</td>
<td>$1.24 \times 10^{25}$ kg m$^2$ s$^{-1}$</td>
<td>$1.38 \times 10^{19}$ kg m$^2$ s$^{-2}$</td>
</tr>
<tr>
<td>0.5 m s$^{-1}$</td>
<td>$0.05$ m s$^{-1}$ day$^{-1}$</td>
<td></td>
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during January–April 2006. Multiple time scales are readily apparent even in this short record. The GWO has 10-, 30-, and 60-day trough-to-trough or peak-to-peak variations while the MJO variations are more like 20, 30, and 40–50 days.

Not surprisingly, the MJO and GWO indices are correlated. The MJO induces torques both within and outside tropics as it moves eastward with the remote component linked to meridional Rossby wave dispersion. Similarly the GWO can excite tropical convection anomalies through the large-scale tropical wind and sea level pressure anomalies that accompany the friction torque or the dispersion of extratropical Rossby wave energy into the tropics that accompany the mountain torque. The relation between the two is summarized in Table 2 where cross-spectral results for 20–120- and 30–80-day frequency bands are shown. The latter and 30–60-day bands have been used to define the MJO. All indices have only the mean and mean seasonal cycle removed, thus the RMMs are not exactly as defined by WH04.

In general there is little difference in the results between the two bands. The strongest relationship is between GWO1 and RMM2 with a nearly in-phase maximum correlation of 0.62 at 30–80 days (boldface in Table 2). The result generally confirms Madden’s (1987) observation of the relationship between $M_R$ and the MJO’s tropical convection but it is also influenced by the 200 zonal wind component of RMM2, not only the convective component. In any case, the result will be used in the next section to justify a GWO phase space where $M_R$ is plotted along the y axis (with RMM2) and $dM_R/dt$ is plotted along the x axis (with RMM1). The GWO2/RMM1 relationship is also relatively large for both bands (Table 2) and consistent with the fact that RMM1 and RMM2 are in quadrature.

Figure 2 shows the frequency spectra of the two components of the MJO and GWO. The comparison of the observed spectra to the red noise background emphasizes the primary difference between the two phenomena. The MJO is an oscillation with a peak in both RMM spectra at around 45 days. The GWO on the other hand shows two red noise processes: one with fast (2 days) and the other with slow (14 days) e-folding times that effectively bracket the MJO’s 30–80-day variance band giving considerable overlap in their spectral signature.

There is some structure in the GWO spectra worth commenting on. GWO1 has a nearly significant peak at 52 days, which partially reflects MJO forcing. The “peak,” however, is clearly on top of a red noise background with a 14-day decay time scale, a separate phenomenon from the MJO. The GWO2 ($dM_R/dt$) spectrum forms a plateau of variance from 5 to 40 days with a hint of separate maxima of 5–15 and 25–40 days. These are significant at the 95% level, at least with respect to the chosen red noise background. The backgrounds are determined from the e-folding time of the $M_R$ and $dM_R/dt$ time series (i.e., not from the lag 1 correlation). The 5–15-day band reflects the global mountain torque produced by synoptic wave trains moving over the mountains (Iskenderian and Salstein 1998; W03). Such events induce small but discernible responses in global AAM as can be seen in Fig. 1a. The 25–40-day band is also dominated by the mountain torque (WRP), which has 2–3 times the variance of the frictional torque in this frequency range. This band is the primary driver for both the MJO and non-MJO portion of the GWO.

While a portion of the GWO variance is related to the MJO, there are many subseasonal events where the
mountain torque is much larger than the frictional torque. WRP discussed the global and zonal aspects of global mountain torque events while W03 illustrated the horizontal patterns that accompany them. The similar frequencies involved with the MJO and this mountain-frictional torque adjustment process suggest the possibility of mutual excitation and interaction.

4. Phase space plots

The phase space plots introduced by WH04 are an efficient and objective way to monitor the MJO. They are being applied widely for diagnostic research and by operational centers to monitor their model’s prediction of the MJO. In this section, we introduce a similar phase plot for the GWO and then summarize some key results from composites computed from the MJO and GWO indices.

To start, the WH04 phase plot for the MJO is reproduced in Fig. 3 showing phases 1–8 defined as eight 45° segments in the 360° phase space. The text boxes inside the circle of arrows highlight important events when compositing on the RMMs including the location of tropical convection and changes in the large-scale circulation. Outside the circle of arrows, the components of the GWO are shown when compositing on the RMMs. The orbits rotate counterclockwise (CCW) during an eastward-propagating MJO but can rotate clockwise for a variety of reasons including tropical waves (Roundy et al. 2009) and SST anomalies. Figure 3 depicts a familiar time sequence of active tropical convection and related surface torques are shown while outside the arrows composites for tropical convection are shown.

During GWO phases 8–1 the tropical forcing is oscillatory. Westerly and easterly angular momentum are exchanged with the solid earth during an orbit.

Inside the arrows, important events in the circulation and related surface torques are shown while outside the arrows composites for tropical convection are shown. Along the GWO phase space trajectory from 8 to 1, a negative global frictional torque is followed by negative global mountain torque and together these processes give a strong negative AAM tendency that means westerly momentum is being removed from the atmosphere. A regional-scale response is for the extended North Pacific Ocean jet to collapse, often leading to a trough in the western United States (see the case study discussed in section 5). Monitoring experience suggests that the global numerical models perform poorly in these situations.

Table 2. Cross-spectral analysis is shown between the MJO and the GWO for two frequency bands using daily, standardized anomalies. The record length is the 9862 days from 1979 to 2005. The entries are coherence squared (correlation coefficient) and phase in radians. The largest values are shown in boldface where GWO1 (M8) is correlated with RMM2 in the 30–80-day band. The numbers following the index identification are the fractional variance contained in the frequency bands [e.g., (0.58) means that the 20–120-day band contains 58% of the variance]. For the GWO in column 1, the numbers in parentheses refer to the variance fraction for 20–120- and 30–80-day bands, respectively.

<table>
<thead>
<tr>
<th>Frequency band “oscillations”</th>
<th>20–120-day periods</th>
<th>30–80-day periods</th>
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<tbody>
<tr>
<td></td>
<td>RMM1 (0.58)</td>
<td>RMM1 (0.45)</td>
</tr>
<tr>
<td>GWO2 (0.4, 0.25)</td>
<td>0.2 (0.45)</td>
<td>0.25 (0.50)</td>
</tr>
<tr>
<td>GWO1 (0.28, 0.22)</td>
<td>0.21 (0.46)</td>
<td>0.26 (0.51)</td>
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<td></td>
<td>1.9</td>
<td>1.8</td>
</tr>
</tbody>
</table>


a. Phase space plots

Figure 5 is the MJO phase plot for the 59 days from 28 March to 25 May 2007 with a 5-day running mean applied. In contrast to the standard plot (e.g., WH04), interannual variations are retained. This causes the center of the orbits to shift slightly (~0.5σ) toward the La Niña phases 3–4. The MJO activity shows three coherent episodes where projections of >1σ or systematic eastward propagation occurred. These were interrupted...
by two periods with nearly zero signals, 10–22 April and 8–15 May. The plot starts with a MJO that developed over the Indian Ocean in mid-March 2007 and has now moved past the Maritime Continent around phase 5. From there, the MJO moves toward phase 1 before weakening around 10 April. The standard MJO phase plot (not shown) has >1σ projections during this time. Another weak event develops at the end of April 2007 at phase 2–3, moves east briefly to phases 4–5, weakens further ~6 May, but then reintensifies to >1σ at phase 7 as it moves east through the Western Hemisphere and Africa.

The annotations in Fig. 5 depict four periods with extreme $dM_H/dt$ anomalies. Together they produce two ~30-day GWO oscillations whose orbits in phase space will be discussed shortly. The mountain torque contributes substantially to the extreme tendencies. In Fig. 5, the two periods (10–22 April and 8–15 May) with

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**Fig. 2.** The frequency spectra for the components of the (a),(b) MJO and (c),(d) GWO. The blue line is the observed spectrum, the red line is a red noise background (obtained from the $e$-folding time of the time series, see text), and the black line is the 95% level of the red noise spectrum. The spectra are plotted with log frequency as the abscissa and with frequency multiplied by variance as the ordinate. In this type of presentation there is a “peak” in a red noise spectrum whose location is proportional to the decay or $e$-folding time of the time series, with 50% of the variance contained on either side of this peak. The degrees of freedom (dof) for the 95% levels were estimated from the number of data points divided by the $e$-folding time of the time series. For each bin, this gives (a) 7.2, (b) 7.2, (c) 5.4, and (d) 38 dof.
near-zero MJO but extreme GWO2 projection are highlighted using thickened line segments. The thickened segments occur just before MJO convection re-intensifies over the Indian Ocean in late April and over the western Pacific in mid-May 2007. The connection is highlighted using heavy black arrows. The composites to be presented in the companion paper confirm these relationships between the GWO tendency and the subsequent tropical convection anomalies.

Turning to the GWO, Fig. 6 shows its phase plot for the same period as the MJO in Fig. 5. The same dates have thickened line segments applied. Two prominent orbits are seen during the 59-day period: one from 28 March to 25 April (29 days) and the other from 26 April to 26 May (31 days). The first is a single orbit while the second combines a fast and slow orbit. On average the orbits are centered slightly away from zero toward phases 3–4 signifying a persistent negative global AAM anomaly, characteristic of a La Niña circulation state.

The regularity of the GWO orbits contrasts with the more variable MJO projection seen in Fig. 5. The relationship between the GWO and MJO projections discussed in Fig. 5 is also evident in Fig. 6. Indian Ocean (IO) convection follows the extreme negative tendency in mid-April and west Pacific Ocean (wPO) convection follows the extreme positive tendency in early May. On the other hand, the other two extreme tendencies in late May and early April are more integrated with the MJO convection anomalies so that forcing and response relative to midlatitude or tropical forcing is less clear cut.

For example, early in the first orbit, both the eddies that responded to west Pacific tropical forcing and to a
positive mountain torque from the Tibetan Plateau were easy to follow in a sequence of daily weather maps. Atmospheric Rossby wave dispersion, linked to both forcing mechanisms in a rapid sequence, contributed to a zonal mean southward momentum flux across 40°N. This is consistent with the GWO feature seen at phase 6 in Fig. 4 and will also be evident in the evolution of zonal AAM described in the next section. It is just one example of a process that can be anticipated when the signals in the GWO or the MJO are large and appear to be making a circuit or orbit.

Realistic subseasonal signals are clearly complex and it is not easy to disentangle the forcing–response feedback. The main point is that subseasonal events evolve through the mutual interaction between tropical convection and midlatitude mountain-torque-dominated processes. For the zonal mean, the tropics and major mountainous regions are linked via meridional momentum transports across 35°N (35°S). In the next section the variations of the zonal mean circulation are related to \( M_R \), while \( dM_R/dt \) is shown to be dominated by mountain torques from three primary regions: the

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**Fig. 4.** The GWO phase plot as proposed in this paper. The MJO is embedded in the GWO, but in addition, the GWO is sensitive to midlatitude processes like mountains and meridional momentum transports. The relation between the phase spaces was determined via cross-spectral analysis between the MJO and the GWO (see Table 2). The eight phases were defined to be the same between the two phase spaces. However, the GWO and MJO are not exactly “in-phase/quadrature” as is implied by the figure. Fast and slow time scales tend to be clustered in certain phases during the GWO thus phase moves faster or slower depending on its location in phase space. The dashed and truncated sequence of arrows emphasizes that the GWO is not oscillatory but on average gets excited and then decays. The text within the sequence of arrows is based on DJF composites for the eight phases. The text outside the sequence is also from composites but additionally shows the link of the GWO to tropical convection anomalies. Note the rapid movement of convection across Indonesia and the west Pacific during phases 3–6 compared with the MJO (Fig. 3).
Tibetan Plateau, the Rockies of North America, and the Andes of South America.

b. Zonal-vertical integrals

Figure 7 presents the $M_R$ time series and the $\{\langle \ln R \rangle \}_v$ anomalies for the same time period as in Fig. 6. The bottom panel shows the two orbits in time series form while the top panel shows the related zonal anomalies. The GWO phases and the location of positive tropical convection anomalies have been marked on the figure alongside the time period when they occurred. See Fig. 6 for more details. Additionally the thickened red and blue lines denote two of these large tendency periods, which are seen to precede growth of the MJO projections during late April and late May.

FIG. 5. The MJO phase plot for the 59-day period from 28 Mar to 25 May 2007. The red line with the dates track the first orbit of the GWO and the blue line tracks the second orbit. The interannual variations have been retained in this figure, so total anomalies have been projected onto RMM1 and RMM2. Since the climate was in a strengthening La Niña at this time the orbits are shifted slightly ($-0.5\sigma$) toward phases 3–4, which represent La Niña phases. Four cases of extreme global relative AAM tendency are marked on the figure alongside the time period when they occurred. See Fig. 6 for more details. Additionally the thickened red and blue lines denote two of these large tendency periods, which are seen to precede growth of the MJO projections during late April and late May.

Meridional momentum transports are the primary forcing for the poleward shifts and while tropical mass circulations may initiate the events, they are extended poleward and in time by the mountain torque and favorable midlatitude eddy structures. Within the general Fig. 7a pattern of negative zonal mean zonal flows, there are time periods and latitudes where westerly wind anomalies develop and persist. In the first orbit this occurs near 35°N while in the second it occurs more weakly near 20°N and 15°S. These are related to a combination of the strong meridional momentum fluxes and large positive mountain torques. The weak but positive global anomalies seen in Fig. 7b develop because of these zonal mean westerly wind anomalies. As shown below, the zonal anomalies develop in latitude bands that contain the Asian, North
American, and South American mountains. Although they are embedded in strong meridional fluxes of zonal momentum, the mountains act as additional momentum sources that have regional impacts downstream and can even change the zonal mean or global zonal flow.

Figure 8 shows the zonal-vertical and global integral of the relative AAM tendency corresponding to Fig. 7. The anomaly budget is dominated by the flux convergence of AAM followed by the mountain torque, the frictional torque, and the Coriolis torque in order of importance (WKS; W03). The purpose here is not to analyze the complete budget but rather to illustrate the timing of important physical processes during the two GWO orbits. Recall that the orbits start after maximum easterly flow anomalies have been established around 20°N and 20°S. The top panel in Fig. 8 shows the negative tendencies that create these anomalies and the positive tendencies that follow and weaken them after the start of the orbits.

Despite the complicated structure of the tendency field, a careful comparison with Fig. 7 confirms a poleward movement of discrete negative and positive tendency events, and these have been highlighted in the figure. They appear to emanate from north of the equator in the Northern Hemisphere. The progression of negative and then positive events is especially well defined during the second orbit. The flux convergence of AAM is the primary driver for this behavior (WKS). Anomalous meridional mass circulations forced by either tropical convection or eddy momentum fluxes likely drive the tropical–subtropical tendencies while eddy momentum fluxes become the dominant driver at high latitudes. The suggestive temporal connection in zonal mean flow anomalies for periods of 1–3 months between the tropics and polar latitudes is not well understood dynamically (Chang 1998; Feldstein 1998; Lorenz and Hartmann 2001; Lee et al. 2007) but often observed. On average, the MJO composite based on the RMMs (not
shown) only has propagation of zonal mean zonal wind anomalies to 20°N (20°S) so it provides no full explanation. Possibly a combination of the GWO and MJO are important, and this will be examined in a follow-up paper on zonal and regional composites. In general the interplay between the momentum transports, the mountain torque, and tropical convective forcing is still poorly understood.

The flux convergence of AAM cannot produce a global AAM tendency but it can lead to zonal wind anomalies that then produce zonal and global mountain torques. Two large momentum transport events are marked in Fig. 8 and coincide with the two large global tendencies seen in the bottom panel. The meridional transports are directed southward in early April and early–mid-May. The colored curves in the bottom panel confirm that mountain torques due to North American and Asian topography make an important contribution to the first tendency and that South American and Asian topography contribute to both the smaller tendency at the start of the second orbit and the much larger tendency 10 days later.

Quantitative data analysis and diagnostic modeling is required to understand the complete progression of the AAM tendency curve seen in Fig. 8. But for forecasting purposes, Figs. 3 and 4 supply an expected sequence of events that can be monitored and anticipated, thereby helping to evaluate model predictions and a probable future atmospheric state. In this case study, the events that typically accompany phases 8–1 were used to forecast a western U.S. trough that developed ~20–23 May leading to severe local storms on the Great Plains and significant temperature and precipitation anomalies across the country. The initial forecast was based on the size of the positive tendency during ~10 May when in phases 4–5 and the fact that one orbit had already occurred. A well-known synoptic sequence accompanies phases 8–1: the Pacific jet stream strengthens, extends east, and then breaks down leaving a trough over the southwestern United States. The acceleration of the zonal mean jet...
FIG. 9. A portion of the (a) MJO and (b) GWO life cycle of 250-hPa streamfunction anomaly during DJF is shown. The contour and color interval is 0.2σ, where σ is the local daily standard deviation. The zero line is bold. See the text for further discussion.
during the two orbits is seen by the large positive zonal AAM tendencies around 30°N in Fig. 8a. Of course the forecast challenge is to determine when or if the jet will break down, and this involves impacts from the synoptic as well as the interannual time scales.

6. Summary and conclusions

The GWO has been introduced as an additional aid to monitor and help understand subseasonal variations of the global atmospheric circulation. It is defined using global relative AAM and its tendency and when plotted in a phase space diagram eight phases are defined. Frequency spectra were used to contrast the ~45-day oscillations of the MJO with the multiple time-scale, red noise behavior of the GWO.

A case study from April to May 2007 compares the time evolution of the GWO and the MJO. The GWO was strong and coherent throughout the case compared to a transient and weak projection for the MJO. The GWO variations were linked to zonal mean flow anomalies in tropical regions between 30°N and 30°S. During two well-defined GWO orbits, anomalies of one sign in this latitude band are replaced with anomalies of opposite sign while the original anomalies shift poleward. Mountain torques embedded within strong meridional momentum fluxes contributed additional momentum sources and sinks in specific latitude bands and also had a major contribution to the global relative AAM tendency. In time–latitude plots, zonal mean westerly wind anomalies were observed to emanate from the latitude bands that contain major mountain ranges, especially Asia and South America.

The MJO can produce a signal in the GWO as shown by the moderate correlation between them. However, it was argued that a separate mode of variation dominates the GWO tied to the atmospheric circulation adjusting to large or clustered mountain torque events. Both the MJO and the GWO produce zonal wind anomalies in the tropical band and thus it is reasonable to suppose the oscillations can interact and excite one another. These “oscillations” are being monitored in real time as the primary components of the global synoptic dynamic model introduced by WB07. Understanding the dynamical processes explained by the GWO allows for a more sophisticated evaluation of the numerical models as part of a complete forecast process.

A companion study uses the GWO to construct eight phase composites of zonal mean and global teleconnection patterns. These are contrasted with the MJO’s composite patterns. Figure 9 shows an example of a partial sequence from both the GWO and MJO life cycles during December–February. The sequence focuses on the breakdown of a strong jet stream anomaly that develops over the North Pacific Ocean in both cases. There is about 4–8 days between the phases. The composite differences confirm that the GWO is dominated by zonal Rossby wave dispersion while the MJO has prominent meridional dispersion of Rossby waves. For the MJO (Fig. 9a), the jet anomalies are part of a meridional Rossby wave train, established over 1–3 weeks as convection anomalies move into the western and central tropical Pacific. The pattern breaks down when convection anomalies propagate into the western hemisphere. For the GWO (Fig. 9b), the jet anomalies extend farther eastward in response to the Asian mountain torque and weaken in response to anticyclonic or cyclonic wave breaking events over the midlatitude east Pacific (not shown). This is followed by the slow dispersion of Rossby wave energy into the tropical Western Hemisphere. A comprehensive analysis of both the MJO and GWO life cycles, including their sensitivity to the seasonal cycle and ENSO, is planned in future work.

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REFERENCES

Irkenderian, H., and D. A. Salstein, 1998: Regional sources of mountain torque variability and high-frequency fluctuations...


