Mechanisms Linking Global 5-Day Waves to Tropical Convection

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ABSTRACT

Reanalysis data and satellite-derived rainfall measurements are examined to determine possible mechanisms linking the “5 day” Rossby–Haurwitz wave to localized variations of tropical convection. The mechanisms in all regions rely on the modulation of zonal winds near the equator by the wave, but the nature of these mechanisms depends strongly on local topography and local climate. In the upper Amazon basin, the wave modulates the strength of prevailing easterlies and thus the upslope flow and associated convection on the eastern edge of the Andes. Similar modulation of upslope flow is involved off the Panamanian and Colombian Pacific coasts, but the deflection and confluence of low-level wind in the presence of the Andes and moisture transports across the Andes from the Amazon basin are also factors. Similar deflection and confluence of winds around and through the Maritime Continent lead to low-level divergence and convection anomalies over the eastern Indian Ocean. Anomalous moisture transports from the Congo basin to the eastern and northeastern Gulf of Guinea due to the wave affect atmospheric moisture over the Gulf of Guinea and thus convection in the region. Over oceanic convergence zones, modulations of the prevailing winds by the wave affect the overall wind magnitude, changing evaporation from the ocean surface and atmospheric moisture. Most of these mechanisms arise from the nonuniform nature of Earth’s surface and suggest that other external Rossby–Haurwitz waves may have similar interactions with convection.

1. Introduction

There are two broad classes of global, barotropic normal modes of the atmosphere, corresponding to the two types of wave solutions to the Laplace tidal equations: gravity waves and Rossby waves. The global normal-mode Rossby waves (also known as Rossby–Haurwitz waves) have horizontal structures related to the Hough functions and are largely governed by Earth’s rotation and present in the atmosphere as large-wavelength waves that propagate westward. The presence and structure of the normal-mode Rossby waves in the atmosphere has been well studied since their first identification in the 1960s (Eliassen and Machenhauer 1965), with the existence of discrete normal Rossby modes up to zonal wavenumber 4 and meridional index 4 having been identified in analysis and reanalysis data (Weber and Madden 1993; Elbern and Speth 1993; Madden 2007).

Although the presence of these waves is well established, less effort has gone into identifying their possible weather and climate impacts. The role of the normal-mode Rossby waves on the occurrence of blocking events has been investigated (Lejenä and Madden 1992), with up to 40% of blocks related to westward-propagating, zonal-wavenumber-1 waves. The wavenumber-1, meridional-index-1 “5 day” wave has been shown to modulate tropical convection and rainfall (Burpee 1976; King et al. 2015),...
and wavenumber–frequency cross spectra such as Fig. 1 show significant coherence between zonal winds and convective fields at westward zonal wavenumber 1 and frequencies of around 0.2 day\(^{-1}\), corresponding to the 5-day Rossby–Haurwitz wave (Hendon and Wheeler 2008; King et al. 2015, 2016). However, beyond characterizing the geographical distribution and magnitude of the relationship, as in King et al. (2015), the nature of the 5-day-wave interaction with tropical convection has not been well investigated. In particular, the 5-day wave is unlikely to directly associate with rainfall in the same manner as the convectively coupled equatorial waves and other tropical waves, as it is associated with small surface convergence and divergence and is thus unlikely to drive convection through the wave alone promoting surface convergence of moist air.

The aim of this paper is to investigate in detail the modulation of precipitation and dynamical fields in the regions found in King et al. (2015) to have significant convective modulation by the 5-day wave and to suggest mechanisms by which the observed modulation of convection by the 5-day wave occurs. The remainder of the paper is organized as follows. Section 2 describes the data and methods used in this paper. Sections 3–7 investigate the modulation of convection in specific regions, with section 3 concerning the Amazon basin, section 4 concerning the Colombian Pacific coast, section 5 concerning western central Africa and the Gulf of Guinea, section 6 concerning the western Maritime Continent and the eastern Indian Ocean, and section 7 concerning the intertropical convergence zone in the western Pacific. Finally, commonalities and differences between these regions are discussed and conclusions are presented in section 8.

2. Data and methodology

a. Data

Regions of interest within the tropical band in this study are identified by the boxes shown in Fig. 2. These regions represent the locations of the strongest variance in convective activity associated with the 5-day wave, with the West African region (20°W–40°E) and South American region (90°–30°W) being identified in King et al. (2015) as having the largest variances. Additional regions are examined in this paper, as the Colombian Pacific coast has precipitation anomalies with magnitudes similar to that seen in the Amazon region, but with opposite phasing, and the eastern Indian Ocean and western Pacific Ocean region (75°E–150°W) have smaller magnitude precipitation anomalies associated with the wave distinguishable from background variance.

Horizontal winds, vertical wind, divergence, temperature, specific humidity, total column water vapor, surface pressure, and surface heat fluxes were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) dataset (Dee et al. 2011; ECMWF 2011). These data were obtained for the period 1998–2012 on a 1°×1° grid and a 6-h temporal resolution, and for nonsurface fields was obtained for pressure levels every 50 hPa from 1000 to 250 hPa. From these reanalysis fields, moisture flux divergence and equivalent potential temperature fields were calculated for the same period and pressure levels.

Precipitation data come from the Tropical Rainfall Measuring Mission (TRMM) 3B42 rainfall estimates (Huffman et al. 2007, 2011), obtained over the period 1998–2012 at 3-hourly temporal resolution, and for nonsurface fields was obtained for pressure levels every 50 hPa from 1000 to 250 hPa. From these reanalysis fields, moisture flux divergence and equivalent potential temperature fields were calculated for the same period and pressure levels.

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b. Method

A reference time series of 5-day-wave 850-hPa zonal wind anomalies was obtained by first filtering 850-hPa zonal wind data for each latitude from ERA-Interim in wavenumber–frequency space through Fourier transforms, with data from westward-propagating zonal-wavenumber-1
disturbances with periods between 4 and 6 days being retained, as further described in King et al. (2015). The reference time series is then generated by having these components reverse transformed back to time-longitude space, and then averaged in latitude between 5°N and 5°S at a reference longitude close to the area investigated. These reference longitudes are 60°W for the South American and Colombian regions, 10°E for West Africa, 105°E for the eastern Indian Ocean and western Maritime Continent, and 180° for the tropical Pacific.

Lagged composites of 5-day-wave-associated anomalies are generated for the regions of interest by regressing unfiltered “field” data at each grid point against the reference time series for a range of lags from 5 days before to 5 days after zero lag. To improve signal to noise, the regression is only performed for periods where the variance in a 19-day window of the reference time series is greater than the overall variance of the series, and the resulting regression coefficients are scaled by a two-standard-deviation anomaly in the reference time series in order to produce anomalies that are representative of a relatively strong wave event. The regression method used here is like that used in King et al. (2015) and has been shown to be sufficient in extracting a westward-propagating 5-day wave with barotropic horizontal wind fields close to theoretical structures and those generated from other composite methods (King 2016). Statistical significance where calculated is done through a Student’s t test, with the temporal degrees of freedom reduced to account for the temporal autocorrelation in both time series going into the regression, as described in Livezey and Chen (1983).

It is worth noting that the small spectral range of the filter used to generate the 5-day-wave horizontal wind data series, while dominated by a signal related to the wave, will unavoidably include some variability from zonal wind disturbances that are not related to the 5-day wave. Furthermore, as most composites in this paper are generated from all available data from 1998 to 2012, anomalies seen in the composite will not be associated with all wave events but may only occur in a small subset of these events or during a particular time of the annual cycle, particularly in the time-longitude plots where no significance tests have been applied.

3. Amazon basin

a. Climatological basic state

Climatological winds in equatorial South America east of the Andes over the period 1998–2012 (shown at the 850-hPa level in Fig. 3) are primarily easterly, with a decrease in magnitude at the 850-hPa level over the Amazon basin from around 6 m s⁻¹ near the Atlantic coast to 0 m s⁻¹ on the eastern edge of the Andes. Above this level, an easterly jet is observed over much of the midtroposphere, and a reversal to weak westerlies is apparent near the tropopause.

Rainfall is above 6 mm day⁻¹ over most of equatorial Amazonia west of 55°W (Fig. 3) with precipitation increasing to the west within Amazonia, with mean rainfall of over 10 mm day⁻¹ observed on the eastern edge of the Andes in Ecuador (2°S, 77°W), southern Peru (13°S, 70°W), the upper northwest of the Amazon basin (2°N, 67°W) and the Venezuelan areas of the Guyana highlands (5°N, 65°W).

The mean easterly wind introduces moist air from the Atlantic into the Amazon basin and transports moisture in the basin westward (Arraut et al. 2012). Within the basin, the dense rain forest reintroduces around 50% of precipitation into the atmosphere through evapotranspiration, which leads to specific humidity increasing in the lower troposphere from the coast toward the upper Amazon basin (Salati and Vose 1984; Nobre et al. 1991). The convergence of this near-surface moist air on the eastern side of the Andes due to topographic blocking is recognized to be the key factor in driving the observed climatological convection through the resulting uplift of moist air (Salati and Vose 1984; Figueroa and Nobre 1990). Precipitation within the upper Amazon basin has a well-defined spectral peak at a period of around 5–6 days (King et al. 2015), which along with the variance...
seen in Fig. 2 suggests the 5-day wave may play an important role in precipitation variability in this region.

b. Wave effect on local conditions

Figure 4a shows a Hovmöller time–longitude section of precipitation and 850-hPa zonal wind anomalies associated with the 5-day-wave zonal wind reference time series at 60°W. Over most of the Amazon east of 75°W, 850-hPa zonal wind anomalies appear somewhat like a standing wave, with the regressed zonal wind reaching a maximum over most of the basin on day 0. This is unlike zonal wind anomalies higher in the troposphere, and geopotential anomalies, which propagate evenly westward with the 5-day wave, as can be seen in Fig. 5. West of the Andes, however, the 850-hPa zonal wind anomalies do seem to propagate westward. Precipitation anomalies on the eastern edge of the Andean cordillera at 75°W are well aligned with the local zonal wind anomalies, with easterly anomalies associated with enhanced precipitation and westerly anomalies associated with suppressed precipitation. A similar phase relationship is observed between the precipitation anomalies and zonal wind anomalies near the Atlantic coast at 50°W. Precipitation anomalies appear to propagate eastward from the eastern edge of the Andes to ~57.5°W at a speed of around 15° day−1 (19 m s−1). This propagation speed is roughly consistent with convectively coupled Kelvin waves (Wheeler and Kiladis 1999), and the existence of Kelvin waves in this region has previously been shown (Wang and Fu 2004; Liebmann et al. 2009). As the eastward propagation of anomalies does not strongly appear to the west of the Andes, this suggests the source of the convective variability is the 5-day wave, which drives this Kelvin wave–like dynamic response over the Amazon basin.

Precipitation anomalies are strongly correlated with 950-hPa moisture flux convergence (MFC) anomalies over the entire Amazon basin from 72° to 50°W, as is shown in Fig. 4b. The near-surface MFC anomalies show the same eastward Kelvin wave–like propagation as the precipitation anomalies and strongly suggest that the low-level MFC anomalies lead directly to the observed modulation of convection. On the other hand, total column water vapor (TCWV) does not appear to be a key driver of the precipitation anomalies (Fig. 4c), but instead the anomalous convection appears to moisten the atmosphere with maximum total column water vapor lagging maximum precipitation by around half a day. Outside of the Amazon basin the total column moisture anomalies show westward propagation, with fast propagation west of 80°W and slower westward propagation in the region east of 55°W over the Atlantic, where it has a phase speed of around 6–8 m s−1. The propagation speed and location of these anomalies over the Atlantic suggest this may be a result of modulations in African easterly waves (AEWs) by the 5-day wave as postulated by Patel (2001), but as the column moisture anomalies here do not seem be strongly linked with local convection, further investigation of this is out of the scope of this paper.

The relationship between precipitation and the wave varies throughout the year, being strongest during March–May (MAM) and weakest during September–November (SON), as with the evolution of precipitation anomalies during these seasons shown in Fig. 6. Anomalies along the eastern edge of the Andes at 77°W are twice as strong during MAM as they are during SON, and the location of the strongest anomalies during SON appears farther east.
at 70°W. This seems connected to the weaker MFC and zonal wind anomalies west of 70°W during SON.

Figure 7 shows maps of precipitation, 950-hPa horizontal wind, and 950-hPa MFC anomalies associated with the easterly phase of the 5-day wave in the Amazon basin region. Note that the sign of the anomalies is reversed compared to Fig. 4, which was scaled relative to the westerly phase at day 0. In advance of the easterly anomaly phase of the 5-day wave (~2 days before peak easterlies), a northerly anomaly along the flank of the Andes leads to enhanced MFC along much of the Peruvian Andes (~13°S, 70°W) and enhanced precipitation in the southwestern Peruvian Andes. The onset of the easterly phase around a day before peak easterlies leads to primarily easterly anomalies in the upper Amazon basin, with these reducing in magnitude and changing direction as they approach the Andes. This reduction in zonal wind magnitude leads to positive MFC and precipitation anomalies between 60° and 78°W, originating with anomalies along the very edge of the Andes a day before peak easterlies, before spreading eastward with the strongest anomalies occurring around 2°N–4°S on the day of peak easterly anomalies. The area between 2°N and 4°S is where the Andes change from being roughly northeast–southwest oriented to being northwest–southeast oriented, with the corresponding deflection of low-level easterly winds along the eastern flank of this region leading to the large region of convergence (Lenters and Cook 1995). A day following the peak easterly phase, anomalous winds in the upper Amazon basin become southerly and positive MFC anomalies are no longer present over most of the upper Amazon. Instead, strong positive MFC anomalies are located to the east (~0°, 60°W) and to the north (~4°N, 68°W) of where they are for the peak easterlies. The MFC anomaly to the east continues propagating eastward for another day before it decays and is no longer discernable, in line with the Kelvin wave–like propagation seen in Fig. 4.

Figure 8 shows the vertical composites of specific humidity and zonal circulation anomalies in this region during the day preceding peak easterlies. The initial easterly anomalies and corresponding MFC anomalies lead to increased moisture between the surface and 850 hPa over most of the Amazon basin, except to the immediate east of the Andes, where increased moisture extends up to 600 hPa. The shallow moistening at the eastern edge of the Andes continues as the easterly anomalies build, with a maximum moisture anomaly of almost 0.1 g kg⁻¹ being observed at the 800-hPa level at 76°W a quarter-day in advance of the strongest wind anomalies. The maximum moisture anomalies here coincide with deep convection lifting this accumulated

![Figure 4](image-url)
moisture, which decreases the magnitude of the specific humidity anomalies in the low troposphere and distributes the anomaly in the vertical, with a resulting moistening of the midtroposphere.

With the anomalies observed, the likely mechanism behind convective modulation by the 5-day wave in the upper Amazon basin is as follows. The onset of easterly anomalies on top of the climatological easterlies increases the magnitude of zonal wind in the basin. Because of the topographic barrier of the Andes, this leads to increases in the low-level convergence and moisture flux convergence in the upper Amazon basin. The convergence tends to increase deep convection and precipitation on the eastern flank of the Andes, which also uplifts moisture from the surface to the midtroposphere. The deep convection on the edge of the Andes generates a Kelvin response that propagates eastward. Conversely, the westerly anomaly phase of the 5-day wave reduces the net magnitude of easterlies in the basin, reducing the convergence and MFC on the eastern edge of the Andes and leading to suppressed convection in the upper Amazon basin.

4. Colombian Pacific coast
   a. Climatological basic state

   Climatological-mean precipitation and 850-hPa horizontal winds in the region around the Colombian Pacific coast are shown in Fig. 3. At the 850-hPa level pictured, the mean climatological winds appear to be weak near the Colombian Pacific coast with weak onshore flow along the coast. However, below this level a strong westerly jet (the Choco jet; Poveda and Mesa 2000) directed toward the coast is present and above this level exists a mean easterly flow.

   Precipitation rates of up to 20 mm day$^{-1}$ are observed along the Colombian Pacific coast (Fig. 3), with this area having the highest-known average precipitation rates in the world (Poveda and Mesa 2000; Zuluaga and Houze 2015). Rates exceeding 10 mm day$^{-1}$ are seen along 6$^\circ$N latitude from 77$^\circ$W to 87$^\circ$W, along the Caribbean coast of Costa Rica and on the southern Pacific coast of Costa Rica. The high rainfall rates along the Colombian coast are thought to be due to the combined influence of the Choco jet introducing moisture at low levels, surface heating along the western flank of the Andes lifting this moisture, and convergence due to interactions with the Andes and midlevel easterlies (Poveda and Mesa 2000; Poveda et al. 2014). Convergence drives much of the convection along 6$^\circ$N latitude, although propagation of diurnally forced gravity waves from Colombia (Mapes et al. 2003a,b) also appears to play a role.

   b. Wave effect on local conditions

   A time–longitude section of anomalous precipitation and 850-hPa zonal winds shows that precipitation anomalies along the Colombian coast (∼76$^\circ$W) occur roughly in quadrature with wind anomalies, with enhanced precipitation occurring in advance of westerly anomalies (Fig. 9a). Precipitation anomalies appear to

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Time–longitude plots of precipitation anomalies (shaded; mm day$^{-1}$) with (a) 600-hPa zonal winds (contoured) and (b) 850-hPa geopotential (contoured) anomalies averaged between 2$^\circ$N and 5$^\circ$S associated with a westerly 5-day-wave 850-hPa zonal wind anomaly at 60$^\circ$W with a magnitude of two standard deviations of the basis time series at a lag of 0 days. Contour intervals are 0.1 m s$^{-1}$ for zonal winds and 10 m$^2$ s$^{-2}$ for geopotential, with the zero contour not shown and negative contours dashed.}
\end{figure}
propagate westward from the coast to 82°W over a period of 24 h. From this point west to 95°W, enhanced precipitation anomalies appear over the entire region roughly in phase with westerly wind anomalies.

Precipitation anomalies west of the Colombian coast closely match both 850-hPa MFC and TCWV anomalies (Figs. 9b and 9c), with positive MFC and TCWV anomalies associated with increased precipitation. However, along the coast (77°W), positive TCWV precedes enhanced precipitation and positive MFC by around a day, suggesting that the modulation of moisture along the coast is a key factor in the local modulation of convection by the 5-day wave. This is unlike what occurs in the upper Amazon basin, where TCWV anomalies are preceded by MFC and precipitation anomalies. These upper-Amazon precipitation anomalies are captured in Fig. 9 as the anomalies that appear east of 75°W, which appear to move eastward as a result of the positive MFC and precipitation anomalies that occur over the boundary between the Amazon and Orinoco basins in line with the southerly wind anomalies (as in day 1 of Fig. 7).

The seasonal strength of the precipitation signal is also opposite that seen in the upper Amazon, with strongest anomalies during SON and weakest anomalies during MAM, as seen in Fig. 10. Differences in the precipitation behavior between these two seasons can be seen, with the rainfall anomalies during SON being strongest near the coast at 77°W with a clear westward progression of the anomalies being visible, while during MAM anomalies close to the coast are weaker and have a phasing roughly matching that in the Amazon.
basin, suggesting the anomalies near 77°W during MAM occur on the eastern side of the coastal mountains. This is supported by the MFC anomalies, which show an east–west band of convergence to the west of the Andes preceding enhanced convection during SON but strong MFC anomalies confined to the east of the Andes during MAM.

Composite maps of 950-hPa horizontal winds, precipitation, and 950-hPa MFC anomalies are displayed in Fig. 11. At a lag of 2 days before the peak westerly phase, wind anomalies at the 950-hPa level are northeasterlies over the Pacific near Panama and Colombia, with suppressed precipitation and negative MFC anomalies along 6°N latitude. The northerly component of the anomalous winds appears to come from deflection around the northern edge of the Andes and across the Panamanian isthmus, with the negative MFC anomalies and suppressed precipitation associated with the descent of this anomalous flow on the lee side of Panama. However, positive MFC anomalies are observed along 3°N latitude, as the anomalous winds decrease in magnitude and become more easterly, and along north-facing aspects of the Pacific coast, where the wind anomalies are roughly onshore. A day later this band of positive MFC anomalies has moved northward to 5°N with southerly anomalies south of this latitude converging with the northeasterly anomalies north of it. At this stage, 950-hPa MFC anomalies have a maximum at the coast, and this low-level convergence is matched with anomalous convergence up to the 400-hPa level, leading to enhanced precipitation near the coast. The band of positive MFC and precipitation anomalies is located at 6°N during the peak westerly phase of the 5-day wave, but maxima for these is now located offshore at around 82°W, as southwesterly anomalies weaken owing to deflection over the Panama isthmus. The band of enhanced convection moves farther north to 8°N a day after the peak westerlies to be situated off the Costa Rican coast.

In addition to the local low-level MFC anomalies promoting convection in this region, anomalous cross-Andean moisture transports and midlevel moisture convergence seem to play a role, as shown in Fig. 12. The modulation of convection in the upper Amazon as described in the previous section leads to anomalous levels of moisture crossing the Andes at its low point near 5°S,
with anomalous midlevel moisture flux convergence at 750–700 hPa leading to sizable column moisture anomalies at around 8°S on day −2. While much of this moisture is advected westward, in the midtroposphere southerly winds advect some of this moisture northward, where it appears to assist in promoting convection over the oceanic region during the local westerly phase of the 5-day wave.

5. Gulf of Guinea and central Africa

a. Climatological basic state

Unlike South America, near-surface climatological winds in equatorial Africa over the period 1998–2012 are very weak (Fig. 13), with mean 850-hPa winds over the Congo basin and the Gulf of Guinea being less than 1 m s$^{-1}$.
Mean daily rainfall is above 4 mm for almost all of the Congo basin and with rates above 8 mm day$^{-1}$ observed for small areas of the upper Congo basin and over the northeastern part of the Gulf of Guinea where a local maxima of mean rainfall is seen (Fig. 13). This region of central Africa is one of the most convectively active areas in the world, with latent heat release into the upper atmosphere second only to the Maritime Continent (Washington et al. 2006, 2013). This convection is associated with meridional inflow into the ITCZ from subtropical highs (Jury et al. 2009) and convergence of low-level moisture coming from the tropical Atlantic and upper-level moisture from the Indian Ocean (Matsuyama et al. 1994). These moisture transports, along with high rain forest evaportranspiration in the Congo basin, keep the low-level atmosphere over western central Africa more humid than the nearby Gulf of Guinea and more unstable owing to surface heating from the land surface.

Precipitation over the Gulf of Guinea shows a strong spectral peak in the 4–6-day range (King et al. 2015), as does outgoing longwave radiation over both the Gulf of Guinea and the Congo basin during much of the period November–May (Nguyen and Duvel 2008). While much of this variance is due to the influence of convectively coupled Kelvin waves over this region, most of the convective variability in the 4–6-day range is generated locally with the Gulf of Guinea and Congo basin instead of Kelvin waves entering the region from the west (Nguyen and Duvel 2008), and thus the 5-day wave may play a small role in this.

b. Wave effect on local conditions

Time–longitude sections of anomalous precipitation, 850-hPa zonal wind, 850-hPa MFC, and total column water are in Fig. 14. Over the Gulf of Guinea and western central Africa, precipitation anomalies associated with the 5-day wave appear to be roughly in quadrature with anomalous zonal wind (Fig. 14a) with easterly (westerly) anomalies preceding enhanced (suppressed) convection. Unlike what is observed in the Amazon basin and over the eastern Pacific, a clear westward propagation in the 850-hPa zonal wind anomalies can be seen west of 10°W over the Atlantic Ocean. From the strongest precipitation anomalies of up to 2.5 mm day$^{-1}$ around 9°E, near the Gulf of Guinea coast, precipitation anomalies propagate westward at a slightly slower rate than the wind anomalies. Eastward propagation of precipitation anomalies from the Gulf of Guinea coast is also apparent at a rate of around 10° day$^{-1}$, corresponding roughly to the propagation speed of convectively coupled Kelvin waves (Wheeler and Kiladis 1999).

Over the Gulf of Guinea (west of 10°E), the relationship between anomalous 850-hPa MFC and precipitation (Fig. 14b) is similar to that between anomalous zonal wind and precipitation, with enhanced
convection following enhanced MFC by around a quarter-cycle. The near-quadrature relationship between the wind and 850-hPa MFC anomalies and precipitation anomalies west of 10°E is unlike what is observed in the previous two regions, suggesting a different mechanism than the modulation of upslope flow on the windward edge of topography is involved in this region. Over the Congo basin, however, enhanced convection is approximately in phase with anomalous 850-hPa MFC, which also propagates eastward at around 10° day⁻¹. The correspondence between the MFC anomalies and precipitation over the Congo basin is further indicative of convectively coupled Kelvin waves, which have been often observed in this region (e.g., Nguyen and Duvel 2008). Precipitation anomalies over the Gulf of Guinea are closely aligned with total column water vapor anomalies (Fig. 14c), with positive moisture anomalies leading enhanced precipitation by 6h. This approximately in-phase relationship between anomalous moisture and precipitation over the Gulf of Guinea, as well as the quadrature relationship between low-level MFC anomalies and precipitation, suggest that the local modulation of precipitation by the 5-day wave is through the buildup of atmospheric moisture.

The anomalies occurring over the Gulf of Guinea and central Africa are highly seasonal, as can be seen in the difference between the larger anomalies in MAM and the almost nonexistent anomalies during June–August (JJA) shown in Fig. 15. The location and evolution of the anomalies during MAM almost exactly match that seen

**Fig. 10.** Time–longitude plots of precipitation anomalies (shaded; mm day⁻¹) with (a) 850-hPa zonal winds (contoured) and (b) 850-hPa MFC (contoured) averaged between 9° and 2°N associated with a westerly 5-day-wave 850-hPa zonal wind anomaly at 60°W with a magnitude of two standard deviations of the basis time series at a lag of 0 days during (left) MAM and (right) SON. Contour intervals are as in Fig. 4.
in the annual anomalies (Fig. 14), with precipitation, MFC, and TCWV anomalies being almost two-thirds greater than seen in the annual composite. However, during JJA, precipitation anomalies are less than half that of the annual anomalies, and MFC anomalies east of $5^\circ$E are much reduced. Despite this, a strong, slowly westward-propagating TCWV anomaly signal can be seen, possibly due to interactions with African easterly waves, which are strong during July and August, have a 4–5-day periodicity, and are hypothesized to interact with the 5-day wave (Patel 2001; Mekonnen et al. 2006).

Figure 16 shows vertical composites of the anomalous zonal circulation and specific humidity in a cross section over the equatorial Gulf of Guinea and central Africa, along with precipitation anomalies. Near the time of the local peak easterly wind phase of the 5-day wave (2.5 days before peak westerlies) the easterly wind anomalies over the Congo basin lead to increased moisture over the coastal ranges that separate most of the Congo basin from the Atlantic. This moisture anomaly strengthens over the next 24 h as the easterly anomalies continue, with shallow convection and enhanced precipitation being observed 2 days before the peak westerlies and a maximum moisture anomaly of around 0.2 g kg$^{-1}$ occurring at the 800-hPa level 1.5 days in advance of the peak westerly phase. At this stage, the increased moisture is sufficient to promote deep convection, with the increased moisture being distributed both vertically through convection and zonally through the mean easterly winds over the Gulf of Guinea. Convection and associated precipitation begin to remove the anomalous moisture half a day in advance of peak westerlies, and surface dry anomalies are established with westerly anomalies reducing the moisture transport from the Congo basin. The composites in Figs. 14 and 16 are reminiscent of those in Fig. 6 of Nguyen and Duvel (2008), where four composites are presented showing the mean anomalies during suppressed, developing, enhanced, and decaying phases of 2–10-day band-passed convection of the Congo basin during March and April. For example, the developing phase in their composites (cat. 2 in their Fig. 6) is preceded by positive
convergence and low-level moisture anomalies at around 10°E and easterly anomalies over the Congo basin. This is matched here by the vertical structure and 850-hPa MFC anomalies on day −2, which have moisture, MFC, and zonal wind anomalies of matching sign in the same locations. This, along with the relative strength of the MAM anomalies as seen in Fig. 15, suggests that the 5-day wave is strongly linked to the robust 5–6-day convective variance during March and April identified in Nguyen and Duvel (2008), and

**Fig. 12.** Total column water vapor anomalies (kg m$^{-2}$) (top left) 5 days before, (top center) 4 days before, (top right) 3 days before, (bottom left) 2 days before, (bottom center) 1 day before, and (bottom right) on the day of a westerly 5-day-wave 850-hPa zonal wind anomaly at 60°W on day 0 with a magnitude of two standard deviations of the basis time series. Anomalies are only shown if locally significant at the 95% level.

**Fig. 13.** Climatological-mean daily precipitation (shaded; mm) and 850-hPa horizontal winds (vectors) over equatorial West Africa for the period 1998–2012.
further research the nature of this connection may be instructive.

To determine the pathways of the anomalous moisture seen over the Atlantic coast of central Africa leading to the modulation of convection by the 5-day wave, composites of TCWV anomalies are displayed in Fig. 17. It appears that around 4 days before enhanced rainfall, the westerly wind anomalies of the 5-day wave strengthen the African westerly jet over tropical West Africa and the northern Congo basin, leading to a buildup of anomalous moisture over these areas 3 days before peak westerlies. Furthermore, anomalous up-slope flow on the eastern African highlands leads to a moistening of the atmosphere here, which is strongest 4 days before peak westerlies. Through a combination of uplift to the midtroposphere, where climatological easterlies dominate, and the onset of the easterly phase of the 5-day wave, these moisture anomalies propagate from the northern Congo basin toward the northeastern Gulf of Guinea, and the easterly wind anomalies over the rest of the Congo basin lead to moisture buildup over the rest of the Gulf of Guinea. The weak northward moisture transport anomalies on the same day as peak precipitation anomalies help focus this moisture toward the northeastern corner of the Gulf of Guinea, possibly explaining why more precipitation is observed in this location.

6. Indian Ocean

a. Climatological basic state

Figure 18 shows the mean 850-hPa zonal winds and daily precipitation over the eastern Indian Ocean region. Unlike the other tropical ocean basins, where climatological winds on both the north and south of the convergence zone are easterlies, winds north of 5°S are westerly and south of 5°S are easterly. The low-level westerlies are associated with a zonal circulation with ascending motion over the Maritime Continent and subsiding air over East Africa (Hastenrath 2000, Hastenrath and Polzin 2004).

Mean precipitation above 8 mm day⁻¹ is observed along the 5°S parallel, corresponding to the mean position of the ITCZ. Precipitation over 12 mm day⁻¹ is seen along the western coasts of Sumatra, Thailand, and Myanmar, where onshore westerlies lead to increased coastal rainfall as part of the diurnal cycle of surface heating and circulations along the tropical coasts (Wu et al. 2009). The diurnal cycle of land–sea convection and complex interplays between mesoscale convective systems, convectively coupled equatorial waves, and the Madden–Julian oscillation are involved in observed precipitation patterns over the eastern Indian Ocean.
and Maritime Continent, and this region is widely investigated as part of improving the understanding of tropical convection and its role in the global climate system (Neale and Slingo 2003, Rauniyar and Walsh 2011, Vincent and Lane 2016).

b. Wave effect on local conditions

Time–longitude sections of anomalous rainfall with anomalous 850-hPa zonal winds, MFC, and total column water vapor are shown in Fig. 19. Precipitation anomalies in the eastern Indian Ocean appear in two locations, with different phasings between the zonal wind anomalies and the precipitation: at \( \sim 86^\circ \text{E} \), where enhanced precipitation leads the westerly phase of the 5-day wave by a quarter-cycle, and a stronger precipitation anomaly at 95\(^{\circ}\)E, where enhanced precipitation is almost in phase with the westerly anomalies. The separate behavior of these two areas of precipitation anomalies is further seen in the MFC and TCWV anomalies, where enhanced precipitation at 86\(^{\circ}\)E follows a very weak enhanced MFC anomaly by almost a quarter-cycle but appears in phase with positive TCWV anomalies, while precipitation anomalies at 95\(^{\circ}\)E are roughly in phase with enhanced MFC but lead increased TCWV by around a quarter-cycle. Unlike the other regions explored so far, the seasonality of the precipitation anomalies here is somewhat weak, with JJA showing higher-magnitude anomalies relative to the other seasons (not pictured). This is lack of seasonality is particularly true for the anomalies near 95\(^{\circ}\)E.

Figure 20 displays composites of 950-hPa horizontal wind and MFC anomalies along with precipitation
FIG. 16. Specific humidity (shaded; contoured every $4 \times 10^{-5}$ kg kg$^{-1}$), zonal and vertical winds (vectors), and precipitation anomalies (line plot) averaged between $5^\circ$N and $5^\circ$S (top left) 3 days before, (top right) 2.5 days before, (middle left) 2 days before, (middle right) 1.5 days before, (bottom left) 1 day before, and (bottom right) half a day before a westerly 5-day-wave 850-hPa zonal wind anomaly at $10^\circ$E with a magnitude of two standard deviations of the basis time series. Vertical wind scaling, significance, and topography shading are as in Fig. 6.
anomalies and shows how the differences in behavior between these two areas of precipitation anomalies arise. Enhanced precipitation near 86°E is preceded by positive MFC anomalies, associated with the confluence between easterly anomalies to the north and southeasterly anomalies to the south. As the phase of the 5-day wave becomes westerly, this MFC anomaly persists as a result of convergence between westerly and southwesterly anomalies. This positive MFC anomaly promotes convection, eventually leading to enhanced deep convection half a day before peak westerlies. On the other hand, enhanced convection around 95°E does not appear until the westerly phase of the 5-day wave begins and is associated with low-level MFC anomalies due to deflection of the westerlies over and around Sumatra. This is similar to the process driving the convective anomalies in the upper Amazon; however, it appears along the western edge of Sumatra due to the composite anomalies being on top of

FIG. 17. Precipitation (shaded; mm day$^{-1}$), total column water vapor (contoured every 0.2 kg m$^{-2}$), and total column water vapor flux (vectors) anomalies (top left) 5 days before, (top center) 4 days before, (top right) 3 days before, (bottom left) 2 days before, (bottom center) 1 day before, and (bottom right) the day of a westerly 5-day-wave 850-hPa zonal wind anomaly at 10°E with a magnitude of two standard deviations of the basis time series. Negative contours are dashed and zero contours are not shown. Scalar anomalies only shown if locally significant at the 95% level, and flux anomalies shown if at least one component is locally significant at the 95% level.

FIG. 18. Climatological-mean daily precipitation (shaded; mm) and 850-hPa horizontal winds (vectors) over the eastern Indian Ocean and western Maritime Continent for the period 1998–2012.
the westerly climatological winds, thus modulating the eastward moisture flux toward Sumatra.

7. Western Pacific

a. Climatological basic state

Over the western Pacific Ocean, the winds over most of the region are easterlies; however, the strength of these winds varies over the region (Fig. 21). East of 180°, the winds are strongest about the equator, reaching a maximum of 9.5 m s⁻¹ around 150°W. North of this, a band of slightly weaker easterlies of 7.5 m s⁻¹ is located at 6°N, and winds weaken with increasing distance south of the equator, with magnitude of around 5 m s⁻¹ at 15°S.

b. Wave effect on local conditions

Time–longitude sections of anomalies of 850-hPa zonal wind and precipitation, MFC, and TCWV over the western Pacific are displayed in Figs. 22a–c, respectively. Precipitation anomalies of up to 1.4 mm day⁻¹ are seen near 170°W and 155°E, where enhanced precipitation appears around a quarter-cycle in advance of peak westerly wind anomalies. The enhanced precipitation anomalies east of 180° are almost in phase with positive 850-hPa MFC anomalies; however, on their eastern edge, precipitation lags MFC by approximately half a day. Locally, positive precipitation anomalies appear after dry but before moist TCWV anomalies, suggesting that the modulation of convection anomalously moistens the atmospheric column. Moist anomalies also appear to the east and dry anomalies to the west of enhanced convection associated with the wave at both 170°W and 155°E. However, Fig. 21 also seems to show that the mean total column moisture anomalies associated with the wave west of 165°E seem to propagate westward at a slower propagation rate than the precipitation and low-level zonal wind anomalies as well as the 5-day wave itself, and east of 175°W this westward propagation in TCWV anomalies is also observed. This means there is no consistent phasing between total column moisture anomalies and convective anomalies associated with the wave in this region, and it is not entirely clear what leads to this observed propagation in total column anomalies.

Despite this inconsistent phasing with total column moisture, a different relationship exists between these precipitation anomalies and low-level moisture, as can be seen with 1000-hPa specific humidity in Fig. 23. Positive low-level moisture anomalies appear around a quarter-cycle before enhanced precipitation, although they appear slightly later to the east of the precipitation anomalies. The low-level moisture anomalies correspond closely to the near-surface zonal wind anomalies, with enhanced moisture appearing around 6–12 h after

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**FIG. 19.** Time–longitude plots of precipitation anomalies (shaded; mm day⁻¹) with (a) 850-hPa zonal winds (contoured), (b) 850-hPa MFC (contoured), and (c) TCWV (contoured) anomalies associated with a westerly 5-day-wave 850-hPa zonal wind anomaly at 105°E with a magnitude of two standard deviations of the basis time series, averaged between 5°N and 10°S. Contours are as in Fig. 4.
easterly anomalies in the east of the region and at roughly the same time toward the west of the region.

The close relationship between near-surface zonal wind and humidity anomalies suggests that wind variations due to the 5-day wave affect surface evaporation from the ocean surface in the western Pacific by modulating the magnitude of the climatological easterlies. The horizontal structure of surface latent heat flux variation...
2W m$^{-2}$ are seen in the ITCZ at about 165°W and 165°E. These increased latent heat fluxes persist for around 1.5 days, reaching a maximum magnitude of 4.4 W m$^{-2}$ at 170°W and 5.8 W m$^{-2}$ at 161°E 2.5 days before peak westerly anomalies. The modulation in surface latent heat fluxes affects near-surface moisture and thus the propensity for shallow and deep convection. However, it is unclear why evaporation and latent heat anomalies would appear to localize to these two regions either side of 180° at 5°N when zonal wind anomalies appear over the entire region and the background winds are close to uniform over the region. Furthermore, outgoing longwave radiation anomalies associated with the 5-day wave in this region are occur closer to 180° (King et al. 2015), instead of the locations that show anomalous precipitation. One possible explanation is that surface wind speeds near the precipitation anomalies are also influenced by meridional wind anomalies, as is visible on day –1 in Fig. 24, where northerly anomalies to the north and southerly anomalies to the south of the convergence zone at 165°W coincide with westerly anomalies in the convergence zone.
However, further investigation into this region is required to elucidate why precipitation anomalies associated with the 5-day wave are localized either side of 180°.

8. Discussion and conclusions

The majority of the proposed mechanisms linking precipitation and convection modulation to the 5-day wave in this paper arise from nonuniformity in Earth’s surface topography and climatological basic state, specifically zonal nonuniformities. As such, this suggests why many of these interactions have not been studied much previously. Where external Rossby–Haurwitz waves have been studied, researchers have not looked closely at interactions with Earth’s surface outside of interactions between zonal wind and topography forcing these waves (Cheong and Kimura 1997, 2001). Other studies have investigated the global behavior of the waves and, thus, where they investigated the non-uniform nature of Earth’s surface and the basic state, they looked primarily at variations in the meridional direction while looking at zonal averages (Kasahara 1980, Ahlquist 1982). However, variations in the zonal direction affect how these planetary waves propagate near the surface and lead to convergence and divergence that is sufficiently strong to modulate convection, despite the large-scale convergence being small.

However, it is worth keeping in mind that the level of total precipitation variance attributable to the 5-day wave is rather low—Fig. 2 shows that over the whole year, the level of 6-hourly precipitation variance directly attributable to the 5-day wave is at most 2 mm² day⁻² and comprises only over 0.1% of the total variance in the 6-hourly precipitation for some parts of the regions investigated here in this paper. The variance is less than that from convectively coupled equatorial waves, with the mean variance due to the 5-day wave in the areas investigated here being about 20% of that from either westward or eastward inertio-gravity waves during December–April as found by Guo et al. (2015) when calculated on the same grid.

![Fig. 24. Precipitation (shaded; mm day⁻¹), latent heat flux from surface to atmosphere (contoured every 1 W m⁻²), and 1000-hPa horizontal wind (vectors) anomalies (top left) 3.5 days before, (top right) 3 days before, (middle left) 2.5 days before, (middle right) 2 days before, (bottom left) 1.5 days before, and (bottom right) 1 day before a westerly 5-day-wave 850-hPa zonal wind anomaly at 180° with a magnitude of two standard deviations of the basis time series. Negative contours are dashed and zero contours are not shown. Scalar anomalies only shown if locally significant at the 95% level, and wind anomalies shown if at least one component is locally significant at the 95% level.](image-url)
The modulation of tropical convection associated with the 5-day wave has been known since the 1970s, but mechanisms behind this modulation have remained elusive. Much of the observed modulation appears to be related to interactions between zonal wind anomalies due to the wave, local topography, and local climatological conditions, with different phasings between the zonal wind, moisture convergence, moisture, and precipitation anomalies suggesting the ways these interactions lead to convective modulation. In the upper Amazon, off the Pacific coast of Panama and Colombia near 5°N, and off the western coast of Sumatra, precipitation anomalies occur at about the same time as low-level moisture convergence and zonal wind anomalies, suggesting the modulation of moist zonal flows into the topographic barriers by the 5-day wave leads to the observed convective modulation through moist up-slope flow. Off the coast of Panama and Colombia, anomalous midlevel moisture transports from across the Andes may also play a role.

In the Gulf of Guinea region, however, low-level zonal wind and moisture convergence anomalies associated with the 5-day wave are in near quadrature with the precipitation anomalies, with moisture anomalies being closely aligned to precipitation anomalies. This suggests anomalous transports of warm moist air from both the Congo basin and the low-level African jet modulated by the wave lead to a moistening of the atmosphere over the upper-northeast corner of the Gulf, affecting the convection observed in the region.

Over the western Pacific, 850-hPa zonal wind anomalies also appear to be in near quadrature with precipitation anomalies, and small moisture convergence anomalies slightly lead precipitation. While there is no consistent relationship between column moisture and precipitation anomalies, there is a consistent signal in near-surface moisture leading precipitation by around a quarter-cycle in line with zonal wind anomalies, suggesting the modulation of moist zonal flows into the topographic barriers by the 5-day wave leads to the observed convective modulation through moist up-slope flow. Off the coast of Panama and Colombia, anomalous midlevel moisture transports from across the Andes may also play a role.

The role that the 5-day Rossby–Haurwitz wave has in modulating local convection suggests that any variation in winds in the tropics, regardless of its source, would similarly affect convection in the regions investigated in this study, and that global normal-mode waves may have greater effects on convection than currently thought.

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