On the role of Western North Pacific tropical cyclones in shaping the extratropical circulation response to the Madden-Julian oscillation

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ON THE ROLE OF WESTERN NORTH PACIFIC TROPICAL CYCLONES IN SHAPING THE EXTRATROPICAL CIRCULATION RESPONSE TO THE MADDEN–JULIAN OSCILLATION

by

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PREFACE

The first chapter of this dissertation comprises a published manuscript in its entirety and original wording, referenced herein as Gloeckler and Roundy (2019a). The dissertation author (the primary researcher and first author of the included publication) has obtained written permission from the publisher (the American Meteorological Society) to include this work in the body of the dissertation. The included publication is part of a coherent and appropriately sequenced scientific investigation that culminated in the authoring of this dissertation.
ABSTRACT

Relationships between the Madden–Julian oscillation (MJO) and the extratropical circulation have been leveraged extensively to improve subseasonal prediction. However, in certain situations, tropical cyclones (TCs), which often coincide with enhanced MJO activity, can constructively or destructively interfere with MJO organization and common pathways through which the extratropics responds to the MJO. To examine this potential interference, the first portion of this study leverages a statistical experiment to relate West Pacific TC presence in different parts of the basin during a given MJO phase to subsequent remote extratropical circulation outcomes. The results of this experiment demonstrate that significant, high amplitude remote circulation anomalies that align with or differ from those expected to lag a given MJO phase tend to develop in association with TCs that cluster in specific parts of the basin and at specific leads—in some cases, more than two weeks before a pattern emerges. These spatial and temporal clusters vary between MJO phases.

In the second portion of this study, composite patterns of anomalous 200-hPa geopotential height associated with a set of non-recurving TCs transiting the South China Sea when MJO convection is located over the Maritime Continent and adjacent West Pacific Ocean are examined relative to their full MJO reference patterns through a 200-hPa zonal momentum budget. Zonal wind is linearly decomposed into components that occur on MJO timescales (i.e., 20–100-day periods), as well as those that occur with lower and higher frequency (background and transient timescales, respectively). Composite results suggest that TCs help to accelerate the East Asian subtropical jet that evolves with the MJO by modulating the transient subtropical circulation over Southeast Asia. The phasing of this circulation with its
underlying MJO-timescale (intraseasonal) component enables it to transfer momentum to the emerging subtropical jet. This momentum is integrated into the more slowly evolving flow and carried forward by other processes, which leads to the development of a westerly momentum surge along the subtropical jet that spans the length of the North Pacific Ocean.

The final portion of this study examines the interplay between the intraseasonal zonal wind and transient eddy circulations that are linked in part to the aforementioned set of non-recurving TCs. Results show that these eddies contribute to the poleward shift of an anomalously strong subtropical jet by inducing westerly acceleration on its poleward flank and easterly acceleration on its equatorward flank. These accelerations are facilitated by anomalous meridional momentum transport and convergence thereof. Transient eddies encounter anomalous anticyclonic shear imparted by the background zonal wind as they migrate poleward in tandem with the subtropical jet, which causes them to develop more pronounced southwest–northeast-oriented tilts. This change in eddy tilt further enhances the meridional transport and convergence of momentum, which feeds back onto the subtropical jet by increasing westerly acceleration on its poleward flank and shifting it farther poleward. A feedback loop is thus described between the featured discrete timescale circulation components.
ACKNOWLEDGMENTS

This dissertation marks the culmination of a seven-years-and-change journey through the Department of Atmospheric and Environmental Sciences graduate program at the University at Albany, SUNY. These past years have consisted of many high and low points that have taught me much about my abilities as a scientist, my commitment as a friend, son, and partner, and about how to deal with life’s stresses and hardships. Without the unwavering support and patience of my family, friends, colleagues, and mentors, I suspect I would not have achieved this milestone. To that end, I warmly acknowledge the many wonderful people comprising my support network through the entirety of my graduate studies.

My parents and sister were undoubtedly my biggest advocates through this journey. While sometimes expressing concern about my slow progress, they never hesitated to offer words of encouragement and comfort during times of frustration. My father, in particular, was a steadfast pillar of support. At one point in the distant past, he aspired to obtain a doctorate degree in education, but he never completed his dissertation for fear of forfeiting a prestigious position in the New York State Education Department. He, more than anyone, wanted me to be the first family member to obtain a PhD.

Quality friendships have supplied a great deal of stability to a rather chaotic period in my life. I express gratitude to my close friends, Kevin Tyle and Ross Lazear, for providing unconditional support, many laughs, stimulating conversations, and countless spontaneous adventures over the past decade. From “model watching” and “snarties” during the winter season to hiking, lake swimming, and Control Tower ice cream pit stops on hot summer days, I have always been able to count on these two individuals to help me establish treasured
memories. Even after leaving the Capital Region more than one year ago, I still consider Kevin and Ross to be my closest friends and confidantes.

I am eternally grateful to my loving husband, Artit Kantiya, for tolerating my elevated stress and anxiety as I authored this dissertation over the past year. I cannot imagine how difficult this process would have been without his willingness to perform daily and weekly household chores, cook, and keep our pantry stocked, all while enrolled full-time in several English language programs, volunteering at a local elementary school, and applying for an immigration status change. I intend to return all of these favors to him post-defense. Additionally, I plan to help Artit travel to Thailand to visit his family, from whom he has been absent for more than two years. This is the least I can do in return for everything he has done for me. He is my superhero.

Professional development has been a key focus of mine through most of my graduate studies. I was fortunate to have had the opportunity to collaborate with many talented scientists, mentors, colleagues, and friends at EarthRisk/Riskpulse for the better part of five years. It was through this collaboration that I secured a full-time position as Riskpulse’s sole Customer Success Scientist. Of particular note is my mentor, colleague, and friend, Steve Bennett, who championed my transition to a full-time Riskpulse team member. To Steve: Thank you for supporting my professional and personal growth from the moment we met more than five years ago.

There are many other individuals to whom I owe immeasurable gratitude—my extended family, my former office mates and classmates, my PhD committee members, my world-class professors, my colleagues at the American Meteorological Society, and so on. Although I cannot name every individual who has left a positive imprint on my life, please know that you are not forgotten, and that your influence in my life is greatly appreciated.
As I pause to reflect on this chapter of my life, it is clear to me that the most difficult part of my graduate career involved overcoming self-doubt. I have never considered myself to be an outstanding scientist or researcher, and my work undoubtedly suffered from this mindset. I owe a debt of gratitude to my research advisor, Dr. Paul Roundy, for helping me realize my abilities and hone my strengths, and grow my confidence and self-esteem as a scientist. Paul has expressed patience from the very start of my journey as I struggled to acclimate to the graduate program. He supplied the springboard from which I launched into my own curiosity-driven research and professional pursuits. To Paul: I consider myself very fortunate to have worked with you for almost a decade. You have enabled me to become an independent scientist and have never questioned my judgment along the way. Thank you for allowing me to explore many extracurricular activities during my time as a graduate student under your advisement. Your willingness to set me on an independent course has allowed me to flourish as a scientist and a professional more than I could have ever imagined. I am forever grateful.

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1. A statistical analysis of relationships between western North Pacific tropical cyclones and extratropical circulation patterns accompanying the Madden–Julian Oscillation

1.1 Introduction

Understanding the various pathways through which anomalous moist deep tropical convection modulates higher-latitude atmospheric circulations has been the focus of numerous studies during the past few decades. Many of these studies have examined relationships between the Madden–Julian oscillation (MJO; e.g., Madden and Julian 1971, 1972, 1994; Zhang 2005) and remote anomalous extratropical circulation patterns associated with high-impact weather events. The onset of heat waves and cold air outbreaks (e.g., Cassou 2008; L’Heureux and Higgins 2008; Lin et al. 2009; Zhou et al. 2012; Riddle et al. 2013; Schreck et al. 2013, 2015), the initiation and termination of drought conditions and periods of extreme precipitation (e.g., Higgins et al. 2000; Jones et al. 2004; Donald et al. 2006; Lin et al. 2010; Zhou et al. 2012; Riddle et al. 2013; Moon et al. 2012; Klotzbach et al. 2016), and the organization of severe weather events that produce destructive hailstorms and violent tornadoes (e.g., Barrett and Gensini 2013; Thompson and Roundy 2013; Barrett and Henley 2015) have all been statistically linked to the MJO. Since these impactful events can occur in association with anomalously organized MJO activity, the MJO is not fundamental to their occurrence, so their predictability does not necessarily hinge on its state at any given time. Yet, it has been demonstrated that gains in forecast skill at leads of two to four weeks can accompany periods of enhanced MJO activity, and that skill is generally lower for this same lead window when the MJO is inactive (e.g., Vitart and Molteni 2010; Johnson et al. 2014; Jones et al. 2015). Thus, the MJO has been recognized as a key component in the global monitoring and prediction of periods of extreme and hazardous weather on timescales of weeks to
months, and it remains at the center of continued efforts to understand its influence on the ocean-atmosphere system (Zhang 2013).

Statistical relationships between the MJO and large-scale extratropical circulation patterns are underpinned by studies of physical mechanisms that relate these components of the global circulation. Work presented by Sardeshmukh and Hoskins (1988) demonstrated an association between upper-level divergence linked to anomalous tropical heating (e.g., moist deep convection) and the development of extratropical Rossby wave trains that originate poleward of these heat sources in the vicinity of the Northern and Southern Hemisphere subtropical jets. The strength of the Rossby wave response is modulated by the magnitude of these jets and the sharpness of their associated gradients, and its structure depends upon the mean state flow (and variations thereof) on which it is superimposed (e.g., Jin and Hoskins 1995). Tropical convective heating anomalies, including those that accompany the MJO, vary in location and amplitude, so the manner in which the extratropical circulation responds to these anomalies also varies. L’Heureux and Higgins (2008) and Lin et al. (2009) examined links between northern winter MJO events and the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO). Both studies concluded that the MJO contributes to the variance of these teleconnection patterns by helping to trigger poleward-propagating Rossby waves that project onto them. The latter study also suggested a relationship between Rossby waves that project onto the NAO and Western Hemisphere tropical intraseasonal zonal wind variability, wherein these Rossby waves influence the equatorward propagation of zonal wind signals that may help to organize or disrupt the onset of subsequent MJO events. Schreck et al. (2013) investigated relationships between the MJO and North American temperature variability using a modified version of the Pacific/North American (PNA) pattern. Their results suggested a strong connection between MJO convection, the North Pacific jet and associated wave breaking, and preferred downstream anomalous temperature outcomes. Such large-scale anomalies can sometimes persist for weeks at a time in association with atmospheric blocking, whose frequency is modulated by the MJO (e.g., Moore et al. 2010). Gollan
related enhanced Indian Ocean MJO convection to a significant reduction in blocking frequency across the North Pacific, and enhanced Maritime Continent/West Pacific MJO convection to a significant increase in blocking frequency across much of the Northern Hemisphere. They attributed their results to the placement of diabatic heating anomalies that accompany the MJO, and adjustments in the location and amplitude of the subtropical jet in response to these changes in diabatic heating. They also suggested a relationship between the state of the North Pacific tropospheric circulation, sudden stratospheric warming events, and the onset of blocking at a later time across the North Atlantic and Europe. Such a relationship is consistent with those described by Garfinkel et al. (2012) and Garfinkel et al. (2014), and indicates a possible pathway through which vertically propagating Rossby waves triggered by MJO convection can perturb the stratospheric circulation, yielding a slow downward response that then modulates remote tropospheric circulations.

The MJO accounts for only part of the observed local variability in tropical convection and tropical and extratropical circulation, and its influence on these variables adjusts by location and time of year (e.g., Matthews et al. 2004; Zhang 2005). A number of equatorially trapped wave modes (e.g., Matsuno 1966; Kiladis et al. 2009) exist in conjunction with the MJO, and can modulate its structure and organization. Additionally, these modes of tropical wave activity, along with the MJO itself, can modulate tropical cyclone (TC) frequency across the world’s ocean basins (e.g., Frank and Roundy 2006; Schreck and Molinari 2011; Schreck 2015). Like the MJO, TCs contribute to extratropical flow amplification across different parts of the globe, especially following their propagation out of the tropics and into higher latitudes. Archambault et al. (2015) described physical mechanisms through which western North Pacific recurving TCs help to excite extratropical Rossby wave trains as they impinge upon a meridional potential vorticity gradient draped across the Northwest Pacific Ocean. An upper-level trough situated over East Asia that accompanies a preexisting extratropical Rossby wave train (sometimes the result of prior MJO activity; e.g., Roundy 2014) helps to guide the TCs poleward. This wave train is reinvigorated as TCs interact with the
North Pacific Jet and undergo extratropical transition. While they noted that the extent to which the wave train amplifies and the distance over which it disperses downstream depends on the strength of the interaction, they demonstrated that both strong and weak interactions produce large-scale circulation responses across the North Pacific. Their results were corroborated by Quinting and Jones (2016), who investigated the effects of recurving TCs on the evolution of midlatitude Rossby wave packets through a kinetic energy framework. They concluded that recurving western North Pacific TCs that strongly interact with the midlatitude waveguide as they undergo extratropical transition contribute to jet intensification through strong baroclinic conversion, which yields a strong downstream wave response.

Results from the aforementioned studies reveal similarities with regard to how the extratropical circulation responds to heating anomalies associated with MJO convection and to interactions with TCs. Since TCs occur with such great frequency in conjunction with the MJO, it is natural to suspect that they often influence extratropical circulation responses to MJO convection. The majority of studies that have related the MJO to variations in the Northern Hemisphere large-scale extratropical flow have focused on the Northern Hemisphere (NH) winter season, while comparable TC studies have focused primarily on NH summer and fall. Seasonal differences in the extratropical mean state circulation are associated with different preferred responses to convective forcing, which complicates attempts to synthesize results pertaining to different times of year. Additionally, TC-extratropical flow interaction studies have primarily assessed the contributions of recurving TCs to the development of highly amplified extratropical flow while largely ignoring influences from non-recurving TCs. These research gaps yield an opportunity to conduct a broader evaluation of extratropical flow modulation by combined MJO and recurving and non-recurving TC activity through a statistical framework, which is the focus of this study. Section 1.2 lists utilized datasets and describes the statistical experiment applied herein. Section 1.3 is broken into two primary parts. The first part presents a discussion of statistical relationships between the MJO, West Pacific TCs, and large-scale composite circulations across a region spanning the east-
ern North Pacific Ocean, North America, and the western North Atlantic Ocean. In the second part, composite patterns associated with a set of non-recurring TCs transiting the South China during RMM phase 5 are examined relative to their full RMM phase 5 reference patterns. This set of non-recurring TCs is featured because 1) assessments of the extratropical circulation response to non-recurring TCs are few and far between, 2) RMM phase 5 includes the second-highest count of unique non-recurring TCs during the season and period highlighted in this study, and 3) a statistically significant anticorrelation exists between the RMM phase 5 reference composite and its TC-based subset composite. Following statistical and composite analyses presented in section 1.3, section 1.4 summarizes salient results and provides an overview of future work.

1.2 Data and methods

All analyses herein pertain to NH fall (September–October–November) and cover the period 1979–2012. All anomalies are computed relative to a 1981–2010 climatology.

1.2.1 Data

The Real-time Multivariate MJO (RMM) index (Wheeler and Hendon 2004) was used to identify sets of dates in which the MJO is considered active. The index comprises the leading two principal components (PCs) of combined empirical orthogonal functions of meridionally averaged (15°S–15°N) anomalies of outgoing longwave radiation (OLR), and 200- and 850-hPa zonal wind. These PCs are normalized by their 1979–2001 standard deviations and plotted against one another on an eight-phase diagram in order to approximate the state (both location and amplitude) of the MJO in real time. Conventionally, one standard deviation is designated as the index boundary between active and inactive MJO states. Since this boundary is somewhat arbitrary, it was lowered to 0.5 standard deviations in order to include some lower-amplitude events (e.g., Roundy 2014; Sakaeda and Roundy 2015). Such events include those that experience destructive interference from equatorial waves, but are otherwise coherent in structure. The RMM index tends to emphasize its zonal circulation
component more than its convective component (Straub 2013), but this tendency may add utility in applications evaluating connection between the MJO and circulation features. To assess result sensitivity to the selection of a particular index, one based on MJO-filtered OLR (see Roundy 2014) was applied to an otherwise identical set of analyses. The results obtained from this set of analyses were consistent with those based on the RMM index.

TC position and intensity data were obtained from version 3 (revision 6) of the International Best Track Archive for Climate Stewardship (IBTrACS) dataset (Knapp et al. 2010a,b). IBTrACS combines best-track data from each of the World Meteorological Organization Regional Specialized Meteorological Centers and Tropical Cyclone Warning Centers to form a comprehensive global TC dataset. In addition to storm position and intensity, it contains information regarding storm classification, storm basin, storm name, and many other relevant parameters. The dataset is available for seven ocean basins, and extends as far back in time as 1848. Data were retained for storms in all seven ocean basins that achieved at least tropical storm classification during the period of study.

The state of the large-scale circulation was assessed using 200-hPa geopotential height, zonal wind, and meridional wind data from the Climate Forecast System Reanalysis (CFSR) dataset (Saha et al. 2010a,b) for the period 1979–2010, and from the operational CFSv2 dataset (Saha et al. 2011, 2014) for 2011 and 2012. Data are provided at 6-hourly temporal resolution and 2.5° horizontal resolution. OLR data were used as a proxy for tropical convection, and were obtained from the NOAA interpolated OLR dataset (Liebmann and Smith 1996). Although OLR does not provide a complete representation of tropical convective patterns, it has the advantage of spanning a longer period of time than other similar datasets, thereby increasing its utility to generate meaningful statistics. Anomalies for all variables at each grid point were computed by removing their long-term mean values, along with the first three harmonics of their seasonal cycles (e.g., Roundy 2014).
1.2.2 Event classification

All dates in which the RMM index exceeded 0.5 standard deviations during the season and period of study were used to identify intervals of enhanced MJO activity. These dates were separated into each of the eight RMM phases to further describe the state of the MJO. Each date was then assigned to an event based on how close it occurred to other dates in the list. Dates that occurred within eight days of one another during the same RMM phase were grouped into one event. This event classification scheme acts as a smoother by tolerating gaps between dates caused by short periods of interference associated with the projection of various equatorial waves and other noise onto the index.

This MJO event classification technique does not prescribe a minimum or maximum allowable event length. MJO events featured in this study range from 1 to 27 days in length, with an interquartile range of 2–10 days, and median lengths of between 3 and 6 days, depending on the RMM phase. The majority of short events are of low amplitude (i.e., below one standard deviation). In order to assess the extent to which these short-lived events impact bulk conclusions, results were regenerated after removing them from the analysis. Differences between the two sets of analyses were found to be insignificant, meaning that retaining lower amplitude events yields the benefit of increasing sample size without significantly affecting bulk interpretations.

TC event classification was more straightforward since individual TCs are well defined in the IBTrACS dataset. The only criterion imposed was that each storm had to achieve tropical status (i.e., possess the label TS) during the season and period of study in order to be retained for further evaluation. Events in each basin that met this requirement were grouped into track clusters using the regression mixture model algorithm introduced by Gaffney (2004). The motivation to cluster TC tracks stemmed from the idea that certain groupings of TCs might occur in conjunction with preferred background or intraseasonal convective states (e.g., Camargo et al., 2007b). The algorithm is based on a standard polynomial regression model, and is designed to simultaneously solve for curve (TC track) alignment and clustering.
A thorough review of the track clustering algorithm employed in this study is provided in Appendix A of Camargo et al. (2007a).

The number of track clusters, $K$, was allowed to vary for each basin in order to determine if there was an optimal number on which to base subsequent analyses. Results suggested that $K = 2$, indicating two track clusters per basin, would address the objectives of this study. In the West Pacific basin, for example, $K = 2$ clusters yields a group of TCs that exhibits westward movement across the Philippines, from near 150°E into Mainland Southeast Asia, and another group of TCs that recurves and tracks primarily over and east of Japan. Track clusters in other ocean basins are similarly distinct.

The final step in the event classification process was to identify simultaneous events by finding periods of overlap between the MJO and TCs. Since TCs generally occur on shorter timescales than the MJO, and because they often cover a large geographical area in a short period of time, circular grid point-centered search areas were utilized to generate sets of TCs for each track type. A radius of 7.5° was selected for all searches in this study because it is generally large enough to produce suitable TC sample sizes while allowing for geographical consistency among identified storms. Dates associated with TCs found in each search area were then aligned with active MJO dates and used to generate composites of circulation fields for comparison with those based on the all MJO events without regard for TC presence.

1.2.3 Statistical experiment

This study investigates the extent to which large-scale extratropical circulation patterns associated with the MJO relate to the presence of TCs at different general geographical locations. A statistical experiment that utilizes regional pattern correlations aids in this investigation. The technique, adapted from MacRitchie and Roundy (2016), employs non-
parametric bootstrap resampling and the Pearson correlation coefficient,

\[ r = \frac{\text{cov}(x_1, x_2)}{\sigma_{x_1} \sigma_{x_2}}, \tag{1.1} \]

where \( x_1 \) is a vector of composite geopotential height anomalies derived from a list of all dates constituting a specified RMM phase without regard for TC presence, and \( x_2 \) is another vector of composite geopotential height anomalies derived from blocks of consecutive dates randomly drawn from the same date list included in \( x_1 \) for the purpose of simulating simultaneous MJO and TC events. Before correlations were calculated, geopotential fields were smoothed by applying a 7-day running mean and weighted by the square root of the cosine of latitude to account for the latitudinal change in grid point density per unit surface area.

The experiment was designed to test the null hypothesis (\( H_0 \)) that a composite extratropical circulation pattern generated from a complete list of dates in a given RMM phase (the reference pattern) is as correlated with a pattern generated from a subset of these dates that includes TCs in a circular search area (the TC-based pattern) as it is with a pattern generated from sets of consecutive dates (pseudo-TCs) randomly sampled from its associated date list. Rejection of \( H_0 \) implies that linear associations between the reference pattern and its corresponding TC-based pattern cannot be explained by random chance. In other words, the presence of TCs coincident with the MJO yields more information about subsequent extratropical circulation pattern organization than can be obtained from an assessment of consecutive date blocks randomly selected from the complete MJO date list. Letting \( C \) define a grid point-centered circle of 7.5° radius (hereinafter search radius), and letting \( P \) represent a particular RMM phase, the steps of the statistical experiment (depicted in Fig. 1.1) are:

1. Locate TCs that are present in \( C \) on days in which the MJO is active in \( P \) (Fig. 1.1a).

2. Record the dates in which each TC located in step 1 is present in \( C \) (Fig. 1.1b).

3. For each set of dates recorded in step 2, build a set of the same month-day combinations
4. For each set of null events constructed in step 3, draw $n$ event samples ($n = 1,000$ herein) at random and store them in an $n \times m$ matrix, where $m$ is the number of days included in a particular null event set (Fig. 1.1b).

5. Average a field of choice (anomalous 200-hPa geopotential height is selected for this study) over all dates included in each row of the matrix constructed in step 4 (Fig. 1.1c). Store the results in an $n \times \text{lat} \times \text{lon}$ array (Fig. 1.1d). Refer to these averaged fields as null composites.

6. Compute a weighted average of the same field over all dates in $P$ without regard for TC presence in $C$ (Fig. 1.1d). Refer to the averaged field as the reference composite.

7. Using (1), correlate the reference and $n$-th ($n = 1, 2, \ldots, 1,000$) null composite fields and store the correlations in a vector (Fig. 1.1d). Sort the vector in ascending order, and locate the position of the true correlation (that of the reference composite and its corresponding TC-based composite) along this vector. To assess the null hypothesis at the 95% level, locate the 25th and 975th vector elements, which form boundaries around the middle 95% of the correlation values. If the true correlation lies outside of these boundaries, $H_0$ can be rejected at the 95% level (Fig. 1.1d).

8. Repeat steps 5–7 for all desired time lags. Perform all steps for any search radius that contains at least five TCs of any or all track type(s) during a specified RMM phase.

Weighted averages mentioned in step 6 yield more accurate pattern comparisons because TCs might occur preferentially at a particular time of the season, and the extratropical
response to tropical convection exhibits seasonal variation (e.g., Roundy 2017). Weights are generated according to the number of days in which TCs identified in step 1 are active in each month of the target season. They are then applied to every MJO event forming RMM phase $P$. To illustrate this weighting scheme, consider a set of ten randomly distributed days that include TCs in search radius $C$ during RMM phase $P$. If five of these days occur in September, three occur in October, and two occur in November, then MJO events that occur in September are assigned a weight of 0.5, October events are assigned a weight of 0.3, and November events are assigned a weight of 0.2. For cases in which an MJO event contains an equal number of days in adjacent months, an average of the weights assigned to those months is applied. Lastly, if more than half of an MJO event extends outside of the target season, then the weight assigned to the target season month with which it overlaps is utilized.

According to step 8, a minimum of five TCs per circular search area is recommended because a smaller event sample might not yield enough unique resampled combinations from which to build a representative probability distribution. The number of unique resampled combinations for an $N$-event sample is given by

$$C_N = \frac{(2N - 1)!}{(N - 1)!N!}. \quad (1.2)$$

For example, (1.2) yields 35 unique resampled combinations from four events, while five events produces 126 such combinations. The number of unique resampled combinations grows rapidly with increasing sample size.

1.2.4 Assessment of gridded local significance

Bootstrap resampling was applied to test gridded data for local (grid point) significance. In this application, the composite mean value of an anomaly field at a specified grid point was assessed relative to a set of boundaries that encompass the inner 95% of the probability distribution constructed by resampling the list of events applied to its cal-
A modification to this test was made in order to limit its false discovery rate (FDR)—the expected proportion of rejected null hypotheses that are actually true (Wilks 2006, 2016). Once probability distributions were constructed, p-values associated with the composite mean were estimated from these distributions and sorted in ascending order. A threshold p-value, $p_{FDR}$, was then found using

$$p_{FDR} = \max_{i=1,\ldots,J} \left[ p_{(i)} : p_{(i)} \leq \left( \frac{i}{J} \right) \alpha_{FDR} \right],$$

where $J$ denotes the number of local hypothesis tests, $p_{(i)}$ denotes the $i$-th p-value in the sorted distribution, and $\alpha_{FDR}$ denotes the global (field) test threshold. This threshold value was applied to test the local null hypothesis that the composite mean value in question is not statistically significantly different from zero at the 95% level. Wilks (2016) demonstrated that for fields exhibiting strong spatial correlation, like those evaluated in this study, a better estimation of $p_{FDR}$ can be achieved by multiplying $\alpha_{FDR}$ by two (see their Fig. 4). This correction was thusly applied prior to significance testing. Results show that for any field that exhibits local significance, the global null hypothesis can be rejected. Thus, the presence of any statistically significant local anomaly implies a globally significant anomaly field.

### 1.3 Results

#### 1.3.1 Basic MJO-TC statistical relationships

Composite mean anomalies of 200-hPa geopotential height and OLR are shown for each RMM phase in Fig. 1.2. Anomalies reveal characteristic convective and circulation patterns that evolve with the MJO as it progresses across the Indian and West Pacific Ocean basins. Figs. 1.2a,c,e,g portray the growth of anomalous MJO convection over the Indian Ocean and Maritime Continent. A pair of anomalous upper-level subtropical troughs (blue shading over South Asia and the southern Indian Ocean in Figs. 1.2a,c) flanking MJO convection (enhanced convection is suggested by green contours and semi-transparent green shading, while suppressed convection is suggested by yellow contours and semi-transparent yellow...
shading) are replaced by anomalous upper-level ridges (red shading over the same areas in Figs. 1.2b,d,e,g), signaling the well-documented Matsuno-Gill response to upper-level divergence (divergence is not shown) accompanying an anomalous heat source (e.g., Matsuno 1966; Gill 1980; Jin and Hoskins 1995). Extending poleward and eastward from these subtropical circulation anomalies are alternating anomalous troughs and ridges (shown in blue and red shading, respectively), depicting extratropical Rossby wave trains. These circulation anomalies maintain structure and amplitude even as MJO convection moves eastward and diminishes (Figs. 1.2b,d,f,h).

The fields depicted in Fig. 1.2 are unfiltered, implying that they include variability that spans a spectrum of spatial and temporal scales. This spectrum includes contributions by TCs, whose frequency of occurrence is modulated by the MJO (e.g., Frank and Roundy 2006; Kim et al. 2008; Klotzbach 2010; Zhao et al. 2015). Figure 1.3 reveals this relationship to first-order by showing counts of unique TCs that are present within global search radii (recall that each search radius is fixed to 7.5°) during each RMM phase. RMM phases 1, 2, and 8 (Figs. 1.3a,c,h) are associated with increased TC activity relative to other phases across the eastern Pacific Ocean, adjacent to the western coastline of Mexico. Anomalous low-level westerly wind accompanying the MJO circulation that radiates across the Western Hemisphere (not shown) enhances low-level cyclonic relative vorticity and convergence, and reduces vertical wind shear in this region (e.g., Maloney and Hartmann 2000; Aiyyer and Molinari 2008), favoring TC organization. North Atlantic TC activity exhibits a less pronounced peak, but like the eastern North Pacific signal, it coincides with the arrival of enhanced low-level westerlies accompanying the MJO circulation associated with RMM phases 2, 3, and 4 (Figs. 1.3c,e,g). Western North Pacific TC activity peaks out of phase with the aforementioned Western Hemisphere basins, and this peak is closely related to MJO convective enhancement in this region. When MJO convection reaches the eastern Maritime Continent and adjacent western North Pacific Ocean (Figs. 1.2b,d,g and 3b,d,g), a dramatic increase in TC activity occurs relative to other RMM phases. Anomalous low-level westerly wind and convergence,
reduced vertical wind shear, and large-scale moistening of the troposphere, all of which accompany the convectively active phase of the MJO, produce a more favorable environment for West Pacific TCs to organize (e.g., Frank and Roundy 2006).

In addition to modulating TC frequency across different ocean basins, the MJO can influence TC track by yielding an adjustment to the large-scale mean steering flow. Figure 1.4 approximates ambient steering flow that coincides with RMM phases 2 (Figs. 1.4a,b) and 6 (Figs. 1.4c,d) by displaying mean (Figs. 1.4a,c) and anomalous (Figs. 1.4b,d) 500-hPa streamlines (e.g., Chan and Gray 1982). Large mid-level circulation differences between the two phases exist at all latitudes, and are especially pronounced across Southeast Asia and the northern Maritime Continent. A TC crossing the Maritime Continent during RMM phase 2 would likely encounter anomalous mid-level southwesterly flow between an anomalous mid-level anticyclone to the east of the Philippines and an anomalous mid-level cyclone over South Asia. Such a flow configuration would favor its movement out of the tropics after it passes over the Philippines (Fig. 1.4b). However, a TC moving through this same region during RMM phase 6 would likely encounter anomalous mid-level northeasterly flow between an anomalous mid-level cyclone to the east of the Philippines and an anomalous mid-level anticyclone centered on China. This large-scale flow configuration would favor an east-to-west direction of motion across the Maritime Continent and the South China Sea with limited potential for poleward movement. Because of these large-scale circulation differences associated with the MJO, and their effect on storm motion (e.g., Camargo et al. 2007b; Li and Zhou 2013), TC tracks were grouped into two clusters using the algorithm described in section 1.2.2. Figure 1.5 depicts these track clusters (labeled according to dominant track type), irrespective of RMM phase, for expressly West Pacific TCs (the only TCs considered hereinafter).

Approximately 99% of all West Pacific TCs portrayed in Fig. 1.5 are present on at least one day when the RMM index exceeds 0.5 standard deviations (this figure lowers to approximately 82% when the threshold is raised to one standard deviation), which motivates
their stratification by RMM phase. Figure 1.6 depicts unique non-recurring and recurving TC counts, per RMM phase, in blue and yellow bars. The black curve shows the percentage of days included in each RMM phase (indicated by numbers at the top of the figure axis) on which at least one West Pacific TC was present anywhere in the basin. West Pacific TCs coincide with fewer than 60% of the days included in RMM phases 2 and 3, while they are present on more than 75% of those included in RMM phases 5, 6, and 7. There also exists a distinct relationship between RMM phase and preferred TC track type, which is consistent with MJO modulation of the large-scale steering flow (see Fig. 1.4). According to Fig. 1.6, West Pacific recurving TCs are historically more favored than non-recurring TCs during RMM phases 1 through 5, while non-recurring TCs are more favored during RMM phases 6, 7, and 8. RMM phase 6 possesses an especially strong association with non-recurring TCs, which are over 30% more likely to occur than recurving TCs during this phase.

Figure 1.6 suggests that West Pacific TCs most frequently coincide with the MJO during RMM phase 5. Figure 1.7 presents West Pacific TC density patterns by type for storms that occur simultaneous with this RMM phase. Maps in the left-hand column include all unique TCs of the type referenced in their associated panel titles, while maps in the right-hand column include only storms at left that were present when no TCs of the opposite type existed anywhere in the basin. This distinction is important to consider because one type of TC might exert more influence on extratropical flow organization than another. For example, recurving TCs might interfere with circulation response pathways linked to non-recurring TCs when they impinge upon higher-latitude waveguides. Non-recurring TCs that coincide with RMM phase 5 tend to exist in a fairly narrow latitude band (approximately 30° wide), and there is a strong preference for them to transit the northern South China Sea and make landfall along the Vietnam coastline (Fig. 1.7a). Recurring TC density spans a larger area (especially in latitude), but the largest concentration of this storm track type during RMM phase 5 occurs northeast of the Philippines and south of the main island of Japan (Fig. 1.7c). TC density is reduced by up to a factor of two when TCs of one type that coexisted
with those of the opposite type are removed (Figs. 1.7b,d), yet density patterns maintain spatial consistency with those based on the larger TC samples.

1.3.2 Statistical experiment analysis of relationships between the extratropical circulation and combined MJO-TC activity

Section 1.3.1 demonstrated that West Pacific TC frequency exhibits significant association with RMM phase. Disentangling individual MJO and TC contributions to large-scale extratropical flow organization is challenging, but the statistical experiment described in section 1.2.3 supports this task. This experiment is performed on pairs of composite fields of anomalous 200-hPa geopotential height over a domain spanning the North Pacific Ocean, North America, and the North Atlantic Ocean (hereinafter the North American Domain; Fig. 1.8). Figure 1.9 shows a series of correlations that depict linear associations between these paired fields at various time lags. For each composite pair, the reference pattern consists of all RMM phase 5 days without regard for West Pacific TC presence. This pattern is compared to those generated from sets of RMM phase 5 days that include West Pacific TCs within West Pacific search radii. Every search radius corresponds to a single composite pair. Shading, placed at the center of every search radius containing at least one West Pacific TC, depicts paired pattern correlation coefficients. White dots mark coefficients deemed statistically significantly different at the 95% level from those generated by null (pseudo-TC) events. The prevalence of red shading in Fig. 1.9 suggests spatial consistency between most composite pairs. A shortage of white dots reveals that the presence of any type of TC across most of the West Pacific basin during RMM phase 5 does not yield more information about subsequent upper-level pattern organization across the North American Domain than can be obtained from an assessment of randomly selected blocks of consecutive RMM phase 5 days.

There are some notable exceptions to the previous statement. They manifest as a cluster of white dots revealing statistically significant pattern correlations across the northern
South China Sea at time lags of five, ten, fifteen, and twenty days (Figs. 1.9b–e), and to the east of the Philippines at time lags of fifteen and twenty days (Fig. 1.9d,e). In general, shading in these regions suggests positive linear associations between the examined composite pairs, with the exception being the cluster to the east of the Philippines (Fig. 1.9e). This observation implies that 1) TCs that transit the white dotted regions during RMM phase 5 coincide with or precede the development of upper-level circulation patterns across the North American Domain that exhibit general spatial consistency with the reference pattern, and 2) the circulation outcomes statistically linked to these TCs is not likely to be explained by random chance. Similar linear relationships are revealed after separating TCs by non-recurving (Figs. 1.10a,c,e,g,i) and recurving (Figs. 1.10b,d,f,h,j) track type. In particular, non-recurving TCs that traverse the northern South China Sea are associated with pattern correlations at various lags that differ significantly from those that are generated at random (Figs. 1.10a,c,e). This observation suggests a robust statistical link between the examined TCs and subsequent composite mean pattern outcomes across the North American Domain.

These relationships are further evaluated for sets of West Pacific TCs of each track type that are present when no storms of the opposite type exist anywhere in the basin (Fig. 1.11). As in Fig. 1.10 the prevalence of red shading in the right column of Fig. 1.11 suggests general spatial consistency between the reference pattern and corresponding recurving TC-based patterns. However, patterns associated with non-recurving TCs exhibit some discrepancy with the reference pattern (suggested by blue shading; Figs. 1.11c,e,g), and these differences are most noticeable in association with storms that transit the South China Sea. Additionally, at time lags of five and ten days (Figs. 1.11c,e), a cluster of white dots between the Philippines and Vietnam reveals pattern correlations that are statistically significantly different from those generated by null events. This result suggests that non-recurving TCs that transit the South China Sea during RMM phase 5 might interfere with the expected RMM phase 5 circulation response across the North American Domain.

To broaden the scope of the statistical relationships described in the previous para-
graph, a census of statistically significant pattern correlations is performed for each TC type, RMM phase, and time lag combination. Figure 1.12 displays this census as percentages that are computed relative to the total number of search radii containing at least five West Pacific TCs. TC sets only include storms of a specified track type that were present when no storms of the opposite type existed anywhere in the basin. While statistically significant RMM phase 5 linear pattern associations have already been examined for discrete time lags, teal and turquoise shading across the fifth-from-the-top row in Fig. 1.12 suggests that they span many consecutive days. Furthermore, they are not unique to specific combinations of RMM phase and TC type. Another surprising result is that in some cases, coherent temporal groupings of statistically significant pattern correlations emerge more than two weeks after the composite reference dates (lag zero; e.g., second-from-the-bottom row in Fig. 1.12a). This observation suggests possible delayed circulation responses to TC-related forcing.

Select combinations of TC type, RMM phase, and time lag presented in Fig. 1.12 are translated to plan view form to assess corresponding spatial patterns (Fig. 1.13). The time lag noted at the bottom-right corner of each panel in Fig. 1.13 corresponds to that which possesses the largest RMM phase-relative percentage value as depicted in Fig. 1.12. White dots in each panel generally form large clusters, suggesting a significant systematic association between the MJO, West Pacific TCs, and subsequent North American Domain upper-level pattern organization. In some instances, these circulation patterns evolve comparably to their corresponding reference patterns (e.g., Figs. 1.13d–f), while in other cases, they markedly differ (e.g., Figs. 1.13a–c,g). These results suggest that West Pacific TCs might in some cases augment MJO-forced large-scale extratropical patterns, while in other cases, they might produce destructive interference with these patterns.

1.3.3 Extension of the statistical experiment through a composite illustration

A composite illustration is presented to supplement the statistical analysis in section 1.3.2. It begins by examining correlation coefficients (black curves) overlaid on null correla-
tion distributions (box plots) for two paired fields of composite mean 200-hPa geopotential height anomalies (Fig. 1.14). Each correlation assessment is confined to the North American Domain and is performed for the period twenty days before to twenty days after the paired composite reference dates (lag zero). The reference composite consists of all RMM phase 5 days. Subsets thereof that include 1) non-recurving TCs within a 15°N, 115°E-centered search radius (Fig. 1.14a), and 2) recurving TCs within a 20°N, 135°E-centered search radius (Fig. 1.14b), are used to generate comparison patterns. Both TC sets only include storms of the specified track type that are present when no storms of the opposite type exist anywhere in the basin. In both Fig. 1.14 panels, for all days leading lag zero, correlation coefficients overlap with the middle 95% of their corresponding null distributions (enclosed by whiskers). This result indicates that no linear pattern relationships are statistically distinguishable from random chance across this time period. However, between five and thirteen days after lag zero, non-recurving TC-based correlations fall outside of their associated null distribution confidence intervals (Fig. 1.14a). This result suggests a possible physical relationship between the non-recurving TCs and subsequent North American Domain large-scale pattern organization that cannot be confidently described by random chance.

To further understand the suggested physical linkages between the featured set of non-recurving TCs and the large-scale extratropical circulation, longitude-time diagrams of 45°N–60°N-averaged 200-hPa meridional wind anomalies are displayed in Fig. 1.15. Panels compare non-recurving TC-based (Fig. 1.15a) and reference (Fig. 1.15b) composite anomalies, and show differences between the two fields (Fig. 1.15c). Alternating upper-level northerly (blue) and southerly (red) wind anomalies reveal extratropical troughs and ridges that form Rossby wave trains. Fig. 1.15 suggests that large differences between the two composites emerge poleward and eastward of the non-recurving TC search radius (its center in time and longitude is indicated by a red TC symbol). These differences then propagate downstream in association with Rossby wave dispersion (indicated in Figs. 1.15b,c by eastward-expanding blue and red shading), and arrive in the North American Domain.
Their arrival precedes the statistically significant signal in 200-hPa geopotential height (Fig. 1.14a) by two to three days.

Figure 1.16 better illustrates the association between non-recurving TCs and extratropical Rossby wave excitation by displaying pentad means of irrotational wind, potential vorticity (PV) advection by the irrotational wind, and geopotential height anomalies, all analyzed at 200 hPa. In both composites, irrotational wind anomalies suggest broad anomalous upper-level divergence accompanying moist deep MJO convection (not shown). Anomalous irrotational wind is most pronounced in each composite in the middle pentad and is stronger in association with non-recurving TCs (Figs. 1.16d–f). Fig. 1.16f implies enhanced outflow (larger irrotational wind anomalies) in the non-recurving TC-based composite relative to that in the reference composite, and this signal encircles the TC search radius. Poleward of anomalous irrotational wind in the left and middle columns are bands of blue shading. This shading depicts poleward advection of low PV air, which is stronger in the non-recurving TC-based composite (Figs. 1.16i). Upper-level subtropical ridge anomalies (solid black contours) amplify proximate to maxima in poleward PV advection (Figs. 1.16d,e,g,h), but the non-recurving TC-based composite anomaly achieves higher amplitude (Figs. 1.16f,g,i). An anomalous upper-level trough emerges to the northeast of the subtropical ridge anomaly in the non-recurving TC-based composite (Figs. 1.16g,i), implying a Rossby wave response. That this response exhibits clear association with TC presence and achieves greater amplitude in the non-recurving TC-based composite supports the claim that random chance is unlikely to explain the associated geopotential height signal presented in Fig. 1.14a.

Figure 1.17 summarizes the large-scale pattern progression by displaying pentad means of anomalous 200-hPa geopotential height. Columns compare non-recurving TC-based (Figs. 1.17a,c,e,g) and reference (Figs. 1.17b,d,f,h) composite anomalies, and each row represents a composite pair. Hatching depicts paired anomalies that are statistically significantly different from one another at the 95% level. General spatial consistency between the two composites is
evident in the first pentad (Figs. 1.17a,b). The greatest pattern differences at this time lag, which arise across East Asia and the western North Pacific Ocean, generally correspond to amplitude rather than phase shift. This result conforms to the idea of a stronger TC-based Rossby wave response that is otherwise spatially consistent with that in the reference composite. Large structural differences emerge across the North American Domain (delineated by the black box in each panel) in the subsequent two pentads (Figs. 1.17c–f), with hatching highlighting opposite-signed anomalies (i.e., 180° phase shifts). This period coincides with the statistically significant geopotential height signal portrayed by the correlation time series in Fig. 1.14a. Composite geopotential height anomalies remain largely out of phase with one another through the final pentad (Figs. 1.17g,h), but to a lesser extent than in the preceding two pentads (the primary exception being over Alaska).

1.4 Conclusions and future work

A statistical experiment was conducted to assess the extent to which large-scale extratropical circulation patterns that accompany the MJO relate to TC presence in general geographical locations. The experiment, adapted from MacRitchie and Roundy (2016), examined linear associations between paired fields of composite 200-hPa geopotential height anomalies by computing the Pearson correlation coefficient for each pair. All composite pairs associated with a specified RMM phase featured the same reference pattern that was generated from the complete list of dates corresponding to that phase. Subsets of these dates that included TCs within circular search areas of 7.5° radius (referred to in section 1.3 as search radii) were applied to generate TC-based comparison patterns. All pattern pairs were assessed over a domain spanning the eastern North Pacific Ocean, North America, and the western North Atlantic Ocean (referred to in section 1.3 as the North American Domain; see Fig. 1.8).

The statistical experiment tested the null hypothesis \(H_0\) that a reference composite pattern is as correlated with a corresponding TC-based pattern as it is with a pattern
generated from sets of consecutive dates (pseudo-TCs) randomly sampled from its associated date list. Null correlation distributions were generated from these randomized pseudo-TC sets (see section 1.2.3 for a step-by-step explanation of null distribution generation). If the true paired composite correlation lay outside of the middle 95% of values in its corresponding null distribution, then $H_0$ could be rejected at the 95% confidence level. Rejection of $H_0$ implies that the true correlation between the reference pattern and its corresponding TC-based pattern cannot be explained by random chance. One might interpret this result to suggest that TCs included in the TC-based pattern constructively or destructively interfere (depending on the sign of the true correlation) with the extratropical circulation response to MJO convection.

The statistical algorithm was applied to numerous MJO and West Pacific TC event combinations. RMM phase 5 was selected to demonstrate relationships between the MJO, TCs, and subsequent extratropical circulation pattern outcomes because it is historically (over the period of study; 1979–2012) associated with the highest count of unique West Pacific TCs during NH fall (Figs. 1.3b, 6). In general, paired RMM phase 5 composite patterns exhibited positive linear associations (positive correlations), and the majority of these linear relationships were not statistically significantly different from random chance (Fig. 1.9). This result implies that in most cases, TCs that accompany a convectively active RMM phase 5 MJO event are not any more physically relevant to the organization of associated large-scale extratropical circulation patterns than other transient disturbances that occur simultaneous with this phase of the MJO. In these instances, MJO convective forcing likely dominates the progression of the large-scale extratropical circulation.

RMM phase 5 composite pattern relationships were further examined for sets of TCs grouped by dominant track type (i.e., non-recurving and recurving). These sets included all TCs of a specified track type and subsets thereof that featured no overlap with any TCs of the opposite track type (e.g., non-recursing TCs that were present when no recurving TCs existed anywhere in the basin). Consistent with the non-track-type-constrained assessments, most
pattern pairs exhibited positive linear relationships (Fig. 1.10). However, some inverse linear relationships (negative correlations) were observed in association with paired composites featuring sets of non-recurving TCs in the South China Sea when no recurving TCs existed anywhere in the West Pacific basin (Figs. 1.11c,e). A composite pair was selected from this group for further evaluation as a means to better understand the origin of this inverse linear signal. The TC-based pattern belonging to this pair featured a stronger (higher amplitude) extratropical Rossby wave response than its RMM phase 5 reference pattern (Fig. 1.15). The strength of the Rossby wave response was linked to enhanced upper-level divergent wind and associated PV advection poleward of the composite TC (Fig. 1.16). Downstream Rossby wave dispersion in both composites evolved into opposite-signed circulation anomalies across the North American Domain (Figs. 1.17c–h), suggesting that TC presence was associated with long-lived pattern interference.

The results presented herein provide only a partial assessment of relationships between the MJO, TCs, and the organization of large-scale extratropical circulation patterns. Analyses were limited to a small region of the extratropical Northern Hemisphere, and only West Pacific TCs were addressed in the context of extratropical circulation outcomes that accompany the MJO. Since the MJO modulates TC frequency across all ocean basins (see Fig. 1.3; e.g., Frank and Roundy 2006; Zhang 2013), TCs outside of the West Pacific basin will be incorporated into future statistical analyses. Additional regions over which to evaluate composite circulations (e.g., Europe; East Asia; the Northern Hemisphere) will also be considered, as will other seasons.

Another subject of ongoing work relates to better understanding the physical linkages between TCs that coincide with the MJO and the organization of remote large-scale extratropical circulation patterns that align with or diverge from expectation (i.e., the pattern generated from the full list of dates in a given RMM phase without regard for TC presence). Preliminary work suggests that such physical linkages vary according to TC type, TC placement, and RMM phase, which complicates attempts to synthesize and generalize
these relationships. It also remains unclear as to whether TCs themselves physically interfere (constructively or destructively) with MJO-forced circulation patterns, or if they act as proxies to other sources of large-scale interference (e.g., Hart 2011). One way to assess these physical relationships is through a zonal momentum budget analysis, similar to the one presented by Sakaeda and Roundy (2015). Their study examined the relationship between Western Hemispheric tropical upper-level zonal wind and subsequent MJO organization in the Indian Ocean basin. They demonstrated that the upper-level zonal wind signals that precede MJO onset are an amalgamation of circulation anomalies that possess varying characteristic spatial and temporal scales, and they were able to quantify the extent to which each of these circulation anomalies contributes to the larger signal. Their work exemplified the utility of a zonal momentum budget in relating disparate components of the large-scale circulation, which is an objective of subsequent work that connects the MJO, TCs, and the extratropical flow.
1.5 Figures

Figure 1.1: A schematic depiction of the steps employed in the statistical experiment described in section 1.2.3. RMM phase 5 is used for illustration.
Figure 1.2: Composite anomalous 200-hPa geopotential height (shaded according to scale in gpm) and OLR (green and yellow contours and semi-transparent shading; contours are drawn at $\pm 10 \text{ W m}^{-2}$; green contours and shading suggest active convection) for each RMM phase. Statistically significant geopotential height anomalies are stippled. All depicted OLR anomalies are statistically significant. The total number of discrete MJO events and days included in each RMM phase is noted in each panel title. All patterns and statistics presented here and in subsequent figures pertain to Northern Hemisphere fall (September–October–November) and the period 1979–2012.
Figure 1.3: Counts of unique TCs (tropical storm or greater strength) present within grid point-centered search radii (recall that every search radius is $7.5^\circ$; radial boundaries are not shown). Counts are stratified by RMM phase.
Figure 1.4: (a),(c) Mean and (b),(d) anomalous 500-hPa streamlines corresponding to RMM phases (a),(b) 2 and (c),(d) 6. Streamlines are shaded according to wind speed (m s$^{-1}$).
Figure 1.5: West Pacific TC tracks grouped by (a) non-recurving and (b) recurving type. Groups were generated by the track clustering algorithm described in section 1.2.2. Tracks are plotted without consideration for RMM phase.
Figure 1.6: A breakdown of unique West Pacific TC counts by assigned track cluster and RMM phase. Blue bars depict non-recurving TC counts and orange bars depict recurving TC counts. Filled black circles connected by the solid black curve represent percentages of days per RMM phase on which any type of West Pacific TC was present. Numbers at the top of the figure axis indicate the number of days included in each RMM phase.
Figure 1.7: Counts of any (a) non-recurving and (c) recurving West Pacific TCs that were present during RMM phase 5 within grid point-centered search radii. (b),(d) As in (a),(c), except for only West Pacific TCs of the track type indicated in the corresponding panel titles that were present when no West Pacific TCs of the opposite track type existed anywhere in the basin.
Figure 1.8: Fields of anomalous 200-hPa geopotential height displayed for illustrative purposes ten days after their corresponding RMM phase 5 composite events. The top panel depicts the RMM phase 5 reference pattern, while the bottom panel depicts the pattern consisting of RMM phase 5 days that included non-recurving TCs within a 7.5° search radius centered on 15°N, 115°E when no recurving TCs existed anywhere in the West Pacific basin (this is the TC-based pattern). Together, these patterns form a paired composite. The region over which these patterns are displayed—a box bounded by 20°N–70°N, 170°W–40°W—is referred to as the North American Domain throughout section 1.3.
Figure 1.9: Pearson correlation coefficients (shaded according to scale) calculated for paired fields of composite 200-hPa geopotential height anomalies confined to the North American Domain (see Fig. 1.8). Each composite pair includes a reference pattern and a TC-based comparison pattern. Here, reference patterns comprise all RMM phase 5 days, and TC-based patterns comprise RMM phase 5 days that include West Pacific TCs of any track type within grid point-centered search radii. Correlation coefficients are shaded at the center of their corresponding search radii. Correlations that are deemed statistically significantly different at the 95% level from those generated by corresponding null (pseudo-TC) events are marked with white dots. The black polygon that encompasses part of the shaded region in each panel marks the boundary between search radii that contain at least five TCs, and those that contain fewer than five TCs.
Figure 1.10: As in Fig. 1.9, but for (a),(c),(e),(g),(i) any non-recurving West Pacific TC and (b),(d),(f),(h),(j) any recurving West Pacific TC.
Figure 1.11: As in Fig. 1.9, but for (a),(c),(e),(g),(i) only non-recurving West Pacific TCs and (b),(d),(f),(h),(j) only recurving West Pacific TCs that were present when no West Pacific TCs of the opposite type existed anywhere in the basin.
Figure 1.12: A census of statistically significant paired pattern correlations per RMM phase, West Pacific TC type, and time lag combination. Numbers overlaid on shading depict percentages of correlations deemed statistically significantly different from random chance. Percentages are computed relative to the number of search radii that contain at least five (a) non-recursing and (b) recursing West Pacific TCs when no West Pacific TCs of the opposite type existed anywhere in the basin.
Figure 1.13: As in Fig. 1.9 but with reference to the West Pacific TC type and time lag that feature the largest percentage value for each RMM phase as depicted in Fig. 1.12. RMM phase and TC type are indicated in each panel title. The number in the bottom-right corner of each panel indicates the associated time lag.
Figure 1.14: Lagged evolutions (±20 days) of Pearson correlation coefficients (solid black line) calculated for paired fields of composite 200-hPa geopotential height anomalies confined to the North American Domain (see Fig. 1.8), and associated null correlation distributions (box plots). Each composite pair includes a reference pattern and a TC-based comparison pattern. Here, reference patterns comprise all RMM phase 5 days, and TC-based patterns comprise RMM phase 5 days that include (a) non-recurving West Pacific TCs present within a 15°N, 115°E-centered search radius, and (b) recurving West Pacific TCs present within a 20°N, 135°E-centered search radius. Both TC sets include only West Pacific TCs that were present when no West Pacific TCs of the opposite type existed anywhere in the basin. For each null distribution, median values are marked with horizontal black lines, the middle 50% of values are spanned by a colored box, whiskers extend to the 2.5th and 97.5th percentile values (depicting 95% confidence intervals), and gray plus signs lie outside of the 2.5th and 97.5th percentile values. Correlations not enclosed by their associated confidence intervals (indicating statistical significance) are marked with unfilled black circles. The red TC symbol in each panel marks the composite reference time lag (lag zero).
Figure 1.15: Longitude-time diagrams of 45°N–60°N-averaged composite 200-hPa meridional wind anomalies (shaded according to scale in m s⁻¹). Anomaly fields comprise (a) all RMM phase 5 days that include non-recurving West Pacific TCs within a 15°N, 115°E-centered search radius when no recurving West Pacific TCs were present anywhere in the basin (24 events [69 days] included), and (b) all RMM phase 5 days without regard for TC presence (72 events [468 days] included). The result of subtracting the middle panel from the left panel is shown in (c). MJO events included in (b) are weighted according to the technique described in section 1.2.3. Red TC symbols in (a) and (c) mark the center of the TC search radius in time and longitude. Vertical dashed black lines denote the longitudinal boundaries of the North American Domain (see Fig. 1.8). Statistically significant anomalies are outlined in solid black contours. Note that the contour interval in panel (b) is half that in panels (a) and (c).
Figure 1.16: Lagged pentad-mean 200-hPa potential vorticity (PV) advection by the irrotational wind (shaded according to scale in PVU day$^{-1}$; 1 PVU = $10^{-6}$ K kg$^{-1}$ m$^{2}$ s$^{-1}$), irrotational wind (vectors in m s$^{-1}$; only values exceeding 1 m s$^{-1}$ are plotted in the first two columns, and only statistically significant values are plotted in the third column; reference vectors are located above the top-left corner of each top-row panel), and geopotential height anomalies (black solid and dashed contours in gpm; solid contours indicate positive values; contour interval is 15 gpm, beginning at ±15 gpm). Each pentad is represented by a row, and all time lags included in each pentad are labeled along the y-axis of their corresponding left-column panel. Columns are ordered as in Fig. 1.15. MJO events included in the middle column are weighted according to the technique described in section 1.2.3. Statistically significant geopotential height anomalies are hatched, and statistically significant values of PV advection (third column only) are stippled. Red TC symbols in (d) and (f) mark the grid point at the center of the search radius used to identify TCs at lag zero.
Figure 1.17: Lagged pentad-mean 200-hPa geopotential height anomalies (shaded according to scale in gpm). Anomalies depicted in (a),(c),(e),(g) comprise all RMM phase 5 days that feature non-recurving West Pacific TCs within a 15°N, 115°E-centered search radius when no recurving West Pacific TCs existed anywhere in the basin. (b),(d),(f),(h) depict anomalies that comprise all RMM phase 5 days without regard for TC presence. Each pentad is represented by a row, and all time lags included in each pentad are labeled along the y-axis of their corresponding left-column panel. Each row represents a composite pair. MJO events included in the right-hand column are weighted according to the technique described in section 1.2.3. Hatching enclosed by solid black contours identifies paired composite values that are statistically significantly different from one another at the 95% level. The black box drawn in each panel outlines the North American Domain. The red TC symbol in panel (a) marks the grid point at the center of the search radius used to identify TCs at lag zero.
2. An assessment of non-recurving western North Pacific tropical cyclone contributions to anomalous large-scale extratropical circulations that evolve with the Madden–Julian oscillation

2.1 Introduction

Many studies that are concerned with evaluating the variability of the tropical atmosphere have revealed significant associations between the Madden–Julian oscillation (MJO; e.g., Madden and Julian 1994; Zhang 2005) and an array of tropical modes that exhibit different characteristic spatial and temporal scales. Among the more widely studied of these relationships is that of the MJO and tropical cyclones (TCs). The MJO is characterized by an eastward propagating large-scale coupling of anomalous moist deep tropical convection and circulation that evolves over periods spanning approximately 20–100 days (Roundy 2012), and it extends zonally up to 10,000 km (Matthews et al. 2013), yielding a planetary scale (zonal wavenumbers 1–2) footprint. MJO convection usually achieves its greatest amplitude over the tropical Indian and western Pacific Ocean basins, where it couples to the warmest sea surface on the planet (Zhang 2005). Outside of these basins, where sea surface temperatures (SSTs) are generally lower and less able to sustain organized tropical convection, its broad circulation dominates its structure, and this circulation radiates eastward across the Western Hemisphere at a higher velocity than when it is coupled to convection.

The MJO effectively modulates large-scale circulation, temperature, and moisture profiles across the domain through which it propagates, and because of its global reach, these effects are not limited to a particular part of the tropics. Its effect on its environment influences TC organization across various ocean basins. Liebmann et al. (1994) examined physical links between the MJO and Indian Ocean and western Pacific Ocean TCs. They found that TC frequency in both basins is increased during the convectively active phase of the MJO, but that the ratio of mature storms to those less organized remains unchanged.
relative to periods of convective suppression. They related enhanced TC activity to the
development of low-level cyclonic relative vorticity and convergence anomalies westward and
poleward of enhanced MJO convection. Short periods of highly anomalous low-level westerly wind, termed westerly wind bursts, can accompany the MJO as it amplifies over the
West Pacific Warm Pool, and these anomalous westerly wind events have been linked to TC
genesis (often manifesting as twin cyclones about the equator) in this region (Keen 1982,
(2000) evaluated relationships between the MJO and western North Pacific TCs through a
barotropic wave activity flux framework. Their results demonstrated enhanced wave activity
convergence (wave accumulation) in association with active West Pacific MJO phases. 

As precursor disturbances cross the western North Pacific basin during a favorable MJO
phase, low-level flow convergence accompanying enhanced convection in this region can help
to amplify these disturbances and increase their likelihood of undergoing cyclogenesis. 

Relationships between the MJO and TC frequency have also been documented in other
ocean basins. Maloney and Hartmann (2000) presented evidence linking low-level westerly
wind anomalies and associated anomalous low-level cyclonic relative vorticity accompanying
the westerly phase of the MJO to a fourfold increase in eastern North Pacific TC occurrence
relative to periods that are dominated by its easterly phase. Aiyer and Molinari (2008)
demonstrated an association between the MJO and preferred barotropic eddy growth states
over the Gulf of Mexico and eastern North Pacific Ocean, wherein the MJO influences the
spatial distribution of eddy growth activity, and TCs tend to organize where this growth
is maximized. They showed that during convectively inactive MJO phases, eddy growth
tends to be most concentrated across the eastern North Pacific Ocean, but it expands to
the Gulf of Mexico when MJO convective activity increases. Barrett and Leslie (2009)
found a statistically significant link between North Atlantic TC occurrence and frequency of
landfall, and the phase of the MJO. They reasoned that the MJO increases the likelihood
of TC formation and intensification across this ocean basin by enhancing large-scale upper-
tropospheric divergence as its circulation transits the Western Hemisphere. Klotzbach (2010) noted important relationships between the MJO, vertical wind shear, and relative humidity across the North Atlantic basin, and applied these relationships to investigate MJO influence on North Atlantic TC activity. He reported that during phases 1 and 2 of the Real-time Multivariate MJO (RMM) index (Wheeler and Hendon 2004), vertical wind shear values across the North Atlantic basin (including across the Main Development Region [MDR], where the bulk of North Atlantic TCs form) are as much as 4 m s\(^{-1}\) weaker than during RMM phases 6 and 7. This favorable large-scale environmental modification accompanying the westerly phase of the MJO was associated with a threefold increase in major North Atlantic hurricanes and major hurricane days across the MDR relative to peak easterly MJO phases (RMM phases 6 and 7) during the period of study. Camargo et al. (2009) developed a global TC genesis potential index to quantify the extent to which different environmental variables modulated by the MJO contribute to the likelihood of TC formation. They reported that the MJO primarily contributes to TC genesis through its effect on mid-level relative humidity, and secondarily through its effect on low-level absolute vorticity.

The aforementioned studies highlight significant physical and/or statistical relationships between the MJO and TCs across different regions of the global tropics. Yet, little work has been done to assess these relationships in the context of the global circulation. Both modes of tropical variability effectively modulate the large-scale extratropical circulation. For example, the MJO has been linked to the establishment of anomalous temperature and precipitation patterns that occur across different regions of the extratropical Northern and Southern Hemispheres (e.g., Higgins et al. 2000; Jones et al. 2004; Donald et al. 2006; L’Heureux and Higgins 2008; Riddle et al. 2013; Zhou et al. 2012; Matsueda and Takaya 2015; Schreck et al. 2015; Alvarez et al. 2016) via Rossby wave train excitation poleward of its convective envelope (e.g., Lukens et al. 2017). TCs have been connected to similar sets of anomalous circulation outcomes through their roles in initiating periods of highly amplified extratropical flow (e.g., Cordeira and Bosart 2010; Archambault et al. 2013; Parker et al. 2014;...
The prevalence of TCs in association with the MJO suggests that they can affect the extratropical response to MJO convective forcing for varying periods of time, whether by moving out of the tropics and interacting directly with higher-latitude waveguides, modulating the spatial distribution of anomalous convection associated with the MJO, a combination thereof, or through additional pathways. Gloeckler and Roundy (2019a) performed a statistical analysis featuring correlations of anomalous 200-hPa geopotential height to evaluate associations between western North Pacific TCs and MJO-related large-scale pattern organization across a domain centered on North America. Their goal was to identify instances in which these TCs are associated with extratropical circulation outcomes that align with or diverge from those that are expected to occur in conjunction with a particular MJO convective forcing state, and to assess whether those outcomes are distinguishable from random chance. They found that, for certain combinations of MJO and TC activity, TC presence is associated with a subsequent circulation response that is unlikely to be randomly reproduced. However, their assessments were primarily statistical in nature, leaving room for physical attribution studies.

Since the MJO and TCs generally occur on different timescales, quantifying their mutual contributions to the development of large-scale intraseasonal circulation anomalies can be challenging. This study employs a zonal momentum budget following the methods of Sakaeda and Roundy (2015) to examine TC influence on the evolution of the intraseasonal extratropical circulation during Northern Hemisphere fall. Relevant budget terms are averaged over a set of MJO dates that features non-recurving TCs in a specified search radius centered on a South China Sea grid point, and resulting zonal wind accelerations are compared to those that are based on the full population of MJO dates from which the TC-based date set is derived in order to highlight differences that relate to TC presence. Section 2.2 provides an overview of data and describes the momentum budget methodology, and section 2.3 presents salient results. Finally, section 2.4 offers conclusions and offers suggestions for future work.
2.2 Data and methods

2.2.1 Data and event identification

The bulk of the large-scale circulation analysis for this study was accomplished using 200-hPa geopotential height, zonal, and meridional wind data from the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010a,b) dataset for the period 1979–2010, and an archive of the operational Climate Forecast System version 2 (CFSv2; Saha et al. 2011, 2014) for the period 2011–2012. CFSR and CFSv2 data were obtained from the National Center for Atmospheric Research (NCAR) Computational and Information Systems Lab (CISL) Research Data Archive (RDA). The data were provided on a 2.5° horizontal grid spanning the full globe, and at 6-hourly time intervals corresponding to 0000, 0600, 1200, and 1800 UTC. Daily averages of each variable were computed, and anomalies were generated by removing the long-term (1981–2010) mean and the first three harmonics of the seasonal cycle at each grid point.

MJO events were identified using the event classification scheme described by Gloeckler and Roundy (2019a). Briefly, dates during boreal fall (September–October–November) and the period of study (1979–2012) in which the amplitude of the Real-time Multivariate MJO (RMM) index (Wheeler and Hendon 2004) exceeded 0.5 standard deviations were identified. One standard deviation is commonly set as a threshold to distinguish between periods of time in which the MJO is active (greater than this threshold) and inactive (less than or equal to this threshold), but this selection is arbitrary. Gloeckler and Roundy (2019a) noted that their results based on this lower threshold were not statistically significantly different from those obtained by raising the threshold to the conventional value of one standard deviation, and thus advocated for the use of a lower threshold to increase sample size. After a list of dates was compiled, MJO events for each phase of the RMM index were constructed by finding sets of dates that occurred within 8 days of one another during the same RMM phase.

TC events were identified using version 3 (revision 6) of the International Best Track Archive for Climate Stewardship (IBTrACS) dataset (Knapp et al. 2010a,b). IBTrACS
provides storm position, intensity, classification, basin, name, and several other relevant parameters pertaining to TCs that occurred worldwide beginning in 1848. TCs that achieved at least tropical storm (TS) strength during the season and period of study were stratified by the curve clustering algorithm employed by [Gloeckler and Roundy (2019a)] and retained for further examination. Finally, the refined list of TCs was binned into geographical groups by constructing a 7.5° search radius around each grid point across the global domain. These groups aid in the identification of storms that occur proximate to one another during a specified RMM phase.

### 2.2.2 Zonal momentum budget procedure

The zonal momentum budget employed in this study follows the procedure outlined by [Sakaeda and Roundy (2015)]. Budget analysis begins with an equation to calculate the local zonal wind tendency on isobaric surfaces:

$$\frac{\partial u}{\partial t} = - \mathbf{v} \cdot \nabla u - \frac{\partial \Phi}{\partial x} + f v + \frac{u v \tan \phi}{a} + X,$$

(2.1)

where $\mathbf{v} = \langle u, v, \omega \rangle$, $\Phi$ represents geopotential at constant pressure, $f$ is the Coriolis parameter, $\phi$ represents latitude, $a$ represents the radius of the earth, and $X$ includes the sum of all terms whose contributions to the intraseasonal (20–100-day) zonal wind tendency are considered negligible (i.e., Coriolis torque on the vertical wind, the vertical curvature term, friction, vertical diffusion zonal acceleration, and convective zonal momentum mixing acceleration), along with a residual. The second-to-last term on the right-hand side (RHS) of (2.1) is brought about by Earth’s curvature. [Sakaeda and Roundy (2015)] included this curvature term in $X$ because it represents a quantity that is vanishingly small near the equator where their study was focused, but it becomes non-negligible at higher latitudes when assessed on intraseasonal timescales.

Each term on the RHS of (2.1) is linearly decomposed into three temporal bands by first applying a Fourier transform, then zeroing out the resultant coefficients that are not included...
in the specified band, and finally applying an inverse transform to these coefficients. Bands encompass background (periods exceeding 100 days; denoted by an overbar), intraseasonal (denoted by an asterisk), and transient (periods less than 20 days; denoted by a prime symbol) timescales, and they yield the original total field when summed:

$$u = \bar{u} + u^* + u'.$$  \hspace{1cm} (2.2)

Consistent with Sakaeda and Roundy (2015), the background state includes the long-term average, low-frequency variability like the El Niño–Southern Oscillation, as well as the seasonal cycle.

Following linear decomposition, an intraseasonal bandpass filter is applied to the terms $-\mathbf{v}^* \cdot \nabla u^*$ and $-\mathbf{v}' \cdot \nabla u'$, which project onto the intraseasonal band in addition to shorter and longer timescales. The need to post-filter these terms relates to their inclusion of non-constant variable products (e.g., the product of $u'$ and $\partial u'/\partial x$), which can yield output that projects onto higher and lower frequencies due to the inherent nonlinearity of these operations, along with the intention to assess contributions of these features to the intraseasonal band. Terms like $-\mathbf{v}^* \cdot \nabla u'$ do not contribute to intraseasonal zonal wind tendency because intraseasonal variables like $\mathbf{v}^*$, which are roughly constant on transient timescales, act to amplify transient variables like $u'$ without changing their frequency.

Filtered terms whose values are at least one order of magnitude less than the zonal wind tendency ($10^{-5} \text{ m s}^{-2}$), or those that do not contribute to the intraseasonal band, are removed from the analysis. The remaining terms yield the intraseasonal zonal wind tendency
equation used in this study:

\[
\frac{\partial u^*}{\partial t} \approx -u \frac{\partial u^*}{\partial x} - u^* \frac{\partial \pi}{\partial x} - \left[ u^* \frac{\partial u^*}{\partial x} \right] - \left[ u' \frac{\partial u'}{\partial x} \right] \\
\frac{\partial v^*}{\partial y} - v^* \frac{\partial \pi}{\partial y} - \left[ v^* \frac{\partial u^*}{\partial y} \right] - \left[ v' \frac{\partial u'}{\partial y} \right] \\
\frac{\partial \omega^*}{\partial p} - \omega^* \frac{\partial \pi}{\partial p} - \left[ \omega^* \frac{\partial u^*}{\partial p} \right] - \left[ \omega' \frac{\partial u'}{\partial p} \right] \\
- \frac{\partial \Phi^*}{\partial x} + f v^* + \left[ \frac{uv \tan \phi}{a} \right] 
\]

(2.3)

Each term is labeled for reference in the text. All space and time derivatives are approximated using the five-point stencil formula

\[
f'(x) \approx -f(x + 2h) + 8f(x + h) - 8f(x - h) + f(x - 2h)
\]

(2.4)

where \(x\) represents a point in space (for space derivatives) or time (for time derivatives), and \(h\) denotes grid point or temporal spacing in meters or seconds, respectively.

2.2.3 Assessment of statistical significance

Bootstrap resampling was applied to test sample statistics of gridded data for local significance. The list of dates over which a given statistic was calculated was resampled 1,000 times, and probability distributions were generated at each grid point from these resampled dates. The inner 95% of these distributions was selected to establish local significance, meaning that if the value of the statistic at a selected grid point fell outside of this range, it was considered to be statistically significantly different from zero at the 95% level at that grid point. A modification was applied to this test to mitigate the risk of falsely claiming local significance (known as the false discovery rate, or FDR). A thorough explanation of
this modification is found in Wilks (2006) and Wilks (2016), and its application as it relates to gridded data in the context of this study is described by Gloeckler and Roundy (2019a). Bootstrap resampling was also applied more broadly to test non-grid-based results for significance at the 95% level. These tests did not employ the FDR modification.

2.3 Results

2.3.1 Large-scale pattern overview

Pentad-mean 200-hPa geopotential height and zonal wind anomalies associated with a subset of RMM phase 5 dates (69 days) that feature TCs within a 7.5° search radius centered on 15°N, 115°E (TC-based), and the full set of RMM phase 5 dates (468 days) without regard for TC presence (full population), are displayed for comparison in Fig. 2.1. This particular TC-based event set was selected for evaluation because it was featured in the statistical assessment performed by Gloeckler and Roundy (2019a), and because relationships between non-recurving TCs and the extratropical flow have been largely neglected. The left column corresponds to the TC-based composite, the middle column corresponds to the full population composite, and the right column shows the result of subtracting the middle column from the left column. As in Gloeckler and Roundy (2019a), MJO events contained in the full population composite (Figs. 2.1b,e,h,k) were weighted according to the number of days in which TCs contained in the TC-based composite (Figs. 2.1a,d,g,j) were present in each month of the target season during the period of study. This weighting ensures more accurate event set comparisons because TCs of a certain type might occur preferentially during a particular time of the season, and the extratropical response to tropical convective forcing undergoes an adjustment as the background circulation state evolves with the seasonal cycle. Each composite features an anomalous upper-level Rossby wave train (alternating regions of solid and dashed contours) that disperses across the North Pacific and North America, but these wave trains and their associated zonal wind anomalies quickly develop different structures. Differences first arise across East Asia and the adjacent Northwest
Pacific Ocean in association with the development of an anomalous subtropical jet streak that achieves greater amplitude in the TC-based composite (Fig. 2.1c), and they expand eastward in subsequent pentads in conjunction with subtropical jet extension (e.g., Fig. 2.1b).

The greatest differences in upper-level circulation between the two composite sets shown in Fig. 2.1 originate poleward and eastward of the TC search radius marked at its center by the red TC symbol (Fig. 2.1c). This observation suggests a physical link between the composite TC and the poleward large-scale circulation response that is masked by other circulation states included in the full population composite average. Figure 2.2 presents longitude-time diagrams of intraseasonal filtered OLR anomalies averaged between the equator and 15°N (Figs. 2.2a-c), and intraseasonal filtered 200-hPa zonal wind anomalies averaged between 30°N and 50°N, for each composite and the difference between them. An eastward propagating zonally broad envelope of enhanced convection (suggested by negative OLR anomalies depicted in green shading) flanked by regions of suppressed convection (suggested by brown shading) is present in both composites (Figs. 2.2a,b). These convective signals evolve on MJO timescales, and they possess similar structure and amplitude, but Fig. 2.2c highlights subtle differences between them. One of these key differences manifests as a statistically significant zonally narrow westward-propagating envelope of enhanced convection that bisects the broader MJO convective envelope and traverses the TC search radius. This convective signal is not likely to solely reflect the composite TC because tests suggest that it is present substantially longer than the large majority of TCs in the sample. Wavenumber-frequency spectrum analysis reveals that it projects most onto the equatorial Rossby (ER) wave band (periods of 10–100 days and wavenumbers 1–15 westward, not shown). The superposition of ER waves and the MJO can yield a favorable large-scale environment for TC organization (e.g., Frank and Roundy 2006), so it is no surprise that Fig. 2.2 suggests a link between these three modes of tropical variability.

A statistically significant upper-level intraseasonal westerly wind anomaly centered on
120°E emerges in both composites prior to lag zero, and peaks in amplitude several days later. Its development is consistent with the upper-level circulation response to MJO convective forcing (e.g., Kiladis et al. 2005, Moore et al. 2010), which manifests as an anomalous subtropical upper-level anticyclone poleward of MJO convection, and a strengthening and poleward shifting of the subtropical jet relative to its climatological state. Its presence in both composites suggests that it is linked to the MJO, yet it is more than three times stronger in the TC-based composite than in the full population composite. It also appears to possess a westward evolving component in the TC-based composite (its western edge expands westward with increasing time lag), while it exhibits a gradual eastward evolution in the full population composite, which is more consistent with a canonical subtropical jet response to MJO convection (e.g., Moore et al. 2010). The strength and spatial evolution of the TC-based composite anomaly suggests a link to the westward moving convective signal (and the composite TC) embedded within the broader MJO convective envelope (Fig. 2.2c). Fig. 2.2f reveals that the aforementioned intraseasonal zonal wind differences are statistically significant, and that other statistically significant differences arise downstream at subsequent lags.

2.3.2 The East Asian intraseasonal subtropical jet response

2.3.2.1 Primary momentum sources

The intraseasonal zonal wind anomaly positioned poleward of MJO convection in Figs. 2.1a,b and 2a,b is intriguing because it possesses a clear physical relationship to the convection, yet its structure and amplitude differs greatly between the two composites. A box bounded to the west and east by 110°E and 130°E, and to the south and north by 30°N and 45°N, was constructed to evaluate this intraseasonal zonal wind signal and its associated tendency in order to determine its predominant momentum sources in each event set. Figure 2.3 presents these fields across a domain surrounding this box, which is outlined for reference in each panel. Rows represent pentad means that consist of the days indicated
along the y-axis of their left-column panels. Columns are ordered as in Fig. 2.1. A positive intraseasonal zonal wind tendency is evident within the averaging box in both composites (Figs. 2.3a,b,d,e,g,h). Consistent with the results presented in Fig. 2.2, this signal indicates subtropical jet amplification in response to tropical convective forcing. It achieves greater amplitude in the TC-based composite (Figs. 2.3a,d,g), and its amplitude differs most from its full population counterpart in the third pentad (Fig. 2.3i).

In order to identify which terms on the RHS of (2.3) contribute most to the amplification of the intraseasonal zonal wind signal in each event set, all terms were averaged across the selected box for a period spanning twenty days before to twenty days after their composite reference dates (lag zero). Figure 2.4 shows the results of this averaging (note the difference in y-axis scale for each row). The bottom row displays the anomalous intraseasonal zonal wind tendency corresponding to the TC-based composite (left), the full population composite (center), and the difference between them (right; solid black curves), along with the sum of all terms in their corresponding top row panels (dashed black curves). Grey shading in each panel highlights time lags during which the intraseasonal zonal wind tendency in the TC-based composite is statistically significantly different from that in the full population composite, which leads to a focus on three days before to six days after lag zero. It is during this period that the box-averaged intraseasonal zonal wind tendency peaks at approximately $0.5 \times 10^{-5} \text{ m s}^{-2}$ in the TC-based composite (lag zero in Fig. 2.4d), while it maximizes at a considerably lower value four to five days earlier in the full population composite (Fig. 2.4e). The top row reveals that the TC-based composite tendency is driven primarily by the sum of the intraseasonal zonal pressure (geopotential) gradient force and the Coriolis force acting on the intraseasonal meridional wind (term 4; the purple curve in Fig. 2.4a), while the corresponding peak in the full population composite is primarily driven by the zonal advection of the zonal wind (orange curve in Fig. 2.4b). These contributions are statistically significantly different from zero, but their inter-composite differences are not significant (Fig. 2.4c).
Figure 2.5 represents the interplay between the background and intraseasonal wind. Terms plotted in Fig. 2.5a suggest that, for the TC-based composite, the advection of background zonal wind by intraseasonal meridional wind (term 2b; dotted blue curve) is another significant contributor to the positive intraseasonal zonal wind tendency shown in Fig. 2.5d, yet it maximizes more than five days after that of its corresponding tendency, which is already declining in amplitude (but still positive), implying that its primary function is to help maintain the strength of the intraseasonal subtropical jet across the averaging box rather than to amplify it. This notion is further supported its loss in amplitude at the same time that its corresponding tendency switches sign (approximately eight days after lag zero). Other terms, like the advection of the background zonal wind by the intraseasonal zonal wind (term 1b; dotted orange curve in Fig. 2.5a), occur largely out of phase with term 2b, thereby offsetting some of its positive contribution to the intraseasonal zonal wind tendency observed in the TC-based composite. In the full population composite, the advection of the intraseasonal zonal wind by the background zonal wind (term 1a; solid orange curve in Fig. 2.5b) is the dominant momentum source across the averaging box for this set of terms. It is not significantly offset by any comparable advection terms, and it contributes more than 50% of the amplitude achieved by the zonal advection term in Fig. 2.4b (solid orange curve), suggesting that it is the primary driver of its associated positive intraseasonal zonal wind tendency (Fig. 2.5b). It also evolves largely in phase with this tendency, implying that it primarily amplifies the intraseasonal subtropical jet streak across the averaging box in the full population composite.

Figure 2.6 details contributions to the intraseasonal zonal wind tendency by intraseasonal and transient advection terms. Compared to the terms described in the previous two paragraphs, these are relatively small in amplitude when averaged across the selected box. The intraseasonal filtered advection of intraseasonal zonal wind by intraseasonal meridional wind (term 2c; solid blue curve in Fig. 2.6a) is the largest positive contributor to the intraseasonal zonal wind tendency in the TC-based composite when this tendency is positive.
and amplifying (Fig. 2.6d), yet neither it nor its inter-composite difference achieve statistical significance. Other intraseasonal advection terms (i.e., terms 1c and 3c; solid orange and green curves, in Fig. 2.6a) in the TC-based composite are even smaller than term 2c, thus appearing physically irrelevant to the evolution of intraseasonal zonal wind within the averaging box. Transient advection terms (dotted curves in Figs. 2.6a,b) are of greater interest because they represent zonal momentum accelerations that are forced by circulation components whose evolutionary timescales match those of TCs, so they include direct TC contributions to intraseasonal zonal wind acceleration. Surprisingly, none of these terms achieve statistical significance in the TC-based composite when the intraseasonal zonal wind tendency is positive and amplifying inside the averaging box, and they are also small relative to the largest positively contributing term in this set (term 2c). In the full population composite, the intraseasonal filtered advection of transient zonal wind by transient meridional wind (term 2d; dotted blue curve in Fig. 2.6b) is statistically significant and maximizes in phase with its associated tendency (Fig. 2.6b), which suggests that it amplifies the intraseasonal zonal wind signal within the averaging box.

2.3.2.2 Relationship to TC presence

The results in Fig. 2.6a give the impression that TCs do not yield any significant contributions to the intraseasonal zonal wind tendency in the TC-based composite because all transient advection terms averaged across the selected box are small and not statistically significant. In reality, these terms, to which TCs can directly contribute signal, significantly modulate the upper-level intraseasonal zonal momentum budget across East Asia and the adjacent Northwest Pacific Ocean, especially in the early stages of East Asian subtropical jet amplification. Figure 2.7 shows this jet amplification in each composite by overlaying pentad mean 200-hPa intraseasonal vector wind anomalies on intraseasonal geopotential height anomalies at the same level (pentads and columns correspond to those in Fig. 2.3). Anomaly patterns associated with each composite are statistically indistinguishable from one
another in the first pentad (Figs. 2.7a–c). Significant differences between the two composites emerge over East Asia and the adjacent Northwest Pacific Ocean during the second pentad as an anomalous intraseasonal extratropical Rossby wave train takes form in the TC-based composite (Figs. 2.7d–f). These differences appear directly linked to enhanced convection positioned over the Maritime Continent and South China Sea in the TC-based composite (not shown), which manifests as a statistically significant channel of anomalous southerly flow directed from this region toward the averaging box. No analogous signal is present in the full population composite. An even more pronounced northwest-southeast oriented channel of intraseasonal vector wind anomalies develops over Japan (Figs. 2.7d,f), signaling the amplification of the aforementioned intraseasonal subtropical jet streak. These wind anomalies grow in tandem with the amplifying height field through the third pentad, and achieve greater amplitude in the TC-based composite (Figs. 2.7g–i).

A similar set of analyses is presented in Fig. 2.8 to examine the evolution of the transient component of the large-scale circulation. An anomalous transient upper-level anticyclone emerges poleward of the composite TC. Figs. 2.8d,f suggest that its formation is partly associated with diabatically-driven upper-level outflow (indicated by a channel of yellow vectors oriented poleward from the TC symbol) linked to enhanced convection coincident with or proximate to the TC. The full population composite has no comparable signal (Fig. 2.8e). An equatorward-propagating transient upper-level extratropical Rossby wave train (Fig. 2.9) also contributes to the development of this circulation anomaly in the TC-based composite, and this signal is present in a weakened state in the full population composite (not shown). When the extratropical portion of the aforementioned circulation anomaly reaches equatorward of approximately 40°N, it constructively interferes with a poleward-propagating same-signed circulation anomaly that accompanies a poleward-dispersing transient wave train (Fig. 2.9). No analogous signal is present in the full population composite (not shown). A portion of this poleward-oriented signal is contributed by the composite TC, which is embedded within a transient westward-propagating wave packet (Fig. 2.10a).
is a hint of this westward-evolving wave signal in the full population composite (Fig. 2.10b), but it is weaker than in the TC-based composite and generally not statistically significant.

Consolidation of the tropical and extratropical components of the transient upper-level anomalous anticyclone poleward of the composite TC yields a strengthening of this circulation feature and a meridional elongation of its structure relative to that in the full population composite (Figs. 2.8d–i). Its phasing with the intraseasonal circulation allows it to advect transient westerly momentum equatorward on its eastern flank and deposit it into the growing intraseasonal subtropical jet streak over Japan, thereby contributing positive intraseasonal zonal wind acceleration to the amplifying jet (Fig. 2.11d). There is no clear association between transient advection and intraseasonal zonal wind acceleration in the full population composite (Fig. 2.11e). Several days later, following TC passage, an anomalous transient upper-level cyclone supplants the anticyclone partly due to a reduction in transient latent heat release to its south (not shown). Counterclockwise flow around it yields intraseasonal westerly wind acceleration through the jet streak in association with the poleward advection of transient westerly momentum on its eastern flank (Fig. 2.11g). Once again, no analogous signal is present in the full population composite (Fig. 2.11h). Removing the term that describes these accelerations (term 2d) from the RHS of (2.3) yields a net negative intraseasonal zonal wind tendency across the amplifying subtropical jet streak over Japan (not shown), implying that the jet streak would decelerate in its absence. This same process was performed separately for the other two transient advection terms (terms 1d and 3d) to assess their relative importance to the growth of the positive intraseasonal zonal wind signal across East Asia. In neither case did their removal yield a significant change in intraseasonal zonal wind tendency through the amplifying East Asian subtropical jet streak (not shown). These results suggest that the transient meridional advection of transient zonal wind is the most physically relevant transient (TC-scale) advection term to the intraseasonal zonal wind acceleration observed across Japan and the adjacent Northwest Pacific Ocean in the TC-based composite.
2.3.2.3 Jet maintenance

The intraseasonal subtropical jet streak that emerges over East Asia and the adjacent Northwest Pacific Ocean is maintained by additional momentum sources that operate on different timescales. The two largest of these sources are addressed herein. Fig. 2.12 relates intraseasonal zonal wind acceleration to a transfer of zonal momentum from background to intraseasonal timescales (term 2b). Since the background wind acts as a constant momentum source on intraseasonal timescales, it accelerates the intraseasonal zonal wind when it is advected from higher to lower values by the intraseasonal wind. Figs. 2.12a,d,g depict these positive accelerations through and to the southeast of the averaging box in the TC-based composite. Their growth coincides with the advection of higher values of background zonal wind toward lower values by the intraseasonal meridional wind. A similar signal is present in the full population composite, but its placement differs slightly from that in the TC-based composite, and it attains lower amplitude (Figs. 2.12b,e,h). This acceleration mechanism couples with that associated with the meridional advection of transient zonal wind described in the previous subsection to accelerate and maintain the intraseasonal subtropical jet in the TC-based composite. Their simultaneous contributions to intraseasonal zonal wind acceleration are shown in Fig. 2.13. Positive acceleration induced by the meridional advection of transient zonal wind (term 2d; gold curve) peaks about five days after its corresponding zonal wind tendency maximizes (black curve), and about four days prior to when peak positive acceleration is achieved by the advection of background zonal wind by the intraseasonal meridional wind (term 2b; blue curve). The intraseasonal subtropical jet streak begins to decelerate (it crosses the zero-line along the y-axis) immediately after term 2b maximizes, suggesting that this term is a primary contributor to intraseasonal jet streak maintenance, whereas term 2d contributes more to jet streak amplification.

Injection of westerly momentum into the intraseasonal subtropical jet streak depicted in the TC-based composite yields a departure from geostrophic balance, so a mass field adjustment must occur in order to restore balance. To aid in visualizing this process, Fig.
overlays intraseasonal filtered 200-hPa geopotential height and vector wind anomalies on term 4 (the sum of the intraseasonal pressure gradient force and the Coriolis torque on the intraseasonal meridional wind). The Coriolis force contained in term 4 responds to this departure by building easterly acceleration over Japan (concomitant with the subtropical jet streak) that transfers mass from the trough centered on the Kamchatka Peninsula to the developing subtropical ridge over China, thereby amplifying this ridge and deepening the trough to its Northeast, and increasing the horizontal geopotential gradient between them (Figs. 2.14d,g). This Coriolis-driven acceleration is illustrated in Fig. 2.15 and is evident in both composites. As the mass field adjusts, the subtropical jet on the poleward flank of the amplifying subtropical ridge accelerates in response to the strengthening geopotential gradient. This process is most evident in the TC-based composite (e.g., Fig. 2.14g), wherein larger westerly wind accelerations occur as momentum responds to greater mass adjustment than in the full population composite. A portion of this acceleration is facilitated by the advection of background zonal wind by intraseasonal meridional wind (Fig. 2.12g), as well as by the intraseasonal component of the advection of the intraseasonal zonal wind by the intraseasonal meridional wind (not shown). Upper-level outflow associated with tropical convection over the Maritime Continent and South China Sea (not shown) aids in this process by redistributing mass and momentum from the tropics to higher latitudes.

2.3.3 Subsequent intraseasonal extratropical circulation progression

Prior to delving into the mechanisms that influence the intraseasonal zonal wind progression across the rest of the North Pacific Ocean and North America, the disparity between the two composites with reference to the strength of their extratropical Rossby wave responses is considered. Vorticity advection is a common framework through which to assess the Rossby wave response to anomalous tropical heating (e.g., Sardeshmukh and Hoskins 1988, Jin and Hoskins 1995, Lukens et al. 2017). When a tropical heating anomaly is imposed, a Rossby wave source (RWS) grows poleward of the anomalous heating in response
to horizontal vorticity advection by the anomalous divergent wind that is forced by the heat source. Poleward vorticity advection strengthens the horizontal vorticity gradient that maximizes in the subtropics. It is along this vorticity gradient that the subtropical jet resides, and its strength is proportional to the strength of this gradient. Rotational flow anomalies that manifest as upper-level cyclones or anticyclones poleward of anomalous heating (depending on the sign of the heating anomaly) eventually form in association with the meridional displacement of vorticity. This represents one pathway through which to link the previously described momentum anomalies to anomalous tropical convection, although it does not directly address momentum growth sources via scale interactions.

Sardeshmukh and Hoskins (1988) demonstrated that the strength of the RWS is proportional to the local horizontal vorticity gradient to which it is tied. Given the association between the strength of this vorticity gradient and that of the subtropical jet, a stronger subtropical jet response indicates a stronger RWS and portends a more amplified extratropical Rossby wave response. Lukens et al. (2017) demonstrated that vorticity anomalies that form in conjunction with horizontal vorticity advection by the divergent wind are advected downstream by the climatological jet and disperse into the extratropics when they reach its exit region, where the vorticity gradient coincident with the jet weakens to the point that they are able to amplify out of the subtropics (see their Fig. 2.12). They, too, noted that the strength of the Rossby wave response depends on the strength of the horizontal vorticity advection associated with upper-level divergent wind anomalies linked to anomalous tropical heating. Following this logic, it is not surprising that the Rossby wave response in the TC-based composite is much stronger than that in the full population composite. Indeed, horizontal (potential) vorticity (PV) advection by the divergent wind (e.g., Archambault et al. 2013) achieves higher amplitude in the TC-based composite—it is dominated by the advection of background PV by the intraseasonal divergent wind (Fig. 2.16), but transient PV advection (not shown) is its second largest contributor—which relates to its associated convection being locally more intense than in the full population composite (not shown). In
fact, differences in PV advection between the two composites are maximized inside the aver-
aging box, exactly where the intraseasonal zonal wind maximizes. These differences originate
in association with the establishment of a stronger horizontal intraseasonal PV gradient in
the TC-based composite (not shown).

Figure 2.17 illustrates the life cycle of the anomalous intraseasonal extratropical Rossby
wave train in the TC-based composite, and includes the large-scale intraseasonal flow evolu-
tion accompanying the full population composite for comparison. Its transformation is
depicted by four consecutive pentad means of intraseasonal 200-hPa geopotential height and
vector wind anomalies. The background zonal wind at the same level is also overlaid in black
contours. In the first two pentads (Figs. 2.17a,c), the wave train extends from subtropical
East Asia to the Northwest Atlantic and possesses a wavenumber four structure. Stepping
forward one pentad (Fig. 2.17e), the subtropical anticyclone over East Asia has weakened
and retrograded, as has the subtropical jet response on its poleward flank. This evolution
marks a decay and retrogression of the RWS discussed in the previous two paragraphs (not
shown), which occurs as the convectively active phase of the ER wave propagates westward
and decays, and its trailing convectively suppressed phase intersects MJO convection (also
not shown). The extratropical Rossby wave response tied to this convective forcing flattens
as convection weakens, and a surge of westerly momentum develops across the North Pacific.
By the last pentad (Fig. 2.17g), a broad intraseasonal ridge anomaly is present across easter-
n North America, and a broad intraseasonal trough anomaly is located to its west. The
large-scale circulation in the full population composite evolves much more gradually than in
the TC-based composite, with steady Rossby wave dispersion evident across all four pentads
(Figs. 2.17b,d,f,h). In this case, the intraseasonal subtropical jet does not undergo a rapid
metamorphosis across the lag window, so no associated intraseasonal westerly wind surge
occurs.

The aforementioned TC-based composite westerly wind surge originates in association
with several moving parts. Two of its largest forcing terms are shown in Figs. 2.18 and
The superposition of the intraseasonal and background zonal winds yields westerly intraseasonal zonal wind acceleration east of the Date Line, between 30°N and 45°N, as the intraseasonal meridional wind advects higher values of background westerly wind equatorward (Figs. 2.18a–c). This process is also evident to the south of Japan (Figs. 2.18a,b) in association with clockwise flow around the anomalous upper-level intraseasonal subtropical anticyclone anchored by western North Pacific tropical convection to its south (not shown). As convection decays, its associated extratropical Rossby wave response flattens. The anomalous upper-level anticyclone positioned over the central North Pacific (denoted by its clockwise circulation in the vector field in Figs. 2.18a,b) sinks equatorward and grows in zonal extent. This evolution is supported in part by westerly intraseasonal zonal wind acceleration on its equatorward flank, easterly acceleration to the south of that, and easterly acceleration on its poleward flank (e.g., Fig. 2.18b). The anticyclone evolves equatorward in conjunction with these accelerations, which yields an anticyclonic circulation tendency to its south, and a cyclonic circulation tendency to its north (tendency not shown).

Erosion of convective forcing over the Maritime Continent and Southeast Asia triggers a deceleration of the subtropical jet streak over Japan. Westerly momentum contained in this jet streak is transfered eastward primarily by the advection of the background zonal wind by the intraseasonal zonal wind (term 1b; Fig. 2.19), and to a lesser extent, by the advection of the intraseasonal zonal wind by the background meridional wind (term 2a; not shown). This process yields a significant and abrupt westerly intraseasonal zonal wind acceleration (westerly wind surge) across the length of the North Pacific Ocean, which manifests as an elongated branch of the subtropical jet that spans the basin (Figs. 2.19c,d). Injection of westerly momentum into the jet yields a departure from geostrophic balance across the region. The Coriolis force responds by torquing the zonal wind equatorward and building northerly acceleration (Fig. 2.5b). This process enables a transfer of mass from the developing trough over the North Pacific (south of Alaska) to the ridge to its south. Zonal ridge expansion occurs in both directions as these accelerations concentrate on its eastern
and western flanks, and it loses amplitude at its center as the meridional pressure gradient force associated with the strong geopotential gradient between it and the North Pacific trough builds poleward acceleration (Fig. 2.5d) and facilitates mass transfer in this direction. Downstream of this trough, momentum accumulates to the east of the North Pacific jet exit region and yields intraseasonal ridge amplification across eastern North America.

2.4 Conclusions and future work

A 200-hPa zonal momentum budget was performed to investigate the role that western North Pacific TCs play in helping to organize and progress intraseasonal extratropical circulation anomalies that occur with MJO events that include them. Composites of relevant budget terms were generated from a subset of RMM phase 5 dates that included non-recurving TCs within a 7.5° search radius centered on 15°N, 115°E. These composites were compared to another set generated from the full list of RMM phase 5 dates without regard for TC presence in order to assess differences in predominant momentum sources between each event set, and determine the extent to which these differences can be attributed to TC presence in the TC-based composite.

Fig. 2.21 provides a schematic depiction of the primary zonal momentum sources and scale interactions pertaining to the TC-based composite. Each panel is arranged relative to the order in which mechanisms highlighted in sections 2.3.2.2, 2.3.2.3, and 2.3.3 are described. The intraseasonal subtropical jet (depicted by a yellow arrow in each panel of Fig. 2.21) intensifies in association with TC passage to its south (Fig. 2.21a), and is further strengthened and maintained by accelerations (denoted by blue arrows in Fig. 2.21b) that are tied to the growing intraseasonal upper-level subtropical ridge (marked H*) centered on Southeast Asia. A stronger Rossby wave response relative to that in the full population composite (not shown) emerges a few days later as the subtropical jet continues to amplify (Fig. 2.21c), which is consistent with past studies that have related jet strength to extratropical Rossby wave amplitude (e.g., Sardeshmukh and Hoskins 1988; Lukens et al. 1988).
Finally, when intraseasonal convection begins to wane, westerly momentum built up across Southeast Asia is advected eastward by the background and intraseasonal zonal wind, yielding rapid subtropical jet extension across the length of the North Pacific Ocean (Fig. 2.21d). No analogous momentum surge occurs in the full population composite (not shown).

The set of TCs examined herein directly contributes to the organization of the intraseasonal extratropical circulation. Transient latent heat release and associated upper-level outflow (poleward-oriented green arrows proximate to the TC symbol in Fig. 2.21a) accompanying the composite TC and/or poleward-displaced enhanced rainfall yield a strengthening and meridional elongation of a transient upper-level subtropical ridge anomaly over Southeast Asia, which constructively interferes with a preexisting transient extratropical ridge anomaly to its north. Anticyclonic flow around this anomaly draws transient westerly momentum on its poleward flank equatorward (depicted by the equatorward-oriented green arrow on the northeast side of the transient anomalous anticyclone marked H’ in Fig. 2.21a), yielding positive zonal momentum acceleration to the west of the subtropical jet exit region. Although not addressed in this study, anomalous transient flux convergence over Japan (denoted by the two green arrows coming together poleward of the yellow arrow in Fig. 2.21a) might also promote subtropical jet amplification. The transient anomalous circulation pattern reverses at later lags (not shown) and facilitates a continuation of positive zonal momentum acceleration across the same geographical area, thereby yielding a positive zonal momentum source that assists subtropical jet intensification and projects onto intraseasonal timescales.

The previous paragraph describes the manner in which TCs directly contribute to the growth of the intraseasonal subtropical jet in the TC-based composite. Results are consistent with the hypothesis that TCs can indirectly modulate intraseasonal circulations over a longer period of time to the extent that their immediate contributions are integrated into the more slowly evolving circulation and carried forward by other processes. In the TC-based composite, these processes include accelerations related to the horizontal pressure gradient force and Coriolis torque (curved blue arrows in Fig. 2.21b), advection of the background zonal
wind by the intraseasonal zonal and meridional wind (e.g., equatorward-oriented straight blue arrows in Fig. 2.21b), and other smaller advection terms. One way to further test this hypothesis is to perform a set of modeling experiments wherein one experiment features initial conditions with simultaneous MJO and TC activity, while another has all TC-related circulation and moisture anomalies dampened or removed. Such a set of experiments can help to quantify the extent to which the large-scale extratropical circulation response changes in the absence of TC-related forcings. Changes in the extratropical circulation related to the presence or absence of TCs might feed back onto tropical circulation anomalies and, consequently, affect the structure and organization of subsequent MJO events (e.g., Roundy 2014; Sakaeda and Roundy 2015). Testing these hypotheses will further the understanding of TC function in the context of the global circulation.
2.5 Figures

Figure 2.1: Intraseasonal filtered 200-hPa geopotential height anomalies (black contours in gpm; solid contours indicate positive values; contour interval is 10 gpm, beginning at ±10 gpm) and intraseasonal filtered 200-hPa zonal wind anomalies (shaded according to the color scale in m s$^{-1}$), averaged over sequential five-day periods (pentads) between two days before and twenty two days after the composite reference dates (lag zero). Each pentad is represented by a row, and all days included in each pentad are labeled along the y-axis of their corresponding left-column panel. The left column applies to the TC-based RMM phase 5 composite (69 days included), the middle column applies to the full population RMM phase 5 composite (468 days included), and the right column shows the result of subtracting the middle column from the left column. Statistically significant geopotential height anomalies are hatched, and statistically significant zonal wind anomalies are stippled. Red TC symbols in panels (a) and (c) mark the grid point at the center of the search radius used to identify TCs at lag zero.
Figure 2.2: Longitude-time diagrams of (a)–(c) intraseasonal filtered OLR anomalies averaged between the equator and 15°N, and (d)–(f) intraseasonal filtered 200-hPa zonal wind anomalies averaged between 30°N and 50°N. Columns are ordered as in Fig. 2.1. Statistically significant anomalies are outlined in solid black contours. Red TC symbols in panels (a), (c), (d), and (f) mark the center of the TC search radius in time and longitude.
Figure 2.3: The 200-hPa intraseasonal zonal wind tendency (shaded according to the color scale in m s\(^{-2}\) and scaled by a factor of \(1 \times 10^5\)) and intraseasonal filtered 200-hPa zonal wind anomalies (black contours in m s\(^{-1}\); solid contours indicate positive values; contour interval is 1 m s\(^{-1}\), beginning at \(\pm 1\) m s\(^{-1}\)) averaged over three sequential five-day periods (pentads) between seven days before and seven days after the composite reference dates (lag zero). Each pentad is represented by a row, and all days included in each pentad are labeled along the y-axis of their corresponding left-column panel. Columns are ordered as in Fig. 2.1. Statistically significant zonal wind anomalies are hatched, and statistically significant zonal wind tendency is stippled. The black boxes in each panel outline the averaging box referenced in section 2.3.2.1. Red TC symbols in panels (d) and (f) mark the grid point at the center of the search radius used to identify TCs at lag zero. The term in (2.3) indicated by shading is labeled above the top-right corner of each top-row panel.
Figure 2.4: (a)–(c) Lagged evolution of intraseasonal filtered total advection terms and terms 4 and 5 of (2.3). (d)–(f) Intraseasonal zonal wind tendency (solid black curve) and the sum of the terms in the top-row panel of each column (black dashed curve). Columns are ordered as in Fig. 2.1. Statistically significant values are depicted by unfilled circles. Grey shading highlights time lags in which the inter-composite difference in intraseasonal zonal wind tendency is statistically significant.
Figure 2.5: As in Fig. 2.4 but for terms 1a,b, 2a,b, and 3a,b of (2.3). Panels (d)–(f) only depict intraseasonal zonal wind tendency.
Figure 2.6: As in Fig. 2.4 but for terms 1c,d, 2c,d, and 3c,d of (2.3). Panels (d)–(f) only depict intraseasonal zonal wind tendency.
Figure 2.7: Pentad-mean intraseasonal filtered 200-hPa geopotential height (shaded according to the color scale in gpm) and vector wind anomalies (yellow vectors; reference vectors are located above the top-left corner of each top-row panel). Pentads correspond to those in Fig. 2.3. Columns are ordered as in Fig. 2.1. Statistically significant geopotential height anomalies are stippled. Vectors are only plotted where their corresponding anomalies are statistically significant. The black boxes in each panel outline the averaging box referenced in section 2.3.2.1. Red TC symbols in panels (d) and (f) mark the grid point at the center of the search radius used to identify TCs at lag zero.
Figure 2.8: As in Fig. 2.7 but for transient filtered 200-hPa geopotential height and vector wind anomalies.
Figure 2.9: A time-latitude diagram of transient filtered 200-hPa geopotential height anomalies (shaded according to scale in gpm) averaged between 120°E and 140°E. Statistically significant anomalies are hatched. The red TC symbol marks the center of the TC search radius in time and latitude.
Figure 2.10: Longitude-time diagrams of transient filtered 200-hPa geopotential height anomalies (shaded according to scale in gpm) averaged between 15°N and 30°N. Columns are ordered as in Fig. 2.1. Statistically significant anomalies are hatched. The red TC symbols in panels (a) and (c) mark the center of the TC search radius in time and longitude.
Figure 2.11: Pentad-mean intraseasonal filtered advection of transient zonal wind by transient meridional wind (term 2d; shaded according to the color scale in m s$^{-2}$, scaled as in Fig. 2.3 and labeled above the top-right corner of each top-row panel) transient vector wind anomalies (yellow vectors in m s$^{-1}$; reference vectors are located above the top-left corner of each top-row panel), and intraseasonal filtered 200-hPa zonal wind anomalies (black contours in m s$^{-1}$; only positive anomalies are shown; contour interval is 1 m s$^{-1}$). Pentads correspond to those in Fig. 2.3. Columns are ordered as in Fig. 2.1. Statistically significant term values are stippled, and statistically significant zonal wind anomalies are hatched. Vectors are plotted where their corresponding anomalies are statistically significant. The black boxes in each panel outline the averaging box referenced in section 2.3.2.1. Red TC symbols in panels (d) and (f) mark the grid point at the center of the search radius used to identify TCs at lag zero.
Figure 2.12: Pentad-mean 200-hPa advection of the background zonal wind by the intraseasonal meridional wind (term 2b; shaded according to the color scale in m s\(^{-2}\), scaled as in Fig. 2.3 and labeled above the top-right corner of each top-row panel), intraseasonal vector wind anomalies (yellow vectors in m s\(^{-1}\); reference vectors are located above the top-left corner of each top-row panel), and the background zonal wind (black contours in m s\(^{-1}\); solid contours indicate positive values; contour interval is 10 m s\(^{-1}\), beginning at ±10 m s\(^{-1}\)). Pentads correspond to those in Fig. 2.3. Columns are ordered as in Fig. 2.1. Statistically significant term values are stippled. Vectors are plotted where their corresponding anomalies are statistically significant. The black boxes in each panel outline the averaging box referenced in section 3.3.2.1. Red TC symbols in panels (d) and (f) mark the grid point at the center of the search radius used to identify TCs at lag zero.
Figure 2.13: The lagged evolution of the intraseasonal filtered 200-hPa advection of transient zonal wind by transient meridional wind (term 2d; golden curve), the 200-hPa advection of background zonal wind by intraseasonal meridional wind (term 2b; blue curve), and 200-hPa intraseasonal zonal wind tendency (black curve). Values are computed across a domain bounded to the west and east by 120°E and 140°E, and to the north and south by 30°N and 45°N. Statistically significant values are indicated by unfilled circles.
Figure 2.14: Pentad-mean 200-hPa sum of the pressure (geopotential) gradient force and Coriolis torque on the intraseasonal meridional wind (term 4; shaded according to the color scale in m s$^{-2}$, scaled as in Fig. 2.3 and labeled above the top-right corner of each top-row panel), intraseasonal filtered 200-hPa geopotential height anomalies (black contours in gpm; solid contours indicated positive anomalies; contour interval is 10 gpm, beginning at ±10 gpm), and intraseasonal vector wind anomalies (yellow vectors in m s$^{-1}$; reference vectors are located above the top-left corner of each top-row panel). Pentads correspond to those in Fig. 2.3. Columns are ordered as in Fig. 2.1. Statistically significant term values are stippled, and statistically significant geopotential height anomalies are hatched. Vectors are plotted where their corresponding anomalies are statistically significant. The black boxes in each panel outline the averaging box referenced in section 2.3.2.1. Red TC symbols in panels (d) and (f) mark the grid point at the center of the search radius used to identify TCs at lag zero.
Figure 2.15: As in Fig. 2.14, but for only the Coriolis torque component of term 4.
Figure 2.16: Pentad-mean 200-hPa horizontal advection of background potential vorticity (PV) by the intraseasonal divergent wind (shaded according to the color scale in PVU s\(^{-1}\) [1 PVU = 10\(^{-6}\) K kg\(^{-1}\) m\(^2\) s\(^{-1}\)], scaled by a factor of 1 \times 10^{12}, and labeled above the top-right corner of each top-row panel), intraseasonal divergent wind anomalies (yellow vectors in m s\(^{-1}\); reference vectors are located above the top-left corner of each top-row panel), and background PV (black contours in PVU; contour interval is 1 PVU, beginning at 1 PVU). Pentads correspond to those in Fig. 2.3. Columns are ordered as in Fig. 2.1. Statistically significant advection values are stippled, and vectors are plotted where their corresponding anomalies are statistically significant. The black boxes in each panel outline the averaging box referenced in section 2.3.2.1. Red TC symbols in panels (d) and (f) mark the grid point at the center of the search radius used to identify TCs at lag zero.
Figure 2.17: Pentad-mean intraseasonal filtered 200-hPa geopotential height anomalies (black contours in gpm; solid contours indicated positive values; contour interval is 10 gpm, beginning at ±10 gpm), vector wind anomalies (yellow vectors in m s⁻¹; a reference vector is located above the top left corner of each top-row panel), and the 200-hPa background zonal wind (shaded according to the color scale in m s⁻¹). Each pentad is represented by a row, and all days included in each pentad are labeled along the y-axis of their corresponding left-column panel. The left column applies to the TC-based RMM phase 5 composite, while the right column applies to the full population RMM phase 5 composite. Statistically significant geopotential height anomalies are stippled, and vectors are plotted where their corresponding anomalies are statistically significant.
Figure 2.18: Pentad-mean 200-hPa advection of background zonal wind by intraseasonal meridional wind (term 2b; shaded according to the color scale in m s$^{-2}$, scaled as in Fig. 2.3, and labeled above the top-right corner of the top-row panel), intraseasonal vector wind anomalies (yellow vectors in m s$^{-1}$; a reference vector is located above the top left corner of the top-row panel), and the 200-hPa background zonal wind (black contours in m s$^{-1}$; solid contours indicate positive values; contour interval is 10 m s$^{-1}$, beginning at ±10 m s$^{-1}$). Pentads correspond to those in Fig. 2.17. Statistically significant term values are stippled, and vectors are plotted where their corresponding anomalies are statistically significant.
Figure 2.19: As in Fig. 2.18, but for the 200-hPa advection of background zonal wind by intraseasonal zonal wind (term 1b).
Figure 2.20: (a),(c) The pentad-mean sum of the 200-hPa intraseasonal meridional pressure (geopotential) gradient force and Coriolis torque on the intraseasonal zonal wind (shaded according to the color scale below panel (c) in m s$^{-2}$, scaled as in Fig. 2.3, and labeled above the top-right corner of panel (a)), intraseasonal filtered 200-hPa geopotential height anomalies (black contours in gpm; solid contours indicate positive values; contour interval is 10 gpm, beginning at ±10 gpm), and intraseasonal vector wind anomalies (yellow vectors in m s$^{-1}$; a reference vector is located above the top left corner of panel (a)). (b),(d) As in (a),(c), but for only the Coriolis torque component of the term plotted therein. Term values in the right column are shaded according to the color scale below panel (d). Each pentad is represented by a row, and all days included in each pentad are labeled along the y-axis of their corresponding left-column panel. Statistically significant term values are stippled, and vectors are plotted where their corresponding anomalies are statistically significant.
Figure 2.21: A schematic illustration of the primary zonal momentum sources and scale interactions pertaining to the TC-based composite. Each panel is arranged relative to the order in which mechanisms highlighted in sections 2.3.2.2, 2.3.2.3, and 3c are described.

3.1 Introduction

Interpreting the numerous and complex multiway interactions between anomalous tropical convection and the large-scale extratropical flow has been a key facet of subseasonal-to-seasonal atmospheric research for several decades. One of the most developed research avenues associated with this problem is that of the relationship between the Madden–Julian oscillation (MJO; e.g., [Madden and Julian 1994] [Zhang 2005] [Lau and Waliser 2012] and higher-latitude eddy and jet circulations (e.g., [Knutson and Weickmann 1987] [Ferranti et al. 1990] [Yang and Webster 1990] [Jin and Hoskins 1995] [Hsu 1996] [Matthews and Kiladis 1999] [Higgins et al. 2000] [Matthews et al. 2004] [Mori and Watanabe 2008] [Moore et al. 2010] [Riddle et al. 2013] [Goss and Feldstein 2015] [Stan et al. 2017] [Henderson and Maloney 2018]). The MJO is characterized by a tropospheric coupling of moist deep tropical convection and three-dimensional circulation. Its convective envelope is most organized over the region of the equatorial latitude belt that spans the Indian and western Pacific Oceans (e.g., [Adames and Wallace 2014]), while it is generally much less organized or sometimes almost entirely absent across the Western Hemisphere. It modulates the spatial distribution and intensity of smaller convective clusters as its convection and circulation transit the global tropics with a periodicity ranging from 20 to 100 days (e.g., [Roundy 2012]). Although it is widely considered a tropical phenomenon, its impacts are manifested outside of the tropics in the form of Rossby wave dispersion and attendant highly amplified flow patterns (e.g., [Sardeshmukh and Hoskins 1988]). These Rossby waves are guided along a meridional gradient of climatological vorticity by the background wind (e.g., [Lukens et al. 2017]). In the presence of anomalous upper-level equatorial westerly wind ([Webster and Holton 1982]), they are then guided back into the tropics where they can influence subsequent MJO event organization (e.g., [Ray and...])
Although this two-way channel between the tropics and extratropics only describes one mechanism through which the MJO communicates with the extratropical circulation and vice versa, it suggests that the MJO is an important component of variability in the structure and evolution of the global circulation.

Because of its well-documented relationship with extratropical Rossby wave dispersion, recent work has sought to address associations between the MJO and higher-latitude zonal wind currents (jets) along which these waves propagate. Through an intraseasonal (MJO time scale) zonal-mean zonal wind budget analysis, Sakaeda and Roundy (2014) detailed a poleward-migrating zonal wind signal that is largely forced by the interplay between intraseasonal and background circulations. This signal, in turn, modulates the structure and time evolution of transient (high-frequency) eddies by imparting on them large-scale cyclonic or anticyclonic shear. Transient eddies respond to changes in background (which includes intraseasonal) shear by tilting westward or eastward (depending on the sign of the shear) with increasing latitude and breaking poleward or equatorward (Thorncroft et al. 1993). These adjustments in transient wave structure and propagation characteristics feed back onto the intraseasonal circulation by forcing meridional displacement of and accelerating the zonal jet.

One mechanism that regulates meridional zonal jet displacement is the meridional flux of transient momentum and convergence thereof. James and Dodd (1996) demonstrated that equatorward propagating southwest-northeast-oriented (positively tilted) eddy circulations on the poleward side of the subtropical jet yield positive (westerly) zonal wind acceleration on its poleward flank. The jet responds to this acceleration by translating poleward. Feldstein (1998) observed that a poleward shift in zonal mean relative angular momentum, which manifests in positive zonal wind acceleration in the subtropics and midlatitudes, is largely forced by eddy angular momentum flux convergence outside of the tropics. This flux convergence is facilitated by interactions between stationary (low-frequency) and transient (high-frequency)
eddies, which suggests that such interactions are fundamental to the spatial and temporal variability of the subtropical jet. Consistent with these findings, Lee et al. (2007) found through an idealized modeling study that eddy momentum flux convergence dominates the low-frequency poleward migration of anomalous zonal-mean zonal wind by enhancing baroclinic wave activity and breaking midlatitude waves along a background vorticity gradient. Through an observational extension of this work, Yuan et al. (2013) noted that the poleward propagation of the North Atlantic jet results from equatorward-propagating Rossby waves that shift the critical latitude of the jet poleward through a series of wave breaks. Although none of these studies directly attribute the MJO to processes that modulate the position and intensity of the subtropical jet, all of their findings are consistent with those presented by Sakaeda and Roundy (2014), who examined these relationships through an MJO framework.

Despite the fact that the MJO is widely considered a primary source of extratropical Rossby wave forcing, it stands to reason that smaller-scale convective complexes can also modulate extratropical wave and associated jet activity. A recent study by Gloeckler and Roundy (2019b) evaluated the relationship between tropical cyclones (TCs) that traverse the MJO convective envelope and the growth of the intraseasonal subtropical jet over East Asia. Through an intraseasonal zonal momentum budget, they demonstrated that transient eddy circulations over East Asia can inject westerly momentum into and amplify the intraseasonal subtropical jet. They linked the presence and strength of these transient circulation anomalies to a composite non-recurving TC across the South China Sea. The advection of transient zonal wind by transient meridional wind on the eastern and western flanks of these eddies was shown to be the largest and only statistically significant sub-intraseasonal contributor to intraseasonal zonal wind acceleration in the context of their study. Armed with these results, this study seeks to address three questions concerning how these discrete time scale circulations interact with and feed back on one another. First, how does a transient time scale advection term project signal onto the intraseasonal time band? Second, does the intraseasonal circulation, which acts as a constant forcing term on transient time
scales, modulate these interactions? Finally, to what extent are tropical cyclones involved in these interactions? In order to address these questions, section 3.2 presents data and event selection criteria employed in this study. Section 3.3 provides an overview of the momentum budget term examined herein. Section 3.4 links a mathematical simulation of interactions between transient and intraseasonal time scale accelerations to observations thereof in reanalysis data. Finally, section 3.5 presents a concluding discussion of results and offers suggestions for future work.

3.2 Data and methods

All analyses hereinafter correspond to northern fall (September–October–November) and the period 1979–2012.

3.2.1 Data

The upper-level large-scale circulation was evaluated on a 2.5° horizontal grid using 200-hPa geopotential height, zonal, and meridional wind data obtained from the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010a) dataset and an archive of the operational Climate Forecast System version 2 (CFSv2; Saha et al. 2014) dataset. These datasets span the periods 1 January 1979 to 31 December 2010 and 1 January 2011 to present. Outgoing longwave radiation (OLR) data, obtained from the NOAA Interpolated OLR dataset (Liebmann and Smith 1996), were used as a proxy for tropical convection. Local anomalies for each field were calculated by subtracting long-term (1981–2010) means and first three seasonal cycle harmonics from corresponding total field values at every grid point.

The state of the MJO (comprising both location and amplitude of convection and circulation) was approximated using the Real-time Multivariate MJO (RMM) index (e.g., Wheeler and Hendon 2004). The index includes signals that originate outside of the MJO band (approximately 20–100-day periods; e.g., Roundy 2012) and exhibits greater sensitivity to circulation than to convection (e.g., Straub 2013); however, it is leveraged in this study because 1) it is one of the most commonly used metrics in research and operations to ap-
proximate the state of the MJO in real-time, and 2) bulk conclusions are not significantly altered when other MJO tracking indices take its place.

TC position and intensity data were obtained from version 3 (revision 6) of the International Best Track Archive for Climate Stewardship (IBTrACS) dataset \cite{knapp2010b}. This dataset includes information pertaining to TC track and intensity for seven ocean basins and extends as far back in time as 1848. Western North Pacific storms that achieved tropical status during the season and period of study were retained and stratified by the curve clustering algorithm described by \cite{camargo2007a}. See Gloeckler and Roundy \cite{gloeckler2019a} for its application in a similar context to the one presented in this study.

3.2.2 Event classification

MJO event identification follows the procedure developed by \cite{gloeckler2019a}. Dates in which the RMM index exceeded 0.5 standard deviations during the period of study were placed into a list and stratified by each of the eight RMM index phases. This lower index threshold (compared to the more conventional choice of 1 standard deviation) was selected to separate active and inactive MJO states in order to include some lower-amplitude events in the analysis (which some types of MJO-TC interactions might favor). Individual dates were then grouped into sub-lists of pseudo-consecutive days (referred to as events) by finding dates that occurred within eight days of one another. Finally, events that included any northern fall dates were retained for further analysis.

TC event identification directly utilized individual storm information provided by the IBTrACS dataset. A list of combined MJO-TC events was created by 1) selecting an RMM phase, 2) applying a 7.5° TC search radius to each grid point on the global domain, and 3) storing the dates that correspond to TCs found within the search radius. This grouping scheme helps to locate storms that occur proximate to one another during a specified RMM phase, thereby forcing geographical consistency among events.

Compatible with Gloeckler and Roundy \cite{gloeckler2019a}, RMM phase 5 was selected for
detailed evaluation. This RMM phase features the greatest number of unique West Pacific TCs during the season and period of study. Combined MJO-TC events feature non-recurving West Pacific TCs found within a search radius centered on 15°N, 115°E when no recurving West Pacific TCs existed anywhere in the basin. This search radius was selected to constrain TC geography because it contains the largest count of unique TCs of the specified type that coincide with RMM phase 5. All composites presented hereinafter utilize the list of dates belonging to the aforementioned set of combined MJO-TC events. This date list includes 24 unique events consisting of 69 individual days. Non-recurving TCs were selected for evaluation because they are underrepresented in studies that examine TC impacts on the large-scale extratropical circulation.

3.2.3 Statistical significance

All statistical significance herein was assessed by way of bootstrap resampling. For each composite assessment, the list of dates described in section 3.2.2 was randomly resampled 1,000 times, and probability distributions for a particular test statistic (in this study, the mean) were generated at each grid point from these resampled dates. If the value of the test statistic at a selected grid point fell outside of the middle 95% of its associated probability distribution, it was considered statistically significantly different from zero at the 95% level. As in Gloeckler and Roundy (2019a,b), a modification aimed at mitigating the risk of falsely claiming local significance (known as the false discovery rate, or FDR Wilks 2006, 2016) was applied to this test for gridded field assessments.

3.3 Justification of intraseasonal zonal momentum equation term selection

The local tendency of zonal wind on isobaric surfaces,

\[
\frac{\partial u}{\partial t} = -v \cdot \nabla u - \frac{\partial \Phi}{\partial x} + fv + \frac{w \tan \phi}{a} + X, \tag{3.1}
\]
is employed to answer the two questions stated in section 3.1. The first term on the right-hand side (RHS) of (3.1), which models the three-dimensional advection of zonal wind, is the only term that will be considered hereinafter (please see section 3.2.1 in Gloeckler and Roundy (2019b) for a term-by-term explanation of (3.1)). This term can be expanded as

$$ - \mathbf{v} \cdot \nabla u = - \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \omega \frac{\partial u}{\partial p} \right), \quad (3.2) $$

where each term within the parentheses on the RHS of (3.2) represents the advection of zonal wind in one of three directions (i.e., east-west, north-south, and up-down). The second term inside the parentheses describes the meridional (north-south) transfer of the total zonal wind, $u$, by the total meridional wind, $v$. These winds can be linearly decomposed into components that possess discrete characteristic timescales. Following Gloeckler and Roundy (2019b), these time scales include background (greater than 100-day periods, which includes phenomena like ENSO, along with the seasonal cycle; denoted by an overbar), intraseasonal (20–100-day periods, which includes the MJO; denoted by an asterisk), and transient (less than 20-day periods, which includes TCs and extratropical cyclones; denoted by a prime symbol) signals. Please see Gloeckler and Roundy (2019b) for an explanation of the filtering algorithm employed herein.

Applying a high pass (transient) filter to each wind component in (2) yields

$$ - \mathbf{v}' \cdot \nabla u' = - \left( u' \frac{\partial u'}{\partial x} + v' \frac{\partial u'}{\partial y} + \omega' \frac{\partial u'}{\partial p} \right). \quad (3.3) $$

Since it was reported by Gloeckler and Roundy (2019b) that the meridional advection term on the RHS of (3.3; $-v' \partial u'/\partial y$) is the only transient time scale advection term to yield significant intraseasonal zonal wind acceleration in the context of their study, (3.3) is further distilled into this single term. The two variables that comprise this term, $v'$ and $\partial u'/\partial y$, are both transient in time, meaning that their product is nonlinear (see section 3.2.1 for a demonstration of this nonlinear relationship). In other words, the product of the tran-
sient meridional wind and the meridional gradient of transient zonal wind can project onto lower frequency (longer than transient time scale) signals. Consequently, a band pass (intraseasonal) filter must be applied to (3.3) in order to extract the portion of the resultant acceleration that projects onto intraseasonal time scales. Thus, the final form of the advection term under review is $-\left[v' \partial u'/\partial y\right]^*$.

3.4 Results

Results are presented in two parts. First, a mathematical simulation is employed to demonstrate how the product of two same time scale correlated variables, $v'$ and $\partial u'/\partial y$, projects onto higher and lower frequency wave modes. A reanalysis-based observational analysis is then presented to describe physical linkages between MJO time scale zonal wind acceleration and superimposed interacting higher-frequency circulations.

3.4.1 A correlated time series simulation of cross-time scale signal projection

Given the volume of literature that relates transient eddy circulations to background zonal wind behavior, the notion of anomalous high-frequency circulations interacting with and accelerating the time-mean and zonal-mean circulations is not new. Yet, to the authors’ knowledge, there is no literature that couples a mathematical interpretation of these interactions to a simple visual depiction of them. A thought experiment is thus designed to fill this gap and provide a foundation on which to present related observational analyses. Consider two correlated time series, $X$ and $Y$, that are given by cosine waves with the general form

$$y(t) = A \cos(2\pi ft),$$

(3.4)

where $A$ is the amplitude of the wave, $f$ is its frequency, and $t$ represents a given time step. Let $X$ and $Y$ have amplitudes of 1 and 2, and frequencies of $1/2\pi$ and $2/3\pi$, respectively, so that

$$X = \cos(t)$$

(3.5)
and
\[ Y = 2 \cos \left( \frac{4t}{3} \right). \] (3.6)

Figure 3.1a reveals that \( X \) and \( Y \), which are depicted as solid and dashed black curves, exhibit varying degrees of phasing across the featured time window because their frequencies are not identical. Yet, these two time series possess systematic temporal relationships as they evolve. For example, whenever \( X \) and \( Y \) are exactly in phase (when they jointly achieve peak positive amplitude), it takes another three cycles of \( X \) and four cycles of \( Y \) to return to this same phasing. Since this relationship encompasses multiple cycles of each time series, it possesses a lower frequency (higher period) than those that characterize each individual time series. A higher frequency relationship is also evident between the time series, which manifests in one time series leading the other by a phase angle that varies with time.

The same relationships between \( X \) and \( Y \) can be described mathematically by employing the trigonometric identity for the product of two cosine waves with corresponding angles \( \alpha \) and \( \beta \),
\[ \cos \alpha \cos \beta = \frac{\cos(\alpha + \beta) + \cos(\alpha - \beta)}{2}. \] (3.7)
Applying (3.7) to \( X \) and \( Y \) yields
\[ 2 \cos(t) \cos \left( \frac{4t}{3} \right) = \cos \left( \frac{t + 4t}{3} \right) + \cos \left( \frac{t - 4t}{3} \right) = \cos \left( \frac{7t}{3} \right) + \cos \left( \frac{-t}{3} \right). \] (3.8)
Following (3.8), the product of \( X \) and \( Y \) is identical to the sum of cosine waves \( x \) and \( y \), whose frequencies are \( 7/6\pi \) and \( -1/6\pi \), respectively. Fig. 3.1b depicts these lower and higher frequency waves as solid and dashed black curves, respectively, while Fig. 3.1c demonstrates that their product (solid black curve) is identical to the sum of \( x \) and \( y \) (dashed grey curve). These operations are negated in order to relate them to horizontal advection.
3.4.2 West Pacific non-recurving TCs in the context of the transient large-scale circulation

Building on the thought experiment presented in section 3.4.1, Fig. 3.2 sets the stage for the observational portion of this study by overlaying transient 200-hPa vector wind anomalies and intraseasonal-filtered meridional advection of transient zonal wind on 200-hPa intraseasonal zonal wind. These fields are averaged over a five-day period centered on the set of dates that includes a cresting TC over the South China Sea (indicated by the red TC symbol) during RMM phase 5 (lag zero; see section 3.2.2). The black box centered on Japan draws attention to an amplifying intraseasonal zonal jet streak (red shading) accompanying MJO convection to its south (not shown) through which anomalous transient northerly wind is directed. Black contours within this box depict statistically significant positive values of intraseasonal zonal wind acceleration that are produced by the meridional advection of transient zonal wind through the box. Figure 3.3 shows this filtered field averaged over the boxed region along with its unfiltered variant (black curve). Consistent with Fig. 3.1, unfiltered advection (the negated product of $v'$ and $\partial u'/\partial y$) exhibits high-frequency variability superimposed on an apparent low-frequency oscillation. Shading, which represents the intraseasonally evolving component of the nonlinear product depicted by the black curve, closely matches the low-frequency signal through the entire 61-day lag window. This result suggests that intraseasonal time scale accelerations produced by transient time scale motions are significantly influenced by the evolution of the underlying (background) intraseasonal zonal wind.

The relationship between the composite non-recurving TC over the South China Sea and transient eddy presence over East Asia is now examined. Figure 3.4 overlays 10°N–20°N-averaged transient OLR anomalies on 30°N–45°N-averaged transient anomalous geopotential height. A standing geopotential wave pattern centered between 110°E and 120°E is evident across the entire lag window. To its south, the composite TC is embedded in a westward-moving envelope of transient anomalous convection (suggested by negative OLR anomalies...
depicted by solid black contours). On its approach to the Philippines (120°E–125°E), the standing geopotential signal amplifies (its amplitude increases by nearly a factor of two). These results suggest the hypothesis that the transient convective envelope, which includes the composite TC, amplifies the higher-latitude transient eddies. Its arrival in this region also coincides with a change in the zonal motion of the geopotential signal. Prior to lag zero, it is predominantly westward in nature (implied by a leftward translation of blue and red shading with increasing time). However, eastward motion becomes apparent to the east of the composite TC base longitude from approximately lag zero onward, which can be interpreted as an eastward translation of individual transient trough and ridge anomalies.

The link between the composite TC and the amplifying transient geopotential signal to its north is further examined in Fig. 3.5. A maximum in horizontal upper-level irrotational wind (yellow vectors) encircling the red TC symbol closely resembles upper-level divergent outflow that accompanies anomalous latent heat release (the starburst pattern over the South China Sea and adjacent Southeast Asia) and associated vigorous upward vertical motion. Negatively anomalous transient OLR (suggesting enhanced convection) and vertical wind (implying enhanced upward motion; dashed magenta contours) are most pronounced at the location of the composite TC, suggesting that it is largely responsible for this irrotational wind pattern. Poleward of this outflow signature lies an anomalous transient geopotential ridge. While the TC is not responsible for ridge existence because the ridge is part of an established standing oscillation, the fact that its outflow signature is proximate to and directed toward the equatorward flank of the ridge anomaly lends credence to the suggestion that it contributes to ridge amplification.

The transient geopotential ridge investigated in Figs. 3.4 and 3.5 is part of an eastward-translating transient Rossby wave train that evolves on top of the intraseasonal zonal wind, which behaves as a background wind to transient time scale circulations. Figure 3.6 illustrates a two-week pentad-mean progression of this wave train overlaid on the intraseasonal zonal wind. As individual transient trough and ridge anomalies move eastward, they develop
pronounced southwest-northeast-oriented (positive) tilts. This tilt orientation is consistent with anticyclonic (LC1) wave breaking (Thorncroft et al. 1993) over the North Pacific Ocean. Positive wave tilt is most pronounced to the east of the red shading—an anomalously strong intraseasonal subtropical jet—straddling the East Asian coastline, which is consistent with studies that have noted enhanced anticyclonic wave breaking at the exit region of the subtropical jet (e.g., Moore et al. 2010; MacRitchie and Roundy 2016).

In addition to a marked wave tilt signature, there is a pronounced poleward shift in the positive intraseasonal zonal wind anomaly (another characteristic of anticyclonic wave breaking; Thorncroft et al. 1993) and transient eddies that traverse it (note especially the poleward shift in contours over East Asia). To better visualize the meridional evolution of these two fields, Fig. 3.7 displays a time-latitude section of intraseasonal zonal wind and transient geopotential height averaged between 125°E and 145°E (the latitude boundaries corresponding to the averaging box depicted in Fig. 3.2). A clear poleward progression of both fields is evident across the entire lag window (Fig. 3.7a), with both sets of anomalies peaking in amplitude between five and ten days after the composite TC crests in the South China Sea. This time period lags a box-averaged peak in positive intraseasonal zonal wind acceleration associated with the meridional advection of transient zonal wind by transient meridional wind (Fig. 3.7b). Acceleration occurs in conjunction with the emergence of a low-latitude wave train approximately ten days prior to lag zero. This wave train, which exhibits gradual poleward dispersion and rapid poleward translation of individual trough and ridge anomalies, is consistent with an upper-level response to the convective signal detailed in Fig. 3.2. The extent to which this transient wave train facilitates intraseasonal zonal wind acceleration is examined in greater detail in section 3.2.3.
3.4.3 Relating transient time scale motions to intraseasonal zonal wind acceleration through the flux form of advection

The mathematical expression for three-dimensional advection, \( -\mathbf{v} \cdot \nabla u \), can be recast into a form that includes the convergence of the meridional transient flux of zonal momentum (hereafter momentum flux convergence) by applying the vector identity

\[
-\mathbf{v} \cdot \nabla u = u \nabla \cdot \mathbf{v} - \nabla \cdot (u \mathbf{v}).
\]  

(3.9)

Expanding the RHS of (3.9) and rearranging terms yields

\[
-\mathbf{v} \cdot \nabla u = \left( \frac{\partial u}{\partial x} - \frac{\partial(uu)}{\partial x} \right) + \left( \frac{\partial v}{\partial y} + \frac{\partial(uv)}{\partial y} \right) + \left( \frac{\partial \omega}{\partial p} - \frac{\partial(u\omega)}{\partial p} \right). 
\]

(3.10)

Following the discussion in section 3.3, each term on the RHS of (3.10) can be linearly decomposed into discrete temporal bands. In light of this study’s objective, the flux form of advection is only considered with respect to the advection of transient zonal wind by transient meridional wind:

\[
- v' \frac{\partial u'}{\partial y} = u' \frac{\partial v'}{\partial y} - \frac{\partial(u'v')}{\partial y}.
\]

(3.11)

A band pass (intraseasonal) filter is next applied to each of the terms in (3.11) to extract the intraseasonal time scale portion of their signals:

\[
- \left[ v' \frac{\partial u'}{\partial y} \right]^* = \left[ u' \frac{\partial v'}{\partial y} \right]^* - \left[ \frac{\partial(u'v')}{\partial y} \right]^*.
\]

(3.12)

The first term on the RHS of (3.11) emerges from a mathematical property of (3.9). While it is difficult to physically interpret, expanding the second term on the RHS of (3.11; momentum flux convergence) by leveraging the product rule for derivatives provides some
guidance with regard to its utility. The resultant expansion,

\[-v' \frac{\partial u'}{\partial y} = u' \frac{\partial v'}{\partial y} - u' \frac{\partial v'}{\partial y} - v' \frac{\partial u'}{\partial y},\]  

produces an equal but opposite-signed term, which yields cancellation of the original. Thus, the first term on the RHS of (3.11) might be considered an error term that arises from directly relating momentum flux convergence to advection. For completeness, this error term will be broadly related in forthcoming analyses to its parent advection term.

The flux form of the advection of transient zonal wind by transient meridional wind facilitates a comparison of relationships between transient time scale motions and intraseasonal (low-frequency) time scale accelerations to past studies that have examined similar relationships through a flux framework (e.g., Feldstein 1998). Figure 3.8 shows the partition of the total intraseasonal-filtered advection of transient zonal wind by transient meridional wind (dark red curve) into its momentum flux convergence (light red curve) and error (orange curve) components. It reveals that within the averaging box centered on Japan (see Fig. 3.2), the meridional convergence of transient zonal wind flux leads the total advection of transient zonal wind by transient meridional wind by one to two days, suggesting that it helps to amplify this acceleration term. The error component, on the other hand, lags the total advection by one to two days, suggesting that it extends the period of already established acceleration. Figure 3.9 displays the time-latitude relationship between the poleward-shifting transient eddies displayed in Fig. 3.7, the poleward-shifting intraseasonal zonal wind signal, and accelerations induced by meridional flux convergence. Red shading, denoting positive (westerly) zonal wind acceleration generated by transient meridional eddy flux convergence, migrates poleward in lockstep with the poleward-dispersing signal in transient geopotential height (Fig. 3.7a). The jet closely follows both of these meridionally translating signals, shifting toward the red shading (westerly acceleration) on its poleward flank and away from the blue shading (easterly acceleration) on its equatorward flank (e.g., James and Dodd 100)
Box-averaged intraseasonal zonal wind acceleration induced by the advection of transient zonal wind by transient meridional wind (Fig. 3.9) peaks in conjunction with the transit of anomalous meridional flux convergence across the 30°N–45°N latitude band.

Figure 3.9 suggests a robust relationship between meridional flux convergence and the transient eddies implied by the geopotential height anomaly pattern in panel (a). Recall from Fig. 3.4 that the arrival of the composite TC in the South China Sea coincides with the emergence of an eastward-moving signal in the 30°N–45°N-averaged transient geopotential height field to the east of the TC base longitude. That eastward-moving signal, coupled with the equatorward-moving geopotential height signal through the same latitude band in Fig. 3.9 implies positive (southwest-northeast-oriented) eddy tilt. Note, too, poleward-moving geopotential height anomalies equatorward of the subtropical jet spanning the period eight days before to eight days after the composite reference dates (lag zero). These height anomalies, which originate near 15°N (the latitude at which the composite TC crests), also exhibit eastward motion as they migrate poleward (not shown), implying negative (southeast-northwest-oriented) eddy tilt. Positively tilted eddies poleward of the jet produce anomalous meridional flux convergence on the poleward side of the jet and anomalous meridional flux divergence equatorward of the jet, yielding westerly and easterly intraseasonal zonal wind acceleration, respectively, in these regions. In a similar vein, negatively tilted eddies on the equatorward side of the jet enhance the meridional flux divergence (easterly acceleration) observed in this region and contribute to meridional flux convergence (westerly acceleration) at lower latitudes.

Figure 3.8 demonstrated that meridional flux convergence can only describe a portion of the total advection of transient zonal wind by transient meridional wind, meaning that the flux convergence field portrayed in Fig. 3.9 does not provide a complete representation of advection. The error term described at the beginning of this subsection is thus displayed in Fig. 3.10 to briefly highlight the remainder of the advection term. Positive intraseasonal zonal wind acceleration associated with this term is maximized on the poleward side of
the poleward-shifting intraseasonal zonal wind signal, but unlike the meridional eddy flux convergence detailed in Fig. 3.9, it is mainly confined to poleward of 30°N (Fig. 3.10a). There is also a lower amplitude positive acceleration induced by this term on the equatorward side of the subtropical jet, which acts to somewhat offset the negative (easterly) acceleration that results from flux divergence in this area (see Fig. 3.9a).

To synthesize the intraseasonal acceleration terms presented in Figs. 3.9 and 10, Fig. 3.11a displays the intraseasonal-filtered advection of transient zonal wind by transient meridional wind (i.e., the sum of the shaded fields in Figs. 3.9a and 10a). It exhibits poleward motion on the poleward flank of the positive intraseasonal zonal wind anomaly (indicated by solid black contours), as well as peak amplitude that leads the maximum in intraseasonal zonal wind. This space-time relationship implies a contribution to the poleward growth of the anomalous intraseasonal subtropical jet by zonal wind acceleration induced by $-v' \partial u'/\partial y$.

On the equatorward flank of the positive intraseasonal zonal wind anomaly resides easterly zonal wind acceleration, which is largely forced by meridional flux divergence (see Fig. 3.9a). The poleward propagation of the intraseasonal zonal wind signal is thus consistent with the total advection field displayed in Fig. 3.11a, which depicts easterly acceleration on the equatorward side and westerly acceleration on its poleward side of the jet. This acceleration pattern ultimately contributes to a poleward shift of the positive intraseasonal zonal wind anomaly (James and Dodd 1996).

What yields the dramatic adjustment in transient eddy tilt illustrated in Fig. 3.6 and implied by the time-latitude evolution of the geopotential height field in Figs. 3.7, 9, and 10? These results suggest the hypothesis that this wave tilt evolution relates to the change in meridional shear that transient eddies experience (e.g., Sakaeda and Roundy 2014) as they migrate poleward. Figure 3.6 shows pentad-mean transient anomalous geopotential height overlaid on the sum of the background and intraseasonal zonal winds. As the intraseasonal zonal wind maximum shifts poleward, so too do transient eddies that are guided along it. On approach to the latitude at which the maximum in background wind exists, these eddies
experience enhanced large-scale anticyclonic shear imparted by the background zonal wind, which is an order of magnitude larger than the intraseasonal or transient zonal winds. Transient eddies thus become more positively tilted and elongated, which promotes an increase in the poleward flux of westerly momentum. Figure 3.13 depicts the relationship between increasingly positive transient eddy tilt and the intraseasonal zonal wind acceleration attributed to the advection of transient zonal wind by transient meridional wind. An increase in westerly acceleration (red shading) is observed in association with increasingly positive eddy tilt through the highlighted two-week period. Westerly acceleration originates over a relatively confined portion of East Asia and the adjacent Northwest Pacific Ocean in the first pentad (Fig. 3.13a). It then grows in amplitude as it migrates poleward and eastward in the subsequent two pentads (Figs. 3.13b,c), which is consistent with the poleward progression of the transient Rossby wave train to which it relates. Such a progression is also consistent with the gradual poleward shift in the anomalously strong intraseasonal subtropical jet signal depicted in Figs. 3.7, 9, 10, and 11.

3.5 Concluding discussion

An examination of the relationship between transient eddy circulations and intraseasonal zonal wind acceleration was carried out in an attempt to better understand some of the physical mechanisms that relate these discrete time scale components of the global circulation. This study extends work by Gloeckler and Roundy (2019b), who demonstrated that the meridional advection of transient zonal wind by transient meridional wind is a key contributing advection term to westerly intraseasonal zonal wind acceleration over East Asia when MJO convection is active over the Maritime Continent and non-recurving TCs are transiting a South China Sea search radius. In fact, they reported that the meridional component of three-dimensional transient zonal wind advection \((-v'\partial u'/\partial y)\) associated with their set of events is comparable in size to advection terms that represent the interplay between the background and intraseasonal winds. These terms tend to dominate intraseasonal
zonal wind acceleration because intraseasonal and background wind components are generally larger (in the case of the background wind, much larger) than the transient wind. In light of their results, this study seeks to further understand intraseasonal zonal wind acceleration associated with the advection of transient zonal wind by transient meridional wind through the same set of combined MJO-TC events that they utilized.

In order to examine cross-time scale circulation interactions, a correlated time series simulation was first presented to provide a mathematical framework and simple visual depiction of these relationships. This simulation showed that the product of two time series that possess similar frequencies is nonlinear—it is expressed as high-frequency oscillations that are superimposed on a low-frequency wave (Fig. 3.1). The negative product of transient meridional wind and the meridional gradient of transient zonal wind (i.e., the advection of transient zonal wind by transient meridional wind, \(-v' \partial u' / \partial y\)) was then computed over a 20°-by-15° box centered on Japan. The result of this computation revealed a series of high-frequency oscillations superimposed on a low-frequency wave (Fig. 3.3), consistent with the correlated time series simulation, which motivated the remaining analyses presented in section 3.4.

Numerous past studies have related the evolution of the time-mean and zonal-mean zonal wind to accelerations induced by transient eddy circulations (e.g., James and Dodd 1996; Feldstein 1998; Lee et al. 2007; Yuan et al. 2013; Sakaeda and Roundy 2014, 2016). In order to facilitate comparisons between this study and those, the advection of transient zonal wind by transient meridional wind was recast into a form that includes the convergence of the meridional transient flux of zonal momentum. Corresponding results are summarized in the schematic presented in Fig. 3.14. A transient Rossby wave train manifested in anomalous 200-hPa geopotential height emerges and disperses poleward as the composite TC approaches its South China Sea base longitude (Fig. 3.14a). This wave train is likely related in part to enhanced latent heat release and associated upper-level divergent outflow accompanying the TC (see Figs. 3.4 and 3.5). Its poleward and eastward motion
implies negative (southeast-northwest-oriented) tilt to individual trough and ridge anomalies that form it. Such a tilt orientation yields an equatorward flux of westerly momentum and associated transient meridional flux divergence on the equatorward side of an anomalously strong intraseasonal subtropical jet over East Asia and the adjacent Northwest Pacific Ocean. Poleward of this jet resides an equatorward-propagating transient extratropical Rossby wave train. Eastward and equatorward motion of individual trough and ridge anomalies that form this wave train implies positive (southwest-northeast-oriented) eddy tilt. These positively tilted waves are associated with a poleward flux of westerly momentum and attendant transient meridional flux convergence on the poleward side of the jet, while they enhance flux divergence that is partly induced by the TC-related Rossby wave train on the equatorward side of the jet. The resulting accelerations contribute to a gradual poleward shift of the intraseasonal subtropical jet signal observed over this region (Fig. 3.14b).

Transient eddy tilt was identified as a key factor that modulates meridional momentum flux and associated intraseasonal zonal wind acceleration. Consistent with observations by Sakaeda and Roundy (2014, 2016), transient eddies that propagate along an anomalous intraseasonal subtropical jet (a wave guide to these circulations) experience meridional shear that is imparted by the background zonal wind, which is generally much stronger than its transient counterpart. As the intraseasonal zonal wind and accompanying transient eddies shift poleward and approach the latitude of the background zonal wind maximum, the transient eddies experience enhanced anticyclonic shear that forces them to become more positively tilted (see Fig. 3.12). Increased positive wave tilt enhances poleward westerly momentum flux, which converges on the poleward flank of the intraseasonal subtropical jet and contributes to its continued poleward migration (Fig. 3.14b). Intraseasonal zonal wind acceleration attributed to transient meridional advection of transient zonal wind thus appears to be largely regulated by the intraseasonal circulation itself, which, in turn, is modulated by transient eddies that generate these accelerations.

Synthesizing the aforementioned relationships with the correlated time series simulation
presented in section 3.4.1 provides physical justification for the intraseasonal projection of transient time scale accelerations. From a mathematical standpoint, these cross-time scale projections arise from the product of two variables that are not constant with respect to one another over a given time window. Such a product is nonlinear in nature, and its sign is governed by the relationship between the variables that produce it. For example, in the case of the advection of transient zonal wind by transient meridional wind, when $v' > 0$ and $\partial u'/\partial y < 0$, their product, which is negative, yields a positive acceleration due to the leading negative sign associated with the mathematical definition of advection. Figure 3.15 presents a schematic illustration that links these mathematical relationships to wave tilt (discussed in sections 3.4.2 and 3.4.3). In Fig. 3.15a, a positively tilted, equatorward moving transient Rossby wave is associated with positive zonal wind acceleration on its poleward flank and negative zonal wind acceleration on its equatorward flank, consistent with the flux convergence arguments presented in section 3.4.3. As dictated by the mathematics, a positive zonal wind acceleration occurs, for example, where $v' > 0$ coincides with $\partial u'/\partial y < 0$ (poleward of the negative transient zonal wind anomaly downstream of the transient ridge axis). In this region, anomalous transient westerly wind is advected equatorward by the anomalous transient northerly wind. Farther equatorward, where $v' < 0$ and $\partial u'/\partial y < 0$ (equatorward of the negative transient zonal wind anomaly downstream of the transient ridge axis), anomalous transient easterly wind is advected equatorward by anomalous transient northerly wind. These physical relationships concentrate transient westerly wind acceleration on the poleward side of the wave train, and transient easterly wind acceleration on its equatorward side. Opposite relationships can be inferred in association with a negatively tilted wave train (Fig. 3.15b).

A change in wave tilt is not the only mechanism through which changes in the relationship between $v'$ and $\partial u'/\partial y$ (and attendant sign changes in zonal wind acceleration) are realized. Consider a point fixed in space over which a transient Rossby wave passes (Fig. 3.16). At an initial time (Fig. 3.16a), positive zonal wind acceleration is observed at
the reference point, which is located poleward of a transient easterly wind anomaly on the downstream side of a positively tilted transient ridge axis. At a later time, (Fig. 3.16b), the wave train has shifted poleward, placing the reference point on the equatorward side of a transient easterly wind anomaly located downstream of a still-positively tilted transient ridge axis. In both cases, an anomalous transient northerly wind is experienced at the fixed reference point. However, its position relative to a transient easterly wind anomaly changes as the Rossby wave train migrates poleward, much like the wave train that was featured through sections 3.4.2 and 3.4.3. A change in the relationship between $v'$ and $\partial u'/\partial y$ (and the sign of their associated product) is thus realized at the reference point, accounting for a change in the sign of zonal wind acceleration (i.e., a transition from positive to negative, or westerly to easterly).

One somewhat deficient aspect of this study is that which concerns attributing TC presence to the interactions between transient eddy circulations and the intraseasonal zonal wind. There is enough observational evidence to confidently suggest that non-recurving TCs included in the set of events leveraged in this study contribute to a rearrangement of zonal momentum by forcing a poleward-dispersing negatively tilted transient Rossby wave train on the equatorward side of the subtropical jet. That TCs (or other high-frequency tropical convective modes) are a necessary part of this process remains to be evaluated. One way to perform such an evaluation is through an idealized modeling study. Model experiments can include initial conditions that feature and exclude TCs in the presence of a convectively active MJO event. An additional set of experiments might include initial conditions that feature TCs in the presence of a convectively suppressed MJO event. Such a study would likely go a long way toward describing interactions between TCs and the time-mean circulation.
Figure 3.1: (a) Two correlated time series, $X$ and $Y$, that exhibit comparable frequencies across a prescribed period of time. (b) Two correlated time series, $x$ and $y$, with highly dissimilar frequencies across the same time period in (a). (c) The product of the time series in (a; solid black curve) and the sum of time series in (b; dotted grey curve).
Figure 3.2: Intraseasonal-filtered 200-hPa zonal wind (shaded according to scale in m s$^{-1}$, transient-filtered 200-hPa vector wind (yellow vectors in m s$^{-1}$; only statistically significant values are shown; a reference vector is located above the top-left corner of the figure axis), and the advection of transient zonal wind by transient meridional wind (black contours outlining values that exceed $1 \times 10^{-5}$ m s$^{-2}$; only statistically significant values are shown). Statistically significant zonal wind anomalies are stippled. The black box outlines the averaging region described in the text. The center of the TC search radius employed in this study is indicated by a red TC symbol.
Figure 3.3: The advection of transient zonal wind by transient meridional wind (solid black line) overlaid on the intraseasonal-filtered advection of transient zonal wind by transient meridional wind (shaded according to scale and scaled by a factor of $1 \times 10^5$ m s$^{-2}$).
Figure 3.4: Longitude-time section of transient anomalous 200-hPa geopotential height (shaded according to scale in gpm) and transient anomalous OLR (black contours in W m\(^{-2}\); negative values are displayed in solid contours; contour interval is 3 W m\(^{-2}\); the zero contour is omitted). Statistically significant OLR anomalies are hatched and statistically significant geopotential height anomalies are stippled. The longitude-time center of the TC search radius employed in this study is indicated by a red TC symbol.
Figure 3.5: Transient anomalous OLR (shaded according to scale in W m$^{-2}$; only statistically significant values are shown), transient anomalous 200-hPa irrotational wind (yellow vectors in m s$^{-1}$; only statistically significant values are shown; a reference vector is located above the top-left corner of the figure axis), transient anomalous 200-hPa vertical wind (magenta contours in Pa s$^{-1}$; negative values implying upward vertical motion are dashed; contour interval is $1.2 \times 10^{-2}$ Pa s$^{-1}$; the zero contour is omitted), and transient anomalous 200-hPa geopotential height (black contours in gpm; negative values are dashed; contour interval is 3 gpm; the zero contour is omitted). Statistically significant vertical wind and geopotential height anomalies are hatched. The center of the TC search radius employed in this study is indicated by a red TC symbol.
Figure 3.6: Pentad-mean intraseasonal anomalous 200-hPa zonal wind (shaded according to scale in m s\(^{-1}\)) and transient anomalous 200-hPa geopotential height (black contours in gpm; negative values are dashed; contour interval is 5 gpm; the zero contour is omitted). Time lags included in each pentad are indicated to the left of each panel. Statistically significant zonal wind anomalies are stippled and statistically significant geopotential height anomalies are hatched. The black box in each panel outlines the averaging region described in section 3.4.2. The center of the TC search radius employed in this study is indicated by a red TC symbol in panel (a).
Figure 3.7: (a) A time-latitude section of 125°E–145°E-averaged intraseasonal anomalous 200-hPa zonal wind (shaded according to scale in m s⁻¹; statistically significant values are stippled) and transient anomalous 200-hPa geopotential height (black contours in gpm; negative values are dashed; contour interval is 3 gpm; the zero contour is omitted; statistically significant values are hatched). (b) The 30°N–45°N, 125°E–145°E-averaged advection of transient zonal wind by transient meridional wind (black curve). Statistically significant values are indicated by black unfilled circles. The time lag in which the composite TC crests inside its search radius is indicated by a red TC symbol.
Figure 3.8: The lagged evolution of the intraseasonal filtered 200-hPa advection of transient zonal wind by transient meridional wind (dark red curve), the intraseasonal filtered 200-hPa meridional flux convergence of transient zonal wind (light red curve), and the intraseasonal filtered 200-hPa transient meridional mass convergence (orange curve). All values are computed across a domain bounded to the west and east by 125°E and 145°E, and to the south and north by 30°N and 45°N, and are scaled by a factor of $1 \times 10^5$. Statistically significant values are indicated by unfilled circles.
Figure 3.9: As in Fig. 3.7, but shading in (a) depicts the intraseasonal-filtered meridional flux convergence of transient zonal wind \((-[\partial(u'v')/\partial y]^*)\). Additionally, the overlaid semi-transparent grey shading in (a) depicts statistically significant intraseasonal anomalous 200-hPa zonal wind that exceeds 1 m s\(^{-1}\) eastward.
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Figure 3.10: As in Fig. 3.9 but shading in (a) depicts the intraseasonal-filtered product of transient zonal wind and transient meridional divergence ($[u'\partial v'/\partial y]^*$).
Figure 3.11: As in Fig. 3.7, but shading in (a) depicts the intraseasonal-filtered advection of transient zonal wind by transient meridional wind ($- [v' \partial u' / \partial y]$; the sum of the shaded fields in Figs. 3.9 and 10) and contours depict intraseasonal anomalous 200-hPa zonal wind (contour interval is 1 m s$^{-1}$; the zero contour is omitted).
Figure 3.12: As in Fig. 3.6, but shading depicts background (the sum of the seasonal cycle, low-frequency, and intraseasonal) 200-hPa zonal wind (in m s$^{-1}$).
Figure 3.13: As in Fig. 3.6 but shading depicts intraseasonal zonal wind acceleration (in m s\(^2\)) induced by the intraseasonal-filtered advection of transient zonal wind by transient meridional wind \((-[v'\partial u'/\partial y]^*+\partial ([u'v']/\partial y)^*-[\partial (u'v')/\partial y]^*)\). Acceleration is scaled by a factor of \(1 \times 10^5\).
Figure 3.14: A schematic depiction of relationships between transient eddies, the intraseasonal zonal wind, and the background zonal wind at (a) an initial time and (b) after a time step of $\Delta t$ has elapsed. All symbols and processes depicted in the schematic are described in the legend at right.
Figure 3.15: A schematic depiction of relationships between tilted transient Rossby waves, zonal and meridional transient wind anomalies, and zonal wind acceleration accompanying (a) positively tilted and (b) negatively tilted waves. All symbols and processes depicted in the schematic are described in the legend below the graphical depictions.
Figure 3.16: A schematic depiction of relationships between positively tilted transient Rossby waves, zonal and meridional transient wind anomalies, and zonal wind acceleration accompanying at a fixed reference point. (a) Demonstrates these relationships at an initial time, while (b) demonstrates these relationships after the wave train has shifted poleward at a later time. All symbols and processes depicted in the schematic are described in the legend below the graphical depictions.
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