Robustness of Relations between the MJO and U.S. Tornado Occurrence

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(Manuscript received 12 June 2018, in final form 9 August 2018)

ABSTRACT

The Madden–Julian oscillation (MJO) is the leading mode of tropical variability on subseasonal time scales and has predictable impacts in the extratropics. Whether or not the MJO has a discernible influence on U.S. tornado occurrence has important implications for the feasibility of extended-range forecasting of tornado activity. Interpretation and comparison of previous studies is difficult because of differing data periods, methods, and tornado activity metrics. Here, a previously described modulation of the frequency of violent tornado outbreaks (days with six or more tornadoes reported rated EF2 or greater) by the MJO is shown to be fairly robust to the addition or removal of years to the analysis period and to changes in the number of tornadoes used to define outbreak days, but is less robust to the choice of MJO index. Earlier findings of a statistically significant MJO signal in the frequency of days with at least one tornado report are shown to be incorrect. The reduction of the frequency of days with tornadoes rated EF1 and greater when MJO convection is present in the Maritime Continent and western Pacific is statistically significant in April and robust across varying thresholds of reliably reported tornado numbers and MJO indices.

1. Introduction

Tornadoes occur around the world. The largest numbers of tornadoes are reported in the United States, where the combination of instability and circulation in some regions frequently produces favorable conditions for severe thunderstorms, particularly in spring. For this reason, specially trained forecasters and dedicated report collection efforts for tornadoes have existed in the United States since the 1950s (Galway 1989). An important advance in the 1990s was the realization that the favorability of the atmosphere for the occurrence of tornadoes and severe (especially supercell) thunderstorms could be summarized, at least to first order, by relatively simple severe thunderstorm parameters or indices that are functions of the surrounding winds and instability (Davies and Johns 1993; Davies et al. 1993). Advances in understanding, combined with improvements in numerical weather prediction (NWP), allow forecasters to routinely identify in advance regions where conditions will be conducive to severe thunderstorms occurrence. NOAA's Storm Prediction Center issues convective outlooks as far as a week in advance, and NOAA's Climate Prediction Center includes severe weather in its U.S. hazards outlooks, which extends out to 14 days.

There are no operational severe thunderstorm forecast products beyond 14 days, which is near the limit of predictability for weather (Simmons and Hollingsworth 2002). However, forecasts for precipitation and near-surface temperature with lead times of weeks and seasons are now routine. One reason for the lack of severe thunderstorm outlooks at longer leads is that it has proved challenging to identify predictable climate signals that affect the level of severe thunderstorm activity, and that would thereby provide a basis for extended-range forecasts. ENSO is the leading source of seasonal predictability in the climate system, and it influences seasonal averages of precipitation and near-surface temperature in some regions of the United States, especially during winter (L'Heureux et al. 2015). ENSO has a detectable impact on U.S. tornado activity in winter (January–March; Cook and Schaefer 2008) and spring (March–May; Allen et al. 2015), with overall enhanced U.S. tornado activity being associated with La Niña conditions. However, the magnitude of the ENSO signal in tornado activity is modest, even compared to that for hail, and the limited variability of tornado activity explained by ENSO is reflected in the fairly low skill of seasonal tornado activity forecasts based

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DOI: 10.1175/MWR-D-18-0207.1

on the ENSO state (Lepore et al. 2017). The limited explanatory power of ENSO is also apparent in the below-average number of tornado reports so far in 2018 (366 NWS local storm reports through May), despite the La Niña conditions that extended from the fall of 2017 into spring of 2018.

The Madden–Julian oscillation (MJO) is the most important climate signal on subseasonal time scales and a source of subseasonal predictability (Madden and Julian 1972; Vitart 2014). Although a tropical phenomenon, MJO convection excites Rossby waves, which result in extratropical teleconnections. The current generation of numerical weather prediction (NWP) models skillfully predicts the Real-time Multivariate MJO (RMM; Wheeler and Hendon 2004) index 2–4 weeks in advance and, to some extent, the associated MJO teleconnections (Vitart 2017; Lim et al. 2018). The MJO impacts U.S. surface climate, especially during the winter. For instance, November–March daily rainfall in the central United States is enhanced during RMM phases 5–7 (Becker et al. 2011). U.S. impacts of the MJO on surface climate are more limited in summer and confined mostly to the southeast (Zhou et al. 2011). Operational submonthly forecasts of U.S. surface climate use guidance tools that take into account MJO phase and ENSO state (Johnson et al. 2014).

Many studies of MJO impacts and predictability use the RMM index to characterize the MJO state. The RMM index is defined using meridional averages of outgoing longwave radiation (OLR) and zonal winds in the tropics. However, despite containing OLR in its formulation, the RMM index is primarily determined by its wind components (Straub 2013). The OLR-based MJO index (OMI; Kiladis et al. 2014), which is also well predicted by current NWP systems (Wang et al. 2018a, manuscript submitted to *Climate Dyn.*), focuses on MJO convection rather than circulation and consequently emphasizes different aspects of the MJO. In addition to using different variables, OMI differs from RMM by using seasonally varying meridional structures. These differences mean that the amplitude and timing of particular MJO events may be differently described by the RMM and OMI indices. Impacts that depend more strongly on a particular aspect of the MJO are better described by one index than the other. For instance, the spatial structures and propagation patterns associated with different MJO indices may be quite distinct during boreal summer (Wang et al. 2018b).

To date, a handful of studies have examined the influence of the MJO on U.S. thunderstorm activity, where thunderstorm activity takes the form of tornado occurrence (Thompson and Roundy 2013; Barrett and Gensini 2013), days with hail (Barrett and Henley 2015), and cloud-to-ground (CG) lightning flashes (Abatzoglou and Brown 2009). Differing methodologies, choices of thunderstorm phenomena, analysis periods, and seasons considered make a simple reconciliation of these findings difficult. For instance, Thompson and Roundy (2013) found that violent tornado outbreaks[1] (days with six or more significant tornado reports) were twice as likely during phase 2 of the RMM index compared to other phases or neutral conditions in the months of March–May (MAM) during the period 1975–2010. On the other hand, Barrett and Henley (2015, Fig. 12) show that the frequency of days with hail during May was substantially reduced during phase 2 compared to the period 1990–2013. Barrett and Gensini (2013) observed that tornado days (days with one or more tornado reports east of 106° and west of 90°) were more frequent during RMM phases 6 and 8 and less frequent during phases 3, 4, and 7 during April, but had the opposite relation for phases 3 and 8 in May. Abatzoglou and Brown (2009) found reduced numbers of CG lightning flashes in RMM phase 5 and enhanced lightning in phase 6 over large portions of the United States during June–September. Overall, it seems fair to say that a robust picture of the impact of the MJO on U.S. thunderstorm activity has not yet emerged.

Some of these differences may be related to different choices of tornado activity metrics and analysis periods. There is reason to expect that analysis results might be sensitive to these choices because of inhomogeneities in the U.S. tornado report database (Verbout et al. 2006). For instance, the use by Thompson and Roundy (2013) of the 1975–2010 period might be questioned because intensity ratings were assigned based on damage descriptions rather than damage surveys during the first part of that period, with a tendency toward overestimation of the numbers of significant tornadoes. Likewise, one might question the choice of Barrett and Gensini (2013) to include the weakest tornadoes in their definition of tornado days since the numbers of the weakest tornadoes are known to be strongly influenced by changes in technology and reporting practices. Also, previous studies only considered the RMM index. To address these issues, here we examine the influence of MJO phase on the frequency of U.S. tornado occurrence and consider the sensitivity to the tornado occurrence definition, the analysis period, and the choice of MJO index.

2. Data and methods

a. U.S. tornado reports

Tornado reports come from NOAA's Storm Prediction Center (http://www.spc.noaa.gov/wcm/data/1950-2017_actual_tornadoes_prelim.csv). Here, we use reports from

[1] The violent tornado outbreak definition here differs from the convention of classifying violent tornadoes as those rated EF4–5.

the period 1975–2016, which matches the RMM data availability. The first complete year of RMM data is 1975. Tornadoes are rated by damage using the Fujita (F) scale and since 2007 using the enhanced Fujita (EF) scale (Doswell et al. 2009). Both scales go from 0 (least damage) to 5 (most damage). We use the notation E/F0+ to refer to tornadoes rated 0 or greater on either the F scale or EF scale, E/F1+ to refer to tornadoes rated 1 or greater on either the F scale or EF scale, and so on.

b. MJO data

The MJO is an eastward-propagating tropical disturbance characterized by anomalous circulation and convection. The RMM index is based on the leading two multivariate empirical orthogonal functions (EOFs) of latitudinally averaged OLR and zonal wind at 200 and 850 hPa (Wheeler and Hendon 2004). The RMM index has eight phases numbered 1–8 that correspond to the eastward propagation of circulation and convection anomalies. Phases 1–4 correspond to MJO-related convection in the Indian Ocean, and phases 5–8 to MJO activity in the western Pacific. RMM values were obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt). Days with RMM amplitude greater than one were considered as active days, which is the same treatment as in Thompson and Roundy (2013) and Barrett and Gensini (2013). Although the RMM index contains OLR in its formulation, it is more closely tied to circulation anomalies than convection anomalies. The OLR-based MJO index (OMI) has a similar formulation with eight phases, but its development is based on the leading two daily varying EOFs of OLR (Kiladis et al. 2014). OMI values were obtained from NOAA's Earth System Research Laboratory (ESRL; https://www.esrl.noaa.gov/psd/mjo/mjoindex/omi.1x.txt). We exchange the order of the OMI principal components (PCs) and reverse the sign of OMI PC1 when computing the OMI phase in order to match the RMM phase convention.

c. Energy–helicity index

Complementary to the analysis of tornado reports is the analysis of environments that are associated with severe thunderstorm activity. Although environments reflect some large-scale aspects of the favorability of conditions for severe thunderstorm, they provide little information about convective initiation. Favorable environments do not guarantee tornado occurrence. The environment approach using monthly averages has proved useful for interpreting the impacts of ENSO on tornado and hail activity (Allen et al. 2015). Here, we use the energy–helicity index (EHI), which is the scaled product of CAPE and storm-relative helicity (Davies-Jones 1993). Daily values of EHI are computed using 3-hourly values of CAPE and storm-relative helicity taken from the North American Regional Reanalysis (NARR; Mesinger et al. 2006; National Centers for Environmental Prediction 2005) and interpolated onto a $1° \times 1°$ grid as in Tippett and Cohen (2016). EHI values exceeding one indicate favorable conditions for severe thunderstorms (Rasmussen and Blanchard 1998). The statistical significance of EHI differences between active MJO phases 5–8 and active MJO phases 1–4 is assessed by a 1000-sample permutation test that maintains the calendar day and permutes the years.

d. Statistical significance

This study focuses on the question of whether tornado days are more frequent in some MJO phases than others. In any sample of years, more tornado days will occur during a particular MJO phase than others. Statistical significance testing addresses the question of whether the observed differences in tornado-day frequency are greater than would be expected by chance. In particular, the observed frequency difference is compared to the sampling distribution of differences under the null hypothesis of no difference. We describe the statistical significance testing in detail here because of its importance for the results and to make contact with previous studies.

Suppose that during a sample of n_1 days, the frequency of tornado days is $\hat{p}_1$, and that in an *independent* sample of n_2 days, the frequency of tornado days is $\hat{p}_2$. Note that the formulation of the significance test requires that the days be mutually exclusive. The sample proportions $\hat{p}_1$ and $\hat{p}_2$ can be viewed as random variables and the number of tornado days as binomially distributed. If both samples are drawn from the same population distribution with tornado-day frequency p, the difference $\hat{p}_1 - \hat{p}_2$ is a random variable whose mean is zero and whose variance is

$$\mathrm{var}(\hat{p}_1 - \hat{p}_2) = \frac{p(1-p)}{n_1} + \frac{p(1-p)}{n_2} = \frac{p(1-p)}{\frac{1}{n_1} + \frac{1}{n_2}}, \quad (1)$$

where we take tornado occurrence from one day to another to be independent. One approach for testing the statistical significance of the difference $\hat{p}_1 - \hat{p}_2$ is to approximate the population frequency p by a weighted average $\hat{p}$ of the sample proportions,

$$\hat{p} = \frac{n_1\hat{p}_1 + n_2\hat{p}_2}{n_1 + n_2}, \quad (2)$$

and to approximate $\hat{p}_1 - \hat{p}_2$ as being normally distributed. In that case, the quantity

$$Z = \frac{\hat{p}_1 - \hat{p}_2}{\sqrt{\hat{p}(1-\hat{p})\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{3}$$

has a standard normal distribution, and the p value for the difference in proportions is

$$p \text{ value} = 2\min[\Phi(Z), 1 - \Phi(Z)], \tag{4}$$

where Φ is the cumulative distribution function of the standard normal distribution. This approach is called a z test for a difference in proportions and tends to be accurate as long as the samples sizes n_1 and n_2 are not too small, and the sample proportions $\hat{p}_1$ and $\hat{p}_2$ are not near zero or one. Such a z test has been used in previous studies of MJO influence on tropical cyclones, tornadoes, and hail (Hall et al. 2001; Barrett and Gensini 2013; Barrett and Henley 2015). When one of the samples is much smaller than the other, for example, $n_1 \ll n_2$,

$$Z \approx \frac{\hat{p}_1 - \hat{p}_2}{\sqrt{\hat{p}_2(1-\hat{p}_2)\frac{1}{n_1}}}. \tag{5}$$

We refer to significance testing based on (5) as an approximate z test.

Fisher's exact test is an alternative method for computing the statistical significance of a difference in proportions, and its application does not have restrictions on sample size or sample proportions (e.g., Mason and Goddard 2001). Fisher's exact test is described in terms of a 2 × 2 contingency table of the form shown in Table 1. Fisher's exact test is formulated using the hypergeometric function and is included in many statistical software packages. The statistical significance results reported here for proportions use Fisher's exact test except otherwise stated.

The sample proportions are defined as follows unless otherwise indicated. For instance, to assess whether the frequency of tornadoes is different in phase 1 than during other phases, $\hat{p}_1$ is the proportion of active MJO days in phase 1 on which tornadoes are reported, while $\hat{p}_2$ is the proportion of days during which the MJO is inactive or in phases 2–8 and tornadoes are reported. Note that the proportions are computed using mutually exclusive days.

3. Results

a. U.S. tornado report considerations

The presence of trends (more generally serial correlation) in the tornado reports complicates any statistical analysis because standard tests of statistical significance commonly consider a null hypothesis that includes temporal independence. For instance, unrelated quantities may appear to have a statistically significant relation only because they both have trends or the same seasonality. U.S. tornado reports are known to have nonstationary characteristics related to changes in reporting practices (e.g., introduction of the Fujita scale in the 1970s and its subsequent improvement) and technology (e.g., deployment of the WSR-88D system in the 1990s), as well as differences across NWS weather forecast offices (Verbout et al. 2006). As a consequence, some trends in the tornado report data such as the substantial increase from the 1970s to the 1980s in the annual number of E/F0+ tornadoes (Fig. 1a) are not believed to be due to meteorological changes alone. Annual numbers of E/F1+ tornadoes present less indication of trends (Fig. 1b), and many studies restrict their analysis to E/F1+ tornadoes for this reason (Brooks et al. 2014). However, considering only more-damaging tornadoes may not fully remove nonmeteorological variability from the tornado report record. Annual numbers of E/F1+ and E/F2+ tornadoes show some tendency for higher annual values in the 1970s and early 1980s compared with later years (Figs. 1b,c). Previous studies have noted significant changes in the level of year-to-year variability in the annual number of E/F2+ tornadoes, which is likely related to the retrospective rating of tornadoes that occurred prior to the introduction of the F scale (Tippett 2014).

Another issue in the statistical analysis of tornado reports is the presence of outbreaks, which are days or periods when large numbers of tornadoes occur. The number of E/F1+ tornadoes in 2011 is large, but dominated by a few days. Unusually large values are a problem for statistical methods that are sensitive to the presence of outliers. For that reason, tornado days (counts or frequency of days with tornado reports exceeding some number and intensity thresholds) are often analyzed rather than number of tornado reports, although trends have been found in the frequency of days with many tornadoes (Brooks et al. 2014; Elsner et al. 2015). Focusing on tornado days during MAM, there are indications of a reduction in frequency from the earlier part of the record and a stabilization after the mid-1980s for days with at least one E/F1+ report (Fig. 1d), days

TABLE 1. Contingency table for the comparison of tornado-day proportions $\hat{p}_1$ and $\hat{p}_2$ in samples of size n_1 and n_2, respectively.

Sample	Tornado days	Nontornado days
1	$\hat{p}_1 n_1$	$(1-\hat{p}_1)n_1$
2	$\hat{p}_2 n_1$	$(1-\hat{p}_1)n_1$

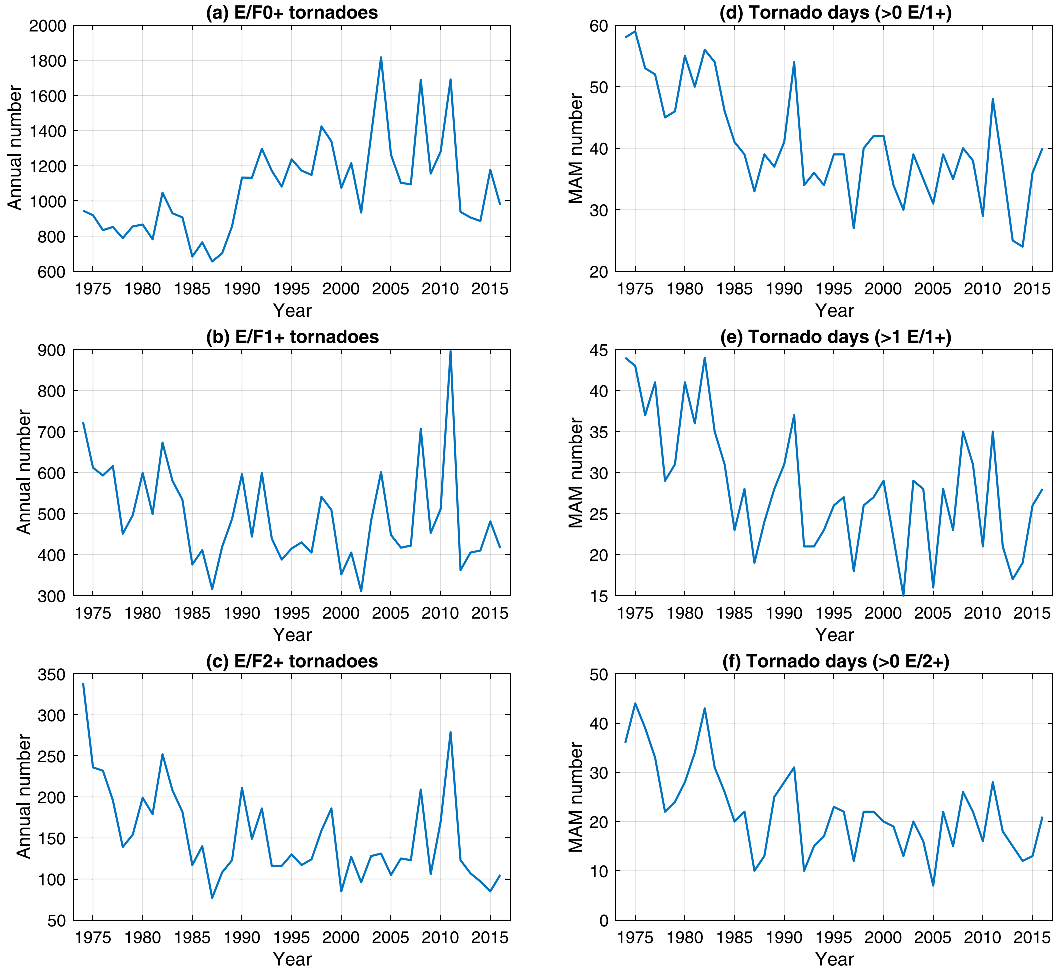

FIG. 1. Annual numbers of U.S. tornadoes rated (a) E/F0 and greater, (b) E/F1 and greater, and (c) E/F2 and greater during 1975–2016. Number of MAM days with (d) one or more E/F1+ tornadoes reported, (e) two or more E/F1+ tornadoes reported, and (f) one or more E/F2+ tornadoes reported.

with more than one E/F1+ report (Fig. 1e), and days with at least one E/F2+ report (Fig. 1f). Given the inhomogeneity of the tornado report record, care should be taken when using earlier parts of the record, and the robustness of the results should be assessed in the more recent and reliable part of the database. For instance, we focus here on the period 1992–2016, but the results do not depend strongly on the choice of starting year. We also vary the tornado per day and intensity thresholds to assess robustness.

b. *Frequency of E/F0+ days*

Barrett and Gensini (2013) found MJO signals in the frequency of days in April and May with at least one E/F0+ report during the years 1990–2011. On the other hand, Thompson and Roundy (2013) found an MJO signal in the frequency of violent tornado days (VTDs; days with six or more E/F2+ tornadoes) during MAM but no MJO influence on the frequency of nontornadic outbreak (NTO) days, which are days when there are large numbers of severe storm reports (tornado, hail, straight-line wind) but the primary expression of severe convective weather is not tornadoes (Shafer et al. 2010). The method for selecting NTO days weights several factors and excludes days with more than six reported tornadoes, regardless of damage ranking (Doswell et al. 2006). The results of Thompson and Roundy (2013) suggest that the influence of the MJO on tornado activity is detectable only in the statistics of relatively rare, high-end severe weather events during which tornadoes feature prominently.

There are other notable qualitative differences between the findings of Thompson and Roundy (2013) and Barrett and Gensini (2013). For instance, Barrett and Gensini (2013) found the largest frequency anomaly, $\hat{p}_1 - \hat{p}_2 = 0.12$, for days in April when phase 8 (RMM)

TABLE 2. Contingency table for tornado days (days with a least one tornado report) during April for active RMM phase 8 days and active RMM phases 1–7 for the period 1990–2011. Values are based on Table 1 of Barrett and Gensini (2013).

RMM phase	Tornado days	Nontornado days
8	22	21
1–7	115	196

was active compared to all days when the MJO was active. Note that this difference in proportions is not between independent days since all active MJO days includes phase 8 active days. In particular, E/F0+ tornadoes were reported in April 1990–2011 on 137 of the 354 active MJO days, and tornadoes were reported on 22 of the 43 days during which phase 8 was active (Table 1; Barrett and Gensini 2013). These values indicate a 12% (22/43–137/354) increase in the frequency of E/F0+ days during phase 8. In contrast, Thompson and Roundy (2013) found that RMM phase 8 is the only phase that has *fewer* MAM VTDs than climatology. The phase-8 April data from Barrett and Gensini (2013) quoted above lead to the contingency in Table 2, where we have made the days mutually exclusive. However, the p values from the Fisher test, z test, and approximate z test are 0.094, 0.073, and 0.054, respectively, indicating no statistical significance at the 0.05 level. This finding contradicts that of Barrett and Gensini (2013), which states a highly significant p value of 0.00. A possible explanation for this discrepancy is that the equation in Barrett and Gensini (2013) that corresponds to our Eq. (5) for Z contains $p_2(1-p_2)$ in the denominator instead of $\sqrt{p_2(1-p_2)}$. This error inflates values of Z by roughly a factor of $p_2^{-1/2}$, which is always greater than one and therefore favors incorrectly concluding statistical significance. The same incorrect expression appears in Barrett and Henley (2015). Another minor issue is that the significance test requires that the proportions be computed from mutually exclusive days. Using the data from Barrett and Gensini (2013) for other phases, we find no statistically significant influence of RMM phase on E/F0+ tornado-day frequency when we compute the p values from Fisher's exact test, the z test, or the approximate z test (Table 3). We note for this data the p value from the z test is less than the p value from Fisher's exact test and that the p value from the z test is less than the p value from the approximate z test (Table 3). The lack of a statistically significant relation between MJO phase and E/F0+ tornado-day frequency agrees with finding of Thompson and Roundy (2013) of no relation with NTO day frequency. The conclusion that there is no relation between E/F0+ tornado-day frequency and the MJO is also not inconsistent with the relatively few grid points where there is a statistically significant association between the MJO phase and meteorological environments associated with severe thunderstorm activity (Figs. 2 and 3; Barrett and Gensini 2013).

c. Violent tornado days

The study by Thompson and Roundy (2013) uses tornado report data going back to 1974, and finds that VTD frequency is enhanced during RMM phase 2. Since the tornado reports are less reliable during the early part of the period, a reasonable question is whether these results depend on the period of analysis. Another question is whether the same relation is observed when

TABLE 3. Numbers of April and May E/F0+ tornado days during 1990–2011 stratified by active MJO phase and their p values from Fisher's exact test, the z test, and the approximate z test. Values are based on Tables 1 and 2 of Barrett and Gensini (2013).

				April				
MJO phase	1	2	3	4	5	6	7	8
Tornado days	20	15	12	19	18	18	13	22
Nontornado days	27	20	26	38	35	23	27	21
Tornado days during other phases	117	122	125	118	119	119	124	115
Nontornado days during other phases	190	197	191	179	182	194	190	196
Fisher p value	0.63	0.59	0.38	0.38	0.54	0.50	0.49	0.09
z-test p value	0.56	0.59	0.34	0.36	0.44	0.47	0.39	0.07
Approximate z-test p value	0.53	0.57	0.31	0.32	0.41	0.44	0.37	0.05
				May				
MJO phase	1	2	3	4	5	6	7	8
Tornado days	50	30	27	33	32	45	60	57
Nontornado days	22	18	17	16	12	22	32	22
Tornado days during other phases	284	304	307	301	302	289	274	277
Nontornado days during other phases	139	143	144	145	149	139	129	139
Fisher p value	0.79	0.52	0.40	1.00	0.50	1.00	0.62	0.36
z-test p value	0.70	0.44	0.36	0.98	0.44	0.95	0.61	0.33
Approx z-test p value	0.68	0.41	0.34	0.98	0.42	0.95	0.57	0.29

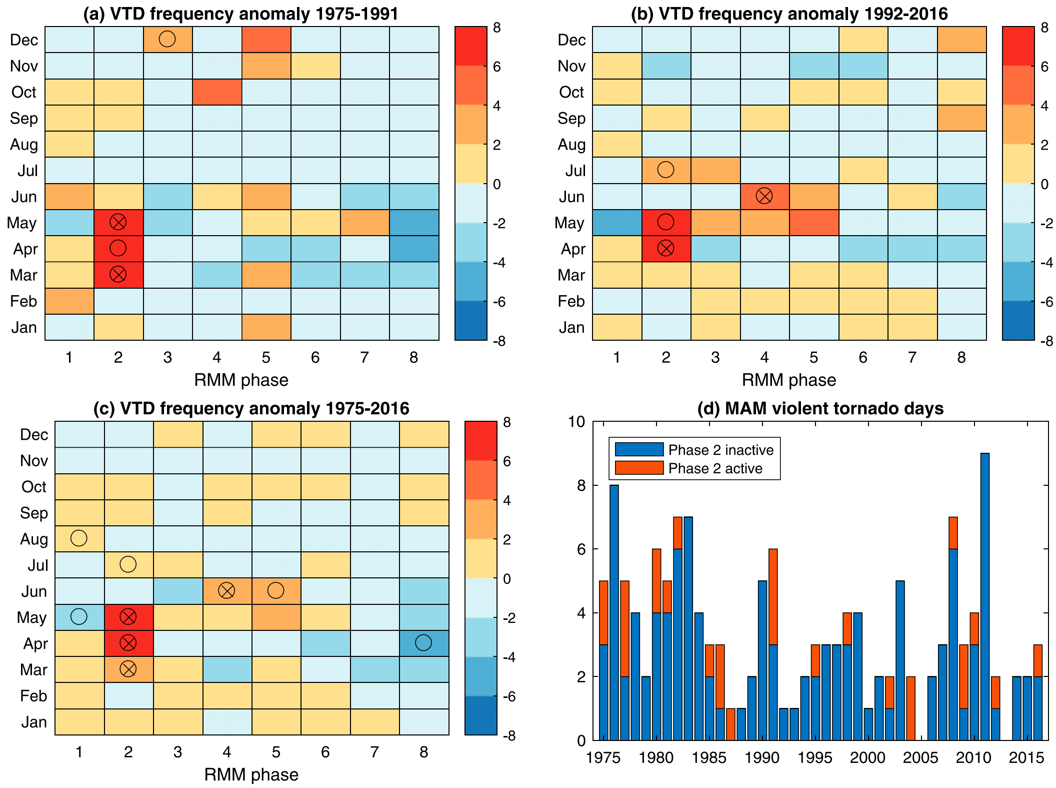

FIG. 2. VTD frequency anomaly (%) by RMM phase and month for the periods (a) 1975–91, (b) 1992–2016, and (c) 1975–2016. Circles indicate statistical significance at the 10% level, and circles with crosses indicate statistical significance at the 5% level. (d) Time series of MAM VTDs.

the OMI MJO index is used. Note the RMM data begin in June 1974 so that MAM analysis begins in 1975, while the OMI data start in 1979. Splitting the data into two periods, 1975–91 (17 yr) and 1992–2016 (25 yr), we find statistically significant (0.05 level) increases in VTD frequency during active RMM phase-2 days in March and May in the first period (Fig. 2a), and a statistically significant (0.05 level) increase in VTD frequency during active RMM phase 2 in April during the second period (Fig. 2b). Over the full period there is a statistically significant (0.05 level) increase in VTD frequency during active RMM phase 2 in March–May. Over the 1975–2016 period, the frequencies of violent tornado days during RMM phase 2 are 5.5%, 10.8%, and 12.5% in March, April, and May, respectively, compared to 1.6%, 3.4%, and 4.8% during other MJO phases and neutral conditions. Violent tornado days during March–May were slightly more frequent during the first period than the second: 4.3% compared to 3.0%. The highest number of MAM VTDs (nine) occurred in 2011, but none occurred during active RMM phase-2 days (Fig. 2d). Two VTDs have occurred in RMM phase 2 since the study of Thompson and Roundy (2013). Overall, the results of Thompson and Roundy (2013) appear robust to the choice of period. The finding of fewer MAM VTDs during phase 8 is present but not statistically significant in any of the three periods at the 0.05 level, but is statistically significant at the 0.1 level during the 1975–2016 period in April.

Given the relative rarity of E/F2+ tornadoes, another reasonable question is how sensitive these results are to the VTD requirement of six or more reports. The frequency of MAM days with more than four E/F2+ tornado reports (one less than needed to qualify as a VTD) is enhanced in RMM phase 2, but the level of statistical significance drops to the 0.1 level in May and April (Fig. 3a). The frequency of MAM days with more than six E/F2+ tornado reports (one more than needed to qualify as a VTD) is enhanced in RMM phase 2, but the difference is only statistically significant in April (Fig. 3b). Overall, the enhanced frequency of days with several E/F2+ tornadoes is not overly sensitive to threshold, though the details of the statistical significance do depend on the threshold. On the other hand, while there is an enhancement in VTD frequency in OMI phase 2 during March and April for all three thresholds (greater than four, greater than five, and greater than six E/F2+), the enhancement is not as great

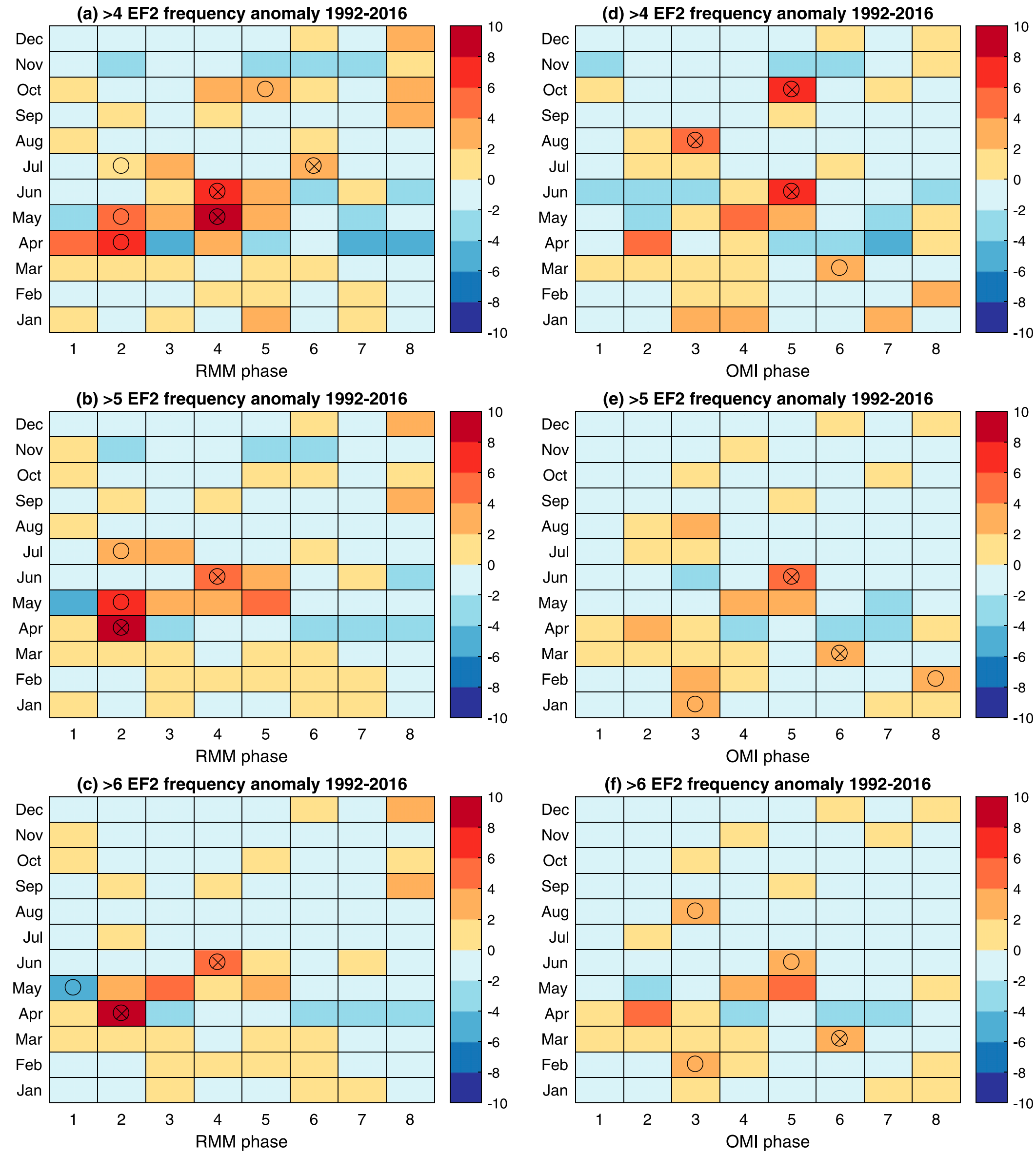

FIG. 3. Tornado day frequency anomaly (%) by MJO phase and month during the period 1992–2016. Tornado days with more than (a),(d) four E/F2+ tornadoes, (b),(e) five E/F2+ tornadoes, and (c),(f) six E/F2+ tornadoes are shown. MJO phase based on (left) RMM and (right) OMI. Circles indicate statistical significance at the 10% level, and circles with crosses indicate statistical significance at the 5% level.

as for RMM phase 2 and is not statistically significant at the 0.05 or 0.1 levels.

d. Frequency of E/F1+ days

Many studies have taken the E/F1+ report record to be reliable and have analyzed the frequency of days with E/F1+ reports exceeding some threshold (Brooks et al. 2014; Elsner et al. 2015). During the period 1992–2016, we see no robust changes in tornado occurrence frequency with respect to individual MJO phases for days with 2 or more, 6 or more, and 12 or more E/F1+ tornadoes (Fig. 4). There is a slight tendency for a lower frequency of days with E/F1+ reports in April during phases 5–8, which corresponds to MJO convection being in the region from the Maritime Continent to the western Pacific. Indeed, the frequency of days with E/F1+ tornadoes is statistically significantly lower in phases 5–8 during April for several thresholds (Figs. 5a,b). April EHI anomalies (the difference of active phase 5–8 and active phase 1–4 averages) are slightly negative in the southeast for RMM-based

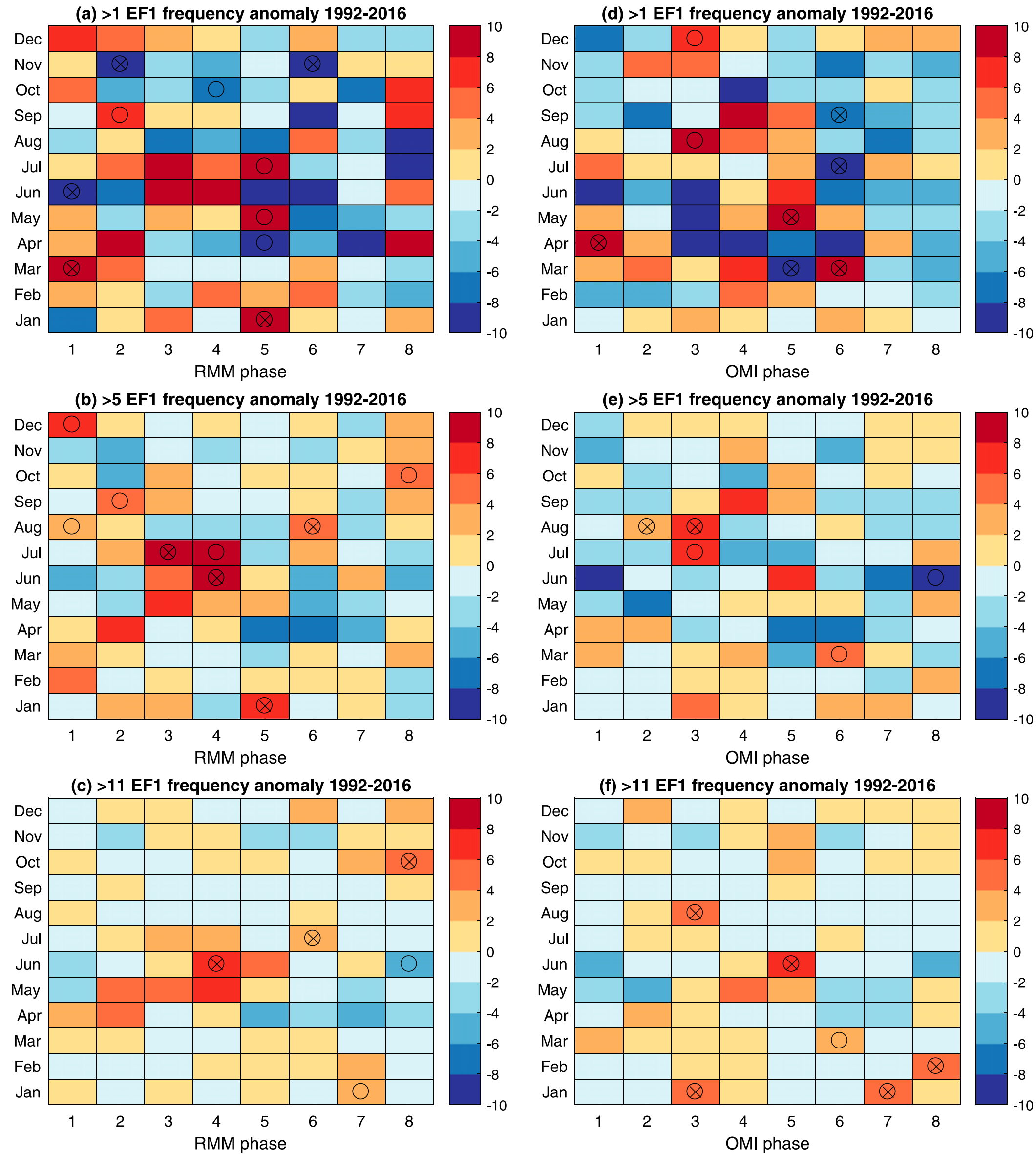

FIG. 4. Tornado day frequency anomaly (%) by MJO phase and month during the period 1992–2016. Tornado day with more than (a),(d) 1 E/F1+ tornadoes, (b),(e) 5 E/F1+ tornadoes, and (c),(f) 11 E/F2+ tornadoes are shown. MJO phase based on (left) RMM and (right) OMI. Circles indicate statistical significance at the 10% level, and circles with crosses indicate statistical significance at the 5% level.

anomalies and negative in the southeast and south for OMI-based anomalies (Figs. 5c,d). April EHI anomalies are mostly not statistically significant except for RMM-based anomalies at some Florida grid points.

4. Summary and discussion

The MJO is to date the most robust and well-documented source of predictability on subseasonal time scales. Since the state of the MJO can be well predicted several weeks in advance, there is the potential for subseasonal predictions of climate variability that are linked to the MJO. Those predictions might take the form of statistical predictions that are conditional on the MJO phase (Johnson et al. 2014) or predictions from dynamical NWP models that capture accurately both the MJO evolution and its impact on the phenomena of interest (Vitart 2014). The question addressed here is whether there are robust relations between the MJO phase and U.S. tornado activity. A robust relation between U.S. severe

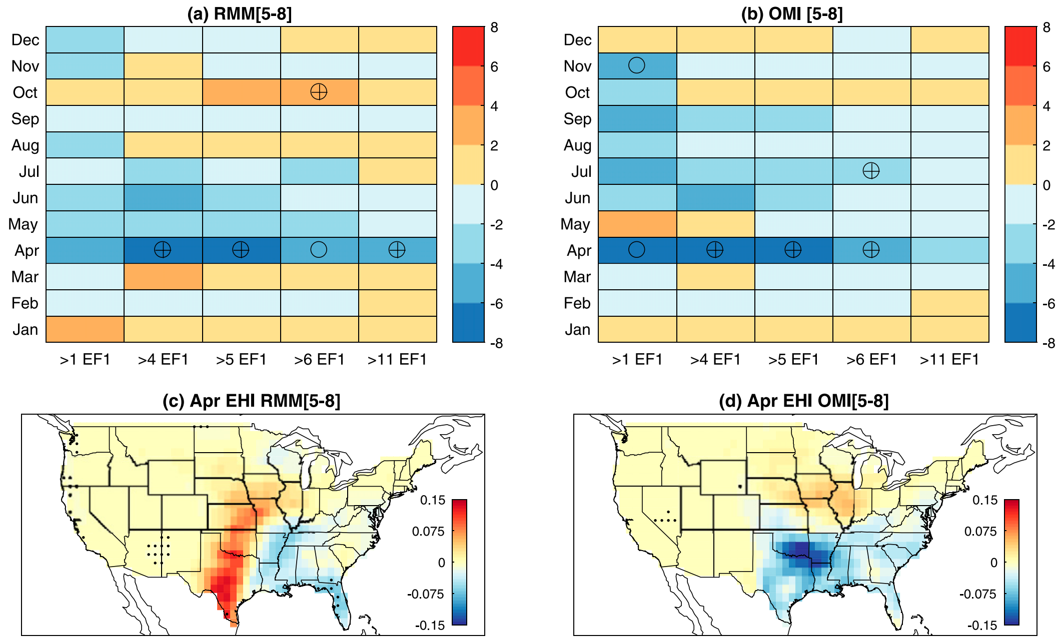

FIG. 5. Tornado day frequency anomaly (%) during the period 1992–2016 by month and number of E/F1+ tornadoes required to qualify as a tornado day for (a) RMM phases 5–8 and (b) OMI phases 5–8. Circles indicate statistical significance at the 10% level, and circles with crosses indicate statistical significance at the 5% level. Anomalies of the daily EHI during (c) RMM phases 5–8 and (d) OMI phases 5–8 are shown. Anomalies are with respect to days during active phases 1–4, and dots indicate anomalies that are statistically significant at the 0.1 level.

thunderstorm activity and the MJO would provide a scientific basis for extended-range forecasts with lead times that go beyond the 1–2-week lead times of current operational forecast products for U.S. severe weather.

Previous studies have addressed the question of whether daily MJO phase and tornado occurrence are related, but differing methods, tornado metrics, and analysis periods have made the results hard to compare (Thompson and Roundy 2013; Barrett and Gensini 2013). The apparent sensitivity of previous results to these details also calls into question their robustness. Here, we have used a single methodology and varied the tornado occurrence metric, analysis period, and MJO index to assess robustness. The enhanced frequency of violent tornado day (VTD) occurrences in phase 2 of the real-time multivariate MJO (RMM) index found by Thompson and Roundy (2013) is fairly robust to period and threshold, but is not statistically significant when a convection-based MJO index is used. This sensitivity to the choice of MJO index is not necessarily a sign of a weak relationship with the MJO but may reflect the different variables, circulation versus convection, used to formulate the indices, and the diversity of what is understood to be the MJO. On the other hand, changes in the frequency of days with E/F0+ reports with MJO phase are not statistically significant, which contradicts the conclusions of Barrett and Gensini (2013).

Defining tornado days based on numbers of E/F1+ tornadoes is attractive because E/F1+ tornadoes are less rare than E/F2+ and not overestimated, as are E/F0+ tornadoes in parts of the record. We considered the frequency of days with the number of E/F1+ tornado reports exceeding various thresholds. We found no robust statistical significance with individual MJO phases. However, when the active MJO is divided into two states, RMM2 > 0 and RMM2 < 0, we find a statistically significant MJO relation in April and shifts of the same sign in other months that are not statistically significant. The behavior is similar for the RMM index and the OMI. Corresponding shifts in the environments favorable to supercell thunderstorms are somewhat consistent but mostly not statistically significant. The relation of tornado day frequency with the sign of RMM2 is consistent with enhanced tornado activity occurring during phases of the global wind oscillation when atmospheric angular momentum (AAM) anomalies are negative (Gensini and Marinaro 2016; Moore 2018) since there is a strong relation between AAM and RMM2 (Weickmann and Berry 2009). On the other hand, unlike the MJO, there is no indication to date that details of the GWO phase beyond the sign of AAM can be skillfully predicted beyond a day or two.

This study has examined relations between U.S.-wide tornado activity and MJO phase, and regional impacts remain to be investigated. A challenge in regional studies of tornado activity is that sample sizes are smaller and sampling variability is greater. Also there is the problem of choosing regions that appropriately capture MJO signals but whose selection does not introduce overfitting. Seasonality may also have a regional expression since the climatological location of peak tornado activity varies with season (Tippett et al. 2012), and the same may be true for MJO teleconnections. Here, we have examined the simultaneous relation between daily MJO phase and tornado occurrence. Lagged analysis may offer additional insights (Tseng et al. 2018).

Acknowledgments. This work was partially supported by NOAA Climate Program Office's Modeling, Analysis, Predictions and Projections Program Award NA14OAR4310185, and the Willis Research Network. Useful comments and suggestions from Paul Roundy and two anonymous reviewers are gratefully acknowledged.

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