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Diagnosing the Atypical Extreme Precipitation Events Under Weakly Forced Synoptic Setting: The West Virginia Flood (June 2016) and Beyond

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1. Introduction

June 2016 saw concurrent extreme climate/weather events in the U.S., with scorching heat (Liberto, 2016) in the Southwest associated with an upper-atmospheric ridge and record flooding in West Virginia. The ridge condition on 23 June induced a series of mid-tropospheric short waves that propagated across the Ohio valley, producing the "1-in-1000-year" precipitation event in West Virginia with 10 inches of 24-h rainfall (Grote and Dyer 2017; Corrigan *et al.* 2017; Perfater *et al.* 2017). The extreme precipitation in West Virginia was not associated with a deep synoptic trough, but occurred during the prevailing mid-level northwesterly flow (NWF) setting (Fig. 1a). The ridge type weather pattern that is commonly considered as the warm and pleasant weather condition, have occasionally created extreme weather including the 2012 DC derechos (Fig. 1c). The predominant ridge and NWF setting are related to summer outbreaks of thunderstorms (Johns 1982) and convectively induced windstorms or derechos (Johns and Hirt 1987; Bentley and More 1998). However, most of the climate projection studies overlooked the NWF severe weather outbreaks as they focused on strong low-pressure systems which are sustained by large-scale baroclinic forcing (*e.g.*, Weaver *et al.* 2016; Feng *et al.* 2016; Feng *et al.* 2012; Jiang *et al.* 2006; Berg *et al.* 2015). The aforementioned extreme events occurring under the "weakly forced" synoptic setting, i.e. the continental-scale ridge with the NWF or the so-called warm season pattern (Johns 1982, 1993), prompted us to question whether and how such storms may have changed.

This study is targeted at diagnosing the climatology and variation of weak sub-synoptic-scale features in the central U.S. associated with the propagating mesoscale convective systems (MCSs) during early to mid-summer. The majority of these sub-synoptic features embedded in the NWF are generated on the east of the Rocky Mountains and propagate across the northern plains in the form of serial short-wave perturbations, referred to as the mid-tropospheric perturbations (MPs; Wang *et al.* 2009, 2011a, b). MPs provide the forcing for the progressive MCSs when they travel a long distance creating extreme weather events (Wang *et al.* 2011a, b), but the climate variation linked to their genesis and steering mechanism has not been explored. This study presents a method to track MPs by using reanalysis data and discusses the variation and trend of MPs.

2. Data sources and methodology

We use the 3-hourly North American Regional Reanalysis (NARR, Mesinger *et al.* 2006) data as the main dataset to calculate the MPs. We also utilize the NCEP-NARR reanalysis R1 data and the Storm Prediction Center's Warning storm reports compiled from the Coordination Meteorologist (WCM) website (http://www.spc.noaa.gov/wcm/). The storm report has been used to construct the NWF outbreak frequency (John 1982). However, storm observations originate from sighting and are highly dependent of population; this presents a data quality problem due to human and population biases (Weiss *et al.* 2002; Gallus *et al.* 2008). During the course of 38 years (1979-2016), the perturbations are calculated based on the midlevel winds and relative vorticity at 600-hPa for the June, July and August. Because the average life cycle of MPs is 48 hours (Wang *et al.* 2011a), the vorticity field is filtered using both low- and high-pass filters in order to retain the MPs characteristics. To exclude the synoptic-scale trough, the filtered vorticity is masked out by

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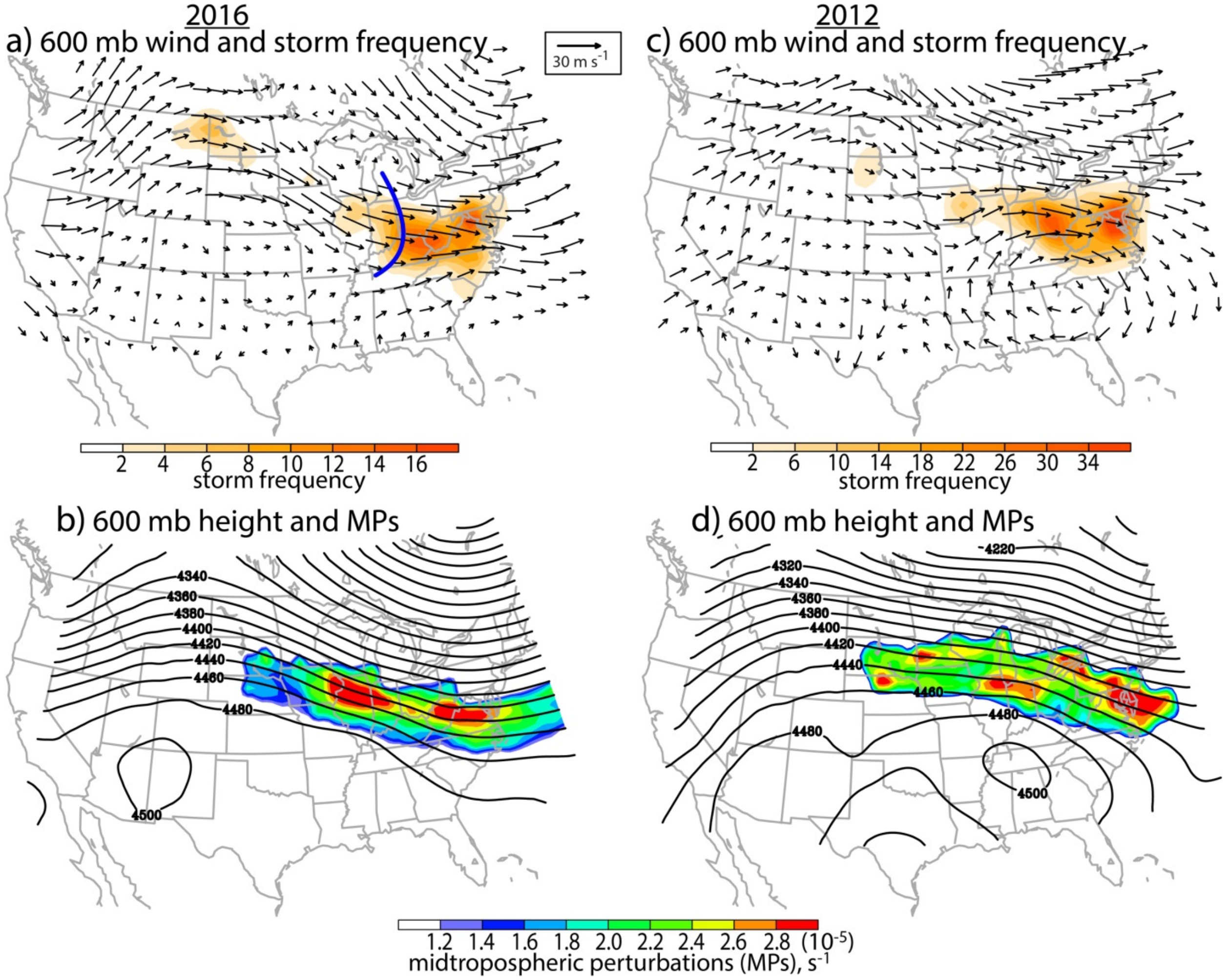

Fig. 1 Synoptic conditions storm frequency and MPs during two extreme weather events of June 2016 (left panel) and June 2012 (right panel). a) and c) are the 600-hPa wind (vectors) with storm (wind, hail and tornado) frequency (shading) from storm reports. Blue curve in a) shows the shortwave trough. b) and d) are the 600-hPa height (contours) with MPs (shading). The MPs (storm frequency) and 600-hPa height, are averaged (added) from the 21-24 June and 28-30 June for 2016 and 2012, respectively. The wind vectors in a) and c) are taken from the middle of the extreme events at 18Z on 23 June 2016 and at 00Z on 30 June 2012, respectively.

applying the circulation criteria; this excludes the region of negative stream function. Moisture is an important precursor for the MP-related convective activity and, therefore, further moisture criteria is applied in which vertically integrated precipitable water should be larger than certain thresholds (we use 24 mm in this study). Finally, the root-mean-square of vorticity (RMSVORT) is averaged weekly from June to August. The storm report data are used for verification by mapping onto a 1° x 1° grid mesh and averaging similarly with RMSVORT.

3. MPs events and climatology

3.1 Case analysis

The 2016 West Virginia flood and the 2012 Mid-Atlantic derecho, both occurring in late June, serve to exemplify the extreme events related to NWF outbreaks. In both events, the mid- to upper-level high pressure was centered over the southcentral U.S. spreading prevailing NWF from the northern plains to the mid-Atlantic regions. The 2012 NWF produced several damaging hail and wind events throughout the Midwest and Mid-Atlantic regions in 2012 (Fig. 1c) while 2016 system produced 8-10 inches of precipitation in West Virginia within 12-24 hours (NOAA NCEI, 2016) in addition to the wind and hail damage (Fig. 1a).

The noticeable difference with the 2016 case was the presence of a mid-level shortwave trough on the 23rd of June (Fig. 1a). Such a shortwave feature was not present in the June 2012 case when the Derecho propagated with the MP (Fig. 1c). We note both cases show a good agreement between the storm track (Fig. 1a and c) and propagated MPs (Fig. 1b and d). More detailed comparison between the two cases is given in Box 1.

3.2 Climatology and variability of MPs

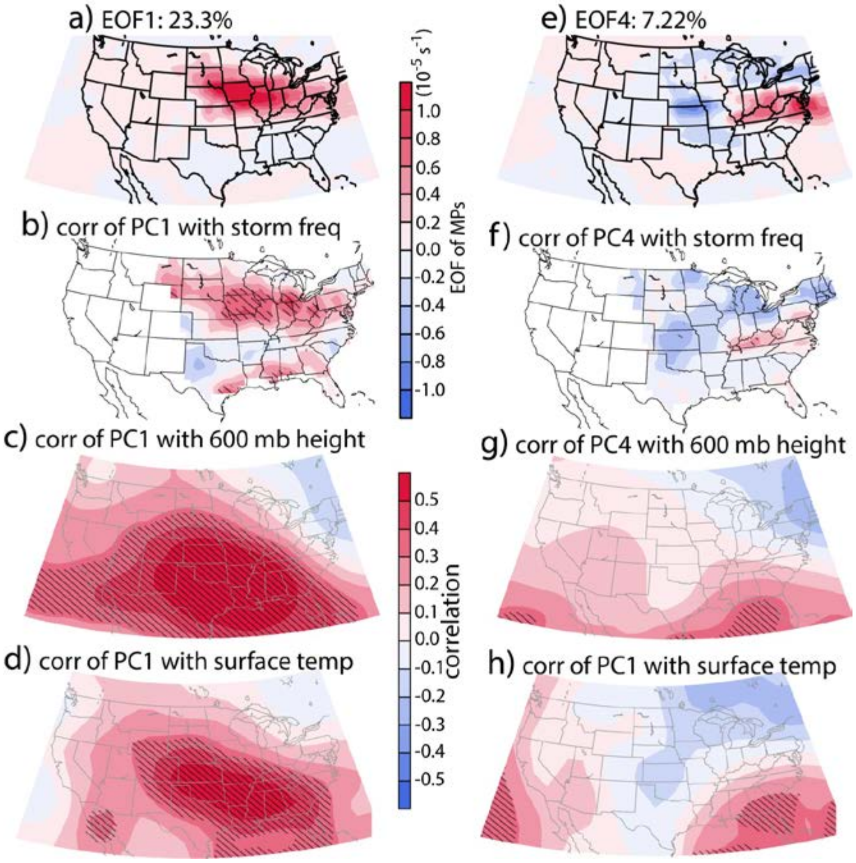

Fig. 2 Interannual variation of MPs a) first EOF and e) fourth EOF from 17June to 7July for 38 years (1979-2016). Temporal correlation of PC1 and PC4 with June-July average of storm frequency ((b) and (f)), 600-hPa height ((c) and (f)), and surface temperature ((d) and (h)), respectively. Hatched areas indicate significant values with $p<0.05$.

The 38-year climatology of RMSVORT shows similar pattern with the 10-year, manually tracked MP climatology by Wang *et al.* (2011a, b). The spatial distribution of the MP climatology developed here is also in good agreement with the derecho frequency in mid-summer (Guastini and Bosart 2016; John and Hirt 1987). The MP frequency peaks in the three-week period of 17 June to 7 July, which is adopted to examine the interannual variability using the empirical orthogonal function (EOF). As shown in Fig. 2, the first and fourth EOFs reveal the MP spatial pattern that is most relevant to 2016's West Virginia case, including the Upper Midwest track and the increased frequency in the East Coast. EOF1 reveals the main track of MPs (Fig. 2a) while its corresponding principal component (PC1, not shown) correlates well with the storm frequency (Fig. 2b). EOF4 (Fig. 2e) reveals the east-west fluctuation of MPs and its PC correlates with

Box 1

COMPARISON OF TWO EXTREME EVENTS BETWEEN JUNE 2012 AND 2016

Even though we applied a moisture criteria in our MPs calculation, a continuous source of moisture plays an important role to create the extreme precipitation. During the 2016 case, the low-level jet and mid-level shortwave provided continuous moisture from the Gulf of Mexico (GoM), helping to create deep convection (figure not shown). The hydrometeor mixing ratio was significant during the 2016 event – as high as 100-hPa – indicating the extreme magnitude of the continuous source of moisture and mid-level shortwave moisture pooling. However, the 2012 derecho case shows slightly different flow – mainly at low levels – reducing the moisture supply from the GoM. Another noticeable difference between these two cases is that the location of the high pressure center was located westward during the 2016 case compared to a more eastward placement during the 2012 event.

the eastward shift of extreme weather (Fig. 2f), similar to the one over West Virginia in 2016 which has the largest values of PC1 and PC4. Though not shown, we note that the north-south shift of MPs is reflected in EOF2 and it resembles the 2012 storm track with a high PC2 value.

Since EOF1 depicts the major MP track and mimics the NWF outbreaks (Fig. 2b), we analyzed the anomalous circulations associated with PC1. The correlation map of 600-hPa geopotential height with PC1 (Fig. 2c) shows a predominant anticyclone centered in the southern U.S. providing enhanced NWF conditions. Surface air temperature in the southern U.S. increases correspondingly during high PC1 (Fig. d). By comparison, PC4 is positively correlated only with increased meridional gradient of the geopotential height over the mid-Atlantic region (Fig. 2g) and this corresponds with the increased storm frequency and warmer air in the southeast US (Fig. 1h). We further diagnosed the correlation of PC1 with GoM SST for different months and observed that the Gulf SST seems to respond during the early summer months (not shown). We also observe an increasing trend in the MP frequency as well as PC1 (Fig. 3). The increasing trend of MPs is even larger after 1990 (not shown), suggesting a post-1990 increase in MPs and arguably in NWF outbreaks.

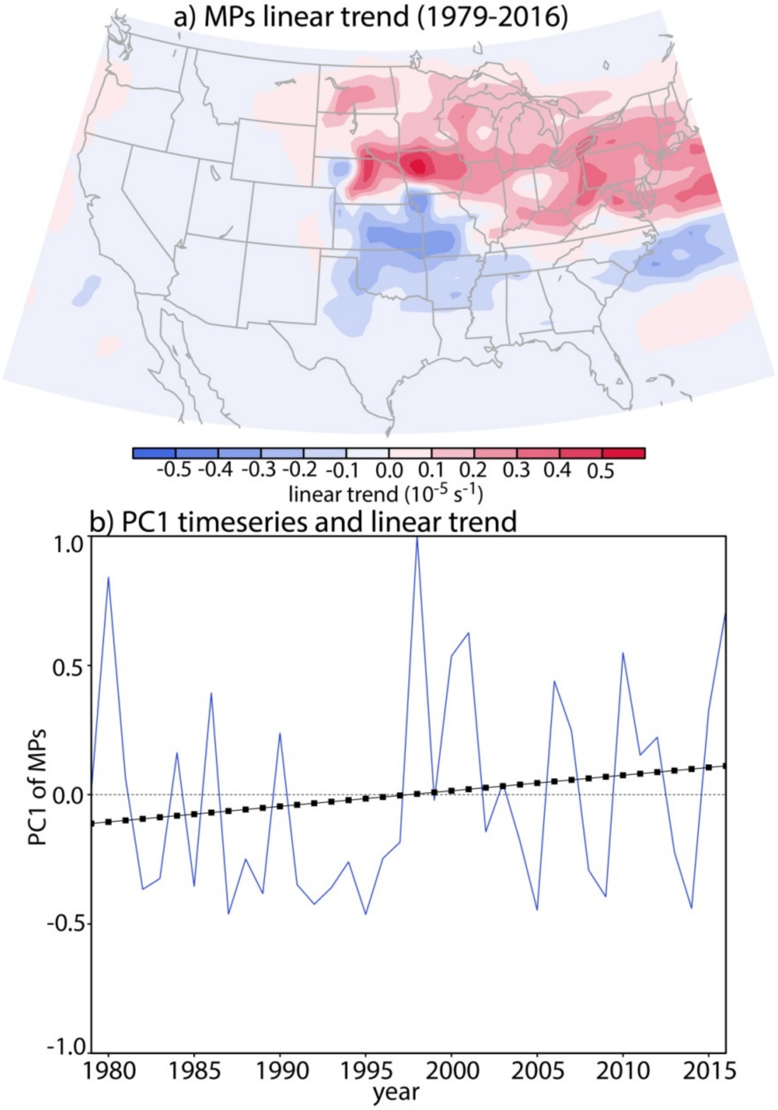

Fig. 3 (a) Linear trend (slope multiplied by number of years which is 38 years here) of MPs and (b) timeseries of PC1 (blue line) with linear trend line (black line) from 1979 to 2016.

4. Discussion

Climate models have a difficulty producing weakly forced storms and resultant extreme precipitation and this drawback may affect how the models project future climate extremes. To understand the extent to which devastating floods like the one in West Virginia will occur relies on how well climate models depict the NWF synoptic settings and embedded MPs. The present objective analysis for the MP climatology is intended to help develop metrics that will evaluate model projections of the MP track. Future work will also include the diagnosis of larger-scale teleconnections associated with the circulation setting relevant to the MP track and frequency (*e.g.*, Fig. 2). Preliminary analysis not included here has indicated that ENSO does not correlate with the MP frequency, but the Pacific-North American (PNA) and the Arctic Multidecadal Oscillation (AMO) do. During the positive phase of AMO and PNA, the MP frequency over the Midwest and Mid-Atlantic region seems to enhance.

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