The Relationship between the Madden–Julian Oscillation (MJO) and Southeastern New England Snowfall

PHILIP J. KLOTZBACH

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

ERIC C. J. OLIVER

Institute for Marine and Antarctic Studies, Australian Research Council Centre for Climate System Science, University of Tasmania, Hobart, Tasmania, Australia

RONALD D. LEEPER AND CARL J. SCHRECK III

Cooperative Institute for Climate and Satellites, North Carolina, NOAA/National Centers for Environmental Information, North Carolina State University, Asheville, North Carolina

(Manuscript received 14 December 2015, in final form 10 February 2016)

ABSTRACT

The winter of 2014/15 brought record snow totals to portions of southeastern New England. Additionally, over 90% of Boston Logan Airport snowfall during the winter fell during phases 7 and 8 of the Madden–Julian oscillation (MJO) index. This motivated the authors to investigate potential connections between intense southeastern New England snowstorms and the MJO in the historical record. It was found that southeastern New England snowfall, measured since the 1930s at several stations in the region, recorded higher than average winter snowfalls when enhanced MJO convection was located over the western Pacific and the Western Hemisphere (phases 7–8). Similarly, snowfall was suppressed when enhanced MJO convection was located over the Maritime Continent (phases 4–5). The MJO also modulates the frequency of nor'easters, which contribute the majority of New England's snowfall, as measured by reanalysis-derived cyclone tracks. These tracks were more numerous during the same MJO phases that lead to enhanced snowfall, and they were less common during phases with less snowfall.

1. Introduction

Southeastern New England experienced one of its snowiest winters in history in 2014/15, with many cities in the region approaching or exceeding seasonal snowfall records. For example, Logan Airport in Boston experienced 110.6 in. (1 in. = 2.54 cm) of snow during the winter, eclipsing the old record of 107.6 in. set in 1995/96. February 2015 was especially noteworthy for Logan Airport, with 64.8 in. of snow falling during the month, shattering the old record for a single month of 43.3 in. set in January 2005. Other southern New England cities approached record seasonal snowfall totals as well, with TF Green Airport in Providence observing 76.2 in., trailing only 1995/96 when 106.1 in. fell.

These dramatic snowfall totals motivated us to consider the mechanisms behind intense snowfall events in southeastern New England. In particular, we considered the possibility that a tropical influence might have increased the frequency of these events. One of the primary modes of subseasonal tropical variability is the Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972). The MJO propagates around the globe in 30–70 days and typically has its convective origins over the Indian Ocean. The MJO modulates many different tropical weather phenomena around the globe (Zhang 2013) including tropical cyclone frequency (Camargo et al. 2009, Klotzbach and Oliver 2015, Schreck et al. 2012), as well as flooding and drought in parts of the tropics (Wheeler et al. 2009, Hidayat and Kizu 2010).

The MJO also influences midlatitude weather. For example, Jones (2000) and Bond and Vecchi (2003)

Corresponding author address: Philip J. Klotzbach, Department of Atmospheric Science, Colorado State University, West LaPorte Ave., Fort Collins, CO 80523.
E-mail: philk@atmos.colostate.edu

DOI: 10.1175/MWR-D-15-0434.1

related extreme precipitation events in California and the Pacific Northwest, respectively, to the MJO, with more active periods of the MJO favoring extreme precipitation. The MJO also modulates high-latitude air temperatures in Alaska by up to 5°C (Vecchi and Bond 2004; Oliver 2015). Recently, the MJO has been shown to impact both temperature and precipitation across the United States (Zhou et al. 2012; Schreck et al. 2013, 2015).

Despite these documented impacts of the MJO in the extratropics, relatively few studies have examined the relationship between the MJO and snowfall. Moon et al. (2012) showed that when the MJO was enhancing convection over the central Pacific during the winter of 2009/10, the subtropical jet stream was enhanced, and anomalous troughing dominated the East Coast of the United States. This trough was also tilted westward with height, promoting significant cold air advection and enhancing baroclinicity. Barrett et al. (2015) found a relationship between changes in springtime snow depth over both North America and Eurasia and MJO phase, with MJO convection implicated in altering Rossby wave patterns that then alter snow depth changes through fluctuations in temperature and precipitation. The present study builds on that previous work by focusing on the relationship between the MJO and major snowfall events in southeastern New England. We propose that MJO modulation of extratropical cyclone tracks is the driving mechanism for that relationship.

2. Data and methodology

We utilize two metrics to evaluate the position and amplitude of the MJO on a particular day. The first is the canonical Wheeler–Hendon (WH) index (Wheeler and Hendon 2004), which uses a combination of 850- and 200-mb (1 mb = 1 hPa) zonal winds and outgoing longwave radiation to estimate the current state of the MJO through the use of multivariate empirical orthogonal functions (EOFs). The annual-mean and previous 120-day-mean signal are removed from the data, which typically removes the El Niño–Southern Oscillation (ENSO) signal. This dataset is available from 1 June 1974 to present.

To include a longer period of snowfall data into our analysis, we utilized the MJO index developed by Oliver and Thompson (2012). This index, referred to as the OT index through the remainder of the manuscript, uses surface pressure estimates from the Twentieth Century Reanalysis (20CR) (Compo et al. 2011) and a multiple regression technique to reconstruct the WH MJO index prior to 1 June 1974. The previous 120-day mean is removed to reduce any ENSO influence on the index. The OT index was shown to closely replicate the WH index over the joint period from 1979 to 2008 (Oliver and Thompson 2012) and has since been used to investigate the relationship between the MJO and a variety of systems, including global tropical cyclones (Klotzbach and Oliver 2015) and surface air temperatures over Alaska (Oliver 2015). We utilize version 2c of the 20CR, which is available through 2011 (the OT MJO index can be downloaded from http://passage.phys.ocean.dal.ca/~olivere/histmjo.html).

We used sea level pressures anomalies from the National Centers for Environmental Prediction–Department of Energy Reanalysis 2 (NCEP–DOE 2) (Kanamitsu et al. 2002). We obtained daily data over the 1979–2014 period and calculated anomalies from a 1981 to 2010 daily climatology. NCEP–DOE 2 is considered to be an upgrade of the earlier NCEP–NCAR reanalysis (Kistler et al. 2001) because of data fixes as well as improved physical parameterizations.

We obtained daily snowfall data for eight stations in southern New England from the National Centers for Environmental Information (http://www.ncdc.noaa.gov/cdo-web/). All analysis started on 1 January 1936 (or later), as this is when Boston Logan Airport daily snowfall became available. Logan Airport likely has the most reliable snowfall data, as this is an international airport with over 93% complete daily snowfall reports from 1936 to 2011.

We identified extratropical cyclone (ETC) tracks using pressure fields from a 56-member ensemble of the 20CR (Compo et al. 2011). We created these ETC tracks separately for each ensemble member by linking centers of low pressure between successive 6-hourly time steps, using a 750-km search radius. When no candidate ETC locations were identified, the ETC was assumed to have dissipated. This process was repeated iteratively over the duration of the model run from November to March when ETCs were generally stronger.

Tracks from the 56 ensemble members were associated with one another for the same ETC event if any of the low pressure centers of a track were collocated within 200 km on the same date and time (year–month–day hour). To improve the performance of the association method, we filtered out spurious tracks by requiring members to exist for a minimum of 72 h, have a track length of at least 1000 km, and a nonmeandering path identified by taking the ratio of the start-to-end distance by track distance, which had to be greater than or equal to 0.6. Associated member tracks were spatially averaged to create an ensemble-mean track per ETC event. Additional information on the ETC track dataset used in this study can be found at etcsrv.cicsnc.org:8080/apps/ETCv8.

This study focused on tracks during mature phases of the MJO index (amplitude > 1) after 1950 when the quality and density of surface observations assimilated into 20CR were sufficiently reliable. Ensemble-mean tracks must also have been detected by at least 38% of the 56 ensemble members (≥21) to be used in this study. This ensures the quality of simulated tracks used in this study and focuses on periods of time when the MJO phase was well developed. ETC tracks that met these requirements were gridded to a uniform, polar equidistant 120-km grid over the Northern Hemisphere by counting the number of unique ETCs that passed within 260 km of a grid's center. We selected the 260-km search radius because it allowed for 200 km of uncertainty in the exact track path outside of the 60-km grid radius. The results are insensitive to large variations in these radii (not shown).

We evaluated the gridded track frequencies for the entire dataset (November–March from 1950 to 2011) to create a track climatology. In addition, MJO track frequencies were also generated based on the phase of the MJO index on track start dates.

The counts were normalized from the number of MJO days to 365 days for direct comparison. ETC density anomalies were calculated by subtracting the normalized climatology from the normalized counts in each phase.

ETC track and station snowfall composites were constructed using the OT index, while sea level pressure composites and analysis of the 2014/15 southeastern New England snowfall season were constructed using the WH index.

3. Results

Our analysis begins by examining the typical sea level pressure pattern associated with heavy snowfall events in southeastern New England (Fig. 1). We composite the mean sea level pressure (MSLP) pattern associated with at least 6-in. daily snowfall accumulations for Logan Airport since the winter of 1979/80. We start with that winter given the availability of the NCEP–DOE reanalysis. A total of 72 days from 1979/80 to 2014/15 witnessed 6 in. or greater snowfall accumulations. For statistical significance testing, we treated any case where consecutive days recorded 6 in. or more of snow as a single event [see Schreck et al. (2013)]. A well-defined area of low pressure off of the southeastern U.S. coast is seen in the composite, along with a strong blocking high pressure to the north over Quebec and the Maritime provinces (Fig. 1). The pressure gradient in this region drives stronger northeasterly winds into southeastern New England. This type of setup is typical of nor'easters

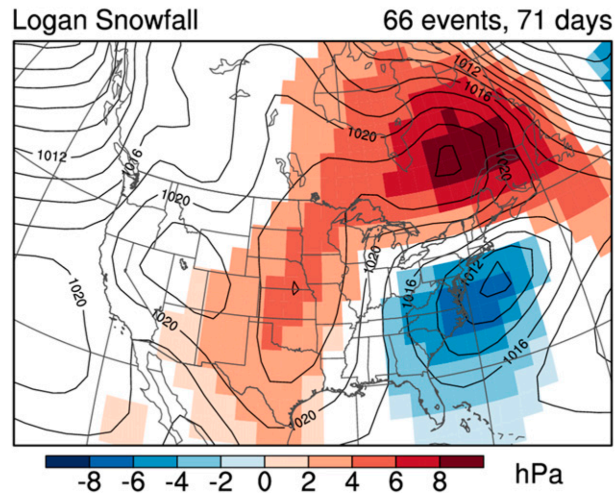

FIG. 1. Composite total (contours) and anomalous (shading) MSLP for 72 days (66 nonconsecutive events) when snowfall exceeded 6 in. at Logan Airport since the winter of 1979/80. Anomalies are only shaded where they are statistically significant at the 95% level following the methodology of Schreck et al. (2013). Contour interval is 2 hPa.

(Davis and Dolan 1993), which are well documented to produce heavy snowfalls in southeastern New England.

We hypothesize that the typical nor'easter impacting southeastern New England with heavy snowfall can be either a Miller A or Miller B type (Miller 1946) (Fig. 2). A Miller A type set up is associated with an intensifying area of low pressure in the Gulf of Mexico that moves up the eastern seaboard and deposits very heavy rain and snow in its path. A Miller B type setup is associated with an area of low pressure over the continent, such as an Alberta clipper, that weakens as it moves toward the East Coast. As it does so, its energy gets transferred to a developing low pressure that then undergoes rapid deepening over the warm waters of the Gulf Stream. An important criterion for heavy snowfall from Miller A and Miller B systems in southeastern New England are that the low pressure centers remain off of the East Coast, near 40°N, 70°W. This benchmark is frequently noted in National Weather Service forecast discussions for major snowstorms impacting southeastern New England. This type of track causes the wind direction to have a predominant northeasterly component, bringing in cool, moist air off of the Atlantic Ocean with associated heavy snowfall. An inland track, on the other hand, causes the wind direction to have a southerly component, bringing in warm air and rain.

We now examine how such large-scale weather patterns, including the nor'easters described in the previous paragraph, are modulated by the MJO. Figure 3 displays December–March MSLP anomalies across the continental United States for MJO phases 1–8 when the

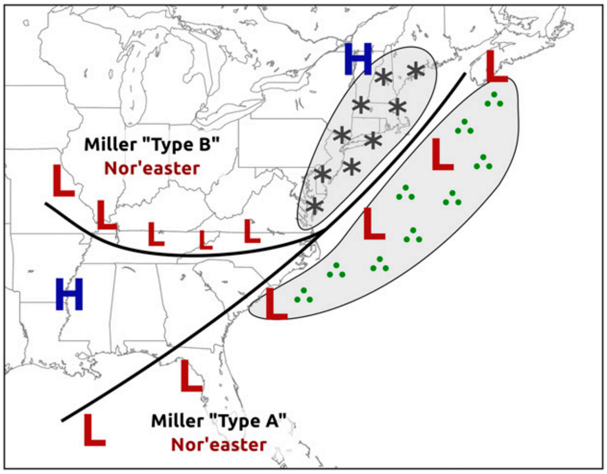

FIG. 2. Schematic of typical nor'easter storm tracks associated with heavy snowfall in southeastern New England. Adapted with permission from a schematic on the National Weather Service's State College Office's website: http://www.weather.gov/ctp/.

amplitude of the WH MJO has a magnitude greater than one. The total MSLP values (contours) illustrate the climatological trough along the U.S. East Coast in all phases. However, the associated anomalies (shading) illustrate that this trough significantly strengthens and weakens with the MJO. For example, positive MSLP anomalies in phase 5 indicate a weakening of the trough, which would be associated with decreased nor'easter activity. By contrast, the negative MSLP anomalies in phase 8 suggest an amplified storm track, qualitatively similar to the Logan snowfall composite including the enhanced ridging near Hudson Bay (Fig. 1), that would favor heavy snowfall events for southeastern New England.

We confirm the relationship between these MSLP anomalies and storm activity by exploring how the MJO index modulated ETC tracks (Fig. 4). We observed an increase in ETC track frequency (November–March) just offshore of New England in MJO phases 7 and 8 and a notable decrease in phases 4 and 5 (Fig. 4). These changes are consistent with the MSLP anomalies in Fig. 3 for those phases. A closer examination of Fig. 4 hints that Miller B type nor'easters are enhanced in phase 7, while Miller A type nor'easters tend to be more enhanced in phase 8. Both types of nor'easters look to be suppressed in phases 4 and 5.

We next examine if observed snowfalls in southeastern New England indicate a response to the MJO index in the way hypothesized given the changes in the large-scale atmospheric signals demonstrated in the preceding paragraphs. Figure 5 displays the change in the probability of in situ snowfall accumulation for December–February by MJO phase, relative to the baseline probability across all MJO phases. The baseline probability of daily snowfall in December–February (DJF) varies by station and is in the range of 7%–23%. A value in Fig. 5 of 10% means snowfall is 10% more likely in that MJO phase than what is expected from the baseline probability. We found the probability of snowfall is increased by 5%–15% at most stations in MJO phases 7, 8, and 1 and is suppressed by a similar factor in MJO phases 4, 5, and 6. The timing of the increase and decrease of

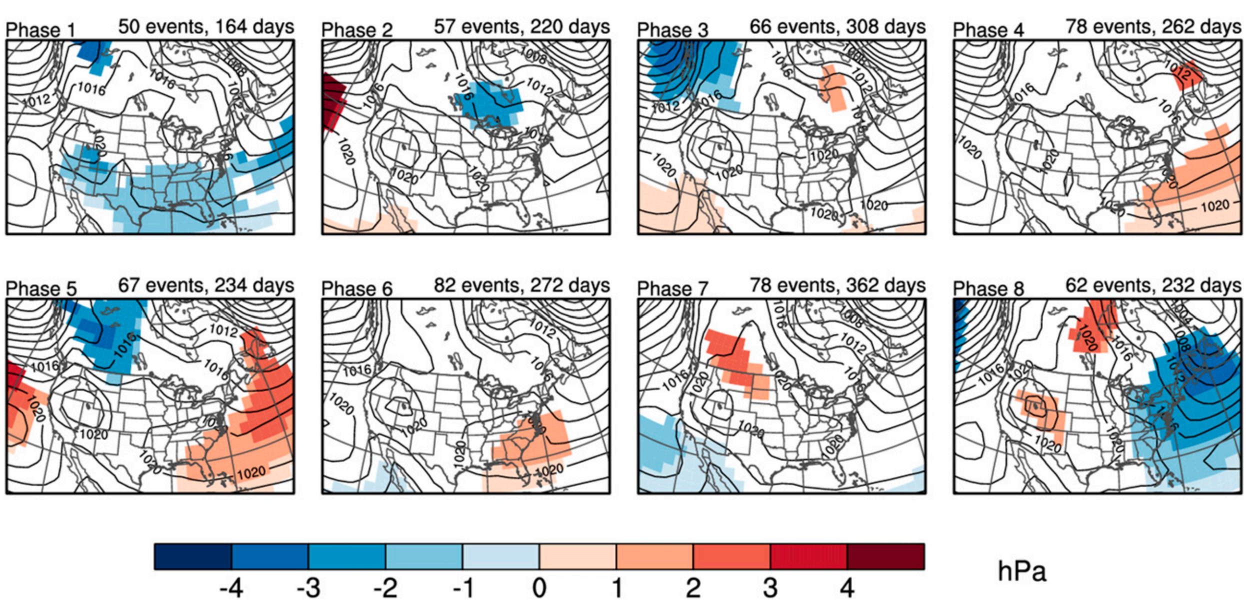

FIG. 3. As in Fig. 1, but for all days during December–March where the WH MJO index was in phases 1–8 with an amplitude greater than one.

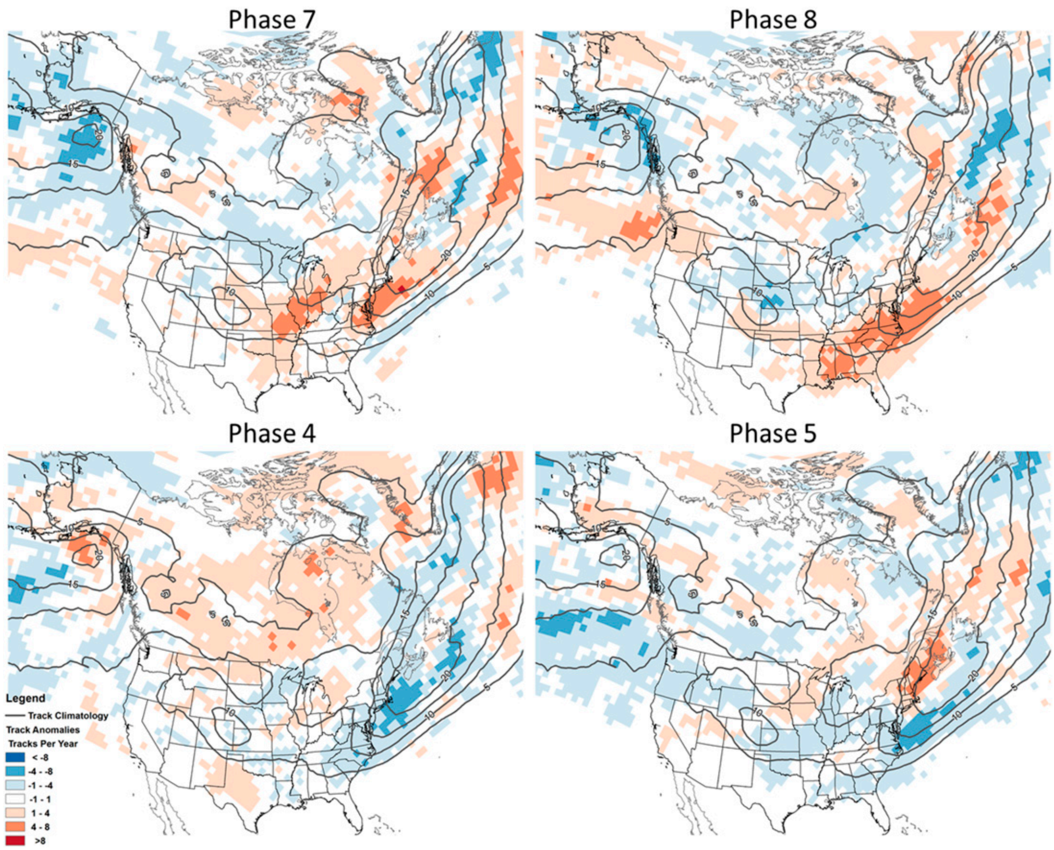

FIG. 4. Anomalous extratropical cyclone track density stratified for MJO phases (top) 7 and 8 and (bottom) 4 and 5 overlaid with track climatology (contours) for the 1950–2011 period.

snowfall probability with MJO phase is consistent with the large-scale mechanism hypothesized.

The relationships between the MJO, large-scale flow, and southeastern New England snowfall demonstrated in the previous paragraph were present in the winter of 2014/15. An incredible 90.2 in. of snow fell during the 23-day period from 24 January to 15 February 2015 at Logan Airport. Only two full seasons (1993/94 and 1995/96) at Logan Airport had more snow than this short 23-day period. The WH MJO index was in phases 7 and 8 for 18 of these days (Fig. 6), with an average amplitude of 1.0. In addition, 99.7 in. of the 110.6 in. that fell during the entire winter of 2014/15 did so during days when the WH MJO index was in phases 7 and 8.

4. Conclusions

We document a significant relationship between southeastern New England snowfall, nor'easter frequency, and the MJO. When the MJO index is located in phases 7, 8, and 1, there is an increase in the probability of snowfall events for most observing stations, while snowfall tends to be reduced in MJO phases 4 and 5.

These results are broadly consistent with Barrett et al. (2015). They found an increase in March snow depth for the 7 days following phases 6–8, which would equate well with the findings of our study, given the approximate time lag of 7 days per one phase of the MJO. Their findings also found no air temperature response, indicating that the increase in snowfall was driven by increased storminess and not by a decrease in melt rates. Our results verify this relationship by showing the concomitant modulation of extratropical cyclone activity.

This study examined contemporaneous relationships between MJO phase and New England snowstorms. Thousands of kilometers separate these features, so we do not imply that the MJO's effect is instantaneous. Rather, the MJO's typical phase speed dictates that the MJO goes through one WH phase every 5–7 days, so some lag from the previous phase is implicit in our composites. The physical mechanisms were discussed in greater detail by both Cassou (2008) and Moon et al. (2012). Cassou (2008) found that when the MJO index was in phase 6, with a 7–10-day lag, the negative phase of the North Atlantic Oscillation (NAO) was favored. A negative NAO was typically associated with an East

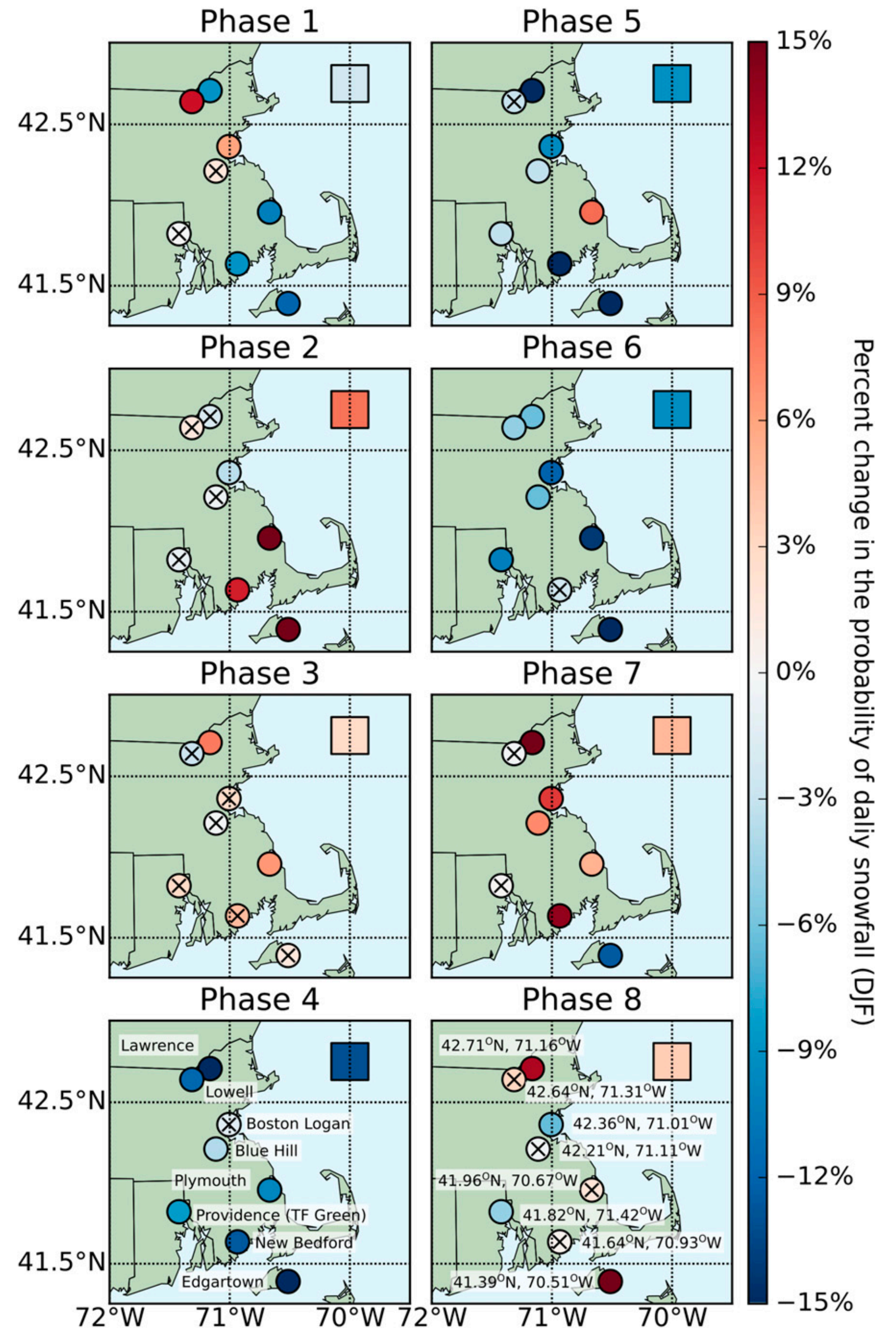

FIG. 5. The change in the probability of DJF snowfall in southeastern New England by MJO phase relative to the baseline probability over the 1936–2011 period. Results for individual stations are indicated by circles and the mean across all stations is indicated by the large square; station results not statistically significant at the 5% level are denoted with "×." Statistical significance was calculated using a Monte Carlo technique whereby the MJO phases are randomly shifted relative to the snowfall time series 1000 times and the composites recomputed.

Coast trough. In addition, anomalous upper-level divergence associated with deep convection in the central Pacific (typical of MJO phase 6) propagated northward and eastward with time, favoring cyclonic wave breaking in the northeast United States with a 7–10-day lag. Enhanced moisture associated with the anomalous upper-level divergence also moved northward with time. This increase in East Coast troughing is also associated with cold air advection in the Northeast, enhancing baroclinicity (Moon et al. 2012). Given the MJO's

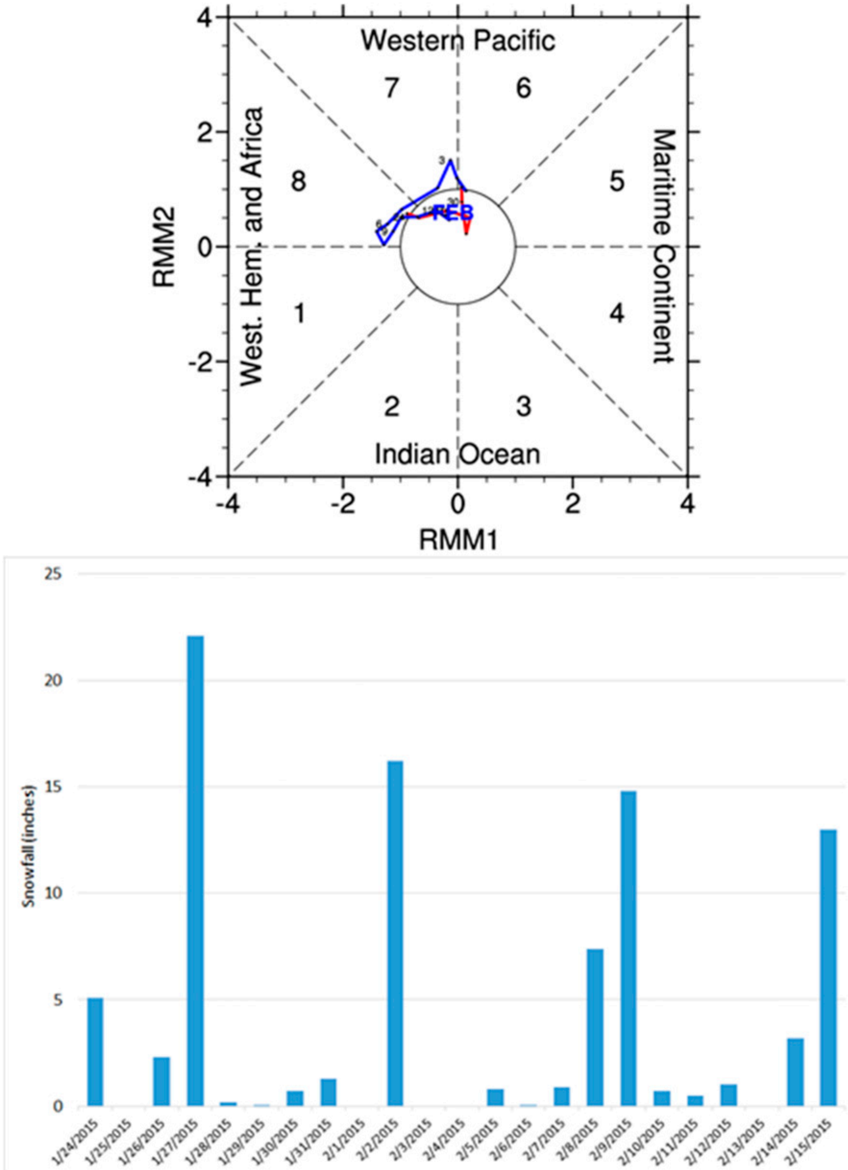

FIG. 6. (top) WH MJO index for 24 Jan–15 Feb 2015. January dates are in red and February in blue. (bottom) Daily snowfall reports at Logan for the same period.

typical phase speed, the 7–10-day lag from phase 6 found by these previous studies is consistent with the contemporaneous signal we see in phases 7 and 8.

This study indicates the possibility of increased long-term predictability of heavy snowfall events for southeastern New England. While there are certainly many other factors that are required for heavy snowfall, the predictability of the MJO out to ~30 days (Neena et al. 2014) allows the prospect for broad timescale predictions for increased or decreased risk of nor'easters significantly impacting southeastern New England.

Acknowledgments. We would like to acknowledge the efforts of Scott Applequist, David Easterling, and Ken Kunkel in the development of the extratropical cyclone (ETC) dataset used in this study, which was funded by the NOAA's Climate Program Office by Grant NA09OAR4310104. Klotzbach would like to thank the G. Unger Vetlesen Foundation for financial support that helped fund this research. Schreck and Leeper were supported by NOAA through the Cooperative Institute for Climate and Satellites, North Carolina, under Cooperative Agreement NA14NES432003. This paper makes a contribution to the objectives of the Australian

Research Council Centre of Excellence for Climate System Science (ARCCCS).

REFERENCES

Barrett, B. S., G. R. Henderson, and J. S. Werling, 2015: The influence of the MJO on the intraseasonal variability of Northern Hemisphere snow depth. *J. Climate*, **28**, 7250–7262, doi:10.1175/JCLI-D-15-0092.1.

Bond, N. A., and G. A. Vecchi, 2003: The influence of the Madden–Julian oscillation on precipitation in Oregon and Washington. *Wea. Forecasting*, **18**, 600–613, doi:10.1175/1520-0434(2003)018<0600:TIOTMO>2.0.CO;2.

Camargo, S. J., M. C. Wheeler, and A. H. Sobel, 2009: Diagnosis of the MJO modulation of tropical cyclogenesis using an empirical index. *J. Atmos. Sci.*, **66**, 3061–3074, doi:10.1175/2009JAS3101.1.

Cassou, C., 2008: Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation. *Nature*, **455**, 523–527, doi:10.1038/nature07286.

Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis project. *Quart. J. Roy. Meteor. Soc.*, **137**, 1–28, doi:10.1002/qj.776.

Davis, R. E., and R. Dolan, 1993: Nor'easters. *Amer. Sci.*, **81**, 428–439.

Hidayat, R., and S. Kizu, 2010: Influence of the Madden–Julian Oscillation on Indonesian rainfall variability in austral summer. *Int. J. Climatol.*, **30**, 1816–1825.

Jones, C., 2000: Occurrence of extreme precipitation events in California and relationships with the Madden–Julian oscillation. *J. Climate*, **13**, 3576–3587, doi:10.1175/1520-0442(2000)013<3576:OOEPEI>2.0.CO;2.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP-DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.*, **83**, 1631–1643, doi:10.1175/BAMS-83-11-1631.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.*, **82**, 247–267, doi:10.1175/1520-0477(2001)082<0247:TNNYRM>2.3.CO;2.

Klotzbach, P. J., and E. C. J. Oliver, 2015: Variations in global tropical cyclone activity and the Madden-Julian Oscillation since the midtwentieth century. *Geophys. Res. Lett.*, **42**, 4199–4207, doi:10.1002/2015GL063966.

Madden, R. A., and P. R. Julian, 1971: Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**, 702–708, doi:10.1175/1520-0469(1971)028<0702:DOADOI>2.0.CO;2.

——, and ——, 1972: Description of global-scale circulation cells in the tropics with a 40–50 day period. *J. Atmos. Sci.*, **29**, 1109–1123, doi:10.1175/1520-0469(1972)029<1109:DOGSCC>2.0.CO;2.

Miller, J. E., 1946: Cyclogenesis in the Atlantic coastal region of the United States. *J. Meteor.*, **3**, 31–44, doi:10.1175/1520-0469(1946)003<0031:CITACR>2.0.CO;2.

Moon, J.-Y., B. Wang, and K.-J. Ha, 2012: MJO modulation on 2009/10 winter snowstorms in the United States. *J. Climate*, **25**, 978–991, doi:10.1175/JCLI-D-11-00033.1.

Neena, J. M., J. Y. Lee, D. Waliser, B. Wang, and X. Jiang, 2014: Predictability of the Madden–Julian oscillation in the Intraseasonal Variability Hindcast Experiment (ISVHE). *J. Climate*, **27**, 4531–4543, doi:10.1175/JCLI-D-13-00624.1.

Oliver, E. C. J., 2015: Multidecadal variations in the modulation of Alaska wintertime air temperature by the Madden–Julian Oscillation. *Theor. Appl. Climatol.*, **121**, 1–11, doi:10.1007/s00704-014-1215-y.

——, and K. R. Thompson, 2012: A reconstruction of Madden–Julian oscillation variability from 1905 to 2008. *J. Climate*, **25**, 1996–2019, doi:10.1175/JCLI-D-11-00154.1.

Schreck, C. J., J. Molinari, and A. Aiyyer, 2012: A global view of equatorial waves and tropical cyclogenesis. *Mon. Wea. Rev.*, **140**, 774–788, doi:10.1175/MWR-D-11-00110.1.

——, J. M. Cordeira, and D. Margolin, 2013: Which MJO events affect North American temperatures? *Mon. Wea. Rev.*, **141**, 3840–3850, doi:10.1175/MWR-D-13-00118.1.

——, and Coauthors, 2015: Natural gas prices and the extreme winters of 2011/12 and 2013/14: Causes, indicators, and interactions. *Bull. Amer. Meteor. Soc.*, **96**, 1879–1894, doi:10.1175/BAMS-D-13-00237.1.

Vecchi, G. A., and N. A. Bond, 2004: The Madden-Julian Oscillation (MJO) and northern high latitude wintertime surface air temperatures. *Geophys. Res. Lett.*, **31**, L04104, doi:10.1029/2003GL018645.

Wheeler, M. C., and H. H. Hendon, 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea. Rev.*, **132**, 1917–1932, doi:10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2.

——, ——, S. Cleland, H. Meinke, and A. Donald, 2009: Impacts of the Madden–Julian oscillation on Australian rainfall and circulation. *J. Climate*, **22**, 1482–1498, doi:10.1175/2008JCLI2595.1.

Zhang, C., 2013: Madden–Julian oscillation: Bridging weather and climate. *Bull. Amer. Meteor. Soc.*, **94**, 1849–1870, doi:10.1175/BAMS-D-12-00026.1.

Zhou, S., M. L. Heureux, S. Weaver, and A. Kumar, 2012: A composite study of MJO influence on the surface air temperature and precipitation over the Continental United States. *Climate Dyn.*, **38**, 1459–1471, doi:10.1007/s00382-011-1001-9.