A Framework for Evaluating Model Credibility for Warm-Season Precipitation in Northeastern North America: A Case Study of CMIP5 Simulations and Projections

JEANNE M. THIBEAULT AND ANJI SETH

University of Connecticut, Storrs, Connecticut

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ABSTRACT

Future projections of northeastern North American warm-season precipitation [June–August (JJA)] indicate substantial uncertainty. Atmospheric processes important to the northeast-region JJA precipitation are identified and a first evaluation of the ability of five phase 5 of the Coupled Model Intercomparison Project (CMIP5) models to simulate these processes is performed. In this case study, the authors develop a set of process-based analyses forming a framework for evaluating model credibility in the northeast region. This framework includes evaluation of models’ ability to simulate observed spatial patterns and amounts of mean precipitation; dynamical atmospheric circulation features, moisture transport, and moisture divergence important to interannual precipitation variability; long-term trends; and SST patterns important to northeast-region summer precipitation. Wet summers in the northeast region are associated with 1) negative 500-hPa geopotential height anomalies centered near the Great Lakes; 2) positive 500-hPa geopotential height anomalies over the western Atlantic east of the Mid-Atlantic states; 3) northeastward moisture flow and increased moisture convergence along the Eastern Seaboard; 4) increased moisture divergence off the U.S. Southeast coast; and 5) positive sea level pressure (SLP) anomalies in the western Atlantic, possibly related to cold tropical Atlantic SSTs and southwest ridging of the North Atlantic anticyclone. Models are generally able to simulate these features but vary compared to observations. Models capture regional moisture transport and convergence anomalies associated with wet summers reasonably well, despite errors in simulating the climatology. Identifying sources of intermodel differences in future projections is important, determining processes relevant for model credibility. In particular, changes in moisture divergence control the sign of northeast-region summer precipitation changes, making it a critical component of process-level analyses for the region.

1. Introduction

Warm-season precipitation [June–August (JJA)] is important to the economy and ecology of the midlatitude region of eastern North America, which encompasses the U.S. Northeast, southeastern Ontario, and southern Quebec [defined as 35°–50°N and 70°–80°W (Fig. 1), which is referred to hereafter as the northeast region]. The northeast region is densely populated with large urban centers located preferentially along the coast, yet much of the region is rural, covered by forests or agricultural land. Precipitation amounts are moderate and consistent throughout the annual cycle (Sabbagh and Bryson 1962; Leathers et al. 2000). Perhaps because precipitation is generally reliable, relatively little research has been done to examine northeast-region warm-season precipitation at the regional scale. Yet, the northeast region is sensitive to variations in water quality and availability and is known to experience periods of flooding and drought (Leathers et al. 2000; Hayhoe et al. 2007; Bonsal et al. 2011; Seager et al. 2012). This research identifies atmospheric processes important to northeast-region warm-season precipitation on interannual time scales and performs an initial case study examining the ability of the coupled climate models from phase 5 of the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012) to simulate these processes using a subset of five models: CanESM2, CCSM4, CNRM-CM5, GFDL-ESM2M, and
FIG. 1. Mean JJA precipitation (1981–2000) for (a),(b) observations (CMAP and UDel, respectively) and (c)–(g) historical simulations. The white box in (a) delineates the northeast region.
MIROC5 (Table 1). Model selection was based on the availability of 6-hourly data from the CMIP5 archive at the time of writing, which are required to compute vertically integrated moisture transport. This research also takes a first look at future projections in this subset of models, highlighting processes that lead to model disagreement about the direction of change in northeast-region warm-season precipitation, which may be particularly important for evaluating model credibility.

One of the largest droughts to affect the northeast region occurred in the 1960s, spanned several years, and was driven by a lack of precipitation. This drought greatly reduced the availability of freshwater in the northeast region, threatening the water supplies of large metropolitan areas. For example, New York City discontinued the release of water from its reservoirs along the Delaware River in the summer of 1965 to maintain its supply, consequently lowering streamflow levels and threatening the water quality of downstream Philadelphia (Hayhoe et al. 2007). In 1963–64, several wells ran dry in southern Ontario and Great Lakes water levels dropped to extremely low levels (Bonsal et al. 2004, 2011). Since the early 1970s, the northeast region has been experiencing a relatively wet period (Seager et al. 2012), which in recent years includes a series of abnormally wet summers (Baringer et al. 2010). Lakes and streams, which are important to recreation and tourism in the northeast region (Hayhoe et al. 2007), are impacted by both extremely wet and dry conditions. Heavy downpours increase runoff, raising the levels of pollutants delivered to northeast-region waterways. In dry periods, summer streamflows can be particularly low, allowing abnormally large increases in water temperatures, impacting water quality and aquatic ecosystems (Karl et al. 2009; Bonsal et al. 2011; Hodgkins and Dudley 2011). Furthermore, high summer water temperatures can disrupt the operation of thermoelectric power plants because of environmental restrictions on thermal discharges into streams and a lack of cooling water (van Vliet et al. 2012).

The largest use of freshwater in the northeast region is for thermoelectric power generation, followed by withdrawals for the public water supply, including domestic, commercial, and industrial uses (Kenny et al. 2009). As temperatures increase in the future, longer summer low-flow periods and associated higher water temperatures may potentially impact water quality and disrupt the supply of electricity in the northeast region (see van Vliet et al. 2012). With warming, the impacts of abnormally wet and dry years are likely to worsen, stressing water resource management systems and natural ecosystems, and will likely have additional economic consequences because of the importance of freshwater to tourism and agriculture (Hayhoe et al. 2007).

The northeast region is located in the trough of the stationary planetary wave produced by the Rocky Mountains, within the band of midlatitude westerlies (Manabe and Broccoli 1990). During summer, the North Atlantic subtropical anticyclone steers low pressure and frontal systems toward the northeast region, directing moisture flow from the Atlantic Ocean (Wang et al. 2009; Lau et al. 2004) and Gulf of Mexico (Schubert et al. 1998; Namias 1966). A shift from westerly flow to more meridional flow changes the dominant air mass carrying moisture into the northeast region from dry continental air to moist Gulf of Mexico or Atlantic air masses (Hubeny et al. 2011).

<table>
<thead>
<tr>
<th>Modeling center</th>
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<th>Realization</th>
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<td>CNRM-CM5</td>
<td>Centre National de Recherches Metéorologiques Coupled Global Climate Model, version 5</td>
<td>r1i1p1</td>
<td>128 × 256</td>
</tr>
<tr>
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<td>GFDL-ESM2M</td>
<td>Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model 4 (MOM4) component</td>
<td>r1i1p1</td>
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<td>Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology</td>
<td>MIROC5</td>
<td>Model for Interdisciplinary Research on Climate, version 5</td>
<td>r1i1p1</td>
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Previous work on northeast-region regional hydroclimate and its relationships to large-scale circulation patterns have largely focused on winter and spring streamflow variability (e.g., Leathers et al. 2000; Bradbury et al. 2002a,b; Kingston et al. 2007). Coulibaly and Burn (2005) examined the relationships between Canadian seasonal streamflows and atmospheric teleconnection indices. Leathers et al. (2000) evaluated growing-season moisture deficits in the northeast region and found that anomalously wet years are associated with the presence of negative geopotential height anomalies over the eastern United States, centered near the Great Lakes. This pattern causes a shift toward increased meridional flow, enhancing moisture transport into the northeast region. Abnormally dry years in the northeast region were found to be associated with anomalous ridging over the eastern United States, reducing the flow of moisture from the Gulf of Mexico and Atlantic Ocean.

In a study of Canadian summer drought variability, Girardin et al. (2006) found that intensified troughing in eastern Canada produces anomalous midlevel southerly flow, advecting moist, warm, unstable air along the U.S. East Coast from the subtropical Atlantic toward interior Quebec. Conversely, the presence of anticyclonic circulation over eastern Quebec is associated with a northerly flow of Arctic air, producing dry conditions. Seager et al. (2012) found that the transition from the 1960s northeast-region drought to the present wet period resulted from changes in midlatitude circulation anomalies that caused a change in the direction of meridional flow over eastern North America from northerly and descending during the drought to southerly and ascending, producing the current wetter conditions.

The North Atlantic subtropical high (NASH) exerts a major influence on the climate of the eastern United States (Davis et al. 1997). In summer, moisture entering the North American continent along the U.S. Gulf Coast is transported by the mean flow associated with the western edge of the NASH (e.g., Rasmussen 1967; Schubert et al. 1998; Weaver and Nigam 2008). Variations in NASH extent and strength determine the strength of the Great Plains low-level jet (GPLLJ) that transports moisture into central and eastern North America (Wang 2007; Mestas-Núñez and Enfield 2007; Wang et al. 2007). Li et al. (2011) suggest that the recent observed increased variability in the southeastern U.S. (SE) summer precipitation is related to increased intensity of the NASH, accompanied by a westward shift of its western ridge. On interannual time scales, the latitudinal position of the NASH western ridge regulates vertical motion over the SE and moisture transport from the Gulf of Mexico and Atlantic Ocean (Li et al. 2011; Li et al. 2012, 2013), suggesting that recent changes in the NASH may also have implications for northeast-region summer precipitation.

Analysis of model simulations for the northeast region was conducted as part of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), employing 21 models from the WCRP CMIP3 (Meehl et al. 2007). Rainfall projections for the northeast region suggest an increase in annual mean precipitation, but winter changes are larger and more certain than those projected for summer (Christensen et al. 2007). An analysis of nine CMIP3 models by Hayhoe et al. (2007) showed that most models were able to reproduce observed temperature trends; observed precipitation trends were found to be sensitive to interdecadal variability and the length of period examined and are therefore not robust. Their analysis showed that winter precipitation in the northeast region is expected to increase in the future, but summer rainfall is not expected to change or may even decrease.

Policymakers and stakeholders have a growing need for quantitative projections of future climate that are considered reliable enough to inform decision making for adaptation and mitigation purposes (Collins et al. 2012; Knutti et al. 2010). Analysis of multimodel ensembles is commonly used to quantify uncertainty in future climate projections (Knutti et al. 2010), but assessing the reliability of projections is a challenge (Collins et al. 2012). Increasingly, a number of methods based on the ability of models to simulate observed climate are being used to assess the reliability of multimodel projections, including such measures as assessing model skill, assigning weights or ranks to the models, or even eliminating models that perform poorly in a particular region (Overland et al. 2011; Collins et al. 2012).

In this research, we take a first step toward developing a consistent set of process-oriented analyses for the northeast region. We describe the datasets and methods used for our analysis in section 2. We present our results in section 3, beginning with an evaluation of the models’ ability to simulate the large-scale processes important to northeast-region precipitation at the interannual time scale. Results for twentieth-century projections follow. We present a discussion and summary of our results in section 4. Concluding remarks follow in section 5.

2. Data and methods

This research examines processes important to interannual warm-season (JJA) precipitation for the northeast region. The northeast region is defined as the area located within 35°–50°N and 70°–80°W (see Fig. 1), which provides a domain suitable for the resolution of the CMIP5 models. The study region encompasses the
Mid-Atlantic states northward into Ontario and southern Quebec and includes Pennsylvania, New York State, and most of New England. In particular, we examine the relationships between regional northeast-region precipitation anomalies and anomalies of large-scale precipitation and atmospheric circulation over central and eastern North America and the Atlantic Ocean: 850-hPa and 500-hPa winds (zonal and meridional components are designated as ‘u’ and ‘v,’ respectively), 500-hPa geopotential height, sea level pressure, and vertically integrated moisture transport [computed from 6-hourly wind and specific humidity fields and integrated from the surface to 500 hPa (VIMT)] and its divergence. Historical simulations from five CMIP5 global coupled models (Table 1) are analyzed using a single realization from each model, with a focus on the models’ ability to simulate the observed processes important to northeast-region warm-season precipitation at the interannual time scale. CMIP5 projections use a new set of future scenarios known as representative concentration pathways (RCPs) (Moss et al. 2010). Future projections in this set of models are evaluated for the high-emission RCP 8.5 scenario, where atmospheric CO2 concentrations reach ~1370 ppm by 2100.

Observed relationships are evaluated using twentieth-century reanalysis version 2 data (20CR) provided by National Oceanic and Atmospheric Administration/Office of Oceanic and Atmospheric Research/Earth System Research Laboratory Physical Sciences Division (NOAA/OAR/ESRL PSD), Boulder, Colorado, from their website (at http://www.esrl.noaa.gov/psd/; Compo et al. 2011); University of Delaware (UDel; Legates and Willmott 1990) precipitation; and Climate Prediction Center Merged Analysis of Precipitation (CMAP), version 2 (Xie and Arkin 1996). The UDel dataset consists of global monthly high-resolution (0.5° × 0.5°) gridded station pressure for precipitation over land. Monthly data are analyzed for all observed and simulated variables except for VIMT, which was computed from 6-hourly 20CR and model data. All northeast-region area-averaged model precipitation data are masked to exclude grid points over the ocean.

Regression analysis is used to identify spatial patterns of observed and simulated summertime (JJA) relationships between northeast-region precipitation anomalies (UDel) and large-scale anomalies of precipitation, 850-hPa winds, 500-hPa geopotential height and winds, sea level pressure, VIMT, and VIMT divergence. All variables are detrended prior to performing regression analyses. Regression coefficients are tested for statistical significance at the 90% confidence level. Late-twentieth-century (twenty-first century) regressions are computed covering 1981–2000 (2081–2100).

3. Results

a. Spatial patterns of northeast-region precipitation

Observed and simulated summer precipitation patterns for the northeast region are shown in Fig. 1. Precipitation averages about 3 mm day$^{-1}$ near the coast and decreases toward the northwest with amounts of 2 mm day$^{-1}$ in the eastern Great Lakes region, southern Ontario, and southern Quebec. CMAP differs from UDel over parts of Maryland, Delaware, New Jersey, Pennsylvania, and much of New York State, with JJA precipitation averaging 2 mm day$^{-1}$. The models simulate a gradient in precipitation that declines away from the Eastern Seaboard toward the continental interior, though amounts and spatial patterns vary compared to UDel and CMAP. CanESM2 is too dry over Pennsylvania, New York, and southern New England, while CNRM-CM5 and MIROC5 are too wet over much of the northeast region. Consistent with CMAP, all models simulate an area of precipitation amounts exceeding 4 mm day$^{-1}$ that extends northeastward from the Gulf of Mexico over the Atlantic Ocean toward the Canadian Maritimes, but this region varies spatially among the models and in comparison to observations.

b. Relationships between northeast-region precipitation and large-scale atmospheric variables

Observed and simulated relationships between northeast-region summer precipitation anomalies and precipitation, 850-hPa winds, 500-hPa winds and geopotential height, and sea level pressure (SLP) are shown in Fig. 2. Observed results (UDel precipitation) indicate that wet summers in the northeast region are significantly related to low-level southwesterly flow that extends from the Gulf of Mexico near Alabama and Mississippi toward Nova Scotia (Fig. 2a). High rainfall summers are associated with two prominent features in the large-scale circulation: 1) a reduced center in the 500-hPa height field located over the Great Lakes, consistent with Leathers et al. (2000) and Seager et al. (2012), and 2) positive height anomalies located over the Atlantic Ocean covering a region east of the Mid-Atlantic states (approximately 35°–40°N and 50°–70°W) (Fig. 2b). During wet summers, these features work together to direct southwesterly low-level and midlevel flow into the northeast region. Wet summers are also associated with a region of positive SLP anomalies that extends along the eastern coast of North America from south of the Canadian Maritimes to the Gulf of Mexico west of Florida (Fig. 2c), implying that wet summers are associated with a westward shift or expansion of the NASH.

All of the models are able to simulate a statistically significant flow of southerly to southwesterly low-level
Fig. 2. Regressions of observed and simulated twentieth-century (1981–2000) northeast-region JJA precipitation anomalies with (left) precipitation and 850-hPa wind, (middle) 500-hPa wind and geopotential height, and (right) SLP. All regression coefficients are shown for geopotential height, precipitation, and SLP (colors). Contour lines (black) indicate regions where regression coefficients are significant at 90%. Only wind vectors significant at the 90% level are shown. Reference wind vectors given in meters per second. (b) White boxes delineate z500GL and z500ATL regions; (c) the slpATL region is shown by the dashed box.
and midlevel winds into the northeast region during wet summers (Fig. 2, left). The models also simulate negative 500-hPa geopotential height anomalies approximately centered near the Great Lakes during wet summers in the northeast region (Fig. 2, middle), but the patterns vary in size and location compared to 20CR. In CCSM4, the negative geopotential height anomalies are shifted to the northwest and the relationship is not significant, but it is significant and centered near the Great Lakes when the regression is computed for a longer period, 1950–2000 (not shown). All of the models simulate statistically significant relationships with positive 500-hPa geopotential height anomalies in the western Atlantic (Fig. 2, right), but the simulated patterns vary in size and location compared to 20CR. For example, CanESM2, CCSM4, and CNRM-CM5 (Fig. 2) display regions of positive height anomalies that are shifted northward compared to 20CR, located north and east of the Canadian Maritimes rather than east of the Mid-Atlantic states. CanESM2 also shows a region of significant positive height anomalies that is shifted to the southwest compared to 20CR, centered near southern Florida and the Bahamas. All of the models simulate a region of positive SLP anomalies in the western Atlantic (Fig. 2, right) associated with wet summers in the northeast region, but the position and strength of the anomalies vary among the models. The relationship is not statistically significant in CNRM-CM5 but is physically consistent with 20CR and significant when evaluated for 1971–2000 (not shown). CCSM4 and GFDL-ESM2M show regions of significant negative SLP anomalies near the Great Lakes associated with northeast-region precipitation, consistent with areas of depressed geopotential heights.

Mean summer VIMT into the northeast region is from the west (Fig. 3a), carrying moisture from the central United States that enters the United States from the Gulf of Mexico near the coasts of Texas and Louisiana. There is weak to no net divergence present in summer from Pennsylvania northward, consistent with short-duration rainfall events where convergence is not apparent in the seasonal mean. Regression analysis shows that wet summers are characterized by a northeastward flow of moisture with increased convergence in much of the central and eastern United States (Fig. 4a). Significant areas of convergence are located near and east of the Great Lakes, consistent with the reduced 500-hPa geopotential height center identified in Fig. 2b, as well as along the Eastern Seaboard. A significant area of increased divergence is located in the western Atlantic, again suggesting that wet summers in the northeast region are influenced by a westward shift in the NASH with diverging equatorward flow over the Atlantic and converging poleward flow along the east coast. This pattern is consistent with the presence of positive 500-hPa height and SLP anomalies over the western Atlantic, as well as the low-level and midlevel wind patterns associated with wet summers in the northeast region (Fig. 2).

Simulated mean summer VIMT compares well to 20CR: moisture is transported eastward from the central United States after entering the continent at the Gulf Coast (Fig. 3). However, models vary in their ability to simulate mean divergence in the northeast region.
20CR shows weak to no net divergence (Fig. 3a), CCSM4, CNRM-CM5, and MIROC5 show mean convergence during summer over much of the northeast region (Figs. 3c,d,f). CanESM2 simulates mean divergence over much of the northeast region (Fig. 3b). The model biases in mean precipitation result from biases in divergence. CanESM2 simulates too little precipitation in much of the northeast region (Fig. 1c), consistent with its divergence bias. CCSM4, CNRM-CM5, and MIROC5 (Figs. 1d,e,g) overestimate precipitation in the northeast region, consistent with their biases of mean convergence. GFDL-ESM2M underestimates precipitation along coastal regions of the northeast region including much of New Jersey, southeastern New York State, southern New England, and coastal Maine (Fig. 1g) but is generally consistent with its simulation of divergence in the northeast region (Figs. 3e, 4e).

Though the models have some errors in simulating mean moisture transport and divergence, models generally capture the anomalous moisture transport and convergence associated with wet summers (Fig. 4). In CNRM-CM5, the flow of moisture is from the east and northeast but is not significant, so vectors are not shown in Fig. 4d. This result is consistent with the location of positive 500-hPa geopotential height anomalies in CNRM-CM5, north of Nova Scotia (Fig. 2k), which would direct flow from the North Atlantic westward into the northeast region. In CanESM2 the southwesterly flow of moisture along the southeastern United States becomes southeasterly over northern New England and southern Quebec (Fig. 4b), consistent with its positive z500 anomaly situated over eastern Canada (Fig. 2e). All models show increased divergence to some extent over the western Atlantic; this divergence is statistically significant in CanESM2, CCSM4, GFDL-ESM2M, and MIROC5.

To further explore the observed relationships important to northeast region summer precipitation in regions identified above, Spearman’s rho statistic was computed for detrended anomalies of area-averaged northeast-region precipitation (1950–2008) and 20CR 500-hPa geopotential height (z500; 1950–2010), 850-hPa meridional winds (y850; 1950–2010), SLP (1950–2010), and meridional VIMT (abbreviated qvIntNE, 1979–2010) (Table 2). Geopotential height anomalies are area averages for the Great Lakes region (z500GL; 42°–47°N and 75°–85°W) and the Atlantic region east of the Mid-Atlantic states (z500ATL; 35°–40°N and 50°–65°W). These regions (delineated by boxes in Figs. 2b,c) were selected based on results shown in Fig. 2b as well as regressions computed with CMAP precipitation anomalies for the northeast region (not shown). SLP anomalies are area averaged over the western Atlantic (slpATL), covering the area 30°–40°N and 60°–70°W. Results show that northeast-region JJA precipitation anomalies have significant relationships with 500-hPa geopotential height anomalies: positive with z500ATL and negative with z500GL, consistent with the results shown in Fig. 2b. All relationships are significant at the 95% confidence level, with the exception of UDel/z500ATL (significant at the 90%
TABLE 2. Spearman’s correlations for detrended observations (precipitation, v850, z500ATL, z500GL, qvIntNE, and slpATL), simulated v850 and precipitation (1950–2000), and projected v850 and precipitation (2050–2100). See text for region definitions. Bold (italic) print indicates significance at the 95% (90%) confidence level. All anomalies are standardized relative to the 1981–2000 average. Summer AMO indices were provided by NOAA/ESRL.

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<tr>
<td>UDEL/z500GL (1950–2008)</td>
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<td>UDEL/v850 (1950–2008)</td>
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Confidence level). Correlation results for v850 anomalies and anomalies of precipitation and z500 are consistent with results presented in Fig. 2; precipitation anomalies are significantly related to low-level northward wind anomalies that are associated with negative height anomalies centered over the Great Lakes and positive height anomalies located off the Mid-Atlantic coast. As expected, there is a strong and highly significant positive relationship between v850 and northward moisture transport in the northeast region. Results for slpATL indicate significant positive relationships between SLP in the western Atlantic and northeast-region summer precipitation, consistent with Fig. 2c.

Correlation analysis shows that all five models are able to simulate a statistically significant positive relationship between northeast-region precipitation and v850, consistent with observations (Table 2). With the exception of CNRM-CM5, the simulated relationships are stronger than those observed for 20CR/UDel.

Trend significance in observed area-averaged time series was evaluated using Mann–Kendall trend tests (Table 3). A positive but insignificant trend is present in UDel summer rainfall over 1950–2008. Significant positive trends are present in z500ATL and v850 anomalies for the northeast region over 1950–2010. Consistent with the increasing trend in v850 for the northeast region, there is a positive trend in northeast-region meridional VIMT (1979–2010), significant at the 90% level, suggesting that summer northward moisture transport into the northeast region has increased during recent decades. No significant trend exists in slpATL over 1950–2010.

Simulated trends covering 1950–2000 were also evaluated (Table 3). CCSM4 and CNRM-CM5 show small insignificant positive trends in northeast-region summer precipitation, consistent with UDel observations. CanESM2, CCSM4, and CNRM-CM5 all show positive trends in v850 (not significant) and z500ATL (significant), consistent with the direction of trends in 20CR. The precipitation trend in CanESM2 is negative, inconsistent with observations. In MIROC5, trends in northeast-region precipitation, v850, and meridional VIMT are negative, inconsistent with the direction of trends in 20CR.

c. Future projections

In this section, future projections are examined to identify processes that may lead to model disagreement about the direction of change in northeast-region summer precipitation. Regression analysis for 2081–2100 (Fig. 5; v850/precipitation regressions not shown) suggests that the processes important to northeast-region warm-season precipitation are likely to remain the same: a reduced geopotential height anomaly in the vicinity of the central United States and positive z500 and SLP anomalies in the western Atlantic that work to direct a southerly to southwesterly flow of moisture into the northeast region. Interestingly, CanESM2, GFDLE-ESM2M, and MIROC5 indicate that the region of SLP anomalies in the Atlantic associated with northeast-region rainfall expands in size and/or westward extent (Fig. 5, right).

Except for CanESM2, all models project a strengthening of the relationship between northeast-region precipitation and v850 during the second half of the twenty-first century (Table 2). Modeled v850, precipitation, and z500ATL trends covering 1950–2100 are given in Table 3. All models show increasing trends in northeast-region v850, significant in CanESM2, CCSM4, and GFDL-ESM2M. Significant positive trends in z500ATL are present in all models for 1950–2100. With the exception of CanESM2, positive trends are seen in northeast-region precipitation in all models, significant in CCSM4, CNRM-CM5, and MIROC5. Trends in northeast-region meridional VIMT cover 2071–2100 with the exception of CCSM4 (2081–2100) and are not significant. Though mean meridional VIMT trends are negative in CCSM4 and CNRM-CM5 during the late twenty-first century, regression analysis indicates that
northward moisture transport is still important during wet summers (Fig. 5).

Examination of zonal and meridional components of northeast-region VIMT for the late twenty-first century (Fig. 6) indicates that the largest increase is projected to occur in the zonal component, suggesting increased moisture transport by the GPLLJ. All models exhibit positive shifts in distributions of westerly zonal transport, significant according to Kolmogorov–Smirnov tests. Meridional VIMT projections suggest that northward moisture transport into the northeast region will also increase, but the magnitude of the change varies among the models and is small compared to the change in zonal transport. CanESM2 is the only model projecting a large increase in northward moisture transport, consistent with its significant positive trend in northeast-region \( y_{850} \) anomalies and increase in northward VIMT. This inconsistency is explained by the weakening of the relationship between northeast-region precipitation and \( y_{850} \), as well as the projected increase in mean moisture flux divergence for CanESM2 over portions of the northeast region (Fig. 7a). CanESM2 also projects decreased evaporation from the Mid-Atlantic coast northward to the Canadian Maritimes, including much of New England (not shown), consistent with the projected divergence increase over the same area.

4. Discussion and summary

This study has identified atmospheric processes important to northeast-region warm-season (JJA) precipitation at the interannual time scale and performed a first evaluation of the ability of five CMIP5 models to simulate these processes in the twentieth-century historical experiment. Twenty-first-century projections were also examined to highlight processes that lead to disagreement among the models about future precipitation changes in the northeast region, identifying processes that may be particularly relevant for evaluating model credibility.

Results indicate that wet summers in the northeast region are associated with two prominent features of the
large-scale circulation that direct southwesterly flow into the region: a depressed geopotential height anomaly centered near the Great Lakes and positive height anomalies located over the western Atlantic east of the Mid-Atlantic states. This dipole pattern of $z_{500}$ anomalies is consistent with the pattern of geopotential height anomalies present during wet summers in the SE (Diem 2006), though the negative height center over the continent is shifted northward compared to its position during wet summers in the SE. Murray and Colle (2011) show that interannual variations in the distribution of convective storms in the northeast region are related to differences in the mean flow between warm seasons. Consistent with our results, composite analysis of active convective days in the northeast region revealed a mean trough in the 500-hPa geopotential height field over the Great Lakes and low-level (925 hPa) southwesterly flow along the Eastern Seaboard. Increased convective activity in New England is associated with increased cyclone and trough activity (Murray and Colle 2011), suggesting that wet summers in the northeast region feature more frequent cyclone and trough activity.

Fig. 5. As in Figs. 2 and 4, but for RCP8.5, 2081–2100 regressions of northeast-region precipitation anomalies with (left) 500-hPa wind and geopotential height, (middle) VIMT and moisture divergence, and (right) SLP.
FIG. 6. Density plots of northeast-region area-averaged (left) zonal and (right) meridional VIMT: 1981–2000 (solid line) and 2081–2100 (dashed line).
FIG. 7. Differences in JJA (left) precipitation and (right) moisture divergence: RCP8.5 (2081–2100) minus historical (1981–2000). Stippling indicates differences significant at 95%.
Wet summers in the northeast region are also characterized by a northeastward flow of moisture and increased moisture convergence along the Eastern Seaboard. The presence of positive SLP anomalies in the western Atlantic and increased moisture divergence off the coast of the SE during wet summers suggests that a westward shift of the NASH leads to increased summer precipitation in the northeast region. This result is consistent with composite analyses of U.S. precipitation anomalies showing wetter conditions in the northeast region when the NASH western ridge is shifted to the southwest (Li et al. 2012, 2013), suggesting the possibility that interannual variations in northeast-region summer precipitation are related to zonal shifts in the position of the NASH western ridge.

To investigate the sensitivity of the regression analyses to our definition of the northeast region (35°–50°N and 70°–80°W), which was used for area-averaged precipitation, we repeated regression analyses for smaller regions of the northeast region: an area in the northeast section (45°–49°N and 70°–73°W) and one in the southwest section (36°–40°N and 77°–80°W) (not shown). Results from these tests are consistent with results for the larger region, other than small variations in the geographical position or extent of the atmospheric features described above. Results from the sensitivity tests as well as consistencies with other studies (e.g., Leathers et al. 2000; Girardin et al. 2006; Murray and Colle 2011; Li et al. 2012, 2013) suggest that our results using area-averaged precipitation for the larger region reasonably represent northeast-region summer precipitation processes.

In CNRM-CM5, CCSM4, and MIROC5, the positive z500 anomalies found in the western Atlantic during wet summers are displaced northward, located near the Canadian Maritimes (Fig. 2, middle column) rather than east of the Mid-Atlantic coast as seen in 20CR/UDel. This pattern resembles a summertime teleconnection pattern identified by Lau et al. (2004, their Fig. 5a) that links summertime interannual climate variability in North America to North Pacific sea surface temperature (SST) anomalies and, consistent with our results, is also associated with increased northward flow and higher precipitation amounts in eastern North America.

Other studies point to the importance of Atlantic SST anomalies to northeast-region warm-season precipitation. During the 1960s northeast-region drought, cold SSTs stretched along the east coast from the Carolinas toward Newfoundland. These cold SST anomalies were associated with anomalous northerly flow and subsidence, which stabilized the atmosphere over the northeast region producing dry conditions (Namias 1966). To explore the role of SST anomalies on northeast-region summer precipitation, regression analysis was performed between northeast-region precipitation anomalies and SSTs using NOAA optimum interpolation (OI) SST version 2 (V2), provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado (http://www.esrl.noaa.gov/psd/; Reynolds et al. 2002). Results confirm the presence of cold SSTs in the Caribbean during wet summers in the northeast region (Fig. 8), consistent with strengthening and southwest ridging of the NASH (Kushnir et al. 2010; Li et al. 2012). The presence of cold SSTs in the western Atlantic also suggests that wet summers in the northeast region occur when the Atlantic warm pool is anomalously small, which enhances the GPLLJ, increasing northward moisture transport into North America from the Gulf of Mexico (Wang et al. 2007). A significant negative relationship exists between slpATL anomalies and the JJA Atlantic multidecadal oscillation (AMO) index (provided by NOAA ESRL at http://www.esrl.noaa.gov/psd/data/climateindices/index.html; Enfield et al. 2001; Table 2),
further suggesting that cold SSTs in the tropical Atlantic are linked to wet summers in the northeast region. These results imply that some of the differences among simulations of northeast-region summer precipitation may be related to differences in model simulations of SST anomalies and how they interact with the NASH. This question will be addressed more completely in future research.

Regression analysis suggests that the region of SLP anomalies in the Atlantic associated with northeast-region rainfall may increase in size and/or westward extent by the late twenty-first century (Figs. 5c,i,1). This result is consistent with an analysis of 23 CMIP3 models in the A1B scenario by Li et al. (2011), suggesting that the NASH is likely to intensify and expand westward during Northern Hemisphere summer. Consistent with CMIP3 projections, CMIP5 models also project that the NASH western ridge is expected to shift westward (Li et al. 2013). Li et al. (2013) also note that this will likely lead to more frequent occurrences of southwest ridging of the NASH, suggesting a possible increase in the frequency of wet summers in the northeast region. All models show increased moisture transport into the northeast region, but they do not all project increased convergence, suggesting that circulation changes and the resulting effects on moisture divergence are important factors in determining future changes in northeast-region warm-season precipitation.

A major motivation for this study was to gain a better understanding of northeast-region warm-season precipitation processes that would be useful in developing a set of consistent process-level analyses that would allow for meaningful differential weighting of models, which may provide more reliable projections of future climate for the northeast region. Therefore, it is natural to ask whether any judgment can be made about the credibility of northeast-region warm-season precipitation projections for the five models analyzed in this case study.

The five models analyzed here vary in their ability to simulate mean warm-season precipitation in comparison to observations (Fig. 1). CanESM2 is too dry and the remaining models overestimate rainfall amounts, but their spatial patterns all show a gradient in mean summer precipitation that declines away from the coast toward the northwest. CanESM2 simulates mean divergence, while the other models simulate areas of mean convergence over much of the northeast region. The mean divergence error in CanESM2 simulations of the late twentieth century may influence the evolution of errors in future projections, perhaps rendering precipitation projections from CanESM2 to be less credible than in other models. On the other hand, models that simulate mean convergence over the northeast region may not be any less likely to have errors in their future projections of northeast-region warm-season precipitation. They overestimate precipitation in the twentieth century (Fig. 1) and may project increases that are too large.

All of the models simulate the observed processes related to northeast-region warm-season precipitation to some extent, but the models do have some errors. For example, observed trends are generally not well simulated, except for z500ATL. Also, the relationship between northeast-region precipitation and u850 is too strong in four of the five models (Table 2). Errors are evident in MIROC5; z500 and SLP anomalies in the western Atlantic during wet summers cover areas much larger than seen in 20CR/UDel (see Fig. 2), likely explaining its strong convergence along the east coast in wet summers (Fig. 4f) and its excess mean precipitation in much of the northeast region (Fig. 1). All models capture the anomalous moisture transport and convergence during wet summers, though CCSM4, CNRM-CM5, and MIROC5 overestimate it in some portions of the northeast region (Figs. 4c,d,f).

Clearly, the small sample of models analyzed here can only suggest which models are more or less credible. Process evaluation of a larger suite of models, planned for future work, may identify model credibility with more confidence. In cases where it is not possible to clearly differentiate between models, knowledge of model errors and biases may help to inform decision making by identifying process-based sources of uncertainty in multimodel projections. A potential limitation of this study is that questions remain about how well models simulate northeast-region summer precipitation processes at submonthly time scales. Future model evaluation of northeast-region warm-season precipitation processes should include examining (i) the distribution of daily summer precipitation in the models, (ii) how well they simulate storms and storm tracks, and (iii) how well models simulate z500 and moisture convergence anomalies on wet days.

It is also possible that future changes in northeast-region summer precipitation may be outside the current GCM projection range even when evaluating a larger suite of models. The influence of Arctic amplification on Northern Hemisphere Rossby waves provides one example. Arctic amplification, not well captured by all CMIP5 models (e.g., Liu et al. 2013), leads to earlier spring snowmelt and drying of soils in high-latitude land areas, slowing the progression of Rossby waves in Northern Hemisphere summer (Francis and Vavrus 2012). This, in turn, is likely to increase the probability of flooding and drought in midlatitudes due to persistent weather patterns (Francis and Vavrus 2012). Models that poorly simulate circulation changes associated with Arctic amplification may underestimate future changes
in the intensity or frequency of extreme precipitation or drought events in the northeast region.

It is worth noting that other studies suggest that model selection or culling based on performance in a particular region has little effect on multimodel projections (Brekke et al. 2008; Pierce et al. 2009). It may also be more reasonable to select models based on the needs of stakeholders and decision makers. For example, Horton et al. (2011) describe a collaborative stakeholder driven approach to climate hazard assessment and climate change projection methods that addresses the specific needs and time constraints of decision makers in New York City. They suggest that the use of a large group of GCMs may be preferable if stakeholders prefer to sample a broad range of climate sensitivities to inform their decision making, as was the case in New York City.

5. Concluding remarks

The case study presented here suggests that it is possible to develop a set of process-based analyses that form a framework for evaluating model credibility in the northeast region. This framework includes evaluation of models’ ability to reproduce observed spatial patterns of mean precipitation and precipitation amounts; to simulate dynamical features of the atmospheric circulation, moisture transport, and moisture divergence related to interannual precipitation variability; to reproduce observed long-term trends; and to reproduce SST patterns that are important to northeast-region summer precipitation.

This study has identified several processes important to northeast-region precipitation that can be used for evaluating model credibility:

- Wet summers in the northeast region are associated with positive 500-hPa geopotential height anomalies located in the western Atlantic off the Mid-Atlantic states.
- Wet summers in the northeast region are associated with negative 500-hPa geopotential height anomalies centered near the Great Lakes.
- Wet summers in the northeast region are associated with positive SLP anomalies in the western Atlantic, which are possibly related to cold tropical Atlantic SST anomalies and southwest ridging of the NASH.
- Wet summers in the northeast region also feature increased southwesterly moisture transport and moisture convergence along the Eastern Seaboard and increased moisture divergence off the southeast coast of the United States.

The coarse horizontal resolution of global models needs to be considered when GCMs are used to provide precipitation projections at decision-making scales. This is especially true in coastal areas or regions of complex topography where there can be large variations in precipitation processes over small spatial scales. Furthermore, prior to dynamical downscaling, it is critically important to evaluate the quality of GCM simulations, including their ability to simulate large-scale atmospheric processes, especially those related to moisture transport from remote sources, important to regional precipitation.

Future analysis for the northeast region, using a larger suite of models, will attempt to identify whether multimodel results are more credible when models are selected or weighted based on a process-level analysis in comparison to results from the entire suite of models. Future work will also include examination of simulated surface fluxes and SSTs, in the context of their importance to northeast-region warm-season precipitation. Identifying sources of intermodel differences in future projections is important, determining processes relevant for model credibility. In particular, changes in moisture divergence control the sign of northeast-region summer precipitation changes, making it a critical component of process-level analyses for the region.

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