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Sho Kawazoe
Iowa State University

William J. Gutowski Jr.
Iowa State University, gutowski@iastate.edu

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Keywords
extremes, NARCCAP, Regional climate models, multi-model ensembles, precipitation extremes

Disciplines
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Evaluation of Regional, Very Heavy Precipitation Events during the Summer Season
using NARCCAP Contemporary Simulations

Sho Kawazoe* and William J. Gutowski Jr.

* Correspondence to: Sho Kawazoe, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 3173-25 Showa-machi, Kanazawa-ku, Yokohama-city, Kanagawa, 236-0001, Japan.

Email: kawazoe@jamstec.go.jp

Telephone: (045)-778-5557

Fax: (045)-778-5498

Affiliations:

Kawazoe, Gutowski: Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa

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Regional climate models (RCMs) from the North American Regional Climate Change Assessment Program (NARCCAP) are compared with the two gridded precipitation datasets (Climate Prediction Center (CPC) and the University of Washington (UW)) and the North American Regional Reanalysis (NARR) to examine if RCMs are able to reproduce very heavy precipitation under similar physical conditions seen in observations. The analysis focuses on contemporary climate (1982-1999) in an upper Mississippi region during the summer (June-July-August) months and utilizes output from NARCCAP RCMs forced with a reanalysis and atmosphere-ocean global climate models (AOGCMs).

The NARCCAP models generally reproduce the precipitation frequency vs. intensity spectrum seen in observations up to around 25 mm day$^{-1}$, before producing overly strong precipitation at high intensities. CRCM simulations produce lower precipitation amounts than the rest of the models and observations past the 25 mm day$^{-1}$ threshold. Further analysis focuses on precipitation events exceeding the 99.5$^{th}$ percentile that occur simultaneously at several points in the region, yielding so-called “widespread events”. Apart from the CRCM and EPC2 simulations, models and observations produce peaks in widespread events during 0300 UTC-0900 UTC, though the models typically produce slightly weaker intensities compared to observations. Widespread precipitation falls too frequently throughout the day, especially between 1500 UTC and 2100 UTC, compared to observations. Composite precipitation shows intermodel differences in magnitude and
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1. Introduction

Catastrophic U.S. Midwest flooding events, highlighted by the summer floods of 1993 (Kunkel et al. 1994; Anderson et al. 2003) and 2008 (Dirmeyer and Kinter 2010; Coleman and Budikova 2010), have resulted in massive social-economic damages. In a region where agricultural farmland covers more than two-thirds of the land use and dominates the regional economy (Pryor et al. 2013), these two events resulted in an estimated $21 billion and $15 billion of damages respectively (Lavers and Villarini 2013). Many flooding events vary in spatial and temporal characteristics, as some may be caused by single extreme events falling on surfaces saturated in previous seasons, while others may be caused by a series of storms that by themselves may not be classified as extreme events (Senevirantne et al. 2012). In addition to the variability of precipitation characteristics, the frequency of heavy precipitation events has increased since the middle of the last century, even in locations where mean precipitation shows minimal changes (Groisman et al. 2005; Karl et al. 2008). There is also strong indication that frequency and intensity of precipitation extremes will continue to increase into the future (Zwiers and Kharin 1998; Meehl 2000; Alexander et al. 2006) including results from the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5), which states that more frequent and/or
intense heavy rainfall events around much of the mid-latitude regions are “very likely” as a result of projected increases in global temperatures and atmospheric water content (Allen and Ingram 2002; Held and Soden 2006; Min et al. 2011). Policy makers, stakeholders, as well as the general public are wary of such events becoming increasingly common and require reliable forecasts in order to determine if adaptive responses are needed to mitigate the societal impact they may have.

Mesoscale convective systems (MCSs) are the dominant contributor to heavy rain events in the central US (Houze 2004; Schumacher and Johnson 2006). However, coarse resolution models, particularly global climate models (GCMs; ~100-300km grid spacing), do not capture the complex regional topography and forcing mechanisms that is vital to convective storm development (Wehner et al. 2010). Therefore, it is imperative that (i) higher resolution climate simulations that better resolve orographic and mesoscale forcing is utilized (Fowler et al. 2005; Gutowski et al. 2010; Dulière et al. 2011; Bukovsky et al. 2013) and (ii) models are first evaluated in the contemporary climate to ensure that the physical mechanisms that produce very heavy precipitation events are consistent with observations (Gutowski et al. 2008).

One such project is the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009,2012), a set of dynamically downscaled simulations nested within a reanalysis or atmosphere and ocean GCMs (AOGCMs). Dynamically downscaling GCMs by nesting regional climate models (RCMs) adds more realistic spatiotemporal
details to GCMs, which is especially important as mesoscale forcing dominates the development of convective summer storms (Leung et al. 2004; Christensen et al. 2007; Mahoney et al. 2013). In this study, we will evaluate climate simulations from NARCCAP during the summer months (June-July-August) in the upper Mississippi region.

This paper will follow the framework of our two previous publications, which focused on very heavy precipitation events during the winter season in the upper Mississippi region. Kawazoe and Gutowski (2013a) used RCMs from NARCCAP, while Kawazoe and Gutowski (2013b) used 21 GCMs from the Coupled Model Intercomparison Project – Phase 5 (CMIP5; Taylor et al. 2012). We now shift our focus to the summer season, where local and regional scale convective forcing plays a larger role in producing very heavy events compared to the winter, which is largely governed by synoptic-scale dynamics (Maddox et al. 1979; Schumacher and Johnson 2006).

The goals of this study are to assess the ability of the ensemble of NARCCAP models to reproduce very heavy daily precipitation seen in observations and to provide a baseline for understanding how very heavy daily precipitation and its causal processes change under enhanced greenhouse warming scenarios. Multi-model ensembles are commonly used to identify and reduce characteristic bias and uncertainties associated with how a particular climate model represents the climate system (Hagedorn et al. 2005; Meehl et al. 2007; Mailhot et al. 2011). If an ensemble analysis produces precipitation characteristics similar to those seen in observations, and under similar physical conditions, greater confidence can
be put into the collective ability climate models have in the assessment of the changing risk of heavy precipitation events in the future (Murphy et al. 2004; Gutowski et al. 2008). This is in line with our study objective, which is to offer better potential for assessing the capability of climate models to produce very heavy precipitation events.

This paper is structured as follows: section 2 provides an overview of the NARCCAP models and observational datasets, along with the analysis methods used. Precipitation characteristics and their supporting environmental conditions appear in section 3, followed by the conclusion section summarizing our results in section 4.

2. Data and Methods

a. Verification datasets

For this study, we use the same gridded observational datasets of daily precipitation as Kawazoe and Gutowski (2013a):

- Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Daily Precipitation (Higgins et al. 2000). 0.25° x 0.25° horizontal resolution. Data available from 1948-2006.
- University of Washington (UW) gridded precipitation (Maurer et al. 2002). 0.125° x 0.125° horizontal resolution. Data available from 1950-1999.

The additional observational dataset (UW) is to acknowledge the uncertainty that may exist in different gridding products when identifying days with very heavy precipitation.
For all other fields, we use the North American Regional Reanalysis (NARR; Mesinger et al. 2006). The fields we use are 2-m specific humidity, convective available potential energy (CAPE), vertically integrated moisture flux convergence (hereafter VI-MFC) and vertically integrated moisture transport (hereafter VI-MT). These fields represent key supporting environmental conditions during very heavy precipitation development. The NARR is also used for diurnal cycle precipitation analysis, as the gridded datasets used in this study did not provide precipitation at sub-daily intervals.

b. NARCCAP models

Climate model output comes from the two main phases in NARCCAP. Phase I (Mearns et al. 2012) includes six regional climate models (RCMs; Table 1) from the National Centers for Environmental Prediction (NCEP) and U.S. Department of Energy (DOE) Reanalysis II for their boundary conditions. For ECP2, we only analyze surface characteristics, as the output on the native vertical coordinate has not been interpolated to standard pressure levels. All NCEP-driven RCMs used approximately 0.5° horizontal resolution for the period of 1980-2004. Convective parameterizations used in the RCMs is also listed in Table 1, because of their importance to precipitation simulations during the summer season.

Phase II used the same six RCMs to downscale four GCMs from World Climate Research Program’s (WCRP’s) Coupled Model Intercomparison Project - Phase 3 (CMIP3; Table 1). All GCM-driven RCMs spans the period of 1971-1999. Of the 24 RCM-GCM
nesting combinations possible, 12 pairings were completed as part of NARCCAP. A full list of model combinations available from NARCCAP and used for this study is shown in Table 2. Further details are available on both the NARCCAP website (http://narccap.ucar.edu) and in Mearns et al. (2009, 2012).

c. Analyses

This study utilizes the same domain (upper Mississippi region) and years (1982-1999) studied in Kawazoe and Gutowski (2013a,b). Figure 1 shows our analysis domain with elevation from the MM5I. Because elevation vary only slightly between the RCMs, one model should be a fair representation of NARCCAP. We define our “day” as 1200 UTC - 1200 UTC (0600 - 0600 local standard time in the upper Mississippi region) so precipitation from nocturnal storms commonly seen during the summer is accumulated throughout the storm duration (e.g., Anderson et al. 2003). The CPC observational data set is already in daily increments that match our defined “day”, while the UW observational dataset defines a “day” as 0600 UTC – 0600 UTC (0000 – 0000 local standard time in the upper Mississippi region), a factor that may affect some of our results. Both the CPC and UW output have been regridded to a 0.5° grid using bilinear interpolation to give the datasets the same nominal resolution as the RCMs, as recommended by Chen and Knutson (2008). Precipitation characteristics for the RCMs were computed using their native grids, similar to Wehner (2013). Analysis examining conditions other than precipitation during very heavy events focused on instantaneous fields at 2100 UTC (1500 local standard time
in the upper Mississippi region), which provided information on the state of the atmosphere prior to the time of maximum frequency of convective storms (Wallace 1975).

We defined a “precipitation event” as precipitation above 0.25 mm day$^{-1}$. Very heavy precipitation was defined as any event above the 99.5$^{\text{th}}$ percentile. We then found widespread events by searching for very heavy events occurring on multiple grid points on the same day. For our analysis, we designated simultaneous very heavy events on 10 or more grid points as widespread events. This threshold is lower than our previous studies (Kawazoe and Gutowski 2013a,b), as summer storms usually concentrate over a smaller area than do winter storms. Several atmospheric fields were examined (2-m specific humidity, CAPE, VI-MFC, and VI-MT) to understand conditions conducive to very heavy events. These fields gave insight into the preferred conditions for very heavy precipitation events and became the basis for assessing simulated versus observed processes yielding very heavy precipitation. For specific humidity and CAPE, anomalies were calculated from the difference of our widespread very heavy composites and the summer climatology. We also evaluated whether differences were statistically significant from summer climatology using a two-tailed student t-test at the 0.01 level.

3. Results

a. Precipitation statistics
Table 3 shows the average precipitation rate and frequency of precipitation events in the upper Mississippi region for models and observations. The numbers in parentheses are frequency of precipitation above 2.5 mm day\(^{-1}\). Among the simulations, 15 of the 18 produce a lower average precipitation rate than CPC, with the RCM3 simulations producing the most and WRFG simulations producing the least. Average precipitation rates tend to vary more with RCM choice than the lateral driving source. Among the simulations, 9 of the 18 show lower frequencies of precipitation than CPC, 6 of which are either the MM5I or WRFG simulations. For precipitation exceeding 2.5 mm day\(^{-1}\), models typically produce frequencies in the range of 16-32\%, which is approximately \(\pm 6\) percentage points of the CPC frequency, 26.7\%. The differences between CPC and UW results may come from how each gridded dataset defines a “day”. Because UW reports precipitation from 0600 UTC - 0600 UTC, nocturnal storms may not be accumulated in their entirety, and may spill over to the next day. This could account for the lower average and higher frequency of precipitation in UW compared to CPC. The difference may also come from the gridding schemes and quality control procedures used by each dataset.

Table 3 also shows precipitation for each simulation and for observations at the 95\(^{th}\), 99\(^{th}\), and 99.5\(^{th}\) percentiles. At the respective percentiles, 8, 12, and 13 of the 18 simulations produce higher precipitation rates compared to the CPC. Similar to precipitation intensity and frequency of precipitation, consistency at each percentile seems to be determined more by the downscaling RCM rather than the boundary conditions source. The highest
precipitation intensity (RCM3ncep) is approximately 38%, 32%, and 32% higher than the lowest precipitation intensity (CRCMccsm) at the 95th, 99th, and 99.5th percentiles, respectively. The CRCM simulations consistently show the lowest precipitation rates at each percentile, while the RCM3 simulations tend to produce the highest precipitation. The CRCM and ECP2 are spectrally nudged models. Spectral nudging, as the term implies, “nudges” large-scale characteristics (e.g., geopotential height, U and V wind components, and temperature) within the RCM domain towards the driving reanalysis or GCM simulation (Waldron et al. 1996; von Storch et al. 2000). The potential value of spectral nudging has been well documented (Miguez-Macho et al. 2004; Alexandru et al. 2009; Mearns et al. 2012; Glisan et al. 2013). For the CRCM, our results show an evident lowering of precipitation at high-intensity thresholds. This was also seen Alexandru et al. (2009), where a reduction of precipitation extremes appeared when the spectral nudging became stronger and overly adjusted the large-scale characteristics within the RCM domain back towards the driving GCM simulation. It is unclear if this in itself explains our results, particularly because the EPC2 simulations do not show similar precipitation characteristics. Our results may also be due to the tendency for CRCM to underestimate the precipitation maxima (e.g., Mailhot et al. 2007), or how the parameterization scheme (Table 1) used by the CRCM initiates convection with respect to the rest of the NARCCAP models. The differences are important to keep in mind, as the CRCM consistently deviates from the rest of the models in our study.
Figure 2 shows a histogram of normalized frequency vs. intensity in the upper Mississippi region using 2.5 mm day$^{-1}$ bins. Models generally reproduce the precipitation frequency vs. intensity spectrum seen in observations up to around 25 mm day$^{-1}$. Beyond this threshold, the ECP2 and MM5I simulations closely resemble the CPC distribution throughout the entire intensity spectrum, while the rest of the models (other than CRCM) show more high intensity events. The CRCM produces precipitation amounts that are lower than the rest of the models and observations. As mentioned earlier, observations were interpolated to the same nominal resolution as the RCMs. Chen and Knutson (2008), among many others, highlight the importance of this procedure. In their analysis, precipitation from CMIP5 models were compared with the CPC’s native 0.25º x 0.25º resolution and with those interpolated to the same resolution for each CMIP5 model. Results showed that when using the CPC’s native resolution, most of the models underestimate observations, while interpolation to a model’s grid showed most models either agreeing or overestimating high-intensity precipitation, which is consistent with our findings.

Figure 3 shows the number of very heavy events occurring simultaneously over a given number of grid points. This simultaneity plot represents the approximate spatial scale of very heavy precipitation events (x-axis) and the frequency of days in which they occur (y-axis). Compared to our winter analysis in Kawazoe and Gutowski (2013a), a much steeper drop with increasing number of event grid points occurs at lower spatial scales, indicating...
that very heavy events during the summer months in both the models and observations result from systems with smaller spatial scale than in winter. The CRCM, and to a lesser extent the ECP2, shows a larger spatial scale for their very heavy events. While spectral nudging may play a role in increasing the spatial scale of simulated very heavy events, it is difficult to conclude at this point.

**b. Widespread very heavy precipitation**

Table 4 shows the monthly distribution of widespread very heavy events. Both the CPC and UW show July having the highest frequency of widespread events. Among the simulations, 14 of the 18 model combinations show June to have the highest frequency of widespread very heavy events, though large intermodel differences are seen on the actual percentages. These differences may be from the strength and timing of the North American monsoon (NAM), as its onset can strengthen and enhance the monsoon high in our study domain, creating subsidence and suppressing low-level jet (LLJ) related rainfall in the central US (Higgins et al. 1997; Wang and Chen 2009).

Area-averaged precipitation’s diurnal cycle during widespread very heavy precipitation events appears in Figure 4. Again, results are more dictated by the individual RCMs than the driving boundary conditions. CRCM simulations show good agreement with each other throughout the day, but they deviate greatly from observed behavior, as their timing of the peak is 6-9 hours earlier, and approximately 40% of the peak intensity seen in observations. The ECP2 simulations also deviate from observations, with only a slight change in
precipitation occurring (~0.3 mm) throughout the day. With the exception of the MM5Iccsm (which resembles CRCM simulations and the ECP2gfdl), the rest of the RCMs show peak precipitation near the 0300-0900 UTC hours peak seen in observations, with model peak intensities slightly lower that observations on average. Climate models, particularly during the warm season in and around our analysis domain, tend to have precipitation that occurs too frequently, too light, and too early, compared to observations (Randall et al. 1991; Liang et al. 2004; Lee et al. 2007), often because of the model’s convective parameterization schemes (Liang et al. 2006; Bukovsky and Karoly 2011). Although simulated precipitation tends to be lighter at its peak and more frequent throughout the day than observed, it does not peak too early, other than the exceptions mentioned earlier. For the GCM driven HRM3 simulations, we also note a secondary peak occurs around 1800 UTC.

Figure 5 shows composite daily precipitation during widespread very heavy events. Observational composites show a local maximum around the center of our domain, similar to some of the models, while others show multiple precipitation maxima within the domain. Precipitation intensities are clearly lower in the CRCM simulations, which was seen in our precipitation intensities in Table 3, and throughout the precipitation intensity spectrum in Figure 2. This, as well as our simultaneity plots in Figure 3, suggests that the CRCM does not produce the intense, convective storms seen in the rest of the models and observations. As for the rest of the models, there seems to be a high amount of variability in the
precipitation characteristics. Other than the CRCM simulations and perhaps the slight southern bias of precipitation in the WRFG simulations, no clear similarities are seen among the RCM type or driving boundary source. These results seem typical of summer very heavy precipitation events, when storms are often highly localized and scattered in space and time (Gershunov 1998).

c. Supporting environmental conditions

Figures 6-8 show composite fields produced by averaging over the widespread event days from each data source. The NARR provided the observational results, with the days to composite determined from the CPC and UW widespread event days.

Figure 6 shows composite 2-m specific humidity anomalies during widespread very heavy events. Both models and observations show a significant positive specific humidity anomaly in our region, and the location with strongest positive specific humidity anomaly coincides reasonably well with locations of precipitation maxima. However, models with greatest specific humidity anomaly in the region does not imply the strongest precipitation intensities. In addition to the strong positive anomalies within our domain, there is a corresponding dry anomaly in the southwestern US for both models and observations. This negative anomaly may be due to the pre-onset of the NAM. As discussed earlier, lack of a NAM provides an environment that favors the development of very heavy precipitation events around our study domain. A deeper look into the connection between the NAM and
precipitation in our analysis domain is needed before a more robust statement can be made. However, such diagnosis is outside the scope of this paper.

Figure 7 shows VI-MFC (contours) and VI-MT (vectors) composites during widespread very heavy events. For VI-MT, there is strong moisture transport from the Caribbean and the Gulf of Mexico, with a northwestward moisture flow near central Texas turning northeastward toward our study region for all models and observations. VI-MT anomalies (not shown) show enhanced moisture transport into our study region compared to climatology for all models and observations. This is seen in a wide range of studies, as heavy rain events are often caused by the added contribution of remote moisture from the Gulf/Caribbean (Bell and Janowiak 1995; Trenbreth and Guillemot 1996; Brubaker et al. 2001; Moore et al. 2012) to the existing terrestrial moisture (Dirmeyer and Brubaker 1999; Dirmeyer and Kinter 2010). For most models, strongest VI-MT vectors are at locations close to where composite precipitation is the greatest, though models with the strongest VI-MT does not seem to necessarily imply strongest precipitation intensities. Strong VI-MFC, especially near the base of the storm, implies upward motion and convective initiation (Banacos and Schultz 2005). During widespread very heavy precipitation events, VI-MFC tends to be more positive (convergence), and aside from the RCM3ncep (which deviates rather drastically from models and observations), show spatial patterns similar to the composite precipitation figures. VI-MFC anomalies (not shown) show positive convergence anomalies at or near the area where precipitation is seen in the composites for
all models and observations. This was also seen in Min and Schubert (1997) in the U.S. Central Plains, and Holman and Vavrus (2012) in the state of Wisconsin, where heavy rain locations occurred in areas of high VI-MFC.

Figure 8 shows composite CAPE anomalies during widespread very heavy precipitation events. CAPE is not field provided by NARCCAP, but certain simulations were calculated and made available for this analysis. NARR does provide CAPE, and is used for this study. It is noted that differences in how CAPE is calculated between the two datasets may induce differences in our results. CAPE represents the amount of buoyant energy available in an air parcel and is related to the maximum vertical velocity within an updraft. High CAPE values will therefore represent enhanced convective potential. Both models and observations show higher CAPE values during widespread very heavy events compared to climatology, with their maxima predominantly located in the southwest portion of our domain. The location of CAPE maxima is usually southwest of the precipitation maxima and strongest VI-MT vectors for both models and observations. Like specific humidity, VI-MT, and VI-MFC, models with higher CAPE do not always imply higher precipitation composites. This could be an artifact of the time in which we extract instantaneous CAPE values, a possible disconnect between the diurnal cycle of maximum CAPE and maximum precipitation (Lee et al. 2007), or the destruction of CAPE by cumulus parameterization (e.g. Arakawa and Schubert 1974; Emanuel et al. 1994; Kain 2004). Liang et al. (2004) mention that the timing of convection may not be predicted by CAPE, but when and how
convection is triggered based on parameterization schemes. CAPE for the RCM3 ensemble was also made available, but produced extremely low CAPE values (maximum values ~300 J kg\(^{-1}\), while the rest of the models and observations have maxima 4 to 5 times larger). The reason for this is unclear at present and requires a deeper look into vertical structure characteristics of this model. For this reason, we have omitted the RCM3 from our analysis.

4. Conclusion

Six different RCMs from the NARCCAP project, driven by the NCEP reanalysis and four AOGCMs, were compared with observational data from the Climate Prediction Center (CPC) and the University of Washington (UW), along with the North American Regional Reanalysis (NARR) to assess the capability of climate models to produce very heavy precipitation during summer. Our study region is an upper Mississippi region, where we examine the years 1982-1999 during the months June-July-August. Widespread very heavy precipitation was defined as the top 0.5% of all precipitation of above 0.25 mm day\(^{-1}\) occurring on at least 10 grid points simultaneously. During these events, composites were created for 2-m specific humidity, vertically integrated moisture flux convergence (VI-MFC), vertically integrated moisture transport (VI-MT), and convective available potential energy (CAPE).

Most simulations show lower average precipitation compared to observations and approximately half the simulations show fewer days of precipitation than observed. In
contrast, for precipitation at the 95th, 99th, and 99.5th percentiles, most simulations produce higher precipitation rates than observed at each threshold. The CRCM simulations show the lightest precipitation at each percentile. The CRCM also has a larger spatial scale for their very heavy events. Models and observations are in good agreement for frequency vs. intensity up to about 25 mm day\(^{-1}\). The ECP2 and MM5I simulations reproduce the frequency-vs.-intensity seen in observations throughout the entire spectrum, while the rest, other than the CRCM, produce higher intensity precipitation compared to observations.

Models tend to produce their most frequent widespread very heavy events in June, perhaps because of the pre-onset environment of the NAM, when the monsoon high does not act to suppress LLJ-related rainfall over the Great Plains. Aside from the CRCM and ECP2, whose precipitation tends to peak 6-9 hours earlier than observations, the models do well in producing the observed timing of peak precipitation, which occurs between 0300 UTC-0900 UTC. Simulated precipitation peaks tend to occur at slightly lower intensities than observed on average. As with many model evaluation studies, NARCCAP models tend to precipitate too much and too frequently throughout the day, especially between 1500 UTC and 2100 UTC. Precipitation composites show differences in spatial and intensity characteristics between models and observations. Unlike the winter, where synoptic scale forcing dictates widespread very heavy precipitation, more complex local and regional scale forcing, in addition to the large-scale forcing, appears to play a critical role during the summer, yielding a spread of precipitation spatial distribution and statistical characteristics.
The 2-m specific humidity shows high moisture anomalies in the region in both models and observations during the widespread events, with corresponding lower moisture anomalies to the southwest. The location of positive VI-MFC during the widespread events agrees reasonably well with the location of precipitation, and both models and observations show VI-MT from the Gulf of Mexico. Positive CAPE anomalies in the composites dominate the areas where widespread very heavy precipitation is present as well.

In summary, though there are differences in precipitation characteristics, NARCCAP models as an ensemble appear capable of producing very heavy precipitation events in the analysis region for the correct physical behavior seen in observations. While differences between models and observations and between models themselves need consideration, results here should support the use of the NARCCAP models to evaluate changes in future climates.

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References


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Figure 8. Composite CAPE anomalies during widespread very heavy events for observations and RCM simulations. Contour scale for all plots is in the bottom right, in J kg$^{-1}$. Hatching indicates statistically significant differences from JJA climatology at the 0.01 level.
Kawazoe; Figure 2.tif
Kawazoe; Figure 3.tif
Table 1. RCMs and GCMs used in NARCCAP. Convective parameterization schemes for each RCM is in italics.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>RCMs and convective parameterization schemes</th>
</tr>
</thead>
</table>
| CRCM    | Canadian Regional Climate Model (Caya and Laprise 1999)  
          *Bechtold–Kain–Fritsch (Bechtold et al. 2001; Kain and Frisch 1990)*  
| ECP2    | Scripps Experimental Climate Prediction Center/Regional Spectral Model (Juang et al. 1997)  
          *Simplified Arakawa–Schubert (Pan and Wu 1995)*  
| HRM3    | Third-generation Hadley Centre Regional Model (Jones et al. 2004)  
          *Mass flux with downdraft and momentum transport (Gregory and Rowntree 1990; Gregory and Allen 1991; Gregory et al. 1997)*  
| MM5I    | International Centre for Theoretical Physics Regional Climate Model version 3 (Pal et al. 2007)  
          *Grell with Fritsch–Chappell closure (Grell et al. 1993; Fritsch and Chappell 1980)*  
          *Kain–Fritsch 2 (Kain 2004)*  
| RCM3    | Geophysical Fluid Dynamic Laboratory (GFDL) Climate Model version 2.1 (Anderson et al. 2004). 2.0º x 2.5º horizontal resolution.  
          *Grell–Devenyi (Grell and Devenyi 2002)*  
| WRFG    | Weather Research and Forecasting model (Skamarock et al. 2005), Pacific Northwest National Laboratory (PNNL) version  
| cccm3   | NCAR-Community Climate Model version 3 (Collins et al. 2006). 1.4º x 1.4º horizontal resolution.  
| cgc3m   | Canadian Third Generation Coupled Global Climate Model (Flato et al. 2000). 1.9º x 1.9º horizontal resolution.  
| gfdl    | Geophysical Fluid Dynamic Laboratory (GFDL) Climate Model version 2.1 (Anderson et al. 2004). 2.0º x 2.5º horizontal resolution.  
| hadcm3  | Hadley Centre Climate Model version 3 (Gordon et al. 2000; Pope et al. 2000). 2.5º x 3.75º horizontal resolution.  

GCMs

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Model and horizontal resolution</th>
</tr>
</thead>
</table>
| cccm3   | 1.4º x 1.4º horizontal resolution.  
| cgc3m   | 1.9º x 1.9º horizontal resolution.  
| gfdl    | 2.0º x 2.5º horizontal resolution.  
| hadcm3  | 2.5º x 3.75º horizontal resolution.  

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Table 2. NARCCAP RCM and GCM simulations. “X” designate combinations available and used for both precipitation and their supporting environments, “O” represents combinations available but only used for surface analysis.

<table>
<thead>
<tr>
<th>Model</th>
<th>ncep</th>
<th>cccm</th>
<th>cgcm3</th>
<th>gfdl</th>
<th>hadcm3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRCM</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECP2</td>
<td>O</td>
<td></td>
<td></td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>HRM3</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MM5I</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
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<tr>
<td>RCM3</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>WRFG</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Properties of NARCCAP, CPC, and UW precipitation: overall average intensity, frequency of precipitation (in parentheses: frequency of precipitation exceeding 2.5 mm), and intensity at the 95th, 99th, and 99.5th percentiles for all precipitation events.

<table>
<thead>
<tr>
<th>Model</th>
<th>Average (mm day(^{-1}))</th>
<th>Frequency (%)</th>
<th>95th (mm day(^{-1}))</th>
<th>99th (mm day(^{-1}))</th>
<th>99.5th (mm day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPC</td>
<td>3.35</td>
<td>47.0 (26.7)</td>
<td>26.52</td>
<td>47.05</td>
<td>56.41</td>
</tr>
<tr>
<td>UW</td>
<td>3.28</td>
<td>56.4 (31.2)</td>
<td>20.24</td>
<td>34.77</td>
<td>41.37</td>
</tr>
<tr>
<td>CRCMccsm</td>
<td>1.97</td>
<td>53.4 (23.4)</td>
<td>12.38</td>
<td>23.18</td>
<td>28.57</td>
</tr>
<tr>
<td>CRCMegcm3</td>
<td>2.66</td>
<td>57.0 (27.7)</td>
<td>16.69</td>
<td>29.69</td>
<td>35.51</td>
</tr>
<tr>
<td>CRCMncep</td>
<td>2.75</td>
<td>53.0 (28.8)</td>
<td>17.42</td>
<td>30.41</td>
<td>36.55</td>
</tr>
<tr>
<td>ECP2gfdl</td>
<td>3.94</td>
<td>48.9 (30.0)</td>
<td>28.18</td>
<td>47.36</td>
<td>56.41</td>
</tr>
<tr>
<td>ECP2hadcm3</td>
<td>3.12</td>
<td>53.5 (23.7)</td>
<td>21.65</td>
<td>40.59</td>
<td>49.32</td>
</tr>
<tr>
<td>ECP2ncep</td>
<td>2.64</td>
<td>29.1 (19.7)</td>
<td>30.54</td>
<td>51.30</td>
<td>61.75</td>
</tr>
<tr>
<td>HRM3gfdl</td>
<td>3.04</td>
<td>52.2 (26.3)</td>
<td>21.56</td>
<td>43.68</td>
<td>57.54</td>
</tr>
<tr>
<td>HRM3hadcm3</td>
<td>3.26</td>
<td>48.7 (25.6)</td>
<td>25.33</td>
<td>54.08</td>
<td>70.32</td>
</tr>
<tr>
<td>HRM3ncep</td>
<td>2.28</td>
<td>41.7 (17.6)</td>
<td>22.34</td>
<td>47.71</td>
<td>63.48</td>
</tr>
<tr>
<td>MM5Iccsm</td>
<td>2.75</td>
<td>38.1 (24.1)</td>
<td>24.47</td>
<td>44.43</td>
<td>55.20</td>
</tr>
<tr>
<td>MM5Ihadcm3</td>
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<td>35.4 (23.4)</td>
<td>30.26</td>
<td>56.43</td>
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</tr>
<tr>
<td>MM5Incep</td>
<td>2.52</td>
<td>32.4 (20.8)</td>
<td>26.53</td>
<td>48.30</td>
<td>59.85</td>
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<tr>
<td>RCM3cgcm3</td>
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<td>49.3 (30.1)</td>
<td>32.97</td>
<td>61.60</td>
<td>75.02</td>
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<tr>
<td>RCM3gfdl</td>
<td>4.07</td>
<td>54.2 (32.2)</td>
<td>28.12</td>
<td>53.23</td>
<td>66.09</td>
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<td>RCM3ncep</td>
<td>3.11</td>
<td>35.7 (20.7)</td>
<td>34.10</td>
<td>70.81</td>
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<tr>
<td>WRFGccsm</td>
<td>1.69</td>
<td>34.7 (13.5)</td>
<td>20.97</td>
<td>47.29</td>
<td>59.11</td>
</tr>
<tr>
<td>WRFGcgcm3</td>
<td>2.13</td>
<td>38.4 (15.9)</td>
<td>24.52</td>
<td>50.74</td>
<td>62.31</td>
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<tr>
<td>WRFGncep</td>
<td>2.23</td>
<td>35.5 (16.2)</td>
<td>27.21</td>
<td>59.11</td>
<td>74.28</td>
</tr>
</tbody>
</table>
Table 4. Percentage of widespread very heavy events by month for simulations and observations. Month with the highest frequency of very heavy precipitation events per source is bolded.

<table>
<thead>
<tr>
<th>Source</th>
<th>June</th>
<th>July</th>
<th>August</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPC</td>
<td>31.8%</td>
<td>38.6%</td>
<td>29.5%</td>
</tr>
<tr>
<td>UW</td>
<td>28.8%</td>
<td>44.1%</td>
<td>27.1%</td>
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<tr>
<td>CRCMccsm</td>
<td>91.4%</td>
<td>7.1%</td>
<td>1.4%</td>
</tr>
<tr>
<td>CRCMcgcm3</td>
<td>51.7%</td>
<td>24.1%</td>
<td>24.1%</td>
</tr>
<tr>
<td>CRCMncep</td>
<td>57.8%</td>
<td>36.1%</td>
<td>6.0%</td>
</tr>
<tr>
<td>ECP2gfdl</td>
<td>47.7%</td>
<td>23.1%</td>
<td>29.2%</td>
</tr>
<tr>
<td>ECP2hadcm3</td>
<td>51.2%</td>
<td>32.9%</td>
<td>15.9%</td>
</tr>
<tr>
<td>ECP2ncep</td>
<td>51.3%</td>
<td>28.2%</td>
<td>20.5%</td>
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<tr>
<td>HRM3gfdl</td>
<td>35.6%</td>
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<td>42.5%</td>
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<tr>
<td>HRM3hadcm3</td>
<td>36.9%</td>
<td>35.4%</td>
<td>27.7%</td>
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<tr>
<td>HRM3ncep</td>
<td>59.3%</td>
<td>25.9%</td>
<td>14.8%</td>
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<td>MM5Iccsm</td>
<td>52.2%</td>
<td>34.8%</td>
<td>13.0%</td>
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<tr>
<td>MM5Ihadcm3</td>
<td>35.0%</td>
<td>47.5%</td>
<td>17.5%</td>
</tr>
<tr>
<td>MM5Incep</td>
<td>47.2%</td>
<td>30.6%</td>
<td>22.2%</td>
</tr>
<tr>
<td>RCM3cgcm3</td>
<td>49.0%</td>
<td>27.5%</td>
<td>23.5%</td>
</tr>
<tr>
<td>RCM3gfdl</td>
<td>29.1%</td>
<td>36.4%</td>
<td>34.5%</td>
</tr>
<tr>
<td>RCM3ncep</td>
<td>34.3%</td>
<td>51.4%</td>
<td>14.3%</td>
</tr>
<tr>
<td>WRFGccsm</td>
<td>70.6%</td>
<td>23.5%</td>
<td>5.9%</td>
</tr>
<tr>
<td>WRFGcgcm3</td>
<td>64.5%</td>
<td>16.1%</td>
<td>19.4%</td>
</tr>
<tr>
<td>WRFGncep</td>
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<td>41.4%</td>
<td>13.8%</td>
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</tbody>
</table>