An Examination of Precipitation in Observations and Model Forecasts during NAME with Emphasis on the Diurnal Cycle

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ABSTRACT

Summertime rainfall over the United States and Mexico is examined and is compared with forecasts from operational numerical prediction models. In particular, the distribution of rainfall amounts is examined and the diurnal cycle of rainfall is investigated and compared with the model forecasts. This study focuses on a 35-day period (12 July–15 August 2004) that occurred amid the North American Monsoon Experiment (NAME) field campaign. Three-hour precipitation forecasts from the numerical models were validated against satellite-derived estimates of rainfall that were adjusted by daily rain gauge data to remove bias from the remotely sensed estimates. The model forecasts that are evaluated are for the 36–60-h period after the model initial run time so that the effects of updated observational data are reduced substantially and a more direct evaluation of the model precipitation parameterization can be accomplished.

The main findings of this study show that the effective spatial resolution of the model-generated precipitation is considerably more coarse than the native model resolution. On a national scale, the models overforecast the frequency of rainfall events in the 1–75 mm day$^{-1}$ range and underforecast heavy events (>85 mm day$^{-1}$). The models also have a diurnal cycle that peaks 3–6 h earlier than is observed over portions of the eastern United States and the NAME tier-1 region. Time series and harmonic analysis are used to identify where the models perform well and poorly in characterizing the amplitude and phase of the diurnal cycle of precipitation.

1. Introduction

Precipitation is a fundamental element of the earth's weather, water, and climate system, and is a primary link in the transfer of mass and energy between the atmosphere and ocean. Because of that, it is important to monitor variations in precipitation, yet it remains a challenge to quantify precipitation over all regions of the planet and even more of a challenge to forecast it correctly. Furthermore, even where rain gauge density is relatively dense, such as over the United States, precipitation data are not generally available at the temporal resolution that is sufficient to diagnose important subdaily variations such as the diurnal cycle.

Diurnal variations in precipitation, in particular, dominate the variability at all other time scales over much of the Tropics and warm season extratropics, including the Americas and particularly over the NAME tier-1 domain. Therefore, it is important not only to document the variations on diurnal time scales, but also to know the extent to which numerical weather and climate prediction models can simulate this fundamen-
tal behavior. The first concern (i.e., documentation) has been addressed by researchers over the United States (e.g., Dai et al. 1999) and over the globe in a large-scale climatological sense by Hendon and Woodberry (1993) and Janowiak et al. (1994, 2005).

Briefly, the first harmonic dominates over most of the planet’s land surfaces; that is, single daily preferred times of maximum and minimum precipitation are observed. For the vast majority of the earth’s land surface, the preferred time of maximum daily precipitation is in the late afternoon or early evening after the land has heated up, which results in considerable rising atmospheric motions that lead to vapor condensation and, very often, precipitation. The time of daily minimum precipitation over the continents is during the postmidnight to noon period when the surface cools and the rising motions subside. There are exceptions to this behavior such as the nighttime maxima over the central United States and over parts of central South America that are associated with low-level jet streams and orographic features.

The main purpose of this paper addresses the second concern and thus we present an evaluation of the ability of the National Oceanic and Atmospheric Administration’s (NOAA) Global Forecast System model (GFS) and the regional Eta Model [currently referred to as the North American Mesoscale model (NAM)] to characterize the behavior of precipitation during the North American warm season, and in particular, the diurnal cycle of precipitation. We focus on the 12 July–15 August 2004 period, which occurred during the field campaign of the North American Monsoon Experiment (NAME; Higgins et al. 2006). The validation dataset to which the model data are compared is the Climate Prediction Center (CPC) daily rain gauge analysis (Higgins et al. 2000) that has been disaggregated via the 1/2-hourly CMORPH precipitation analyses (Joyce et al. 2004). We refer to these disaggregated data as RMORPH. Comparisons between the Eta and GFS model 36–60-h forecasts of precipitation and RMORPH during this period are presented and discussed.

Although the focus of the NAME field campaign is on the relatively small tier-1 domain (see Fig. 7 for location), the North American monsoon system is a continental-scale phenomenon. For example, Higgins et al. (1997) have shown an out of phase relationship in summertime rainfall between the southwest and eastern portions of the United States. Therefore, we show and discuss the results of continental-scale comparisons between the models and validation data in addition to those over the NAME tier-1 area.

In section 2 we describe the data used in this paper. In section 3 we present comparisons of the distribution of rainfall amounts between the model and validation data. Comparisons of the diurnal variations in precipitation between the model and validation data using time series and harmonic analysis are discussed in section 4. The propagation of precipitating systems during the study period is examined and discussed in section 5, and results are briefly summarized in section 6.

2. Data description

The spatial resolution of the three datasets used here are $1^\circ \times 1^\circ$ latitude–longitude and 3-hourly for the GFS forecasts, $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$ latitude–longitude and 3-hourly for the Eta forecasts, and $0.25^\circ \times 0.25^\circ$ latitude–longitude and $\frac{1}{2}$-hourly for the validation data. Therefore, the Eta and validation data were interpolated and the validation data were accumulated to match the GFS model resolution in both space and time. Separate datasets were created that contain the period-mean diurnal cycle for the 12 July–15 August 2004 time frame. That is, for each 3-h period (0000–0300, 0300–0600 UTC, etc.) the period-mean value was computed. All of the precipitation rates are portrayed in units of millimeters per day.

a. Validation data

The CMORPH methodology is described in detail in Joyce et al. (2004). Briefly, precipitation estimates from all available passive microwave (PMW) sensors aboard low earth orbit space craft are merged for each 30-min period. Even though eight PMW instruments are used, considerable gaps in coverage remain. Infrared (IR) data from the present-day constellation of five geostationary meteorological satellites are used to infer the movement of precipitation features that have been identified by the PMW information. Movement is determined from the IR data by performing spatial lag correlations on IR imagery that is 30 min apart in time. Essentially, the IR data are used to determine cloud motion, and that motion is applied to the PMW-derived rainfall, which results in temporally and spatially complete estimates of precipitation that are available every 1/2 hour.

Because satellite-derived estimates of precipitation tend to overestimate (at times significantly) over land (Scofield 1987; Rosenfeld and Mintz 1988; McCollum et al. 2002), we adjusted the hourly CMORPH rainfall. The CMORPH hourly estimates were multiplied by the ratio of the daily Climate Prediction Center gauge analysis (Higgins et al. 2000) to the daily CMORPH value at each grid location resulting in a new dataset that we call RMORPH. This process essentially disaggregates the gauge data so that the sum of the hourly RMORPH estimates for each day adds up to the CPC.
daily gauge totals. Over the oceans, the validation data are the original CMORPH estimates that are composed of satellite-derived estimates of precipitation data only.

b. Eta and GFS model precipitation forecasts

Forecasts of precipitation from the Eta and GFS models were collected over the study period at 3-h intervals from the 0000 UTC model initialization runs. The model forecasts for 36–60 h after model initial time were used so that the effect of the assimilation of observed data could be eliminated as much as possible. This is especially important because the Eta Model forecasts that are used in this evaluation assimilate precipitation estimates from radar (over the United States only), while the GFS does not assimilate rainfall information directly. Therefore, our examination yields information about the performance of the model physics for each model and, in particular, the convective precipitation parameterization schemes since the period of this study occurs during the convective season over the United States.

c. Comparison of the spatial scales among the Eta, GFS, and RMORPH precipitation

As discussed above, the diagnostics in this paper are based on comparisons of all products on a common 1° × 1° grid, which is the standard horizontal resolution for precipitation intercomparisons at NOAA’s Environmental Modeling Center (EMC), which developed, maintains and operationally runs the Eta and GFS models. However, the horizontal resolutions of the Eta and GFS models during the period of this study were 12 and ~35 km, respectively, while the CMORPH data that were used to disaggregate the daily rain gauge analyses were computed on a grid that is approximately 8 km at the equator. So, to first order, the native spatial scales of the processes that generated these datasets are comparable. However, this does not imply that the precipitation fields of the models effectively operate at these finescales.

To make an assessment of the effective spatial scale of precipitation among the three datasets, we correlated the time series of precipitation at each grid point with the time series of precipitation at each surrounding grid point, centered on the grid point of interest. This exercise yields eight correlation coefficients at each grid point, which were then averaged and are plotted in Fig. 1. Note that the pattern of correlation is more coherent and the magnitudes are larger in the models compared to RMORPH. This result indicates that the model precipitation generation process in the models, that is, the parameterization schemes, operate at a spatial scale that is considerably more coarse than the native model spatial resolutions.

3. The distribution of rainfall amounts among RMORPH, Eta, and GFS

The 35-day mean difference field in rainfall between the models and validation data is shown in Fig. 2a. The GFS is generally wetter than RMORPH (more positive differences) compared to the Eta, particularly over much of the East Coast, the Ohio River valley, Texas, and the Dakotas. Both models exhibit large negative differences, that is, drier than RMORPH over the Pacific coastal range in western Mexico.

The pattern of differences over the adjacent oceanic regions is quite similar for both models, with large negative differences eastward from the Bahamas and off the mid-Atlantic coast, and positive differences between those regions. The precipitation differences between the models and validation data are much less over the Pacific, but that is largely because rainfall is climatologically low there during this time of year.

a. Rainfall distribution over the continental-scale domain (20°–50°N, 65°–130°W)

Comparisons of the frequency of categorical rainfall amounts between RMORPH and the model forecasts are useful in determining whether the differences discussed above are due to model biases or are the result of a few events that skew the means because of the short study period. The largest differences between the models and validation data occur over the Atlantic but there are substantial differences over land as well.

During the study period, 85.3% of the validation data had zero precipitation compared to 77.0% for the Eta Model and 76.7% for the GFS, indicating that the models forecast rainfall about 8% more frequently over the nation compared to RMORPH. Both models forecast rainfall over the central and southern U.S. Rockies and the Appalachians about 10%–15% more often than is observed (Fig. 2b). From southern Georgia to southern South Carolina, including all of Florida, the GFS forecasts rainfall with a frequency that is more than 25% higher than the observed frequency. Overforecasts of this magnitude are also observed in the GFS over the coastal regions of the Northeast from New Jersey to Maine. For rainfall rates in excess of 10 and 25 mm day⁻¹ (Figs. 2c and 2d, respectively) both models forecast events of these magnitudes 5%–15% more frequently over portions of the central and eastern sections of the nation and over much of the adjacent Atlantic. Conversely, the models forecast rainfall 5%–15% less often than RMORPH over central and
western Arizona and the Pacific coastal range in western Mexico.

The large differences between the models and validation data over the Atlantic oceanic regions (Fig. 2a) combined with the fact that the validation data over water is purely satellite derived, prompted us to mask out ocean locations when computing the rainfall rate distributions that we now discuss. A summary of statistics derived from $2 \times 2$ contingency tables (Panofsky and Brier 1963; Wilks 1995) for various precipitation rates is presented in Table 1. Note the large false alarm ratios (FARs) in the model forecasts and the modest probability of detection (POD) values, which mean that even though the models frequently forecast rainfall, it often does not occur when or where it is forecast. Also, the FAR values are not significantly different among the various rainfall intensities while the POD falls rapidly for increasingly intense events. The bias ratio sta-

![Mean Correlation with Surrounding Grid Points](image-url)
Fig. 2. (a) Mean difference in precipitation during 12 Jul–15 Aug 2004 between the Eta Model and RMORPH (left) and the GFS model and RMORPH (right). Units are mm day$^{-1}$. (b) The difference in frequency of precipitation $>1$ mm day$^{-1}$ (expressed as a percentage difference) between the Eta Model and RMORPH (left) and the GFS model and RMORPH (right). (c) Same as in (b) except for precipitation $>10$ mm day$^{-1}$. (d) Same as (b) except for $>25$ mm day$^{-1}$. 
Table 1. Statistics computed from 2 × 2 contingency tables regarding the performance of the GFS and Eta models to forecast precipitation at various intensities. These statistics were compiled during the 12 Jul–15 Aug 2004 period over the United States and Mexico (land areas only). Each column contains the statistics based on rainfall (in mm day$^{-1}$) that exceeds a specified rate. Italicized values are from the 12–36-h model forecasts from the 0000 UTC cycle; other numbers are from the 36–60-h model forecasts from the 0000 UTC cycle.

<table>
<thead>
<tr>
<th></th>
<th>Eta (12–36-h forecasts)</th>
<th>GFS (12–36-h forecasts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;1</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Probability of detection</td>
<td>0.43 0.17 0.09 0.33</td>
<td>0.18 0.08</td>
</tr>
<tr>
<td>False alarm ratio</td>
<td>0.37 0.90 0.94 0.82</td>
<td>0.91 0.95</td>
</tr>
<tr>
<td>Bias ratio</td>
<td>1.67 1.68 1.34 1.82</td>
<td>1.96 1.42</td>
</tr>
<tr>
<td>Heidke skill score</td>
<td>0.22 0.08 0.05 0.11</td>
<td>0.07 0.04</td>
</tr>
<tr>
<td>(12–36-h forecasts)</td>
<td>1.84 1.73 1.37 2.31</td>
<td>1.92 1.35</td>
</tr>
<tr>
<td>(12–36-h forecasts)</td>
<td>0.27 0.22 0.17 0.28</td>
<td>0.25 0.19</td>
</tr>
</tbody>
</table>

The frequency of zero rainfall over the NAME tier-1 region is 83.1% for the validation data compared to 79.4% and 80.8% for the Eta and GFS forecasts, respectively; so the model rainfall detection over this region is quite good. The distribution of rainfall rates between the model forecasts and validation data are in much better agreement over the NAME tier-1 region (Fig. 4) compared to the continental-scale domain (Fig. 3) for rainfall rates <10 mm day$^{-1}$. Excellent agreement is also observed for rainfall rates in the 40–55 mm day$^{-1}$ range. The models overforecast rainfall rates of 10–25 mm day$^{-1}$ by 30%–70%. Conversely, both models (particularly the Eta) underforecast extremely heavy rainfall events (>60 mm day$^{-1}$) by as much as a factor of 2 over this region.

4. Mean diurnal variability of precipitation over the United States and Mexico

Because 3-hourly amounts are used for the diurnal cycle examinations, we use the middle of each 3-h period in the plots and computations in this paper. For the continent as a whole (United States and Mexico), the mean diurnal cycle of precipitation over the 35-day study period shows that both models forecast precipitation amounts that are considerably higher than the validation data (Fig. 5), which is consistent with earlier discussions. The Eta Model forecasts are about 20% higher than the validation data while the GFS forecasts are about 45% higher.

The continental-scale mean diurnal cycle of precipitation in RMORPH exhibits a peak near 2230 UTC followed by a sharp decrease in precipitation rate during the following 3-h period, then a steady to gradual decrease in rate to a minimum near 1630 UTC. Note a slight rise in precipitation rate near 1330 UTC in RMORPH that is not observed in the model forecasts. This feature may be a reflection of the nocturnal maximum in precipitation that is observed over the central part of the country or it may be an artifact due to of the short sampling period of this study caused by synoptic-scale variability.

The Eta Model forecasts exhibit a behavior similar to that of RMORPH, except that the amplitude of the diurnal cycle is not as strong. The Eta forecasts also peak near 2230 UTC and exhibit a smooth and monotonic decline in precipitation rate to a minimum between 1330 and 1630 UTC. There is no evidence of a sharp decline in precipitation rate after the daily peak, as is seen in the RMORPH and GFS data.

The GFS data are rather different than both the Eta and validation data. The GFS data indicate a uniform precipitation intensity between 0130 and 0430 UTC, then a gradual decrease in precipitation thereafter until about 1330 UTC. A sharp increase in precipitation follows to a daily peak near 1930 UTC, which is then followed by a sharp drop in intensity during the next 6 h. The daily precipitation maximum in the GFS is about 3 h earlier than in either RMORPH or the Eta forecasts.
Because the continent spans three time zones, the phase of the diurnal cycle is muddled in a continental examination. Therefore, we present the mean diurnal cycle of precipitation for selected regions in Fig. 6. It is apparent that overforecasting of precipitation amount and the early initiation of convection relative to the validation data occur mainly in the eastern United States for the GFS model (Fig. 6, right panels). Note the steep increase in the model precipitation that begins over the Southeast area around 0830 LST (Fig. 6, bottom right) and in the Northeast region near 0830 LST (Fig. 6, top right). In contrast, the validating RMORPH data begin ramping up about 3 h later than the GFS over both regions. The daily peak precipitation over both regions occurs about 3 h later in RMORPH compared to the GFS forecasts.

The mean diurnal cycle of the Eta Model forecasts over the Northeast region has a much smaller amplitude than the validation data and is almost completely out of phase with RMORPH. Over the Southeast re-
region, the Eta forecasts suggest a daily peak that is about 6 h earlier than is seen in the validation data. Overall, however, the phase of the diurnal cycle is considerably better than that over the Northeast.

Over regions in the western part of the United States, including the NAME tier-1 domain, the model forecasts are in much better agreement with the validation data than in the eastern part of the country (Fig. 6, left panels). For the NAME tier-1 region, the diurnal cycles in the models agree with each other quite well in both amplitude and phase, and the amplitude of the diurnal cycle agrees very well with RMORPH. However, the daily precipitation peak and minimum are about 3 h too early compared to the validation data.

Over the plains region east of the Rockies (Fig. 6, upper-left panel), the RMORPH and Eta Model forecasts have a similar diurnal cycle phase but the amplitude of the Eta diurnal cycle is small compared to RMORPH. The amplitude of the diurnal cycle is also weak in the GFS forecasts over this region and the precipitation peak occurs near local noon as opposed to near sunrise in both the RMORPH and the Eta Model forecasts.

a. Harmonic analysis

A harmonic analysis was performed on the 3-hourly precipitation estimates and model forecasts over the 35-day study period. The results are plotted as a harmonic dial that conveys the amplitude and phase of the
peak of the diurnal cycle for the validation data (Fig. 7) and the Eta and GFS model forecasts (Fig. 8). The shading in the figures indicates where the variance explained by the first harmonic exceeds 50%. There is substantially more area with 50% variance explained in both models compared to RMORPH.

In general, the GFS amplitudes are the highest and the Eta forecasts are the lowest, which is consistent with earlier discussions. Over the NAME tier-1 region (outlined by a rectangle in Fig. 7), daily precipitation peaks between about 1600 and 2300 local time in the RMORPH data for locations that possess relatively large first harmonic amplitudes. The Eta Model forecasts tend to peak between about 1500 and 1900 LT while the GFS generally peaks earlier yet between about 1300 and 1600 local time. The relatively early peak in precipitation for the models over this region is also depicted in Fig. 6 (lower-left panel) as discussed earlier.

The validation data exhibit a peak in precipitation in the midafternoon over the central Colorado Rockies that peaks later and later in the day to the east, as convective systems form over the mountains and advect in that direction. Thus, peak rainfall tends to occur near 1800 local time in eastern Colorado, near midnight over western Kansas, and in the predawn hours over eastern Kansas and Missouri. However, this area is also af-
affected by the low-level jet and the associated precipitation “midnight maxima” (Bonner 1968), and thus the advection of systems that formed to the west of the region is not the only factor. The Eta Model forecasts exhibit similar behavior with RMORPH over this part of the country while the GFS forecasts initiate convection too early (local noon) over the Colorado mountains and the phase of the diurnal cycle over locations to the east of the mountains is chaotic.

Over the southeastern states from Virginia to Georgia, the GFS portrays a consistently strong and phased diurnal cycle of rainfall maxima that peaks in midmorning. The amplitude of the diurnal cycle in the GFS is strongest over this region compared to elsewhere in the United States, but it is not observed with that intensity and is too early compared to the validation data. The Eta Model data indicate a very weak amplitude and chaotic phase of the entire southeastern quadrant of the United States, except Florida.

Interesting differences in the amplitude and phase of the diurnal cycle among the three datasets are observed over the eastern and southeastern coastal regions of the United States and adjacent oceanic areas. The Eta forecasts exhibit considerably smaller amplitude in the diurnal cycle over the land portions of these areas compared to RMORPH and the GFS. Over the adjacent waters, the Eta and GFS both exhibit considerably more uniform phase over the Atlantic and Gulf of Mexico that contrasts with a comparatively chaotic pattern in RMORPH. In general, however, all three indicate an early morning maximum in precipitation near the eastern Atlantic coast that occurs later in the day to the east of that region. This feature is likely the result of two factors: one being the formation of convective systems near midday over the Appalachians that advect to the east and the other being the reamplification of some of those systems and formation of new systems at night and in the early morning when the Gulf Stream becomes a source for atmospheric instability and rising motion. Over the eastern Gulf of Mexico, precipitation tends to peak before sunrise in RMORPH and the GFS but at midmorning in the Eta.

b. The NAME tier-1 region

A time series of 3-h rainfall accumulation over the NAME tier-1 area for the entire study period is displayed in Fig. 9. The diurnal cycle is readily apparent in the figure, as is the the fact that the model forecasts often peak earlier in the day than the validation data, particularly the GFS. The temporal correlation coefficients between the model forecasts and the validation data are 0.27 and 0.32 for the Eta and GFS, respectively. Because the GFS tends to exhibit a peak in daily precipitation that is several hours early relative to the
5. Propagation of precipitating systems

Convective systems generally propagate from west to east across the country, and sometimes have life cycles of longer than 24 h (Carbone et al. 2002; Janowiak et al. 2005). We investigate this movement via time-longitude diagrams in this section. A time-longitude plot of the mean diurnal cycle at 35°N between 120° and 60°W (Fig. 10) suggests eastward propagation of precipitating systems, in a mean diurnal cycle sense. Specifically, the figure depicts the percentage of the daily mean rainfall that occurs during each 3-hourly period. The diurnal cycle is repeated below the dashed lines to aid in identifying locations where precipitating features with life cycles longer than 1 day can be discerned.

As discussed in previous sections, the validation data exhibit a diurnal cycle that is characterized by daily peaks in the mid- to late afternoon over the Rockies that occur later in the day in a steady progression eastward. There is also a hint that some features may have life cycles that exceed 24 h. However, because this is a time mean, eastward “movement” and the apparent continuum with time do not necessarily imply that systems remain intact and simply advect eastward, although some individual systems may. Near the Atlantic coast at this latitude (~75°W), the peak daily precipitation tends to occur earlier in the day as one looks eastward, which is consistent with the harmonic analysis results in Fig. 7. Both the Eta and GFS model forecasts behave similarly to RMORPH between 120° and 90°W but there is little correspondence between them east of that area. The GFS data show an abrupt change in the time of maximum precipitation from late afternoon to early morning near 75°W, which is consistent with the harmonic analysis results (Fig. 8).
As mentioned above, other studies have documented the existence of warm season precipitating systems that have life cycles beyond a day. These are often meso-scale convective systems that form in the central part of the country and progress eastward with time, and may remain intact for several days. We present in Fig. 11 a time–longitude diagram of precipitation (again at 35°N) from RMORPH, Eta, and GFS for the entire 35-day study period. Unfortunately, no such long-lived system occurred during the period. There is a propagating feature that appears to remain intact during 11–13 August in the RMORPH data, but close inspection shows a break at 90°W. We looked closely at the individual hourly RMORPH data to determine whether this break was real or a data artifact, and we determined that a system advected eastward to 90°W but dissipated and a new system formed to its east and propagated to the east from there.

The overall pattern of precipitation development and movement is captured by the models, although there are some noticeable differences with the validation data in terms of rainfall intensity. It is evident visually that both models exhibit a tendency to produce several long-lived precipitating systems, particularly in the eastern part of the nation, that are not as continuous in

**6. Summary**

The distribution, frequency, and diurnal cycle of rainfall over the United States were examined during the 35-day (12 July–15 August 2004) period of study that occurred during the NAME field campaign. The Eta and GFS 36–60-h forecasts from the 0000 UTC initial run time for both models were compared to validation data in the form of high-resolution rain gauge analyses that were disaggregated by CMORPH precipitation analyses. We refer to these disaggregated rain gauge data as RMORPH. Our main conclusions are summarized below.

1) The model precipitation generation process in both models, that is, the parameterization schemes, operate at a spatial scale that is considerably more coarse than the native model spatial resolutions.
2) For the nation as a whole, both models overforecast rainfall rates in the range of 1–75 mm day⁻¹ by as

![Fig. 10. Time–longitude diagram (at 35°N) of the percentage contribution to the daily mean rainfall total for each 3-h period, computed over the 12 Jul–15 August 2004 period for RMORPH, GFS, and the Eta Model. The plot is repeated below the dashed line to assist in viewing features that persist for longer than 24 h.](image)

![Fig. 11. Time–longitude diagram (at 35°N) of precipitation for RMORPH, GFS, and the Eta Model over the 12 Jul–15 Aug 2004 period. Units are mm day⁻¹.](image)
much as 50% in the 1–5 mm day$^{-1}$ range, and underforecast rainfall rates in excess of 85 mm day$^{-1}$. Over the NAME tier-1 region, both models agree well with the validation data for light (1–10 mm day$^{-1}$) and medium (35–60 mm day$^{-1}$) rain rates, but both models underforecast rainfall rates in excess of 70 mm day$^{-1}$. The Eta Model forecasts underestimate these heavy rainfall rates by a factor of 2.

3) Both models exhibit a peak in daily rainfall that is 3–6 h earlier than the validation data over much of the United States east of the Mississippi and over the NAME tier-1 region.

4) Harmonic analysis on the various datasets reveal that the Eta Model does a credible job in resolving the diurnal cycle over the central portion of the country where convective systems often form over the Rockies and advect eastward over the plains of eastern Colorado and Kansas.

5) Both models indicate multiday precipitation events that propagate eastward over several days that are not as coherent in space and time in the observations during the 35-day study period.

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