A seasonal and diurnal climatology of precipitation organization

in the southeastern United States

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Abstract

This paper describes results from a new four-year (2009-2012) radar-based precipitation climatology for the southeastern United States (SE US). The climatology shows that a size-based classification between mesoscale precipitation features (MPF) and isolated precipitation reveals distinct seasonal and diurnal variability of precipitation. On average, from 70%-90% of precipitation is associated with MPF, generally less in the summertime and in southern coastal regions. MPF precipitation has a relatively small seasonal cycle except in Florida and the warm offshore waters of the Gulf Stream. In contrast, isolated precipitation has a dramatic seasonal cycle that outlines the SE US coastline whereas the MPF precipitation does not, consistent with a thermodynamic mechanism for onshore isolated storms in coastal regions. In summer, the isolated precipitation preferentially forms offshore at night, and dramatically “flips” inland by early afternoon. In contrast, MPF precipitation has no clear diurnal variations except in the southern coastal region in the summer, likely associated with sea breeze convection organized on the mesoscale. These results suggest that the MPF versus isolated precipitation system framework provides a useful basis for future studies of large scale and local controls on precipitation and resulting implications for long-range predictability of precipitation.
1. Introduction

The southeastern United States (SE US) is notable for a wide variety of precipitation regimes – mesoscale systems associated with baroclinic waves, cold season frozen precipitation, tropical cyclones, and diurnally-modulated local convection. Since the region is generally subtropical, these precipitation regimes are strongly modulated by the daily and seasonal cycle of solar radiation, locally generated convection, and baroclinic frontal precipitation. Appropriately, the SE US has been the focus of many studies of precipitation variability, predictability, and impacts (Konrad, 1997; Geerts, 1998; Hansen et al., 1998; Carbone et al., 2002; Parker and Ahijevych, 2007, Shepherd et al., 2007).

This paper describes results from a four-year surface radar-based precipitation climatology for the SE US, that addresses whether a simple size-based classification of precipitation features can reveal key differences in seasonal and diurnal variability of precipitation. This approach is different from existing climatologies that emphasize convective versus stratiform precipitation (Schumacher and Houze, 2003). Separation of convective and stratiform precipitation has been used to quantify the impact of distinct modes of diabatic heating on atmospheric circulations, whereas the present climatology relates to the reverse connection – the impact of atmospheric circulation on precipitation. Large-scale features of the atmospheric circulation are better represented and more accurately reproduced in climate models compared to precipitation (Kalnay et al., 1996). Accordingly, one approach to improving precipitation predictability in climate models is
to distinguish between precipitation systems associated with more predictable large-scale features of the atmospheric circulation and precipitation associated with less predictable local processes. This paper is a first step toward that goal, by examining for the SE US distinct seasonal and diurnal variations of precipitation organization that may suggest differences in forcing mechanisms.

It has been recognized over the past several decades that the spatial scale of precipitation system organization, as measured by weather radar, has some relation to precipitation forcing mechanisms (e.g. mesoscale – synoptic scale versus local scale forcing). The pioneering work of Leary and Houze (1979), using shipboard radar observations of precipitation systems in the tropical eastern Atlantic, established a paradigm of the radar-observed mesoscale precipitation feature (MPF) as being associated with larger scale dynamical forcing (in that case, tropical easterly wave troughs). In the mid-latitudes, such forcing includes the frontal regions of extratropical cyclones, as well as synoptic-scale ascent associated with the divergent region of a jet stream trough (Houze et al., 1990; Laing and Fritsch, 2000; Parker and Johnson, 2000). These and other studies of tropical and warm-season subtropical precipitating cloud systems (e.g. Cheng and Houze, 1979; Gamache and Houze, 1983, McAnelly and Cotton, 1989, Alexander and Young, 1992, Steiner et al., 1995) emphasized MPFs of convective origin, which came to be known as mesoscale convective systems (MCS). The MCS is defined (Houze, 1989; Houze, 2004) as a contiguous region of precipitation of convective origin at least 100 km in horizontal dimension. In the TRMM era, surface and spaceborne assets including radar and passive microwave radiometer (Mohr and Zipser, 1996; Rickenbach and Rutledge, 1998; Nesbitt
et al., 2000, Schumacher and Houze, 2003, Nesbitt et al., 2006) have shown that MCS are the dominant unit of tropical precipitation.

When generalizing precipitation organization beyond tropical and warm-season rain to the higher latitudes, including winter precipitation, it is useful to consider the more general construct of an MPF, which as applied herein, does not constrain precipitation to be necessarily of convective origin. In this regard, an MCS may be thought of as a subset of MPF comprised in part by convective rain, noting that the MCS definition of Houze (1989) does not specify a convective rain fraction threshold. For example, in the southeastern U.S., MCS have been shown to be most common generally in the spring and early summer, since at that time of the year the combination of baroclinicity and thermodynamic instability are greatest in that region (Geerts, 1998). Yet, the relative contribution of frozen precipitation to the annual precipitation climatology in the subtropical southeastern U.S. has not received much attention. This suggests that the MPF, with no requirement of convective origin for precipitation, is an appropriate construct in studying year-round precipitation outside of the Tropics.

Rain features of smaller scale than MPF, that is, isolated precipitation systems, tend to form in response to local scale circulations such as the sea breeze, topographic circulations, or thermal circulations in the boundary layer, modulated by the diurnal cycle of solar radiation (Wallace, 1975). Though isolated systems are not uniquely associated with either local or large scale forcing, in certain regimes isolated precipitation systems may account for a larger fraction of the precipitation climatology. Rickenbach and
Rutledge (1998) showed that for an oceanic location in the equatorial western Pacific, isolated convective systems accounted for about 15% of the precipitation during a three-month field campaign, concentrated in periods when the suppressed phase of equatorial waves resulted in fewer large convective systems. Due to their small spatial scale and dependence on complex surface energy fluxes, processes controlling thermodynamically forced precipitation are more crudely represented in forecast and climate models. For example, there remains a persistent early bias in the diurnal timing of precipitation in general circulation models (GCM), as most cumulus parameterization schemes exhaust convective available potential energy (CAPE) as soon as it occurs, leading to diurnal rainfall maxima several hours earlier than observed (Pritchard and Somerville, 2009). New breakthroughs to improve the diurnal precipitation phase and amplitude produced by GCM cumulus parameterizations (Chao, 2013) may benefit from observational validation such as that presented here.

This paper presents a four-year climatology (2009-2012) of precipitation from MPF and isolated precipitation systems across the southeastern U.S., based on a high-resolution national surface radar composite dataset. The goal of this paper is to determine whether and how the seasonal and diurnal variations of MPF versus isolated systems are distinct. These results will form a basis for future studies of large scale and local controls on precipitation and resulting implications for long-range predictability of precipitation. Section 2 describes the radar-based National Mosaic and Multi-sensor Quantitative Precipitation Estimation (NMQ) radar reflectivity and precipitation data sets (Zhang et al., 2011) along with the implementation of MPF and isolated system identification.
Section 3 presents the seasonal cycle and geographic distribution of both types of precipitation organization. In section 4, the diurnal variation of precipitation organization is analyzed regionally and seasonally. Conclusions and next steps are offered in section 5.

2. Methods and Examples

The NOAA National Severe Storms Laboratory (NSSL), in conjunction with the University of Oklahoma and others have developed high-resolution precipitation and radar reflectivity data sets for the contiguous United States, based on the national network of Next-generation Doppler Radars (NEXRAD). These are the National Mosaic and Multi-sensor Quantitative Precipitation Estimation (NMQ – “Q2”) precipitation dataset, and the corresponding radar reflectivity field (NMQ - “Mosaic-2D”) that includes precipitation phase and type (Zhang et al., 2011). The dataset covers the contiguous United States, extending approximately 200 km offshore in the southeastern U.S. In a few regions where NEXRAD coverage is not optimal, data from terminal Doppler weather radars (TDWR) and other gap-filling radar systems are ingested. In mountainous terrain, use of adjacent radars and multiple elevation angle scans are optimized to mitigate the inevitable beam blockage problems. The NMQ system was placed in a high-resolution (1 km x 1 km x 5 minutes) set of multisensory precipitation products (Prat et al., 2010) and generated at the National Climatic Data Center (NCDC), which we utilize in the present study. The Q2 is a radar-based precipitation product that incorporates surface and radar observations to provide a state-of-the-art estimation of precipitation rate. Mosaic-2D contains the corresponding quality-controlled radar reflectivity field, with precipitation
separated into convective and stratiform components (Steiner et al., 1995), and flagged as liquid or frozen precipitation based on the position and structure of the radar bright band and the vertical profile of temperature from model-derived sounding data. Though both products are extensively quality controlled (Zhang et al. 2011), inevitable limitations remain such as range issues affecting beam blockage and resolution that impact uniform coverage of the radar scans as well as the determination of precipitation type.

To construct the MPF and isolated system precipitation climatology, we extracted the Q2 and Mosaic-2D data over the southeastern U.S., from Louisiana to the Ohio Valley in the west, and from South Florida to the Chesapeake Bay in the east. The range of NEXRAD coverage over the ocean extends approximately 200 km from the coastline (Fig. 1). There are three regions (western Virginia, western North Carolina, and western Alabama) where limited overlapping coverage, mountainous terrain, or both required use of radar reflectivity up to 3 km above the surface. In the NMQ dataset, the western North Carolina region was supplemented by TDWR radar, “filling in” most of the coverage in that area (NOAA ROC).

The climatology was constructed by producing daily averages of MPF and isolated system rainfall, then compositing the daily averages into seasonal and annual means. For the daily averages, data was analyzed at a 15-minute interval, rather than the native five-minute interval of the data, to reduce high demands on processing resources without sacrificing sufficiently high temporal resolution to adequately capture precipitation variability on daily and longer timescales. Both Q2 and Mosaic-2D were ingested
simultaneously into a fully automated processing system. For each 15-minute snapshot, all contiguous precipitation features were identified and thresholded at 0.5 mm hr\(^{-1}\) (about 18 dBZ, roughly light drizzle intensity) to ensure that any residual non-meteorological artifacts in the NMQ product were not included. The maximum length of each feature in the domain was determined, with those features exceeding 100 km in length placed into the MPF category with the remainder of features placed into the isolated systems category, conceptually following Rickenbach and Rutledge (1998) and Nesbitt et al. (2006). Precipitation features were not tracked in time but determined independently from each 15-minute snapshot, then integrated into daily averaged maps at 1 km pixel resolution of precipitation rate. From the daily averaged maps, seasonal and annual composite maps were produced. For the diurnal analysis, the precipitation organization analysis data were saved every three hours on the hour, and composited seasonally and annually.

To illustrate the implementation of the MPF vs. isolated system climatology, two examples are presented for typical summer and winter days. The Q2 precipitation map for 4 August 2009 at 2030 UTC (Figure 2) shows an MPF moving eastward across the Ohio Valley with a leading edge of convective cells and extensive embedded convection within the trailing stratiform rain area (a “classic” MCS). Scattered isolated convective cells occur across the southeast U.S., concentrated in Florida along the coastal region, as is common on summer afternoons. The Mosaic-2D product provides the corresponding precipitation type, primarily convective rain cores surrounded by stratiform rain. The convective rain in the MPF is further classified by the NMQ algorithm as ‘tropical’,
indicating minimal rain evaporation below the 0°C level as inferred from the vertical profile of reflectivity at those pixels (Xu et al. 2008). If the maximum distance between border points of each contiguous precipitation feature is greater than 100 km, all pixels within those features are identified as MPF while all smaller features are flagged as isolated systems. For example, Figure 2 identifies three features as MPF: the large system in the Ohio Valley, a merging group of convective cells over Cuba, and the remnant of a dissipating MCS off the South Carolina coast near the ~ 200 km (1.5°) range limit of the coastal radars. Precipitation maps like these were similarly analyzed at 15-minute intervals to produce the daily averaged maps of MPF, isolated, and total precipitation for 4 August 2009 (Fig. 3). From the total daily averaged map, the two widespread rain regions (the Ohio Valley and offshore from the southeast coastal plain) are associated with MPF, while scattered isolated rain occurred across the entire domain, concentrated along the Florida coast. The daily-mean precipitation maps clearly show the scattered heterogeneous spatial pattern of isolated rain systems, in contrast to the widespread rainfall associated with each MPF.

A contrasting example is a wintertime extratropical cyclone that occurred on 26 January 2011 (Fig. 4). The precipitation pattern at 0230 UTC reveals the ‘comma’ shape typical of an extratropical cyclone, with a large squall line MCS in the warm sector from the Gulf of Mexico to North Carolina and lighter precipitation wrapping around the cyclone center in northern Alabama. The precipitation in the warm sector is convective on the leading edge of the MCS with trailing stratiform rain. North of the cyclone center light stratiform rain gives way to frozen precipitation in the northwest quadrant. The feature
analysis identifies four large MPF. The largest, a squall line MCS, extends over 1000 km from eastern Virginia to the radar domain limit north of western Cuba, while the others in the northern domain are large areas of stratiform rain with weak embedded convection. The isolated rain systems identified across the region are characterized by weak convective cells or small areas of light rain. The daily mean precipitation maps for the winter case (Fig 5) reveal that most of the precipitation was associated with MPF, with light isolated precipitation features moving generally to the northeast with the propagating cyclone.

These contrasting examples of winter and summer precipitation demonstrate that the analysis approach is able to distinguish between the distribution and structure of MPF and isolated systems. Next we examine the four-year annual mean and seasonal cycle climatologies.

3. **Four-year Climatology of Precipitation Organization**

We begin with a comparison of the general features of the four-year (2009-2012) mean climatology of precipitation across the SE US between the NMQ product and the satellite-based TRMM 3B-42 climatology for the same area (Fig. 6). These two independent data sets are quite consistent with each other, both with a similar pattern and magnitude of precipitation. The conspicuous features of the climatology include the higher precipitation amounts over land east of the Mississippi River and lower amounts on the lee (east) side of the Appalachian Mountains to the coastal plain. Precipitation
associated with the warm Gulf Stream current increases dramatically just off the Atlantic coast south of the North Carolina Outer Banks barrier islands (Cape Hatteras) and down to the northeast coast of Florida. Note the range limit of the NMQ product to about 200 km offshore, as well as two small regions of reduced data coverage, due to blockage of the radar beam and limited NEXRAD coverage, in northwestern South Carolina and in the northwest corner of Virginia.

3.1 Southeastern U.S. overview

The 2009-2012 climatology of MPF and isolated precipitation (Fig. 7) reveals important contrasts between the two precipitation types. The MPF rain distribution looks very much like the total precipitation (Fig. 6a), consistent with the observation from Fig. 7c that 70%-90% of the precipitation over the Mississippi and Ohio river valleys, as well as the coastal plain, belongs to the MPF category. A relative minimum in MPF precipitation can be seen in the lee (east) of the Appalachian high country in the Carolinas. This is broadly consistent with the observation by Parker and Ahijevych (2007) that eastward-moving warm-season MCS tend to weaken over the Appalachians and restrengthen or reform over the Piedmont region. In contrast, isolated precipitation occurs in much lower quantity across the entire domain, but is concentrated in four regions (in order of increasing amount): the southeastern Atlantic coast, the Gulf Stream off the Carolina coast, the Florida Gulf Coast, and the southern Florida peninsula. Isolated precipitation clearly outlines the SE US coast whereas the MPF precipitation does not, consistent with a thermodynamic mechanism for onshore isolated storms in coastal regions. Note also
that the fraction of MPF precipitation is a relative minimum along the immediate SE US coast and across the Florida peninsula. Though coastal precipitation in the SE US has been studied in previous climatologies (Wallace, 1975; Carbone and Tuttle, 2008, Prat and Nelson, 2014), our results clearly associate the coastal rain generally with isolated storms, not MPF. Coastal isolated precipitation will be explored further in Section 4.

The 2009-2012 mean seasonal cycle of MPF precipitation (Fig. 8) illustrates that although MPF precipitation occurs across the SE US throughout the year, there are notable regional differences. The most extensive MPF precipitation occurs in springtime (MAM) in the southern Ohio Valley, western Tennessee and Mississippi. This observation is consistent with a 15-year climatology (Ashley et al., 2003) of mesoscale convective complexes (long-lived warm-season MCS) showing a monthly precipitation maximum in that region in springtime (May), migrating northward to the upper Midwest during the summer. The Appalachian region from western Virginia to the western Carolinas has a summertime (JJA) minimum. Parker and Ahijevych (2007) documented a regional minimum in warm season MCS occurrence in the southern Appalachian high country, which they attributed to the disruption of MCS circulations by the mountain ridges as MCS approach from the west. In addition, persistent troughs of low pressure downstream of the Appalachians favor MCS initiation or resurgence to the east of the mountains (Koch and Ray, 1997). In southern and central Florida, MPF rainfall increases from a winter (DJF) minimum to a summertime (JJA) maximum that extends both over the land and ocean. Although the Gulf Stream MPF rainfall maximum off the Carolina
coast persists year round, the MPF rainfall is greatest during summer (JJA) and fall (SON), at nearly twice the wintertime amount.

The seasonal cycle of isolated precipitation (Figure 9) is quite marked, in contrast with the weak seasonal cycle of MPF. In winter (DJF) isolated precipitation is nearly absent except for over the ocean off the southern and eastern Florida coast up to the Carolinas, which coincides with the relatively high wintertime SSTs (Figure 10a) along the Gulf Stream near the SE US coast. In spring (MAM) isolated precipitation increases across the domain, particularly in southern Florida. The summer (JJA) pattern clearly shows the outline of the entire SE coast, the warm Gulf Stream current, and the island of Cuba. The isolated precipitation generally decreases to the north and also decreases away from the coast. A very strong isolated rain gradient over the ocean north of 35°N latitude (Cape Hatteras, North Carolina) corresponds to the sharp climatological decrease in SST as the Gulf Stream is directed northeastward by the coastal contour, away from land. There is an interesting summertime “rain shadow” over the ocean within 100 km of the Georgia and northern Florida coast, which is also clearly visible in TRMM satellite 3B-42 rain climatologies (Prat and Nelson, 2014). This feature is most evident in the isolated precipitation maps (rather than the MPF maps), primarily during spring and summer.

There is a climatological minimum of SST along the southeastern coast (Fig. 10), from Florida to North Carolina, in generally the same region. However, the precipitation minimum is most evident in the summer, the season when the SST minimum and associated SST gradient is smallest. Yet the location and season suggest that the precipitation minimum is related to a land-ocean heating contrast in some way. In the fall
months (SON) the isolated precipitation greatly decreases across the domain, but persists in south Florida and along the Gulf Stream where the SSTs remain near their summertime values. In summary, the annual cycle of isolated precipitation appears rather clearly to be thermodynamically driven, suggesting that isolated rain responds to surface heating either directly through high moisture content and thermodynamic instability, or indirectly through thermal circulations such as the sea breeze, or both.

3.2 Regional differences

These results indicate that in addition to the general SE US characteristics of the annual cycle of precipitation, there are important regional differences that provide some insight with respect to mechanisms controlling seasonal changes in precipitation. Five 1° x 1° boxes were chosen for analysis (box locations shown in Figure 7), based on qualitative differences in regional precipitation noted in the previous discussion. These regions include ocean and land, coastal and inland locations, as follows: the Gulf Stream off the southeast coast of North Carolina (box 1), the Florida panhandle (box 2), western North Carolina (box 3), offshore from the Georgia-North Florida coast (box 4), and the Ohio River Valley (box 5). Figures 11-12 present the four-year-averaged seasonal means of isolated and MPF precipitation, along with the fractions of the total precipitation and time present for MPF, for these five regions. The Gulf Stream off the southeast Carolina coast (box 1) has the highest annual-mean precipitation than any region in the SE US (c.f. Figure 6), with the MPF precipitation contributing up to 90% of the total winter precipitation and down to 71% in the summer (Figure 12). Kuwano-Yoshida et al.
(2010), in a modeling study of the precipitation response to the warm Gulf Stream, suggested that deep atmospheric vertical circulations are driven by SST gradients (perhaps once SSTs reach a certain threshold value), favoring widespread summertime precipitation systems over the Gulf Stream. Over the Gulf Stream off the Carolina coast the MPF precipitation increases steadily from winter to fall (Fig. 11a), while MPF are most common in the fall. Although during fall (SON) that region is generally impacted by both tropical and baroclinic systems, there were only two tropical systems off the Carolinas during the 2009-2012 period (Tropical Storm Beryl in late May 2012, and Hurricane Irene in August 2011). The maximum MPF activity during fall in that region is possibly related to seasonally high SSTs (25°C-26°C) combined with a large SST gradient (Fig. 10d). There is a clear summer (JJA) maximum in the isolated precipitation (Figure 11a) in all regions except the rain shadow off the Georgia coast, strongly suggesting a general thermodynamic enhancement of local precipitation over warm land and ocean in the summertime. Over the Florida panhandle along the Gulf coast, MPF rainfall decreases from spring to fall by nearly a factor of two. In the summer (JJA), isolated rain along the Florida panhandle makes up over half (57%) of summer rainfall in that region. Western North Carolina is situated in the Appalachian high country, where Parker and Ahijevych (2007) have documented a minimum in MCS occurrence as discussed earlier. The low amount of MPF precipitation in western North Carolina shown in Figure 11 is consistent with that finding. Isolated precipitation also makes up over half of the total summertime rain in that region. The Ohio Valley has maximum MPF precipitation in the spring and summer with just over 90% of springtime precipitation in the MPF category, decreasing to 78% in the summer as isolated rain increases. Aside
from the Gulf Stream, MPF precipitation is most common in winter and spring (Figure 12b), in particular the Ohio Valley to the north. Nieto-Ferreira et al. (2013) show that the seasonal changes in extratropical cyclone precipitation across the SE US are quite similar to the seasonal pattern of MPF precipitation shown herein, suggesting a strong association of MPF with baroclinic forcing. Taken together, these observations suggest that farther north the isolated precipitation regime generally yields to a baroclinic regime in the fall and winter dominated by MPF, while farther south isolated precipitation dominates into the summer season.

The annually-averaged (2009-2012) time series of daily-mean precipitation (Fig. 13), averaged over each of the five boxes, examines the annual precipitation cycle of those five regions in more detail. Though all regions have clear warm season maxima in isolated rain, the duration, amplitude, and timing show regional differences. The Gulf Stream off the Carolina coast has a broad maximum in isolated precipitation from March to November, while in contrast the coastal Florida Panhandle has a shorter May-October isolated rain season with a larger and more peaked August maximum. Off the Georgia-Florida coast (box 4, Figure 13) there is an indication of two seasonal isolated precipitation maxima – June/July (smaller) and October (larger). Over the Gulf Stream, the extremes in MPF precipitation are scattered evenly throughout the year, reaching values up to about three times the “background”. The lack of a clearly defined seasonal cycle of MPF precipitation is common to all regions, illustrating that there are both warm and cold season regimes of organized precipitation. In the Ohio Valley, there is an indication of two seasonal maxima of MPF precipitation – May (spring) and August
(summer). To quantify the regional differences in extreme precipitation, Tables I-II give the 2009-2012 frequency distributions of daily-mean precipitation (isolated and MPF separately) for each of the five box regions. The Florida panhandle has the largest tail of mid-to-high-range daily averaged isolated precipitation, consistent with strong thermodynamic forcing from strong coastal solar heating combined with a constant moisture source from the Gulf of Mexico. In contrast, the distribution is shifted to lighter isolated precipitation in the western Carolina high country. For MPF precipitation, the Gulf Stream off the Carolina coast has the broadest distribution of daily-mean values, while the distribution is shifted to more frequent lower values in the western Carolina high country (consistent with Parker and Ahijevych, 2007).

Shown in Table III is the seasonal cycle of the percentage of frozen precipitation relative to the total in each of the five regions. Two of the regions, western North Carolina and the Ohio Valley, have a significant frozen precipitation regime with 11.7% and 15.9% of winter season precipitation in solid form, consistent with the higher elevation, farther distance from the ocean, and more northerly latitude of those regions. Frozen precipitation makes up less than 1% of precipitation in the spring and fall seasons, with a slightly higher percentage in the spring. The Florida panhandle had a trace amount of frozen precipitation in the winter and spring seasons, while the two ocean regions had no occurrence of frozen precipitation during any season.
4. Seasonal changes in diurnal cycle of MPF and isolated precipitation

Seasonal changes in the diurnal cycle of isolated and MPF precipitation across the SE US give a revealing perspective on the modulation of local and larger scale precipitation organization by the daily solar cycle.

Shown in Figure 14-15 is the seasonal variation of the three-hourly diurnal variation of isolated precipitation, for 2009-2012. Not surprisingly, the greatest diurnal change occurs in the summer season (JJA), with essentially no diurnal variation during winter (DJF). In summer, the isolated precipitation preferentially forms offshore at night, increasing from just after midnight local time to a few hours after sunrise (0300-1200 UTC). The offshore nocturnal isolated precipitation clearly follows the outline of the coastal region, with the notable absence of nocturnal rain over the ocean just off the Georgia and North Florida coasts (box 4) discussed earlier. In the three hours between late morning and early afternoon (1500-1800 UTC), the isolated precipitation dramatically switches from ocean to land, including Cuba and the Bahamas, clearly responding to daytime land surface heating. Inland, the isolated precipitation builds in the early afternoon, though is weaker away from the coast and northward. At 1800 UTC (Fig. 15) there is a clear increase in isolated precipitation over the Appalachian high country in western North Carolina and eastern Tennessee, visible along the mountain ridges, likely related to thermally-induced orographic circulations. The offshore isolated precipitation is weakening by 1800 UTC, but by 2100 UTC (late afternoon) offshore rain has mostly diminished while the inland has filled in over most land areas, particularly along the coastal plain. Around local
sunset (0000 UTC) the land precipitation has begun to weaken. This diurnal evolution of precipitation aligns well with the radar analysis of Carbone and Tuttle (2008), who concluded that radar echo frequency was largest at 2100 UTC (late afternoon) across the Gulf Coast and southeastern coastal region, and increased offshore at night to an early-mid morning maximum (1300 UTC). They implicated the diurnal land-sea breeze circulation to explain that result, an interpretation consistent with the present study. The present result emphasizes that this diurnal rain variation is tied to isolated precipitation that increases in both frequency and intensity onshore during the day, with a reversed pattern at night. To the extent that isolated precipitation is locally generated, we conclude that there is a clear diurnal thermodynamic forcing in local precipitation in the summertime that reverses in phase between coastal land and ocean.

Figure 14-15 show that during the transition seasons of spring (MAM) and fall (SON), the summer pattern is also evident in isolated precipitation, but at a lower intensity. Interestingly, while the increased afternoon isolated precipitation over land is similar in spring and fall, the nocturnal rain over the ocean is greater in the fall season where SSTs are 3-4 degrees Celsius warmer along the Atlantic and Gulf coasts (not shown). This result is very likely due to the greater thermal inertia of the ocean compared to land, with warm coastal water generally persisting into the fall season even after the advent of cold air advection into the southeast.

In contrast, there is no clear diurnal cycle of MPF precipitation (Figure 16-17) for much of the year except for summer. As with isolated precipitation, the greatest diurnal changes
occur in the summer season (JJA), but with important regional differences not found in the isolated precipitation diurnal composites. The summertime MPF precipitation in the Ohio Valley in the northern domain has no diurnal pattern, suggesting that mesoscale and synoptic scale precipitation is not modulated by diurnal heating and cooling, but likely by the essentially random timing of baroclinic system passage (e.g. Nieto-Ferreira et al. 2013). In the coastal region, the warm season land-sea contrast also occurs with MPF precipitation, though not nearly as dramatically as with isolated precipitation. The summer MPF precipitation increases by 1800 – 2100 UTC, about three hours after isolated precipitation, suggesting a transition from local to mesoscale organization as the afternoon progresses. With MPF precipitation, there is a clear regional difference in the diurnal timing of offshore rain. The Gulf Stream off the Carolina coast has a strong MPF rain maximum in the early to mid-morning (0900 – 1200 UTC), while off the Gulf Coast the MPF maximum is several hours later (1500-1800 UTC). The reasons for the different diurnal timing of both ocean locations are not clear. Over land near the Carolina coast, the summertime MPF rain begins by 1800 UTC (early afternoon), expanding farther inland and intensifying over the next 3-6 hours. This is very likely sea breeze precipitation organized on the mesoscale, and is observed to largely diminish by 0300 UTC (late evening before midnight). The diurnal timing and location of the mesoscale sea breeze precipitation along the Carolina coast is consistent with the detailed study of Koch and Ray (1997).

We can understand more about the mechanisms for the differences between coastal and offshore precipitation by focusing on the summertime diurnal variation of isolated and
MPF precipitation in the vicinity of the Florida Panhandle. Figure 18 shows the mean JJA diurnal variation of precipitation for the $1^\circ \times 1^\circ$ region on the Florida panhandle coast, compared to a similarly-sized region 100 km offshore over the ocean. This figure may be used to test the hypothesis (extending from Carbone and Tuttle, 2008) that on the western Florida Gulf coast, isolated convection forms onshore in the afternoon, organizes on the mesoscale, and propagates offshore in the evening (as found for coastal Panama systems by Mapes et al. 2003). Figure 18 shows that the maximum in isolated rain over land occurs about three hours after the maximum in MPF rain over ocean, inconsistent with that hypothesis. Moreover, over the ocean, isolated precipitation has a maximum at 1200 UTC (just after sunrise) followed three hours later by a maximum of ocean MPF precipitation, consistent with the formation and upscale evolution of offshore systems independently from land systems. Therefore the offshore precipitation likely forms and evolves independently of the land precipitation, suggesting diurnal changes in initiation of precipitation (for example by a land-sea breeze reversal) rather than the propagation offshore of a system formed earlier over land. Case study analysis is underway to explore this relationship.

5. Conclusions

A four-year (2009-2012) radar-based precipitation climatology of the SE US, including seasonal and diurnal regional variations, was constructed using a simple framework of precipitation organization. Precipitation was classified into two categories of organization, mesoscale precipitation features (MPF) and isolated precipitation features.
The aim is to determine whether and how the seasonal and diurnal variations of MPF versus isolated systems are distinct. The National Mosaic and Multi-sensor QPE dataset was analyzed at 15-minute intervals for four years over the SE US from the Florida peninsula to the mid-Atlantic region, including the oceans within 200 km of the coast.

On average, 70%-90% of precipitation is associated with MPF, generally less in the summertime and in southern coastal regions, with a relatively small seasonal cycle except in Florida and the warm offshore waters of the Gulf Stream. In contrast, isolated precipitation has a dramatic seasonal cycle that clearly outlines the SE coast in the summertime. Along the Florida panhandle, isolated rain makes up over half of summer rainfall, with a shift to higher extreme events in the frequency distribution of daily-averaged precipitation compared to the other regions. Isolated precipitation in the summertime therefore appears to be more thermodynamically driven, suggesting that isolated rain responds to surface heating either directly through high moisture content and thermodynamic instability, or indirectly through thermal circulations such as the sea breeze, or both.

Diurnal variations of MPF and isolated precipitation suggest clear distinctions in the mechanisms controlling both precipitation types. In summer, the isolated precipitation preferentially forms offshore at night, increasing from just after midnight local time to a few hours after sunrise. In the three hours between late morning and early afternoon (1500-1800 UTC), the isolated precipitation rapidly and dramatically “flips” from offshore to the coastal regions, including Cuba and the Bahamas, clearly responding to
daytime land surface heating. By early afternoon there is a clear increase in isolated precipitation over the Appalachian high country in western North Carolina and eastern Tennessee along the mountain ridges, likely related to thermally-induced orographic circulations. In contrast, MPF precipitation has no clear diurnal variations except in the southern coastal region in the summer, likely associated with sea breeze convection organized on the mesoscale. In the Gulf Coast region of western Florida, offshore summertime precipitation likely forms and evolves independently of the land precipitation, suggesting diurnal changes in initiation of precipitation (for example by a land-sea breeze reversal) rather than the propagation offshore of a system formed earlier over land.

These results suggest that the MPF versus isolated precipitation system framework provides a useful basis for future studies of large scale and local controls on precipitation and resulting implications for long-range predictability of precipitation. Building on the general results of this four-year MPF and isolated precipitation climatology, we plan to use the Weather Research and Forecasting Model (WRF) model to investigate mechanisms for the different seasonal and diurnal behaviors of precipitation organization. We will also use WRF simulations to study potential changes in the precipitation organization climatology for future climate scenarios in Coupled Model Intercomparison Project Phase 5 (CMIP5) projections. We also envision extending the precipitation climatology back to 1996, and perform interannual variability studies of regional and seasonal changes in the MPF and isolated precipitation across the SE US.
6. Acknowledgements

This study was funded by a grant (AGS-1118141) from the National Science Foundation’s Division of Atmospheric and Geospatial Science, both the Climate and Large-Scale Dynamics program and the Physical and Dynamic Meteorology program. We appreciate the comments of the anonymous reviewers, which led to substantial improvements to the paper. Dr. Gary Lackmann is gratefully acknowledged for useful discussions on the design of this study.
7. References


List of Figure Captions

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Table I. Frequency distribution of 2009-2012 daily-mean isolated precipitation values for the five $1^\circ \times 1^\circ$ box regions illustrated in Figure 7.

<table>
<thead>
<tr>
<th>Daily-mean Isolated Precipitation (mm day$^{-1}$)</th>
<th>Gulf Stream off Carolina coast</th>
<th>Florida Panhandle</th>
<th>Western North Carolina</th>
<th>Off Georgia coast</th>
<th>Ohio Valley</th>
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<th>Daily-mean MPF Precipitation (mm day$^{-1}$)</th>
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Table III. The 2009-2012 seasonal fraction of frozen precipitation relative to the total, for the five 1° x 1° box regions illustrated in Figure 7.

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<th>% Frozen Precipitation</th>
<th>Gulf Stream off Carolina coast</th>
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<td>Summer (JJA)</td>
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<tr>
<td>Fall (SON)</td>
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<td>0</td>
<td>0.06</td>
<td>0</td>
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</table>
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