Diurnal and Seasonal Lightning Variability over the Gulf Stream and the Gulf of Mexico*

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ABSTRACT

Recent observations from the World Wide Lightning Location Network (WWLLN) reveal a pronounced lightning maximum over the warm waters of the Gulf Stream that exhibits distinct diurnal and seasonal variability. Lightning is most frequent during summer (June–August). During afternoon and early evening, lightning is enhanced just onshore of the coast of the southeastern United States because of daytime heating of the land surface and the resulting sea-breeze circulations and convection. Near-surface wind observations from the Quick Scatterometer (QuikSCAT) satellite indicate divergence over the Gulf of Mexico and portions of the Gulf Stream at 1800 LT, at which time lightning activity is suppressed there. Lightning frequency exhibits a broad maximum over the Gulf Stream from evening through noon of the following day, and QuikSCAT wind observations at 0600 LT indicate low-level winds blowing away from the continent and converging over the Gulf Stream. Over the northern Gulf of Mexico, lightning is most frequent from around sunrise through late morning. During winter, lightning exhibits a weak diurnal cycle over the Gulf Stream, with most frequent lightning during the evening.

Precipitation rates from a 3-hourly gridded dataset that incorporates observations from Tropical Rainfall Measuring Mission (TRMM), as well as other satellites, exhibit a diurnal cycle over the Gulf Stream that lags the lightning diurnal cycle by several hours.

1. Introduction

The Gulf Stream is a strong western boundary current located in the Atlantic Ocean to the east of the United States. The warmth of sea surface temperature (SST) in the Gulf Stream destabilizes the lower troposphere and induces low-level wind convergence (Raman and Riordan 1988; Sublette and Young 1996; Chelton et al. 2004) through pressure adjustments in the marine atmospheric boundary layer (MABL; Minobe et al. 2008). In the climatological mean, the region of the Gulf Stream receives about twice as much precipitation as the southeastern United States (Fig. 1). The sharpness of the SST gradients associated with the Gulf Stream plays a key role in focusing the precipitation maximum: when the SST front is smoothed, an atmospheric general circulation model (GCM) cannot reproduce the observed convective precipitation pattern over the western Atlantic Ocean (Minobe et al. 2008; Kuwano-Yoshida et al. 2010).

Precipitation over the Gulf Stream exhibits pronounced diurnal variability. Minobe and Takebayashi (2015) showed that the diurnal cycle of precipitation rate over the Gulf Stream is stronger during summer than during winter, with relative amplitudes of 40%–70% of the diurnal mean rain rate. Summertime precipitation over the Gulf Stream peaks during the morning (0500–1100 LT), and high cloud occurrence increases from evening to the morning, reaching a maximum an hour or two after the precipitation (Alliss and Raman 1995;

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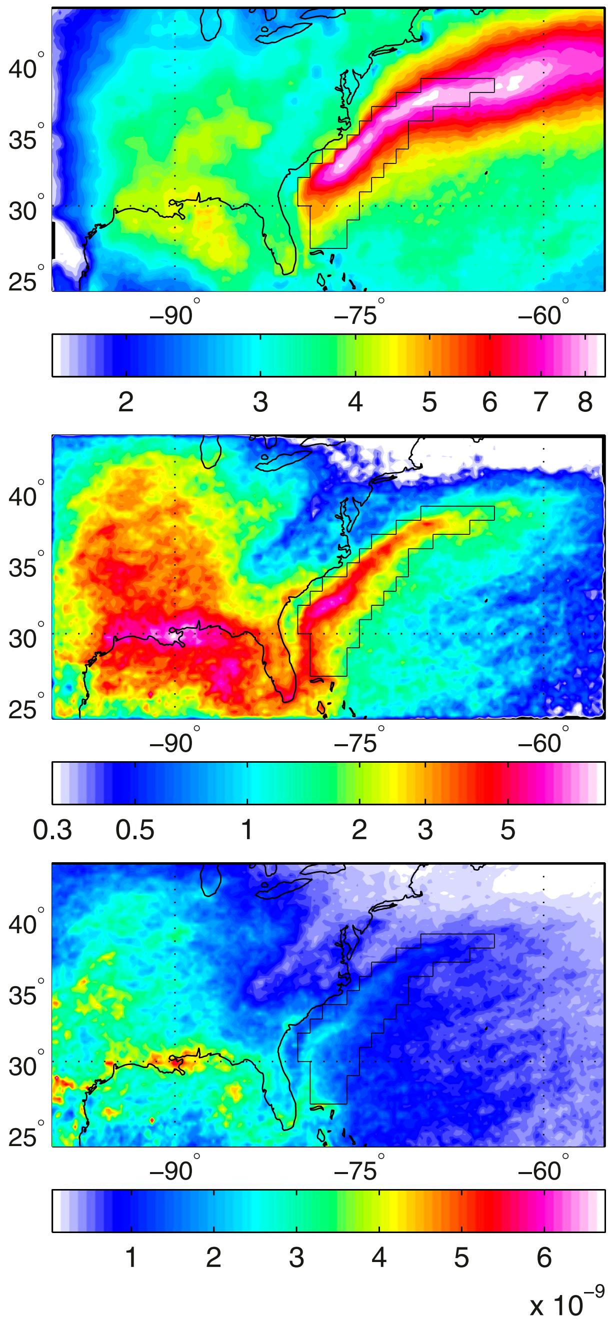

FIG. 1. (top) Annual-mean TRMM precipitation (mm day^{-1}); (middle) WWLLN lightning (strokes km^{-2} yr^{-1}); and (bottom) ratio of WWLLN lightning to TRMM rainfall (lightning strokes per kg of rain) over the eastern United States and western Atlantic Ocean. Black box outlines the area designated as the Gulf Stream.

Minobe et al. 2008; Minobe and Takebayashi 2015). The southeastward propagation of the time of maximum diurnal precipitation across the Gulf Stream suggests that the convection may be driven by gravity waves (Minobe and Takebayashi 2015).

Tropospheric instability over the warm waters of the Gulf Stream provides an environment favorable for intense convection. Annual-mean lightning frequencies over the Gulf Stream rival those along the Gulf Coast, creating a relative maximum in the number of lightning strokes per unit precipitation amount (Fig. 1). Based on data from the wintertime Genesis of Atlantic Lows Experiment (GALE), Hobbs (1987) reported bands of clouds and precipitation localized over the Gulf Stream, and Biswas and Hobbs (1990) demonstrated that lightning was more frequent there than over the nearby land surface, particularly during prefrontal periods. Orville (1990) found that the width of the lightning maximum was similar to the width of the Gulf Stream itself. Enhanced lightning over the Gulf Stream has been observed during the passage of individual midlatitude cyclones (Orville 1993). A wintertime lightning maximum has also been observed over the Kuroshio Extension (Tokinaga et al. 2009).

While wintertime thunderstorms have been the focus of the studies cited above, recent work has shown that lightning is most frequent over the Gulf Stream during summer (Minobe et al. 2010; Holle et al. 2011). Holle (2014), analyzing the diurnal cycle of annual-mean lightning over the United States, noted a morning maximum in lightning over the Gulf Stream and suggested that it might be related to nocturnal land breezes. In this paper, we investigate the timing and intensity of the diurnal cycles of lightning and precipitation over the Gulf Stream, the southeastern United States, and the Gulf of Mexico using recent ground-based and satellite observations, and we confirm the suggestion by Holle (2014) that this variability is related to the diurnal cycle in the near-surface winds. We further show that the nocturnal enhancement of lightning is more narrowly focused on the Gulf Stream than that of precipitation.

2. Data

The ground-based World Wide Lightning Location Network (WWLLN) detects lightning by monitoring the time of group arrival of very low-frequency (VLF) lightning sferics at five or more of its sensors (Dowden et al. 2002). Although WWLLN's detection efficiency increases as more sensors are added to the network, its continuous monitoring has enabled it to detect nearly all lightning-producing storms since 2005 (Jacobson et al. 2006). Currently, the detection efficiency is ~11% (Abarca et al. 2010; Hutchins et al. 2012; Rudlosky and Shea 2013), with about 70 sensors as of the end of 2013. Virts et al. (2013) demonstrated WWLLN's ability to capture the diurnal cycle of lightning in a variety of geographical regions. The present study makes use of the monthly, hourly lightning climatology at 0.25° resolution introduced in Virts et al. (2013), updated to include data from 2008 to 2013.

The Tropical Rainfall Measuring Mission (TRMM) satellite carried a radar designed to measure precipitation intensity. Launched in 1997, TRMM's orbit was confined to within 35°N/S, thus limiting its observations to the southern portion of the Gulf Stream. The TRMM 3B42 dataset supplements TRMM observations with those from microwave imagers and infrared sensors aboard other satellites to generate gridded precipitation rates at 3-hourly temporal resolution and 0.25° spatial resolution, extending to 50° latitude (Huffman et al. 2007). This study is based on 15 yr of TRMM data (1998–2012).

The Quick Scatterometer (QuikSCAT) satellite carried SeaWinds, a microwave radar that measured power backscattered by ocean waves, which was converted to estimates of 10-m wind speed and direction (Hoffman and Leidner 2005). QuikSCAT was a polar-orbiting satellite, with equatorial crossings at 0600 and 1800 LT, enabling it to observe two contrasting times in the diurnal cycle. The Jet Propulsion Laboratory offers daily gridded QuikSCAT data at 0.25° resolution, separated according to ascending and descending passes (morning and evening, respectively) for the full data record (July 1999–November 2009).

This study also makes use of a 16-yr (1998–2013) weekly, 1°-resolution SST dataset from the Earth System Research Laboratory that incorporates both in situ and satellite observations.

3. Results

The diurnal cycle of precipitation and lightning over the Gulf Stream during each of the four seasons is shown in Fig. 2. For this figure, data have been averaged over the region enclosed by the black box in Fig. 1, which focuses on the upstream portion of the Gulf Stream, including the Florida Current. During spring, summer, and autumn, convection over the Gulf Stream is suppressed during the afternoon; the minimum in lightning frequency around 1600 LT is followed by a minimum in precipitation approximately 3 h later. Diurnal lightning variability over the Gulf Stream does not follow a simple sine curve; rather, the late afternoon minimum lasts for only a few hours, and the lightning frequency increases during the evening hours to a broad nighttime maximum. Lightning exhibits what appears to be a double maximum, with one occurring a few hours after midnight and the other later in the morning around 0800–1000 LT. An animation of 3-h running-mean lightning frequency, included in the online supplement to this article, indicates that this double maximum is observed over much of the Gulf Stream. The coarser temporal resolution of the precipitation data makes detection of a double maximum difficult, although there is a suggestion of one during March–May (MAM) and September–November (SON) in Fig. 1. During June–August (JJA), precipitation exhibits a single peak at 1000 LT, around the end of the nighttime lightning maximum, and high cloud fraction peaks shortly afterward, between 1000 LT and noon (Alliss and Raman 1995; Minobe and Takebayashi 2015). JJA is also the season of strongest diurnal variability, with peak-to-peak variations of a factor of approximately 2.5 and 3 observed for precipitation and lightning rates, respectively.

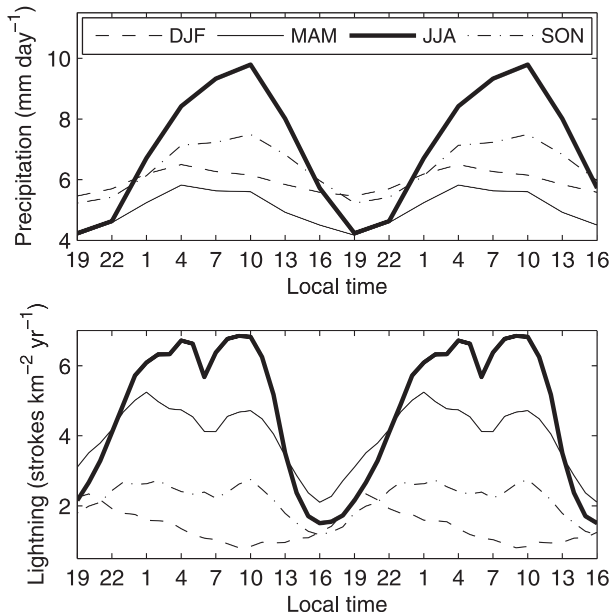

FIG. 2. Diurnal cycle, repeated for clarity, of (top) TRMM precipitation (mm day^{-1}) and (bottom) WWLLN lightning (strokes km^{-2} yr^{-1}) averaged over the black box outlined in Fig. 1, for each season. For this and all subsequent lightning and precipitation plots, local times are given for standard time in the eastern time zone of the United States.

Minobe and Takebayashi (2015) analyzed the diurnal phase of hourly precipitation during July and noted southeastward phase propagation from the Gulf Stream. Because of the nonperiodic and double peak behavior noted above, calculation of the diurnal phase of lightning is problematic. Note, however, that the animation in the online supplement shows no propagation of the lightning over the Gulf Stream, although there is a mid-to-late morning lightning maximum to the east of the Gulf Stream.

Although its amplitude is smaller, the timing of the diurnal cycle of precipitation during DJF is similar to that in the shoulder seasons, with a minimum during the evening and a maximum during the morning. In contrast, wintertime lightning peaks around 1900 LT, at the time of minimum precipitation, and declines steadily through the night to a minimum in the hours after

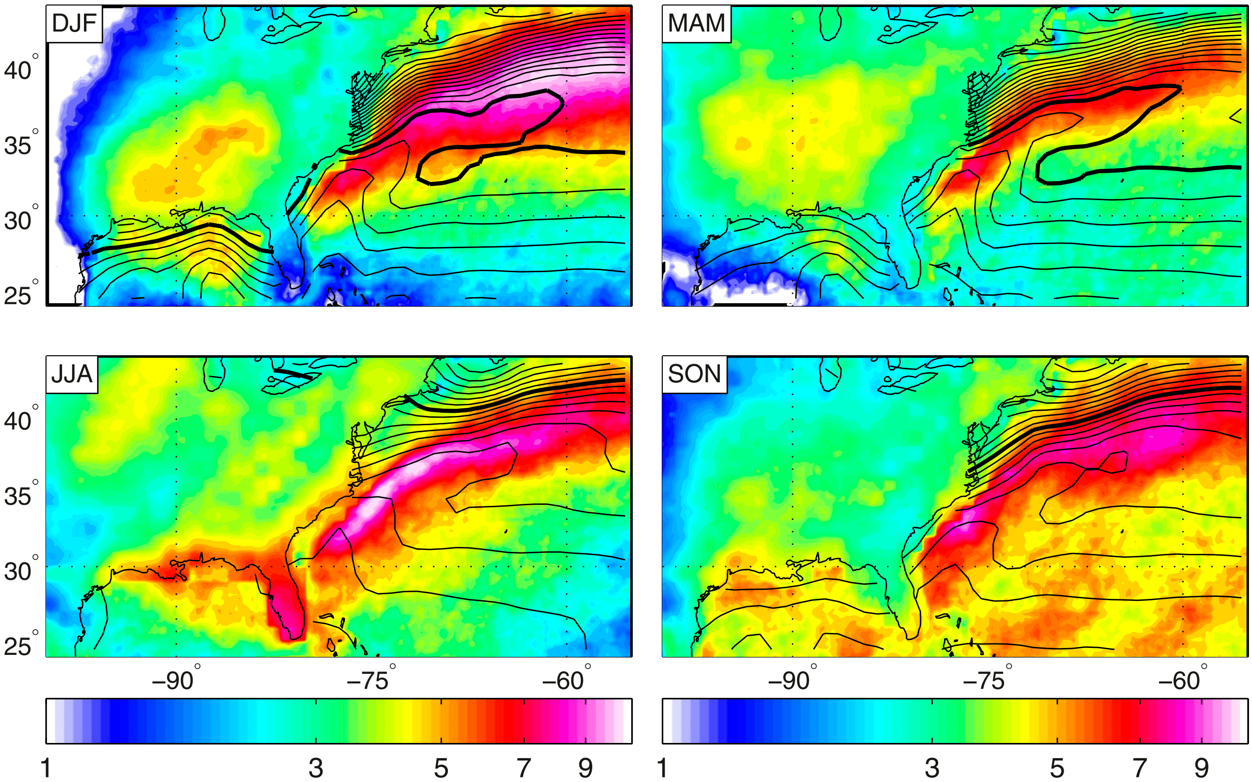

FIG. 3. Seasonal-mean TRMM 3B42 precipitation (shading, mm day^{-1}) and SST (contours). Contour interval (CI) = 1°C, with 20°C contour thickened.

sunrise. Interestingly, the results in Fig. 2 indicate that lightning frequencies during early evening (from 1700 to 2000 LT) are of comparable magnitude during summer and winter.

Seasonal-mean precipitation and lightning over the eastern United States and western Atlantic are shown in Figs. 3 and 4, respectively, along with contours of SST. During each season, the northward bulge of the isotherms to the east of the United States indicates the position of the upstream portion of the Gulf Stream. Around Cape Hatteras, the Gulf Stream turns eastward, with the strongest current observed south of the sharp SST gradient ~40°–45°N (Minobe et al. 2008, 2010). A local maximum in lightning and precipitation is observed over the Gulf Stream during all four seasons, clearly separated from the eastern coast of the United States. The precipitation maximum follows the Gulf Stream eastward into the northern Atlantic [also noted by Minobe et al. (2010), analyzing TRMM data] and merges with the precipitation associated with the so-called storm track, particularly during December–February (DJF). The lightning maximum also extends toward the north-central Atlantic, along the northern edge of the warm waters. Composites of sea level pressure on days with enhanced lightning over the Gulf Stream (not shown) confirm the influence of synoptic-scale weather systems, particularly during DJF.

In agreement with Fig. 2, lightning is most frequent over the Gulf Stream during MAM and JJA (Fig. 4). Strong JJA-mean ascent and lightning localized over the Gulf Stream were also reported by Minobe et al. (2010), based on forecast fields from the European Centre for Medium-Range Weather Forecasts and observations from the Lightning Imaging Sensor, respectively. A spring and summertime maximum in lightning is also observed over the northern Gulf of Mexico and southern United States, in agreement with observations from the National Lightning Detection Network (NLDN; Holle et al. 2011; Rudlosky and Fuelberg 2011). The coastal areas, including Florida, are particularly convectively active during JJA. Over the central United States, lightning is most frequent during MAM, when midlatitude cyclones forming to the east of the Rocky Mountains often produce thunderstorms as they track across the Great Plains. A relative minimum in lightning is observed over and to the east of the Appalachian Mountains during all four seasons, and the low values of annual-mean lightning strokes per unit rain amount in

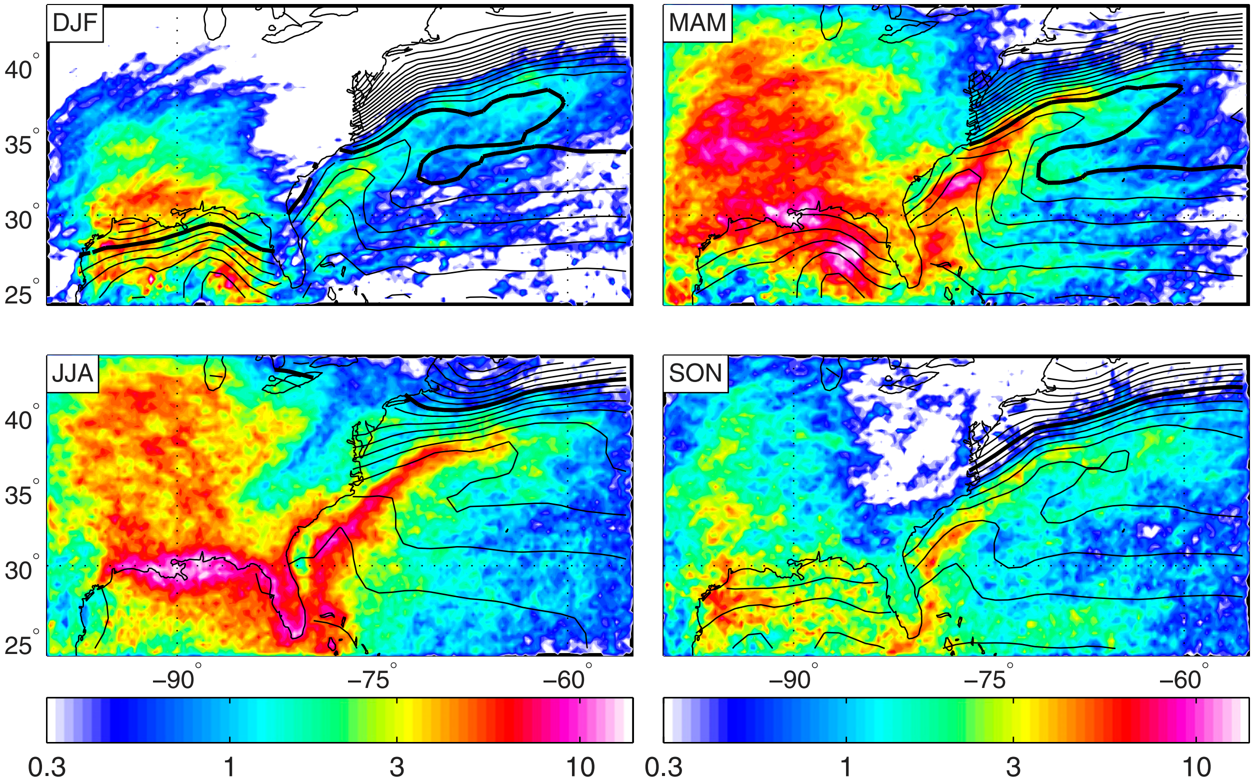

FIG. 4. As in Fig. 3, but for WWLLN lightning (strokes km^{-2} yr^{-1}).

that area (Fig. 1) emphasize the comparatively nonconvective nature of the precipitation.

As noted above, convection over the United States and adjacent oceans is often associated with migrating synoptic disturbances. These disturbances tend to be less intense during summer; as indicated by the large diurnal modulation in Fig. 2, convection in JJA is predominantly diurnally driven. Based on the animation of diurnal lightning frequency in the online supplement and in Fig. 2, the diurnal cycle in lightning can be summarized as consisting of two contrasting periods: the afternoon hours and the remainder of the day. Mean lightning and precipitation during these two periods are shown in Fig. 5. Note that the averaging intervals were selected to best represent the diurnal cycle of each variable and are thus slightly different.

To understand the diurnal cycles of lightning and precipitation shown in Fig. 5, it is necessary to consider the diurnal cycle of the atmospheric circulation in this region. QuikSCAT near-surface winds at 0600 and 1800 LT are shown for the Gulf Stream and Gulf of Mexico in Figs. 6 and 7, respectively. Daytime heating of the land surface by solar radiation drives sea-breeze circulations along the southern and eastern coast of the United States during JJA, as illustrated by the landward component of the 1800 LT QuikSCAT winds. The convergence of sea breezes produces enhanced lightning and precipitation along and just inland of the coastlines during the afternoon, at which time convection is suppressed in the broad area of divergence over the near-coastal waters (Fig. 5). Afternoon lightning along the coasts, particularly over Florida, has been previously documented based on audible thunder data (Wallace 1975; Easterling and Robinson 1985) and observations from NLDN (Zajac and Rutledge 2001; Holle 2014).

At night, the local coastal circulation patterns reverse. QuikSCAT 0600 LT winds along the East Coast have a seaward component (Fig. 6). Over the Gulf of Mexico, surface winds are still primarily landward but weaker, as indicated by the seaward component of the difference vectors (Fig. 7). Relatively little lightning and precipitation are observed over the southeastern United States from late evening through the morning (Fig. 5), although there is a broad convective maximum over the central United States related to nocturnal mesoscale convective systems (Wallace 1975; Maddox 1980). Offshore, an area of surface wind convergence extends along the Gulf Stream (Fig. 6, left panel), and this in combination with the destabilizing influence of the warm SSTs promotes the generation of convection throughout the night (Fig. 5). The nocturnal lightning maximum is more

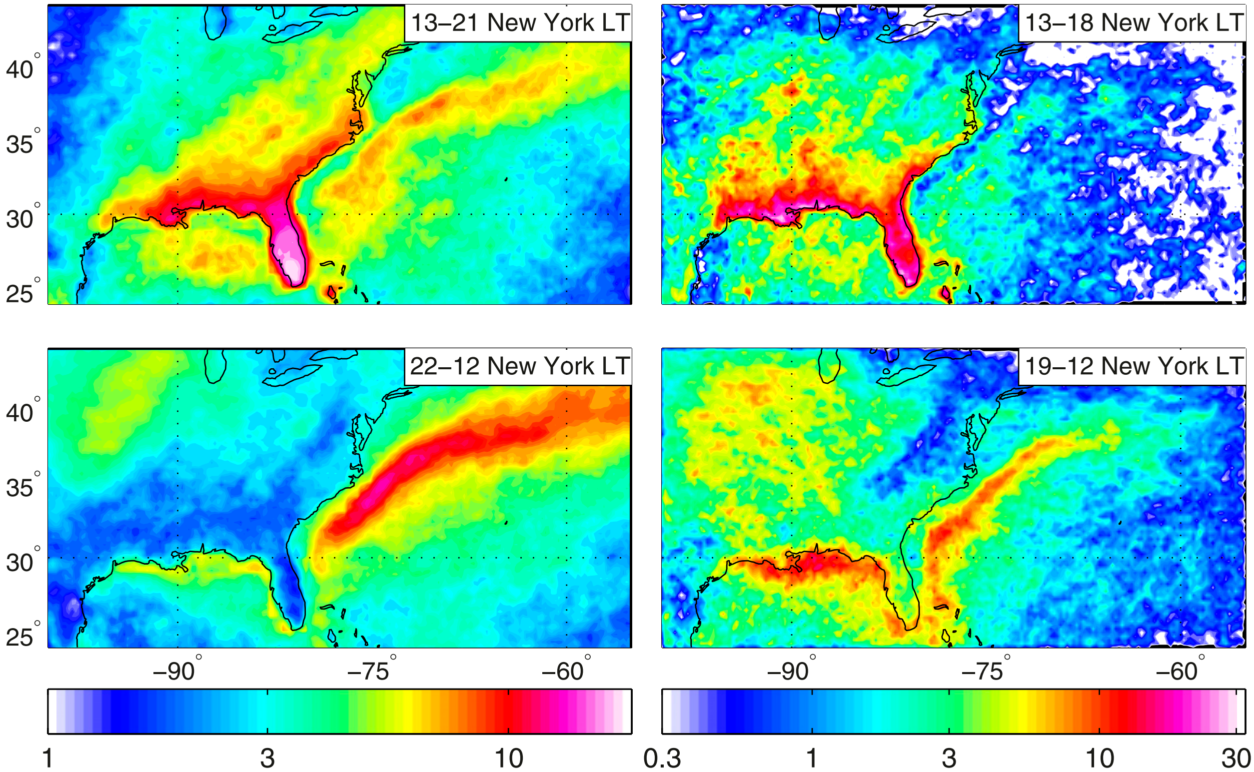

FIG. 5. Summaries of diurnal cycle of JJA-mean (left) TRMM 3B42 precipitation (mm day^{-1}) and (right) WWLLN lightning (strokes km^{-2} yr^{-1}). Time intervals are given at the top of each panel.

narrowly focused on the baroclinic zone at the western edge of the Gulf Stream than the precipitation maximum.

Anomalous convergence is also observed over the Gulf of Mexico during the morning (Fig. 7), and lightning starts to become more frequent over the northern Gulf just before sunrise [Fig. 5; Kucienska et al. (2010); Holle (2014); see the hourly lightning animation in the supplementary material]. Enhanced morning precipitation can also be seen over the coastal waters of the Gulf of Mexico in Fig. 5, although rain rates are lower there than over the Gulf Stream.

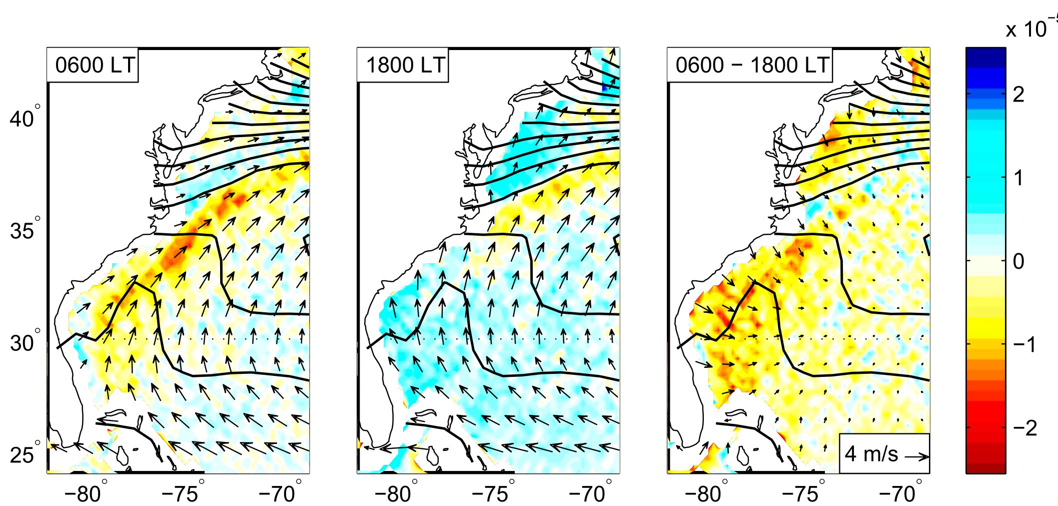

FIG. 6. JJA-mean QuikSCAT wind vectors and divergence (shading) at (left) 0600 and (middle) 1800 LT. (right) The difference between them. Contours are JJA-mean SST (CI = 1°C).

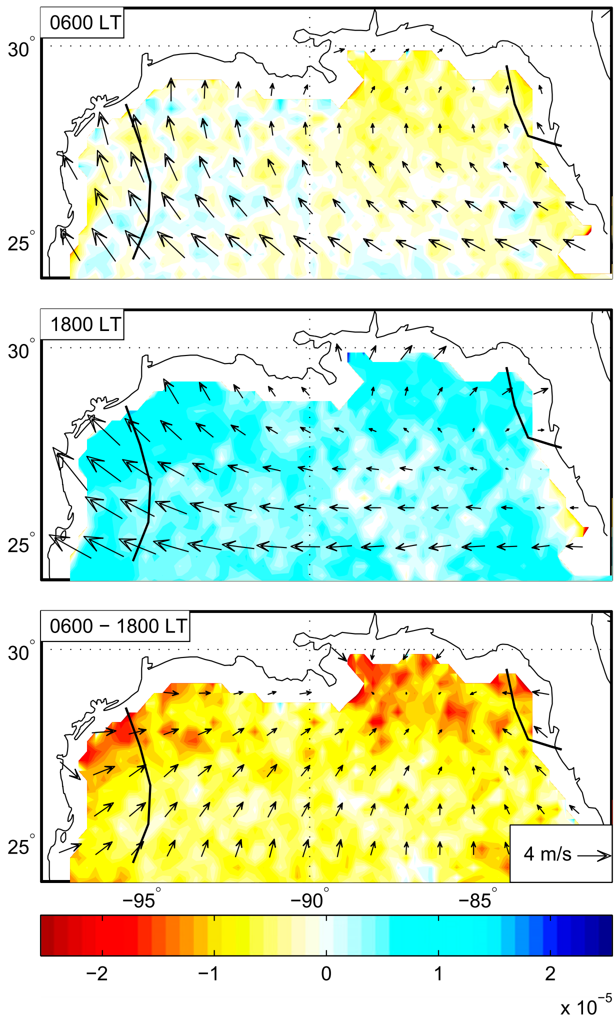

FIG. 7. As in Fig. 6, but for the Gulf of Mexico.

While we have analyzed the climatological diurnal cycle of lightning and precipitation, previous work has shown that the direction and strength of the synoptic-scale low-level winds modulate the strength of the local coastal circulations and the lightning occurrence on a day-to-day basis (Camp et al. 1998; Lericos et al. 2002; Smith et al. 2005). These studies have focused on Florida, the Gulf Coast, and the near-coastal waters. It remains to be seen how differing synoptic flow regimes affect the nocturnal lightning over the remainder of the Gulf Stream.

4. Conclusions

A strong diurnal cycle is observed in lightning and precipitation over the eastern United States and western Atlantic Ocean during summer and, to a lesser degree, during the shoulder seasons. Over the Gulf Stream, the magnitudes of the diurnal and seasonal cycles of lightning are comparable. During the warm season, low-level winds converge over the warm waters of the Gulf Stream during the night and morning hours, consistent with a pronounced maximum in convective activity. Surface wind convergence and morning convection are also observed over the northern Gulf of Mexico. Daytime heating of the land produces sea breezes and enhanced convection over the near-coastal regions of the southeastern United States. Lightning and precipitation are also enhanced over the Gulf Stream during winter, but diurnal variability in that season is smaller, and convective activity is driven mainly by synoptic-scale disturbances.

The results presented in this paper underline the challenge of accurately representing diurnal variability in GCMs that seek to represent convection over the northern Atlantic. The GCMs utilized by Lee et al. (2007) and Ploshay and Lau (2010) generally showed low-level convergence off the eastern coast of the United States during morning, although it is difficult to discern from their plots whether the convergence was localized over the Gulf Stream as it is in Fig. 6. The diurnal cycle in precipitation over the Gulf Stream was too weak in the Geophysical Fluid Dynamics Laboratory (GFDL) GCM analyzed by Ploshay and Lau (2010), while Dirmeyer et al. (2012) showed that the diurnal cycle was approximately the correct magnitude in the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) model and too large in the Nonhydrostatic Icosahedral Atmospheric Model (NICAM). Of these models, timing was shown for NICAM only, and the model successfully reproduced the mid-to-late morning maximum (Fig. 2). It remains to be seen whether the models correctly represent the strongly convective nature of the precipitation.

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Distributive Active Archive Center (http://podaac.jpl.nasa.gov/); and SST data were obtained from the Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/).

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