Synoptic and Large-scale Circulation Causes of Extreme Precipitation on the Southeast Coast of the Atlantic Ocean

by

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Executive Summary

Extreme precipitation has been an increasing problem due to global warming recently. Heavy rainfall not only causes huge economic losses over the eastern coastal region in North Carolina, but also could cause causalities and damages to infrastructure. The patterns and climatology of heavy precipitation have been explored in recent researches, especially with the development of remote sensing. The winter rainfall over the coastal region receives more attention than the summer precipitation. However, little research has been conducted to study the causes of extreme summer precipitation over the US southeast coast.

In this master project, the author discussed the summer precipitation pattern and extreme rainfall formation mechanism over the US southeast coast. This report states that extreme precipitation is largely due to strong and deep convection with the existence of an upper-level trough and three types of surface low systems in the region.

In the first portion of the report, the author introduces the data and method used in this research. The high temporal and spatial resolution of the Multi-Radar/Multi-Sensor System (MRMS) can produce a detailed diagram presenting the intricate feature of the precipitation and thus is employed in the study. The ERA-5 tool is also used for large-scale atmospheric condition analysis. The composite analysis is the main method that the author employed to investigate the mechanism of extreme rainfall events. The author also introduces the criteria of days with extreme rainfall – the top 10% days with the greatest amount of rainfall.

In the second portion of the report, the author discusses the overall climatology of the heavy rainfall over the US SE region, and a region (the CGAR region: 31N to 36N, 80W to 72W) with heavy rainfall is discovered. The author then discussed the extreme composite cases of the rainfall located in the CGAR region.

In the third portion of the report, the author presents the potential causes of the heavy precipitation over the CGAR region. An upper-level trough is discovered and meeting the hypothesis that the extreme rainfall in the SE US summer could be related to strong and deep convection. In addition to the upper-level trough, three types of surface Low systems are discovered: the Continental Low, the Gulf Low, and the Surface Low belt. Among them all, the Continental Low and the Surface Low are the two major surface lows causing the heavy rainfall. The author reaches the conclusion that the extreme rainfall could be associated with deep

convection that is caused by one upper-level trough and one surface low.

In the last portion of the report, the author discussed some potential future works. More research could be done on the rainfall pattern and its relationship with the summer North Atlantic Oscillation. Further work could also discuss the potential relationship between the deepening of the trough and different types of surface lows. This report makes the major science discoveries: (i) persistent occurrences of a heavy precipitation region near the coast of North and South- Carolina, (ii) a 500 hPa trough located at that position, and (iii) a peculiar flow configuration comprised of two types of surface lows (the Gulf low and Continental low) that contribute to the formation of this extreme precipitation region.

I. Introduction

Extreme rainfall has been impacting the Southeast coast of the Atlantic Ocean and cause disasters. These severe rainfall event triggers flash flood and landslides, causing loss of coastal infrastructures. For instance, coastal edge locations around the North Carolina coastal barrier islands have experienced severe structural damages. In contrast, inland places experience moderate infrastructure damages in storm surges and property loss due to flash flooding damages. (Hudula and Dolan, 2010). These disasters cause negative socio-economic impacts like harming the tourism and fishing industry, therefore hinders the economic growth in the coastal region. (Hamburg University of Technology, 2006). Although fish distribution is mostly modified by climate through the change of sea surface temperature (SST), coastal fishing is still very vulnerable to flooding hazards, which is closely related to severe storm (Sarwar 2005). Moreover, extreme rainfall negatively affects the fishing industry for causing danger when fishing boats go out to catch (Niiler 2014). Previous researches suggest losses at the North Carolina coast ranks the costliest natural disasters in the US, with an estimation of about one billion. Hence, extreme rainfall on the Southeast coast has caused an extensive amount of losses both to the NC state and the US, although the processes and factors cause such excessive rain over the Southeast coast region are mostly unknown.

Existing studies found that storms are one major cause of extreme precipitation in the US SE coast. Davis et al. (1993) discussed the formation of the winter storms comprises various types of formation with eight distinctive types, and they cause hazardous damage associated with lots of rainfall. Compare to its winter counterpart, the southeastern coast storm in summer (SCSS) has not been systematically studied (Hirsch et al., 1999). This study aims to explore the extreme rainfall in summer caused by the SCSS's along the Southeastern coast of the Atlantic Ocean and analyze the synoptic drivers of the SCSS. The SCSS usually develops as they move north along the coastline, causing increasing vulnerability as they induce flooding and landfall (Colle et al., 2015). Colle et al. (2015) show that these storms are related to the Atlantic SST gradient and dynamical interactions at the jet level, and there is latent heating within the storms as well. Composite analysis of the large-scale circulation will be used to investigate the favorable conditions for the formation and development of SCSS and their induced extreme rainfall. This study focuses on SCSSs; extreme rainfall-induced by Atlantic hurricanes is not included.

II. Data & Methods

2.1) Data

In this research, precipitation from the Multi-Radar Multi-Sensor (MRMS) is analyzed for the summer season (JJA) 2015 to 2018. The MRMS is developed by the National Severe Storms Laboratory (NSSL) and the National Oceanic Atmospheric Administration (NOAA), based on a product from the Next-generation Doppler Radars (NEXRAD). The MRMS, produced by the National Climate Data Center (NCDC), is a system of automated algorithms that derive and integrate data streams from multiple NEXRAD radars, numerical weather prediction models, and surface and upper-level observations (NOAA, 2018). The MRMS has a range that covers the coast and extends into the ocean for approximately 190 ~ 210km. The MRMS product has a very fine spatial resolution of 1km × 1km and temporal resolution of 2 min update cycle with 3D reflectivity mosaic at 31 levels. (NOAA, 2018). The MRMS corrected their radar products uses multiple gauge products like ones from NSSL and other local gauge products (NOAA, 2018). The MRMS rain algorithms classified the precipitation into seven categories (e.g., Warm stratiform rain and cold stratiform rain) and is a more developed severe weather product than the QPE algorithm (Zhang, 2016). By classifying the seven categories, the MRMS reduces the uncertainty in radar-based rainfall estimation. The MRMS product is known to have relatively accurate results and thus is used in this study (Qi and Martinaities, 2015). The NEXRAD uses high-frequency Doppler radars and can observe extreme weather events mesoscale weather systems with accuracy, both three-dimensional kinematically and microphysically (Battaglia and Kollias 2014). With the high precision of the NEXRAD radars, we expect the MRMS to be a reliable product to analyze. The NEXRAD radar covers a limited amount of region in the Atlantic Ocean; however, it includes some crucial areas like the fishing region for the SE coast (South Atlantic Fishery Management Council 2020).

Large-scale circulation is analyzed using ERA reanalysis. The ERA reanalysis is from the European Center for Medium-Range Weather Forecasts (ECMWF), and it is the data assimilation system that combines observation data with models to compute the changing of atmosphere beneath it. ERA reanalysis extends back into 1979 with a higher spatial resolution (0.25 degree) and has a temporal resolution of 6 hr. ERA-5, the newest one, has high accuracy with considerable improvement from ERA-Interim. Although the ERA products are known to perform better inland than coastal regions, it is currently one of the most accurate reanalysis products; ERA-5 reduced much of the cold coastal biases and therefore is used in this study (Tetzner et al., 2019). ERA-5 is used to compute the composite analysis for large scale circulation patterns: geopotential high (500 hPa and 850 hPa), moisture flux, and sea-level pressure.

2.2) Identifying extreme rainfall days

A total of 368 days' daily precipitation rate during the 2015-2018 summer (JJA) is computed and ranked. The climatology of daily precipitation is constructed first by daily computing averages, and then special attention is given to the coastal region of the highest amount of rainfall. From the climatology of the daily summer rainfall, we discovered an area with very high intensity – the CGAR region (31N to 36N, 80W to 72W). We then analyzed the causes of extreme precipitation in the CGAR region. Since the definition of extreme precipitation can be quite diverse, we here use the quantile of upper 10% daily rainfall in the CGAR region using a rain rate threshold of 480 mm-1 that some previous research work does (Rickenbach 2018). upper 10% daily rainfall corresponds to 480 mm/day. Moreover, choosing the top 5% or 1% as the criteria will not significantly change the overall results, we thus use the upper 10% to increase the significance.

2.3) Methods:

The composite analysis is carried out by using the climate reanalysis product of meteorological parameters from ERA-5. We analyzed the large-scale circulation pattern (geopotential high, and sea-level pressure). We obtain the precipitation data over the Southeastern part of the CONUS from MRMS. The archived data of MRMS is retrieved from Iowa University, and the climatology of the extreme precipitation is extracted by producing daily average rainfall. The mean daily rainfall is integrated using the 2-min interval product at the 1km × 1km spatial resolution.

The MRMS is chosen over the ERA-5 because the MRMS has better precision in the intricate features such as precipitation, and the ERA-5 has better performance in large scale circulation patterns than rain with more intricate spatial features (Fallah et al. 2019)

III. Results

3.1) Climatology of the summer precipitation over the Southeast coast region

Figure 1 shows the MRMS product 2015-2018 climatology of daily precipitation of the Southeast US. The coastal region (Gulf of Mexico) and Florida state experience a significant amount of rainfall (120 to 200 mmday-1), and the other part of the SE US also receive precipitation 40 to 120 mmday-1. What to notice is there is a CGAR region (31N to 36N, 80W to 72W) with substantial precipitation located at the North Carolina coast (with maximum mean daily precipitation 200 to 240 mmday-1) near the place of Outer Banks, and is within the Fishing region for the SE coast (South Atlantic Fishery Management Council 2020). The CGAR region is also located on the Gulf Stream and not far away from the shore.

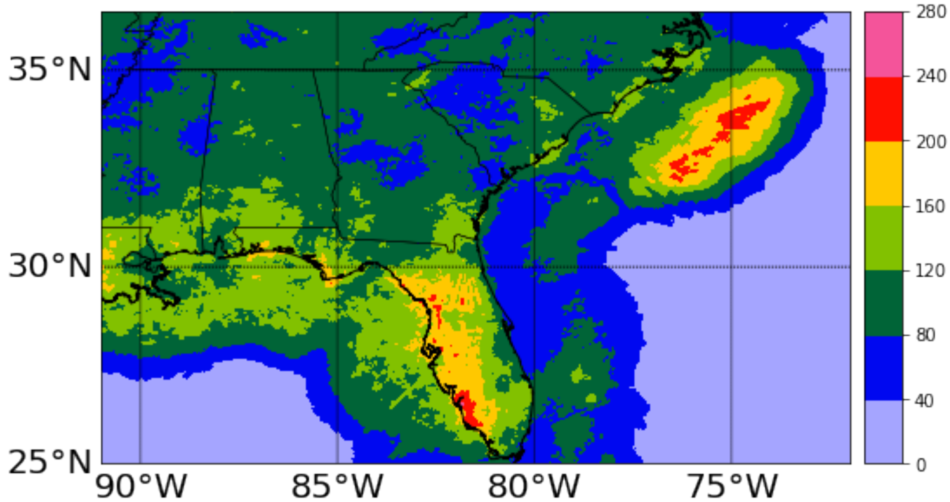

Fig1. the 2015-2018 climatology of mean daily total precipitation (mm day-1) of the SE US

Figure 2 shows the composite extreme rainfall event over the Southeast coastal region. Within the region, the strongest rainfall is concentrated in the CGAR region (lat-lat, longitude-longitude), with some precipitation along the Gulf Coast and the northeastern part of the US. The extreme precipitation in the CGAR region has a very high rain rate (600 mm/day to 1600 mm/day), 400% times higher than the precipitation rate in the CGAR region in the climatology analysis(Fig. 1). Compare to the climatology (Fig. 1), the area of the stronger rainfall region (Fig. 2) extends more towards inland, indicating more of the coastal region might be subject to extensive precipitation damage.

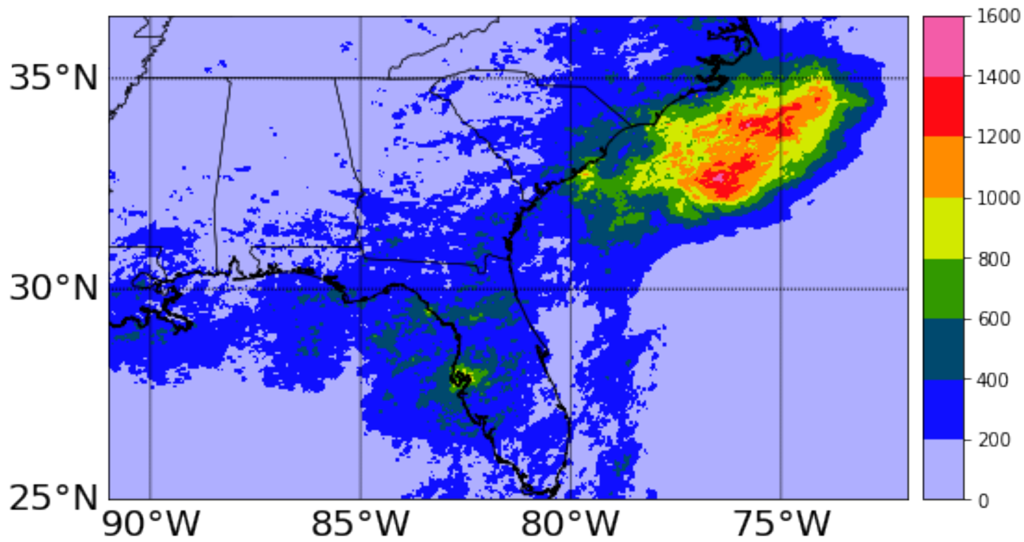

Fig2. The composite extreme rainfall event in the CGAR region. The extreme rainfall events use the average of upper 10% of all daily averages in the interested CGAR region. There are 37 cases in this composite analysis.

3.2) Large-scale conditions favorable to the extreme precipitation

The CGAR region is located in a position very close to the Gulf Stream. Extreme rainfall events around this region are usually caused by surface convergence and deep convection (Kuwano-Yoshida et al., 2010). Minobe et al. (2008) discovered the deep convection along the Gulf Stream, and the convection could extend to the upper troposphere. The surface convergence is likely to because of the sharp SST gradient near the CGAR region. Constructive atmospheric conditions for strong and deep convection events are usually associated with the presence of an upper-level trough and a surface low located to the east of the trough. When the surface low is located at the east of the trough and the west of the ridge, strong convection events associated with storms are likely to happen (UBC, 2019).

This research shows that the extreme rainfall in the CGAR region is likely to be caused by deep convection. Moreover, this study also suggests that the extreme rainfall events could be associated with a surface low and an upper-level trough, with the surface low positions to the eastern side of the upper-level trough to create a constructive situation. (Wirth and Riemer, 2018)

In this research, an upper level(500hPa) trough is discovered to the west of the CGAR region. Three different types of surface lows are also discovered CGAR region, each originated from different places and traveled to the CGAR region, creating an ideal condition for deep convection and extreme precipitation.

Fig 3 shows the composite analysis of the geopotential height at 500 hPa. We can discover an upper-level ridge in the eastern United States, and therefore indicates the eastern US might experience fine weather. What to notice is that an upper-level trough is presented at the over the eastern United States. The trough is the most distinct at 5680 geopotential meters, and it is located to the west of the CGAR region. This result indicates that the upper-level trough is presented at the ideal location and could be the cause of strong convection in the CGAR region.

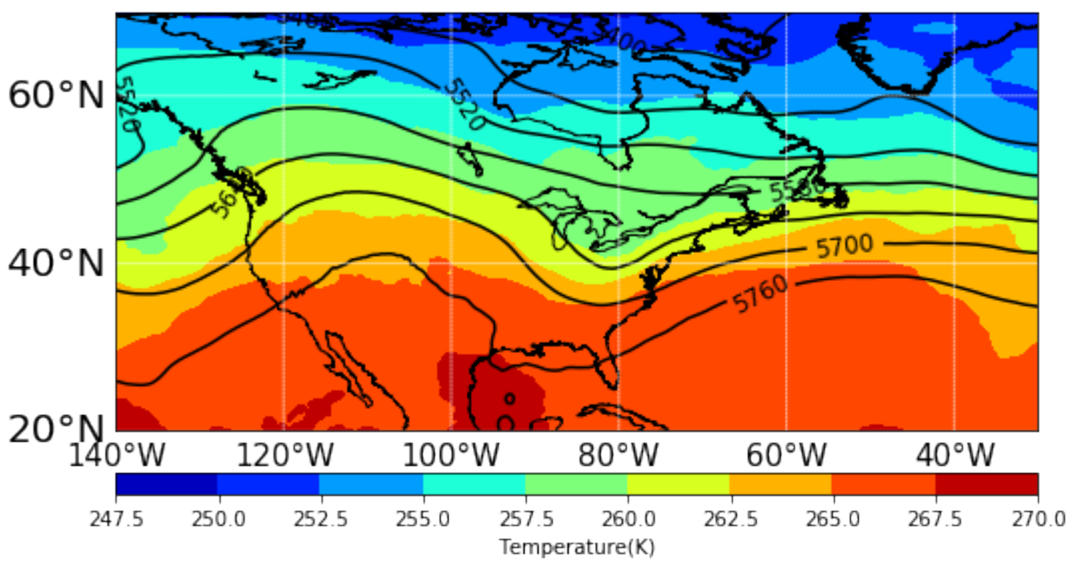

Fig 3. Geopotential height and the temperature plot at 500hPa, the black contour indicates the geopotential high, and the colored gradient indicates the temperature contours. An upper-level trough is discovered to the west of the CGAR region.

The next step is to find the surface lows. What is interesting is that the surface lows are also discovered too. According to detailed analysis, these surface lows move always move into the CGAR region and could cause extreme precipitation. The surface lows are classified into three major types that contribute to the extreme precipitation: The Continental Low, the Gulf Stream Low, and the Surface Low Belt. Table 1 shows the distribution of the three types of surface lows. With the Continental Low has the maximum amount of the cases (24), and the Gulf Stream Low has the second highest (10), the extreme precipitation is associated primarily with these two types of Surface Low. There is only one case of extreme events that are associated with the Surface Low Belt, and thus not a distinct feature in the CGAR heavy precipitation—shown in Fig4.a. The Continental Low is associated with a low system that travels across the US continent towards the east coast and intensifies as it reaches the coast into the CGAR region, further intensify as it moves northerly along the Gulf Stream (Colle et al., 2015). The Continental Low is also blocked by the high-pressure system that is at further north. This result agrees with Davis et al. (1993), stating some winter storms are also caused by Continental Lows that moves off to the east. Fig4.b indicates the Gulf Stream Low showing a surface low formed over the warm water of the Gulf Stream, and the closed surface low moves along the Gulf stream with faster speed than the Continental Low. Davis et al. (1993) show that the low formed by the Gulf Stream usually intensify along the coast due to the high baroclinity over the coastal region.

Classification	**Number of Cases**
Continental Low	24
Gulf Low	10
Surface Low Belt	3

Table1. Distribution of the three types of surface lows: The Continental Low, the Gulf low, and the Surface Low belt. Each case is examined and classified according to their trajectory.

Both surface lows move into the CGAR region, interacting with the upper-level trough (located at 500 hPa), and cause extreme rainfall. What to note is that two major surface lows also can coexist, for instance on June 6, 2016, there is a Continental Low traveling to the east, and a Gulf Stream Low travels to the north, and merged into the Continental Low at the CGAR region.

We also discovered that a deeper upper-level trough is associated with the Gulf Stream Low, and a shallower one is associated with the Continental Low. Fig 5.a and Fig 5.b show the composite geopotential high for the Gulf Low and the Continental Low, respectively. We can observe one upper-level trough located in the eastern US in each diagram. However, Fig5.a shows a deeper trough than Fig5.b. According to UIUC(2020), a deeper upper-level trough could relate to stronger cold and warm advection, which are correlated to the change of the sea surface temperature anomalies. Further researches can focus on the variation of the trough and types of the surface low and their potential relationship with the SSTA.

Fig 4.a

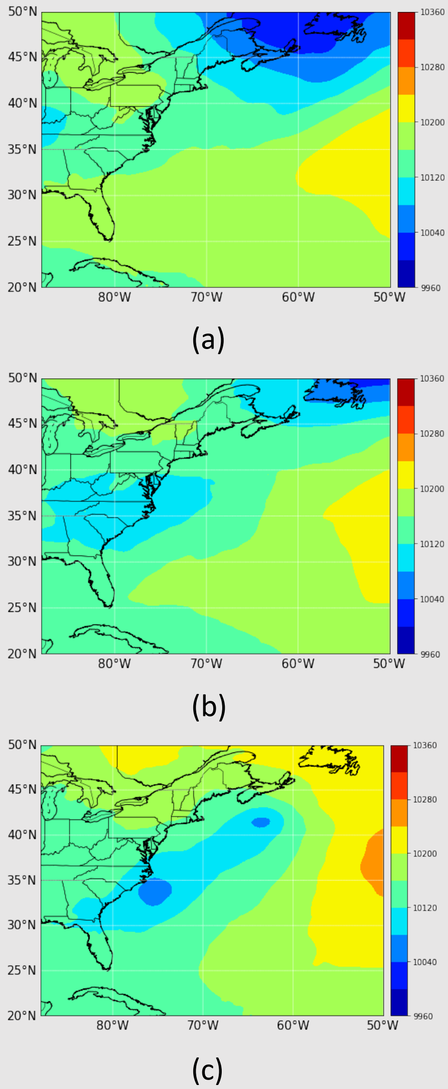

Fig4a. The pathway and progression of the Continental Low on (a) Aug 6th 2015 UTM 12:00:00, (b) Aug 7th 2015 UTM 12:00:00, (c) Aug 8th 2015 UTM 12:00:00;

Fig 4.b

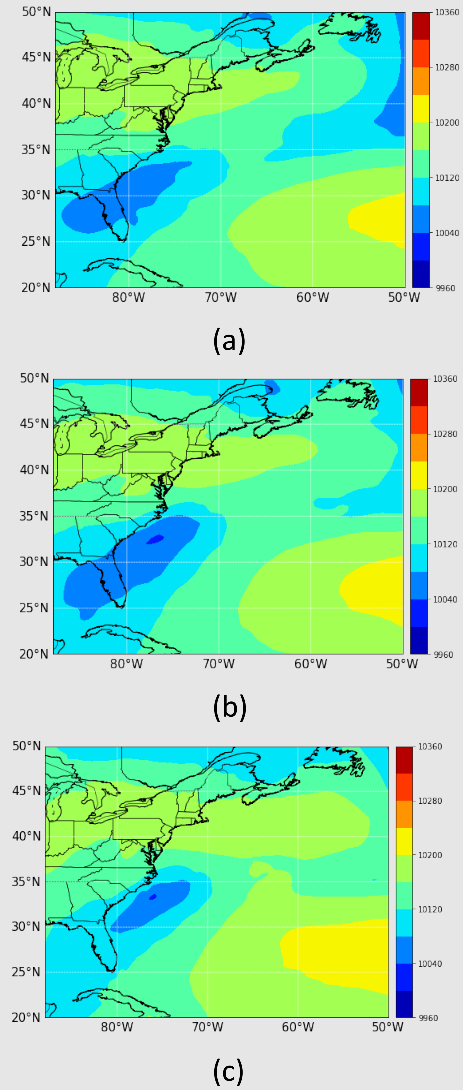

Fig4b. The pathway and progression of the Gulf Stream Low on (a) Aug 8th 2017 UTM 04:00:00, (b) Aug 8th 2017 UTM 14:00:00, (c) Aug 8th 2017 UTM 16:00:00

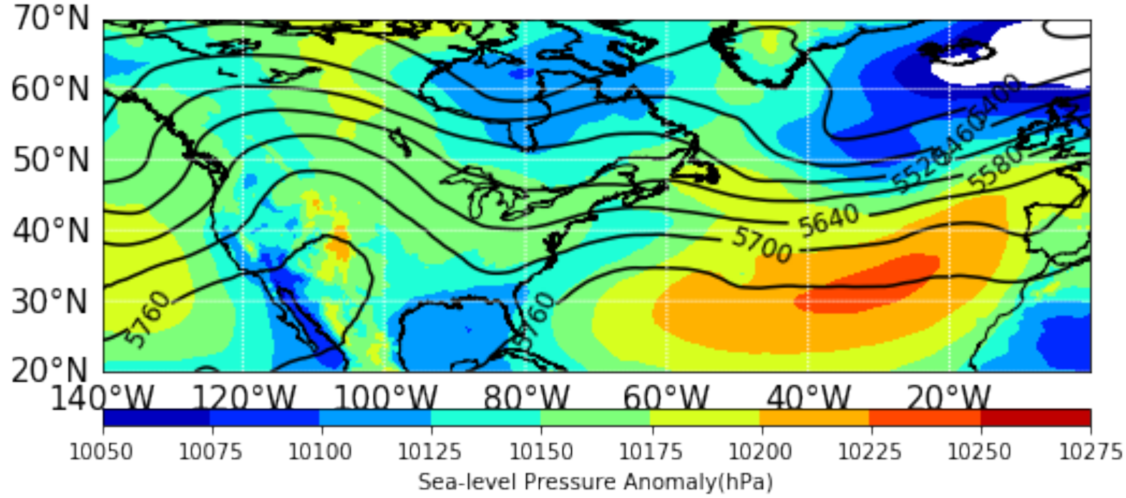

Fig 5.a The composite Geopotential height and the sea-level pressure anomaly plot for the cases of the Gulf Low(10 cases). The black contours indicate the geopotential height, and the color-filled gradient indicates the sea-level pressure anomaly plot.

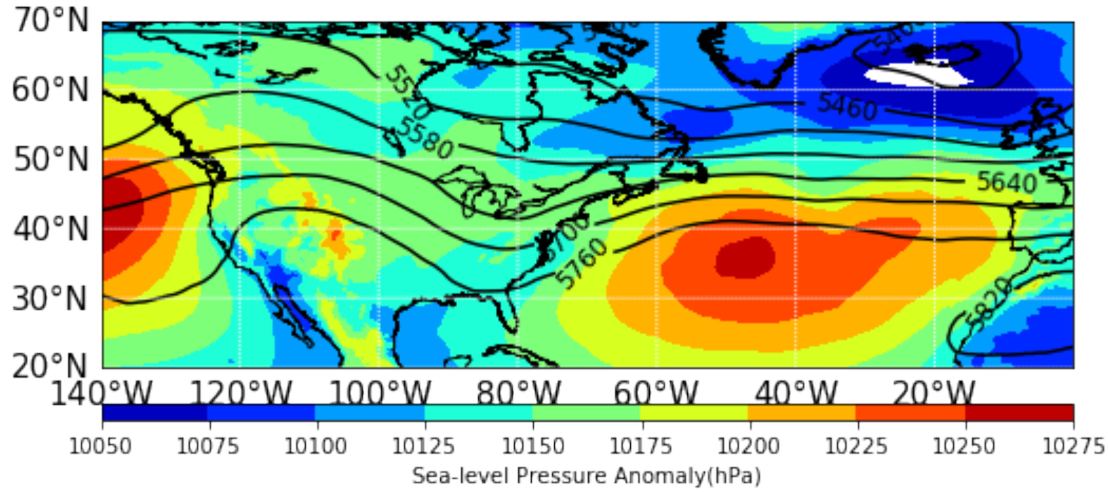

Fig 5.b The composite Geopotential height and the sea-level pressure anomaly plot for the cases of the Continental Low (24 cases). The black contours indicate the geopotential height, and the color-filled gradient indicates the sea-level pressure anomaly plot.

The winter precipitation at the US SE coast is also more associated with ENSO, and the extreme summer precipitation has less impact from ENSO and more from the summer North Atlantic Oscillation (SNAO). Research indicates that the El Nino winter storms by influencing the Gulf Coast to be cooler with more precipitation (NOAA, 2019). Due to the influence of the subtropical jet stream, there are more winter strong rainfall. While there is some researchers state that summer extreme precipitations are more impacted by the summer NAO and NAO instead of ENSO, but little research is conducted (Folland and Knight, 2008). Moreover, there are also researches showing that the Gulf Stream might change with the impact of ENSO, and the extreme summer precipitation might be affected as well (Taylor and Jordan, 1998). Further research might be beneficial to discuss the association between the extreme precipitation in the CGAR region and the summer NAO.

This research's result might be beneficial to improve the weather forecast in the CGAR region. Although Davis et al. (1993) do a similar research conducted on the coastal storms along the US east coast, and they discover that the storms in summer are mainly due to coastal fronts, their result does not necessarily apply to the cause of extreme precipitation in the CGAR region. The CGAR region's extreme precipitation, on the other hand, is most likely to be caused by the Continental Low and the Gulf Stream Low, according to this research.

IV. Conclusion

This research analyzed synoptic and large-scale key to the non-hurricane related extreme precipitation over the SE US during 2015-2018 using MRMS product and ERA-5 reanalysis data. A region (the CGAR region: 31N to 36N, 80W to 72W) has been found to experience extreme rainfall with 600mm/day and above. The extreme precipitation in the CGAR region is likely due to strong and deep convection. A suitable atmospheric condition is discovered, i.e., an upper level (500 hPa) trough and a surface low located to the east of the trough. Three types of surface lows are associated with the cause of this extreme precipitation, the Gulf Stream Low, the Continental Low, and the Surface Low belt. The first two types of low-pressure systems contributed to what percentage of deep convections. These results advance our understanding of extreme rainfall, which potentially improve weather prediction in the region.

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