AMAZON PLUME BARRIER LAYER STRUCTURE ANALYSIS AND ITS IMPACT ON HURRICANE INTENSIFICATION

A Dissertation

by

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ABSTRACT

The dissertation seeks to elucidate the interaction of Amazon Plume Barrier Layer (BL) with hurricanes using a combination of observational analysis and high-resolution regional coupled model simulations. Firstly, multiple observational datasets, including 905 qualified in-situ Argo floats and two shipment cruise datasets, were used to characterize the climatological spatial structure of the BL associated with the Amazon plume. BL is more prominent in the horizontal boundary region of the plume, where the horizontal salinity gradients are the greatest, than in the plume interior, where the freshwater volume is larger. That's because the strong stratification there could levitate temperature Mixed Layer Depth (T-MLD) to as shallow as the density Mixed Layer Depth (D-MLD). This process has been underestimated in the previous studies.

Then, 64 pairs of Argo float profiles coincident in time and space with the passage of a hurricane has been compared to examinate the relationship between SST cooling and BL thickness. Each pair captured the vertical profiles before and after each Hurricane arrival. Our analysis finds more evidence for reduced SST cooling due to the BL effect in the plume boundary region than in the plume interior, especially for slow-moving hurricanes. Also, the reduced cooling is seen mostly in the cool hurricane wake, reducing the possibility of a feedback on hurricane intensity.

In order to examine the direct feedback of the reduced SST cooling on Hurricane intensification. 21 Hurricanes were simulated by the Regional Coupled Earth System Model (RCESM) running at 10km spatial resolution, which has crossed over the Plume region. In addition to carrying out control simulations to reproduce the observed evolution

of hurricanes, two sensitivity simulations were carried for each hurricane case: a BL- simulation that eliminated the barrier by removing the freshwater; a BL+ simulation that enhanced the BL by adding more freshwater in order to check the saturation of the BL effect, and other conditions were kept the same (to the extent possible). Analysis of the suite of simulations shows that, for strong hurricanes, the model is able to simulate the reduced SST cooling due to the BL effect in the Hurricane cold wake. But the reduced SST cooling has only a modest effect on the hurricane intensity, because of the fast translation speed of the Hurricanes in the Plume region. The area-averaged SST cooling is observed near 0.1°C 12 hours after Hurricane passed by, by then hurricanes have moved 200-300km away, making it too late to have an impact. Moreover, the quantitively analysis shows that the Hurricane intensity measured by the Sea Level Pressure only changed 2 hpa, with a 0.1°C change in the SST.

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Contributors

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CHAPTER I

INTRODUCTION

Why are we interested in this research?

Hurricane Intensification

Hurricanes or tropical cyclones (TC) are one of the most destructive weather phenomena in the world. They form in the warm ocean and can be viewed as Carnot heat engines during intensification [Emanuel, 1986, 1988; Kleinschmidt 1951; H. E. Willoughby 1999]. Under favorable oceanic and atmospheric conditions, a hurricane could continue intensifying. For the oceanic part, the pre-existing high sea surface temperature (SST) in the warm ocean serves as an energy source, which affects the hurricane intensity via heat flux through the air-sea surface. For the atmospheric part, the latent heat can be transformed into kinetic energy, which drives a stronger hurricane wind, under the high humidity in the low troposphere and low wind shear conditions. Our research focuses on the oceanic part, in which the SST plays a crucial role in hurricane intensification. When constructing TC intensity forecast schemes, the theoretical and empirical relationship between SST and TC maximum potential intensity (MPI) needs to be taken into consideration [DeMaria and Kaplan 1994; DeMaria et al. 2005].

Besides the pre-existing SST before hurricane arrival, density-related stratification has been claimed to be effective at reducing the vertical mixing and SST cooling caused by hurricane wind [Cione and Uhlhorn 2003]. First, we need to understand the ocean's response to hurricane wind stress. The hurricane usually generates upper ocean near-inertial currents, enhanced vertical mixing, SST cooling and subsurface warming when the hurricane translation speed is higher than the first baroclinic wave speed. In other words, the slower the hurricane moves, the stronger the hurricane induced mixing, and the greater the SST cooling. The response is also affected by hurricane intensity, size, ocean stratification, upper ocean heat content, mixed layer depth and eddies [Zhang et al., 2021]. These upper ocean characteristics modulate the mixing process and SST cooling under hurricane.

Barrier Layer In Amazon Plume

Barrier Layer Definition and Introduction

The barrier layer (BL) has been widely used to explain the freshwater effect during air-sea interaction. BL, which is commonly caused by freshwater, is defined as the layer between the top of the thermocline (temperature mixed layer bottom) and the top of the halocline (density mixed layer bottom). The temperature inside the BL can be as high as the surface, and the strong salinity stratification contributes to the stability of the BL water column. Therefore, BL can be viewed as an insulating layer between the deep cold water and the surface warm water. Its effectiveness as a barrier is measured by its thickness [de Boyer Montégut et al., 2004,2007; Mignot et al. 2007].

The definition of Barrier Layer Thickness (BLT) is based on previous barrier layer studies [de Boyer Montégut et al., 2004,2007; Mignot et al. 2007]

$$BLT = D_{\sigma} - D_{T^{*}-02}$$

D_{σ} is the depth of density mixed layer (D-MLD), where the density has increased by the threshold value Δ_{σ} from the reference depth 10 m. Here, threshold value is defined as $\Delta_{\sigma} = \sigma_{\theta}(T^{*} - 02, S^{*}, P_{0}) - \sigma_{\theta}(T^{*}, S^{*}, P_{0})$, represents the density change of the water parcel when its temperature decreased by 0.2°C, while the salinity and pressure keep the same. D_{T^*-02} is the depth of temperature mixed layer (T-MLD), where the temperature has decreased by 0.2°C from the reference depth 10 m.

We could interpret the physical meaning of BLT as follows: it represents the salinity-caused mixed layer change. If the salinity is uniform in the upper ocean, the density profile would vary exactly the same as temperature profile, in that case, the density changes between $DT*-02$ and the reference depth would only depend on the potential temperature, namely, it's equal to $\Delta\sigma$. Therefore, with no salinity change in the upper ocean, T-MLD and D-MLD should be at the same depth, and BLT is zero.

Barrier Layer Distribution in Amazon River

The Amazon River has the largest freshwater discharge each year and its freshwater plume has been observed as far away as the Caribbean Sea near Barbados [Steven and Brooks, 1972], which lies under the North Atlantic hurricane tracks. Lagrange particle tracking observations to detect the advection of the Amazon-Orinoco Plume by North Brazilian Current showed that particles launched in the middle of June were advected partly northward and toward the Caribbean Sea after 2-3 months, and partly towards the Plume extension regions (13-18°N), where there is a persistent SST gradient and the largest freshwater amount in August each year, which is also a peak season for hurricane. The spatial and temporal overlap of the largest volume of freshwater in the Plume extension region with the paths of North Atlantic hurricanes has motivated many researchers to study the Plume.

The BL distribution in the Amazon Plume region is found to be uneven based on the climatological barrier layer thickness (BLT) distribution plot in [Mignot et al., 2007a]:

the BL appears deeper at the boundary than in the interior. It is worth noting that the interior has the greatest freshwater volume. This phenomenon has not been discussed before, especially during Summer, when hurricanes move over the Plume Boundary region.

BL intensities and locations are found to differ from Summer to Winter. The Climatological BLT from Argo dataset shows that the barrier layer phenomenon mainly exists during the winter, and is weak during the summer [Mignot et al., 2007]. During the winter, the maximum BLT exists within the Caribbean Sea (December, January) and at the mouth of the Orinoco and Amazon Plume. So, our research will focus on the BL distribution, and the formation mechanism during the hurricane season.

The Amazon/Orinoco Plume edge is described by the salinity value of 35.8 psu [Reul et al., 2014, S. Fournier et al., 2017]. Our study will use observational data to display the detailed horizontal distribution in the Plume extension region.

Even though the BL is found in many oceans across the world, the BL in the North Atlantic Warm Pool (NAWP-BL) is one of the most prominent BL features of the global tropics and persists all year long [de Boyer Montégut et al., 2007a], and is thus separated from western tropical Atlantic BL (5°N, 30-40°W). Moreover, the freshwater layer seems to play a role in hurricane intensification, in addition to the warm SST, over the Western Atlantic region. Model results show a significant statistical relationship between Atlantic hurricane intensification and SST increase (16% per 1°C increase). However, over the southeastern Caribbean Sea, the model's intensification prediction is lower than expected with the given SST [Fraza and Elsner, 2015]. That's the reason why we choose this region for our study.

Barrier Layer Formation Mechanism

In terms of the BL formation mechanism on the Northwestern Atlantic (NWAT) region, it has been widely acknowledged that the advection of the freshwater from the Amazon River plays a crucial role [Sprintall and Tomczak, 1992; Pailler et al., 1999; Masson and Delecluse, 2001; Mignot et al., 2007]. However, it involves different processes between winter and summer.

During the winter, the subduction of the high salinity waters under the freshwater at the subtropics explains the barrier layer formation in the NWAT. The subsurface salty water parcel is referred to as the "salinity maximum", which is generated from the subtropical high evaporation zones and flows southwestward into the Caribbean. The BLT is mainly controlled by the density mixed layer depth (D-MLD) change, which coincides with the maximum gradient in SSS, since temperature mixed layer depth (T-MLD) is deeper than 40 meters cross the whole Atlantic region as a result of strong wind mixing during the winter. This salty water mass raises the pycnocline and in that process results in thicker BLT (15-20 m) from the model study. As a result, SST increases about 0.1-0.2°C in the region of BL existing as a feedback [Balaguru et al., 2012].

However, during the summer, the shallow D-MLD comes from the advection of fresh water from the Amazon and the ITCZ area, by the North Brazil current, northward Ekman currents and anticyclonic eddies formed at the retroflection of the NBC [Pailler et al., 1999; Ffield, 2007]. Apparently, that is insufficient since previous research only explained the formation of D-MLD, but did not consider the T-MLD distribution, which is also different from that in the winter in the Plume and plays a crucial role in explaining the extraordinary BLT distribution during the Summer.

During the summer, the wind is not as strong as in winter. So, there is no deep T-MLD widely spreading the whole Plume region. Besides, it's highly possible that the freshwater will modify the upper ocean temperature as well as the T-MLD distribution, therefore forming the unique BLT distribution. In the freshwater Amazon/Orinoco Plume area, the upper 100 m water temperature is significantly warmer than non-Plume areas, due to the freshwater barrier layer effect of the Plume [Ffield (2007)]. We will check the vertical structure from the observational data concerning how the T-MLD and D-MLD vary in different regions and give a detailed explanation on the summer BL formation mechanism.

Considering the freshwater resources, net evaporation (E-P) associated with the migration of the Atlantic Ocean ITCZ and the Amazon/Orinoco River runout are the two main freshwater resources in the Atlantic equator region. During the winter and spring (Dec-May), the net evaporation maximum band is between 10-20°N, while the net precipitation maximum band is between 0-10°N. Both are over 2000 mm/yr. therefore, forms a strong meridional SSS gradient between the two bands. Since the maximum BLT exists in the evaporation band, horizontal advection is required for the freshwater supplement to form an isohaline layer above the isothermal layer in the subsurface of this region. Therefore, the water resource of the BL formation is still mainly the Amazon and Orinoco River outflow. It's found that the northward advection of freshwater flux is maximum at 10°N [Schmitt et al., 1989]. This transportation is carried by the Atlantic South Equatorial Current (SEC) which extends northwards, and later converges with the Atlantic North Equatorial Current (NEC). In all, in the region of BLT maximum, we could summarize that the salinity profile distribution is caused by the three effects: surface evaporation, subsurface horizontal advection and salinity maximum subduction from the subtropical ocean [Sprintall and Tomczak, 1992, Newmann 1969]. During the Hurricane season (Jun-Nov), the bands of maximum evaporation and precipitation migrate northward. There is more precipitation to offer freshwater to the BLT formation on the surface.

Effects Of Barrier Layer on Hurricane Intensification

When it comes to oceanic effects on hurricane intensification, it's widely accepted that there is a significant relationship between the pre-existing SST (which serves as the energy source) under the hurricane path and the hurricane strength [Malkus and Riehl 1960; Emanuel 1999; Holland 1997]. BL can provide a higher pre-existing SST condition before hurricane arrival. That's because with the existence of BL, there is a stronger stratification which could block the mixing of cold water from below and the upper ocean retains heat from the summer strong solar radiation, forming a significantly warmer upper ocean temperature. We refer to this as the *pre-heating* effect of BL in our research.

Besides the pre-existing SST, how the SST response to the hurricane mixing during its passage is also an important topic. Features, such as deep BLT, high ocean heat content or Tropical cyclone heat potential (TCHP) [Potter et al., 2019], fast hurricane translation speed [Lin et al., 2017], are considered as favorable for hurricane intensification. Among them, BL is claimed to increase stratification and stability within the mixed layer, thus reduce hurricane induced vertical mixing and SST cooling and help maintain high SST during hurricane passage, and therefore provides higher energy for hurricane intensification, especially for the intense hurricanes [Balaguru et al., 2012]. We refer to this as the blocking effect of BL in our research.

There are three important scientific questions unaddressed in terms of the BL effects:

First, observational studies confirm that the Plume with the BLT (stable halocline) could inhibit cooling and vertical mixing of hurricanes. During hurricane Katia, the Argo profile shows the mixed layer depth barely changes due to the Plume BLT in the Plume region, while mixed layer deepens heavily outside the Plume [Grodsky et al., 2012]. However, later Hernandez et al. (2015) argued that this different cooling result is because of the different wind strengths. During hurricane Igor, nearly 25 m thick BL is detected before the storm passage, located in the central part of the Plume northwestern extension, and the vertical mixing depth stays almost the same during hurricane passage, while it deepens greatly due to the hurricane wind in the no-BLT region. From the satellite product results, the cooling effect for the most intense storms is seen to be systematically reduced by nearly 50% over the Plume area where this is a strong salt-driven vertical stratification and BL, compared with that over the open ocean during 1998-2012 [Reul et al., 2014]. More prior studies with numerical model simulation will be discussed in the following section.

However, even though it can be proved that BL is able to reduce SST cooling efficiently, we still need a confirmed relationship between the reduced SST cooling and further hurricane intensification. It's highly possible that the oceanic feedback through the heat flux will have little impact on a fast translation speed hurricane, which has already moved out of the BL affected region. So, in this case, the reduced cooling effect of BL doesn't make a difference to further hurricane intensification, and only the pre-existing SST condition matters as an energy source.

The second scientific question is that even though the observed hurricane intensity is stronger in the BL region than in the no-BL region, we want to separate BL's mixing inhibition effect from its pre-heating effect. Previous statistical and observational studies have not clearly addressed this problem, as they did not compare the two effects while taking into account that both the temperature and density vary in different observed locations. So, we have to use a numerical model to modify density profile, artificially changing the stratification in the upper ocean, while keeping temperature profile the same.

The last scientific question is to quantify the effectiveness. This could also be fulfilled by running a series of numerical model simulation experiments: modify the BL structure in the model initial condition and record how much the degree of hurricane intensify has been changed.

Scientific Objectives and Dissertation Layout

To summarize the above discussions: there are three Amazon Plume BL related topics that need systematic study:

The first is to reconstruct the BL horizontal distribution in the Amazon Plume region during hurricane season and better understand its formation mechanism during summer.

In the second chapter, we will analyze multiple observational datasets (from satellite, Argo floats and ship observations) to reconstruct the vertical and horizontal BL structures. First, describe the horizontal BLT distribution and give a clear definition of "Plume Boundary" and "Plume Interior" by their sea surface salinity (SSS) derived from climatological reanalyzed Argo datasets and SMOS satellite datasets. Second, composite vertical profiles in Plume Boundary and Plume Interior from in-situ Argo floats, to describe the temperature and salinity structure in the upper ocean, as well as the D-MLD and T-MLD value in each region. With a clear vertical and horizontal structure, we can further explain the BL formation mechanisms.

The second objective is to study the effect of the freshwater in Amazon Plume extension region on hurricane intensification. I will split this topic into two chapters. The chapter 3 will show the effect of freshwater with observational and statistical results.

In chapter 4, numerical model simulations will be used with a series of sensitive experiments in our research with Regional Community Earth System Model (RCESM). There are three important questions to be answered:

1. Will BL/freshwater cause a reduced SST cooling?

2. If yes, will the reduced SST cooling improve further hurricane intensification? In other words, when is the reduced SST cooling happening after hurricane passage? Is it out of the hurricane coverage region?

3. If yes, give a quantitative analysis on how much the intensity increases per degree of reduced SST cooling.

CHAPTER II

BARRIER LAYER DISTRIBUTIONS FROM OBSERVATIONS

Introduction

Observational Datasets

In this chapter, we will use multiply observational datasets to reconstruct the Amazon Plume, including the observational sea surface salinity (SSS) from Satellite SMOS, SST from OISST, gridded BLT derived from Argo datasets,, in-situ Argo profiles which carries temperature and salinity, cross-section of oceanic vertical structure from CTD cruise datasets.

Observed sea surface salinity data is from Satellite SMOS (ESA's Soil Moisture Ocean Salinity) [SMOS Team, 2014], the satellite could capture 50 km horizontal resolution images, and over oceans, SMOS could describe the salinity by 0.1 psu of 10-30 days running mean. The SMOS satellite was in mission from November 2009 through 2017. The data we use is the global monthly SSS from 2010 to 2016 with the spatial resolution of 0.5 degrees.

The observational SST data is from Optimum Interpolation Sea Surface Temperature (OISST) [Gentemann, C. L. et al, 2004] from www.remss.com. The data is observed by satellite microwave radiometers at a 25 km resolution which owns the through-cloud capabilities, and was optimally interpolated (OI) into a regularly gridded space. The data is available from 1998 to 2020 in a spatial resolution of 1/4 degree, and a time resolution of daily.

The global BLT climatology dataset is produced by de Boyer Montégut et al. 2007 and Mignot et al. 2007, which is gridded into the 0.2 degree × 0.2 degree spatial resolution, and monthly time resolution. The original data resources are from instantaneous temperature and salinity profiles collected from 1961 to 2008, and gathered by National Oceanography Data Center (NODC-WOD2005 (CTD)), World Ocean Circulation Experiment (WOCE) database (Global Data Version 3.0 (CTD, PFL)), and Argo (until Sep. 2008). The climatological BLT data is averaged from the individual BLT in each profile, therefore has more ability to capture the detailed and realistic signals at stake. The only deficiency is that it was only updated to 2008, without integrating the recent 10 years in-situ database (Argo) inside. Therefore, we will update their data in our research.

Historical in-situ temperature and salinity profiles we use are from the Argo dataset, available via the Global Data Assembly Centers (GDACs), which covers the period 2000-2019 [Argo 2000; Argo 2020]. We collected all available profile data within the Plume region but out of the Caribbean Sea (64– 40°W; 0–25°N), and we only selected profiles with SSS< 36 PSU, which are related to the freshwater region. Besides the Argo floats, the datasets also integrated in situ data profiles from WOD (the World Ocean Database), which are collected from Ocean stations, high and low-resolution CTD (Conductivity-Temperature-Depth), moored buoys, drifting buoys, and gliders.

CTD cruise datasets have been used to fully reproduce the observational 2-dimensional cross-section crossing the Plume interior and boundary along the cruise track. The CTD dataset is from CLIVAR and Carbon Hydrographic Data Office (CCHDO) https://cchdo.ucsd.edu/. The dataset is a collection of the observational physical characteristics of ocean, including real-time pressure, temperature, conductivity/salinity and dissolved oxygen, provided by WOCE, CLIVAR and numerous other oceanographic research programs (GO-SHIP, SOCCOM, USHYDRO, DIMES, ELLETT) in decades. Two cruises chosen are CLIVAR A22 [Curry, R. 2012], and AR04 [Rhein, M. 2005].

Besides the observational datasets, Simple Ocean Data Assimilation (SODA) datasets [Carton, J.A. and B. Giese, 2008; Carton, J.A. et al., 2000] serve as the supporting material to display the spatial distributions of the upper ocean characters, such as TCHP and T-MLD.

Methods

For in-situ data profiles, we removed the low-quality data and only picked the peak hurricane season (Aug, Sep, Oct) profiles. We end up with an ensemble of 931 qualified profiles in the region of our interest. For each profile, we did the depth interpolation from the original interval to the 5 meters interval depth in the upper 100 meters. Considering the large measurement error in the upper 10 m, we consider SSS and SST as temperature and salinity at the first 10 m below the surface.

The tropical cyclone heat potential (TCHP) could represent upper ocean heat content in terms of Hurricane, measuring by integrating the temperature from the surface to the depth of the 26°C isotherm. The high TCHP is viewed as the incubator for sudden intensification of TCs [Shay et al. 2000, Maineli et al. 2008, Potter et al., 2019].

$$Q = c_p \sum_{z_0}^{z_{26}} \rho_i (T_i - 26) \Delta z_i$$

Where $c_p = 3.85KJ/(kgC)$ is the heat of seawater, Δz_i is the thickness in depth between z_i and z_{i-1}. T_i and ρ_i are the water temperature and density at the i-th depth.

The peak hurricane season is defined as August, September and October since hurricane numbers are more than other months, according to the monthly distributions in the West Atlantic region.

Results

Climatological Barrier Layer by gridded Argo dataset

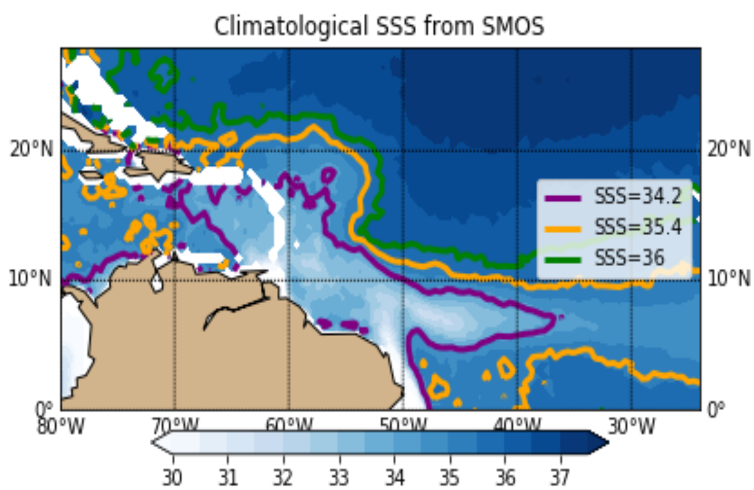
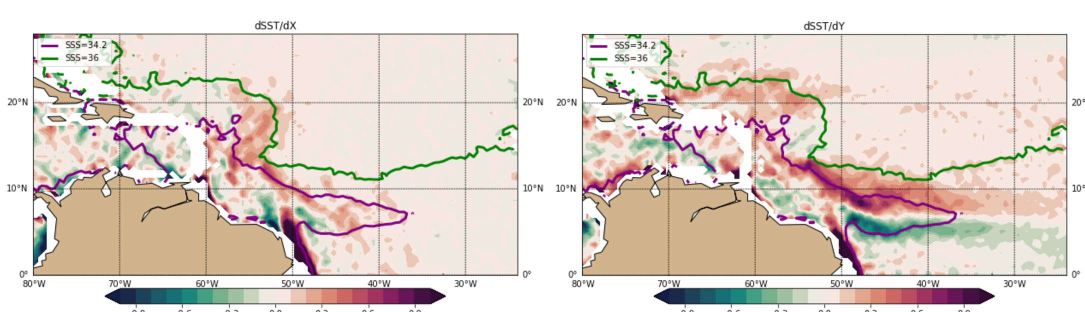


Figure 1. SSS distribution from Climatological SMOS dataset averaged of Aug, Sep and Oct, with the definition of the boundary band.



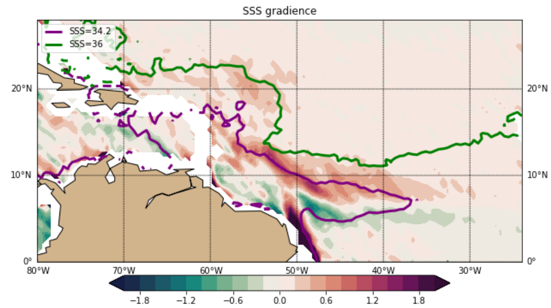


Figure 2. SSS gradients distribution from Climatological SMOS dataset averaged of Aug, Sep and Oct; (a) zonal SSS gradient (b) meridional SSS gradient (c) total SSS gradients (unit of psu/10km). All overlaid by the boundary band contours.

The Plume Boundary has been defined as the band where the SSS is between 34.2 psu to 36 psu (Figure 1, purple and green lines), instead of a single contour (Figure 1, orange line) that SSS equals to 35.4 psu which has been widely used [Ffield, A. 2007; Rudzin et al., 2016], because the shape of Plume would vary a lot by using different SSS datasets if the boundary is just defined by a single line. For example, from the climatological SMOS data (Figure 1), the SSS=35.4psu contour, which is the popular Plume edge definition, failed to describe spatial shape of the Plume by covering most of the tropical Atlantic area. On the contrary, the boundary band could describe the Plume Boundary shape very well. 36 psu isohaline could describe the outer boundary of the Plume and separate the fresh water from the saltier water in the Atlantic, and 34.2 psu isohaline could show the structure of Plume on the west of the Plume inside the Caribbean Sea.

Secondly, consider the boundary as a region since it enables us to analyze the unique structure and dynamic process in the boundary, such as the mixed layer and barrier layer structure, which might be different from those in the Plume interior shown later. Moreover, horizontal and vertical advection processes might also be different from those in the Plume interior, since the SSS gradient has been shown the largest in the Plume boundary we defined, namely the isohaline range from 34.2 psu to 36 psu (Figure 2). More specifically, the largest zonal gradient is in the box of (51-56°W, 13-18°N) in Figure 2a, and the largest meridional gradient is in the box of (63-52°W, 18-24°N) in Figure 2b. Those SSS front characters have also been mentioned by 2012 Katsura et al., 2015; Fournier et al., 2017. This feature along with its generated dynamic processes were also beyond a single line could describe.

Furthermore, in order to count the Argo floats later, "Plume Boundary" region has been confronted into two boxes: (51-56°W, 13-18°N) and (63-52°W, 18-24°N) (Figure 10, yellow box). Regions where the SSS<34.2 psu are defined as the "Plume Interior", Similarly, the Plume Interior was described as the boxes: (56-63°W, 13-18°N) and (45-63°W, 0-13°N) (Figure 10, yellow box).

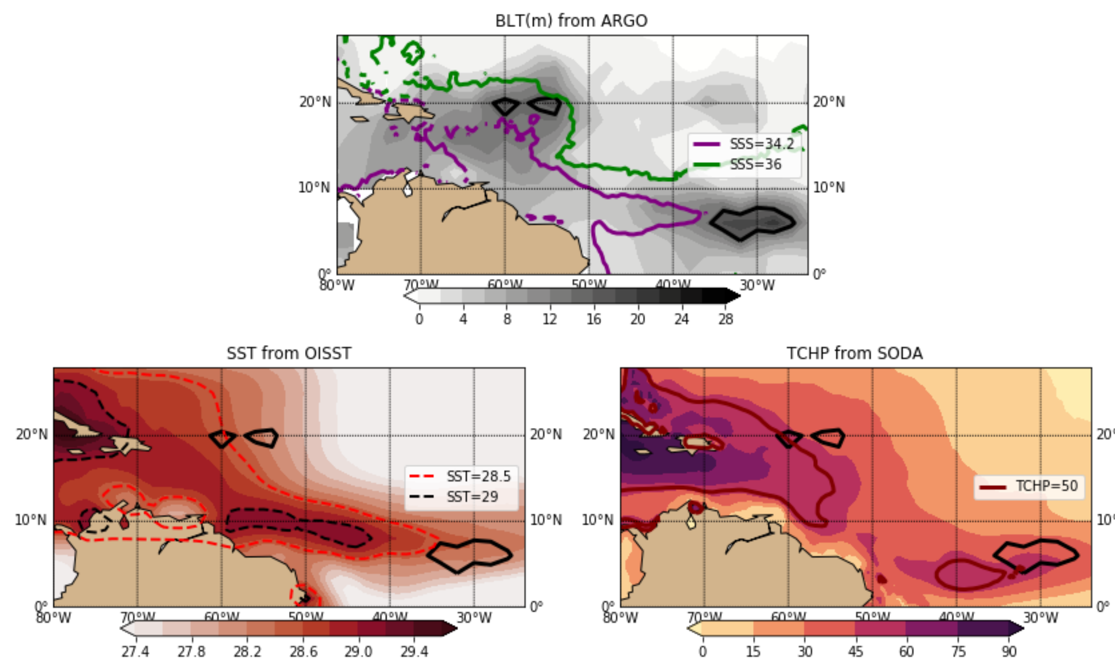


Figure 3. Aug, Sep and Oct Climatological mean of each variable from different data resources: (a) Barrier layer thickness (BLT) from Argo gridded dataset overlapped by Plume Boundary SSS contours

(34.2 and 36 psu). (b) SST from Climatological OISST. (c)TCHP from SODA. The black solid contours show the BLT maximum region where BLT=15m in (a-c).

Comparing the BLT distributions with SSS horizontal distributions shown in Figure 3a, it seems that the BLT maximas (BLT>15m) fall within the Plume Boundary defined by the band where SSS is between 34.2 and 36 psu, instead of within the Plume Interior where the freshwater volume is greatest. To be more specific, they are on the "tongue" of the Plume, where the freshwater extends into the open ocean. As part of the Amazon freshwater is driven eastward by the shedding North Brazilian Current Rings [Korosov, A. et al., 2014; Reul et al., 2009], forming the first BLT maxima region around (5°N, 30°W), the center of which could be as strong as 25m climatologically. However, it's not under the hurricane track region since the latitude is less than 10°N, where the Coriolis force is not considered strong enough to generate hurricanes. Another part of the freshwater is driven northward to the Caribbean Sea by the North Brazilian Current, forming the second BLT maxima around (20°N, 53-63°W) high as 15m. In both regions, the current direction is perpendicular to the boundary, forming the freshwater front, which was considered essential to BL formation in the Pacific Ocean [Katsura et al., 2015]. Considering it is the climatological mean BLT, the magnitude is reduced by the averaging. Nevertheless, we can still capture the BLT distribution feature over the Plume region during the summer season (Aug, Sep, and Oct).

Our results differ from previous studies, which have argued that the barrier layer is caused by the freshwater output from the Amazon and Orinoco rivers [Ffield et al., 2007], therefore should be thickest where the most freshwater is present, namely the

Plume Interior. In the following sections, we will discuss the formation mechanism of the strong BL in the Plume Boundary by comparing vertical profiles there to those in the Plume Interior.

The maximum BL locations are located away from the high SST region and high ocean heat content region (Figure 3bc), while the SST and Ocean heat content (OHC or TCHP) are also important in this region, because they have been claimed as key factors for hurricane intensification [Leipper and Volgenau, 1972; Shay et al., 2000; Wang et al., 2018; Potter et al., 2019]. Therefore, we can isolate the effect of BL from the effects of SST and TCHP in this region when explaining its effect on hurricane intensification.

The area to the west of 63°W is out of consideration in this paper, because there is no significant horizontal SSS gradient. More importantly, it's inside the Caribbean Sea, where its TCHP or ocean heat content is significantly higher (>60 KJ/cm^2) than other Plume regions (Figure 1d). Since TCHP also plays an important role into the hurricane intensification, it's hard to separate the effect of BLT with that of TCHP in this region from an observational analysis viewpoint.

Barrier Layer by individual Argo floats profiles

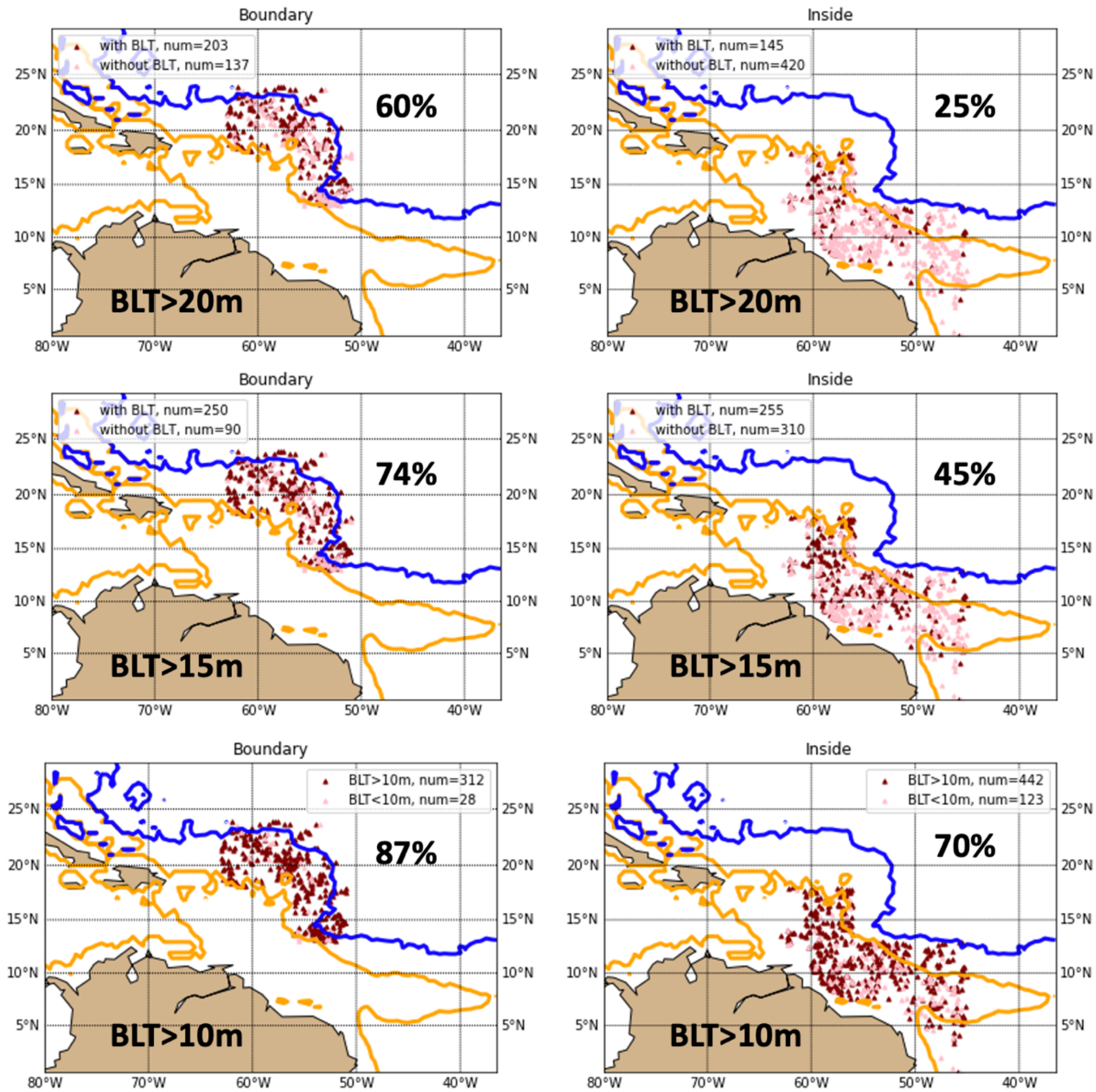


Figure 4. The total Argo floats distributions on the climatological SSS in the Plume Boundary (a) and the Plume Interior (b) from 2000 to 2019. The maroon color means the BLT of the profile is greater than different criteria (20m, 15m, 10m). The pink color means the BLT is less than the criteria.

Since we have already noted that the BLT on the Plume Boundary is greater than that inside the Plume based on the climatological BLT dataset, we now analyze the BLT distribution with the in-situ Argo profile data in order to confirm this conclusion from the individual profile perspective. Overall, there are 905 qualified Argo profiles found over those two regions during peak hurricane seasons (Aug-Oct) from 2000 to 2019. Argo floats are separated into two regions based on their locations: there are 340 qualified Argo profiles in the Plume Boundary region (Figure 4a), though the SSS of the individual Argo profile doesn't necessarily fall into the boundary definition; there are 565 qualified Argo profiles in the Plume Interior region (Figure 4b). Here, the "qualified" means removing outlier data which may come from observational errors, as explained in the methodology section. In order to classify the location of the Argo profile, the definitions of the boundary and interior are simplified into boxes: (51-56°W, 13-18°N) and (63-52°W, 18-24°N) as boundary, while (56-63°W, 13-18°N) and (45-63°W, 0-13°N) as Plume Interior as mentioned before.

	BLT >20m counts (proportion)	BLT>15m counts (proportion)	BLT>10 counts (proportion)	Total counts	Averaged BLT
Plume-Boundary	203 (60%)	250 (74%)	296 (87%)	340	21 m
Plume-Interior	145 (25%)	255 (45%)	397 (70%)	565	13 m
Total	348 (38%)	505 (56%)	693 (77%)	905	

Table 1.BLT>20m/15m/10m counts and their proportions to the total counts in two regions

Then, the number and proportion of the profiles which its BLT meet different criteria have been counted. For example, in Table 1, "BLT>20m counts" means the number of profiles that have a BLT greater than 20 meters; The proportion of profiles having a BL greater than the criteria among all profiles in each region, called "proportion".

The results in Table 1 show that BLT is stronger on the Northern boundary than that inside the Plume based on all three different critical values chosen, namely 15m, 20m or 10m. It shows that 60% (203 out of 340) of the profiles in the boundary have a BLT greater than 20m, while only 25% (145 out of 565) of the profiles are in the Plume Interior. Similarly, there are 74% profiles with a BLT greater than 15m on the boundary, while only 45% in the interior. And 87% versus 70%. Therefore, the BLT proportions are greater on the boundary in different scales.

Besides the proportion, the averaged BLT for profiles in the Northern boundary domain is 21.2 m, while the averaged BLT inside the Plume is only 13.2 m.

Overall, the BLT distribution derived from the Argo float profiles proves that the averaged Barrier Layer is stronger in the boundary than that is inside the Plume, which is consistent with the conclusion from the climatological dataset.

Barrier Layer formation mechanisms with Argo vertical profiles

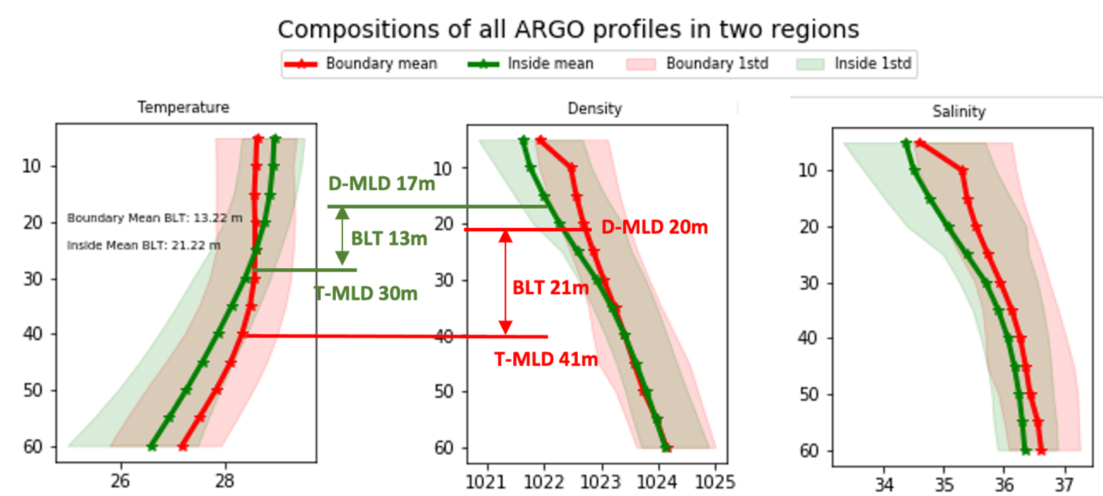


Figure 5. The profile compositions in two regions. (a) Temperature profile, (b) Density profile, (c) Salinity profile, Mean of Aug, Sep, Oct. The shading shows one standard deviation range. D-MLD: density mixed layer, T-MLD: The Averaged temperature mixed layer. The MLD & BLT are calculated of each profile first and then averaged.

Mignot, J. et al. [2012] explained the BL formation mechanism in the summer as follows: freshwater discharge thins the mixed layer, so that intense radiative heat flux can penetrate below and warm the mixed layer, therefore induce a barrier layer between the deep temperature mixed layer and shallow freshwater-induced density mixed layer. However, our observation result shows that the T-MLD (20m) seems as shallow as the D-

MLD (17m), resulting in a thin BL (13m) in the Plume interior region, while the T-MLD is deep as 41m in the Plume boundary.

T-MLD and D-MLD for each profile are calculated and then averaged for two regions respectively (Figure 5).

Firstly, averaged D-MLDs in two regions are found both very thin (interior: 17 m and boundary: 20 m), even though the average salinities show a significantly difference (Figure 5c), with solid green line lies outside of one standard deviation of the red line. That is because the definition of the D-MLD requires a density difference of ~ 0.07 kg/m^3 between the density at the D-MLD and the reference depth (10m), which could be easily achieved by a ~0.1psu salinity difference considering the constant temperature of 28.5°C. From the in-situ Argo profiles, the vertical salinity varies a 0.1psu within upper 20m in the Plume boundary, which easily levitate the D-MLD to above 20m. Similarly, the averaged salinity varies 0.1 psu within 17 m in the Plume interior. That is to say, given the relatively lower freshwater volume in the boundary, it could still trigger a halocline (pycnocline) ranging 0.1 psu in the upper 20m.

However, considering the solar radiation penetrating through the upper ocean part, there is a large difference (>10m) between the interior and boundary. The averaged T-MLD on the boundary is 41m while it's only 30m in the interior. The previous study argued that the T-MLD reached around 40m across the Plume region because the penetrative flux (0.6°C/month) exceeds the subsurface temperature increase rate (0.5°C/month) from July to October [Mignot et al., 2012]. However, our result shows that it's only true on the boundary where the freshwater volume is lower, but not the case in the Plume Interior, where the larger volume of freshwater will levitate the T-MLD.

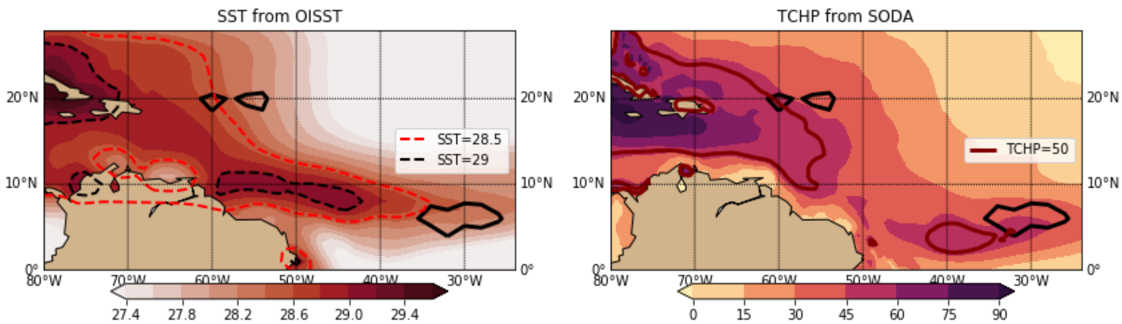


Figure 6. Aug, Sep and Oct Climatological mean of each variable from different data resources: (a) SST from Climatological OISST.(b) TCHP from SODA.

There are two characteristics of the freshwater which could reduce the T-MLD from deepening in the Plume interior region: stratification and ocean color.

One is that with fresher water floating near the surface, the upper ocean turns into more stratified in the interior region. It's harder for the upper ocean to undergo turbulent mixing. Another reason is that the Amazon Plume is turbid and mixed with sediments, colored dissolved organic matter, and phytoplankton [Hu et al., 2004; Smith and Demaster, 1996], which are all light absorbing particles. Those particles will make the Solar radiation absorption depth shallower [Denman, 1973; Ohlmann et al., 1996], and therefore trap heating near the surface. Two effects combined together form extremely high SST but colder subsurface, therefore a shallow T-MLD.

This could be demonstrated by the spatial distribution relationship between SST, T-MLD, and TCHP and SSS. The SST tends to be warmer in the Plume Interior where freshwater volume is greater. For example, the Atlantic Warm Pool (defined by SST > 28.5°C) shape is highly overlapping with the Plume Interior shape, especially the SST >

29°C is right at the same location the greatest freshwater volume exists (Figure 6a). The freshwater provides higher SST because of continuous solar radiation heating over the strong stratified upper ocean caused by the freshwater were also described in the previous papers [Pailler et al., 1999; Foltz and McPhaden, 2009; Ffield, 2007].

On the other hand, the reduced mixing in the stratified upper ocean will lift the mixed layer depth (MLD) to shallower depth. The TCHP, which is calculated by integrating the temperature from the surface to 26°C isothermal, is observed lower (<50 KJ/cm^2) in the Plume center than that in the surroundings (Figure 6b). It seems that the freshwater layer will reduce the upper ocean heat content overall while heating up the surface.

In a conclusion, we propose one mechanism to explain how the BL forms as follows: in the Plume Interior, the freshwater volume is extremely large that it not only levitate the D-MLD to 20m, but also modulate temperature profile and shallow the T-MLD by providing stronger stratification and higher solar radiation absorption rate near the surface. However, on the boundary the freshwater volume is not large enough to generate a strong stratification. Nevertheless, it still shallows the D-MLD since the salinity differences required within the D-MLD is only 0.1 psu, which is easily to be achieved in the Plume boundary.

In a word, the different freshwater volumes make no difference in modulating D-MLD, but a great difference in levitating T-MLD. The temperature profile seems to be more essential in determining the BL formation in the whole Plume region, but not the salinity as claimed before. We will show further details from the observational Argo float and CTD shipment datasets.

CTD cross-section ocean profile

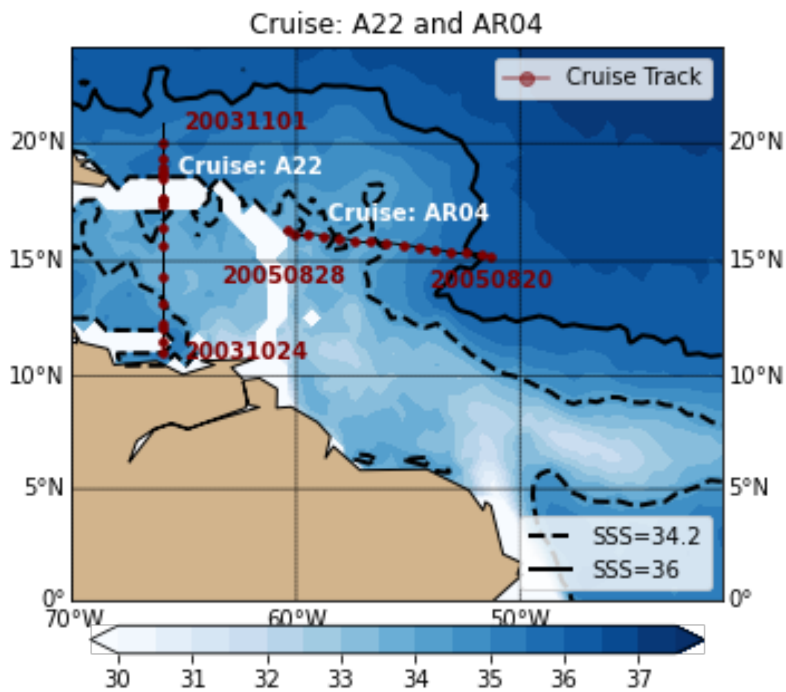


Figure 7. Two cruise tracks in maroon dotted line, marron texts are cruise start dates and end dates. Overlaid on the climatological SSS from the SMOS dataset. Black lines indicate the climatological Plume Boundary.

In order to show the Plume structure observationally, as well as barrier layer and temperature inversion features, we have analyzed two cruise datasets: one cruise is from the Western Atlantic Ocean which sailed across the Plume Boundary meridionally towards the Belem coastline, and lasted from Oct 14th 2003 to Nov 1st 2003, finally crossing Northern Plume Boundary. It captures the Plume Interior and boundary profiles since the cruise has crossed from 11 to 21°N in latitude: 13-17°N is in the Plume Interior, while 17-22°N resides on the boundary. The second cruise sailed from the Western Atlantic

Ocean approaching to the Caribbean Sea crossing the Eastern Plume Boundary horizontally during Aug 20th 2005 to Aug 28th 2005. It captures both the Plume Interior (56-61°W) and Plume Boundary (52-56°W) vertical structures. Then, the vertical cross-sections are shown as follows.

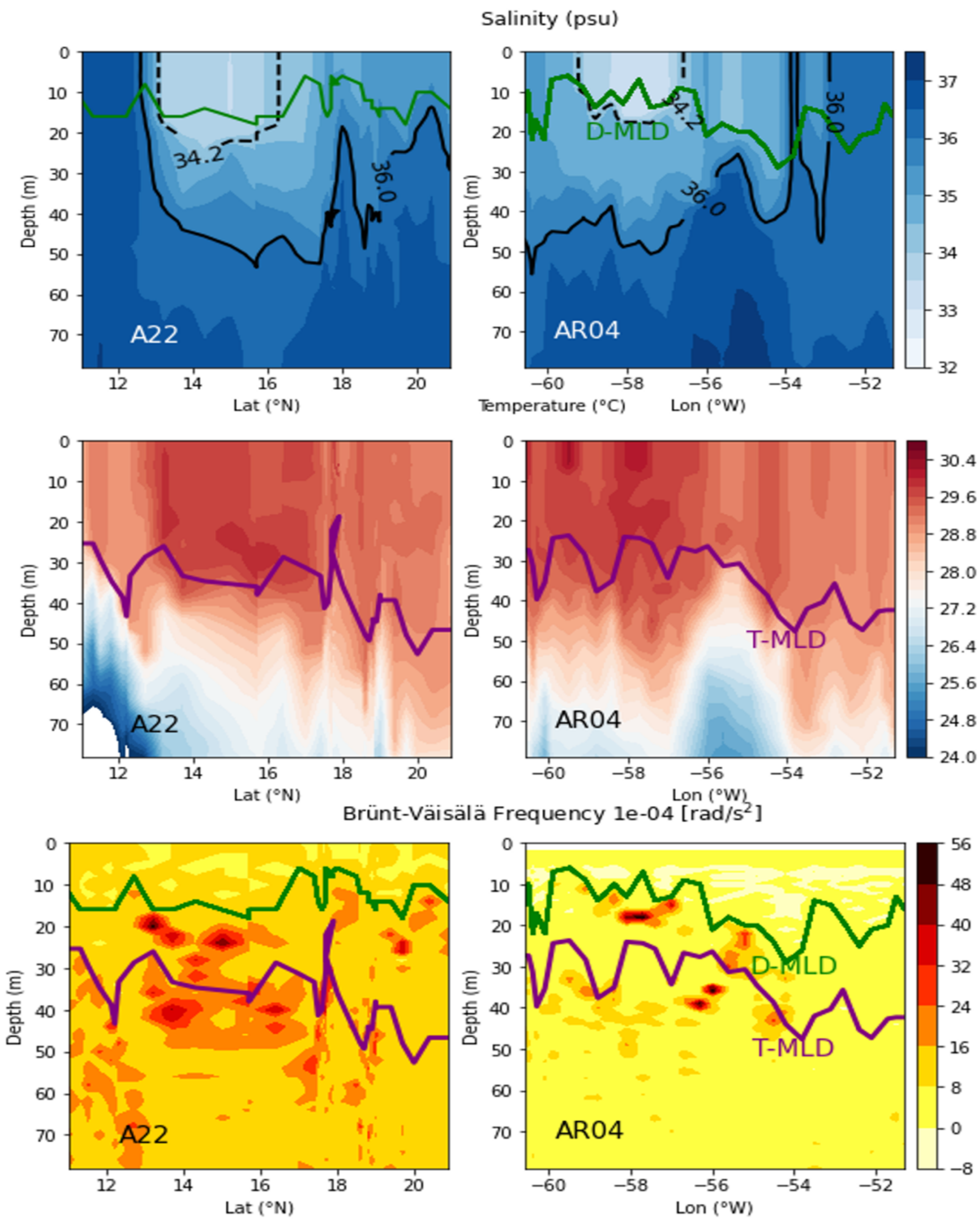


Figure 8. (a) Salinity, (b) Temperature, (c) Brunt–Väisälä frequency cross-sections from two cruises. Black lines indicate the vertical Plume Boundary using the same definition as horizontal (SSS between 34.2 to 36 psu). Green contour represents D-MLD, while purple contour represents T-MLD. The left panel is from cruise A22, right panel is from cruise AR04.

The salinity cross-section (Figure 8 upper panels) shows that the freshwater with the salinity lower than 34.2 psu (dashed lines) mostly exists in Plume Interior regions defined by the climatological datasets, namely 12-16°N and 57-60°W. Moreover, the freshwater lower than 34.2 psu has been found very shallow and only lies at the depth lower than 20m. Within this freshwater parcel, the density has been found well mixed since D-MLD (Figure 8ab green lines) is along the edge of the 34.2 psu pycnocline. What's more, the D-MLD values from the cruises (between 15-20m), are at the same scale of the averaged D-MLD (17m) derived from Argo floats.

There is a great difference between Plume interior and boundary regions. In the Plume interior, the stratification maximum, represented by Brunt–Väisälä frequency, is seen highest at the bottom of the freshwater parcel lower than 34.2 psu (Figure 8ef dashed lines), where the largest vertical salinity gradient is located. From cruise A22, the stratification is over 20E-04 rad/s^2 within the salinity band between 34.2 and 36 psu, with the highest stratification of 20E-04 rad/s^2 right under the freshwater parcel. However, in the Plume boundary, there is no freshwater parcel lower than 34.2psu in the upper ocean, and the salinity is more evenly distributed vertically, while the salinity gradients are titling horizontally. The stratification in the upper ocean is much less (<20 E-04 rad/s^2) comparing to that in the interior region.

The temperature is observed uniform in the boundary (52-56°W in Figure 8d and 18-22°N in Figure 8c) with a T-MLD of 50m, which may be a result of the well mixing caused by the low stratification in the upper ocean, while in the interior the T-MLD is observed near 35 m with the high stratification above 20m.

Overall, the T-MLD is around 50 in the boundary while it's 35m in the interior. This is consistent with the averaged Argo profiles results in Figure 5a red that the average temperature profile in the boundary is more uniform in the upper ocean, which makes a difference in the BLT from that in the interior.

Temperature Inversion

From previous research, temperature inversion, which was claimed to be closely related to the existence of the BL, has been observed prevailing during the winter, which usually comes from the subduction of the Summer salty warm water under the freshwater in the boundary, while the surface water loses heat as the winter approaches [Sprintall and Tomczak, 1992; Blanke et al., 2002; Balaguru et al., 2012a].

However, our study suggests that the temperature inversion also appears during the summer from both the Argo datasets and the CTD observations. It was captured in the average temperature profile, but only evident in the boundary region (Figure 5a red). Moreover, Figure 8cd shows that a 0.2°C temperature inversion appears to be in the Plume boundary region. More specifically between 16-18°N and 55-56°W, where the isolines start titling vertically, which is also the Plume boundary region and consistently with the Argo results.

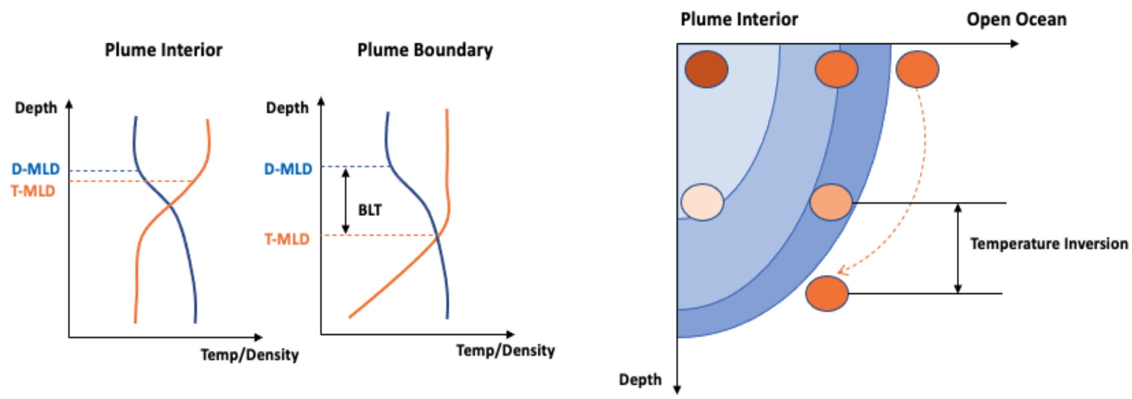


Figure 9. Diagram to explain the Temperature Inversion formation mechanism

We found the possible explanation as shown in Figure 9c. Basically it's the result of the near open ocean salty water from the warm surface sliding under the freshwater in the subsurface along the titling isopycnals, which mainly appears in the Plume boundary. Since the surface is usually warmer than the subsurface water, the warm water parcel forms a temperature inversion. The inversed temperature got balanced by the halocline which successfully maintains a stable upper ocean.

Though the titling isopycnals provides a prerequisite condition, the subduction processes have been revealed to be triggered through the adjustment of initial vertical vorticity induced by salinity fronts. This subduction process has been reproduced by submesoscale-permitting simulations below salinity fronts, where the salinity gradient is high, namely in the boundary between freshwater and open ocean salty seawater [Ramachandran et al., 2018, 2020]. The salinity front on the boundary is essential since it provides the initial horizontal vorticity which later induces low Potential Vorticity and subduction below the surface.

Summary

BLT has been found maximum on the Plume Boundary (18-20°N, 53-63°W), where the freshwater flux is relatively weak, instead of in the Plume Interior where the freshwater volume is larger. This has been verified from both climatological Argo datasets and observational cross-section from the CTD observations. Firstly, the detailed BL spatial distribution was given within the Plume extension region climatologically, and the BLT maxima is between the SSS contour band between 34.2 psu to 36 psu. Then, percentages of thick BL and the averaged BLT of all 905 Argo profiles in two regions, also show that the boundary owns a higher rate of thick BL. Later, the CTD cross-section profiles from CTD observation also verified the thicker BL in the boundary.

In order to better capture the structure of the boundary, the SSS contour band between 34.2 psu to 36 psu has been defined as “Plume Boundary”, instead of a single contour used in the previous studies. Because the boundary band features the highest horizontal SSS gradient, which could also be called “salinity front”, since the isohaline gets titling vertically. It is consistent with [Balaguru et al., 2012], who found that the magnitude of the BLT coincides with the maximum gradient in SSS.

Our study suggests the BLT difference between Boundary and Interior comes from the different temperature mixed layer depths (T-MLDs) while the density mixed layer depths D-MLDs are very close. The T-MLD in the Plume Interior is relatively shallow, which causes a thin BLT there. This is because the greater pycnocline was generated under the larger volume of freshwater, which leads to a stratification twice as strong as it in the boundary and would stabilize the upper ocean and reduce vertical mixing and will enable the upper ocean keeping warming up with less cold water induced from subsurface. This process was clearly shown from the observational CTD cross-section in our study. Besides the stratification, the higher turbidity comes from the river water might also make a contribution to the warmer surface and shallow T-MLD because of the higher solar radiation rates.

The D-MLDs are very close in two regions, because a 0.1 psu change in salinity would create a density change, which is greater than the criterira used to define the D-MLD. And this 0.1 psu difference of the salinity between the surface and the D-MLD in the vertical profile could be achieved at the very shallow depth (17m) in the Plume boundary as well, which means the D-MLD is the boundary is also very shallow.

In the Plume Interior region, the SST is very high (>29°C) while the TCHP is lower than the surroundings because of the shallow and warm mixed layer. This indicates that the energy is concentrated near the surface modulated.

In other words, the freshwater not only modulates the salinity/density profile, but also changes the temperature profile. It could elevate the T-MLD to the same depth as D-MLD. This explains the observed elimination of barrier layer in the Plume Interior. The modulation of T-MLD has been ignored by the previous research, which have highlighted the effect of freshwater on the salinity and density mixed layers but have not considered its simultaneous effect on the temperature profile.

The upper ocean in the Plume Interior features a more stratified, higher SST, but shallower T-MLD and thinner BLT. The upper ocean in the Boundary is less stratified, lower SST, but deeper and thicker T-MLD and BLT.

Temperature inversion is favorable for barrier layer formation and has also been found only in the boundary region from Argo profile composites. Moreover, the temperature inversion always happens at the bottom of the freshwater water region where the largest salinity gradient is seen in the CTD observations. [Balaguru et al., 2012] also showed the strong relationship between the vertical salinity gradient and the temperature inversion in the boundary region by the model simulation. They explained the temperature inversion as being caused by the surface cooling blocked by the BL at the start of winter. For the Summer, the solar radiation penetration differences have been blamed for causing the temperature maxima below the ML [Mignot, J. et al., 2012]. However, the Amazon River water mixed with light absorbing particles will actually trap the energy near the surface, which is not favorable for temperature inversion [Denman, 1973; Ohlmann et al., 1996; Hu et al., 2004]. Recently, the subduction of warm water has been mentioned as the cause of the temperature inversion. One form of subduction is when the warm salty water slides under cold freshwater water along the highly tilting isopycnals, which are usually located in the boundary. Another form of subduction arises from the adjustment of initial vertical vorticity induced by salinity fronts, which also exists in the boundary [Ramachandran et al., 2018, 2020].

Discussion

The dynamic process is also worth analyzing in more detailed. With the stronger front between the salty and fresh water, the dynamic process would be more complicated, such as how the potential vorticity is conserved during the subduction process, and BL's relationship with dSSS/dy, namely, the SSS gradient. What's more, there are a large number of eddies carrying the heat and freshwater from the Plume to mix with the Atlantic Ocean, which makes the dynamic process even more complicated.

With the deep temperature mixed layer and stratification, the Plume Boundary also shows a higher density of major hurricanes, which indicates the boundary may favor the generation of major hurricanes. Therefore, it's important to get a better understanding of the boundary region structure, especially the BLT, TCHP, SST and stratification, which are considered as important factors affecting hurricane intensification.

The effects of other possible freshwater inputs besides the Amazon River are still unknown: How much do advection and precipitation contribute to freshwater flux and BL formation? Furthermore, the freshwater budget quantitatively in the upper ocean, especially the upper 20 meters since we noticed that the salinity is extremely low in the upper 15 meters in the boundary. Moreover, it's also located in the ITCZ band, where the precipitation is high. So it's necessary to figure out the freshwater resource before we place the importance on the Plume freshwater.

In our study, we only care about the Plume and Plume extension region western than 63W (Northwestern Atlanta). Although the Caribbean Sea is within the Plume according to its SSS < 35.4psu, the SST and OHC are significantly higher, which could intensify hurricanes as well – more than other Plume regions since the Caribbean Sea is inside the Atlantic Warm Pool. Therefore, it's hard to separate the effect of the Warm Pool from the effect of the Plume. We will leave this for future discussion.

CHAPTER III

EFFECT OF BARRIER LAYER ON HURRICANE INTERNSIFICATION WITH OBSERVATIONAL AND STATISTICAL ANALYSIS

Introduction

We have analyzed the Barrier Layer formation in the Plume Boundary before. Next, in the remaining two chapters, we will focus on how the barrier layer can affect hurricane intensity from observational analysis and numerical modelling perspectives.

The impact of salinity degrees on TC intensification have been widely studied over the last decades. Most of papers agree that the salinity is the key factor for TC intensification, especially for the Major TC [Balaguru et al., 2012; Reul et al., 2014; Newinger and Toumi 2015; Yan et al. 2017; Rudzin et al. 2019; Hlywiak and Nolan 2019], while a few of them disagree with it [Androulidakis et al. 2016]. Recently, the rapid intensification process has also been suggested to be related to the low salinity condition while SST and TCHP are not significantly beneficial [Balaguru et al., 2020].

However, all of those studies considered the Amazon Plume as a whole, namely the region around 0-30N, 40-70W. Since our previous study has shown the significant difference between Plume Interior and Plume Boundary, in this chapter, we also want to know if we expect any difference in terms of the impact on hurricane intensification.

We use two methods: First, a statistical method to analyze the recorded hurricane datasets in each region, comparing their track density, intensification rates, and densities. Second, using in-situ Argo floats which coincide with hurricane passage. The observational data record of temperature and salinity profiles before and after hurricane passage can give us a measure of how the hurricane-induced cooling is affected by the presence of a freshwater/Barrier Layer.

Previous studies

Previous studies on this topic relating to statistical and Argo floats analysis are as follows:

Statistical studies reveal a significant relationship between SST and TC strength. It's more probable (68%) that the most intense (category 5) hurricanes fell into Plume region[Ffield, 2007]. For the most intense storms, sea surface cooling amplitude is systematically reduced by 50% over the Plume area compared to the surroundings open ocean, as shown by statistical analysis of satellite products [Reul et al., 2014].

For Argo float observations, it has been confirmed that the Plume with the BLT (stable halocline) could inhibit cooling and vertical mixing of hurricanes. During Hurricane Katia, the Argo profile shows the mixed layer depth barely changes due to the BLT in the Plume region, while mixed layer deepens heavily outside the Plume [Grodsky et al., 2012]. During Hurricane Igor, a nearly 25 m thick BL is detected before the hurricane passage, where it's located right in the center of the Plume northwestern extension. In the BL region, the vertical mixing depth stays almost the same during hurricane passage, while it deeps greatly by hurricane winds in the no-BLT region, thus reducing SST cooling [Reul et al., 2014].

Data and Methods

For statistical analysis of hurricanes, tracks and intensities are obtained from international Best Track Archive for Climate Stewardship (IBTrACS) dataset [Knapp et al., 2010], which covers from 1950 to 2017 reanalysis dataset. The recorded wind speed is the 1-minute maximum within a 6-hour interval.

There are 266 pairs of before-after hurricane passage Argo profiles chosen for all 36 hurricanes that crossed the Plume region between 2002-2020. The algorithms we used to choose each pair of profiles are as follows: For each location on the hurricane track, we search for Argo floats within 3 degrees near the hurricane location. We check if there are two Argo profiles that meet these requirements: one profile is within 5 days before hurricane arrives; another is within 5 days after hurricane passed that location. Moreover, the locations of those two Argo profiles should be closer than 2 degrees. We choose those two profiles as a pair related to that hurricane location. As a result, most of the two profiles belong to the same Argo float but are separated by a 10-day time interval, while others may belong to different Argo floats which happen to be close to each other in a time and space.

Among the 266 pairs, there are 204 on the tracks of the hurricane, where the current wind speed is greater than 64 kt (hurricane Category 1) when closest to the Argo float location, that were chosen for further analysis. To analyze the difference between Plume Boundary and Plume Interior, we also separate the Argo float pairs by the SSS of the profile before hurricane arrival. This criterion is based on the Plume Boundary definition: SSS < =34.2psu means that profile pair resides inside the Plume Interior region, 34.2psu <SSS < =36 psu resides into the Plume Boundary region, and 36 psu <SSS means that profile pair fell out of Plume. There are 64 pairs of profiles were inside the Plume region (SSS<36 psu).

The criterion to classify the translation speed as slow or fast is based on [Lloyd and Vecchi, 2011]:

$$C = U_h / fL$$

U_h is the translation speed, f is the Corolis force, and L is set to 100km as the length scale. When C<1, the hurricane translation speed is slower than its baroclinic wave speed, and the oceanic response to the hurricane wind will be under hurricane. Otherwise, the oceanic response will be on the hurricane tail [Geisler 1970; Zhang et al., 2021].

Here, we did further calculations relating to the hurricane translation speed over the Amazon Plume region. In order to meet the criterial C<1, the translation speed should meet the requirement:

$$U_h < fL$$

$$here, f = 2 \times \Omega \times sin(\varphi)$$

Let's assume the latitude is 17N, $\sin(\varphi) = sin(\frac{\pi}{2} \times \frac{17}{90}) \approx 0.3$, $\Omega = 7.29\mathrm{e} - 05$. Then f =4.3e-05 1/s. L=1e+5 m. Therefore, the hurricane translation speed should be slower than 4.3m/s to be considered a slow-moving hurricane. If the latitude is 20°N, the fastest speed could be near 5m/s to be considered as a slow-moving hurricane.

Results

Major Hurricanes Concentrated and Intensified in the Plume Boundary Statistically

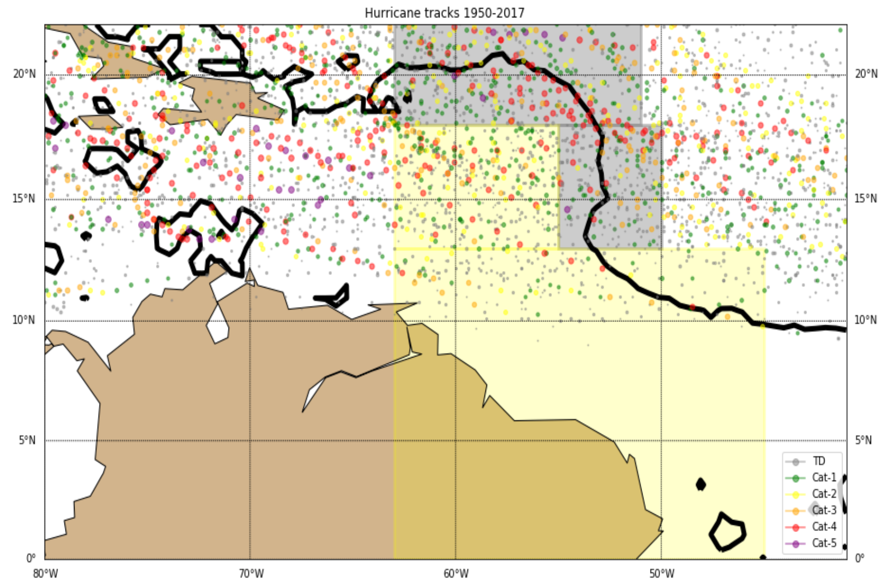


Figure 10. Colored dots show hurricane locations on Aug, Sep, and Oct from 1950-2017, colors are different categories. The black contour shows climatological SSS=35.8. The gray boxes show the Plume Boundary, while yellow boxes represent Plume Interior.

	TS	Cat-1	Cat-2	Cat-3	Cat-4	Cat-5
Plume-Boundary (683)	339 (42%)	143 (56%)	66 (62%)	52 (59%)	74 (66%)	9 (100%)
Plume-Interior (688)	464 (57%)	112 (43%)	39 (37%)	35 (40%)	38 (33%)	0 (0%)

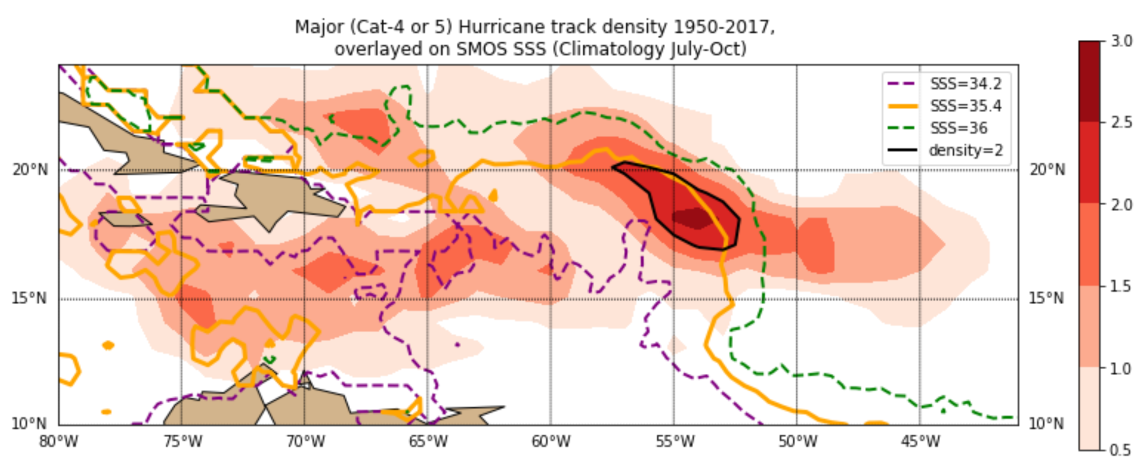
Table 2. The numbers of TC track positions fall into each domain in each category. The percentage is the numbers of points in each domain comparing to all the numbers of points in both regions for each category.

	TS	Cat-1	Cat-2	Cat-3	Cat-4	Cat-5
Plume-Boundary	49%	20%	9%	7%	10%	1%
Plume-Interior	67%	16%	5%	5%	5%	0%

Table 3. The percentages of different categories in each domain.

The hurricane track and intensity distributions from 1950 to 2017 shows that major hurricanes (Cat-4 or Cat-5) mainly occur in the Plume-boundary domain. Here, the Boundary and Plume Interior definitions are same as in the Chapter 2. In Figure 10, major hurricane locations (red and purple dots) are more concentrated in the Plume Boundary (gray) domain instead of in the Plume Interior domain (yellow). Statistically, we collected the numbers of TC locations in each region and split them by their categories starting from TS level to Category-5. From the Table 2, there are 74 Category-4 hurricanes (66% of all) that passed over the Boundary domain while only 38 Category-4 hurricanes (33% of all) passed over the Plume Interior. All the Category-5 hurricanes exist in the Plume-Boundary domain.

What's more, it is more likely to intensify into a Cateogroy-1 hurricane or even major hurricane (>Cateogroy-3) in the Boundary than that in the Plume Interior. From Table 3, there are 51% of all the TCs in the Plume Boundary (688 in total) has reached hurricane, while it's only comprise 33% of all TC in the Plume Interior (683). There are 11% of all the TCs could reach Category-4 in the Boundary comparing with the 5% in the Interior. Those comparisons are under the condition that there are very similar amounts of TC passage over the two regions, which suggests the TC tracks are evenly spread in those two regions.



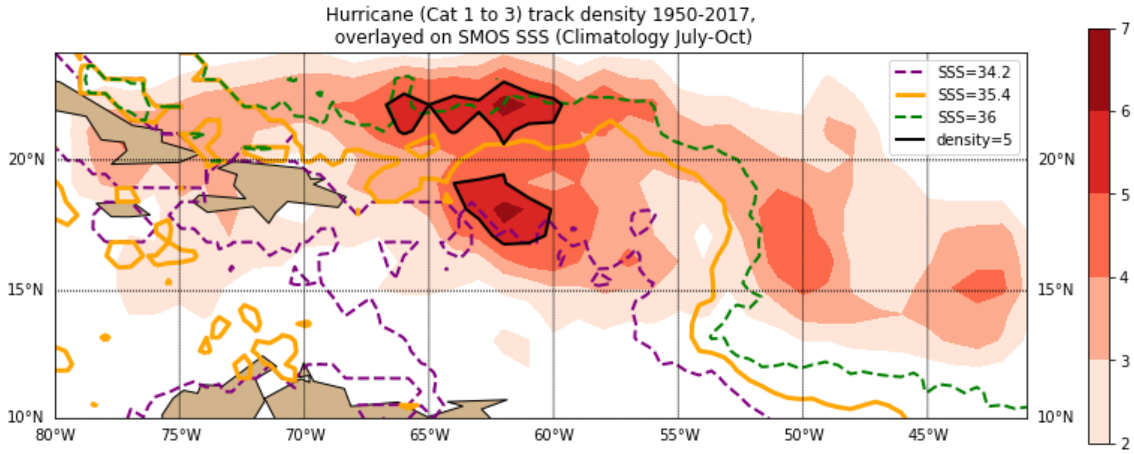


Figure 11. The distribution of historical Hurricane tracks per 1° degree, smoothed by a 3° × 3° block average for Major Hurricanes (a) and Minor Hurricanes. The unit is counts. The colorful contours show the Plume Boundary.

Besides the counts, the major hurricane track density (in Figure 11a) is maximum on the Plume Boundary centered at 55°W, 18°N. The highest density is 3 hurricanes per 1° × 1° degree box, while the minor hurricanes density centers around 62°W, 18°N within the Plume interior (Figure 11b). The highest density reaches over 6 TC numbers per spot 1° × 1° degree box because there are more minor hurricanes.

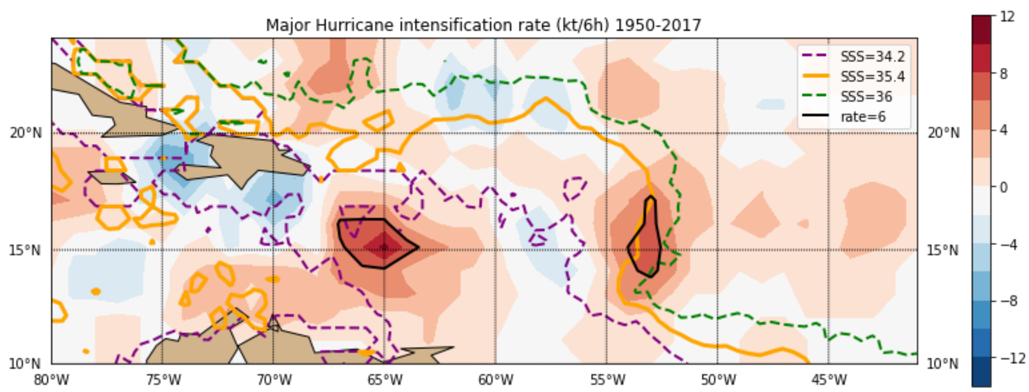


Figure 12. The distribution of historical Hurricane intensity change rate per 1° degree, smoothed by a 3° × 3° block average for Major Hurricanes. The unit is kt/6h. The positive means it's intensifying, negative means it's decaying. The colorful contours show the Plume Boundary from SMOS SSS data averaged from Aug to Oct.

Figure 12 shows the hurricane intensity change rates for Major Hurricanes, more specifically, locations where the hurricane wind speed was greater than 105 kt/h, since this value is just under the Category 4 critical value and could capture the intensification from Cat-3 to Cat-4. The value of each degree is calculated as the difference of the wind speed in the next 6 hours minus the current wind speed, which means it is the intensity change or the "Intensification Rate." Then a 2-D Gaussian Filter with a 3×3 degree averaging was applied.

From Figure 12, the positive value means the TC was intensifying, while the negative color means the hurricane was decaying on the average in that area, which means the environment in that region is not favorable for supporting the development of a Major Hurricane, for example, not having enough heat energy supply from the ocean.. Black contour shows the area where its averaged intensification rate could reach 6 kt/6h (24 kt/day equally), which could be considered as the Rapid Intensification region. Considering that it's already around Major Hurricane strength, the further intensification is very important for the Super Hurricane formation.

There are two centers where the intensification rates are highest for Major Hurricanes. The eastern intensification center is around 52-54°W, 15°N located in the Plume Boundary, where the BLT and T-MLD are higher. The area around 56-58°W, 15°N is the decaying area in the Plume Interior region, even though SST are higher in the Interior, the BL is thinner, and the TCHP has been found lower than the surroundings because of the shallow T-MLD mentioned before, which is not favorable for a Major Hurricane intensification. Both of those two features are the results of the super low salinity.

Therefore, we suggest that the features associated with salinity may play the role in intensifying the Major Hurricane in the Boundary.

The western one is inside the Warm pool. The SST on this area is above 28.8°C, and the TCHP is greater than 60 KJ/cm^2 climatologically from Figure 1, which are favorable conditions for Major Hurricane intensification. As noted before, this study will not discuss this region.

We have already noted the Major Hurricane concentrated on the Plume Boundary at around 18°N and it seems to be the downstream along the hurricane tracks, while the 15°N intensification center is the upstream where the hurricane intensified. They are both in the Plume Boundary, which means the Plume Boundary seems not only help the hurricane intensify, but also help them maintain a Major Hurricane level strength. On the contrary, the intensified Major Hurricanes are more likely to decay in the Plume Interior.

Argo floats before and after Hurricane

It seems that Amazon Plume Boundary provides favorable conditions for Hurricane intensifications and maintenance. However, among all the conditions featured in the Boundary, such as high BLT, deep MLD, high SSS, which are all caused the freshwater input, how much the BLT affects the SST cooling and further hurricane intensity still needs further study. For this section, we will examine the blocking effect of BLT, which is represented by the reducing SST cooling, by comparing the Argo floats before and after hurricane passage.

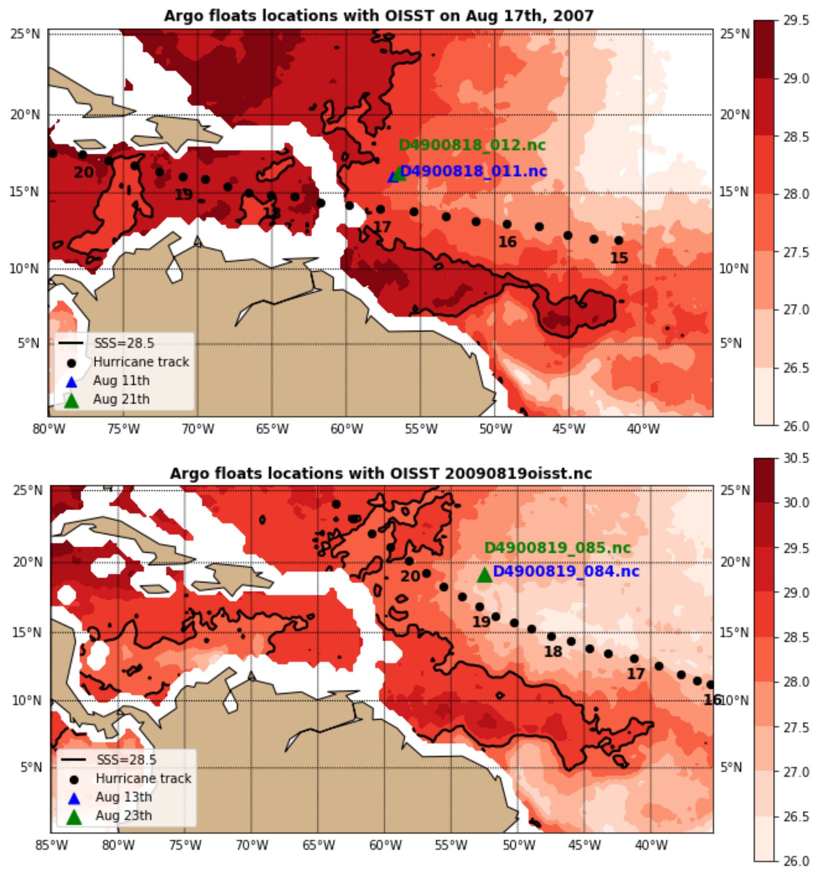


Figure 13. Two hurricane cases as examples. (a) hurricane NO. 200704, with Argo ID: D4900818; (b) hurricane NO. 200902, with Argo ID: D4900819. Each Argo captured two oceanic vertical profiles before and after hurricane passed by the float location. The shading shows the observed SST the day hurricane was closest to the Argo Float.

In order to have a better description of what happens to the upper ocean during hurricane passage, we chose two pairs as examples. One is Argo ID: D4900818 near Hurricane No. 200704, another is Argo ID: D4900819 near Hurricane No. 200902. Each float captured two oceanic vertical profiles in a 10-day interval: one is the pre-existing temperature and salinity profiles before hurricane arrival; another is post-hurricane profiles, which could capture the upper ocean response to hurricane. The locations of two Argo floats and hurricane tracks are shown in Figure 13, overlaid on the SST distribution on the day when the hurricane arrived nearest to the Argo float.

Two Argo floats are selected as examples because they are very comparable in many other environmental conditions except for salinity and BLT. For example, both Argo floats captured the in-situ profiles around 3-5 days before and after the hurricane passed by, during which the hurricane remained as Minor Hurricanes; translation speeds were both considered fast (>5m/s, Lloyd and Vecchi, 2011); they both lie outside of Atlantic Warm Pool (28.5°C). Those similarities could eliminate the effects of super high SST and hurricane itself. The most significant difference is that hurricane No. 200902 passed over the Plume Boundary while the hurricane No. 200704 passed over the Plume Interior.

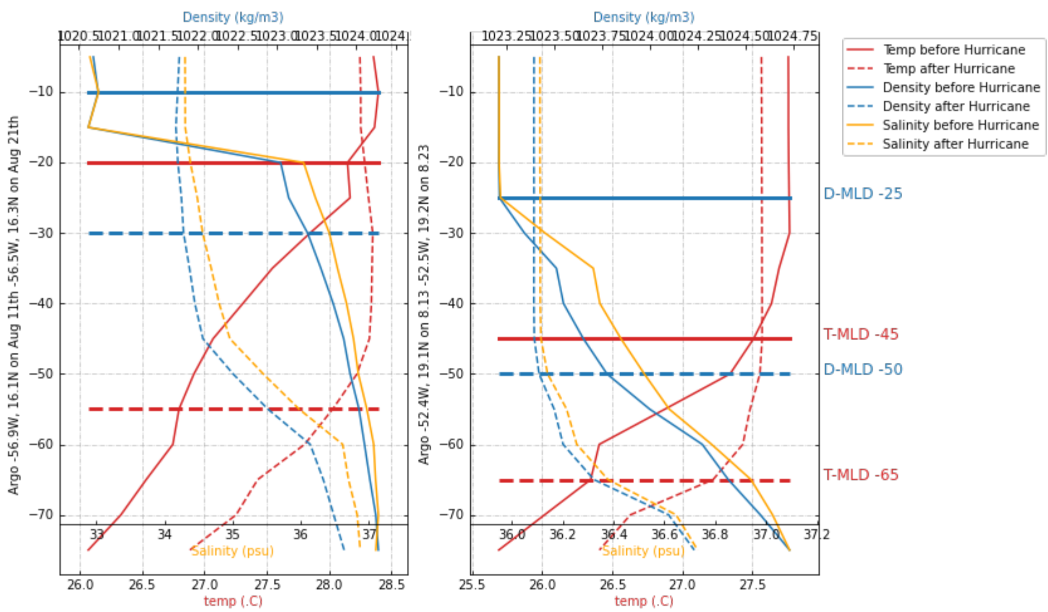


Figure 14. Temperature (red), salinity (yellow) and density (blue) profiles captured by the Argo floats shown in the Figure 13. All solid lines represent before hurricane arrived, and dashed lines represent after hurricane. Left panel is from Argo ID: D4900818, right panel is from Argo ID: D4900819.

Hurricane ID	Location	TC wind speed (kt)/Category	Translation speed (m/s)	SST (C)	SSS (psu)	D-MLD/	T-MLD/change(m)	BLT (m)	Intensification rate (kt/day)	SST Cooling (C)	T-MLD change (m)
200704	Interior	80/(Cat-1)	10.8	28.3	32.9	10	20	10	No-RI	-0.1	35
200902	Boundary	105(Cat-2)	7.1	27.8	35.9	25	45	20	RI	-0.2	20

Table 4. The related environmental factors and Hurricane information for two cases.

Figure 14 shows the clear upper ocean vertical temperature, salinity, and density profiles. The solid lines represent pre-existing conditions, while the dashed lines represent conditions after hurricane passage.

Shown in Table 4, three groups of environmental conditions have been collected: freshwater- related conditions, including the pre-Hurricane (solid lines) BLT, SSS, stratification and the location indexes (1: Boundary, 2: Interior); temperature-related conditions, including the pre-Hurricane SST and MLD; hurricane-related conditions, including wind speed and translation speed.

There are two metrics: one is the SST cooling, which is calculated by the Post-Hurricane minus Pre-Hurricane SST; another is Hurricane intensification rate.

The picked cases show the consistent features from the last chapter. The upper ocean features in the Plume Interior are: higher stratification, higher SST, but shallower T-MLD and thinner BLT comparing to those in the Boundary. In the Plume Interior, the upper 15 meters salinity is as low as 33 psu, below there is a highly stratified halocline/pycnocline — as shallow as 20 meters. The high stratification can stop the mixing and therefore elevate the T-MLD to 20 m and increase the SST. The shallow D-MLD and T-MLD generates the thin BLT of only 10 m residing in the upper 20 m. Contrarily, in the Boundary, the upper ocean is not as fresh as in the interior since it's farther from the river mouth: the whole upper 25 meters salinity is 35.9 psu. The weaker stratification ends up with a deeper T-MLD (45 m) and the thicker BLT (20m).

Table 4 shows that the upper ocean was well-mixed deep into 55 m and 65 m (dashed red lines), with a 35 m and 20 m T-MLD change, and 0.1°C and 0.2°C SST cooling for Hurricane No. 200704 (Plume Interior) and Hurricane No. 200902 (Plume Boundary) accordingly. It shows the T-MLD change is 15 m smaller in the Plume Boundary than that in the Plume Interior. The BLT is 10 m greater in the Plume Boundary. Therefore, the BLT could reduce the T-MLD change. However, for the SST cooling doesn't change that much between the two cases. Moreover, even though the upper oceans in both cases are well-mixed to the similar depths, Hurricane No. 200902 has a greater wind speed (125 kt) and slower (7.1 m/s) translation speed, both of which are considered favorable conditions for increasing mixing and SST cooling. Nevertheless, the mixing depth and SST cooling are still comparable to Hurricane No. 200704. That may be the result of the blocking effect of the greater BLT. However, to confirm it, a climate model would be a better tool, because we can change only the BLT, keeping other effects the same, as discussed in the next chapter.

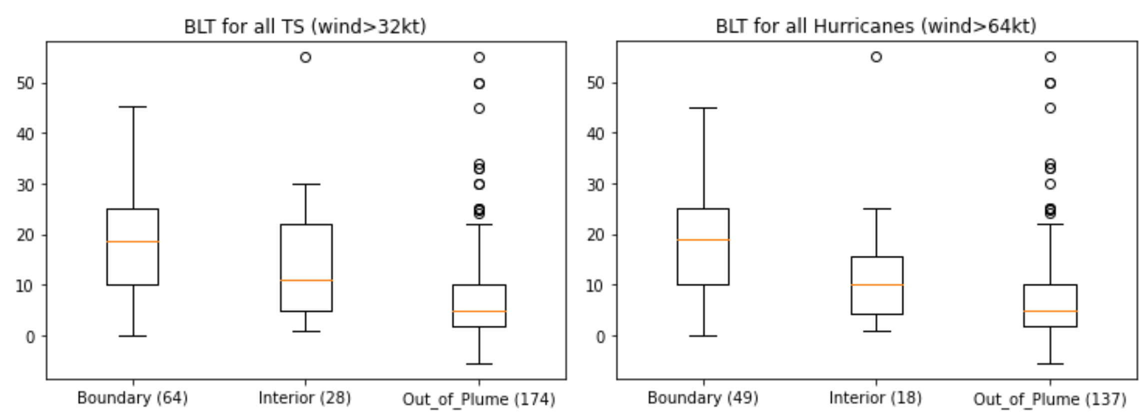


Figure 15. BLT in different locations and their total datapoints. The left panel is for all TS, which means when the TC reached the Argo float location, its intensity was above TS level (wind speed >32kt ; 266 in total); The right panel is for points only when the TC reached Hurricane level (wind speed >64kt; 204 in total).

Following the same analysis procedure as the two examples, we have collected all the Argo floats near the 36 hurricane tracks which has crossed over Amazon Plume regions between 2002-2020. Overall, there are 266 pairs of Argo floats chosen, with 204 pairs that are close to the locations where the storms reached hurricane strength.

Firstly, consistent with previous results in the last chapter, we found that the BLT is the highest in the Boundary region with the median of 20 m, whereas the median of the BLT is only 10 m for the Plume Interior, and even under 10 m for the region outside the Plume. The left panel of Figure 15 shows all the pairs captured near the hurricane track as long as the wind speed is greater than 32 kt. The right panel only contains the hurricane strength datapoints, the wind speed of which is greater than 64 kt. There are 204 pairs of datapoints in total. However, both distributions agree with each other, and show that the Plume Boundary BLT is the greatest.

Next, we only focus on the data points inside the Plume (Boundary or Interior). There are 67 pairs of Argo profiles collected near hurricane tracks, when its intensity reached Cateogory-1 and the location was within Plume region. Among them, 32 pairs were in the Plume Interior (SSS<34.2 psu), while 35 were in the Plume Boundary (34.2 < SSS<36 psu). Here we label the Plume Boundary as location 1 the Plume Interior as location 2 for further discussion. For those pairs, we gathered the similar information as in the examples, and then calculated the Pearson correlations between each two variables, shown in Figure 16. The colored box means the correlation has passed the significant levels. The three different shades from light to dark represents 95%, 98% and 99.5% prospectively.

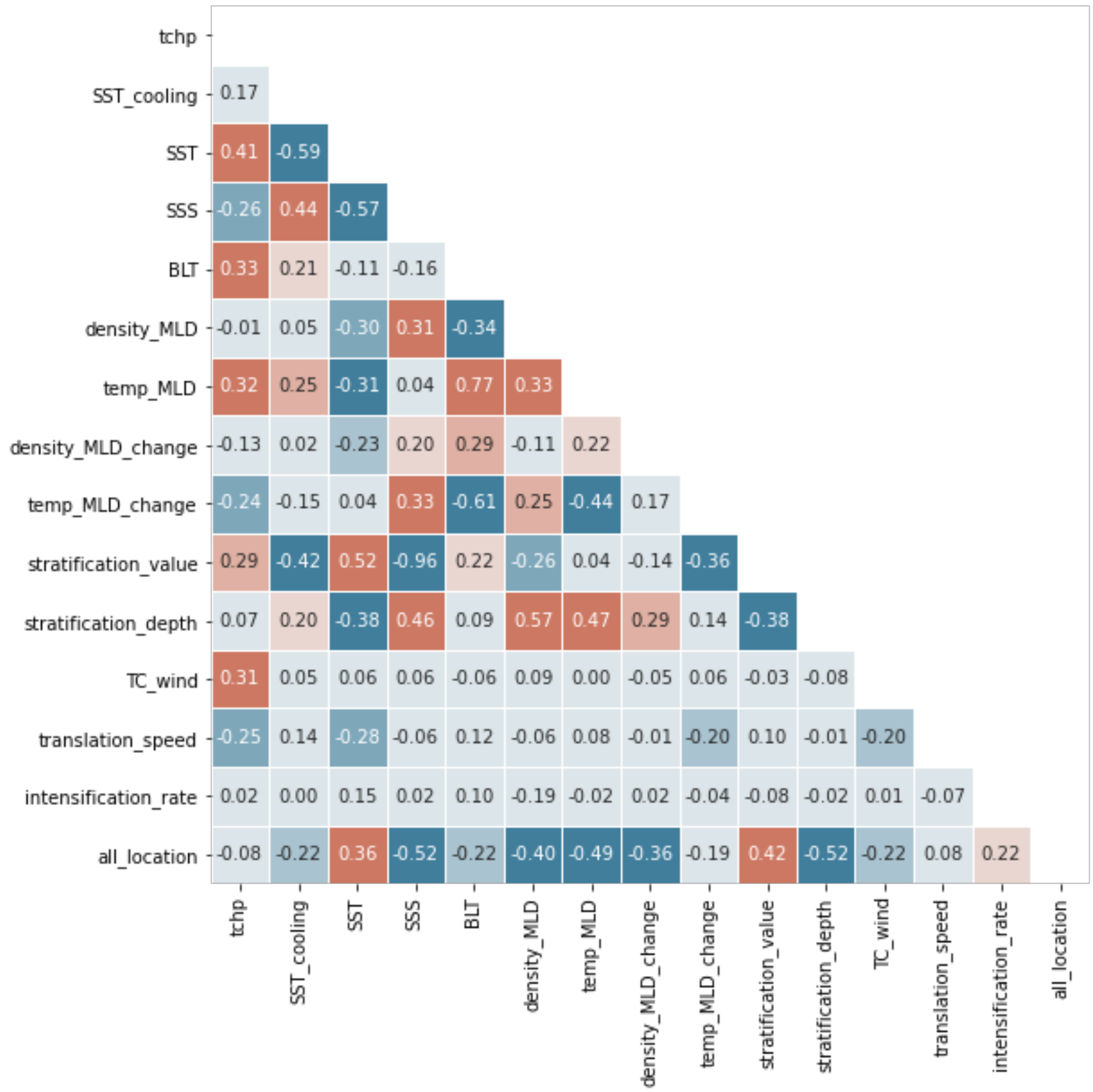


Figure 16. For all hurricane (wind speed>=64kt); 67 pairs in total, and only within the Plume (sss<36) region. The Argo floats are located within 3-degree distance to its closest hurricane center.

The relations between each environmental conditions and three metrics: SST cooling, T-MLD change and hurricane intensification rates will be evaluated.

SST cooling

The colored box in the "SST_cooling" column shows the significantly related environmental conditions with the SST cooling. To be more specifically, the red color means the higher value of the environmental factor would reduce the SST cooling. The blue color means the higher value would relate to more SST cooling.

In order to reducing the SST cooling, the most favorable oceanic conditions should be:

1. higher pre-Hurricane BLT
2. higher pre-Hurricane T-MLD ("temp_MLD")
3. higher pre-Hurricane SSS
4. lower pre-Hurricane SST
5. lower pre-Hurricane stratification value
6. location index 1: boundary

$$\text{location index 1: boundary} = \text{BLT} + \text{T\_MLD} - \text{SST} - \text{stratification value} > 0$$

The positive (+) before each feature means the feature in the Boundary is making a positive contribution to reduce SST cooling, while the negative (-) represents the negative contribution. Since the location index 1 is positively related to lower SST cooling, which means the boundary is more likely to have the lower SST cooling. So the overall contributions of all features should be positive.

Therefore, the BLT and T-MLD together is the key oceanic factors for reducing SST cooling in the boundary region.

The reason why SST tends to be lower in the Plume Boundary is not addressed yet, but here are some hypotheses:

1. The BL is found thicker in the Plume Boundary, which has been blamed for blocking the hurricane induced mixing, and therefore reduce SST Cooling.

2. The deeper MLD in the Plume Boundary will dilute the cold water, and therefore result in a lower SST.

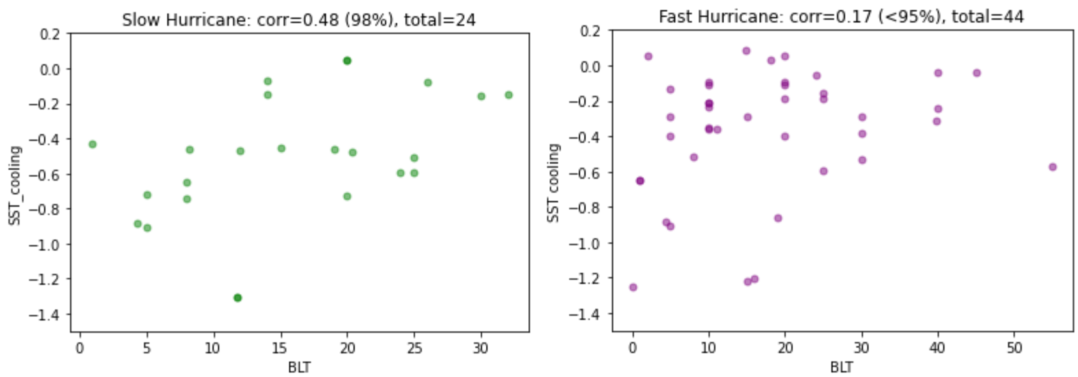


Figure 17. The scatter plots to show the relationship between SST cooling and BLT for slow-moving (translation speed <= 5m/s) and fast-moving (translation speed > 5m/s) hurricanes.

Next, we separate the datapoints into two groups: slow translation speed (<=5m/s; 23 pairs in total) and fast translation speed (>5m/s; 44 pairs in total). TCHP or BLT has been claimed to be more essential for slow-moving hurricanes, in which the air-sea interaction would be more intense, and therefore will provide the interaction process a more important role in determining the SST cooling. On the other hand, the relative location of the cooling area for the slow-moving hurricane is different from the fast-moving hurricane.

Figure 17 shows that the relationship between BLT and SST cooling is more significant in slow-moving hurricanes with a 0.48 correlation coefficient, while it's only 0.17 in fast-moving hurricanes.

Moreover, for slow-moving hurricanes, the reduced SST cooling in the Plume Boundary is more significant than result from all hurricanes. The correlation coefficient is

-0.57 (>99.5%) between "Location" and "SST cooling" variables for slow-moving hurricanes only, while it's -0.22 for all hurricanes.

T-MLD change

"T-MLD change" represents how much the cold water convolutes up into mixed layer. With a greater T-MLD change, the more the cold water input.

The T-MLD change column in the correlation matrix shows that the most significantly correlated factor with T-MLD change is BLT (correlation coefficient is as high as 0.61), which is higher than it with D-MLD (0.25), and with T-MLD (0.44) alone. Since BLT=T-MLD – D-MLD, it means the combination of a shallower D-MLD/stronger stratification and a deeper T-MLD would be the most effective in reducing mixing. This result is meaningful, as it highlights the physical meaning of the BLT definition, which not only considered the freshwater caused strong stratification, but also contains the information of the T-MLD. To get a thicker BLT, both freshwater/stratification and deep T-MLD are required at the same time, which makes the BLT a useful indicator of favorable oceanic conditions for of hurricane intensification.

hurricane intensification rates

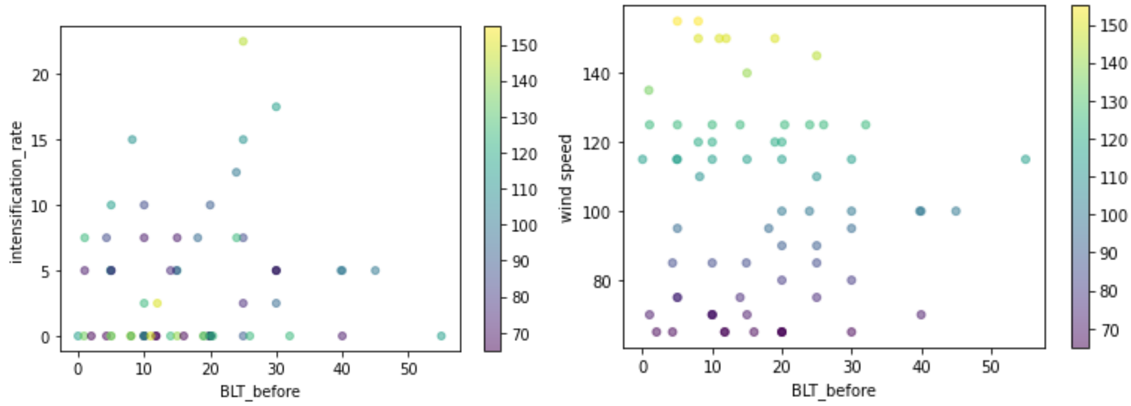


Figure 18.	The scatter plots to show the relationship between intensification rate & BLT and wind speed & BLT. The color shows the wind speed (kt).

The “intensification_rate” column in the matrix shows no colorful box at all, which means even though the BLT has been shown significantly related to the SST cooling, it has nothing to do with the hurricane intensification. Figure 18a shows for different wind speed (Categories), the intensification rate is not related to the BLT.

In a conclusion, with 68 pairs of Argo floats that captured the profile before and after hurricane passage, it shows that BLT could effectively block T-MLD from becoming deeper, namely stop cold water from mixing up. The relationship between BLT and SST cooling is also a very significant for the slow-moving hurricanes. Moreover, the SST cooling has been observed to be stronger in the Plume Boundary, especially for slow-moving hurricanes.

Summary

In this Chapter, we analyzed hurricane observations statistically, and showed the importance of Plume Boundary region in enhancing the intensification of Major Hurricane, as well as their maintenance. The result shows that 68% of the hurricane locations, where the intensity exceeds the Major Hurricane category, were in the Boundary region. Moreover, the Major Hurricane intensification rates is also higher in the Plume Boundary than that in the Plume Interior.

Since the Boundary region is characterized by greater BLT values, and the BLT has been claimed as reducing SST cooling, we need to explain how effective the BLT is in reducing SST cooling. 68 pairs of before-after profiles of Argo floats have been analyzed to retrieve the relationship between the pre-existing BLT and SST cooling. The location of the Argo float is near the hurricane track and within the Plume region. The hurricane intensity should also reach Hurricane Cat-1 when it passed by the Argo float.

Two metrics are used to represent the oceanic blocking effects. One is T-MLD change, which represents the result of oceanic mixing. Another metric is SST cooling. We find that the BLT is the most correlated variable with the T-MLD change, which represents the effect in reducing mixing. Moreover, the BLT is also significantly correlated to the SST cooling (second metric). It shows that the higher BLT is more related to the lower SST cooling.

The SST cooling tends to be less in the Plume Boundary, where there is higher T-MLD and BLT, than it in the Interior, especially for slow-moving hurricanes.

However, there isn't any oceanic environment variable found to be significantly related to the Hurricane intensification.

In conclusion, this chapter reveals the relationship between BLT and hurricanes from the observational perspective. The 64 pairs of Argo profiles have been used to verify the effect of the BLT on reducing SST cooling. Moreover, it shows the Boundary region, which has greater BLT, is more favorable for reducing SST cooling. However, the BLT seems not related to the hurricane intensification. Why does the reduced SST cooling have no feedback on hurricane intensification? Those will be answered in the next Chapter.

CHAPTER IV

EFFECT OF BARRIER LAYER ON HURRICANE INTERNSIFICATION WITH REGIONAL COUPLED EARTH SYSTEM MODEL

Introduction

In the previous Chapter, we showed that the barrier layer can reduce SST cooling, especially for slow-moving hurricanes (translation speed<5m/s). However, the deficiency of using observational Argo float is that there is no comparison between with and within freshwater. Moreover, the Argo float measurement time interval is 10 days, which is longer than one hurricane lifetime (around 3-7 days). Therefore, the float may not capture the real-time feedback between the SST and hurricane mixing at the time of passage over the measurement location. We will apply numerical models to compensate for this deficiency in this chapter.

So, the first question to be answered in this Chapter is: is this reduced cooling still under hurricane coverage at the current translation speed of that hurricane? Can the SST cooling further affect on the energy transferred to hurricane for its intensification? Using a 3D coupled model, we will be able to calculate reduced SST cooling just under hurricane coverage, and its in-time feedback to TC intensification.

In the previous chapter, we also showed that the Major Hurricane density center is located in the Plume Boundary, where also has higher intensification rates. But our observational comparisons are between different locations, which means not only are the BLT/freshwater anomaly different, there may also be other environmental factors that are different. With the sensitive experiments of the 3D model, we can control the salinity and keep other factors the same. Moreover, the multiple hurricane cases are needed since their tracks spread over the entire Plume region. We can exam the effect of the freshwater Plumes under different environmental conditions, eliminating other effects as much as possible.

In this chapter, we will use the RCESM model to simulate 21 hurricane cases have crossed the Plume region. By removing the BLT/freshwater, we can determine how it impacts the hurricane intensities. This chapter is organized as follows: first, Hurricane No. 201711 is used as a case study to describe the blocking effects of the BLT, and its impact on the hurricane. Then, all hurricane simulations are analyzed statistically to affirm the conclusion. Finally, a quantitative relationship between freshwater, reduced SST cooling and hurricane intensity changes will be derived.

Previous Studies

It is still debated how effective the impact of BL on the hurricane intensification would be over the Plume. Statistical and observational results have shown that hurricanes are stronger over the Plume region with a BL than outside the Plume regions without a BL [Ffield, 2007; Reul et al. 2014, Balaguru et al., 2012a, 2018], which could be explained by the observed enthalpy flux from ocean to atmosphere [Rudzin et al., 2019]. However, those comparisons are between different locations, which reduces the persuasiveness of the argument. Therefore, we prefer to use numerical modelling to modify salinity in the Plume to confirm (or refute) the BL mechanism. Similar conclusions arise from hurricane simulations using numerical models combined with in-situ float observations

[Androulidakis et al. 2016], although a few hurricane case studies may not cover enough scenarios to eliminate the bias.

Let us consider the model techniques used to address this problem:

The first technique involves using uncoupled models, and decades-long model simulations have been carried out to reproduce all hurricanes that happened over the Plume, with modified Plumes in different experiments. Ocean models were driven by realistic or idealized hurricane wind input. The ocean model only experiences the SST cooling in the ocean, as well as the role of BL on reducing SST cooling. For example, In Newinger and Toumi (2015), ROMS was run for 11 years to conduct two experiments with and without river input; in Hernandez et al (2016), Nucleus for European Modeling of the Ocean program (NEMO3.6) was driven with realistic wind speed. Their results suggest that the freshwater layer effect could cause a slight reduced SST cooling for strong hurricanes, while almost no difference for weak hurricanes. The reduced SST cooling by the freshwater is 0.12°C after 1-2 days hurricane passed by Hernandez et al (2016) and 0.08°C was concluded from Newinger and Toumi (2015).

However, the problems of in those techniques are that it's impossible to directly show the ocean's feedback on hurricanes regarding BL impact, since there is no atmospheric component. Moreover, using long-term simulations is that after the salinity profile is changed, the density, ocean current, and the temperature profile may also be changed. So, it's hard to tell which one is the key factor for influencing hurricane intensification.

Another uncoupled model technique is to carry out idealized experiments using the Price–Weller–Pinkel (PWP) one-dimensional ocean mixed layer model [Price et al. 1986] to quantify the BL's effect on hurricane cold wake with different oceanic profiles and wind stress [Yan et al., 2017; Rudzin et al., 2018; Balaguru et al., 2020]. In a recent study [Balaguru, et al., 2020], the PWP model is forced by various levels of surface heat and moisture fluxes, and wind stress to represent different hurricane categories. The ocean initial vertical profiles from Argo floats featured in different BL depths. Their results give a detailed quantitative description of reduced SST cooling: the reduced SST cooling is 0.12 °C for Cat-2, 0.3 °C for Cat-3. Maximum reduced SST cooling happens around 21 hours after hurricane passage.

The problems of in those techniques are, firstly there is no feedback on hurricane. More importantly the 1-D model could only describe the reduced SST cooling at a single point, while the oceanic feedback to the hurricane depends on the overall SST cooling under the hurricane coverage, which is unevenly distributed. The averaged reduced SST cooling would be much less than the result from one single point.

The fully coupled 3D model seems to be only solution in terms of capturing the direct SST feedback on the hurricane.

Balaguru et al., 2012 used a coupled model to simulate 315 TCs in the areas with and without BL. It is a robust result because of the large number of simulations. However, the comparison of hurricanes between different locations and between different hurricanes, with multiple variables having been changed at the same time, makes it less convincing.

The ideal solution is to remove BL at the same spot where the same hurricane passes over, namely executing the sensitive experiment with the coupled model, which could control the BL to be the only variable changed during the simulation. In order to eliminate the upper ocean temperature change modulated by the salinity change after the long-time ocean adjusting, we would only run the model for a few days. This makes it easier to isolate the blocking effect of the BL exclusively. Instead of executing one case study, over 20 major hurricane cases are simulated, covering the whole Plume regions, with various BLT conditions, as well as other oceanic conditions (SST, T-MLD, stratification), thus limiting the analysis bias. The large number of simulations also enables us to analyze the impact quantitatively. Moreover, the coupled model allows us to check not only the ocean's response to the hurricane, but also its direct atmospheric feedback on the hurricane.

Data and Methods

RCESM introduction

The Regional Community Earth System Model (R-CESM) is a fully coupled regional model developed by iHESP, (OUC, TAMU jointly with NCAR). There are three fully realized components (Figure 19): Atmospheric Model using the Weather Research and Forecasting Model (WRF); Oceanic Model is using The Regional Ocean Modeling System (ROMS); Land Model is using Community Land model (CLM). In our research, only ATM and OCN components has been coupled since the hurricane tracks are over ocean. The coupling framework is from in the Community Earth System Model (CESM, http://www.cesm.ucar.edu/).

During the coupling process, data output from each model component is transferred every three simulation hours. The ocean model domain is usually smaller than atmosphere domain. The buffer area between the edge of ocean domain and the edge of the atmosphere domain is named "XROMS". The WRF and ROMS models are fully coupled only inside the ocean domain, while in the XROMS domain, there is no ocean model output data supply for the atmosphere model. So we use the reanalysis dataset to generate data only in the XROMS domain, and supply it to the WRF model for each time step. Due to WRF and ROMS having different horizontal grids, a weight function is used for conservative interpolation of fluxes.

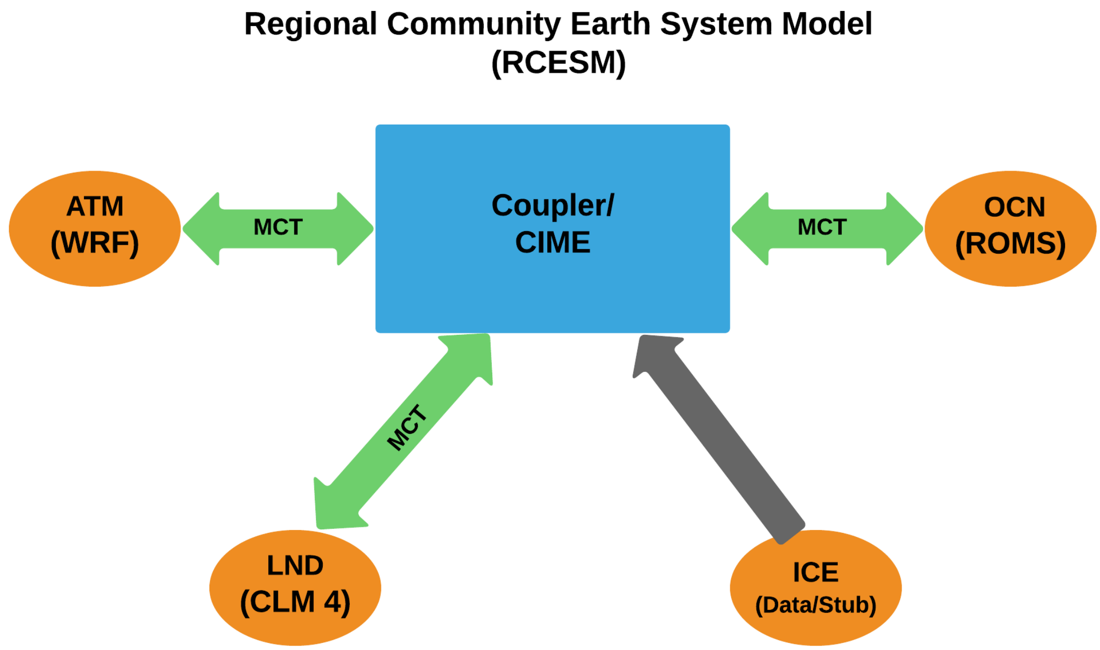


Figure 19. An overall schematic of the Regional Community Earth System model architecture. Source: RCESM website https://ihesp.github.io/rcesm1/introduction.html#id2

Model domains and schemes

Since our research topic focuses on the Amazon Plume region, the model domains are configured as shown in Figure 20. The inner black box is the ROMS domain, while the figure edge is the WRF domain. In order to obtain a the good simulation of the Equatorial Counter Current, as well as boundary currents along the western Brazilian coasts and eastern Africa, the ROMS domain is broadened as far west as 5°W, and the Southern edge is set at 9°W. In order to fully cover the Amazon Plume Extension area (thin black contour in Figure 20), the Northern edge is at 21.5°N, and the Eastern edge is at 83°W. The WRF domain is designed to be slightly larger than the ROMS domain. 0-90°W and 11°S to 26°N.

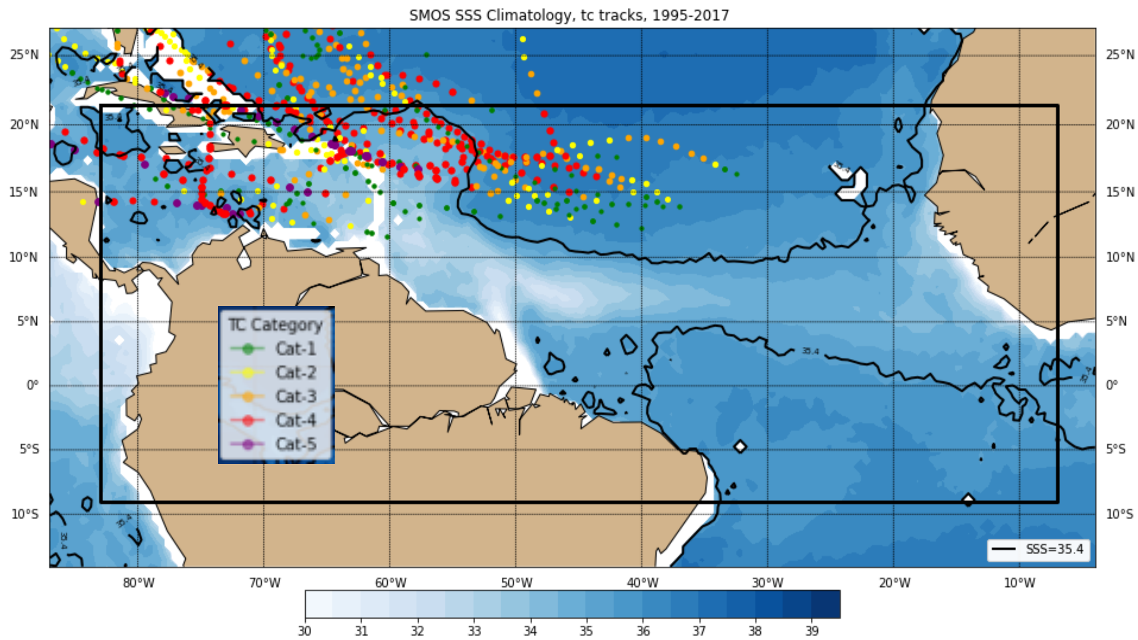


Figure 20. Model domains for WRF and ROMS, with all 21 simulated hurricane tracks from 1995-2007; . The shading is the climatological SSS from SMOS dataset, in which the solid black line represents the Plume Boundary middle line (SSS=35.4 psu). The inner black box shows the ROMS domain, while the outer box shows the WRF domain.

As for the model resolution, the spatial resolution for both WRF and ROMS is set to 10km×10km. For WRF the time step is 60 seconds. After experimenting with different combinations of physical parameterizations, we obtained the best simulation using the following combination in the tropical Atlantic Ocean region shown in Figure 20: WRF Single-moment 66-class micro-physic Scheme; RRTMG Shortwave and Longwave Schemes; Kain–Fritsch cumulus Scheme.

Dataset Input

The reanalysis dataset we use as the WRF initial and boundary input is from Climate Forecast System Reanalysis (CFSR, https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr). This reanalysis product is generated from a global 38 km resolution coupled air-sea-land-ice model, except it's 0.25 degree near the equator. The time resolution is sub-daily. The vertical levels are 40 levels. The start year in this dataset is from 1979 to the present. It is version 1 before 2017, and version 2 after 2017, with different versions requiring different tables for WRF pre-processing. Compared with NCEP datasets, CFSR is better at finer resolution, advanced assimilation schemes, and assimilates satellite radiances. More importantly, CFSR is the only dataset that could reproduce a Category-4 hurricane intensity in our research domain for WRF model when used as initial and boundary conditions, when compared with NCEP, ECWMF datasets.

Copernicus datasets have been used as ROMS model input initial and boundary input (https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_PHY_001_030). It is the CMEMS global ocean eddy-resolving reanalysis dataset, combining with observational data assimilation, the sources of which are in-situ TS profiles, observed sea level and SST. The Copernicus dataset we have chosen has spatial resolution of 0.083 degree and 50 vertical levels, and time interval is daily (averaged). The datasets are for the period 1993/01/01 to 2019/12/31.

For the XROMS domain, the domain resolution and initial dataset resolution should be the same with ROMS, since it's the representative for the ROMS model output. However, it is better to use the same dataset as the WRF ground surface data, in order to eliminating any data inconsistency.

Experimental design

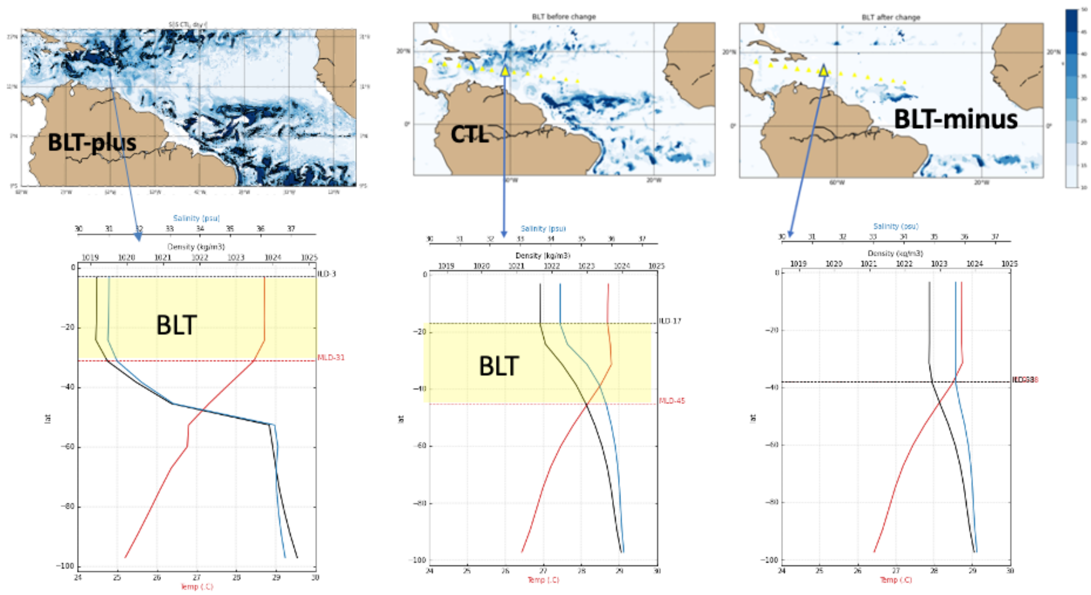


Figure 21. Hurricane No. 200704 tracks (yellow triangles) for BLT-plus, CTL and BLT-minus experiments in the upper panels, the shading is the BLT at the first time of the simulation. The vertical temperature, salinity and density profiles for location at 61°W, 13°N are at the bottom panels. The area between ILD and MLD has been marked as BLT. In the BLT-minus experiment, only the salinity profile has been modified manually in the input datasets.

For each hurricane, we did two sensitivity experiments: one is BL-minus EXP, which reproduces the situation where the freshwater layer is removed, while keeping all other variables the same; another is BL-plus EXP, which reproduces the situation that the freshwater amount is increased.

Figure 21 is 3 hours running output from model, which shows the adjustment of the model responding to the modulation of the salinity profile and serves as the pre-existing conditions before hurricane arrival. Figure 22 shows the Salinity distribution horizontally and vertically.

Figure 21 lower panels show the vertical profiles after salinity has been modified for the sensitivity experiments. Basically, for BLT-minus EXP (Figure 21, right), what we did is to replace all the data, which is lower than 36 psu, namely Plume region, by the uniform value of 36 psu: Salinity_minus = 36 (where Salinity_original < 36 psu). From the BLT-minus vertical profile in Figure 21, we see that the salinity in upper 30 meters has been changed into 36 psu. The horizontal and vertical salinity are all uniform in Figure 22. The density profile is also changed at the same time. It is worth noticing that there is a slight temperature inversion in the CTL temperature profile at 20 meters (Figure 21, middle), which was balanced by the great salinity gradient, resulting in a stable upper ocean. After removing the salinity gradient, the temperature inversion was gone by the model adjustment within the first 3 hours in order to achieving a stable upper ocean.

The second EXP is BL-plus (Figure 21, left), where we increase the freshwater amount: replacing the salinity by half its original value at the Plume region where salinity is lower than 36 psu: Salinity_plus = Salinity_orginal / 2 (where Salinity_orginal < 36 psu). In the horizontal SSS distribution, there is larger area of freshwater shown in Figure 22a. In the vertical salinity profile, the freshwater volume is greater. As a result, the whole upper ocean becomes more stratified, while the halocline becomes deeper and stronger. The T-MLD gets shallower as the temperature profile has also been modulated by the salinity, as we discussed before.

Figure 21 upper panel shows the BLT distributions in three experiments: the BLT turns into higher and more widely distributed in the BLT-plus EXP, while the BLT is almost zero in the BLT-minus EXP.

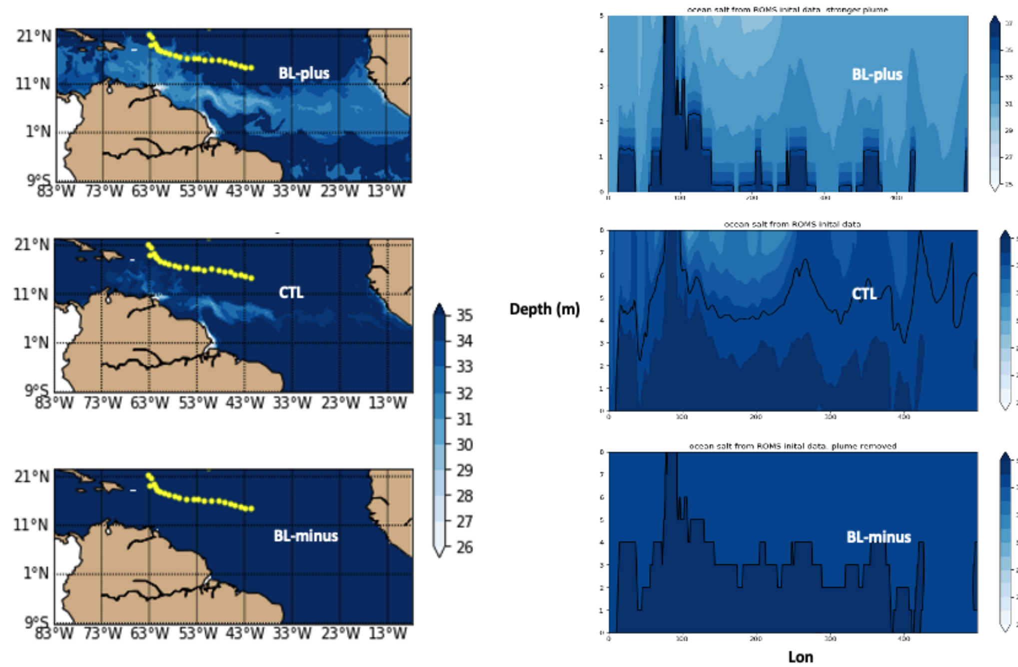


Figure 22. Model input Initial SST horizontal distribution (left panel) and vertical cross-section (right panel) in three experiments. The vertical profile changes with longitude at latitude 15 °N among the Plume. The example is Hurricane No. 200306.

methods

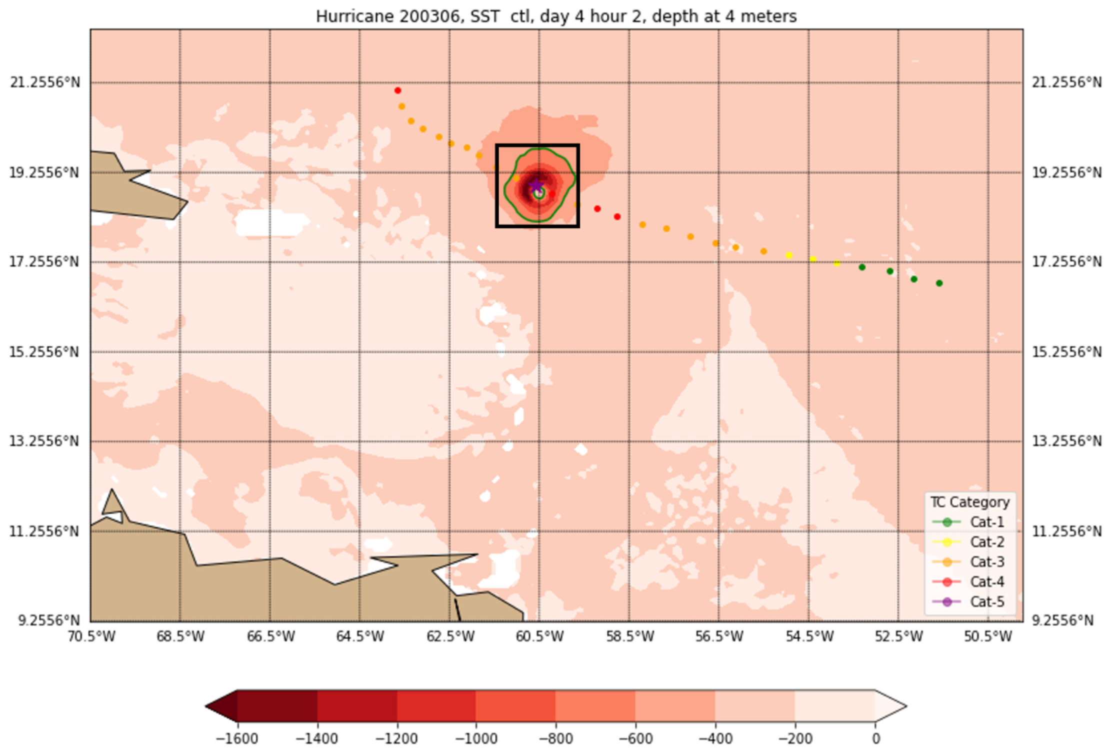


Figure 23. Box size for calculating box-mean comparing to the Cat-4 hurricane (No. 200306) heat flux. The green contours shows Flux=600 $\boldsymbol{Watt/m^2}$ The black box shows the box-mean size.

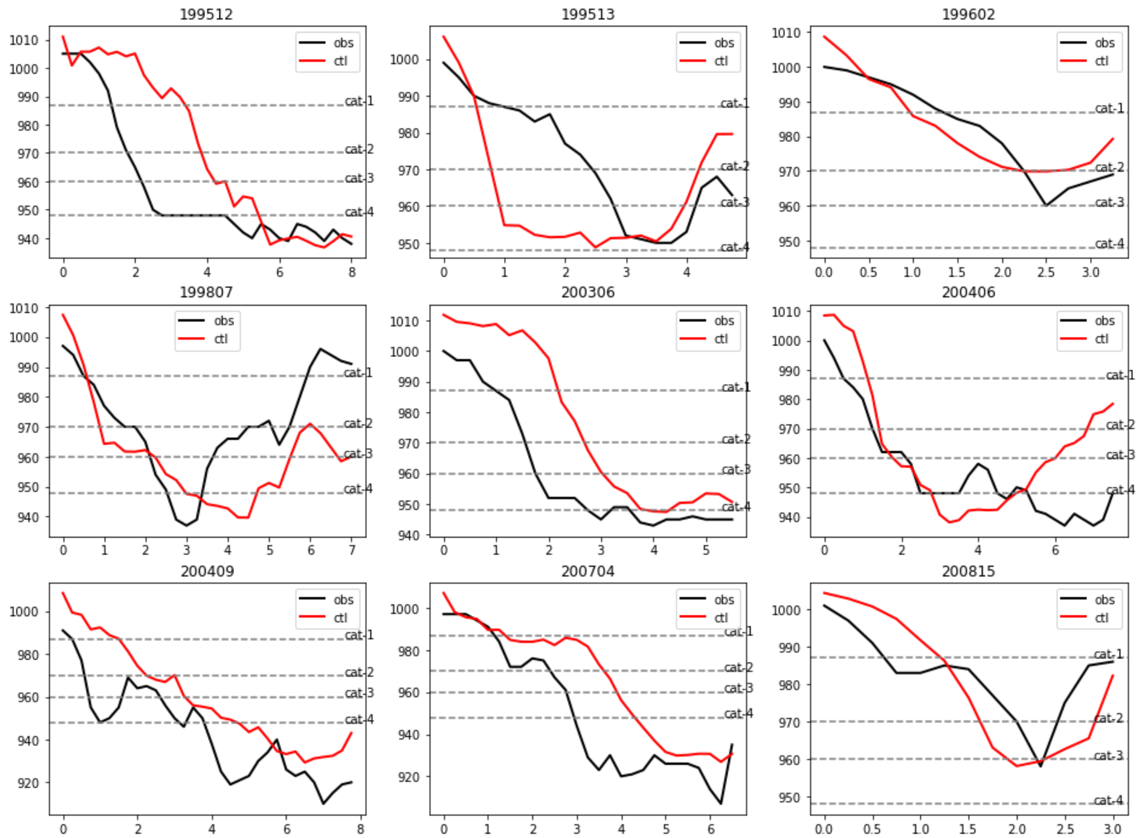
The hurricane flux averaging box size is chosen as 200×200km, since it covers the extent of most of the Cat-4 hurricanes we picked, as well as the weaker hurricanes. Figure 23 shows the heat flux while its intensity reached Cat-4. Fifty percent of the heat flux is concentrated within the green contour region, which means that over 50% heat flux is within the black box.

We didn't make the box size large enough to cover all the heat flux is because the larger the box, the smaller SST cooling value we obtain with the box-mean averaged process. Additionally, a larger box is more likely to capture unrelated phenomena which can also affect the SST change. After testing the box-size with different sizes, we found

200×200km to be a good compromise size, that not only covered most of the hurricane heat flux, but also captured the SST cooling and its reduction due to BLT effects.

Results

Simulation Validation



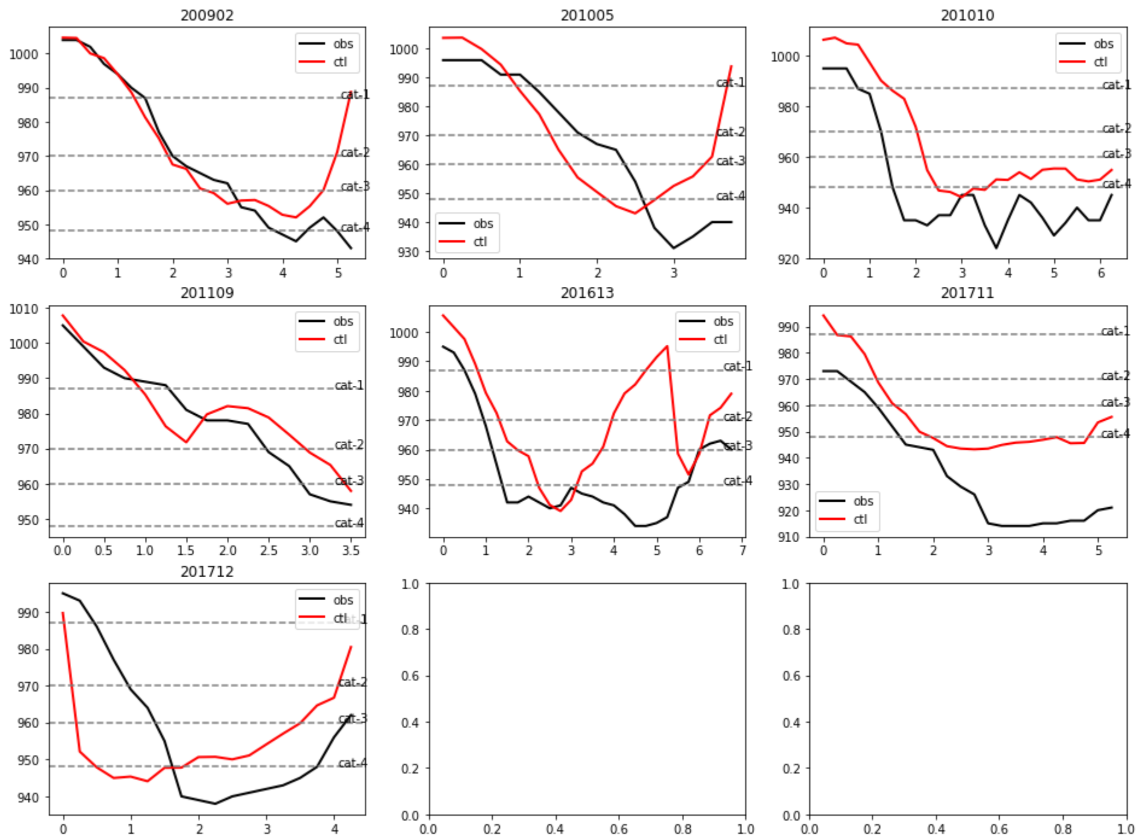


Figure 24. Simulated SLP of all hurricanes (red line) comparing with the observational SLP (black lines). The category by SLP is defined from https://www.ssd.noaa.gov/PS/TROP/CI-chart.html

Categories (Observational/ Simulated)	Median Translation Speed (m/s) intervals: counts	Rapid Internsification (30 kt/24 hrs) counts
Cat-2 (1/1) Cat-3 (2/2) Cat-4 (8/7) Cat-5 (5/2)	4-5: 1 5-6: 10 (9 are major HU) 6-7: 2 7-8: 1 10-11: 2	11
Simulated Category: Cat2: 199602 Cat3: **200815**, 200902, **201109** Cat4: **199512, 199513, 199807**, 200306, **200406,** 201005, **201010, 201613, 201711, 201712** Cat 5: **200409,** 200704 Red color: intensity under simulated hurricanes		

Bold: slow Translation speed (<6m/s) Underlined: Rapid Intensification

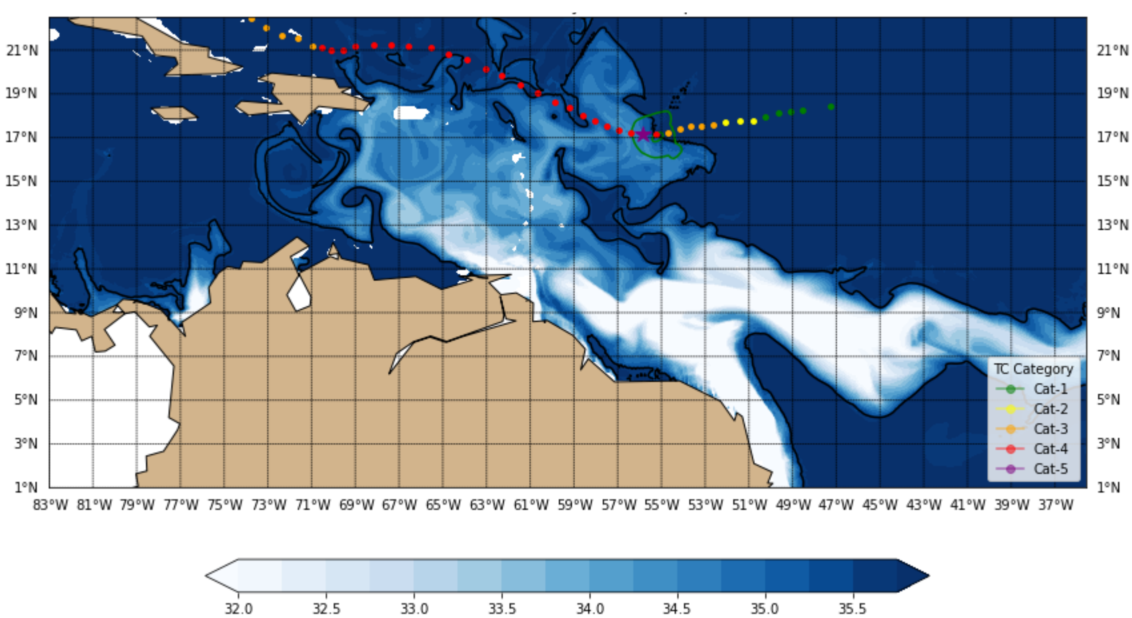
Table 5.Hurricane information from Observations and Control simulations

Overall, out of 21 hurricanes that passed over the Plume region from 1997-2017, there are 16 well simulated hurricanes in terms of both the hurricane intensities and tracks, which means the simulated hurricane intensity matches the observations with the difference ranging within a category. The comparisons between the observed SLP evolution and model simulated SLP are shown in Figure 24 for all 16 cases.

For Category-4 hurricane, it has always been hard to reproduce the observed strength in model simulations, especially with the 10 km spatial resolution. Some techniques, such as bonussing, have been used to improve the intensity simulation. However, with the whole combination of the chosen physical parameterizations and the initial datasets (mentioned in the method section), we successfully reproduced 12 Major Hurricanes in the model out of 13 Major Hurricanes in observations. More details of the hurricane categories are shown in Table 5. There are 8 Cat-4 hurricanes in observations. 7 of them could reach Cat-4 in the model, while one remains as Cat-3. There are 5 Cat-5 hurricanes in observations. 2 of them could reach Cat-5 in the model, while 3 remains in Cat-4. The under simulated hurricanes are marked in red color in Table 5. Moreover, there are 11 hurricanes that experienced a Rapid Intensification (RI) period, which are underlined in Table 5.

Regarding the translation speed, we use the median value as a representative for each hurricane since the hurricane usually passes across the Plume in the middle of its track. Eleven hurricanes move at a speed slower than 6 m/s, marked as Bold in Table 5. Therefore, it shows that those hurricanes are slow-moving, well simulated Major Hurricanes with an RI period: No. 199512, 199807, 200406, 201010, 201613, 201711, 201712, 200409. As we mentioned before, the slow-moving hurricanes usually have stronger air-sea interactions, so do the Major hurricanes. Therefore, the blocking effect of BLT may be easy to identify in those cases.

Experiments results: BLT effect on reducing SST cooling



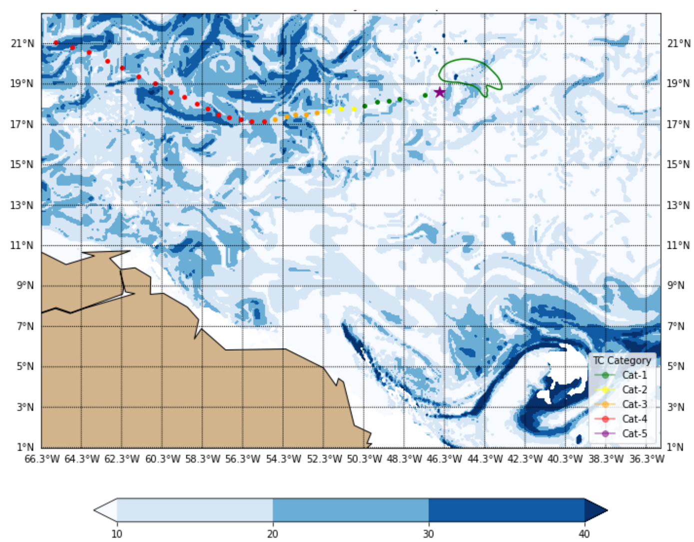


Figure 25. Hurricane No. 201711 simulated track in the CTL run. Shading: the SSS (upper) and its BLT (lower) before the hurricane generated. The purple star represents its location at day 2.

We initially focus on Hurricane No. 201711 because its track crosses the Plume while it's in Cat-4, and the translation speed is relatively slow at 5m/s, making it a slow-moving hurricane. We also see that it crossed the Plume Boundary region, where the Barrier Layer is as thick as 20 meters (Figure 25). Therefore, this slow-moving Major Hurricane over the thick BL could be an ideal example to show the BL effect.

As described in the method section, three experiments were carried out: CTL; BL-minus (removing the freshwater), and BL-plus (lower the salinity to its half). It means, there exists no BL in the BL-minus, while the BL is thicker in the BL-plus.

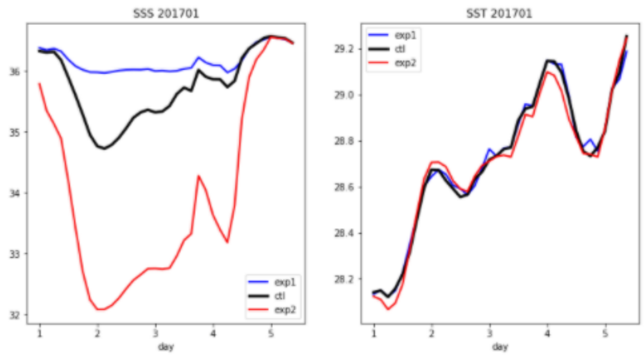


Figure 26. Box-mean SSS and SST in BL-minus EXP and CTL (blue), CTL (black) and BL-plus EXP (red) along the hurricane tracks for hurricane No. 201711.

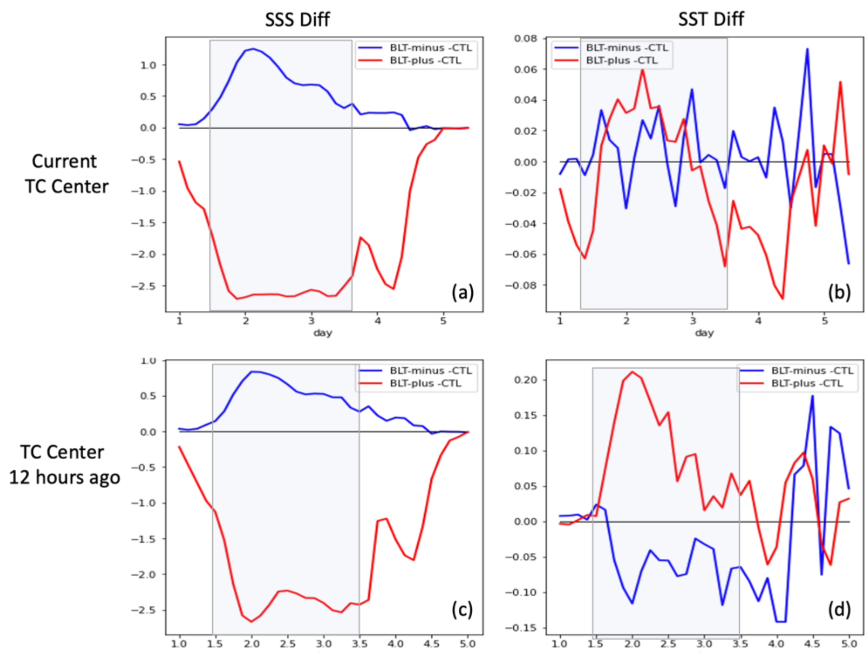


Figure 27. Box-mean SST, SSS difference between BL-minus EXP and CTL (blue), between BL-plus EXP and CTL (red) along the hurricane tracks. The gray shading boxes highlights the adjusted areas for hurricane No. 201711. The upper panels shows the box-mean around the TC center, while the lower shows the box-mean on the TC tail, where it was for the past 12 hours.

Figure 26 shows the box-mean SSS/SST around the hurricane center in three experiments. Figure 27 upper panels are the SSS/SST difference between EXPs and CTL around the hurricane center. The CTL experiment shows the original freshwater condition: during day 1.5 to 3.5, the hurricane passed over Plume region (SSS<36 psu),. Therefore, the great SSS difference between three models will only be shown between day 1.5 to 3.5, which is marked as grad shading in Figure 27.

In BLT-minus EXP (blue), all the salinity under 36 psu has been replaced with the constant 36. Therefore, the SSS difference between BL-minus and CTL (blue line) is positive shown in Figure 27a because the salinity is increased after removing the freshwater. The maximum SSS difference is 1 psu at day 2. However, the SST is very fluky.

In BLT-plus experiment, the SSS is as low as 2.5 psu different from the CTL at day 2, which leads to a very modest SST warming 0.06°C under the hurricane coverage. It means when increases the freshwater volume, the increased BLT effect will perform better for reducing SST cooling. In other words, the BL effect won't saturate.

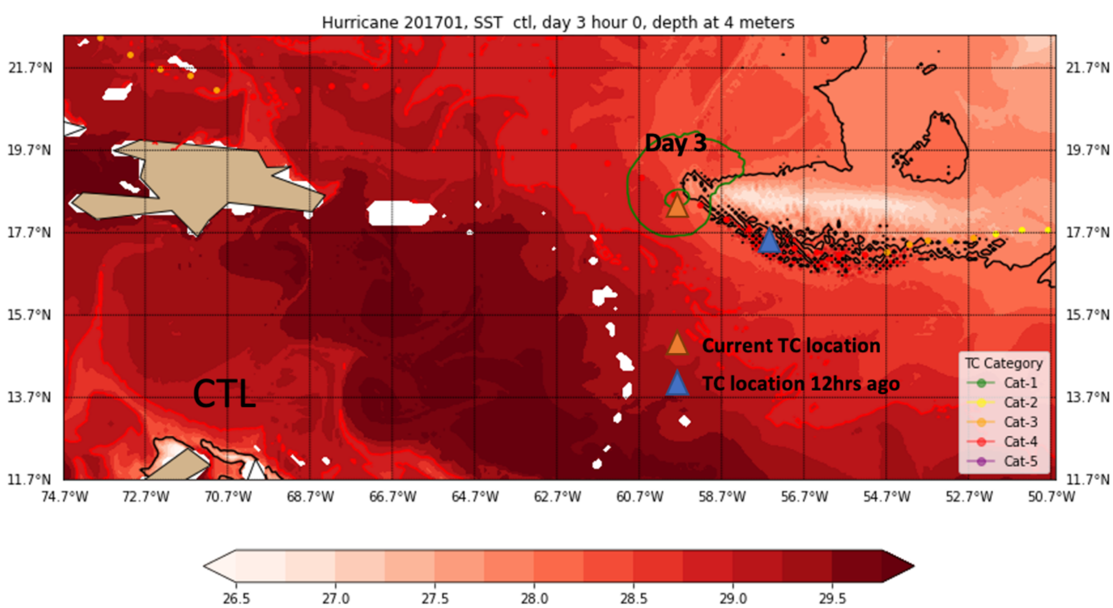


Figure 28. The SST on day 3 for Hurricane No. 201711. The green contour is heat flux=600 $\boldsymbol{Watt/m^2}$, represents the hurricane shape. The black contour shows 28°C isothermal line. Hurricane track is in 3 hours intervals.

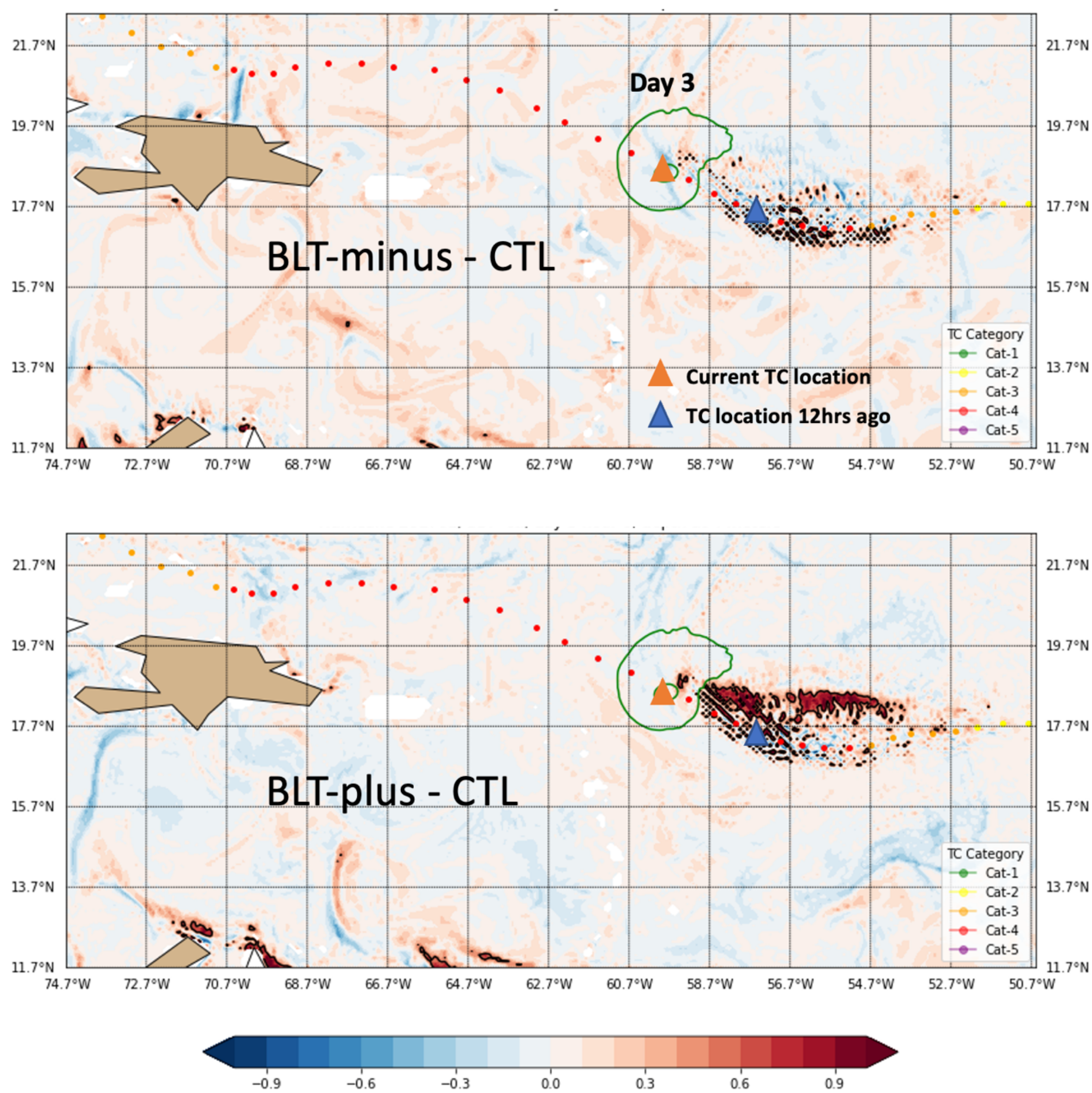


Figure 29. SST differences between experiments at Day 3. Triangles are TC centers currently (orange) and 12 hours ago (blue). Hurricane track is in 3 hours intervals.

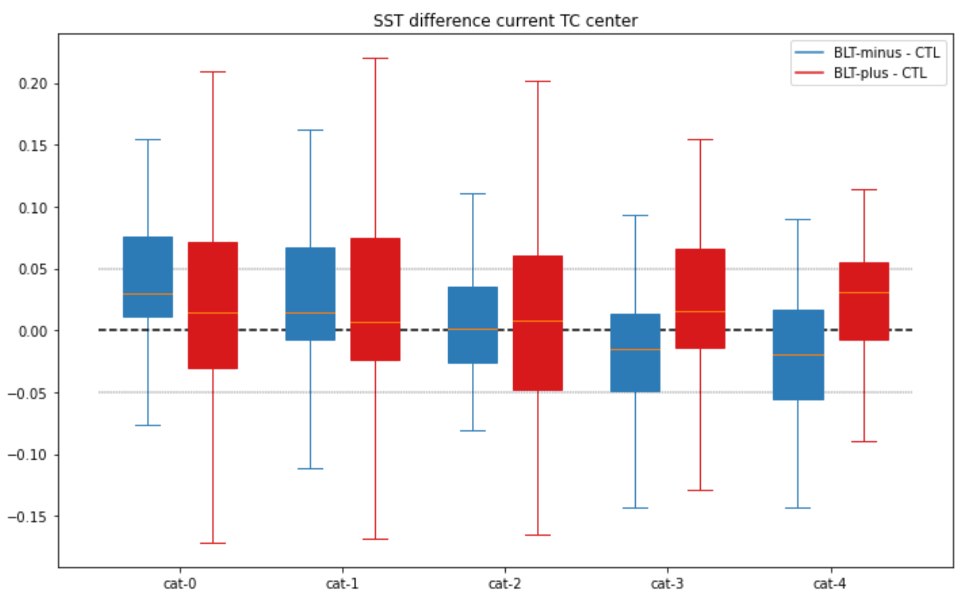
The SST cooling center has been found on its lee, where the hurricane was located 9-12 hours ago. Hurricane No. 201711 passed over the lowest SSS/highest BLT region on day 2. The SST on day 3 could display the cooling over the Plume region (Figure 28). The hurricane induced maximum cooling of nearly 2 degrees at the previous hurricane location 9-12 hours ago. Specifically, the SST is as low as 26.5°C at the cooling center, while the lowest SST under the hurricane center (represented by the green contour) is still over 27°C. Moreover, the cooling area is only very small part of the hurricane coverage region. Therefore, the box-mean cooling under the Hurricane center should be even lower.

Highly depend on the SST cooling, the reduced SST cooling by the BLT effect is also observed strongest at the maximum cooling area on its lee, while very modest under the hurricane center. Figure 29 shows the SST distribution differences between perturbation experiments and CTL at day3. When we remove the BLT/freshwater, the SST is cooler on the tail region of the track (Blue Triangle in Figure 29a). This means without the blocking effect of BLT, the SST tends to cools more. The box-mean averaged SST difference centered at the Blue Triangle (TC location 12 hours ago) shows there is a 0.1°C reduction in SST cooling due to the thickness of the BL in CTL (Figure 27d; blue line).

With increases the freshwater volume from CTL to BLT-plus, the SST tends to be warmer on the tail of the hurricane track. The black contour is 0.5 °C SST warmer, and it exists from the hurricane location 3 hours ago to its location 1 day ago. Similarly, the box-mean around the Blue Triangle (TC location 12 hours ago) shows a greater than 0.1°C warmer SST. For day1.5-3.5 while crossing the Plume, the maximum reduction in SST could be 0.2°C in BLT-plus comparing to CTL (Figure 27d; red line). This means that the reduced SST cooling increase as the freshwater amount increases.

In a conclusion, the case study of Hurricane No. 201711 shows the BLT does not have the effect of reducing SST cooling under the hurricane coverage region because the SST cooling is itself is very small around the hurricane center region. However, it could effectively reduce SST cooling on the hurricane tail at the previous hurricane location near 9-12 hours earlier, which is where the maximum cooling could be 2.5°C.

With increased freshwater volume, the reduction in SST cooling is stronger. Quantitively, the box-mean reduced SST cooling is 0.1°C, while SSS is 1 psu less comparing results from the BL-minus experiment and CTL; the reduced SST cooling is 0.2°C, while SSS is 3 psu less in the hurricane tail comparing the BL-plus experiment and CTL model results.



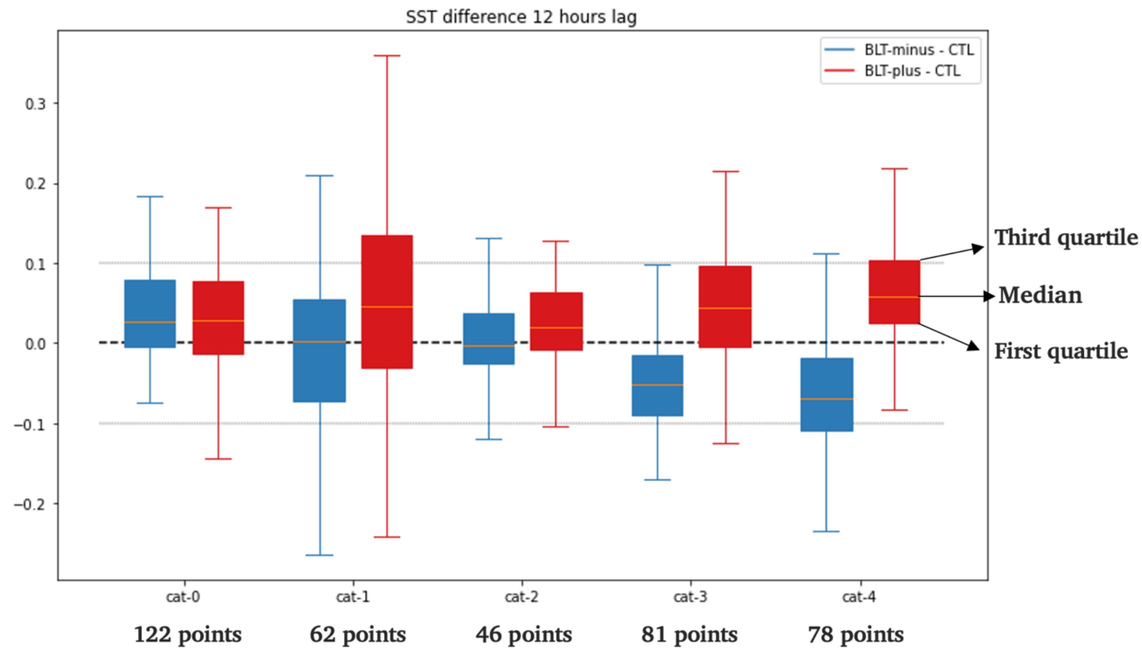


Figure 30. The composition of SST box-mean along hurricane track of 18 simulated hurricane cases during 1995-2017 in BL-minus (blue), CTL (gray), BL-plus (red) (upper panel). SST box-mean difference along hurricane track of all simulated hurricane cases in BL-minus (blue), BL-plus (red) (lower panel). The upper panel used the current TC center. The lower panel used the past TC center in the last 12 hours. 389 points in total.

For our coupled model (RCESM) simulation study, two sensitivity experiments (BL-minus, BL-Plus) were carried out for all 21 hurricane cases, Three hurricanes have been removed from the datasets: No. 199513 due to an unstable simulation in BL-plus EXP; No, 200704 and No.201005 will be explained in the next section. To enlarge the datasets, we have kept all the remaining 18 hurricanes that passed over the Plume region, even if the observed hurricane intensity could not be reproduced exactly, since the purpose here is to compare control and sensitivity experiments. With outliers removed, overall, there are 389 datapoints, where the hurricane was inside the Plume region. Each datapoint contains the box-mean SSS, SST, Heat Flux, and SLP from three experiments: CTL, BL-plus, BL-minus.

Then we collected all the datapoints on the 18 hurricane tracks, where it was over the Plume region, and the SSS is modified in the EXPs. Overall, there are 389 datapoints for each EXP. Moreover, we split the dataset based on the hurricane category when it passes over the analysis location, since the BL's effect usually works better for Major Hurricane, which would generate a stronger air-sea interaction. The stronger hurricanes are likely to have strong BLT effects.

Figure 30 shows the box-mean SST differences between the EXPs and the CTL. The negative value implies reduced SST cooling due to the existence of Plume/BL. The positive value implies increased SST because Plume volume has been increased. The upper panel is the box-mean centered by current hurricane location, while the lower is the box-mean centered the previous hurricane location 12 hours earlier, the same as was done earlier in Figure 19.

In terms of the BLT's effect on reducing SST cooling, the results are very consistent with the case study of No. 201711. Let's first look at the box-mean around the current hurricane center (Figure 30a). Even for Major Hurricanes, the reduced SST cooling by the BLT under the hurricane center is not statistically significant. The median of the box plot for SST cooling difference between BLT-minus and CTL (Figure 30a, blue) is negative, which means that upon removing the freshwater, the SST under the current hurricane gets cooler as we expected. However, the third quartile of both boxes are only -0.05°C. Similarly, when the freshwater volume increases in BLT-plus (Figure 30b, red), the SST under hurricane center gets warmer as we expected since the median of the red box (BLT-minus -CTL) is positive, but it's still very weak. The third quartile only reaches 0.05°C. Moreover, the first quartile of red box overlapped with third quartile of blue box, which means nearly half of their distribution overlapped. The distributions of those two datasets are not significantly different.

Then, for the reduced SST cooling on the tail (Figure 30b, centered by the hurricane location 12 hours earlier), we found that the reduced SST cooling by the BL is much more significant than it's under the current center. The third quartile of both boxes higher than 1 °C (-1°C), and the medians over 0.05°C (-0.05°C). Besides, it reveals that the BLT's blocking effects increases when the freshwater volume increases significantly, since the reduced SST cooling in BLT-plus is significantly different from that from BLT-minus for major hurricanes (>Cat-3). The range from the First quartile to Third quartile of red boxes (BLT-plus – CTL) are totally out of the range of the blue boxes (BLT-plus – CTL).

Comparing to the previous studies, the reduced SST cooling value 0.05-0.1°C we gave is a little lower.

BL effect on vertical mixing

It has been found that the major SST cooling has been found in the hurricane tail, and the SST cooling in the hurricane center is observed modest. However, there is still 0.05 °C box-mean SST difference around the hurricane center between EXPs for major hurricanes. Is this the result of the BLT effect?

As well acknowledged that the rapid oceanic response to the hurricane wind stress is the vertical mixing. Since it occurs within a few hours after hurricane arrival, the vertical mixing could be responsible for the SST cooling under the hurricane, and efficiently have a feedback on the hurricane intensity. Therefore, this process will be well studied in this section.

To be more specifically, the wind stress induces the ocean surface current. The current shear in the upper ocean will generate the turbulence. Since the temperature in the mixed layer is uniform, the velocity shear near the bottom of the mixed layer is essential as the key factor to induce cold water entrainment from the thermocline into the mixed layer (Qiu et al., 2018). thickening and cooling the mixed layer (Glenn et al. 2016; Seroka et al. 2017; Yang et al. 2019).

Actually, the BL has been claimed acting like a buffer to reduce the wind-induced momentum transferring downward to the thermocline (Rudzin et al., 2018). Our model results will be used to examine this results, and explain which process as described before would be prohibited by the BL structure.

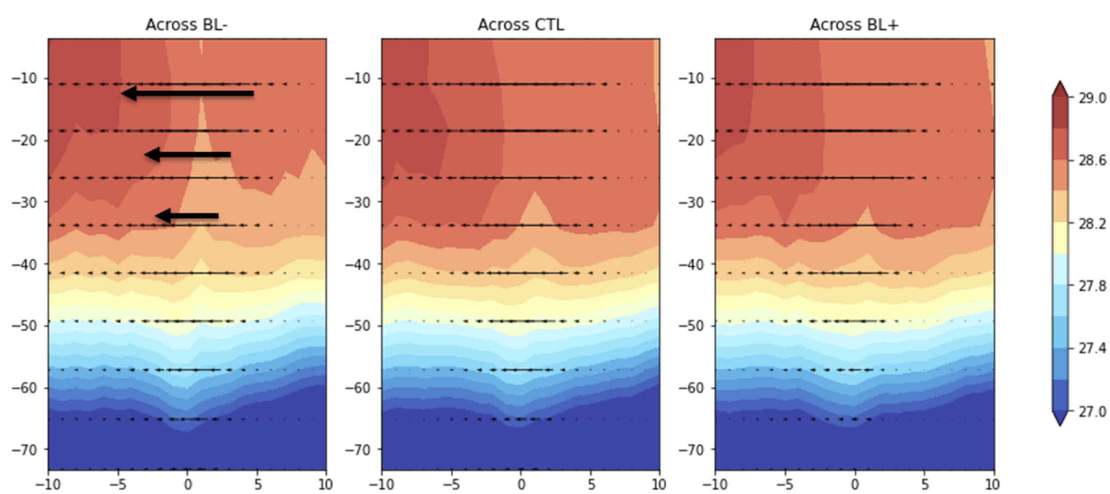


Figure 31. The vertical temperature cross-section compositions for all 21 hurricanes, perpendicular to the track, when it's inside the Plume region in three experiments. The arrow shows the horizontal current velocity.

The vertical cross-section compositions of all the datapoint on the hurricane track, when it's over the Plume, is given in Figure 31. It displays the upper ocean temperature and velocity distribution under the hurricane center. The cross-section is cut perpendicular to the hurricane, and centered by the hurricane eye with a radius of 100km, same with the box-mean size. Figure 31 represents the transient upper ocean temperature feedback to the hurricane wind stress within 3 hours after hurricane arrival.

It seems that the BL structure could efficiently reduce mixed layer from deepening and cooling. The base of temperature mixed layer appears to at 35 m under the hurricane center in CTL and BL-plus, while it is at 25m in BL-minus (without the BL structure).

Moreover, the reduced SST cooling after removing the BL could reach >0.08°C under hurricane center at the right of the track (Figure 32a), while it has been warmed up to 0.05°C in the BL-plus (Figure 32b). The temperature cooling change concentrated at 35 m, between ML and thermocline interfere (transition layer).

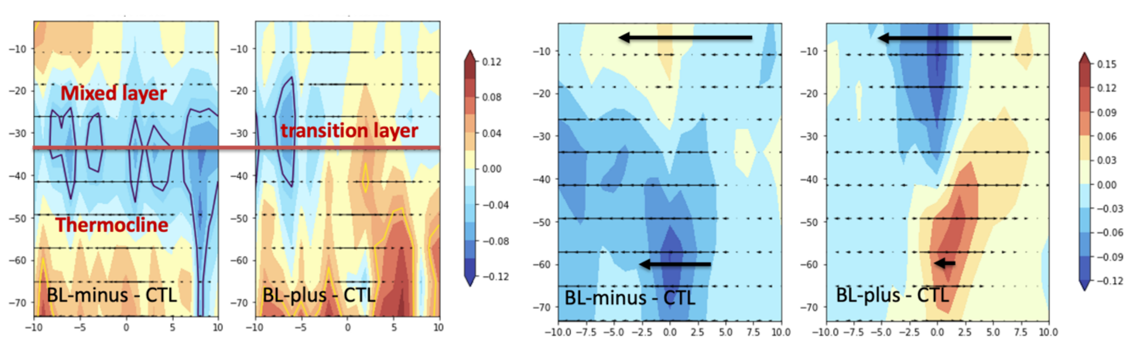


Figure 32. The temperature anomaly between BL-minus and CTL, BL-plus and CTL (a,b). The horizontal velocity anomaly between BL-minus and CTL, BL-plus and CTL (c,d). The arrow shows the horizontal current velocity anomaly. The contour equals to 0.05°C.

The temperature difference around the MLD may be caused by the current velocity difference in the thermocline. The horizontal current velocity induced by the wind stress is maxima near the surface, decreasing as the depth getting deeper (Figure 31). The wind stress momentum caused current velocity could be transferred into the thermocline at 55m in all EXPs, therefore inducing the cold water to the mixed layer.

However, comparing to CTL, the velocity in the thermocline is higher in BL-minus, after removing the BL (Figure 32c). On the contrary, the velocity in the thermocline has been observed lower in BL-plus (Figure 32d). The higher subsurface current velocity will generate a stronger turbulence, which brings more cold water entrainment into the mixed layer, vice versa.

In conclusion, the BL could reduce mixed layer from deepening and cooling by inhibiting the wind-induced current velocity from transferring down. The composition overall displays the BL effect on reducing temperature cooling, however, is under 0.1°C at most near the MLD, which is considered insignificant in terms of hurricane intensification discussed later. Furthermore, the maxima of the reduced temperature change residing at the MLD will later be evenly distributed in the mixed layer, resulting in an even lower reduced SST change.

Experiments results: Heat Flux and SLP

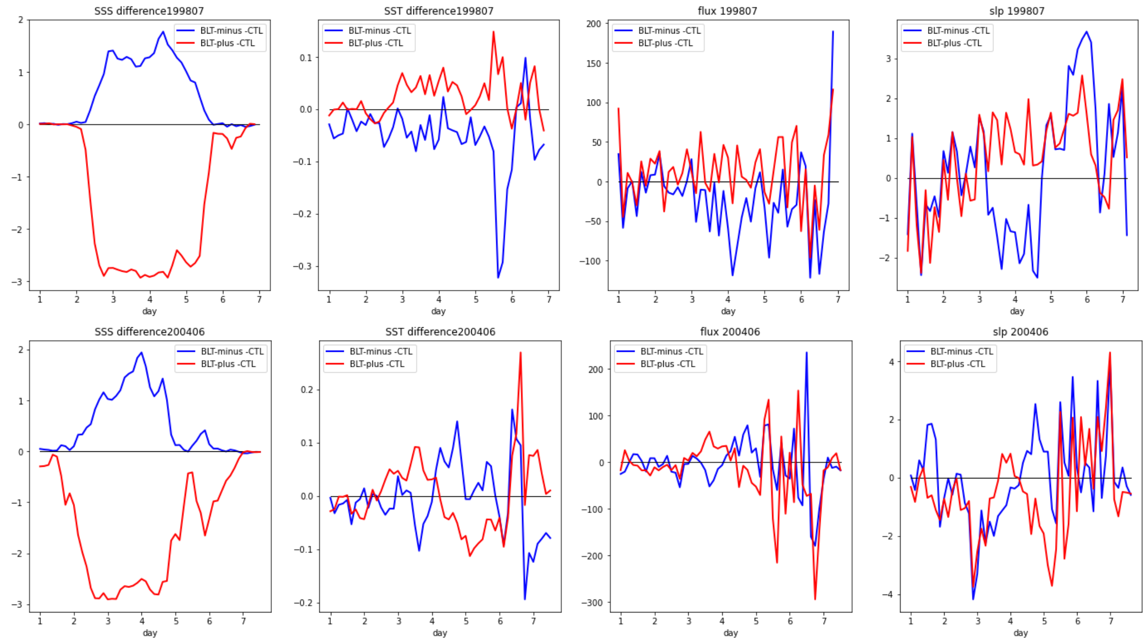


Figure 33. The box mean SSS, SST, Flux, and SLP difference between experience and control for Hurricane N0. 199807 and No. 200406

As we mentioned before, the greatest benefit of using coupled models is being able to study the oceanic feedback on hurricanes directly. Even though most of the cases don’t show a reduction of SST cooling under the TC as describe before, there are two hurricane cases that achieved over 0.1°C reduction in SST cooling for the box-mean around the current TC center: No. 199807, and No. 200406. The box-mean of SSS, SST, heat flux and SLP change are shown in Figure 33.

For No. 200406, which is still considered as a fast-moving hurricane, the max cooling occurred on its tail. The hurricane intensity reached Cat-4 while it entered the Plume with a lower salinity, and lasted longer for 2 days within the Plume (shown in Appendix). The SSS difference is almost 2 psu between CTL and BLT-minus, which is much greater than the difference in No. 201711 (1 psu), which affects the BLT (shown in Appendix). As a result, the reduced SST cooling is a bit more significant: in the middle of day 3, the reduced SST cooling reached 0.1°C. The heat flux was found to be 50 $Watt/m^2$ greater, while SLP is about 2 mph less in CTL comparing with the BLT-minus EXP. In the opposite, in BLT-plus, when the SSS decreases by 3 psu, the SST cooling was reduced by 0.1°C, and the flux increases by 50 $Watt/m^2$, while SLP only changed 1 mph.

For No. 199807, the quantitative changes in SSS, SLP and fluxes are very close to the situation in No. 200406: with a 2 psu change in SSS, resulting in a 0.1°C SST change, 50 $Watt/m^2$ flux change, and 2 mph SLP change.

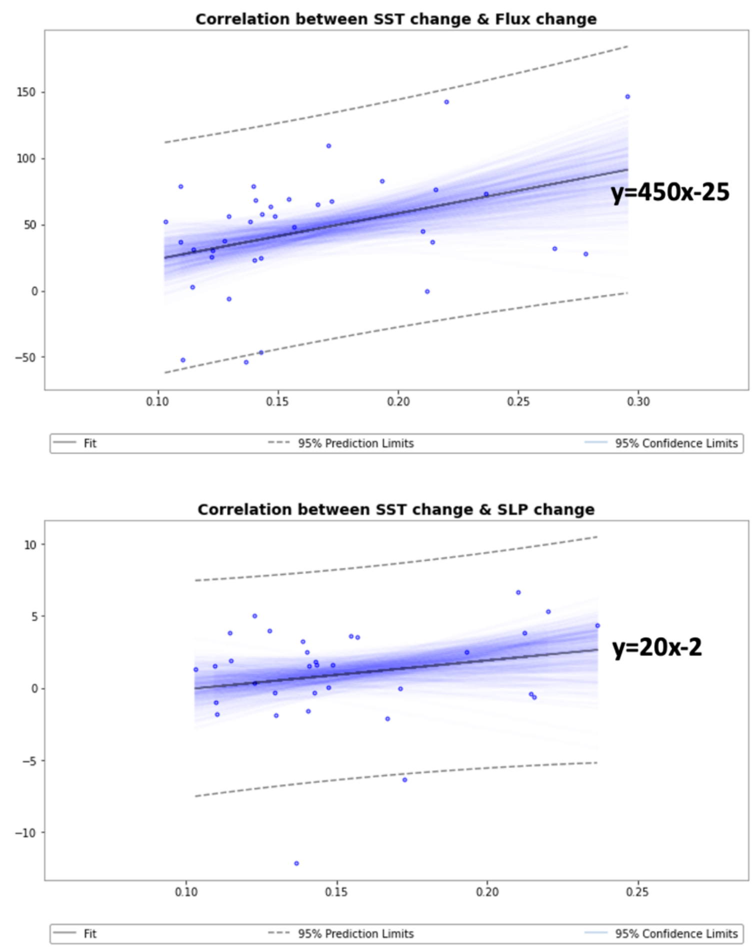


Figure 34. The correlation between SST change & Flux change, and correlation between SST change & SLP change. With a 95% prediction confident limits.

Next, we identify all the datapoints where the reduced box-mean SST cooling (in both CTL - BLT-minus and BLT-plus - CTL) reaches 0.1°C, while the hurricane intensity is over Cat-4. We only consider the Major Hurricanes, since the minor hurricanes has been shown to be less likely to have a reduced SST cooling due to the BLT blocking effect. If we consider minor hurricanes, we more likely to include unrelated signals, such as horizonal advection induced SST cooling. Moreover, we only consider the points with SST difference greater than 0.1°C , since if the reduced SST cooling is so small, their heat flux is very noisy, and it's hard to have significant impact on hurricane intensity (SLP). Overall, there are 36 datapoints identified that satisfy the criteria.

We computer a linear regression for SST change & Flux change and SST change & SLP change, with a 95% confidence limits (in Figure 34). The density of overlapping blue lines indicates improved confidence. It's the resampling residuals for 500 times iterations. The more datapoints falls into the blue shading, the more accurate the fitting is.

The results of the fitting are:

$$\text{Flux change} = 450 \times \text{SST change} - 25$$

$$\text{SLP change} = 20 \times \text{SST change} - 2$$

It means for each 0.1°C reduced SST cooling, there are 45 $Watt/m^2$ more flux transferred into hurricane from the sea surface. For each 0.1 °C reduced SST cooling, the hurricane intensity will increase 2mph. The results are very close to the case study before.

In conclusion, we find that the reduced SST cooling signal could be successfully transferred to hurricane intensity, and cause a hurricane intensification, as long as the SST cooling change is significant. However, the impact on SLP are only 2 mph for a 2 psu change, especially they are all below the Cat-4 wind speed.

Temperature Inversion effect

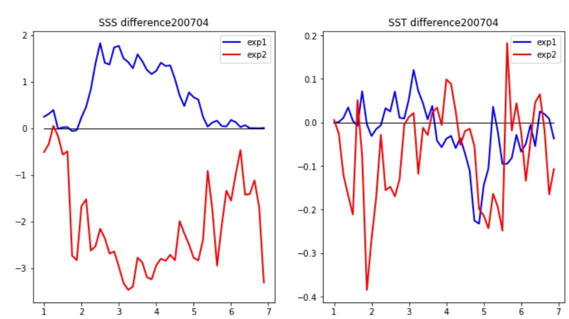


Figure 35. The box-mean SSS and SST difference for hurricane No. 200704

In this section, we will talk about Minor Hurricanes or even tropical storms over Plume region.

Hurricane 200704 has experienced strong Plume, with the SSS as low as 34 psu. However, it's only Cat-2 while moving across Plume. However, the SST change is opposite from what we expected: BLT-minus has a higher temperature while BLT-plus has a lower temperature from day 2 to day 3.5. During those time periods, the hurricane crossed over the Plume with the BLT over 20m, and temperature inversion over 0.1°C shown in Figure 36.

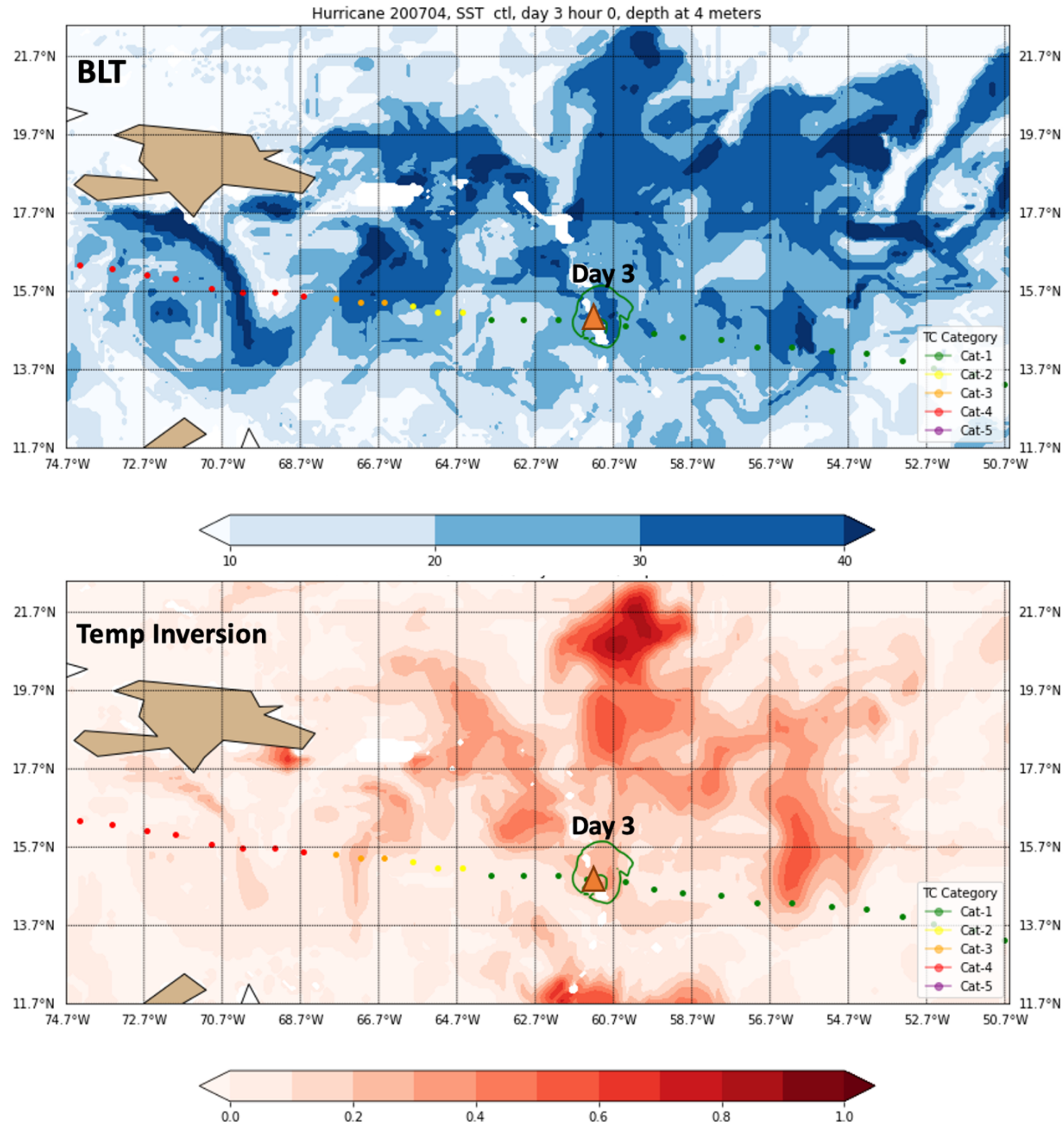


Figure 36. The BLT and Temperature inversion distribution before at the first date of hurricane generations. The triangle shows its location at Day 3.

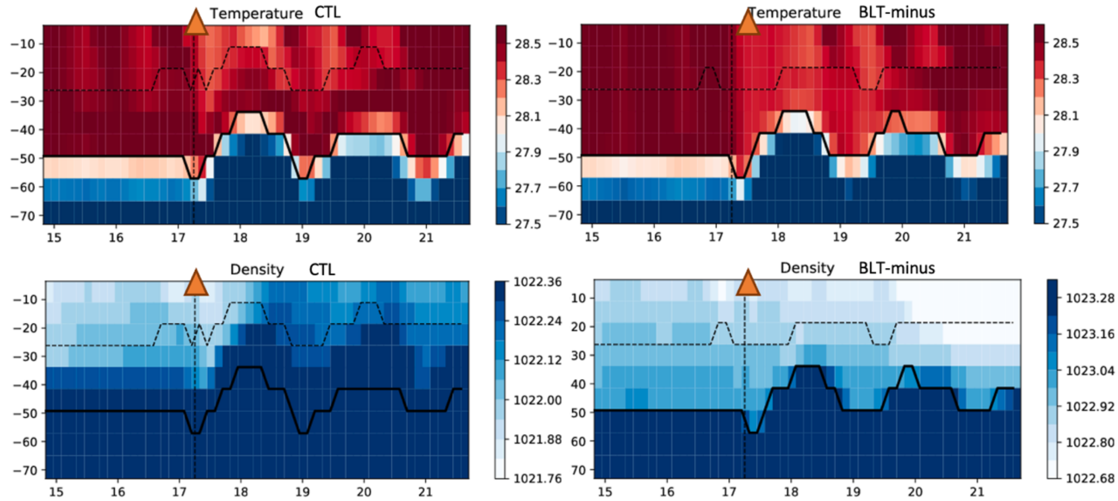


Figure 37. The vertical profile evolution with time at the location marked as an triangle in Figure 36. The dashed black lines are D-MLD, the solid black lines are T-MLD. The triangle shows the time when hurricane arrives.

The vertical profile evolution with time at day 3 (Figure 37) shows that there are two processes:

Before hurricane arrival, with the pre-existing temperature inversion (which usually accompanies the BLT), there is a temperature maximum in the subsurface near 45 m, which migrated to the surface immediately in the beginning of the model run. Because the layered increasing salinity was changed to a uniform value, the density profile changes follow along the temperature profile (shown in Figure 21). The reversed density profile initiates the adjustment immediately after the model starts running, and the subsurface temperature maxima upwelled to the surface, and caused the pre-existing SST to be slightly warmer in BLT-minus.

When the hurricane arrived at day 3, the freshwater-induced strong stratification blocked the mixing due to the Cat-2 wind stress in CTL. Only the upper 20-30 meters cooled, while the temperature maxima at 40 meters remaining stable. It implies that the mixing depth is only 30m. However, in BLT-minus, there is no strong stratification, and the temperature maxima migration process also helps mixing up the ocean, so the upper 50 m is well mixed up before the hurricane arrives. When it arrives, the energy lost to hurricane could well spread in the upper 50 m, resulting in a warmer SST comparing to CTL.

The key factors for those processes are: the weak mixing from the minor hurricane. If the hurricane wind is strong enough (Major) to roll up the deep cold water under 50 m, and mixed up the whole upper 50 meters, the SST cooling will mainly depend on the stratification. With stronger stratification, less cold water could be mixed up.

This is why the weak hurricane (Cat-0, Cat-1) have shown opposite results from the Major Hurricane in our statistical analysis of the model results. The SST cooling in BLT-plus is least, while the SST-plus is the most.

Conclusions

In this Chapter, we successfully simulated 16 hurricanes (13 are Major Hurricanes) using the RCESM coupled model and answered two questions: whether the BLT could reduce SST cooling under the hurricane, whether the BLT could increase hurricane intensity.

We find that the SST cooling could be significantly reduced by the BLT effect on the hurricane tail where is 9-12 hours distance from the current hurricane location at it's moving speed. The box-mean reduced SST-cooling is nearly 0.1°C with the existence of the BLT there. Moreover, we also found the reduction in cooling would increase with the freshwater gets fresher, when we lower the salinity to its half, the reduced SST-cooling also doubled. However, since most of hurricane simulated were considered as fast-moving hurricane, the reduced SST cooling on its cold wake is barely under the hurricane coverage.

Moreover, the BL effect on reducing vertical mixing under the hurricane has been verified. The maxima temperature change (0.08°C) starts from the transition layer (the interface between the mixed layer and the thermocline). That's because the BL prohibits the wind-induced momentum transferring downward and reduces the current velocity near the transition layer, as well as the turbulent generation. Therefore, blocked the cold water entrainments from the thermocline into the mixed layer.

It's well known that the reduced SST cooling is only significant when the hurricane intensity is over Cat-3 — the stronger winds generate more intense ocean mixing. However, we found that for weak hurricanes (Cat-1 or Cat-0), the freshwater/BLT can have an opposite effect: it will confine the cooling to be near the surface, resulting in cooler SST. In some cases, when there is a pre-existing temperature inversion (usually in conjunction with a BL), removal of freshwater can lead to density adjustment will immediately mix the subsurface temperature maxima with the surface waters and increase the pre-existing SST before hurricane arrival. Those two processes can cause a pre-existing higher SST in BLT-minus experiment compared to the CTL simulation.

As to whether the BLT could increase hurricane intensity — even though the BLT can reduce the SST, since the reduced SST cooling does not occur right under the hurricane center, it's impact on hurricane intensity will be limited.

In cases which showed significant reduced SST cooling under the hurricane center, with a 2 psu change, there is about 0.1 °C reduced SST cooling, which induce only a 2 hPa change in the SLP. The quantitative analysis using data from over 20 simulated hurricanes confirms this result. For a 0.1°C reduced SST cooling, the surface heat flux increases by 45 $Watt/m^2$, resulting in hurricane intensity (SLP) increasing by 2hpa.

Discussion

The translation speeds of all the selected hurricanes are over 5m/s. Therefore, the internal wake in the lee (tail) is seen in our simulations. As we noted earlier, we expect the main response to appear right under the hurricane center only if the hurricane speed is slower than the speed of its first baroclinic wave [Geisler 1970; Zhang et al., 2021].

In comparison to previous studies, our quantitative analysis shows a smaller value in terms of the reduced SST cooling associated with the presence of the BLT. The median reduced SST cooling under the Cat-4 wind speed is only 0.08°C. There are two possible reasons for this:

1. Since we were using 200km$\times$ $200km$ box-mean SST around the hurricane location, it's usually lower than single point result. The larger the box area, the smaller the averaged number would be.
2. Even though we also calculated the reduced SST cooling on its tail, we only considered 12 hours SST cooling, i.e., 12 hours after the hurricane passage. Considering that the maximum SST cooling appears mostly around 1-2 days after hurricane passage [Hernandez et al., 2016], we expect the cooling to grow after 12 hours.

CHAPTER V

CONCLUSIONS

The dissertation mainly discusses the Barrier Layer formed by the Amazon Plume during Summer, and its potential impact on reducing SST cooling and hurricane intensification.

First, in Chapter 1, we found that Barrier layer is thicker in the Amazon Plume Boundary region, instead of in the Plume Interior (where the main body of the freshwater is) by analyzing over 900 in-situ Argo profiles in the two regions, and cruise cross-section datasets. That's because the strong stratification comes with a strong halocline in the Plume Interior that acts to suppress upper ocean mixing. As a result, the temperature mixed layer depth (T-MLD) is elevated close to the density mixed layer depth (D-MLD), reducing the gap between two MLDs, namely the BLT.

Then, in Chapter 2, by comparing 68 pairs of Argo float profiles before and after the passage of a hurricane, we showed that the Plume Boundary region has more favorable conditions for smaller SST cooling. The BLT could significantly prevent T-MLD from getting deeper, which could inhibit cold water from being mixing upward. We also found that the thicker BL is significantly correlated with lower SST cooling for slow-moving hurricanes.

In the Chapter 3, 21 realistic hurricanes over the Plume region were simulated using a high-resolution regional coupled ocean-atmosphere model, with sensitivity experiments perturbing the salinity for each hurricane. Our results demonstrate that the BLT does have the effect of reducing SST cooling. The sensitivity experiments with different salinity levels showed that with lower salinity, the reduced cooling by the BLT was stronger. A 3psu SSS change results in 0.1°C reduced cooling, calculated over a 200×200km box-mean centered at the location where the hurricane was 12 hours earlier, namely on the tail of the cooling wake. The 0.1°C reduced cooling is smaller than previous studies, because we consider the box-mean averaged SST, while the stronger SST cooling occurs only in a portion of the box. Moreover, we only measured the SST cooling 12 hours after hurricane passage since it could better describe the mixing process, while the cooling usually reaches a maximum after one day by the upwelling, unrelated to BLT effect.

However, our results show that even though the BLT effect can reduce SST cooling on the tail of the wake, the SST cooling under the hurricane center is almost unchanged for most cases, since the oceanic cooling response to hurricane does not occur right below the center for the hurricanes with a translation speed greater than 5m/s. We analyzed 36 datapoints for all 21 hurricanes, which show SST change greater than 0.1°C in the Plume, when the hurricane strength exceeds Cat-4. It shows that with a 0.1°C reduction in SST cooling, heat flux increases by 45 $Watt/m^2$, and the hurricane intensity (SLP) increases by 2 hpa.

It has been widely acknowledged that BLT effect could reduce SST cooling under major hurricanes, but our results found an opposite effect of the BLT under weaker hurricane (TS, Cat-1). With weaker wind speed, which cannot mix below the T-MLD, the high stabilization under the BLT condition confines the mixing within the temp-ML, resulting in stronger SST cooling. Moreover, the freshwater can trap the warm water under surface, forming temperature inversion, resulting in a cooler pre-existing SST. In such cases, BLT will not weaken the SST cooling.

Overall, for hurricanes over Amazon Plume region, it's hard to meet the slow-moving hurricane criteria ($U_h/fL < 1$), since the Coriolis Force f is relatively low near the equator, which requires the hurricane translation speed to be very slow. Observationally, for all 21 cases that we considered of hurricane tracks passing over the Plume, there was only one case with translation speed under 5m/s. This makes the Amazon Plume region less favorable for generating SST cooling under the hurricane center, instead of on its lee.

Even if the SST cooling and the BLT reduced SST cooling occur right under the hurricane center, and can therefore increase heat flux and hurricane intensity, our quantitative analysis show that a very strong surface salinity anomaly (of 2 psu) is needed to generate just a modest increase in hurricane intensity (of about 2hPa in SLP), even for major hurricanes.

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APPENDIX A

Chapter 2:

APPENDIX B

Chapter 3:

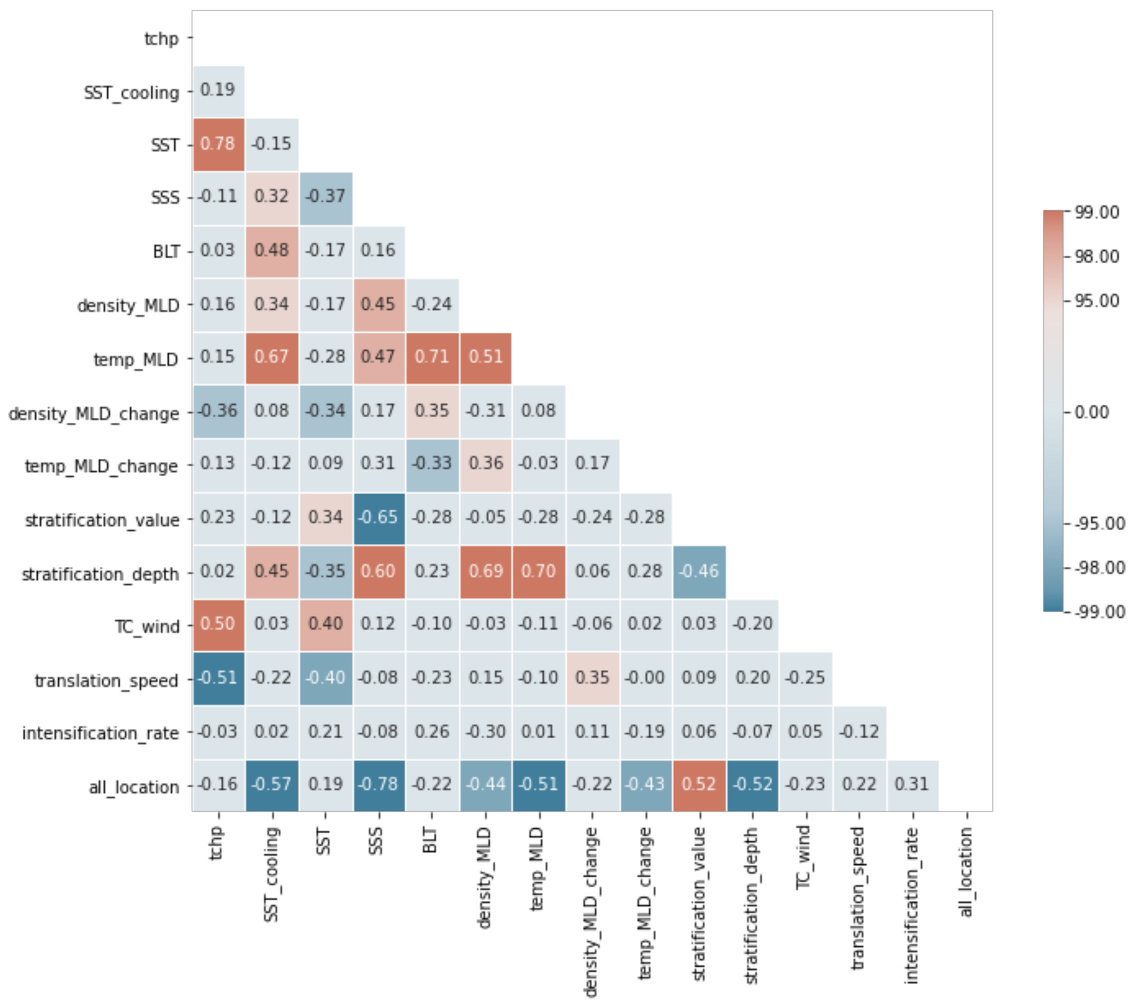


Figure B1. Correlation matrix for slow-moving hurricanes (<5m/s)

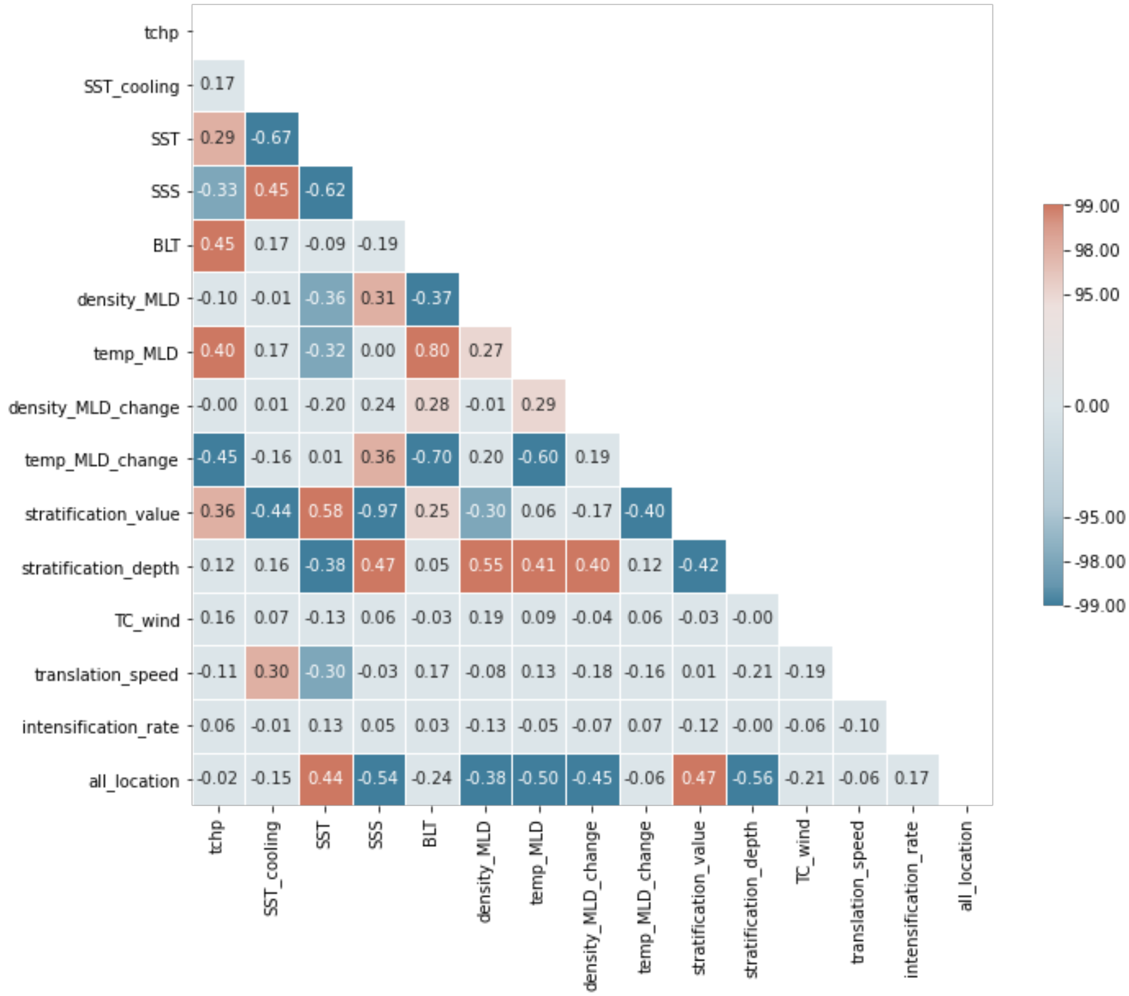
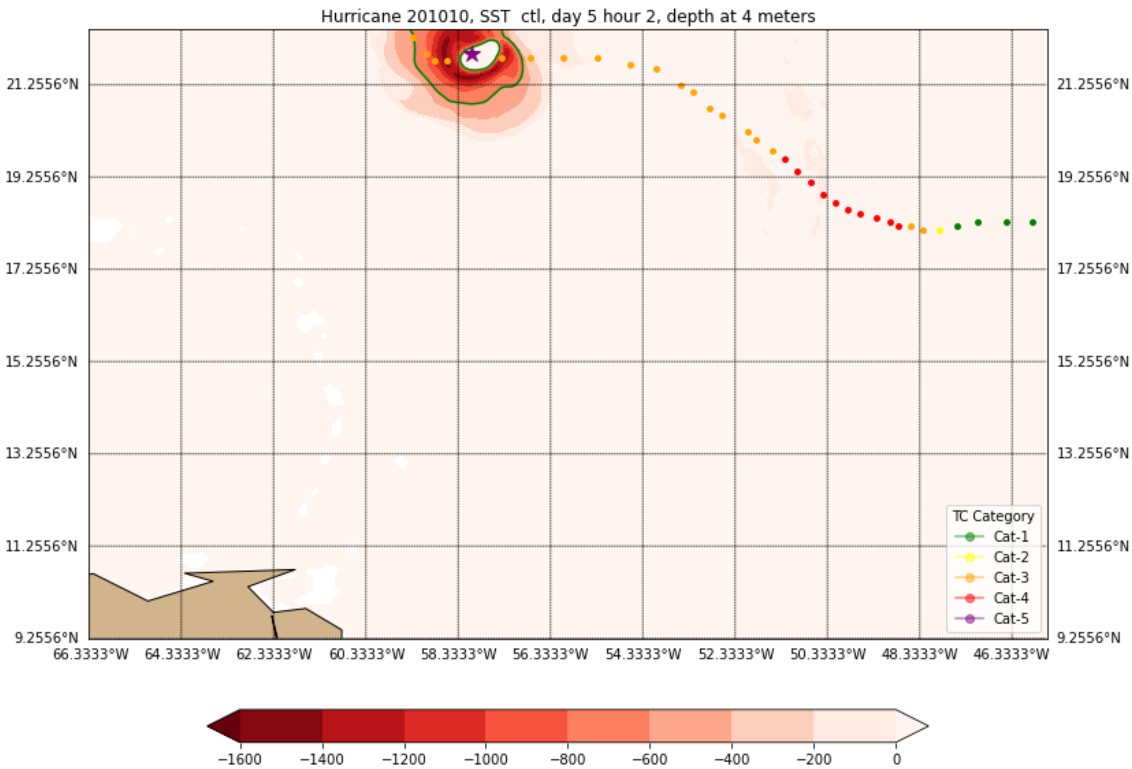


Figure B2. Correlation matrix for slow-moving hurricanes (<5m/s)

APPENDIX C

Chapter 3

How to decide hurricane sizes



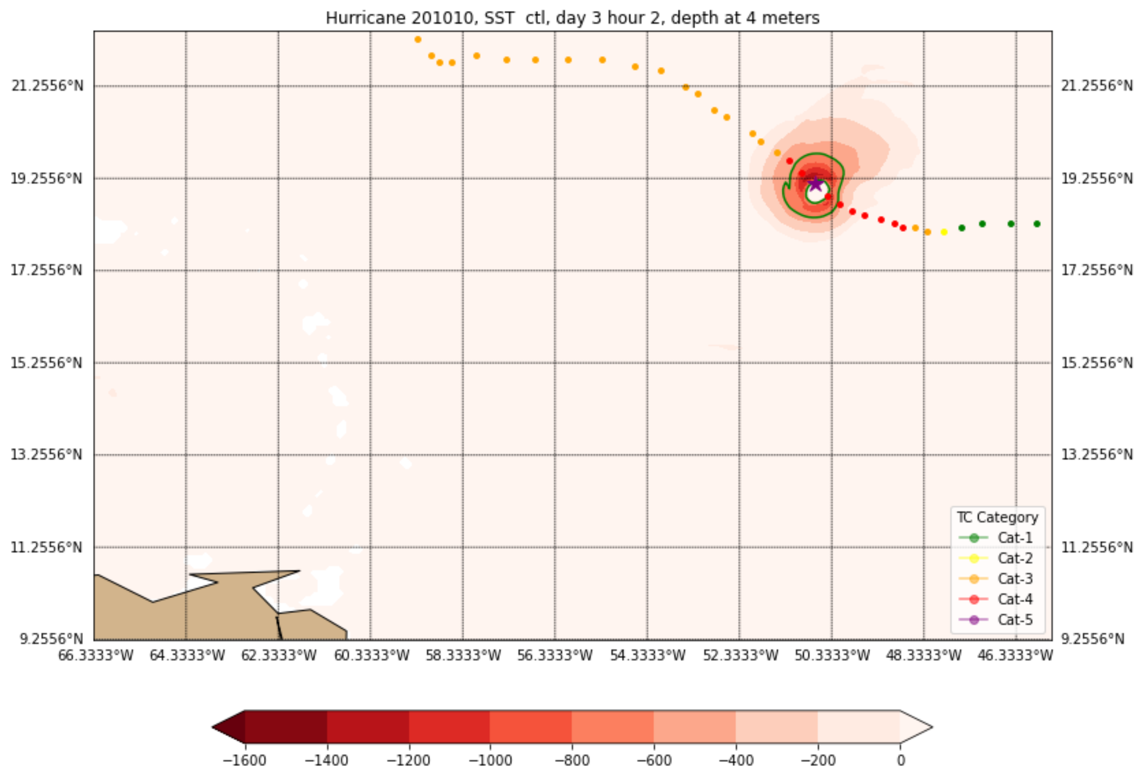
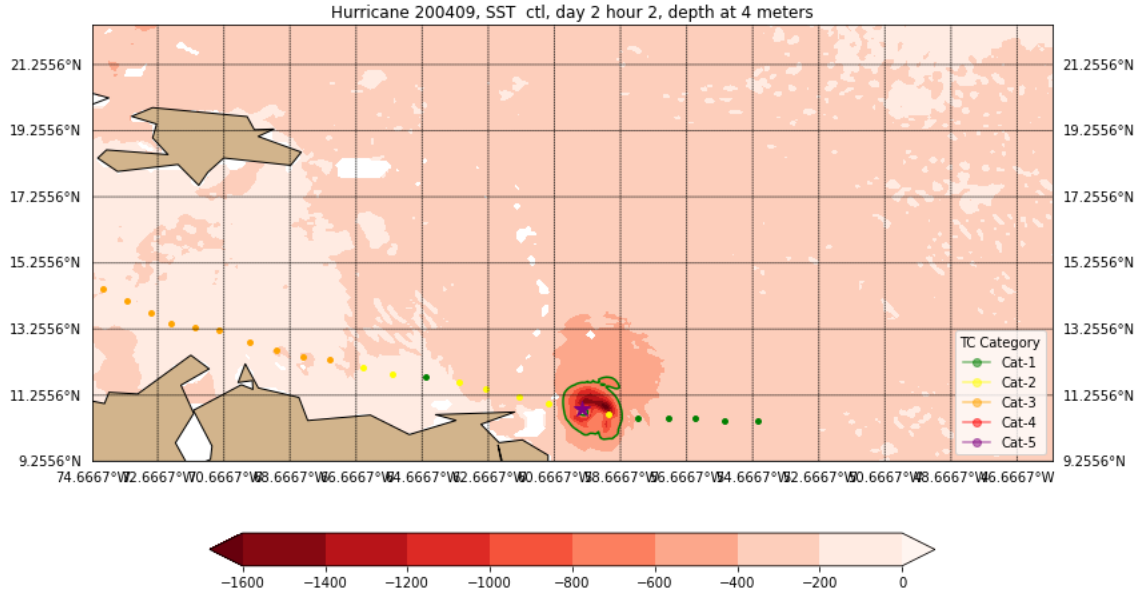
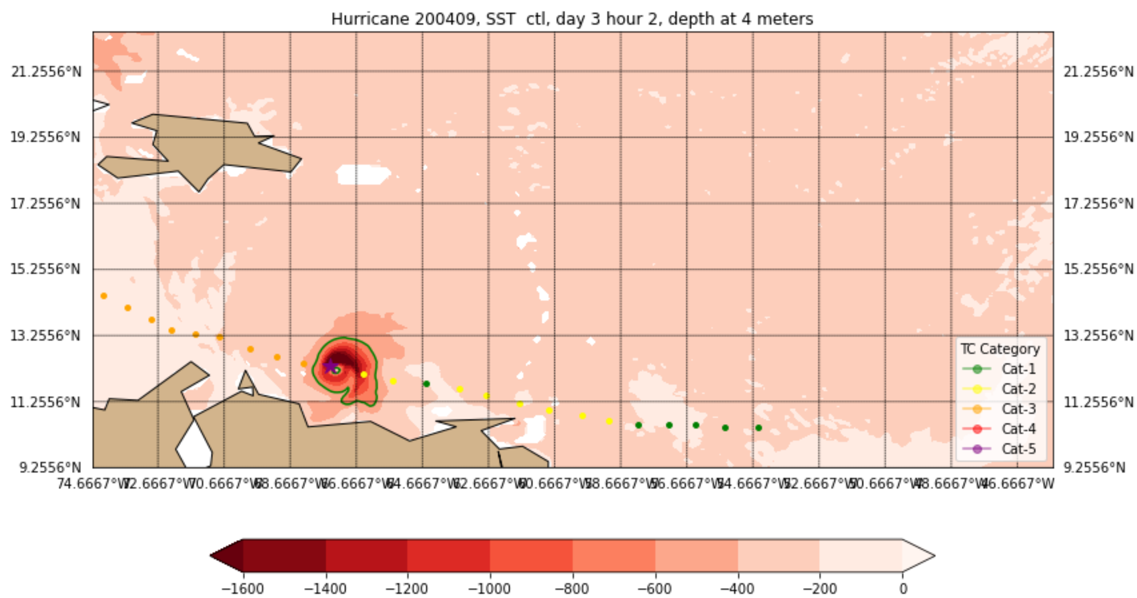


Figure C1. Heat flux for Hurricane 201010 in different categories.

The heat flux at different date for hurricane No.201010. Even though the hurricane at day 3 is stronger in terms of the wind speed, it's size is smaller. It seems with the developing of the hurricane, the size is getting larger. Actually, during the decaying period, the hurricane is also intending to getting larger.


Hurricane 200409, SST ctl, day 2 hour 2, depth at 4 meters
TC Category
Cat-1
Cat-2
Cat-3
Cat-4
Cat-5
−1600
−1400
−1200
−1000
−800
−600
−400
−200
0


Hurricane 200409, SST ctl, day 3 hour 2, depth at 4 meters
TC Category
Cat-1
Cat-2
Cat-3
Cat-4
Cat-5
−1600
−1400
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−1000
−800
−600
−400
−200
0

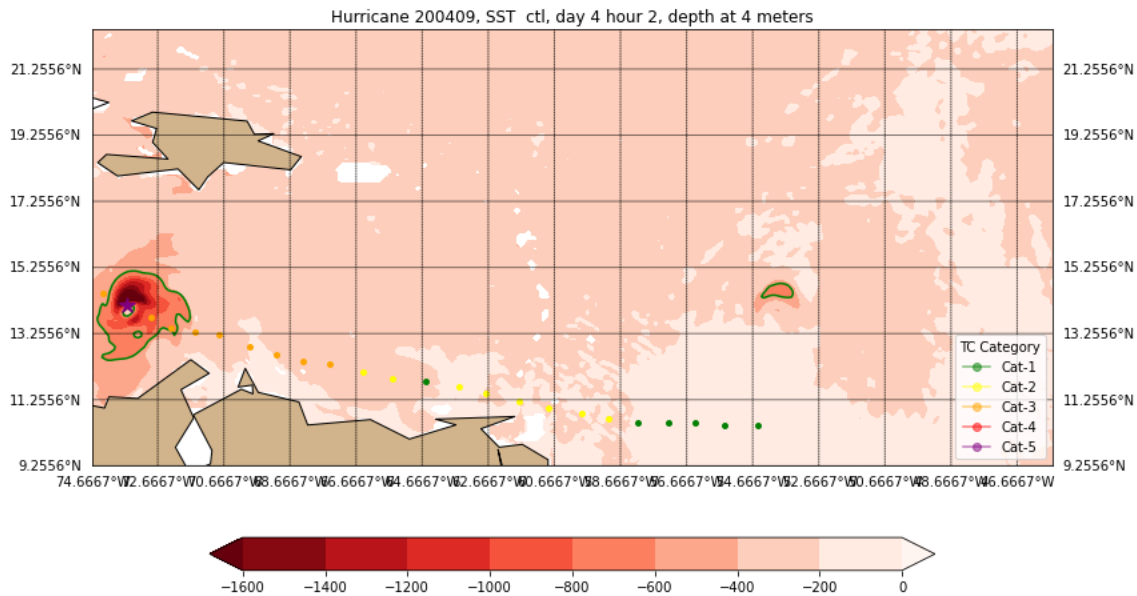


Figure C2. Heat flux for Hurricane 200409 in different categories.

Hurricane induced SST cooling changes with time

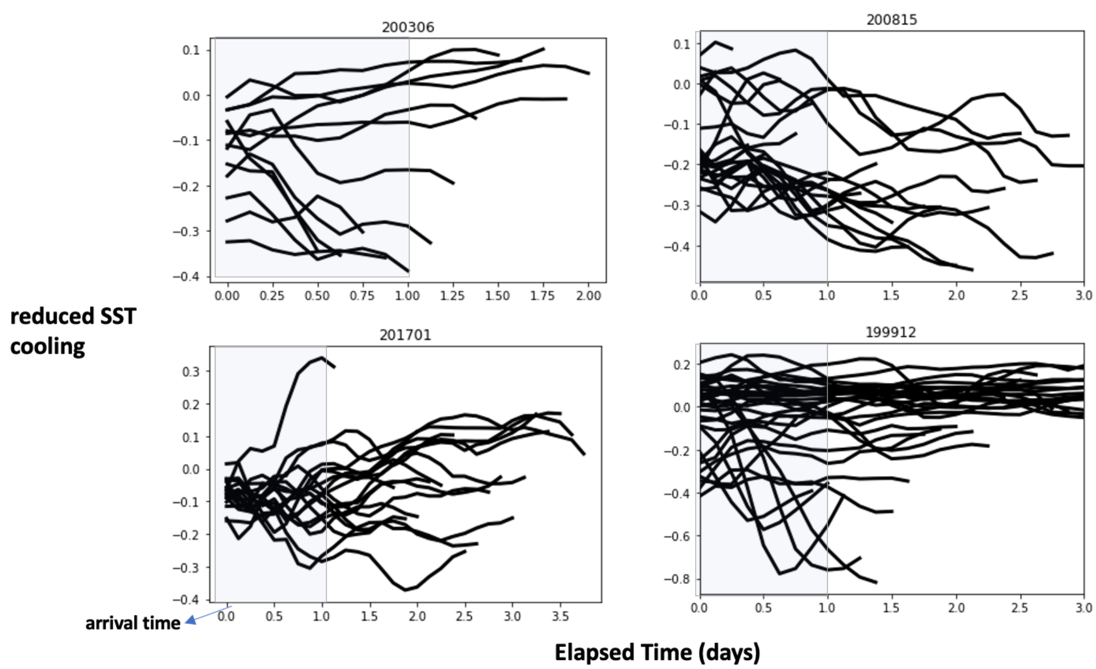


Figure C3. The SST cooling evolution for different elapse time for Hurricanes

Firstly, what happens to the SST cooling after hurricane passed by? Figure C3 shows the SST cooling evolution with time at each point on the hurricane tracks. The shorter lines represent the track tails, while the longer lines are the track heads. It shows that the SST continues cooling as time goes by. In hurricane No. 200815 and No. 201701, the maximum cooling could reach over 0.4 °C appears at around 2 days, and then goes warmer instead. This result is close to the result from Balaguru et al., 2020, which suggested that the maximum reduced SST cooling happens after one day, could reach 0.4 °C.

Other hurricane tracks and SST cooling.

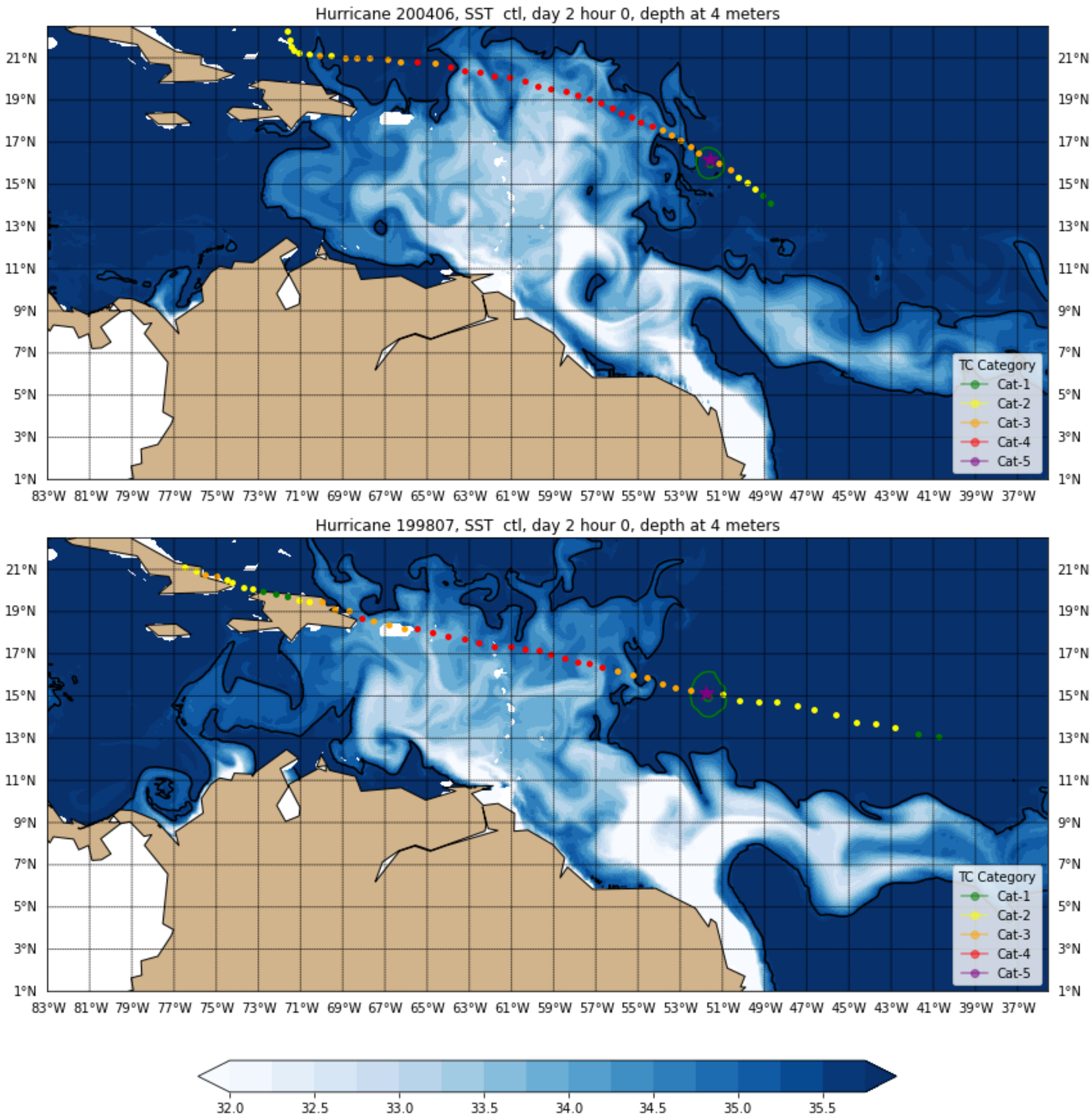


Figure C4. The tracks and SSS distribution for Hurricane N0. 199807 and No. 200406

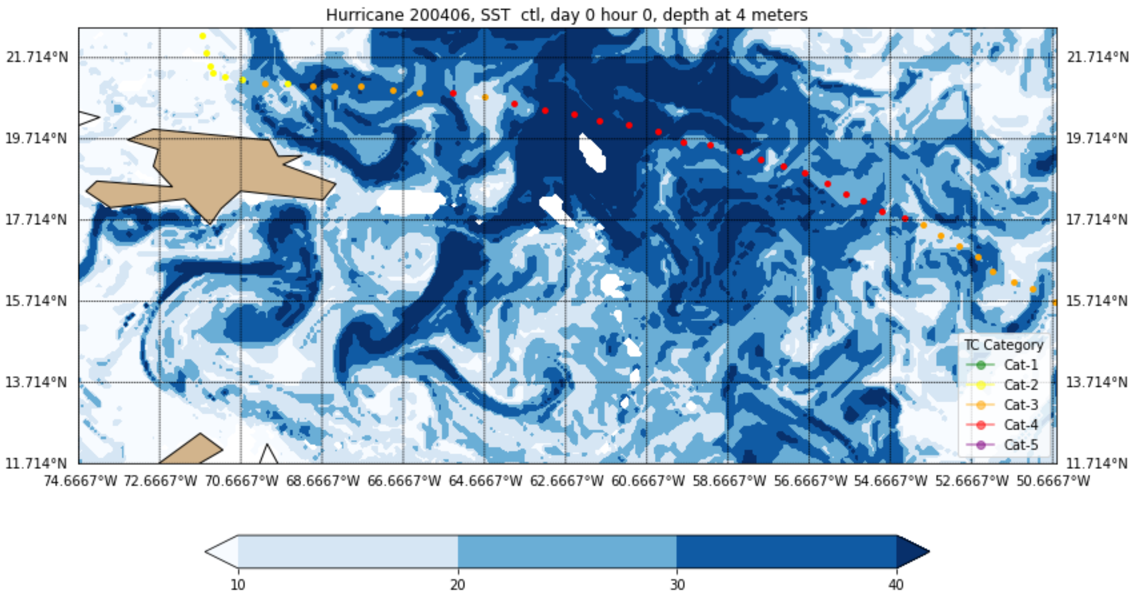
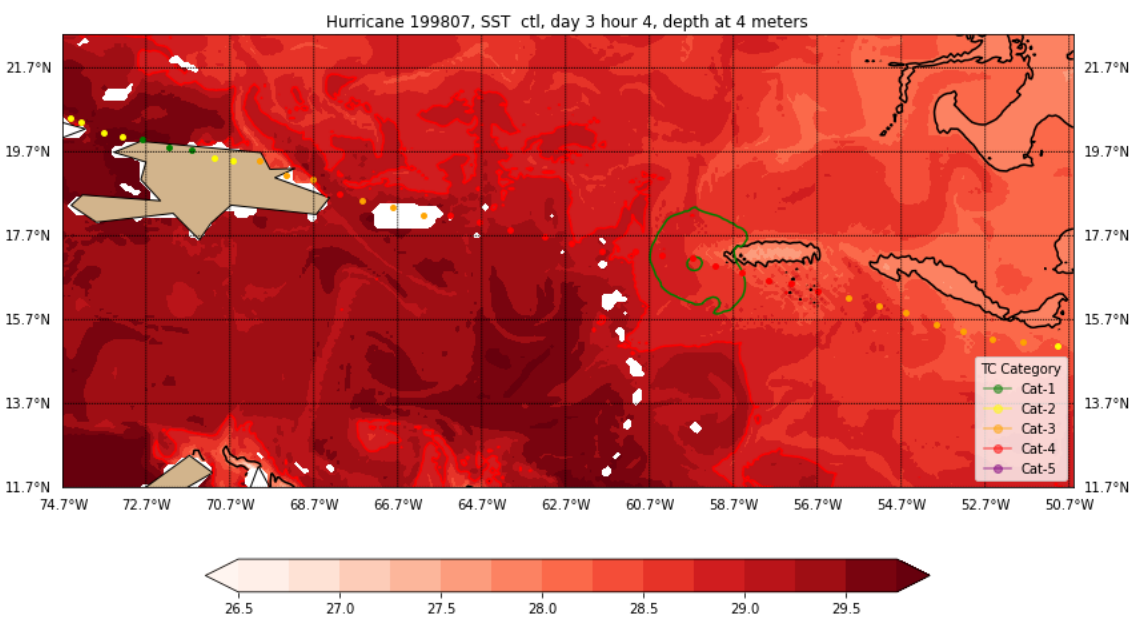


Figure C5. The tracks and BLT distribution for Hurricane N0. 199807 and No. 200406



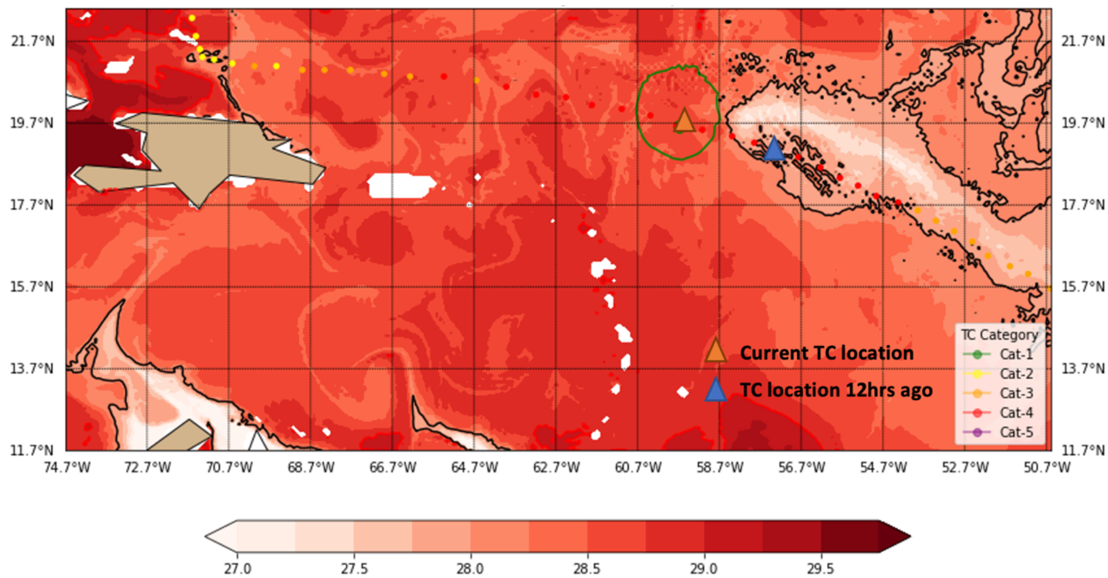
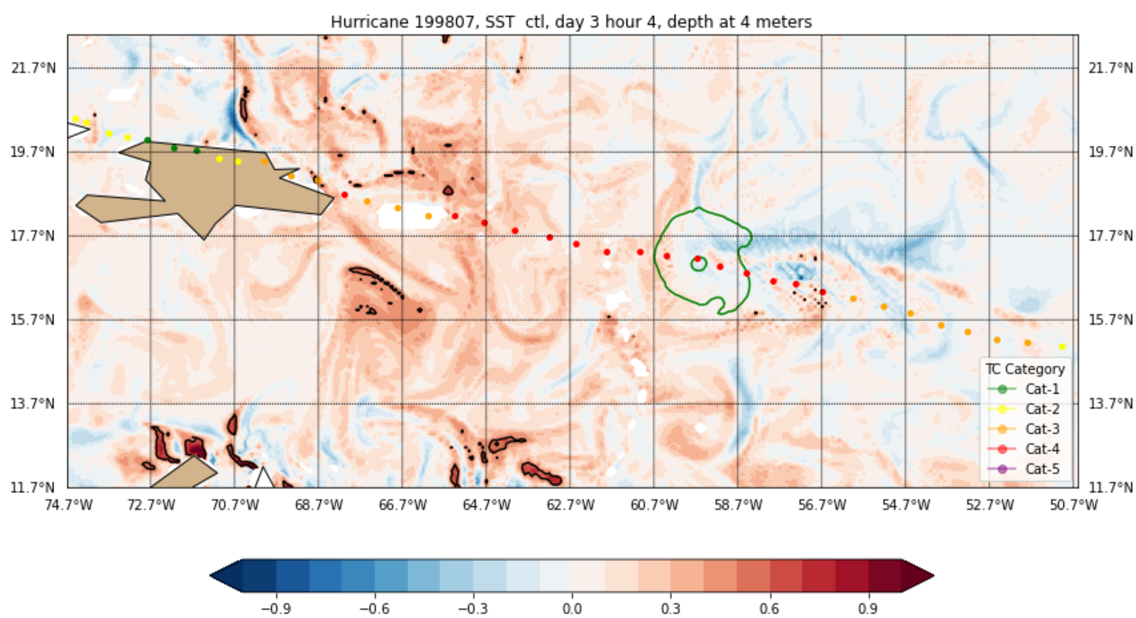


Figure C6. The SST at day 3 for Hurricane No. 200406. The green contour is heat flux=600 $\boldsymbol{Watt/m^2}$, represents the hurricane shape. The black contour shows 28C isothermal line.



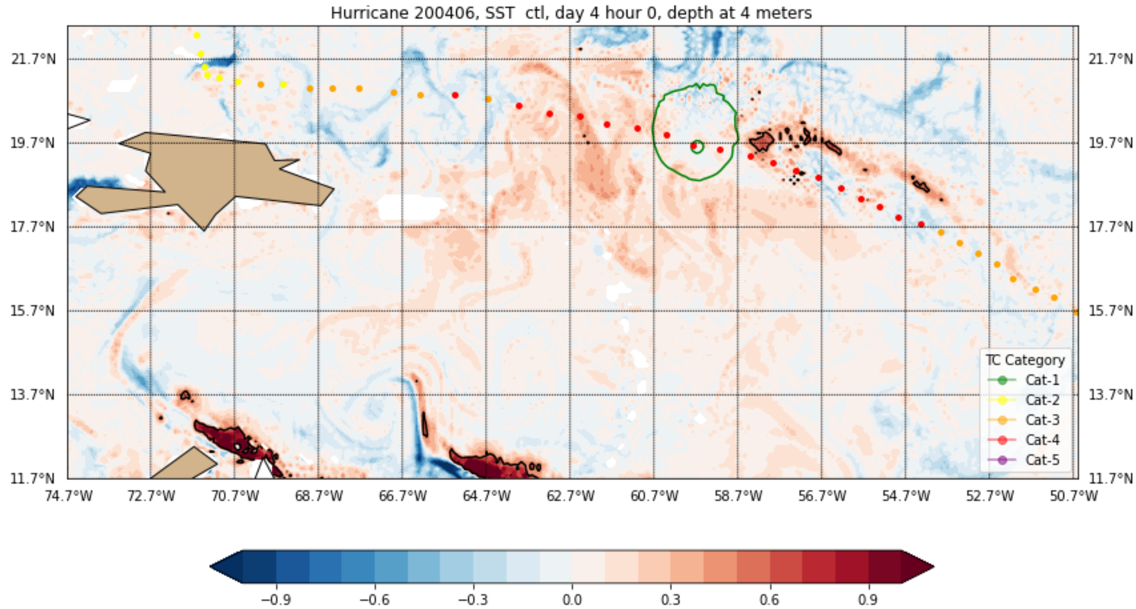


Figure C7. The SST difference between BLT-minus and CTL at day 4 for Hurricane No. 200406.