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The Influence of Mesoscale Sea Surface Temperature Gradients on Tropical Cyclones

Russell Henderson Glazer
THE INFLUENCE OF MESOSCALE SEA SURFACE TEMPERATURE GRADIENTS ON TROPICAL CYCLONES

By

RUSSELL HENDERSON GLAZER

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Russell Henderson Glazer defended this thesis on November 5, 2014.
The members of the supervisory committee were:

Mark Bourassa
Professor Co-Directing Thesis

Robert Hart
Professor Co-Directing Thesis

Mark Powell
Committee Member

Vasu Misra
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.
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ABSTRACT

The effects of mesoscale (50-1000km) sea surface temperature (SST) variability on tropical cyclones (TCs) are investigated with model simulations of an idealized TC as well as simulations of Hurricane Igor (2010) using the Weather Research and Forecasting (WRF) model. Mesoscale SST gradients significantly modify the surface wind speed and direction leading to areas of enhanced divergence/convergence and curl along the gradient. This paper explores the effects that these interactions between mesoscale SST gradients and the atmosphere have on TCs.

In these idealized simulations it is shown that an SST gradient of similar scale to the idealized TC vortex produces asymmetry in the eyewall convection and leads to vertical misalignment of the vortex. Simulations of Igor are conducted with three different SST setups: a run with an unaltered SST field, a run with increased SST gradients, and a run with decreased SST gradients. Igor's intensity and structure is found to be sensitive to the three different SST setups but the specific mechanism could not be identified. It is found that the magnitude of moisture advection increases with increasing SST gradient magnitude on the warm side of a gradient.
CHAPTER 1
INTRODUCTION

It has long been known that the interaction between a tropical cyclone (TC) and the underlying sea surface temperature (SST) is important to TC development and intensification (Gray 1968; Palmén 1948). The conventional wisdom has been that, apart from what the TC cools through upwelling and mixing, one value of SST represents the state of the ocean surface in the region of the storm's inner circulation. It is common in idealized TC simulations to use a constant value of SST to represent the ocean surface (Rotunno and Emanuel 1987; Montgomery et al. 2006; Nolan 2007; Nicholls and Montgomery 2013) because it allows analysis of how the TC responds to specific SSTs. This is a very useful method for conducting idealized experiments but the real ocean is not uniform with respect to SST. Ocean currents and eddies are ubiquitous, and western boundary currents like the Gulf Stream and Kuroshio Extension produce changes in the SST over short distances. It has been shown that on these smaller scales (<1000 km), the ocean forces the atmosphere and can significantly impact the surface wind (see review by Small et al. 2008). In the Atlantic a common path for storms is up the east coast of the United States, coincident with the Gulf Stream which features SST changes of several degrees over only a few tens of kilometers. In addition to the SST gradients seen at ocean fronts, the satellite era has produced high resolution SST datasets that can see small scale SST gradients down to tens of kilometers across all oceans. As a result of these SST products, we know that in reality there are mesoscale (50-1000 km) gradients of SST across which developing TCs move. The influence of those gradients TC development and intensification is largely unknown at this time.

The relationship between mesoscale SST gradients and surface wind has been extensively studied over the past several decades and is a very active area of research today in the field of
air-sea interaction. The focus of these studies has been on how the planetary boundary layer (PBL) adjusts to gradients in SST. There are 2 main schools of thought that have been proposed to explain the physical processes involved in modifying the surface flow via SST gradients. The first theory is based on work by Lindzen and Nigam (1987) who used an analytic model for the PBL to argue that thermally induced pressure gradients accelerate the flow across SST gradients. On the warm side of an SST gradient the hydrostatic pressure will tend to be lower and on the cold side the hydrostatic pressure tends to be higher, thus creating a pressure gradient across the SST gradient. The surface wind has to respond to these pressure perturbations by blowing across the SST gradient from cold to warm water and in this way the surface flow can be accelerated by SST perturbations. This baroclinic-type response is a consequence of the coupling between the SST, air density, and surface wind. Although, some have called into question the validity of some of the assumptions in this model (Song et al. 2006), there is significant support for the importance of a pressure gradient mechanism in modifying the surface wind (Small et al. 2003; O’Neill et al. 2010; O’Neill 2012). The second theory is explained in work by Wallace et al. (1989) and Hayes et al. (1989) in which they argue that atmospheric stability changes over SST perturbations lead to changes in the vertical turbulent mixing in the PBL. Over a warm SST perturbation the vertical turbulent mixing is increased as well as the thickness of the PBL. This increase in mixing allows higher momentum air from aloft to be brought to the surface and increase the wind speed. Recent studies have shown that on the mesoscale, there are strong positive spatial correlations between SST and wind stress perturbations (Chelton et al. 2001, Song and Chelton 2009, reviews in Chelton et al. 2004; Xie et al. 2004) which support the work by Wallace et al. (1989) and the hypothesis that the highest wind anomalies would be over the warmest water. By extension, if warm(cold) SST anomalies produce positive(negative) wind
stress anomalies, then there will be local changes to the wind stress curl and divergence. Figure 1 illustrates this with an idealized SST gradient against a background surface flow. Wind blowing perpendicular (parallel) to the direction of an SST gradient will experience a curl (divergence) along the gradient. Several studies have confirmed this relationship for areas at sharp SST fronts like the eastern Pacific at Tropical Instability Waves, and western boundary currents like the Gulf Stream and Kuroshio Extension (Chelton et al. 2001; Chelton et al. 2004; O’Neill et al. 2005; O’Neill et al. 2010). There is still debate over which set of physical processes is more responsible for the SST - wind relationship but it is becoming apparent that both are valid depending on the spatial-temporal scale and the type of atmospheric forcing (O’Neill 2010).

As this pertains to a developing TC, low-level vorticity generation via an SST gradient could be ingested by convective updrafts that will then increase mid-level vorticity and the overall circulation of the storm. In simulations of Hurricane Sandy (2012), Galarneau et al. (2013) found that cyclonic vorticity anchored over the Gulf Stream was generated ahead of the storm and eventually ingested into its circulation. Additionally, for this study we are interested in how SST-wind coupling, illustrated in Fig. 1, influences the advection of moisture near the surface. Abundance of low and mid-level moisture is important to TC development and intensification, supplying the fuel for deep moist convection and latent heat release which drives intensification. An abundance of moisture also is necessary to suppress dry downdrafts and form an environment of quasi-steady state moist convection which characterizes a TC. It has been shown in previous studies that low and mid-level near saturation is necessary for TC development (Nolan 2007; Davis and Ahijevych 2013). Thus, alteration of the advection of moisture near a TC via a sharp SST gradient could divert moisture into or away from a TC leading to effects on the storm’s convection and intensity. Furthermore, if low level advection is
enhanced leading to greater moisture content ahead of the TC it may precondition the
environment for intensification. This study will characterize the changes in moisture advection
associated with a sharp mesoscale SST gradient.

The effects of SST gradients are not just confined to the PBL but can extend above into
the free troposphere where essential processes of a TC like convection and latent heating can be
affected and lead to modification of a TC’s structure and intensity. At sharp SST gradients like
the Gulf Stream and Kuroshio, convergence of heat and moisture caused by the gradient can
induce convection and precipitation. This in turn produces anomalous latent heating in the upper
troposphere. Minobe et al. (2008) looked at this effect over the Gulf Stream using satellite and
model data and found a persistent band of precipitation collocated with the sharp gradients over
the Gulf Stream. Modeling studies have also been conducted to examine this effect over the
Kuroshio and in the East China Sea (Xu et al. 2011; Tanimoto et al.2011; Sasaki et al. 2012; Toy
and Johnson 2014hereafterTJ14). These studies use a similar methodology in conducting a set of
2 model runs, one run using an unmodified SST field, with a sharp SST gradient feature, and
another run with the SST field smoothed to eliminate the sharp gradient. Their experiment
effectively tested the role that the SST gradients play in their model simulations. TJ14 used a
regional model along with the above methodology to analyze the role that a sharp SST gradient,
associated with the Kuroshio Extension, played in a heavy precipitation even over Taiwan. They
found a decreased amount of precipitation for their model simulation with the SST gradient
removed, a consequence of less horizontal convergence at the gradient and a decreased
production of precipitation producing convection.

We follow a similar methodology to TJ14 by setting up an SST model experiment that
compares the results in a simulation of Hurricane Igor(2010) with a raw SST field, which we call
the control, a smoothed SST field to create decreased SST gradients, and an SST field with added variability to create increased SST gradients. Two sets of model runs using the Weather Research and Forecasting (WRF) Model (Skamarock and Klemp 2008; Skamarock et al. 2008) are conducted, one set using the Yonseti University (YSU) PBL scheme (Hong, Noh and Dudhia 2006) and the other set using the Grenier and Bretherton(2001) (GB) PBL scheme. The GB PBL scheme was chosen for a second set of model runs because of WRF results found in Song and Chelton (2009) that showed the best SST-Wind relationship when using the GB scheme. The goal of these two sets of simulations is to assess the impact that changing the SST gradients has on Igor’s development and subsequent intensification. Two other model runs are conducted with WRF in an idealized framework for a weak TC vortex inserted: one with a uniform SST and another with a large scale SST gradient at the center of the TC. The imposed SST gradient in these idealized runs is of a much larger spatial scale than the individual SST gradients in the simulations of Igor. For this study we make a distinction between SST gradients present at ocean fronts which can stretch for hundreds up to thousands of kilometers, on the same scale as a TC, and SST gradients associated with small scale currents and eddies that are a part of the small scale variability of the ocean, which are on the scale of hundreds to tens of kilometers. Here, the model simulations of Igor represent the latter and the idealized TC simulations represent the former. The purpose of this study is not verify the SST-wind relationship but to apply it to TC-ocean interaction. To the authors’ knowledge, at present, there have been no direct studies on the impact that mesoscale SST gradients have on TCs.

To provide motivation for the model experiments carried out in this study, we first wanted to answer to what degree are there small scale, large magnitude SST gradients present in the environment around developing TCs. The conventional view is that the tropics are mostly
gradientless and this is often termed the Weak Temperature Gradient (WTG) approximation (Sobel and Bretherton 2000; Sobel et al. 2001). To answer this question we conduct an analysis of SST gradients in the area of developing storms. Daily Optimum Interpolation (OI) SST data (Reynolds et al. 2007) on a 0.25° x 0.25° grid are used with data from the National Hurricane Center’s (NHC) Atlantic HURDAT2 database (Landsea and Franklin 2013) to analyze the SST around storms at the time of genesis (first time a storm became a tropical depression) from the 2002-2011 Atlantic hurricane seasons. For the area around each storm, at the time of genesis, we calculate the maximum small scale SST gradient and then subtract out the large scale background SST gradient. This perturbation SST gradient is plotted against the average SST in Figure 2. The majority of the points are clustered, not around 0 but around 1 and 2 °C/200km, showing that in most of the time there are small scale SST gradients of significant magnitude near developing storms. Furthermore, even at high SST, >28°C, there are several instances of an SST gradient of >6°C/200km. This provides observational evidence to show that there are, large magnitude small scale SST gradients present where TCs develop, even in the tropics where the SST is very warm.

Chapter 2 explains the SST model experiment setup and then shows the model results with analysis of the differences in intensity and structure between the runs. We show that Igor's intensity is sensitive to the SST gradient setup in the model runs using the YSU scheme but for the runs using the GB scheme there is less sensitivity. Probability Density Function (PDF)s of moisture advection at an SST gradient near Igor’s track are presented and we show that on the warm side of this gradient there is an increase in the magnitude of moisture advection when the SST gradient magnitude is increased in each of the SST setups. The setup of the idealized model simulations and model results are given in Chapter 3, where we show that in the simulation with
an SST gradient, the TC drifts north toward colder SST and decays. Chapter 4 will provide a summary and conclusions.

Figure 1. A physical representation of the SST wind relationship at an SST gradient. The dark line represents the gradient in SST with warm water to the right and cold water to the left. Arrows indicate wind vectors and their length represents the relative magnitude of the wind. The wind is accelerated over the warmer water and is decelerated over the cold water and turns cyclonically over the cold water when blown from warm to cold in this way. When the wind blows perpendicular to the SST gradient boundary from warm to cold, there is convergence generated. When the wind blows parallel to the SST gradient boundary with the warm above and cold below, there is positive vorticity generated (adapted from O'Neill et al. 2010).
Figure 2. Scatterplot of SST (°C) vs. the maximum small scale SST gradient perturbation from the background large scale SST gradient (°C/200km) at genesis points from the Best Track database for Atlantic hurricane seasons 2002-2011. The large scale SST gradient is calculated by area averaging the SST gradient in a 7°x7°lat-lon box around the genesis point (1st time a TC became a tropical depression) of a storm. The maximum small scale gradient is the maximum SST gradient value in smaller 1.75°x1.75° boxes around the genesis point. The perturbation is found by subtracting the large scale gradient from the maximum small scale gradient. These perturbation values are on the Y-axis. The X-axis is the average SST found within the 1.75° boxes. The SST gradient is calculated over a 50km distance and then rescaled to 200km. All SST gradient values are shown as a magnitude.
CHAPTER 2

IDEALIZED SIMULATIONS

2.1 Experimental Setup and Model Configuration

Two idealized TC simulations are conducted with the WRF model with the goal of comparing the development of a TC vortex over a constant SST field (IDEALcon) with a TC developing under an imposed SST gradient (IDEALgrad). The imposed SST gradient in these simulations is made to resemble an SST front at a western boundary current and is of larger spatial scale than the individual SST gradients present in the Igor simulations which are covered in Chapter 3.

The ideal simulations are conducted on a 600 x 600 grid at 6km grid spacing with an inner nest at the center that is 300 x 300 grid points at 2km grid spacing. The 2km domain encompasses the area of the simulated TC. Both simulations are run for a duration of 9 days. There are 35 vertical levels and the model top is set at 29km. No cumulus scheme is used in these runs. WRF single-moment 6-class (Hong and Lim 2006; WSM6) is used for the microphysics and the boundary layer scheme is YSU. For the shortwave and longwave radiation we use the Rapid Radiative Transfer Model for GCMs (RRTMG) (Iacono et al. 2008). The model is initialized with the Jordan (1958) mean tropical atmospheric sounding. A broad depression vortex is specified at initialization using an analytic equation from Rotunno and Emanuel (1987). The vortex has a maximum wind speed of 12.9 m/s at the surface and decays vertically up to 20km. The background wind is set to 0 so that, at initialization there is no other motion in the model except for the vortex. An east-west cross section of through the vortex and the relative humidity of the initial state in the inner domain is shown in Figure 3. The simulations are run on an f-plane for $f = 5.0 \times 10^{-5} \text{s}^{-1}$ ($20^\circ \text{N}$).
For the IDEALcon run the SST is specified to be 28°C everywhere and is held constant throughout the run. In the IDEALgrad run the SST varies as a sine function of the y grid points for the middle 300km of both domains. This creates a horizontally oriented SST gradient in the middle of the domain such that the SST is a constant 28°C to the south of the gradient and a constant 23.4°C to the north of the gradient. This horizontally imposed SST gradient extends throughout the first and second domains giving it a 3600km extent. Figure 4 displays the SST in the inner domain of the IDEALgrad run with the middle 300 km being the imposed SST gradient. Table 1 provides relevant information related to all model runs conducted in this study.

2.2 Model Results

The simulated reflectivity in the lowest model level for IDEALcon and IDEALgrad are shown (Fig. 5) at two day intervals throughout the simulations. In general the IDEALcon run produces stronger and more robust convection as well as a more intense storm than IDEALgrad. Over days 2 through 8 in the IDEALcon run the vortex steadily contracts, forming a tighter and tighter circulation and a smaller eye. Because there are no limiting variables in IDEALcon; no shear, warm SST, and ample moisture, the IDEALcon run essentially intensifies until the dissipation of energy due to friction from the surface wind over the ocean prevents further intensification. On day 2 a distinct burst of convection is seen in the IDEALcon run which can be attributed to a diurnal cycle produced by the RRTMG radiation scheme.

Of note here is that the amount of heat and energy available to each storm via the SST is not equal in each run, because the average SST under the storm in IDEALcon is a constant 28°C while it is significantly lower in IDEALgrad as a result of the SST gradient, which puts colder than 28°C SST under the storm. Thus from this alone we expect a slightly stronger storm in the IDEALcon run, however the differences in structure and intensity between IDEALcon and
IDEALgrad are drastic in Fig. 5. For one, the convection associated with the vortex in IDEALgrad is much smaller and less robust than in IDEALcon, which is clearly visible from days 2 through 8. Also while IDEALcon contracts and intensifies we see the opposite occur in IDEALgrad, which begins as a tight circulation on day 2 but then enlarges as time progresses in the simulation. But most striking is that the vortex in the IDEALgrad run begins to drift north, over colder water, after 4 days and then turn to the west while also weakening and eventually dissipating. Also, beginning when the vortex starts to drift north, there is a preference for convection in the northeast quadrant of the vortex while little to no convection exists in the southern eyewall.

This occurrence is explored further in Figure 6 which shows a north-south (6a) and east-west (6b) cross-section through the center of the storm in IDEALgrad shortly after the run begins. The evolution of moisture before convection has initiated in the simulation (Fig. 6) gives insight into what is causing the preference for convection to the north and then subsequent movement northward. In Fig. 6a with colder water to the north on the right and warmer water to the south on the left, a buildup of high relative humidity can be seen at the surface to the north of the center over the colder water. A similar buildup is also seen in Fig. 6b to the east of the center with the 90% relative humidity shading extending out to 60km from the center on the right side while to the left of the center it only extends to about 30km. The explanation for this is a consequence of the warm tropical sounding, which is set as the initial condition everywhere, interacting with the SST gradient transitioning to colder waters to the north of the storm. As the cyclonic circulation of the vortex draws air from the south around the eastern side and north over the SST gradient, the SST below these winds is becoming colder while the near surface air temperature essentially stays the same. This air blowing over the colder SST will saturate
quickly creating an area to the northeast of the center which is preconditioned for stronger and more robust convection relative to the southern side of the storm. The consequence of this later in the simulation is shown in Figure 7 and 8, which again show the north-south (Fig. 7) and east-west (Fig. 8) cross-sections of relative humidity and wind, but now at two day intervals throughout the simulation. In Fig. 7, days 2 and 4 indicate deeper and moister convection on the north side of the storm, especially on day 4 where the convection is clearly asymmetric with the north side being dominant. On day 4 as well, there is some evidence that the eye is shifting with the strongest convection on the north side and that on the south side the eye is beginning to fill in as the convection on the north side becomes dominant. On day 6 and 8 we see a complete cutoff of the convection at the upper levels by dry air. This is attributed to a zonal jet that forms over the SST gradient at around 300mb, slightly north of the center of the storm at initialization, as a result of a thermal wind response to the SST gradient at the surface. The jet gets stronger with time and as the storm drifts farther north it runs into the core of the jet which injects dry air into the upper levels of the convection. In Fig. 8 on day 6 the convection on the east side is seen weak and shallow next to a layer of dry air which has already cutoff deep convection on the west side. By day 8 both sides of the storm are cutoff from deep convection by the layer of dry air and the vortex remains shallow for the rest of the simulation.

2.3 Discussion: Idealized Simulations

With the same atmospheric conditions across the gradient, air over colder SST will saturate quicker and this favors convection in the north and northeast sections of the storm. Because the storm is placed over the gradient where, for 150km to its north the SST continuously decreases, the eastern portion of the circulation is continuously moving air over colder and colder SST. In fact, the sharpest portion of the SST gradient is north of the storm at the start of
the run, so not only is the SST increasingly becoming colder but it is also becoming colder at a faster rate. This creates a situation where convection to the north and northeast of the center extend the circulation out farther into cold water and thereby progressively preconditioning the area north of the storm. An illustration of this can be seen in Fig. 5 for day 6 of the IDEALgrad run where convection on the northeast side of the storm has formed two bands, one weaker and closer to the center and another farther removed from the center but larger and more robust. The stronger convection farther from the center pulls the circulation closer to it and in this way the storm drifts northward over time with the increasingly colder water.

This constant pull of stronger convection to the north also imposes a vertical as well as a horizontal asymmetry. From Fig. 7b, day 4 of the simulation the dominance of the northern side convection causes a slight tilt in the vertical alignment. In between day 4 and 6 (not shown) this tilt becomes more prominent as the disparity in strength of convection between the north and south side eyewall increases. While after day 6 dry air has already made further intensification difficult, the vertical asymmetry prevents regeneration of the storm after day 6. Thus, the SST gradient imposes a thermal asymmetry which prevents vertical alignment of the circulation is detrimental to storm.

Additionally we observe the development of a zonal wind jet at around 300mb as a result of a thermal wind response to the SST gradient. While this is not an observed climatological feature near western boundary currents, it does play a major role in these model simulations by injecting dry air into the upper levels and preventing deep convection needed to sustain the vortex.
Figure 3. An east-west cross section through the center of the vortex at initialization. X axis is distance to the west (-) or east (+) of the center in kilometers. Relative humidity is shaded and the V wind component (knots) is contoured every 10.
Figure 4. SST (shaded) in the inner domain in the IDEALgrad run. The x and y axis are the distance from the south west corner of the domain in kilometers.
Figure 5. Shaded simulated reflectivity and wind barbs in the lowest model level for IDEALcon (left column) and IDEALgrad (right column). The x and y axis are distance from the center of the domain in kilometers.
Figure 6. North-south (a) and east-west (b) cross sections through the center of the vortex at 4 hours into the simulation. Relative humidity is shaded. The V wind component is contoured every 10 knots in (a) and the U wind component is contoured the same in (b). The y axis is model levels and the x axis is distance from the center of the domain. In the north-south cross section the side of the SST gradient which is relatively warmer is denoted ‘warm’ and the side which is relatively colder is denoted ‘cold’ underneath the plot.
Figure 7. As in Fig. 4 but only north-south cross sections for two day intervals in the IDEALgrad run.
Figure 8. As in Fig. 4 but only east-west cross sections for two day intervals in the IDEALgrad run.
Table 1. List of model runs conducted for this study and the information that distinguishes them.

<table>
<thead>
<tr>
<th>Model Run</th>
<th>SST</th>
<th>PBL Scheme</th>
<th>Real or Ideal?</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDEALcon</td>
<td>28°C</td>
<td>YSU</td>
<td>Ideal</td>
</tr>
<tr>
<td>IDEALgrad</td>
<td>Gradient in Middle of Domain</td>
<td>YSU</td>
<td>Ideal</td>
</tr>
<tr>
<td>YSU CON</td>
<td>OSTIA</td>
<td>YSU</td>
<td>Real</td>
</tr>
<tr>
<td>YSU LOW</td>
<td>OSTIA w/ Low Gradients</td>
<td>YSU</td>
<td>Real</td>
</tr>
<tr>
<td>YSU HI</td>
<td>OSTIA w/High Gradients</td>
<td>YSU</td>
<td>Real</td>
</tr>
<tr>
<td>GB CON</td>
<td>OSTIA</td>
<td>GB</td>
<td>Real</td>
</tr>
<tr>
<td>GB LOW</td>
<td>OSTIA w/Low Gradients</td>
<td>GB</td>
<td>Real</td>
</tr>
<tr>
<td>GB HI</td>
<td>OSTIA w/High Gradients</td>
<td>GB</td>
<td>Real</td>
</tr>
</tbody>
</table>
CHAPTER 3

IGOR SIMULATIONS

3.1 SST Experiment Setup

To test the effect that mesoscale scale SST gradients have on TC development and intensification, we design a model experiment with 3 different SST setups. In the first model run OSTIA Foundation SST data (Stark et al. 2007) available from NASA's PO.DAAC on a 0.054° x 0.054° global grid, are used and this is deemed the control run (CON). Another run then uses the same OSTIA SSTs but they are now spatially low pass filtered allowing only spatial frequencies larger than 550km to pass. In this way, the variability of SST is decreased to produce a model run with decreased SST gradients (LOW). In a third run, the spatial frequencies that were filtered out in the LOW run are added to the original OSTIA SST field. This adds high frequency variability to the SSTs and produces larger small scale SST gradients (HI).

Figures 9 and 10 show the SST and SST gradient in the CON, LOW, and HI runs. In this region of the east Atlantic the SSTs are coldest near the coast of Africa above 20°N and warmest near 10°N and 50°W in the southwest corner. The SST pattern in this region is characteristic of a transition zone between warm tropical waters to the southwest, and cooler subtropical and coastal upwelled water to the northeast along the African coast. As a result, there are many small scale ocean eddies, especially near the African coast that result in small scale SST gradients in the same area. This area is a region of interest because the early development of Igor passed over this region where small scale SST gradients of 3 and 4°C/200km exist. About 10 degrees west of the Cape Verde Islands there is a substantial SST gradient of around 3°C/200km that is on the order of 500km in spatial scale. This region is an area of interest because of its location near to the track of Igor later in the simulations and will be addressed further in subsequent sections.
Except for some areas near the African coast, there are very little changes in SST between LOW and CON (Fig. 11b). Between HI and CON (Fig. 11a) however, there are changes on the order of 1°C in many places. Specifically, in a region 10 degrees south and west of the Cape Verde Islands there is a several hundred kilometer region of 1°C warmer SSTs in HI and it is in an area near the track of Igor.

The same method for creating HI is used in the GB runs, and OSTIA SSTs are again used for the CON run. From Figure 10b, the authors noticed artifacts in the SST field that were a result of the filtering. Therefore, in the GB runs, instead of using a filter for the LOW run the OSTIA SSTs were nine-point smoothed 20 times to achieve a similar effect.

3.2 Model Configuration

Six model simulations (CON, LOW and HI for two PBL schemes) of Hurricane Igor (2010) are conducted with the WRF model version 3.5.1 to examine the influence of mesoscale SST gradients on the storm’s development and intensity. Igor formed from a tropical wave that moved off of the African coast late on September 6 and slowly intensified into a hurricane several days later on September 12 (Fig. 12). The goal of this study is to examine influences of small scale SST gradients, therefore track and intensity verification are not discussed. All model simulations of Igor begin 12Z September 7 and end 00Z September 11. The National Hurricane Center designated the disturbance that became Igor a tropical depression on 06Z September 8. We start the simulation 18 hours ahead of this time, to allow for several hours of spin-up time and to examine the genesis and pre-depression stages. The ending time three and a half days later is selected because it allows sufficient time for Igor to develop into a hurricane. For the atmosphere initial conditions and boundary conditions we use ERA-Interim Reanalysis from ECMWF on a 0.7° x 0.7° grid with 38 vertical levels from 1000hPa to 10hPa and temporal
resolution of 6 hours. The number of vertical levels for these model simulations is 60 and the top is set at 10hPa. The WRF model vertical levels are sigma coordinate and are stretched to put more levels in the PBL near the surface, and model top. There are 3 domains with grid spacing of 32, 8 and 2km (domains 1, 2 and 3 respectively; Fig. 13), with domains 2 and 3 being nests with 2-way feedback. The finest nest is 2005 x 693 grid points and encompasses the region where Igor formed and developed into a mature cyclone. The microphysics scheme WSM6 and the NASA Goddard (Chou and Suarez 1999) shortwave and longwave radiation scheme is used for the radiation physics. The 1st domain is run with the Grell-Freitas (Grell and Freitas 2013) cumulus scheme turned on but for the 2nd and 3rd domain it is turned off. The SSTs are kept constant throughout the runs and there is no ocean model used. Data from the model is outputted hourly.

### 3.3 Model Results

The sensitivity of Igor's intensity to the three SST configurations is evaluated (Fig. 14) with respect to maximum wind speed and minimum pressure. In general, Igor is more intense in the YSU model runs than in the GB runs, although both follow a similar intensity trend. For the first two days, from 12Z Sept. 7 to 12Z Sept. 9, there is a gradual intensification of 5-10 mb per day in the YSU runs. After 12Z Sept. 9 however, the YSU CON, LOW, and HI runs begin to diverge with YSU LOW attaining the maximum intensity and YSU CON the weakest separated by about 10 mb. In both YSU LOW and HI there is a period of rapid intensification from 00Z Sept. 10 onward but in YSU CON this does not begin until about 12Z Sept. 10. Although YSU LOW attains the strongest intensity, we do not see the opposite for HI, thus there isn't a direct correlation between increased SST gradients and higher intensity or decreased SST gradients and
lower intensity. However, YSU LOW and HI together, do show a departure from the intensity of CON.

In general, the GB model results show little sensitivity to the different SST setups with respect to intensity. All three runs follow a very similar intensity trace and thus the simulations end within a few millibars of each other on 00Z Sept. 11. Development is much slower in the GB runs than in YSU and there is no rapid intensification period like there is in the YSU runs, although the pressure trace seems to indicate that one may be starting in the last hours of the simulation. Worth noting is the better agreement in the GB runs with the observed intensity in the Best Track.

Analysis of the 2-dimensional structure of Igor shows noticeable differences relative to the control case in the convective patterns of the YSU runs but little differences in the GB runs. Figure 15 compares the lowest model level DBZ in YSU LOW and CON, showing that early in the simulation at 8 hours into the simulation there is little difference in convective structure. However by 12Z Sept. 9 (1 ½ days), convective bands develop to the south of the center in YSU LOW, while there is little convection in this area in YSU CON. This is due in-part to a greater amount of lower and mid-level moisture to the south in LOW than in CON. These differences in convective patterns may also contribute to the differences seen at the end of the simulation in which LOW has a more robust and symmetric eyewall with accompanying banding to the south. In general, there is very little convection on the eastern side of the storm in all the YSU runs. This is a consequence of persistent upper level dry air intruding on the eastern side of the circulation and preventing deep convection there until late in the simulation. This is illustrated in Figure 16a and 16b where a hole in relative humidity is seen around 300 mb on the right side of the storm in LOW and CON at 16Z Sept. 9. This dry air originates to the south of the storm and
is wrapped into the eastern side by the storm's circulation. It persists until the storm has sufficiently moistened to shield itself from dry air (Fig. 16c and 16d). In addition, this upper level dry penetrates farther into CON's circulation than LOW on Sept. 9 and is one of the reasons for the difference in intensity between YSU LOW and CON. In YSU CON on Sept. 9 the dry air is impinging directly into the center and prevents deep convection from developing which keeps the circulation shallow. At the same time in YSU LOW, the dry air is kept away from the center allowing deep convection to occur on the right side of the storm. This in turn leads to what is seen on Sept. 10 with YSU LOW displaying the characteristics of a mature cyclone structure that are not completely developed in YSU CON; a tight and symmetric circulation with an eye surrounded by very deep convection.

To rule out large scale environmental factors that could explain the observed differences in intensity seen in the YSU runs and the similar intensities in the GB runs, we examine the wind shear between 850 and 300 mb. Figure 17 compares the wind shear in YSU LOW and CON at 8 hours, 1 ½ days and 3 ½ days, which is when the simulation ends, into the run. Both runs show very similar shear patterns 8 hours into the run, as would be expected, with a patch of moderate 30 knot shear to the west and another patch to the south of the storm. Two days into the simulations there is a patch of moderate 30 knot shear that persists to the south of the storm but is sufficiently far away from the center to not inhibit development. From mid-Sept. 9 (1 ½ days) onward both storms move northwestward away from the moderate shear to the south and enter into an area of light 10 knot shear. Thus, by Sept. 10 the shear conditions over each storm were favorable for intensification. Generally, the 850-300mb shear is quite similar in all the YSU runs and there is little evidence that shear played a role in the intensity of Igor. Similar results were found for the 850-300mb shear in the GB runs, although the storm intensities were similar in
those runs. Additionally, Igor takes a very similar track in all of the YSU and GB runs, therefore SST gradients have little influence, if any, on differences in track and shear.

3.4 Moisture Advection

An abundance of low level moisture is necessary for TC development and intensification by supplying the moisture for deep moist convection that characterizes a tropical system, suppressing dry convective downdrafts, and assisting in formation of a moist core that is required for a mature system (Nolan 2007; Fang and Zhang 2010). The advection of this moisture is then important for determining how the environment around a TC will evolve. Below defines the advection of specific humidity, $\frac{dq}{dt}$, given in Eq. (1) where $U$ is the horizontal vector wind and $q$ is the specific humidity.

$$-U \nabla q = \frac{dq}{dt}$$

(1)

In this case negative (positive) values of moisture advection will indicate that $q$ is decreasing (increasing) over time and a drying (moistening) in that region. At mesoscale SST gradients, perturbations in wind speed and direction, and to a lesser extent perturbations in moisture content and $q$, will influence the moisture advection. On the warm side of a gradient, positive SST perturbations collocated with positive wind speed perturbations will lead to a perturbation increase in moisture advection given an identical $q$ field. The opposite is then true for the cold side of an SST gradient. As this relates to a TC, the extent to which SST gradients can modify moisture around a storm environment is of interest. An analysis of the advection of low level moisture at a sharp SST gradient near the track of simulated Igor highlights the changes associated with small scale SST gradients.
The area encompassing the analyzed SST gradient and its surroundings is shown in Fig. 18a and 18b along with the simulated track of Igor. The area of interest is a sharp SST gradient (circled in black on Fig. 18b) on the scale of 200-300km embedded within a larger scale gradual transition from warm tropical waters to cooler subtropical water. The cyclonic circulation of Igor begins to blow over the sharp SST gradient beginning 17Z Sept. 9 as the storm approaches from the southeast. At this time the storm is southeast of the SST gradient, so the surface circulation associated with Igor is northeasterly and is blowing nearly perpendicular to the gradient, from the cold side to the warm side of the gradient. Fig. 19a illustrates this situation at 17Z Sept. 9 and defines the analysis area for the cold side and warm side of the gradient which is denoted with a black box. As the storm approaches the analysis region, the surface wind increases on either side of the gradient, owing to strengthening of the storm as well as increasing proximity to the center of Igor. Within each box on either side of the gradient, the moisture advection is calculated at each hour of the simulation from 17Z Sept. 9 to 03Z Sept. 10 and then time averaged over this 10 hour period. After 03Z Sept. 10, Igor’s close proximity to the analyzed SST gradient is such that the storm itself is mostly driving the moisture advection and because of this the effects of the SST gradient are difficult to discern. The moisture advection is calculated with centered differences that take into account +10 and -10 grid spaces around a given grid point that avoids unwanted noise owing to the 2km resolution.

To compare the moisture advection occurring across the SST gradient in the SST setups, PDFs are constructed of the time averaged moisture advection within the cold side and warm side boxes. Fig. 20a, b, and c show the PDFs for the 1st, 2nd, and 3rd model levels respectively. Closest to the surface in the 1st model level, Fig. 20a shows that, in general on the warm side of the gradient the moisture advection values are evenly distributed between negative and positive...
advection, although near the tails there are more extreme negative values. On the cold side however, the advection is distributed mostly toward negative values. This leads to the conclusion that the cold side is generally becoming drier for this period and this finding matches with the occurrence of a drier air mass being pulled into Igor’s northwest circulation at this time in the simulations.

Of significance here though are the differences in the shapes of the distribution between the three SST setups in Fig. 20a. Focusing first on the warm side, the distribution of advection in the LOW run (dotted red) has the highest peak in any of the runs near 0, showing that the LOW run has the lowest absolute values of advection in the three SST setups. In the solid red line, the CON run has a peak also near 0 but with a slightly flatter distribution than LOW such that the peak is below LOW. Also near the tails in CON the distribution is wider than LOW at positive values indicating that there are more extreme positive values of advection in the CON run compared to LOW. Lastly, the distribution in the HI run (dashed red) is the flattest of the three runs with a peak still near 0 but below CON owing to less of the distribution being at the peak and more near the tails at larger values of advection. While all three runs have similar minimum and maximum extreme values, the HI run has the most concentration of distribution near these extremes indicating that in general there is a greater magnitude of moisture advection occurring during the analysis period in the HI run than the other two SST setups. Coincident with increasing magnitude of moisture advection between LOW, CON and HI, is increasing magnitude of the SST gradient present in each SST setup. This indicates a general relationship between larger magnitudes of SST gradient and larger magnitudes of moisture advection (both positive and negative). These distinctions are less clear on the cold side of the gradient. There is a general trend of increasing moisture advection at higher levels (Fig. 20b and 20c) that is the
result of increasing magnitude of the wind with height. Fig. 20b and 20c also show the same relation as in the first model level but it is less clear because of the decreasing influence of the SST gradient with increasing height.

3.5 Discussion: Igor Simulations

The results from the PDFs of moisture advection in Fig. 20 show that an SST gradient can affect the moisture transport across the gradient and that moisture advection is increased with increasing magnitude of the SST gradient. This agrees conceptually with previous studies discussed in Chapter 1, showing that positive wind and SST perturbations are collocated. Perturbations in wind will in turn lead to perturbations in the moisture advection through the inclusion of the wind in the calculation of the advection (see Eq. 1). For example in the YSU HI run the magnitude of the analyzed SST gradient is the largest out of the three SST setups. The SST gradient in the HI run should therefore have the largest SST and wind perturbations and by extension then the largest moisture advection perturbation which is shown to be true in the PDFs on Fig. 20. Thus the PDFs show that where there are higher wind and temperature perturbations there is also an increased moisture advection perturbation. In addition to the areas used to define the warm side and cold side for the SST gradient in this analysis, other areas along the larger scale SST gradient shown in Fig. 18 were examined in a similar analysis (not shown) which yielded similar results for the sign of moisture advection.

In the simulations of Hurricane Igor the intensity of the storm is overall, more sensitive to the three SST setups in the YSU runs than in the GB runs, although of note is the closer agreement of the GB runs with the observed best track intensity. In addition, the separation of the YSU runs that begins on 12Z Sept. 9 seems to be primarily due to an upper level dry air intrusion that keeps deep convection suppressed on the east side of the storm. In the CON run this dry air
penetrates farther into the circulation and suppresses almost all deep convection on the east side. In the LOW run however, the dry air is not able to penetrate as far into the core and some deep convection is able to develop on the east side. This enables Igor in the LOW run to form a more symmetric structure that translates to a higher intensity than CON, later in the simulation.

While the differences in intensity between the SST setups for the YSU runs are not trivial, we could not find a linkage between the effects of the SST gradients and the observed differences in intensity and structure for this study. Without this link, we conclude that, for this storm case, larger scale factors such as the upper level dry air intrusion are more significant to the intensity and structure than the effects from SST gradients. This finding indicates that advection perturbations induced by small scale SST gradients have only a small impact on moisture input to deep convection in these model simulations.
Figure 9. Shaded SST(°C) for YSU CON(a), YSU LOW(b), and YSU HI(c). The shaded contour intervals are 0.5°C.
Figure 10. Shaded SST gradient (°C/200km) for YSU CON(a), YSU LOW(b), and YSU HI(c). The shaded contour intervals are 0.5°C/200km. The gradient is initially calculated over a 24km distance and then rescaled to 200km.

Figure 11. Shaded SST Difference (°C) for YSU HI-YSU CON(a), and YSU LOW-YSU CON(b). The shaded contour intervals are 0.2°C.
Figure 12. Observed track and intensity of Hurricane Igor (2010) from Best Track. Each X is the observed location of the storm at 6 hour intervals. The intensity of the storm at each X is given by the color, purple is Tropical Depression, blue is Tropical Storm and yellow is Hurricane strength. Igor became a Tropical Depression on 06Z September 8 and each of the simulations of Igor end on 00Z September 11.
Figure 13. Domain configuration for the Igor model simulations. Domain 1(D1) is 32km grid resolution, Domain 2(D2) is 8km grid resolution, and Domain 3(D3) is 2km resolution.
Figure 14. Timeseries of the minimum pressure (a) and maximum surface wind (b) in the six simulations of Igor. The observed Best Track minimum pressure and maximum wind are given by the solid brown line in both plots. The time interval for the data is hourly and all of the runs begin on 12Z September 7 and end 00Z September 11.
Figure 15. Lowest model level simulated reflectivity from the YSU CON run (top panel) and YSU LOW run (bottom panel). Each plot is centered on the minimum pressure center of the storm at that time. The first column on the left is 8 hours into the simulation (20Z September 7), the middle column is 1 ½ days into the simulation (12Z September 9) and the column on the right is at the end of the simulation on 00Z September 11. Lowest model level wind barbs are shown in knots.
Figure 16. East – West cross section through the minimum pressure center of Igor in the YSU CON run (top panel) and YSU LOW run (bottom panel). The shading is Relative Humidity and the contours are the V wind component in knots contoured every 30. The left column is at 16Z September 9 and the right column is a day later on 16Z September 10
Figure 17. Shaded 850-300mb shear in the YSU CON run (left column) and YSU LOW run (right column). The black cross signifies the minimum pressure center of Igor at that time. The first row is 8 hours into the simulation (20Z September 7), the middle row is 1 ½ days into the simulation (12Z September 9) and the row at the bottom is at the end of the simulation on 00Z September 11.
Figure 18. SST from the CON run (a) along with the track of Igor in the CON run (black line). The SST anomaly and CON track are plotted in (b). The black circle indicates the analyzed SST gradient. The blue box over (a) is the plotted area in (b). For both (a) and (b) each X on the track is 6 hours.
Figure 19. SST anomaly and lowest model wind barbs in YSU CON at the start (a) and end (b) of the moisture advection calculation. Moisture advection is calculated within each of the black boxes on the cold side and warm side of the SST gradient. A black X marks where the minimum pressure center of Igor is at each time.
Figure 20. PDFs of the moisture advection within the cold side and warm side box in each of the YSU runs for the 1st (a), 2nd (b) and 3rd (c) model levels. The values for the warm side are in red and the values for the cold side are in blue.
CHAPTER 4

SUMMARY AND CONCLUSIONS

Two sets of model experiments are conducted with the Weather Research and Forecasting (WRF) model to analyze the effects that mesoscale SST gradients have on TC development and intensification. In one set, two idealized simulations of a TC are run at 2 km grid spacing, one run with a constant 28°C SST (IDEALcon) and another with a horizontal SST gradient at the center of the domain under the TC (IDEALgrad). In the IDEALgrad run, the simulated TC is drastically different in structure, intensity and evolution compared to the constant SST run. While the TC in the IDEALcon run stays mostly stationary, in the IDEALgrad run the TC drifts north and west, over the colder SST and weakens substantially. This is the result of stronger convection to the north of the storm continuously pulling the circulation north over colder water. The colder water allows warm air brought north by the cyclonic flow to saturate quickly and precondition the area north and east of the center for enhanced convection. The asymmetry in the convection causes the vertical alignment of the vortex to be disrupted and prevents intensification. While not a climatological feature of the real atmosphere at western boundary currents, the SST gradient in the IDEALgrad run causes a thermal wind jet to form at 300mb and shears the top of the TC as it moves north.

In a second set of model experiments, real simulations of Hurricane Igor (2010) are conducted at 2km grid spacing with three different SST setups: a run with an unaltered SST field (CON), a run with increased SST gradients (HI), and a run with decreased SST gradients (LOW). Igor's intensity is shown to be sensitive to the SST setup in a set of model runs using the YSU PBL scheme, while in another set using the Grenier and Bretherton (2001; GB) PBL scheme there was less sensitivity. While there was less sensitivity to the SST setup in the GB runs, these
runs were in closer agreement with the observed Best Track intensity. In the YSU runs, much of the sensitivity comes after September 9 at which time an upper level dry air intrusion is observed to limit the intensification of Igor in each of the SST setups. We are unable to find a link between the sensitivity in structure and intensity observed in the YSU runs, and the effects from SST gradients. Therefore, for this storm case, other factors such as the dry air intrusion are more significant to the structure and intensity of the storm than the effects from SST gradients. Also of note here is that the sensitivity of Igor's intensity to the two WRF PBL schemes used is greater than that of the sensitivity to SST setup. Features of Igor that showed little sensitivity to the SST setups in both the YSU and GB runs include the pre-depression/genesis phase of the storm with respect to intensity and structure as well as the track of Igor throughout the runs.

To elucidate the effects that an SST gradient has on a storm environment we analyze a specific area near the track of Igor that featured a sharp SST gradient. The moisture advection on either side of the gradient is analyzed for a length of time when Igor's outer circulation was blowing perpendicular to the SST gradient. PDFs of moisture advection are then constructed separately for the warm and cold sides of the gradient. It is found that when the SST gradient is sharpest (the HI run) the magnitude of the moisture advection is increased on the warm side of the gradient. Further, the moisture advection decreases with decreasing SST gradient indicating that the transport of moisture across the gradient is sensitive to the magnitude of the SST gradient. This is supported by previous work which shows that positive wind perturbations are collocated with positive SST perturbations (Chelton et al. 2001, Song and Chelton 2009, Chelton et al. 2004; Xie et al. 2004). Because the wind is a major part of the calculation of moisture advection, a perturbation in the moisture advection is expected along with a perturbation in wind. This advection extends well above the surface layer, but does weaken with height.
For future work, because we have provided only one storm case here, more storm cases are desired to substantiate the results found in this study. In future model experiments, an equal and opposite SST field for HI and LOW would be desired such that Fig. 11a and 11b would be identical. This study provides a first step in assessing what impact SST gradients may have on TCs. We have shown here that the physics at SST gradients can affect the environment around a TC and that in an idealized environment, an SST gradient on the same scale as a TC can be detrimental to the TC's structure. An important next step would be to answer the question of whether modification of a TC's environment as a result of an SST gradient can be linked to TC intensification or weakening. Further investigation of this topic is important to the TC modeling as well as forecasting community as numerical models and SST satellite datasets become finer resolution and smaller scale processes become more important to study.
REFERENCES


BIOGRAPHICAL SKETCH

I was born April 13, 1989, in Concord, New Hampshire. My family moved to McLean, Virginia outside of Washington, D.C. when I was two years old and have lived there ever since. I have an older brother who lives and works now in Alexandria, Virginia, also outside of Washington. Living just outside of the DC Beltway I grew up in an area very typically suburban, although over the last few decades the area has become increasingly urbanized as the city expands outward. My interest in meteorology came at a young age, around 7 or 8 year old. I remember being very captivated by tornadoes, although I had never actually seen one, through science programs about weather on the discovery channel and TLC (back when these channels actually had educational programming). But it wasn't until college and being confronted with the choice of picking a major that I decided to commit to meteorology not just as a hobby. I attended Virginia Tech, which at that time had no meteorology program, for my undergraduate and majored in Geography. I took what meteorology classes they offered, but these classes somewhat left me wanting so after my junior year I decided I would try to go to grad school for meteorology. One experience that at Virginia Tech that was invaluable to stirring up interest to go to grad school was a summer class that was basically a two week storm chase in the mid-west.

I have thoroughly enjoyed my time at Florida State through working at COAPS as the van driver and a graduate student. The program here was exactly what I was looking for I am greatly appreciative of the opportunity given to me to study meteorology here. In the future I hope to do a PhD in meteorology at FSU or another university, although I am open to job opportunities as well. Beyond that I hope to work at a Nation Laboratory or possibility work internationally as meteorology is a very international (global) field.