The Influence of Atmospheric Cold Air Outbreaks on the Upper Ocean Thermal Variability of the Florida Straits

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The purpose of this study is to investigate the impacts of cold air outbreaks (CAOs) on the sea surface temperature (SST) in the Florida Straits (FS) during different configurations (mature or immature) of the Loop Current (LC). A satellite-derived SST data set is used to calculate the difference in SST anomalies between the FS and the Yucatan Channel (YC). The SST anomaly time series is analyzed during the winter season for times of mature and immature LC configurations determined from a satellite altimetry-derived time series of LC position. This analysis shows a greater likelihood of anomalous cooling of SSTs in the FS compared to the SSTs in the YC during times of an extended, or mature, LC. This result leads to the hypothesis that surface water is subject to greater cooling during a mature LC (due to the greater residence time of the water under cold air masses) than an immature LC, and this cooler water is advected into the FS. This hypothesis is investigated by computing an approximate heat budget for the Yucatan-Loop-Florida Current (YLFC) under identical atmospheric forcing using twin ocean model simulations with mature and immature LC configurations.
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THE INFLUENCE OF ATMOSPHERIC COLD AIR OUTBREAKS ON THE UPPER OCEAN
THERMAL VARIABILITY OF THE FLORIDA STRAITS

By

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# TABLE OF CONTENTS

1. INTRODUCTION ......................................................................................................................6

2. BACKGROUND ........................................................................................................................7
   2.1 the Yucatan-Loop-Florida Current System...........................................................................7
   2.2 Cold Air Outbreaks .............................................................................................................7
   2.3 Previous Research .............................................................................................................8

3. VARIABILITY OF FLORIDA STRAITS AND YUCATAN CHANNEL SEA SURFACE TEMPERATURE ANOMALIES ..........................................................................10

4. CAO IMPACTS ON THE FLORIDA STRAITS COOLING DEPENDING ON LOOP CURRENT POSITION .................................................................................................13
   4.1 HYCOM Simulation ...........................................................................................................13
   4.2 Characterizing Cold Air Outbreaks ....................................................................................14
   4.3 Calculating Lagrangian Temperature Change Within the Loop Current............................17

5. SUMMARY ..............................................................................................................................19
REFERENCES ..................................................................................................................................21
FIGURES .......................................................................................................................................24
The purpose of this study is to investigate the response of the upper ocean temperature in the Florida Straits (FS) during cold air outbreaks (CAOs) and observe whether the thermal variability in the FS is sensitive to the position of the Loop Current (LC). The LC waters have a longer residence time in the Gulf of Mexico (Gulf) during a northerly extended, or mature, LC phase versus an immature phase. Therefore, we expect the LC waters to cool more in response to a CAO over the Gulf during a mature configuration and advect the cooler waters into the FS. Furthermore, for an immature LC, the air mass in the CAO will have more time to potentially transform into a warmer air mass before it reaches the more southern latitude of the LC, resulting in less heat loss from the upper ocean. If the position and residence time of the LC within the Gulf of Mexico play a factor in the thermal variability in the FS, this information might be used to predict the likelihood of anomalously cold surface waters during winter seasons.

Satellite altimetry observations of the LC position and remotely sensed sea surface temperatures (SST) are used to show the impact of LC position on the upper ocean cooling affecting the waters entering the FS. The cooling is explored by using data from numerical ocean model experiments and then is quantified by calculating a simplified heat budget to demonstrate a possible mechanism for the differential cooling under different LC configurations.

The FS are critical to the economic stability of the fishing industry in the Florida Keys [McBride, 1999]. Anecdotal evidence from commercial and charter boat fishermen in the area suggests a link between cooling events and baitfish migration, which may impact the population dynamics of this fishery. Therefore, determining the impact of CAOs and LC position on the cooling of the SSTs in the FS may provide tools to better understand the potential impacts on fisheries sensitive to thermal stresses.
CHAPTER 2

BACKGROUND

2.1 The Yucatan-Loop-Florida Current System

The Yucatan-Loop-Florida Current (YLFC) transports warm tropical water into the FS. The current originates in the Caribbean Sea, flows past the Yucatan Peninsula, enters the Gulf of Mexico and the LC, and then flows into the FS (Figure 1). The LC cycles stochastically between two extreme configurations: mature, which extends far northward, and immature, which immediately turns east after entering the Gulf. The mature configuration usually precedes the shedding of a large anticyclonic eddy, followed by a transition to the immature phase. For this study, the mature and immature phases are objectively defined by analyzing a time series of the latitude of the LC’s northern edge by using satellite altimeter-derived metrics [Leben, 2005] (Figure 2). Leben [2005] provides a time series of LC positions based on sea-surface height (SSH) that is used to characterize the behavior of the LC and eddy separation in the Gulf of Mexico for 1 January 1993 through 1 July 2004. To objectively define the mature and immature LC phases for the purposes of this study, the upper 75th and lower 25th percentile of the latitude of the LC northern edge is calculated from the time series. From this definition, the LC is considered to be in an immature phase when the latitude of its northernmost edge is south of 26.9° N and in a mature phase when the northern edge is north of 25.7° N.

2.2 Cold Air Outbreaks

Henry [1979] found that more atmospheric fronts pass over the Gulf of Mexico during the winter months than during the other seasons. On the basis of the number of fronts entering
the Gulf of Mexico for the period of 1967-1977, Henry [1979] identified the winter months as December, January, February, and March. For this study, winter months are defined as December, January, and February (DJF): the period when at least 50 percent of the cold fronts leave the Gulf of Mexico and enter the Caribbean. During this DJF parameter the cold air is more likely to infiltrate behind a front and enter the area of interest, the Gulf of Mexico (Figure 1). A front remaining in the Gulf may not be strong enough for the cold air to infiltrate fully into the Gulf. Also, in DJF there is a higher incidence of fronts passing south beyond 15° N [Henry, 1979], indicating faster and stronger fronts occur during these months and, consequently, strong CAOs are more likely to occur after frontal passage through the Gulf. Additionally, March is not included in this study because of the higher percentage of fronts that frontolyzed in the Gulf during this month (32%) relative to December (20%), January (18%), and February (17%).

Cases of CAOs are evident from observed air temperature in the Gulf of Mexico and the FS. National Data Buoy Center (NDBC) air temperature data from buoy 42309, located in the Gulf at 28.791° N, 86.008° W, and the Molasses Reef station (MLRF1), located in the FS at 25.010° N, 80.380° W, are used to examine the cases of anomalous CAOs. Buoy 42309 and station MLRF1 record air temperature hourly at 4 m and 15.5m, respectively, above mean sea level. The data are extracted for 20 years, from 1990 to 2009, to remove the bias caused by climate oscillations that may introduce cooling or warming partiality into the data. The air temperatures for the study are extracted at 12Z to eliminate the effect of the diurnal temperature cycle that varies depending on the amount of solar radiation output.

2.3 Previous Research

Walker et al. [1987] examined the heat budget of the Florida Bay during CAO scenarios. However, their research was performed for shallow-water environments where minimal advection occurs. The one-dimensional vertical flux model they used to calculate the heat budget also did not account for advection of SST. In contrast, this study includes a Lagrangian calculation of temperature change in areas of strong advection (LC and FS). This calculation demonstrates the impact thermal advection has on the cooling of surface waters in the FS with respect to LC phase. Thermal variability research in the FS has been limited by a lack of data.
Strong currents prohibit the deployment of buoys, and persistent cloud cover obscures satellite visuals. However, clear conditions during CAOs reduce the cloud contamination, so the infrared satellite data have less error. Microwave observations are adversely impacted by rain, but not by the small droplets in clouds.

In Chapter 3, the impact of LC position on the thermal variability within the FS is examined through joint analyses of SST time series for the YC and the FS and the Leben [2005] LC time series. Chapter 4 discusses cooling identified in the HYCOM + CFSR outputs for CAO occurrences and the application of a numerical model to illustrate the impact of LC position on cooling of the FS during a CAO event. Chapter 5 presents a summary of the findings.
CHAPTER 3

VARIABILITY OF FLORIDA STRAITS AND YUCATAN CHANNEL SEA SURFACE TEMPERATURE ANOMALIES

The upper ocean thermal variability of the Florida Straits (FS) and the Yucatan Channel (YC) is analyzed using satellite data products to investigate the cooling of surface water that occurs with different Loop Current (LC) configurations (mature or immature) in the two regions during cold air outbreaks (CAOs). It is hypothesized that the SST cooling of FS waters will be sensitive to the northerly extent of the LC during the winter season, when the Gulf is subject to cooling under CAOs. Analyzing the change in SST of waters that enter the Gulf through the YC and flow into the FS for both LC configurations during DJF will help determine whether this hypothesis is valid.

To explore the nature of thermal variability in the FS, a satellite-derived SST product is used to evaluate the sea surface temperatures for the YC and the FS. NOAA’s daily Optimal Interpolation 1/4° version 2 AVHRR+AMSR sea-surface temperature (SST) product [Reynolds et al., 2007] assimilates the Advanced Very High Resolution Radiometer (AVHRR) version 5 pathfinder sea surface temperature retrievals from September 1981 through December 2005 and the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) version 5 sea surface temperature retrievals from June 2002 to the present. This data set uses in situ data from buoys and ships and includes a bias correction of the satellite data with respect to in situ data using an empirical orthogonal teleconnection algorithm [Reynolds et al., 2007].

For the analysis, regions within the YC and the FS are defined to encompass the core of YLFC as it passes through each strait. The area for the YC is defined as 21.05° to 21.60° N and 84.4° to 86.8° W. The FS region is defined as 23.35° to 24.4° N and 80.35° to 80.8 °W (Figure 1). Data from the Reynolds et al. [2007] SST product are then spatially averaged over these regions for each day to produce SST time series for the YC and FS.
The difference of thermal variability in the YC and the FS is examined by determining the SST anomalies (relative to the annual SST climatology for each region’s time series) and then subtracting the FS anomalies from the YC anomalies for the period of 1990-2009. First, the daily SST value of the time series is calculated for each region by taking the mean SST for the defined box for each calendar day (excluding leap days). This calculation provides a 20-year record of SST values for each region. A daily climatology for each region is then determined by calculating an SST mean for each calendar day over the 20-year period. Anomalies are calculated for both the YC and the FS by subtracting the daily mean values from each SST in the time series.

The daily difference in regional anomalies is calculated by subtracting the daily SST anomaly values for the YC from the anomalies for the FS. Negative anomaly differences indicate that, at a particular time, the SST in the FS is more anomalously cold than the SST in the YC. Conversely, positive anomaly differences indicate that the FS SST is more anomalously warm than the YC SST. This anomaly difference time series is then divided into subsets on the basis of the northward extent of the LC (as defined in Chapter 2; Figure 2). These LC subsets are then analyzed for the winter months of December, January, and February (DJF) (suggested by Henry [1979] as the months during which CAOs are most common in this region of the Gulf of Mexico).

Histograms (probability distributions) of SST anomaly differences for mature phases of the LC are compared to histograms for immature phases of the LC during winter months (Figure 3). This comparison shows differences in the thermal variability in the FS expected, based on the hypothesis, during mature versus immature phases (Figure 3). The influence of the differing number of samples from mature and immature phases is removed by examining probability distributions (Figure 3).

The histograms of anomaly differences for mature phase LC show a left (negative) skew for DJF, indicating anomalously cooler SSTs in the FS than in the YC. A right (positive) skew is prevalent in the histogram for immature phase LC, illustrating anomalously warmer SSTs in the FS than in the YC during immature phases (Figure 3). This shows that during the winter months, there is a higher probability for FS SST to be colder compared to climatology than YC SST when the LC is mature. It is possible that during this LC configuration, LC waters are either
cooled more in a mature phase compared to an immature phase under a CAO because of (1) the longer residence time of LC waters in the Gulf, or (2) the LC waters flow farther north, where the CAO may have colder air temperatures, and thus the atmospheric forcing onto the waters is stronger than it may be on the waters of an immature phases.
CHAPTER 4

CASE STUDY: CAO IMPACTS ON FLORIDA STRAITS COOLING DEPENDING ON LOOP CURRENT POSITION

4.1 HYCOM Simulation

The oceanic response to the CAOs is examined with the 1/25° resolution Gulf of Mexico HYCOM model; the model domain is that used by Zamudio and Hogan [2008]. The model runs have no data assimilation and they are forced at the open boundaries by climatology fields derived from a 1/12° North Atlantic HYCOM simulation. Surface fluxes are computed using the Wallcraft et al. [2008] bulk flux formulation with CFSR atmospheric variables. The model is forced by overlying atmospheric conditions from CFSR hourly fields from 1992 through 2009, and this atmospheric forcing is cycled three times, yielding a 54-year integration. Since all three cycles are run without data assimilation, the LC is allowed to be stochastic (i.e., not intending to replicate the LC configuration or eddy field for any particular time period, nor the atmospheric forcing period) under the same atmospheric forcing for all simulation runs. Because the model uses 18 years of atmospheric forcing for the three different 54-year runs, there is an increased likelihood of examining the ocean’s thermal responses to identical surface forcing during both mature and immature LC phase simulations. This model experiment is conducted to find a signal of enhanced anomalous cooling within the LC and the FS that agrees with the results found in Chapter 3 (Figure 3). It is hypothesized that there should be anomalous cooling within a mature LC because of the longer residence time of LC waters under the atmospheric forcing.

The model output is inspected to identify examples in which both mature and immature LC phases are present on the same CAO date for different model cycles. To determine time periods of potential CAOs in the Gulf of Mexico and FS, air temperature time series are
constructed for the winter months of DJF (defined in Chapter 2 as the months when CAOs are most common) to show the different cold air instances in the FS (Figure 4) for buoy 42309 and station MLRF1 (Chapter 2; Figure 4). A case is found in which the model runs simulate both mature and immature phases in the winter season of 1996-1997. By chance, the three runs of the model simulate a mature and an immature phase for the same date: 28 January 1997. The air temperature time series show an anomalously cold temperature on 26 January, so the 26-28 January CAO and a CAO prior to this, the 17-19 January CAO, are used to examine the cooling that occurs in the HYCOM+CFSR simulation SST outputs for 28 January.

Outputs of the HYCOM + CFSR simulation for the CAO of 26-28 January indicate cooling of SSTs within the eastern region of a mature phase LC. These SSTs are prevalent in both the LC and the FS, leading to the assumption that these cooler SSTs (on the order of 24-25°C) are being advected from the LC into the FS (Figure 5, top panel). In the immature phase (Figure 5, bottom panel) the cooler SSTs seen in the mature phase exist only in the outer region of the LC. Also, the cooler temperatures seen in the FS for the mature phase LC do not exist in the FS for the immature phase, leading to a second assumption that the SSTs are not cooling as abundantly within an immature phase, than the mature phase, during the model’s atmospheric forcing for the 26-28 January CAO. The cooling and advecting of SSTs in a mature phase LC demonstrates that the position of the LC does impact cooling within the FS during this CAO.

The 26-28 January CAO as well as the CAO preceding it, the 17-19 January CAO, are described in detail in section 4.2.

4.2 Characterizing Cold Air Outbreaks

The specific CAOs identified for this case study are used to show where and to what extent the HYCOM+CFSR simulation SST fields (Figure 5) are cooled. Two CAOs occur near the date of the HYCOM+CFSR model SST outputs for 28 January: the 26-28 January 1997 CAO and the 17-19 January 1997 CAO. Data from the Saha et al. [2010] 1979-2009 Climate Forecast System Reanalysis (CFSR) are used to create atmospheric synoptic maps for these two CAO dates and characterize the atmospheric forcing onto Gulf. The 17-19 January CAO includes the most anomalously cold air temperature (in the FS) for the 1996-1997 DJF air temperature time
series. The minimum temperature of this CAO is 2.7°C colder than the secondary minimum temperature (20 December 1996) and 7.6°C colder than the third minimum (9 December 1996; Figure 4). However, the 17-19 January CAO (Figure 6) occurs primarily over the Southeast and only slightly over the Gulf, the study’s area of interest. The 26-28 January CAO is a smaller CAO, indicated by a less significant air temperature minimum in the Gulf and FS (Figure 4), but it does occur in the targeted region for the LC (Figure 1). Because the 17-19 January CAO occurs only in the northeast quadrant of the targeted region, it is assumed that the cooling effects will depend on whether the LC enters that region.

A progression of synoptic maps of mean sea level pressure (MSLP), dew point temperatures, and wind vectors (Figure 7) from the CFSR are examined for the 17-19 January CAO and the 26-28 January CAO (Figure 4). MSLP is used to detect the center of the low pressure associated with a cold front and the subsequent higher pressure behind the front (the CAO). Dew point temperature shows how much moisture is in the air in comparison to how much moisture the air can hold. Lower dew point temperatures indicate a drier atmosphere, which follows a cold front. Since this drier air occurs after a frontal passage, it is useful to examine dew point temperatures to locate the position of the front and the cooler, drier air that is filtering into a region following the passage of the front. Wind vectors, which are used to detect the magnitude of the wind, show the wind pattern around the low pressure and indicate areas where thermal advection is occurring. The colder temperatures that arise during a CAO can be due to cold air advection if the winds are strong. If the winds are light, radiative cooling may be more dominant than advection.

The progression of synoptic maps (Figures 6 and 7) shows a tight pressure gradient for 00Z Jan 26 (Figure 7, top left) in the southeastern United States accompanied by high dew point temperatures in the Gulf, thus indicating an oncoming frontal passage. The frontal passage occurs in the Gulf and FS on 12Z JAN 26 as denoted by the sharp dew point temperature gradient and tight pressure gradient (Figure 7, top middle). This large pressure gradient creates strong winds from the northeast, illustrated by the wind vectors, because of the incoming high pressure’s clockwise rotation. However, these strong winds seem to penetrate only the northern Gulf.

After the frontal passage in the Gulf for the 26-28 January CAO (Figure 7, top middle), an increase of 3-4 hPa in pressure as well as a decrease of 10°C in dew point temperature occurs
between 00Z Jan 26 and 00Z Jan 27 (Figure 7, top left, middle, and right) in the region of interest. A more uniform pattern of MSLP and dew point temperature prevails over the area 12Z Jan 27 into 12Z Jan 28 (Figure 7, bottom left, middle, and right). This cooling period of the 26-28 January CAO is assumed to occur after the strong cold air advection (00Z January 26-00Z January 27) that is shown by the wind vectors; however, the cold temperatures, illustrated by the large departure in dew point in the Gulf, are maintained by radiative cooling that occurs because of the drier air over the Gulf. This conclusion is reached because any cold air advection that takes place seems to be occurring for only one day and primarily in the northernmost Gulf (Figure 7, top panels).

This tight pressure gradient is not present in the frontal passage of the 17-19 January CAO (Figure 6, top left); however, stronger wind vectors following the frontal passage (Figure 6, top panels) provide the mechanism for cold air advection from the north (where the air is much colder, as indicated by dew point temperatures) into the Gulf. This cold air advection enhances the exchange of energy between the atmosphere and the Gulf waters, allowing the waters to cool. MSLP and wind during the CAO (Figure 6, bottom left and middle) indicate that the winds have slightly lessened in the center of the Gulf; conversely, low dew point temperatures (4-6°C) are present, suggesting cooling is still occurring. In the absence of flux analysis, these findings lead to the assumption that both radiative cooling and wind-driven heat exchange play a role in cooling the surface waters within the area of interest (Figure 1) for the 17-19 January CAO.

The analysis of air temperature time series and the progression of synoptic maps identify the characteristics of the two CAOs that occurred in the Gulf and help to explain the location and extent of the cooling in the HYCOM+CFSR SST fields. In section 4.3, the net downward surface flux from the 1/25° HYCOM Gulf of Mexico simulation is used to compute the change in SST along numerically prescribed mature and immature LC trajectories for a period that encompasses both CAOs.
4.3 Calculating Lagrangian Temperature Change within the Loop Current

Calculating the Lagrangian temperature change within the LC quantifies the results found in the HYCOM + CFSR forced flux model runs (Figure 5). These runs show that cooling SSTs within a mature LC are being advected into the FS. To quantify this assertion, the net surface flux, Q, is extracted from the 1/25° HYCOM Gulf of Mexico simulation with CFSR forcing. The temperature change for a numerically prescribed mature and immature LC trajectory is computed from the Q fields for 13-28 January 1997, a period that encompasses both CAOs.

The trajectories used to calculate ocean temperature changes are numerical paths of water parcels with latitude and longitude positions recorded every three hours for both mature and immature LCs. The trajectories are calculated by numerically solving $\frac{dx(t)}{dt} = -u(x,t)$, where $x(t)$ is the position of the water parcel at time $t$. The variable $u(x,t)$ is the 1/25° HYCOM surface velocity field. The calculations start at the end of the time period, time $t$ (28 January), with $x(t)$ being somewhere in the FS. By integrating the above equation (using 4th order Runge-Kutta) with the negative of the velocity field, the trajectory is calculated backward in time from time $t$ to time 0 (13 January). These calculations are performed for multiple variations of mature and immature LC trajectories; the trajectories chosen for this study were among those that went from the FS through the YC.

The gridded Q output from the HYCOM Gulf of Mexico simulation is bi-linearly interpolated along the prescribed mature and immature LC trajectories to assign a Q value for each three-hourly time step and position in the trajectories. A simple one-dimensional model of the temperature change within the surface mixed layer is

$$\frac{dT}{dt} = \frac{Q}{(\rho C_p h)} \tag{1}$$

where $Q$ is the surface heat flux in W/m$^2$, $\rho$ is density fixed at 1025 kg/m$^3$, $C_p$ is the heat capacity at a constant pressure fixed at 3992 J/kg°C, and $h$ is the mixed layer depth fixed at 50 m, the mean mixed layer depth of the trajectories.

The equation (1) is integrated in time using the trapezoidal method along the trajectory to obtain the ocean temperature $T(t)$ relative to the temperature $T(0)$ at the start of the trajectory for each time and latitude/longitude position of the LC phases. Finally, the change in ocean
temperature from the water parcel’s last position is calculated to retrieve a time series of ocean temperature changes along the given trajectory from 13-28 January (Figure 8).

The ocean temperature for the mature trajectory (Figure 8) shows a change of 0.8°C (cooling) for the period of 16 January to 23 January. This time period coincides with the time period of the 17-19 January CAO. The ocean temperature change occurs when the water parcels are moving through the northernmost part of the mature LC trajectory (Figure 9, top panel), the same time that the CAO occurs. Consequently, the temperature change is seen because the water parcels are in the core area of the CAO. The ocean temperature change time series for the immature phase trajectory shows a change of 0.6°C occurring from 17 January to 23 January. The time periods of cooling differ by a day because the waters in the immature phase are still in the YC during 16 January whereas the waters in the mature phase trajectory are already in the LC (Figure 9). The water parcels for both trajectories for the time periods of cooling have yet to enter the FS. Very little additional cooling is evident from 23 January to 28 January, the remaining time period in the trajectory during which the surface water was subject to the 26-28 January CAO. Hence, we can assert that the 17-19 January CAO is controlling the cooling of the FS waters that is seen in the HYCOM+CFSR model runs (Figure 5). We can also assert that since little additional cooling is taking place although the water parcels are still cooled, there is cold SST advection taking place from within the LC into the FS.

The difference in ocean temperature cooling between the mature and immature LC trajectories for the CAO time periods is on the order of 0.3°C. Note that although 0.3°C is a small temperature change, it is the average over the entire 50-m mixed layer depth. This calculation is very sensitive to the ad-hoc choice of a 50-m mixed layer depth (the temperature change is actually a linear scaling of the mixed layer depth). Additionally, the definition of the mixed layer depth is somewhat arbitrary and typically allows for variations in temperature of several tenths of a degree (up to 1°) vertically, so that the actual temperature change might be larger for the top few meters of the ocean compared to the average over the entire mixed layer. Also, the calculated ocean temperature values are dependent on the numerical path prescribed for them; thus, there could possibly be larger/smaller ocean temperature changes for slightly different prescribed paths. Overall, these results suggest cooler temperatures in the FS for a mature LC trajectory than for an immature trajectory, agreeing with the SST fields in Figure 5 and the initial hypothesis for the study.
CHAPTER 5

SUMMARY

Histograms of the anomaly differences (Chapter 3) show the variability in the SST anomalies between mature and immature LC phases under CAO conditions (Figure 3). The histograms of anomaly differences indicate anomalously cooler SSTs in the FS than in the YC for mature phase LCs and anomalously warmer SSTs in the FS than in the YC for immature phases (Figure 3). These results provide the basis for exploring the impact of LC position on cooling of FS waters.

Three HYCOM+CFSR model runs simulate both mature and immature phases for 28 January 1997 (section 3.1). The model runs suggest that cooling of SSTs occurs within the LC and FS for a mature phase LC, whereas this cooling is not as prevalent in the immature phase simulation. These results suggest that the position of the LC does impact cooling within the FS during the 17-19 January and 26-28 January CAOs, which occurred near the date selected for the model runs.

The air temperature time series (Figure 4) and a progression of synoptic maps (Figure 6 and 7) are used to evaluate the cooling presented by the HYCOM+CFSR model SST fields (Figure 5) for the 17-19 January CAO and the 26-28 January CAO (section 4.2). The findings in the air temperature time series and the synoptic maps for the two CAOs allow us to deduce in the absence of flux analysis that radiative cooling and wind-driven heat exchange both affect the cooling of surface waters within the area of interest (Figure 1) for the 17-19 January CAO. For the 26-28 January CAO, wind-driven heat exchange is present in the northern Gulf because of the strong cold air advection that occurs 12Z January 26-00Z January 27; however, radiative cooling affects more of the area of interest (Figure 1).

The results discussed in section 4.3 indicate that the 17-19 January CAO primarily controls the cooling of the FS waters that is seen in the HYCOM+CFSR model run SST outputs.
(Figure 5). Ocean temperatures are cooler in the FS for a mature LC trajectory than they are for an immature trajectory and the cooler SSTs within the LC are being advected into the FS (Figure 8). These results agree with the SST fields in Figure 5 and the initial hypothesis of the study: the waters in the YLFC cool more in response to CAOs during a mature LC configuration and advect the cooler water into the FS.

The findings from this study can be used to examine the link between cooling events and organisms, such as baitfish, whose behavior may respond to thermal stresses. The migration of these organisms may impact population dynamics in the FS and thus affect the economy of the region. The findings can also be used to examine how other marine inhabitants, such as corals and marine mammals, of the FS are affected during anomalously cold winter seasons and different LC configurations. Understanding the relationship between CAOs and LC configurations could provide a predictive tool for forecasting the probability of anomalous cooling in the FS during an upcoming winter season based on the LC position.

Future work could include analyzing the cooling at different mixing depths along the trajectories, as well as examining the cooling using slightly different trajectories. The ocean temperature change can also be examined during other cases in which the three HYCOM runs produce different LC configurations for times where a CAO affects only the mature trajectory (the cold front frontolyzes in the Gulf).
Data sets:


Journal Articles:

Coleman, F.C., Petes, L.E. (2009), Getting into Hot Water: Ecological Effects of Climate Change in Marine Environments. *S.E. Envir. Law J.*, 17, 337


FIGURES
Figure 1. Schematic of a cold air outbreak penetrating the Gulf of Mexico. The red boxes in the YC and FS represent bins in which the daily OI 1/4° AVHRR + AMSR satellite SST data are averaged to produce the anomaly differences. The larger blue box represents the area of interest for CAOs in the Gulf of Mexico. Black arrows represent mature and immature configurations. The orange X represents the buoy 42309 and the green X represents station MLRF1, the NDBC stations for which the air temperature data sets are extracted.
**Figure 2.** Altimeter-derived time series of the northern boundary produced by Leben (2005). This time series is used to define mature and immature phases of the , where the mature phase is defined as the upper 75\textsuperscript{th} percentile of the northern edge latitude and the immature phase is defined as the lower 25\textsuperscript{th} percentile.
Figure 3. Histogram (probability density) of SST anomaly differences between the YC and the FS for December-February of 1990-2009 from a 1/4° AVHRR+AMSR satellite SST product. Negative values indicate having a colder SST anomaly than YC.
Figure 4. Time series of daily air temperature (in degrees C) during the 1996-1997 winter season from NDBC buoy 42309 in the Gulf of Mexico (top panel) and station MLRF1 in the (bottom panel).
Figure 5. Sea surface temperatures from three model experiments using the HYCOM Gulf of Mexico simulation. Both simulations are forced by identical CFSR surface atmospheric variables but have different and eddy field configurations. These images are from 28 January 1997 (Figure 4). Top panel: Mature LC Simulation. Bottom panel: Immature LC Simulation
Figure 6. Synoptic maps of mean sea level pressure (MSLP) and surface dew point temperature for JAN 17-20 1997 to validate a cold air outbreak from Figure 4.
Figure 7. Synoptic maps of mean sea level pressure (MSLP) and surface dew point temperature for JAN 26-28 1997 to validate a cold air outbreak from Figure 4.
**Figure 8.** Ocean temperature change time series for different trajectories calculated from the surface flux values from 1/25° HYCOM Gulf of Mexico simulation with CFSR fluxes. Black line: Ocean temperature change for mature phase trajectory. Red line: Ocean temperature change for immature phase trajectory.
Figure 9. The path of numerically prescribed trajectories with positions every 3 hours from 13 January 1997 - 28 January 1997. Top panel: Mature trajectory. Bottom panel: Immature trajectory