EARTH Interactions

The Influence of Loop Current Position on Winter Sea Surface Temperatures in the Florida Straits

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ABSTRACT: Influences of the Gulf of Mexico's Loop Current (LC) position on the sea surface temperature (SST) in the Florida Straits (FS) during the winter season are investigated. Satellite-derived SST data are analyzed on the basis of the LC configuration (mature or immature) as determined by satellite altimetry analyses. Cumulative distributions of FS SSTs for both LC phases during the months of January and February show greater likelihood of cooler SSTs in the FS during a mature LC than during an immature LC. This work suggests that differing transit times of LC water parcels during mature and

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immature phases result in differences in heat loss of the LC near-surface water. This may contribute to the observed SST differences in FS during mature and immature LC phases via temperature advection.

KEYWORDS: Air–sea interaction; Florida Straits; Loop Current; Sea surface temperature; CAO; Atlantic sailfish

1. Introduction

This study investigates the sensitivity of sea surface temperature (SST) in the Florida Straits (FS) to the position of the Loop Current (LC) during the winter season. The LC is a western boundary current within the Gulf Stream system in the Gulf of Mexico (GOM). The current flows northward after entering the GOM through the Yucatan Channel, ‘‘loops’’ in a clockwise direction, and exits east through the FS (Leben 2005) (Figure 1). The LC cycles stochastically between two extreme configurations: mature, which extends as far northward as 28°N, and immature, which immediately turns east after entering the GOM. The mature configuration usually precedes the shedding of a large anticyclonic eddy and is followed by a transition to the immature phase. This cycling is evident from inspection of mapped satellite altimetry-derived sea surface height (SSH) fields and from altimeter-derived time series of various LC metrics (e.g., Leben 2005). The transit time of water parcels along the LC should be longer by several days in the GOM during a northerly extended, or mature, LC phase versus an immature phase because of the longer flow pathway (estimates are computed in section 3).

The GOM is subject to several atmospheric cold fronts and cold air outbreaks (CAOs) during the winter months (Henry 1979). However, a number of these fronts weaken and ‘‘die,’’ a process referred to as frontolysis (Glickman 2000), in the northern GOM instead of fully penetrating into the FS and the Caribbean. Local heat losses in the northern GOM during a CAO have been reported to exceed 900 W m^{-2} (sensible plus latent fluxes) (Nowlin and Parker 1974). Large surface wind speeds are also commonly associated with the CAOs and can enhance entrainment of cold subsurface waters into the oceanic mixed layer through mixed layer deepening and Ekman pumping (Villanueva et al. 2010). These CAOs contribute to the wintertime mean cooling fluxes, which have been estimated to be between 50 and 200 W m^{-2} spatially averaged over the GOM (Zavala-Hidalgo et al. 2002) but may reach nearly 300 W m^{-2} over the northern parts of the GOM as illustrated by a spatial map of the DaSilva et al. (DaSilva et al. 1994) January climatology (Figure 1). Molinari (Molinari 1987) discussed the dependence of wintertime airmass modification on LC configuration over the GOM by showing there is a larger loss of heat from this warm current during a mature phase, which warms overlying air masses.

Upper-ocean water of the LC is expected to be subject to more surface cooling during a mature configuration than during an immature LC phase because of the longer transit time and the northward extent of the current in the GOM under a typically cooling atmosphere. During CAOs, the role of entrainment may also be important in cooling the LC waters. Since the LC surface water flows into the FS, we hypothesize that the position and hence transit time of the LC within the GOM play roles in governing the sea surface temperature in the straits. If this hypothesis proves valid, the result might be used to predict the likelihood of anomalously cold

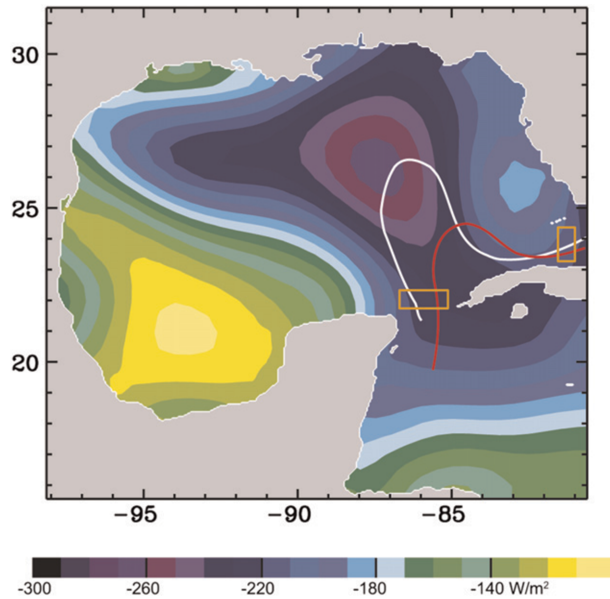

Figure 1. Mean net downward surface heat flux (W m^{-2}) for January for the GOM and FS from the Da Silva et al. (Da Silva et al. 1994) climatology net heat flux dataset. Schematics of the typical mature (white) and immature (red) LC phases are overlaid (actual surface drifter trajectories for different LC configurations are shown in Figure 3). The orange rectangles denote the regions over which SST data are averaged in the FS and YC.

surface waters in the FS during winter seasons, which may have implications for local biota.

To test this hypothesis, a satellite altimetry-derived time series of the LC northward extent is used to define times of mature and immature LC phases, which in turn are used to subsample a time series of SST in the FS derived from a satellite-based product. The results show a substantial shift of the probability of cool SST in the FS during a mature LC versus an immature LC. Large changes in the likelihood of surface temperatures falling below thermal preferences of certain fishes found in the FS are discussed. An estimate of the differences in LC water transit times through the GOM during mature and immature LC phases is inferred from analysis of historical drifter data and is used to produce scale estimates of the differential surface heat loss under different LC configurations.

2. Data and methods

A satellite-derived SST product is used for this study. The National Oceanic and Atmospheric Administration (NOAA) daily optimal interpolation ¼° version 2 Advanced Very High Resolution Radiometer–Advanced Microwave Scanning Radiometer (AVHRR+AMSR) SST product (Reynolds et al. 2007) assimilates the AVHRR version 5 pathfinder SST retrievals from September 1981 through December 2005 and the AMSR for Earth Observing System (AMSR-E) version 5 SST retrievals from June 2002 to the present. This dataset uses in situ measurements from buoys and ships and includes a bias correction of the satellite observations with respect to in situ data using an empirical orthogonal teleconnection algorithm (Reynolds et al. 2007).

For the analysis, a region within the FS is defined to encompass the core of the Florida Current, a segment of the LC/Gulf Stream system that flows through the FS. The region is defined as 23.25°–24.25°N and 82.5°–81.5°W (orange square in Figure 1). Data from the Reynolds et al. (Reynolds et al. 2007) SST product are then spatially averaged over this FS region (consisting of 16 grid points from the SST product) for each day to produce an SST time series from 1990 through 2009.

Mature and immature phases are identified using satellite altimeter-derived metrics (Leben 2005) that approximate the position of the core of the LC. Leben (Leben 2005) provides a time series of the northernmost latitude of the LC core based on SSH that is used to characterize the behavior of the LC and eddy separation in the GOM from January 1993 through December 2011. The 17-cm SSH contour (following removal of the annual steric signal and after superposition of a model mean SSH) is used by Leben (Leben 2005) as a proxy of the position of the core of the LC. To objectively define the mature and immature LC phases for this study, the upper 75th and lower 25th percentiles, respectively, of the northernmost position of the LC core are calculated from this time series. On the basis of this definition, the LC is considered to be in a mature phase when it extends north of 26.9°N and in an immature phase when it remains south of 25.7°N (Figure 1).

The portions of the SST time series falling within January and February from 1993 to 2009 are considered for this study. We focus on January and February because that is the time of year with the greatest likelihood of CAOs and because at this time of year there are relatively large differences in the temperatures between the Yucatan Channel (YC) and FS relative to other times of year. Subsets of the data are selected depending on LC phase as determined by the 25th (immature) and 75th (mature) percentiles of the LC northernmost latitude as defined above. For the distributions and other statistical properties of the data described in section 3 below, the SST data are resampled using a Monte Carlo approach to ensure that each subset of data is similarly distributed throughout January and February. In addition to ensuring that the data are not biased toward a particular time of the study months (e.g., early January or late February), this approach allows simple estimation of confidence intervals for the statistics. Similar distributions of times in each subset are critical because the mean change in SST from January to February is similar in scale to the changes in the SST probability distributions for each subset.

3. Results

The difference in the median FS daily SST during immature and mature LC phases during January and February is 0.56°C (24.77°C during mature LC configurations and 25.33°C during immature LC configurations), with a 90% confidence interval of 0.05°C. The cumulative distribution functions (CDFs) of FS SST for the two LC phases show the probability of SST values not being exceeded or, as shown in the plots, the probability of FS SST being colder than the temperatures along the *x* axis (Figure 2). The distances between these CDF curves indicate a shift

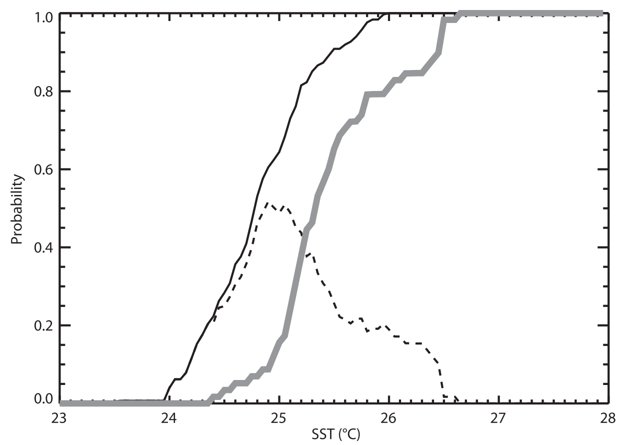

Figure 2. Cumulative distribution function probability of SST in FS for January and February during mature (black) and immature (gray) LC phases. The difference between the two CDFs is shown by the dotted line.

over the broad range of the SST distributions depending on LC phase. The 10th percentile SST is shifted colder by 0.73°C during mature LC phases relative to immature phases, and the 90th percentile SST is similarly shifted by 0.98°C.

The difference (mature phase minus immature phase) in CDFs indicates striking differences in the probability of the FS water being cooler than certain temperatures depending on LC phase. Large differences are found around the 24.5°–26°C thresholds. For example, the surface waters in the FS during January and February have a 64% probability of being cooler than 25°C during a mature phase versus only a 16% probability during an immature phase. Therefore, FS waters are 4 times more likely to be cooler than 25°C during a mature phase than during an immature phase LC. Although the shift in the median temperatures is fairly modest, such large shifts in likelihoods of SST falling below certain temperatures may have significant impacts on organisms in the region that may be living near their thermal tolerances during the winter.

An SST time series for a region encompassing the LC as it approaches the YC is constructed as for the FS time series, but the satellite-derived SST data are averaged over the domain 21.75°–22.25°N and 86.75°–85°W (Figure 1). Separating the portion of the time series from January and February on the basis of LC phase yields distributions that are nearly identical, with a median SST of 26.28°C for the immature LC phase and 26.29°C for the mature LC phase. This is an expected result but verifies that the difference in FS SST is due to cooling within the GOM and not due to differences in temperatures of water entering the Gulf through the YC. This also gives the difference in median SST between the YC and FS of 1.51°C (cooling) during the mature LC phase versus 0.95°C during the immature LC phase.

To examine the potential role of LC water residence time in the GOM under different LC configurations on the FS temperatures, a scale estimate of the surface heat loss is computed using LC water transit times estimated from historical surface drifter trajectories. Wintertime surface heat fluxes over the GOM have strong

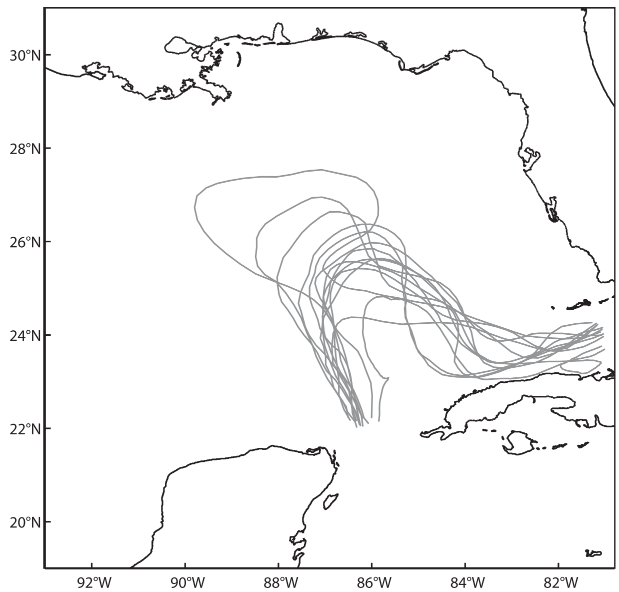

Figure 3. Select drifter trajectories from the NOAA/AOML Surface Drifter Program.

variability at diurnal and synoptic time scales and can range from several hundred watts per square meter of warming of the water to over 900 W m^{-2} of cooling, particularly during CAOs (Nowlin and Parker 1974). A January mean value of cooling heat fluxes over the LC region of the GOM of 240 W m^{-2} (Figure 1) would remove approximately 31 MJ m^{-2} of heat energy per day. Weatherly (Weatherly 2004) estimates wintertime mixed layer depths of between 50 and 150 m in the GOM (typically between 50 and 100 m near the core of the LC and deeper inside the LC ''bulge''). As a scale estimate, if this heat loss is distributed evenly over a 50-m-thick (100-m-thick) mixed layer, the resultant average temperature change over that mixed layer would be approximately 0.1°C (0.05°C) day^{-1}.

All drifter tracks from February 1979 through September 2011 existing within the LC region (22°–29°N, 90°–81°W) are extracted from the NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML) Surface Drifter Program database (http://www.aoml.noaa.gov/envids/gld). Inspection of the drifter tracks identifies 26 drifters that entered the GOM and followed the LC with no evidence of entrainment in frontal eddies or meanders before exiting through the FS. A second subset of drifter tracks, based on the criterion that the mean speed is greater than 1 m s^{-1}, indicating they were traveling in the core of the LC, is then identified. The result is a subset of 13 drifter tracks (Figure 3). Four of these (31%) have a maximum latitude that meets the threshold for immature phase LC as defined previously by the satellite altimeter-derived LC position time series, and three (23%) meet the definition of a mature LC. Thus, this seems to be a reasonably representative sample based on the definition of mature and immature LC phases using upper and lower quartiles of the latitude of the LC core.

The transit time for the drifters in the LC is calculated from the time they cross 22°N in the Yucatan Channel to the time they cross 81°W in the FS, on the basis of

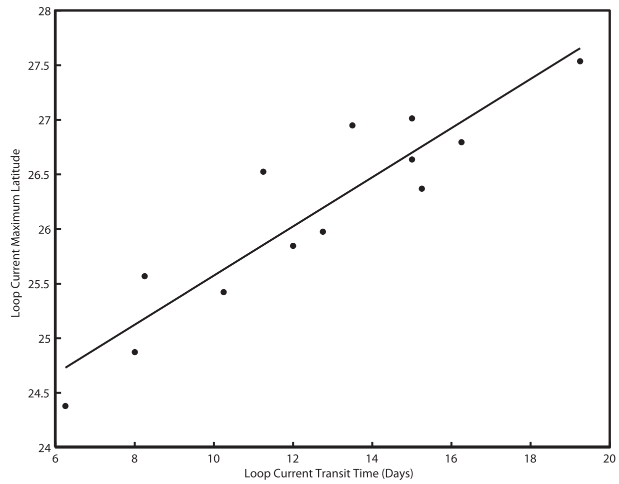

Figure 4. Scatterplot of the northernmost latitude of LC drifter tracks vs the transit time along the portions of the drifter trajectories shown in Figure 3. The linear least squares fit is overlaid.

their 6-hourly positions. A scatterplot of the northernmost position of the drifters versus their transit time in the LC reveals a strong linear relationship, with transit times varying from 6 to more than 19 days over all the drifter tracks (Figure 4). Transit times for drifters in the LC having a maximum latitude that defines it as an immature phase are approximately 6–10 days, and transit times for drifters in a mature LC are approximately 16–20 days. Therefore, for scaling purposes, taking a ''typical'' transit time along an immature LC of 8 days and a mature LC of 18 days, as well as applying the above scale estimate of rate of cooling in a mixed layer of 50 m (100 m) under average winter surface heat fluxes, one can approximate the surface temperature change of a water parcel of between 0.8°C (0.4°C) for an immature LC and 1.8°C (0.9°C) for a mature LC during the transit through the GOM. That is, the difference due to LC phase is between 0.5° and 1.0°C. These scale estimates may be compared to the satellite-observed shift in the FS SST distributions (and hence YC–FS SST cooling) during January and February presented above: 0.56° (shift in medians), 0.73° (10th percentile), and 0.98°C (90th percentile). This simple scale analysis is meant to estimate the potential impact of LC transit time, because of its phase, on the temperature of the water being transported into the FS. It neglects the likely important contribution of entrainment through Ekman pumping and vertical mixing (e.g., Villanueva et al. 2010).

4. Discussion and summary

The analysis of satellite-derived SST in the FS supports the hypothesis that the FS waters are more likely to be cooler during a mature LC as opposed to an immature LC in the winter months because of differences in transit times of LC water depending on LC configuration and the effects of wintertime surface cooling in the Gulf. When the LC extends far northward into the GOM, the surface waters are subject to cooling heat fluxes for a longer duration than during an immature LC configuration. This is particularly the case during CAOs, which are common in the winter over the GOM (often stronger in the northern GOM) and can lead to enhanced cooling through vertical entrainment (Villanueva et al. 2010). An analysis of historical surface drifter trajectories shows a clear relationship between the northward penetration of the LC and the transit time of surface water around the LC. A scale estimate of surface cooling during the LC waters' transit through the GOM illustrates the role that flow pathways and residence times of LC waters under the typically cooling fluxes in the winter play in governing the surface temperature in the FS.

The Florida Straits 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. Coleman and Petes (Coleman and Petes 2009) found that many marine organisms are living near or at their thermal physiological tolerance levels. Thus, relatively small changes in water temperatures may prompt migrations of certain species toward more favorable thermal conditions (Lam et al. 2008).

As an example of the potential application of the results of this work, a report by ICCAT (ICCAT 2011) states that adult sailfish *(Istiophorus platypterus)* prefer temperatures of 25°–28°C and are known to migrate to FS waters during the winter months (Jolley 1977). Kerstetter et al. (Kerstetter et al. 2010) found that, 75% of the time, these fish can be found at depths of less than 20 m. Figure 2 shows that during January and February, on any given day, the surface waters in the FS have a 64% probability of being cooler than 25°C during a mature phase and only an 16% probability during an immature phase. This means that the FS is 4 times more likely to be cooler than the sailfishes' lower threshold during a mature phase than during an immature phase. The results of this study may be applied as part of a probabilistic forecasting method for FS SSTs based on LC configuration that could be useful for managing this and other fisheries in the area.

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