Sea surface temperature influence on a winter cold front position and propagation: air–sea interactions of the ‘Nortes’ winds in the Gulf of Mexico

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Abstract
A high-resolution, regional atmospheric model with different sea surface temperature (SST) boundary conditions (BC) is used to examine the air–sea interactions of the winter cold fronts (CF) advancing over the Gulf of Mexico (GoM). Comparison with oceanic-buoy 10-m wind, 2 m air temperature (AIR.2m), sea level pressure (SLP) and SST reveals good agreement with observations. The CF propagation speed was significantly affected by the SST: higher SST produced faster CF traveling speeds. Using a 1-D ocean mixed layer model as BC reduced the air–sea fluxes and the CF propagated slower but in accordance with the reanalysis data; representing an improvement in the numerical modeling of the CF propagation and airmass modification over the GoM.

Keywords: air–sea interactions; cold front; SST; WRF

1. Introduction
During winter, synoptic-scale cold and dry polar air masses propagate southward along the eastern side of the Rocky Mountains into GoM, resulting in fast moving CF popularly known as ‘Nortes’ winds. As the CF advances over the GoM warm waters, the wind accelerates producing substantial air-mass modification and intensive exchanges of heat, moisture and momentum between the ocean and atmosphere (Nowlin and Parker, 1974; Garreaud, 2001). The cold airflow trailing the CF has strong lower-tropospheric northerly winds; regularly surpassing 15 m s$^{-1}$, cooling the air temperature by 10–15 $^\circ$C in a period of 24 h, and increasing SLP by 15–30 mb (Merrill, 1992; Schultz et al., 1997).

The evolution of a CF over the GoM waters is mainly affected by two non-exclusive governing mechanisms: large surface heat flux (HF) and cold air damming (CAD) dynamics. Before arriving to the GoM, the northerly flow is dominated by CAD dynamics (Colle and Mass, 1995, hereafter CM95). On the central and Eastern GoM, the CF is mainly affected by large surface HF that generates vertical mixing. This mechanism appears to be dominant in the planetary boundary layer (PBL) during the CF progression (Mailhot, 1992; Merrill, 1992; Thompson and Burk, 1993).

Short-term forecasts or simulations (7–10 days) generally assume that SST changes do not propagate into atmospheric adjustments. However, studies in other regions with cold–dry air outbreaks (e.g. Gulf of Lyon, Lebeaupin Brossier et al., 2009 and Lebeaupin Brossier et al., 2013, Gulf Stream, Booth et al., 2012), have shown the importance of changing mixed layer heat content and the higher thermodynamic ocean memory which considerably impact the air–sea interactions and the evolution of CFs.

Because significant air–sea interactions have been observed immediately after the passage of a CF over the GoM (Nowlin and Parker, 1974), our main purpose is to evaluate albeit in the simplest manner the impact of air–sea processes in the evolution of a ‘Norte’ event under different SST BCs setups. Three numerical experiments using the Weather Research and Forecasting (WRF) model version 3.4.1 (Skamarock and Klemp, 2008) are carried out representing different ocean BCs: (1) a constant in time, but spatially varying SST; (2) a time and space varying SST field taken from daily reanalysis, with a superimposed predictive SST diurnal variation scheme (Zeng and Beljaars, 2005); and (3) a 1-D ocean mixed layer that models the effect of wind-driven vertical mixing (Pollard et al., 1973), usually employed in hurricane simulations (Davis et al., 2008).

2. Model description and experimental setup
In this study, we use the WRF with the Advanced Research dynamic solver, WRF-ARW (Skamarock and Klemp 2008), which integrates the fully compressible, non-hydrostatic equations of motion on a terrain-following vertical coordinate system. The physics packages used in this study were implemented after an exhaustive review of literature applying WRF for similar weather events (see Table S1, Supporting
Information for details). To validate the spatial patterns, we compared the model results against Climate Forecast System Reanalysis (CFSR; Saha et al., 2010).

The model includes three one way nested domains with 108, 36 and 12 km grid spacing. The coarser domain encompasses most of North America, and part of Central America, from 60°N to 16°S and 164°W to 29°W. Our analysis in centered on the highest resolution domain, which includes the whole GoM and a substantial area of the North American Cordillera and the Sierra Madre mountains in order to have a realistic depiction of their topographic impact. All domains have 74 vertical levels from sea level to 50 mb, with the lowest level at 10 m over the ocean surface and 36 levels below 750 mb. Each simulation runs from the 1 to 15 January 2010, to simulate conditions before and after the main ‘Norte’ event that occur on 7 January.

The initial and BCs were obtained from the NCEP-FNL, with a resolution of 1° × 1° (available at http://rda.ucar.edu/datasets/ds083.2/). For SST surface initial and BCs (when SSTs vary in time), the NCEP Real Time Global (RTG) 0.5° × 0.5° SST analysis (Thibaux et al. 2003) was used (available at http://polar.ncep.noaa.gov/sst/rtg_low_res/). All the experiment use RTG SST data from 1 January 2010 as initial condition, and for fixed SST experiment (CTE) it was used for the entire run. In the evolving SST experiment (DAY), the SSTs are updated every 24 h. For the ocean mixed layer experiment (OML), the initial mixed layer depth was set to 20 m; although the initial depth is on the shallower end, we decided to use this initial value throughout the domain to force a rapid response. A value of gamma (deep ocean stratification parameter) of 0.14 was used for the simulation.

3. Results

3.1. Synoptic description

Time series of the three WRF experiments as well as observational data from NDBC buoy 42001, located 330 km South of Southwest Pass, Louisiana (Figure 1), show the arrival of a CF on 1 January at 1200 UTC. With the CF, SLP (Figure 1(b)) and both AIR.2 m and SST (Figure 1(c) and (d) respectively) decrease afterwards. On 7 January, a wind shift produced by a ‘Return Flow’ (Crisp and Lewis, 1992) generates a drop of roughly 8 mb in SLP, and AIR.2 m increases roughly 10°C. The main ‘Norte’ arrives on 8 January at 0650 h with a dramatic change in 10 m wind speed magnitude (WSPD) and direction, producing a drastic drop in the AIR.2 m, and a consistent increase in SLP. The wind veers rapidly from southerly to northerly, and accelerates from 7 m s−1 to persistent winds above 12 m s−1 for more than 48 hours. The AIR.2 m gradually rises on the early hours of 8 January until the end of the simulation. We will focus our discussion using results from this buoy which is located in the middle of the GoM; although we also did comparisons with other NDBC buoys (42035, 42047, 42002 and 42055) to validate the model.

3.2. Discussion

The observed SST at buoy 42001 (Figure 1(d)) has a slight cooling trend. The ocean cools about 2°C after the first CF event (1 January) but then warms up 1°C maintaining a nearly constant value. After the arrival of the main CF on 7 January, the ocean cools down slowly to 21°C, warming up again after 13 January. The WRF experiments with variable SSTs, (DAY and OML), also show a cooling trend with DAY producing a more noticeable cooling only after the main CF of 7 January, but almost no change before that (Figure 1(d)). OML is somewhat closer to observations during the first week of the simulation but clearly it has a cooling SST bias (Figure 1(d)). Mallard et al. (2013) use a method whereby the mixed-layer routine is reinitialized every day from observed SSTs to reduce the bias in month-long hurricane simulations. We decided to use the mixed layer model with no restarts to investigate its impact. Experiment CTE has the warmest (unchanging) SST, OML has the lowest, and DAY run is in-between, but both DAY and OML improve the simulation of the atmospheric variables (Figure 1(a)–(c)).

Although not shown, all the compared NDBC buoys and their correspondent simulation time series present a similar behavior as NDBC 42001. There are clear biases because all simulations underestimate SLP, and AIR.2 m is mostly warmer than observations throughout the entire run. The intensity of the warmer/weaker AIR.2 m/SLP bias is buoy dependant. Biases are related to the CF air–sea interaction, as OML with coldest SST and lower HF (Figure 2) consistently produces better results.

The 10 m winds are less affected by the changes in surface BCs and relatively similar in all experiments; they all show good agreement with CFSR both in magnitude (not shown) and direction (Figure 2). OML has the lowest winds root mean square errors when compared with the buoys.

To better understand the impact of the changing BCs on a larger scale, we now look at differences in the spatial structure and time evolution of some key aspects of its synoptic evolution. In particular we investigate the structure of the CF and identify its leading edge (CF_LE) by analyzing the magnitude of AIR.2 m and WSPD gradients. We define the CF_LE as the region where both quantities have maximum values across the GoM, in accordance with the concepts of CM95 and Schultz and Steenburgh (1999). Both criteria are consistent with each other and appear to be in good agreement with the CFSR data over the ocean. The procedure is deemed sufficient to locate the front position and is consistent with the methods used for detecting weather fronts (Hope et al., 2014).

Figure 2 displays a snapshot of the CF progression over the GoM on 8 January 2010 at 0600 UTC including 10 m wind vectors, SLP, latent heat flux (LHF) and
Figure 1. Time series of wind vectors (a) sea level pressure (b) 2 m air temperature (c) and, SST (d) at NDBC Buoy Mid-Gulf (42001). The black line represents the observations at the buoy. Blue, red and green represent the WRF data from the CTE, DAY and OML model experiments, correspondently. The red dashed vertical line signals the time of arrival of the main CF at the buoy location.

the CF_LE. A sharp LHF contrast trails the CF_LE in CFSR and in all the WRF experiments (Fig. 2). CFSR and OML show magnitudes of 100–300 W m\(^{-2}\) before the CF_LE and values higher than 500 W m\(^{-2}\) behind the front, related to the wide-spread invasion of cold air. CFSR has weaker LHF than all the WRF experiments with OML (due to its cooling bias) being the closest. LHF patterns are also different: CTE and DAY produce similar and very high LHF (up to 600 W m\(^{-2}\)) on a band along the Louisiana, Texas and western Mexican GoM coast with particularly high values over Texas, whereas CFSR has maximum values off-shore (on the Louisiana, Texas region). It is not clear whether the large LHF values near the coast in the northern and western GoM produced by WRF are realistic.

It is necessary to emphasize that the values of LHF of OML are more in accordance with CFSR values, even though that experiment has higher LHF especially in the western GoM and in northern coastal areas where the CF enters in contact with the ocean (Figure 2). CFSR relative humidity (not shown) exhibits to be wetter than any WRF experiment. Furthermore, post-frontal values for CFSR LHF tend to have a negative bias in the GoM for the winter months (Xue et al., 2011) and for the annual mean (Wang et al., 2011). Therefore, care should be exercised in the above comparisons that use CFSR as a reference. Nevertheless, our results indicate that the OML latent (Figure 2(b)) and sensible (not shown) heat fluxes are more in agreement with CFSR (Figure 2(d)) than any of the other experiment.

We noticed that the traveling speed of the CF in each simulation was different. This is a very relevant factor for the amount of precipitation delivered by CFs in the GoM, as less winter precipitation is produced by faster moving fronts (Pérez et al., 2014). To confirm this premise, CF_LE traveling speeds were calculated from observed NDBC buoys along the central GoM and each WRF experiment at the same locations (Table 1). All the WRF simulation experience an increase of the CF_LE velocity as the CF enters the GoM waters. CTE has the most dramatic acceleration as the front progresses southward. OML accelerates at the lowest rate, reaching CF_LE traveling speeds comparable with NDBC speeds.

To emphasize these results we present the position of the CF_LE for CFSR and the WRF experiments at four
Figure 2: CFSR reanalysis data and WRF CTE, OML and DAY experiments for latent heat (W m\(^{-2}\), colors), 10 m wind vectors (black vectors), sea level pressure (hpa, gray contours) and 10-m wind speed gradient (s\(^{-1}\), white contours) at 0600 UTC on 8 January 2010. Only higher values of wind speed gradient are presented, ranging from 0.0001 to 0.0002 s\(^{-1}\) with contours every 0.00005 s\(^{-1}\). Wind speed gradient contours represent the positions of the CF. The black dashed line represents country borders.

Table 1. Cold front leading edge travelling speeds (m s\(^{-1}\)) calculated based on the arrival time of the front at each buoy and the distance between them. The percentages indicate the WRF experiments travelling speed in comparison to the observed NDBC buoy.

| Buoy     | Speed | %   | Speed | %   | Speed | %   | Speed | %   |
|----------|-------|-----|-------|-----|-------|-----|-------|-----|
| GALV–TABS | 6.6952 | -23.81 | 11.1710 | +33.34 | 11.1710 | +33.34 | 8.7875 |
| TABS–W GULF | 16.2770 | +58.34 | 13.0220 | +13.0220 | 10.8510 | +10.8510 | 10.2800 |
| W GULF–CMPC | 19.5080 | +83.35 | 13.0050 | +13.0050 | 11.7050 | +11.7050 | 10.6400 |

4. Conclusions

We implemented the high-resolution, regional atmospheric WRF model to represent the progression of winter CF in the GoM with the interest of investigating its response to three different SST BCs: constant, daily observed and an ocean mixed layer model. Each simulation lasted 14 days, focusing our results on the event entering the GoM on 7 January 2010. In general, the model is in good agreement with NDBC buoy SLP.
AIR.2M and surface winds. The biases obtained are strongly influenced by the SST BCs, as CTE produced higher biases and OML is the closest to observation values.

Based on the type of weather event, we found that analysis of AIR.2m and gradient magnitude of the WSPD magnitude are a good method to locate the CF_LE position and its progression. Different CF propagation speeds were found for the different WRF experiments (Figure 3), and were corroborated by calculating them from observed NDBC buoys along the central GoM, revealing sensitivity to the SST specification and consequently the HF, resulting in higher speeds under CTE and the lowest in OML.

The air–sea interactions are strongly modified by SST BCs that significantly influence the corresponding HF; and have an effect on the structure and organization of the CF. Higher HF have a more frontolytic effect over the front (Burk and Thompson, 1992; CM95). As OML has lower SST and consequently the lowest HF, the CF_LE has a well define and organized structure across the GoM (Figures 2(b) and 3). In the CTE and DAY experiments, the front organization and structure are considerably affected.

Our results suggest that the use of 1-D ocean mixed layer model with the WRF system improves the representation of the CAO in the GoM and its corresponding CF, in accordance with Nicholls and Decker, in press results. We based our statement in the better representation of the CF_LE, and a well-organized and defined front without a pre-frontal wind shift, trailed by a sharp gradient of LHF with similar magnitudes as in the CFSR data. In addition, OML has a closer to buoy-observed SLP and AIR.2m. Although, OML trails the CFSR front on the western Gulf and over Florida, it has a similar overall position, and OML has closer to buoy-observed propagation speeds (Table 1). In general terms, the OML front has a better performance on the progression, structure and organization of the CAO over the GoM. Details about how the SST BC affect the mechanisms involved on the CF progression speed, should be addressed by studying different events during the Nortes season, in order to take account of the intra-seasonal variability and obtain a more robust analysis. Nevertheless, this short paper highlights the importance of SST BC and the resulting air–sea interaction processes for short and medium term weather forecasting. We have shown that these interactions have considerable implications for the CF winds, heat, and humidity fluxes that affect the CF organization and propagation speed; consequently, could impact the amount of precipitation each storm produces.
Supporting information

The following supporting information is available:

Table S1. List of WRF physics packages.

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