

**Mesoscale variability in the Gulf of Mexico and its importance in climate extremes over
North America**

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Results and Accomplishments

1. Analysis of an ocean-only high-resolution Gulf of Mexico simulation

Two types of simulations have been completed and analyzed with the high-resolution (1/50°) implementation of the HYbrid Coordinate Ocean Model in the Gulf of Mexico (GoM-HYCOM 1/50): (i) a free running simulation from October 1st, 2009 to December 31st, 2013; and (ii) a data assimilative simulation, with a scheme based on the Kalman filter approach, developed specifically for HYCOM (*Halliwell et al.*, 2014). The 2014 data assimilative simulation has been evaluated in detail (*Le Hénaff and Kourafalou*, 2016) and is compared to two existing HYCOM models covering the same domain, both run in real-time at the Naval Research Lab (Stennis Space Center), namely the global HYCOM at 1/12° resolution (GLB-HYCOM 1/12) and the GoM-HYCOM 1/25 (at 1/25° resolution). We have demonstrated that our simulation has lower errors, even though it currently assimilates only Sea Surface Height (SSH) and Sea Surface Temperature (SST). The improved fidelity of our model is a result of better performance at both large scale and mesoscale, particularly the realistic depiction of fronts and eddy dynamics, as well as more realistic depiction of river plume dynamics that influence the SSS field.

The reanalysis (data assimilative) simulation has also been employed to study processes in the GoM influenced by the variability of the mesoscale field and its role on the export of riverine low salinity waters across the Northern GoM continental shelf and crossing the entire basin (*Le Hénaff and Kourafalou*, 2016). An example of the role of cyclonic eddies in the process of formation and shedding of an anticyclonic Loop Current Eddy (LCE) is shown in Fig. 1 for the GoM-HYCOM 1/50 reanalysis the AVISO data. The model simulation and the data agree well, demonstrating that good resolution of small cyclonic eddies is crucial for the correct representation of changes in the Loop Current from an elongated extension (before LCE shedding) to a retracted position (after LCE shedding).

The analyses of oceanographic fields in the Gulf of Mexico (GoM) were extended to the full Intra America Seas (IAS) region, to achieve a better understanding of how results from this project can be used on a broader scale that also includes the Caribbean Sea. We employed the North Atlantic HYCOM model. The model has been run at 1/25° resolution for the period 2009-2014, with climatological boundary conditions and no data assimilation. It has been used as the “Nature Run” component of an ocean system of Observing System Simulation Experiments (OSSEs) and has been shown to represent several air-sea interaction processes, especially related to tropical storm activity (*Kourafalou et al.*, 2016; *Androulidakis et al.*, 2016; *Halliwell et al.*, 2017).

Effort in this project concentrated on the evaluation of model fields in the GoM and IAS regions. An example is shown in Figure 2 (left panel), for the evolution of Sea Surface Temperature (SST) over each region, averaged over the simulation period. The model SST is compared to data from the Global High Resolution SST (GHRSSST). Daily values reveal a strong seasonal cycle in both regions, with inter-annual variability stronger in the GoM region. The Pearson correlation coefficients (r) are 0.99 for both regions, indicating excellent agreement. When the seasonal cycle is removed, inter-annual variability is more prominent in the GoM region, with $r = 0.90$, while $r = 0.73$ in the IAS region. Although somewhat lower than the daily values, the correlation is still high when the seasonal cycle is removed, indicating that both the GoM and IAS domains are adequately reliable for providing fields that represent ocean heat variability.

Gulf of Mexico SST and High Impact Weather over the US

Severe storms threaten lives throughout the United States (US) every year, suggesting that any predictive capability is of large societal benefit. While it is well recognized that predicting individual tornado outbreaks or severe storms is only possible a few hours in advance, the large-scale background atmospheric conditions that influence the likelihood of severe storms may be more predictable. In *Jung and Kirtman (2016)*, Convective Available Potential Energy (CAPE) is used as background state in which variations create conditions that are more or less favorable for severe weather occurrence, noting that moist instability is an important ingredient in influencing the storm characteristics. Motivated by the fact that CAPE appears to be related to tornado activity (Fig.3), we ask: Can we predict seasonal variability of CAPE in the US during May-July (MJJ)? Our hypothesis is that GoM SST anomaly (SSTA) variability on monthly and seasonal time scales provides a source of warm season North American Hydroclimate. We are not, however, suggesting that specific storms can be predicted with this approach.

We analyzed 30 years of MJJ CAPE from May 1st initialized forecasts from NCAR Community Climate System Model version 4.0 (CCSM4) that are part of the North American Multi-Model Ensemble (NMME; *Kirtman et al. 2014*) seasonal prediction system. The analysis emphasizes the co-variability among extreme weather and environmental variables in observational estimates, and how well this co-variability is simulated and predicted within the context of a 30-year retrospective forecast experiment with CCSM4. CAPE and convective precipitation are used as a proxy of extreme weather over the USA, and SSTA over the Gulf of Mexico is used as an environmental predictor. This approach is, in part, motivated by the collocation of CAPE and the geographical distribution of tornadoes in the US during MJJ.

Since relatively high CAPE emerges in the Gulf of Mexico and Gulf Coast in early spring, and then expands north and northeastward during the primary tornado outbreak period, we correlated CAPE anomalies in the US to SST anomalies in the Gulf of Mexico. The linear relationship between them is examined by introducing CAPE and GoM indices, which are area-averaged CAPE anomalies in the US and SST anomalies in the Gulf of Mexico, respectively.

The results show that an area-averaged Sea Surface Temperature (SST) anomaly in the Gulf of Mexico (GoM index) is a possible predictor for forecasting CAPE anomalies in the US: The

warmer the SST in the Gulf of Mexico, the higher CAPE in the contiguous US during MJJ seasons. The mechanism behind the correlation between GoM index and CAPE in the US is due to the variations in moisture transport from the Gulf of Mexico to US. Considering our current ability to predict SST in the Gulf of Mexico compared with the difficulty of predicting high impact weather in the US, the findings are promising for the seasonal prediction of enhanced or decreased severe storms (e.g., tornado activity) in the US during May-July using the Gulf of Mexico SST. This study further emphasizes that the influence of ENSO (contemporaneous as well as antecedent winter ENSO) on the Gulf of Mexico SST (and ultimately high impact weather in the US) is weak during MJJ, and thus, there is no clear relationship between US CAPE and ENSO during MJJ.

Specifically, we diagnosed the spatial patterns associated with the correlation we found between Gulf of Mexico (GoM) SST and CAPE (Figure 4). To obtain the characteristic patterns of CAPE associated with anomalously warmer SST in the GoM, MJJ CAPE anomalies were averaged for all years of positive GoM indices. When the GoM SST is anomalously warm, positive CAPE anomalies are found in the US. Similarly, cold GoM SST is associated with reduced CAPE over the US (not shown). The maximum positive CAPE anomalies are detected along the Gulf Coast, Tornado Alley and Florida, where relatively high CAPE variance and high frequency of tornadoes are found, implying that CAPE anomalies in the US are contemporaneously related to the SST anomalies in the GoM during MJJ. The forecasts show similar patterns to the observational estimates, but notably do not extend as far north into the US. We further examined correlations between GoM index and US CAPE during MJJ and partial correlations between GoM index and US CAPE while the influence of Niño 3.4 SST held fixed. The resulted correlation maps confirm the little influence of ENSO on US tornado activity during MJJ.

3. Mesoscale variability and the air-sea interactions in the Gulf of Mexico

Mesoscale variability of currents in the Gulf of Mexico (GoM) can affect oceanic heat advection and air-sea heat exchanges, which can influence climate extremes over North America. *Putrasahan et al.* (2017) explored the influence of the oceanic mesoscale variability on the lower atmosphere and air-sea heat exchanges. The analysis of the importance of oceanic mesoscale variability in the air-sea interactions over the Gulf of Mexico is carried out using two coupled atmosphere/ocean/ice simulations. The first simulation (referred to as LR) is a present-day climate simulation of the 0.5° atmosphere (zonal resolution 0.625°, meridional resolution 0.5°) coupled to ocean and sea-ice components with zonal resolution of 1.2° and meridional resolution varying from 0.27° at the equator to 0.54° in the mid-latitudes. The LR simulation is, therefore, relevant to current generation of GCMs that are still unable to resolve the oceanic mesoscale. The second simulation uses the same atmospheric model but coupled to 0.1° ocean and sea-ice component models, and is referred to as HR. This comparison offers a unique opportunity to examine the importance of eddy advection for the upper ocean heat distribution, under an active atmosphere.

We analyzed the variability in model-simulated sea surface height (SSH), sea-surface temperature (SST) and the LC shedding events. The resulting distribution of the LC northern extension has a mean value only slightly more southward than in observations. The secondary peak is, however, close to the main peak observed in altimetry. The standard deviation in the HR-simulated LC

extension and the minimum and maximum values of the LC latitude in the HR simulation are almost identical to the observed values. The intervals between two consecutive LC shedding events, are on average a little longer than in observations, but well within the observed range. Substantial SST variability is seen in both observations and HR simulation along the northern and eastern GoM coasts, and in the deep eastern GoM. This SST variability is well represented in HR, despite a slightly larger amplitude compared with observations. LR, on the other hand, is unable to capture any of the above-mentioned SST variability.

In agreement with observations, the correlation between the latent heat flux out of the ocean and surface temperature anomalies in HR is large and positive in the vicinity of the Loop Current, whereas the correlation is negative in LR. The difference is explained by the heat redistribution due to mesoscale eddies in HR. To demonstrate that, we decomposed GoM currents into the slow (LC and rings) and fast (“eddies”) fluctuations. We find that the eddy flux divergence/convergence dominates the lateral advection (Figure 5) and correlates well with the SST anomalies and air-sea latent heat exchanges. This result suggests that oceanic mesoscale advection supports warm SST anomalies that in turn feed surface heat flux. In contrast, the meandering LC corresponds to nearly non-divergent oceanic heat flux and has a weaker local effect on the distribution of oceanic heat anomalies and air-sea interactions in the GoM. The diffusion-based parameterization in LR is also clearly unable to capture the above effects of mesoscale advection.

The warm anomalies associated with anticyclonic eddies have an identifiable imprint on surface turbulent heat flux, atmospheric circulation and convective precipitation in the northwest quadrant of the eddy composite. To demonstrate this, multiple anticyclonic (warm-core) eddies are identified from HRC Sea-Level Anomalies (SLA) using an eddy-tracking algorithm. Over 1100 snapshots of anticyclonic eddies are detected, with an averaged eddy diameter of ~350 km. The composite analysis of these eddies shows that the associated SST anomalies (SSTA): (i) are generally found on the northwestern part of an eddy (Fig. 6b); (ii) warm the atmospheric boundary layer, as is seen through their collocation with larger LHF out of the ocean and higher planetary boundary layer (PBL) height (Fig. 6c-d); (iii) induce an anomalous surface low and surface wind convergence (Fig. 6e) that supports convection and hence enhanced precipitation (Fig. 6f). As in the Loop Current region, these SSTAs are supported by the upper-ocean heat advection by mesoscale eddies.

Collectively, these results highlight the importance of mesoscale variability for the upper ocean heat budget and air-sea interactions, which has potentially important implications for climate variability in the United States. This study emphasizes the importance of oceanic mesoscale variability in coupled atmosphere-ocean dynamics. Global climate models with high spatial resolution in the oceans, combined with observational datasets, reveal new regimes of coupled dynamics, in which highly energetic ocean currents generate strong SST variability and can significantly modulate air-sea interactions and induce atmospheric response. Although more research on these regimes is needed for further understanding of coupled atmosphere-ocean processes, it is clear that air-sea interactions at oceanic mesoscale are capable of influencing local climate and its variability and potentially have substantial remote influence on the climate of North America (*Jung and Kirtman 2016*).

FIGURES

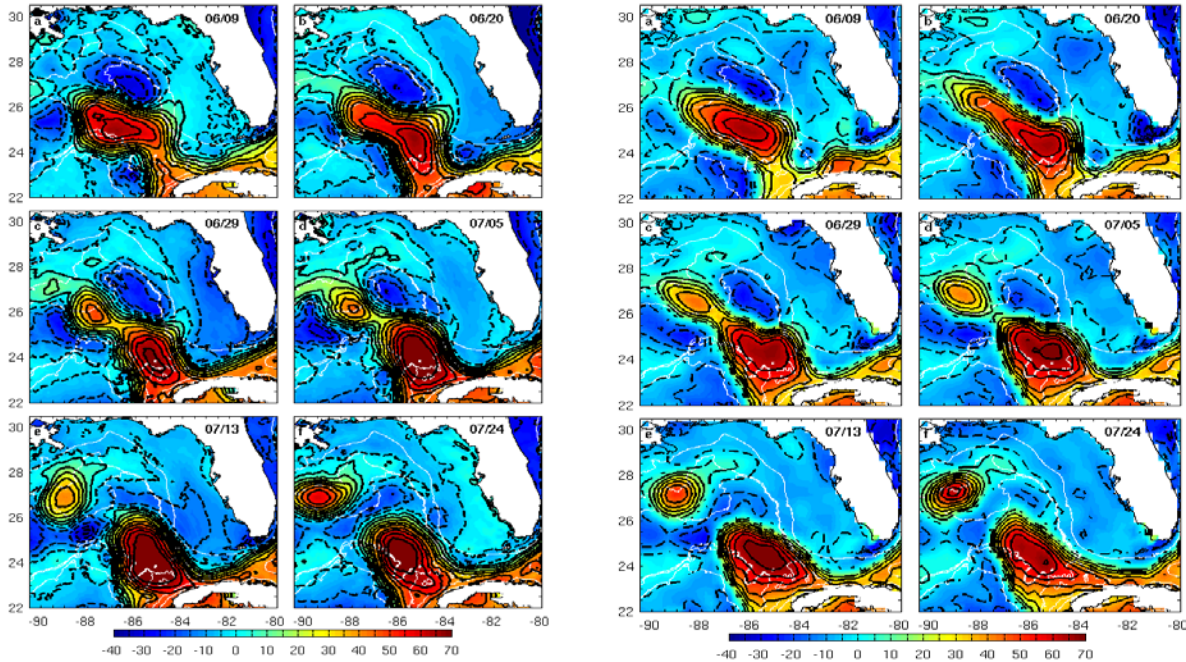


Figure 1: Snapshots of the 1/50° GoM-HYCOM reanalysis Sea Surface Height (**left 6 panels**) and Observed Mapped Absolute Dynamic Topography (MADT; **right 6 panels**), corrected from the instantaneous mean over the Gulf of Mexico. White lines represent the 200, 2000, and 3000 m isobaths.

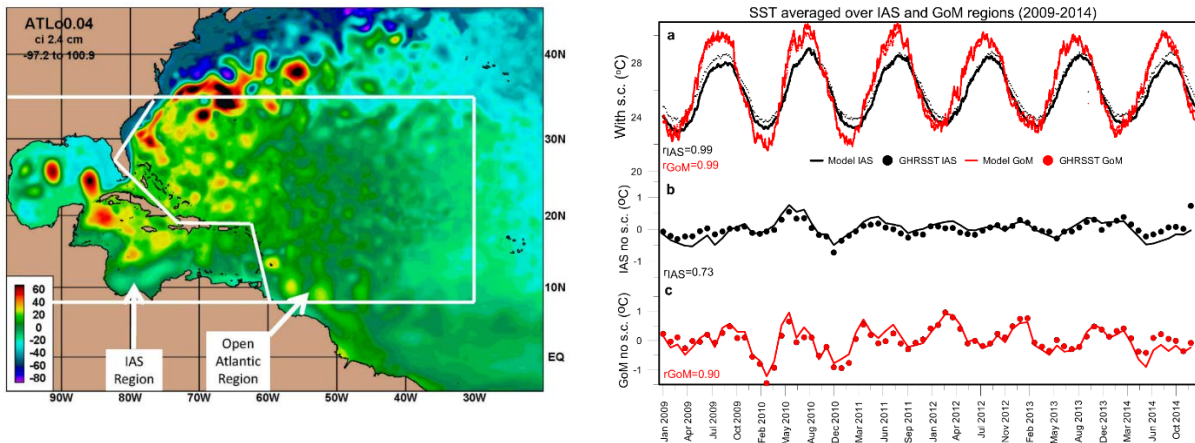


Figure 2: The Intra America Seas (IAS) model domain. Field shown is an example of Sea Surface Height (SSH; **left panel**). Evolution of Sea Surface Temperature (°C) for the 2009-2014 study period (**right panel**), as derived from the model (solid lines) and GHRSSST satellite data (dotted lines) averaged over IAS (black) and GoM (red) regions using (a) daily values (both regions), which include the seasonal cycle; (b) and (c), monthly values without the seasonal cycle (IAS and GoM, respectively). The Pearson correlation coefficients (r) are also shown for each case.

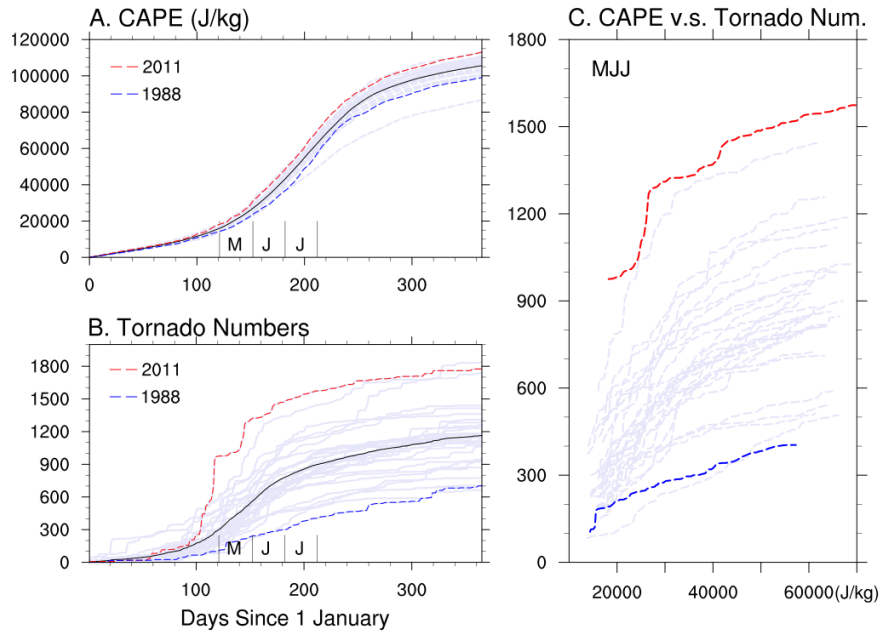


Figure 3: Accumulated CAPE and accumulated number of tornadoes in the US for 1982-2011. The lavender shading represents (a) CAPE and (b) tornado numbers for each year, and the climatology is shown as a bold solid black line. Accumulated MJJ CAPE versus accumulated MJJ tornado numbers are shown in figure 2(c). MJJ indicates May June and July. Individual years 2011 (red) and 1988 (blue) are shown as dashed lines. CAPE is obtained from NARR. Tornado data are obtained from Severe Weather Database (SWD) from NOAA. Numbers are counted for tornadoes F0 or greater on Fujita-Person scale.

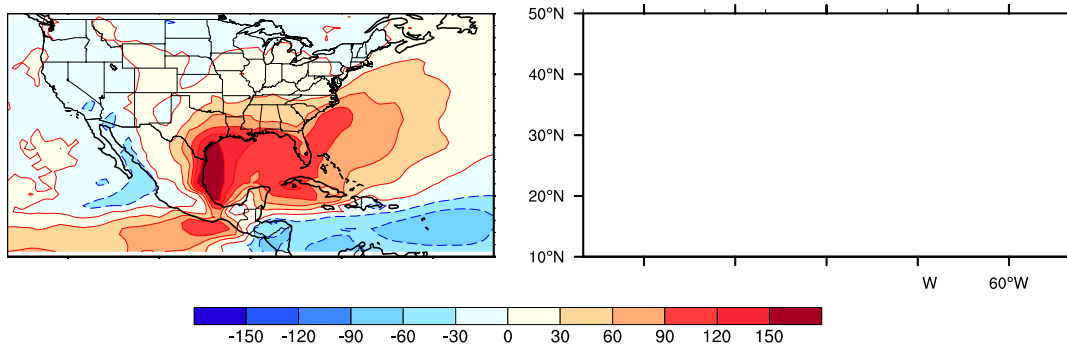


Figure 4 Composite maps of characteristic pattern associated with the linear relationship between US CAPE and GoM index. CAPE anomaly composite maps [J kg^{-1}] associated with warm SST anomaly in the Gulf of Mexico, in the CCSM4 forecasts (left) and NARR (right) for 1982-2011. MJJ CAPE anomalies were averaged for all years of positive GoM indices.

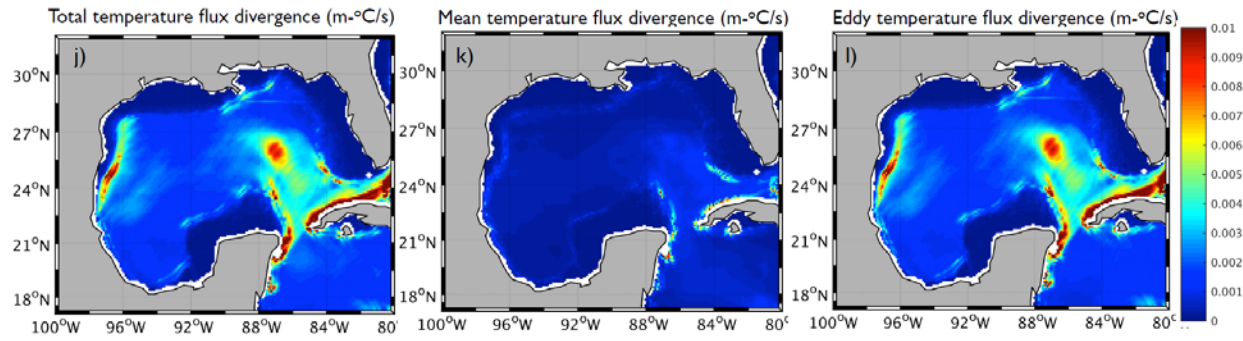


Figure 5 Spatial distribution of the heat advection in the coupled simulation with high resolution in the ocean. Shown is the standard deviation of monthly anomalies of integrated upper 200 m temperature flux divergence ($\text{m}^\circ\text{C s}^{-1}$) for: *left*) total, *middle*) mean and *right*) eddy components.

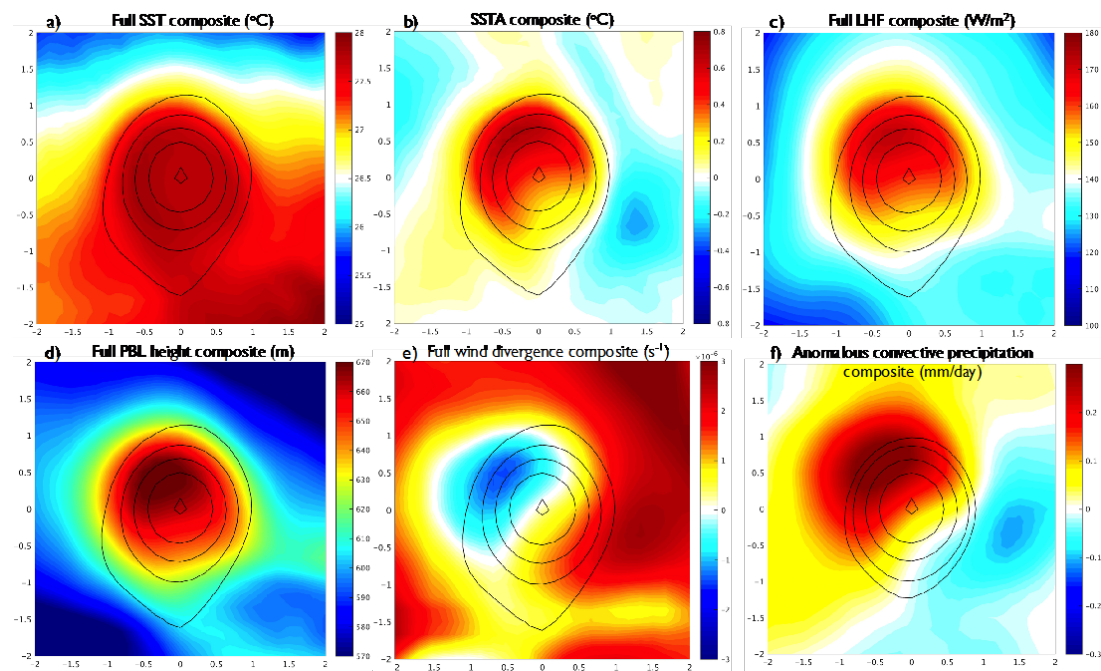


Figure 6: Averaged composites over the GoM anticyclones, normalized to two-radii length. Contours are SSH anomalies at 1, 10, 20, 30, 40 cm intervals. Colors represent: a) full SST ($^\circ\text{C}$); b) SSTA anomalies ($^\circ\text{C}$); c) full latent heat flux (W m^{-2}); d) full PBL height (m); e) full wind divergence (s^{-1}); f) convective precipitation anomalies (mm/day)

References (see also Publications from this Project)

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Highlights of Accomplishments

- New comprehensive Gulf of Mexico (GoM) model at $1/50^\circ$ (~2km) spatial resolution exhibits improved simulation of the Loop Current and its variability, relative to models at coarser spatial resolution.
- The analyses of oceanographic fields in the GoM were extended to the full Intra America Seas (IAS) region. The comparison of daily model and observed (GHRSSST) SST indicates excellent agreement.
- Convective available potential energy (CAPE) can serve as a proxy for extreme weather over the North America during the warm season; CAPE and GoM SSTA indices are strongly correlated. In contrast, the correlation of both indices with Niño 3.4 is significantly lower.
- An area-averaged Sea Surface Temperature (SST) anomaly in the Gulf of Mexico (GoM index) is a possible predictor for forecasting Convective Available Potential Energy (CAPE) anomalies in the US: The warmer the SST in the Gulf of Mexico, the higher CAPE in the contiguous US during MJJ seasons.
- Advection of heat by mesoscale eddies (defined as submonthly anomalies) dominates the upper Gulf of Mexico heat budget and correlates well with the turbulent air-sea heat exchanges.
- The warm anomalies associated with anticyclonic Loop Current rings have an identifiable imprint on surface turbulent heat flux, wind anomalies, and convective precipitation in the northwest quadrant of the ring composite.

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