Intraseasonal Variability of the Gulf Stream Current:
Physical Mechanisms and Connections to Atmospheric Forcing

MIDN 1/C Keely V. Martin, Assoc. Prof. Bradford S. Barrett, and Instr. Alexander R. Davies, Oceanography Department

Research Hypotheses:

1) **Sea surface temperatures (SSTs) in the Gulf Stream region off the U.S. Southeast coast vary intra-seasonally by phase of the MJO.**
2) **The SST-atmosphere relationship is time-lagged because of (*a*) a 7–10 day delay between tropical MJO forcing and the extratropical wind, and (*b*) a 10–20-day delay between surface wind forcing and SST change (Figure 1).**

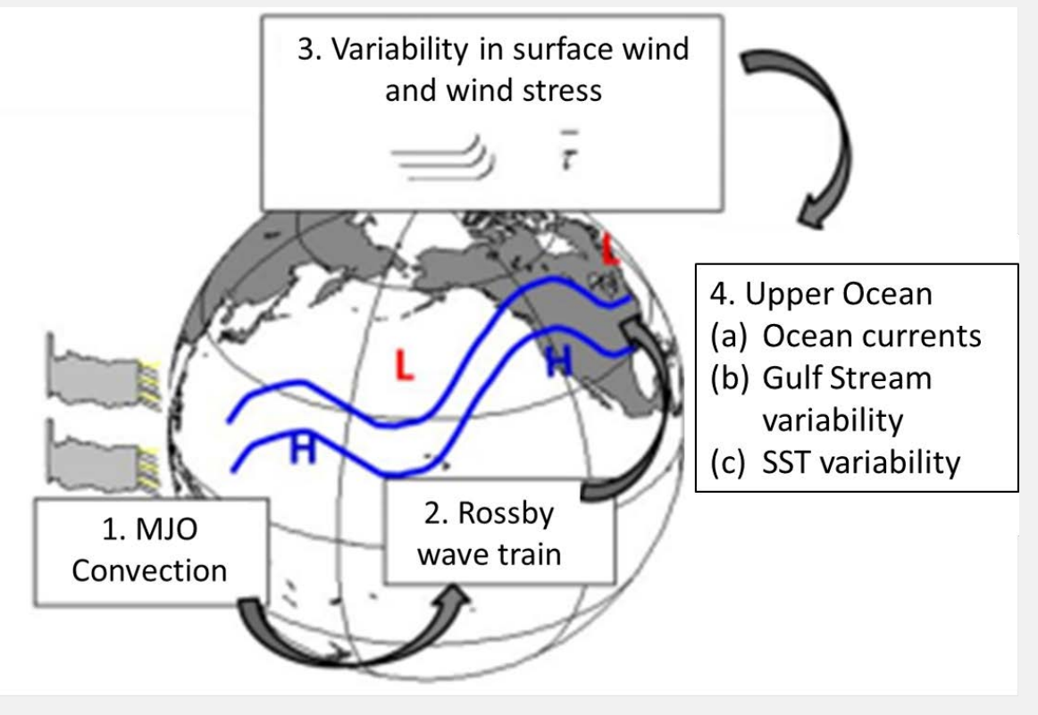

Figure 1. Teleconnection mechanism by which the MJO may affect the ocean as adapted from Barrett et al. (2017).

Background and Motivation:

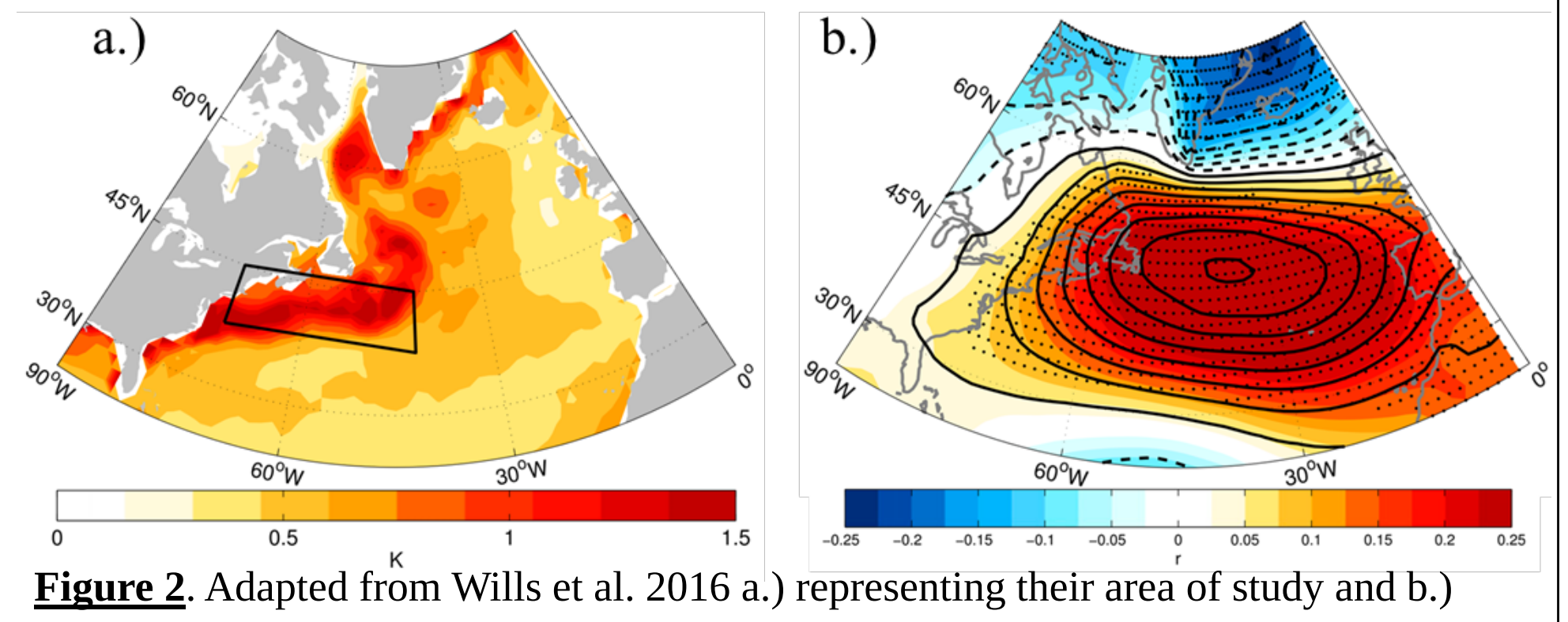

Figure 2. Adapted from Wills et al. 2016 a.) representing their area of study and b.) correlations between 1000 mb height and SST lagged 20 days.

The Madden-Julian Oscillation (MJO) is an expansive, equatorially centered convective (and subsidence) envelope that propagates eastward around the Earth at a speed of ~5 m s^{-1}. Heating associated with the convective envelope excites upper-tropospheric Rossby waves that propagate eastward and poleward (**Figure 1**). These MJO-driven Rossby waves are known to affect semi-permanent pressure systems, including over the North Atlantic Ocean (Zhang 2005). The MJO has also been shown to influence mid-latitude ocean currents in the North Pacific Ocean (Barrett et al. 2017). The eight phases of the MJO roughly correspond to the geographical location of the convective envelope.

The position and SSTs of the **Gulf Stream** are known to respond to atmospheric forcing on the synoptic (Nelson and He 2012, Taylor and Stephens 1998) and yearly-to-decadal (McCarthy et al. 2018; Sturges et al. 1997) time scales. However, intraseasonal variability of the Gulf Steam remains understudied but relevant, including to fisheries.

Wills et al. (2016) examined the northern Gulf Stream, linking SST variability in a selected area to the lower troposphere (**Figure 2a**). The authors applied a lead-lag analysis based on daily mean data and analyzed the peak response using **correlations** and linear regression (**Figure 2b**). The methodology of this study closely follows Wills et al. (2016).

Data and Methods:

The Gulf Stream was analyzed using the NASA MURSST SST dataset (JPL MUR MEaSUREs Project 2010).

- MURSST data (**Table 1**) were quality controlled by eliminating days subjectively determined to have non-physical Gulf Stream and SST signatures. The SST data were further linearly resampled to 0.1° horizontal resolution for computational efficiency.

The atmosphere was analyzed for December, January, and February using the European Center for Medium Range Weather Forecasting Reanalysis (Dee et al. 2011) dataset (ERA-Interim).

- ERA-Interim variables (**Table 1**) were subset by active (amplitude > 1.0) phase of the Revised Real-Time Multivariate MJO index (Liu et al. 2015).

Surface ocean variability (**Figure 3**) was analyzed using a time series of daily mean SST anomalies averaged over the area of the Gulf Stream determined to have the greatest variability by analyzing the standard deviation of the sea surface temperature in the months of December, January, and February (**Figure 3d–f**).

A 30-day moving average was used to smooth the annual time series (**Figure 4**). The data were de-trended by removing the long-term trend ($SST_{detrended} = (0.000124 * day) - 0.3396186$). Linear Pearson product-moment correlation coefficients were calculated between MSLP, *u*-wind, and *v*-wind and SST, lagged 0-30 days. Statistical significance was determined using a Student's t-test and degrees of freedom were calculated using Eq. (31) from Bretherton et al. (1999).

Data sets used

Source	Variables	Levels/Resolution	Time Period
NASA MURSST	Sea Surface temperatures	sea surface Daily 0.1° x 0.1°	2003-2017 December-February
ERA-Interim Reanalysis	*u* , *v* , height, MSLP	surface, 850 hPa, 500 hPa, 300 hPa Daily at 0000 UTC 0.5° x 0.5°	1979-2016 December-February
Revised Real-Time Multivariate MJO Index	RMM1 and RMM2	Daily	1979-2017 December-February

Table 1. Variables and datasets used in this study.

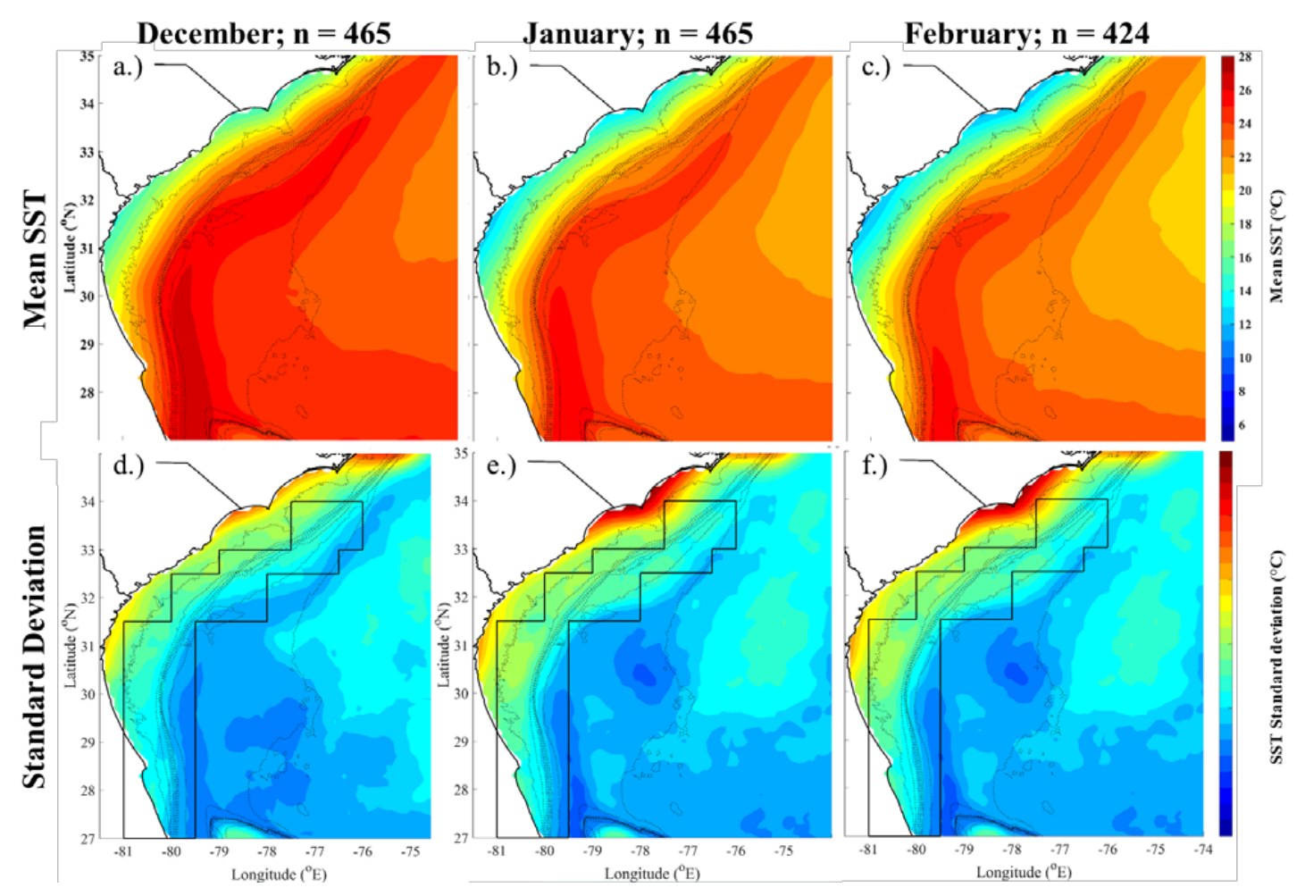

Figure 3. Contoured average sea surface temperatures of a.) December, b). January, and c.) February and standard deviation of sea surface temperatures for d.) December, e.) January, and f.) February. Dotted lines represent bathymetry for 25, 50, 100, 150, 200, 250, 500, 1000 meter depths. Region of greatest variability of the southern Gulf Stream is boxed in panels d–f.

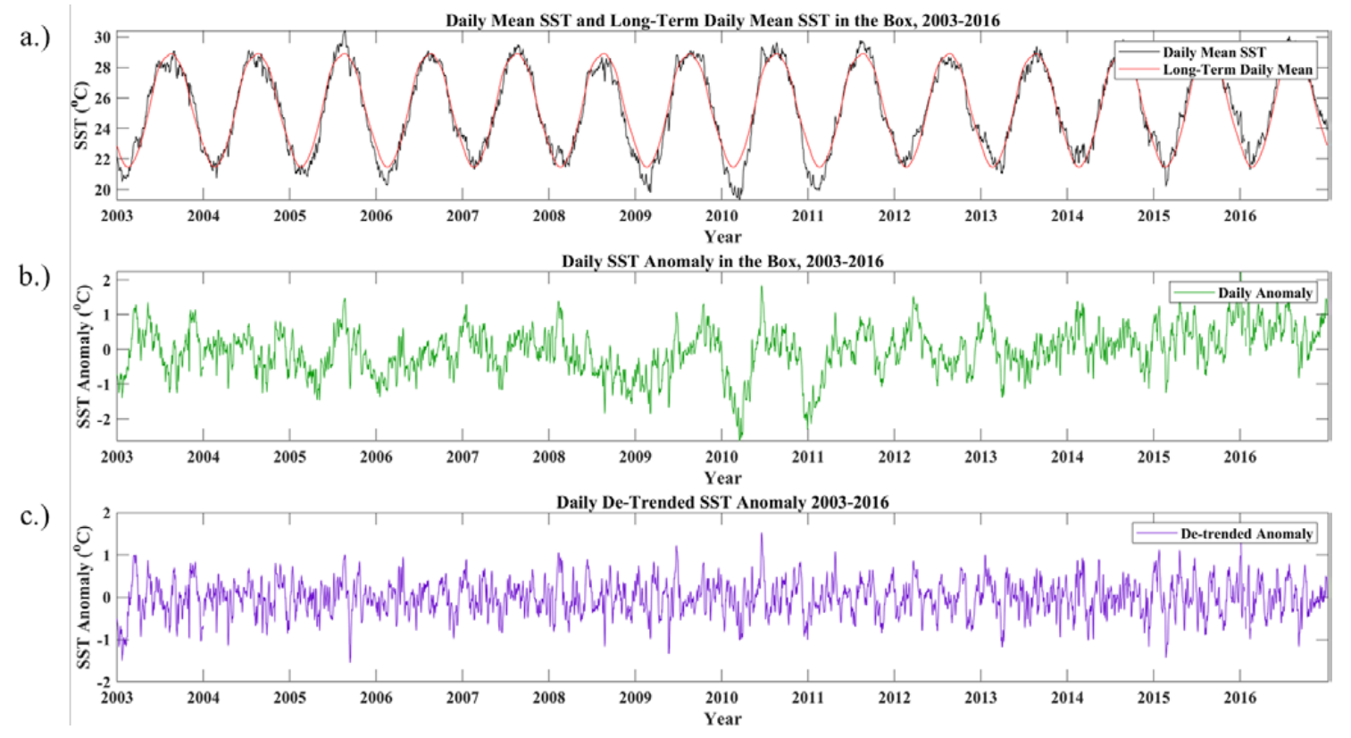

Figure 4. a.) Long term (red line) and daily mean (black line) SST. b.) Daily SST anomaly (green line, black minus red from panel a). c.) Daily de-trended SST anomaly (purple line). All four time series are for values inside the box in Figure 3.

Result 1: Lagged 10-Day SST Response

In DJF, 10-day lag correlations over the Western Atlantic Ocean indicate the following:

1.) Mean state:

- Positive MSLP over the western Atlantic leads warmer SSTs 10 days later in the southern Gulf Stream (**Figure 5a**).
- Negative *u*-wind (easterly winds) over the Western Atlantic, Gulf of Mexico, and the Caribbean leads warmer SSTs in the Gulf Stream 10 days later (**Figure 5b**).
- Positive *v*-wind (southerly winds) over the Great Lakes and negative *v*-wind over the Central Atlantic lead warmer SSTs in the Gulf Stream 10 days later (**Figure 5c**).

2.) MJO modulation of the mean state

- Phases 1, 4–7 (**Figure 5a,b**) show strongest agreement with mean MSLP-SST and *u*-wind-SST relationships. Phases 4–6 show the strongest agreement with mean *v*-wind relationships (**Figure 5c**).
- Phases 2 and 3 show the weakest agreement (**Figure 5a–c**).

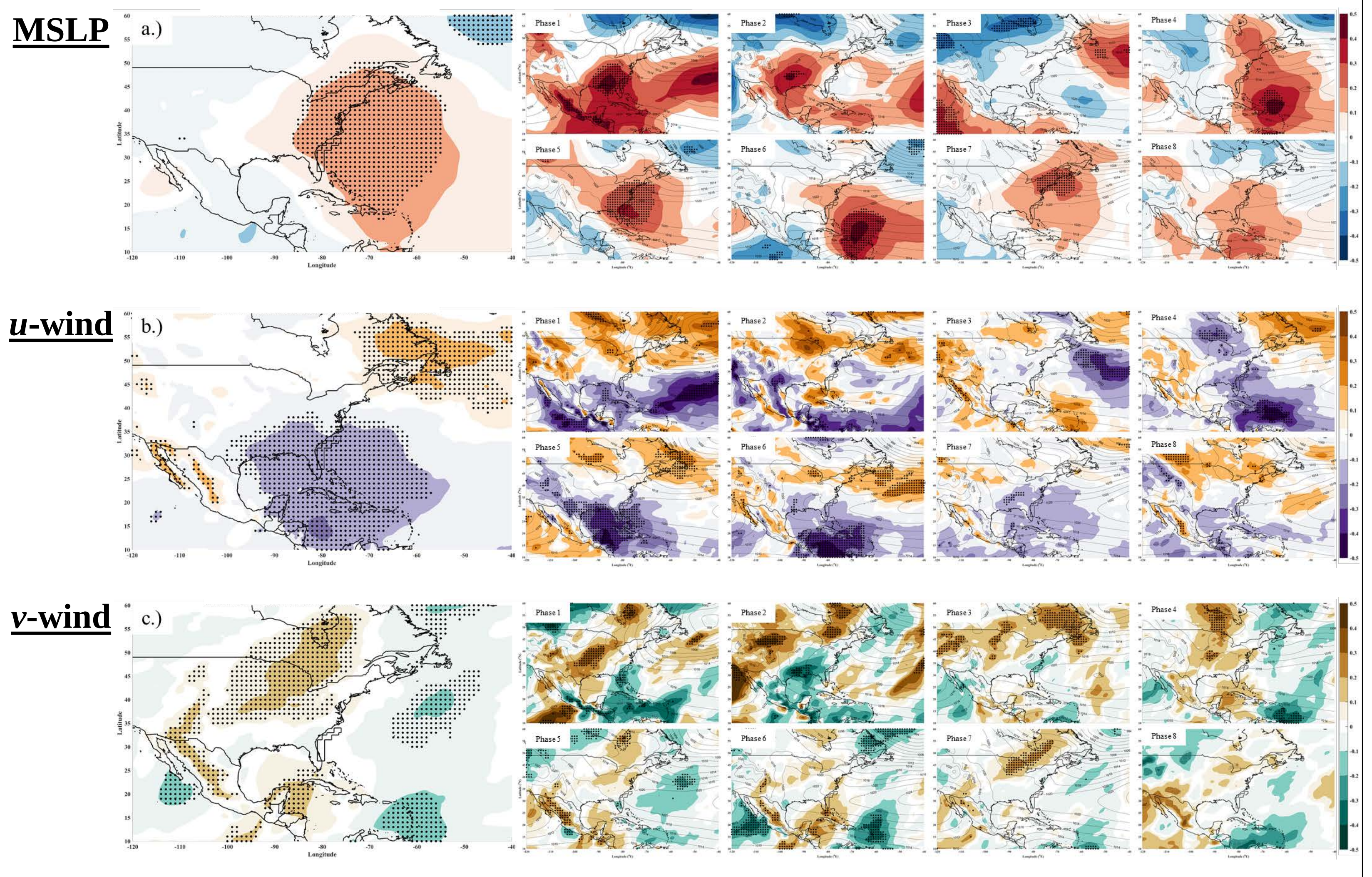

Figure 5. Linear Pearson product-moment correlation coefficients between a.) MSL, b.) *u*-wind, and c.) *v*-wind and SST lagged 10 days. Dots indicate correlations that are statistically significant at the 95th percentile.

Result 2: Lagged 20-Day SST Response

In DJF, 20-day lag correlations over the Western Atlantic Ocean indicate the following:

1.) Mean state:

- Positive MSLP over the Northern Western Atlantic Ocean leads warm Western Gulf Stream (**Figure 6a**).
- Negative *u*-wind (easterly winds) over the Western Atlantic Ocean, eastern Gulf of Mexico, and Western Caribbean Sea leads warm Gulf Stream SST (**Figure 6b**).
- Positive *v*-winds (southerly winds) over the eastern Gulf of Mexico, western Caribbean Sea and negative *v*-winds (northerly winds) over the eastern Caribbean Sea leads warm Gulf Stream SST (**Figure 6c**).

2.) MJO modulation of the mean state:

- Phase 1, and to a lesser extent, phases 5 and 6 support the mean state relationship between MSLP and SST, *u*-wind and SST, and *v*-wind and SST (**Figure 6a–c**).
- Phases 2, 3, and 4 show the weakest agreement (**Figure 6a–c**).

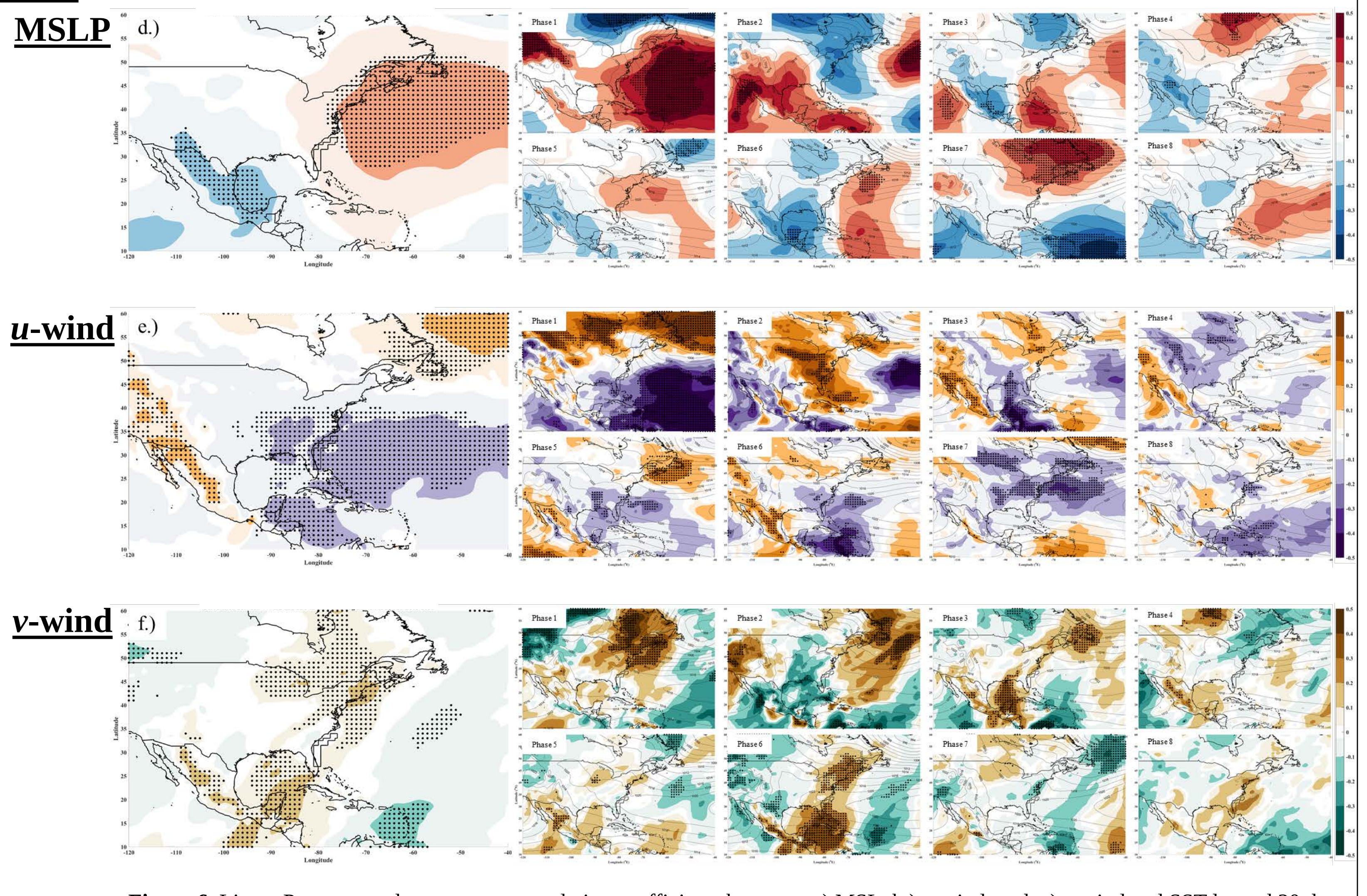

Figure 6. Linear Pearson product-moment correlation coefficients between a.) MSL, b.) *u*-wind, and c.) *v*-wind and SST lagged 20 days. Dots indicate correlations that are statistically significant at the 95th percentile.

Conclusions and Future Work:

Deep tropical convection associated with MJO forces Rossby waves in the upper troposphere. Through quasi-geostrophic theory, this results in anomalously high and low MSLP, which manifests as atmospheric (wind) forcing. There is clear correlation between lagged SSTs and MSLP and the surface wind field. Furthermore, the lagged relationship varies by MJO phase, with the strongest relationship most often found 10 and 20-days after MJO phases 1, 4, 5, and 6. We thus have found a mechanism by which the MJO can modulate the southern Gulf Stream.

References

Barrett, B. S., A. R. Davies, and J. I. Rose, 2017: Wind-Driven response of the Upper Ocean Along the U.S. West Coast to Tropical MJO Convection. *J. Geophys. Res.*, **122**, 8196-8207, https://doi.org/10.1002/2017JC013086.

Bretherton, C. S., and Coauthors, 1999: The Effective Number of Spatial Degrees of Freedom of a Time-Varying Field. *J. Clim.*, **12**, 1990-2009, https://doi.org/10.1175/1520-0442(1999)012<1990:TENOSD>2.0.CO;2.

Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. Roy. Meteor. Soc.*, **137**, 553–597, https://doi.org/10. 1002/qj.828.

JPL MUR MEaSUREs Project, 2010: GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis, version 2. PO.DAAC, accessed 23 August 2018, http://dx.doi.org/10.5067/GHGMR-4FJ01.

Liu, P., Q. Zhang, C. Zhang, Y, Zhu, M. Khairoutdinov, H. Kim, C. Schumacher, and M. Zhang, 2015: A Revised Real-Time Multivariate MJO Index. *Mon. Weath. Rev.*, **144**, 627-642, https://doi.org/10.1175/MWR-D-15-0237.1.

McCarthy, G. D., T. M. Joyce, and S. A. Josey, 2018: Gulf Stream Variability in the Context of Quasi-Decadal and Multidecadal Atlantic Climate Variability. *Geophys. Res. Let.*, **45**, https://doi.org/10.1029/2018GL079336.

Nelson, J., and R. He, 2012, Effect of the Gulf Stream on winter extratropical cyclone outbreaks. *Atmos. Sci. Let.*, **13**, 311-316, https://doi.org/10.1002/asl.400.

Sturges, W., B. G. Hong, and A. J. Clarke, 1997: Decadal Wind Forcing of the North Atlantic Subtropical Gyre. *J. Phys. Oceanogr.*, **28**, 659-668, https://doi.org/10.1029/2018GL079336.

Taylor, A. H., and J. A. Stephens, 1998: The North Atlantic Oscillation and the latitude of the Gulf Stream. *Tellus*, **50**, 134-142. https://doi.org/10.1034/j.1600-0870.1998.00010.x.

Wills, S. M., D. W. J. Thompson, and L. M. Castro, 2016: On the Observed Relationship between Variability in the Gulf Stream Sea Surface Temperatures and the Atmospheric Circulation over the North Atlantic. *J. Clim.*, **29**, 3719-3730, https://doi.org/10.1175/JCLI-D-15-0820.1.

Zhang, C., 2005: Madden-Julian Oscillation. *Rev. Geophys.*, **43**, RG2003, https://doi.org/10.1029/2004RG000158.

Acknowledgements:

The authors gratefully acknowledge financial support from NASA award NNX16AH61G.