SPECIAL
Climate and Frontal Air-Sea Interaction
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Reply to "Comments on 'The Gulf Stream Convergence Zone in the Time-Mean Winds'"

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(Manuscript received 5 February 2018, in final form 28 February 2018)

We appreciate the opportunity to restate and clarify the main conclusions of our recent article (O'Neill et al. 2017). Plougonven et al. (2018) raise a concern about the use of conditional means that we employed in our analysis and whether they provide sufficient evidence to question the hypothesized role of SST in generating the Gulf Stream convergence zone (GSCZ) in the time-mean winds. The authors comment that the absence of the GSCZ in the time-mean winds after storms are removed does not necessarily mean that an SST-induced response of the winds consistent with the Ekman-balanced mass adjustment (EBMA) mechanism is not occurring here. While we agree with this point, we would like to clarify that this was not our conclusion. Our main conclusion was that SST by itself cannot account for the GSCZ in the time-mean winds, since removing a small number of strong convergence anomalies associated with storms also removes the GSCZ, leaving a time-mean divergence field inconsistent with the EBMA mechanism. In light of this evidence, we question whether the hypothesized EBMA mechanism has any dynamical relevance to the GSCZ since the GSCZ in the time-mean winds is the sole observational evidence of the hypothesized EBMA mechanism over the Gulf Stream in the literature.

A point that is implicit in our paper is that if a response consistent with the EBMA mechanism exists near the Gulf Stream, it is extremely difficult to isolate unambiguously from the time-mean derivative wind fields, vertical velocity, and surface pressure because of storms. This is because storm anomalies of these three variables (upward motion, surface convergence, and low surface pressure and positive surface pressure Laplacian) coincide with those anomalies predicted by the EBMA mechanism over the Gulf Stream. Furthermore, the storm track is focused narrowly over the Gulf Stream where the SST Laplacian is also most intense. It therefore becomes difficult to assign causation from correlations between these variables, which have been averaged in time. The challenge is finding a robust diagnostic that removes storm-track variability from these (and other) variables while retaining the comparatively weak SST-induced signal. Our analysis demonstrates that a straight time mean is not sufficient to mitigate storm-related variability in these variables and is thus not a robust diagnostic for isolating the EBMA mechanism here.

To explain this behavior of the time-mean divergence, we made what we believe is a compelling case that large-amplitude anomalies on the extreme tails of the distribution [defined in our paper as being more than two standard deviations (2σ) from the time mean at each grid point] significantly alter the statistics of the divergence distribution. We argued that the asymmetry of the divergence distribution toward transient and large-amplitude storm events substantially alters its time mean.

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DOI: 10.1175/JAS-D-18-0044.1

Whether or not the SST Laplacian signature of the Gulf Stream forces surface convergence, it is important to point out that we find no evidence of it from instantaneous data. Evidence for this statement in our paper came mainly from the lack of significant correlation between the divergence and SST Laplacian and the divergence and SLP Laplacian, computed from instantaneous data, either from the satellite observations or from the model simulations. Plougonven et al. (2018) provide no additional observational evidence for such a coupled process and have assumed that such a process is present without justification. We believe this is an important weakness in their case.

The physical mechanism(s) that contribute(s) to the formation and maintenance of the GSCZ is (are) therefore still very much an open question. Our results show clearly that large-amplitude and short-duration anomalies associated with storms leave a significant imprint on the time-mean wind field (including the divergence and vertical velocity), in many places changing the sign of the time mean. We cannot reconcile this observational result with that predicted by the EBMA mechanism, which associates the negative SST Laplacian signature of the north wall of the Gulf Stream with surface convergence. Since the Gulf Stream is persistent in time, the response should also be relatively persistent, but this is evidently not the case.

Our analysis also shows clearly that the cross correlation between instantaneous values of the satellite- and model-derived SST Laplacian and divergence over the Gulf Stream is not statistically significant, thus raising a serious question about whether a persistent SST-induced coupled response consistent with the EBMA mechanism truly exists. In contrast, the divergence and downwind SST gradient are significantly correlated ($\rho = 0.3$) on instantaneous scales in the satellite observations, consistent with the analytical model of Schneider and Qiu (2015). On dynamical grounds, Schneider and Qiu (2015) suggest a reconciliation between the EBMA mechanism and this long-standing empirical correlation between the divergence and the downwind SST gradient, whereby the EBMA mechanism is dynamically relevant for very low wind speeds, and the downwind SST gradient is the relevant forcing for moderate winds, such as those most frequently found over the midlatitudes. This is consistent with the idealized modeling study of Lambaerts et al. (2013), which shows that, in the limiting case of zero background surface flow, the EBMA mechanism is the relevant dynamical description of the local SST-induced boundary layer response.

It is also noteworthy that the hypothesized link between the SST Laplacian and the GSCZ was an inconsistency that plagued the applicability of the Schneider and Qiu (2015) analytical model analysis over the Gulf Stream. Even though the background winds over the Gulf Stream were squarely within the downwind SST gradient forcing regime, it appeared that the model did not work there in light of the correlations between the time-mean SST Laplacian and the time-mean surface divergence reported in numerous studies over the past decade. At face value, this result suggested that their model and interpretation of it were inconsistent with previous evidence. Our results suggest otherwise, since the GSCZ in the time-mean winds can be explained by processes associated with the storm-track activity and location rather than a local boundary layer response to Gulf Stream SST. Storm dynamics are not included in that model. The conditional sampling employed in our study was designed specifically to remove storm-related variability and leave behind conditions more conducive to identifying a weaker SST-induced response. After mitigating storm-related variability, the conditionally averaged and extreme-value-filtered divergence was more consistent with the Schneider and Qiu (2015) analytical model and earlier empirical studies showing a correlation between surface divergence and the downwind SST gradient, as discussed in our paper.

The effect of intermittent storms on the mean state of the North Atlantic has also been noted by Parfitt and Czaja (2016) based on a detailed analysis of vertical velocity, sea level pressure, and meridional wind anomalies associated with storms. In particular, they show that the time-mean omega vertical velocity is strongly influenced by transient weather disturbances, a point supported by our model simulation.

Previous studies used the presence of rain as a less sensitive indicator of storms than the 2σ extreme-value filter to show a sensitivity of the time-mean derivative wind fields to storms (e.g., Milliff et al. 2004; O'Neill et al. 2015; Kilpatrick and Xie 2016). This result was part of our motivation for investigating the role of storms in shaping the time-mean state of the wind and pressure fields in the northwest Atlantic. Although not mentioned in our paper, we believe that the analysis of the conditional averages based on rain represents the classical Simpson–Yule paradox in statistics. In a simple form, this paradox describes how associations evident in aggregated data may change compared to data split into subgroups. If splitting data into subgroups alters or reverses associations, then the criterion used for splitting the data likely represents a variable or process that must be controlled for in the analysis. This additional process is called a confounding variable. The Simpson–Yule paradox is a specific case of the more familiar omitted variable bias, where regression analysis is performed without one or more key explanatory variables.

In our case, we believe that rain, as a proxy for storms, represents a confounding factor since grouping data based on rain produces much different time-mean divergence fields. The correlation between rain and divergence is in fact how we identified this confounding process. An additional complication is that storms and rain are also both correlated with the SST Laplacian over the Gulf Stream (not shown), in addition to being correlated with the divergence. This greatly contributes to difficulties in attributing direct causality between the SST Laplacian and divergence, since it is also possible that a causal pathway exists such that the SST Laplacian forces storms, which forces convergence. In our view, rain and storms represent a confounding variable in previous analyses that must be accounted for when attempting to assign direct causality between SST and divergence.

Conditional sampling is a natural tool to gain insight into the effects of confounding variables in a statistical analysis. The fact that excluding rain drastically changes the time-mean divergence, SLP Laplacian, and vertical velocity suggests rain and storms are confounding effects, which differs from the interpretation of Plougonven et al. (2018).

Besides demonstrating the large differences in the time-mean divergence field between all-weather and rain-free cases, we provide further evidence to justify why we believe that storms represent a critical process that must be controlled for in the statistical analysis. This evidence included the strong collocation of the meridional wind variance and the GSCZ, the extreme-value filter, and the analysis of the time-mean surface pressure and vertical velocity.

Our conclusion that the EBMA mechanism does not appear to account for the GSCZ is thus based on a combination of evidence, not just our analysis of the conditional averages based on rain occurrence or extreme divergence anomalies. It is possible that the EBMA mechanism may be a relevant dynamical description at times, but observational evidence to support this possibility has not yet been presented. It may also be that the proper diagnostic tools to isolate air–sea coupling processes from synoptic-scale weather variability have just not yet been identified. In the search for more appropriate diagnostic tools in the future, conditional sampling may play an important role in isolating intermittent coupled processes from observational data. The underlying reasoning of the Plougonven et al. (2018) comment suggests that details of conditional sampling may not be sufficient to draw definitive conclusions. In this respect, we agree. However, we do not agree that conditional sampling cannot be used in combination with other evidence to build a case for or against certain mechanisms.

The most important conclusion from our paper and from the Plougonven et al. (2018) comment from our perspective is that the community is still searching for a robust diagnostic, uncontaminated by storm-track variability, that demonstrates the coupled air–sea response in western boundary currents.

Acknowledgments. This paper was funded under NASA Grants NNX11AF31G, NNX14AM66G, and NNX14AM72G and Jet Propulsion Laboratory Subcontract 1540785.

REFERENCES

Kilpatrick, T. J., and S.-P. Xie, 2016: Circumventing rain-related errors in scatterometer wind observations. *J. Geophys. Res. Atmos.*, **121**, 9422–9440, https://doi.org/10.1002/2016JD025105.

Lambaerts, J., G. Lapeyre, R. Plougonven, and P. Klein, 2013: Atmospheric response to sea surface temperature mesoscale structures. *J. Geophys. Res. Atmos.*, **118**, 9611–9621, https://doi.org/10.1002/jgrd.50769.

Milliff, R. F., J. Morzel, D. B. Chelton, and M. H. Freilich, 2004: Wind stress curl and wind stress divergence biases from rain effects on QSCAT surface wind retrievals. *J. Atmos. Oceanic Technol.*, **21**, 1216–1231, https://doi.org/10.1175/1520-0426(2004)021<1216:WSCAWS>2.0.CO;2.

O'Neill, L. W., T. Haack, and T. Durland, 2015: Estimation of time-averaged surface divergence and vorticity from satellite ocean vector winds. *J. Climate*, **28**, 7596–7620, https://doi.org/10.1175/JCLI-D-15-0119.1.

——, ——, E. Skyllingstad, and D. Chelton, 2017: The Gulf Stream convergence zone in the time-mean winds. *J. Atmos. Sci.*, **74**, 2383–2412, https://doi.org/10.1175/JAS-D-16-0213.1.

Parfitt, R., and A. Czaja, 2016: On the contribution of synoptic transients to the mean atmospheric state in the Gulf Stream region. *Quart. J. Roy. Meteor. Soc.*, **142**, 1554–1561, https://doi.org/10.1002/qj.2689.

Plougonven, R., A. Foussard, and G. Lapeyre, 2018: Comments on "The Gulf Stream convergence zone in the time-mean winds." *J. Atmos. Sci.*, **75**, 2139–2149, https://doi.org/10.1175/JAS-D-17-0369.1.

Schneider, N., and B. Qiu, 2015: The atmospheric response to weak sea surface temperature fronts. *J. Atmos. Sci.*, **72**, 3356–3377, https://doi.org/10.1175/JAS-D-14-0212.1.