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Key Points:

- Tropical cyclones leave cold wakes that affect winds and air-sea fluxes for weeks
- Cloud cover and rainfall are reduced in the wake
- Ocean small-scale structures generate spatial variability in the atmosphere

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Air-Sea Interactions in the Cold Wakes of Tropical Cyclones

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Abstract Tropical cyclones generate a large and wide cold wake along their trajectories, which conditions the subsequent evolution of the tropical cyclone themselves. The cold wakes persist for weeks, impacting both the upper ocean, the air-sea fluxes, and the atmosphere. The study by Z. Ma et al. (2020, https://doi.org/10.1029/2020GL088873), for the first time analyzes a composite of remotely sensed data sets to show that cold wakes modify surface winds and reduce cloud coverage and rainfall. These results contribute to shedding light on the mechanisms at the origin of the air-sea feedbacks, which can differ at different latitudes depending on the stability of the marine atmospheric boundary layer. The work stimulates further research to assess whether the cloud cover anomalies induced by tropical cyclones significantly modify the radiative budget of the Earth.

Plain Language Summary Strong winds in tropical cyclones stir the upper ocean and generate a cold wake at the sea surface. The reduced sea surface temperature can limit further intensification of the cyclone itself. In the wake, temperatures can be up to 10°C colder than in normal conditions and the anomalies last for weeks. Their effects on the ocean have been extensively investigated but not those on the atmosphere. Z. Ma et al. (2020, https://doi.org/10.1029/2020GL088873), use a combination of satellite derived data and demonstrate that winds, clouds, and rainfall are largely modified by the cold wake. This stimulates further research to understand whether the effects are just local or whether they also modify the seasonal mean basinwide insolation at the surface.

1. Background

The climate system is composed of different compartments which communicate and exchange properties at their boundaries, such as at the air-sea interface, modifying momentum, gas concentrations, heat, and moisture content. The air-sea fluxes depend on the thermal, chemical, and dynamical disequilibrium between the upper ocean and the lower atmosphere. Despite being crucial for both weather and climate phenomena, their observations are still challenging, especially at high-spatiotemporal resolution (Cronin et al., 2019; Gentemann et al., 2020).

Air-sea fluxes are enhanced in presence of strong winds, which favor the vertical mixing both in the atmosphere and in the ocean, inhibiting the formation of a very shallow interface layer in quasi-equilibrium conditions that would limit further exchanges. Strong winds increase sensible heat flux and evaporation from the ocean into the atmosphere and input momentum into the upper ocean, generating turbulence that deepens the oceanic mixed layer. Both processes tend to reduce the sea surface temperature (SST). Atmospheric internal dynamics generates variability in the surface winds at the synoptic scale (O(1,000 km) and more), driving an upper ocean response that results in a widespread negative correlation between large-scale winds and SST (see Figure 1a, the positive correlation in the eastern equatorial Pacific is due to the dynamics of El Niño Southern Oscillation, which is a fully coupled phenomenon). At smaller scales, the negative correlation disappears (see Figure 1b), indicating that winds no longer drive ocean surface conditions but rather are affected by SST mesoscale and submesoscale variability (O(100s km) and less). The scale separation between the two behaviors is thus related to the scale of the instabilities that generate balanced structures in the two media. Tropical cyclones are atmospheric phenomena with a size of O(100s km), in between atmospheric synoptic scales and oceanic mesoscales. They both affect and are affected by the SST

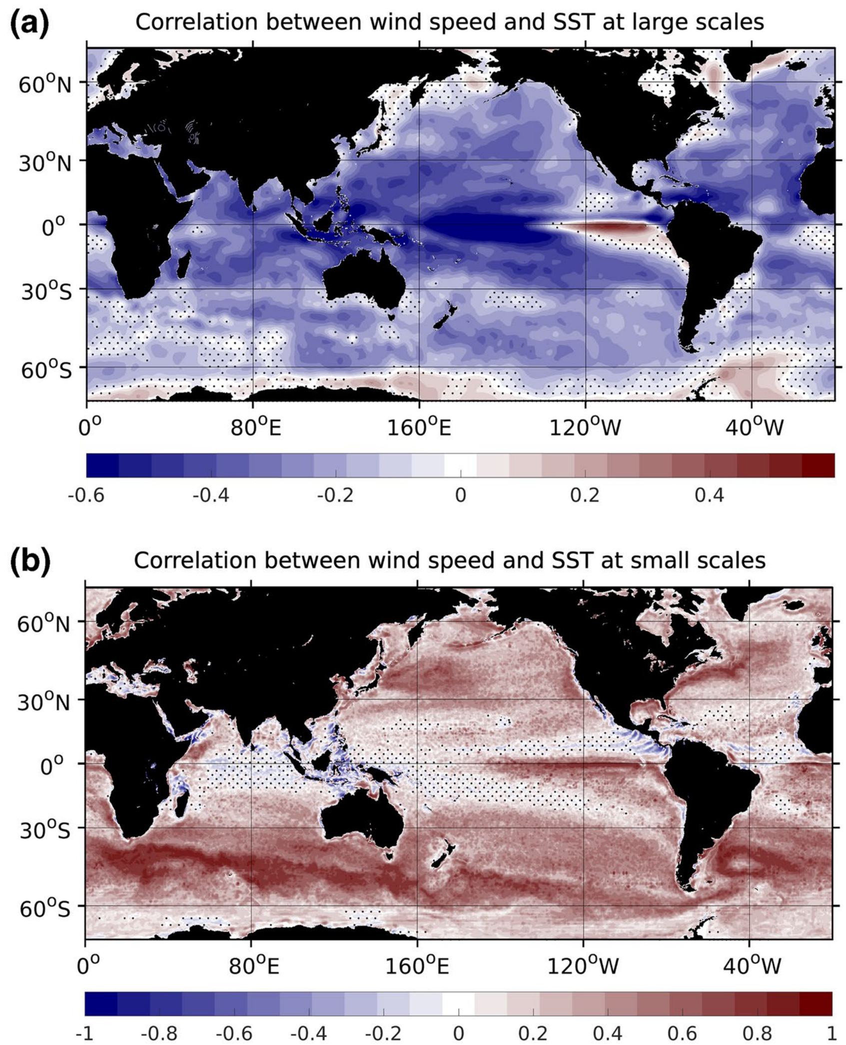

Figure 1. Correlation between ERA5 monthly mean wind speed and SST (a) at large scales and (b) at small scales. The spatial scales are mathematically defined using a 2D-half-power Lanczos filter with a cutoff wavelength of 10°. A transfer function analysis shows that the −3 dB is reached at about 650 km between the large-scale data and the original one. The climatological seasonal cycle has been removed for the calculation of correlation at large scales. On both panels, black dots denote pixels where correlations are not significant ($p > 0.05$). This diagnostic has been inspired by Figure 1 of Gentemann et al. (2020). SST, sea surface temperature.

and are associated with very large air-sea fluxes. Warm SSTs favor their intensification, and their strong winds generate ocean surface cooling. For those reasons, they modify the environment in which they are embedded, impacting on the air-sea interactions both during and after their passage.

2. Cold Wakes and Their Effects on the Evolution of the Tropical Cyclone

Tropical cyclones are a clear example of the air-sea feedback loop: they are fueled by the large sensible and latent heat fluxes occurring over warm waters and convert thermal energy into mechanical energy (Emanuel et al., 2004). The resulting winds are responsible for the generation of cold wakes, with SST anomalies as large as −10°C, very clearly visible in satellite images (Chiang et al., 2011). The tropical-cyclone-induced surface cooling is partly due to the Ekman response to the cyclonic winds, which create strong surface divergence and upwelling of colder water from below (Price, 1981). This process sums up to wind-induced vertical mixing and enhanced air-sea fluxes, resulting in a particularly strong SST response (D'Asaro et al., 2007; Sanford et al., 2007). The surface ocean cooling reaches its maximum 1 or 2 days after the passage of the tropical cyclone, but in many cases is already present below the eye (Mei et al., 2015; Mei & Pasquero, 2013), limiting the intensification of the cyclone itself.

Very intense hurricanes, such as Katrina in 2005, often form in the presence of a limited ocean surface cooling under the eye associated with the presence of an anomalously deep ocean mixed layer, such as in warm core eddies, that prevents subsurface colder water from reaching the surface and acting as inhibitor of further intensification (e.g., Lin et al., 2013). The air-sea feedback loop has been extensively studied in the last decade, and its effects have been shown to significantly reduce forecast errors of tropical cyclone intensity (Chen & Zhang, 2019; Courtney et al., 2019).

3. The Fate of the Cold Wakes and Their Longer Term Effects

The tropical-cyclone-induced cold surface anomaly typically disappears over a time scale of a couple of weeks (Dare & McBride, 2011; Mei & Pasquero, 2013; Price et al., 2008), thanks to reduced air-sea fluxes in the presence of a lower SST and to upper ocean vertical heat transport associated with baroclinic instabilities in the presence of a thermal front (Mei & Pasquero, 2012). While these processes have been extensively studied for their effects on upper ocean heat content and dynamics (Jansen & Ferrari, 2009; Mei et al., 2013; Price et al., 2008), the possible effects of the cold surface anomaly on atmospheric processes in the period after the tropical cyclone passage have not been fully quantified yet. The study by Z. Ma et al. (2020) fills this gap, demonstrating that tropical cyclones affect winds and suppress cloud cover and rainfall 1 week after their passage. Their results, obtained using a combination of satellite observations over a 10-year long period, indicate a mean reduction of precipitation of about 15% with respect to the prestorm period.

4. Surface Ocean SST Structures Contribute to Small-Scale Atmospheric Variability

These results contribute to the recent advances in the study of the effects that both permanent and transient spatial SST structures have on the marine atmospheric boundary layer. As mentioned above, despite the existence of a negative correlation between large-scale wind speed and SST, a modulation of wind velocity is found in the presence of the thermal signatures of oceanic structures at the mesoscale and submesoscale (Chelton et al., 2004; Laurindo et al., 2019; Gaube et al., 2019; Shao et al., 2019).

The mechanisms responsible for this modulation (typically referred to as thermal feedback, see the review by Renault et al. [2019]) are essentially two: the downward momentum mixing and the pressure adjustment. The former one is related to the fact that cool waters reduce the heat fluxes into the atmosphere and thus the buoyancy of the low-level air mass, stabilizing the marine atmospheric boundary layer and decoupling the surface winds from the stronger winds aloft. This results in a smaller surface wind speed over cold waters and a larger one over warm waters (Figure 2a), where the increased atmospheric instability is responsible for a stronger vertical mixing and brings horizontal momentum downward (Hayes et al., 1989; Wallace et al., 1989). This mechanism leads to a positive correlation between SST and surface winds. When blowing over a thermal front from a warmer to a colder water mass, surface winds thus generate convergence, and conservation of mass is responsible for a corresponding upward air motion.

The second mechanism, the pressure adjustment, is related to the thermal expansion of warm air when it is overlying warm waters: this generates a pressure gradient force across a front, from the warm to the cold region at some height above the surface, and from the cold to the warm region at the surface, resulting in a circulatory cell across the front with ascending branches on SST maxima and descending branches on SST minima (see Figure 2b, Lindzen & Nigam 1987). This mechanism does not result in a direct correlation between wind speed and SST but rather in a correlation between wind divergence and SST: surface convergence preferentially occurs over SST maxima.

The vertical air movements described above, ultimately related to the presence of SST patterns, favor condensation of water vapor (for upward air motion) and evaporation (for downward air motion). Indeed, composite analyses of atmospheric conditions over cold cyclonic mesoscale ocean eddies in the Southern Ocean and in the Kuroshio extension region have revealed a slackening of the surface winds and a decline in cloud fraction, water content, and rainfall (Frenger et al., 2013; J. Ma et al., 2015). These results are consistent with

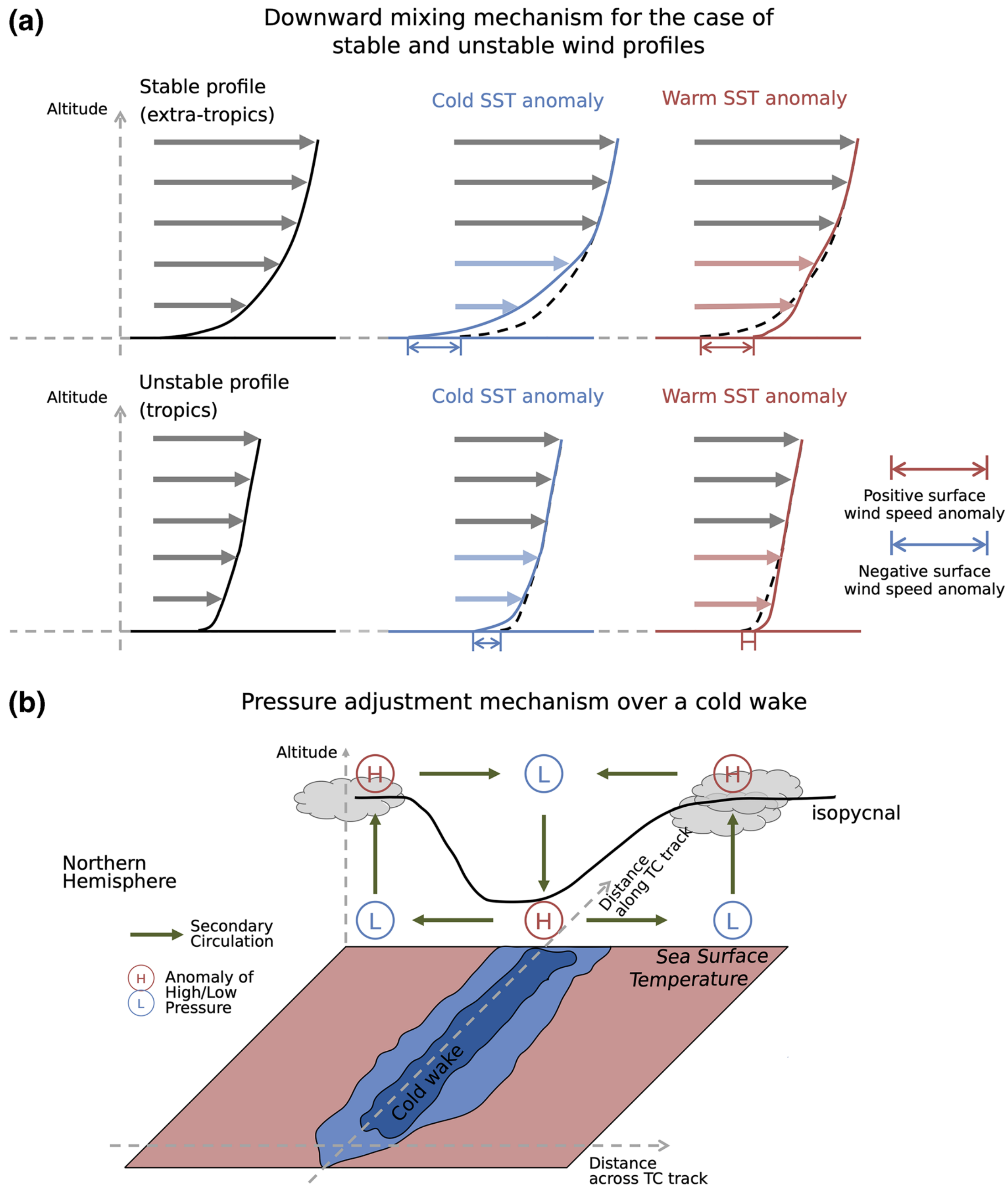

Figure 2. (a) Schematic of the effect of the downward momentum mixing mechanism for stable (top panel) and unstable (bottom panel) background atmospheric conditions. The blue (middle panel) and red (right panel) profiles correspond to an atmosphere over cold and warm SST anomalies, respectively. The thick arrows represent the wind at different altitudes and the double-headed arrows highlight the surface wind speed response induced by the mechanism. (b) Schematic of the pressure adjustment mechanism over a cold wake. The diagram is shown respect to the across and along tropical cyclone track axis and the diagram sketches atmospheric and oceanic conditions after the passage of the storm. The colored surface represents the sea interface with warm (red) and cold (blue) SST, the thick green arrow the secondary atmospheric circulation driven by anomalous high/low pressure cells (denoted with H and L, respectively). SST, sea surface temperature.

a reduction of the turbulent mixing in the marine atmospheric boundary layer in the presence of a cold SST anomaly (downward momentum mixing mechanism).

In the Z. Ma et al. (2020) analysis, the anomalous winds clearly show the presence of a strong surface wind divergence centered along the line of maximum SST anomaly in the cold wake (see their Figure 2d). This is consistent with the action of the pressure adjustment mechanism and induces downward motion above the cold wake, reducing cloud cover and rainfall. Rather than being a direct effect of the reduction in surface sensible and latent heat fluxes from the ocean into the atmosphere, the presence of an anomalously clear sky can thus be an indirect effect, through the generation of a high surface pressure anomaly over the cold wake. The pressure adjustment mechanism has been invoked in the previous studies to explain the increased wind convergence over SST maxima observed in the tropical western Pacific Ocean (Li & Carbone, 2012), the modeled enhanced convection over warm eddies in the tropical Indian Ocean (Skyllingstad et al., 2019), and the origin of the rainfall band anchored along the Gulf Stream (Minobe et al., 2008).

It is thus clear that the thermal coupling between small-scale SST structures and surface winds can be affected by both mechanisms. Trying to understand which of the two dominates in what conditions, Foussard et al. (2019) performed a numerical investigation in idealized settings and concluded that the relative importance of the two mechanisms depends on the background atmospheric stability. We notice that this is in line with the results published in the (small but growing) literature and mentioned above: the pressure adjustment mechanism tends to dominate in the tropical regions, where atmospheric stability is marginal or weak and the surface winds are not effectively decoupled from the winds aloft, while the downward momentum mixing dominates in the midlatitudes to high latitudes, where the lower troposphere is stable and the SST effectively affects the magnitude of the surface winds (see Figure 2a). Indeed, the positive correlation between small-scale SST and wind speed (an indication of the action of the downward momentum mixing) is evident in the extratropics but not in most of the low latitudes (see Figure 1b), suggesting that other mechanisms come into play near the equator. The tropical regions with a positive correlation between small-scale winds and SST are the ones next to upwelling regions, characterized by a larger atmospheric stability of the air column above compared to the rest of the tropics. It is worth noticing that particularly cold tropical cyclone wakes can lower the surface air buoyancy so much that an effective decoupling of the surface winds from the winds aloft might happen: the downward momentum mixing can be dominant even in the tropics, provided that the surface anomaly is cold enough. This argument is supported by the study of the response to two strong typhoons in the western Pacific Ocean that showed a surface wind reduction over the cold waters of the wakes (Lin et al., 2003). Further studies will be needed to fully disentangle the air-sea feedbacks operating at the small spatial and temporal scales.

5. Relevance for Climate Studies

There is growing evidence of the fact that small-scale patterns in SST affect the marine atmospheric boundary layer and the troposphere dynamics, modifying winds, cloud cover, and rainfall. Air-sea heat and gas exchanges depend nonlinearly on surface winds and SST, indicating that their covariability impacts the mean fluxes. A reliable partitioning of energy and gasses between ocean and atmosphere in the evolution of the Earth system requires a full understanding of the relevant mechanisms at the base of their coupled variability. This task calls for the collection of a larger number of joint atmosphere and ocean observations at the surface, to cover a range of different situations that can be linked with different coupling mechanisms.

The study by Z. Ma et al. (2020) clearly shows how the tropical cyclone cold wakes locally reduce cloud cover. In the tropical regions, clear skies have a net surface warming effect, as the abundant solar radiation can better penetrate the atmosphere and reach the surface. Further studies allowing to get both a local radiative budget during the passage of the cyclone and in the cold wake, and a seasonal basinwide radiative budget will allow us to better understand the effects of tropical cyclones onto the overall energy budget of the planet, and possibly to infer how changes in their properties feedback onto the climate system.

Finally, we mention that cold surface wakes are associated with warm subsurface anomalies. They form when the mixed layer deepens in response to the strong winds. The evolution of the anomalous subsurface heat content, which can impact local stratification and ocean transport for long times (Korty et al., 2008; Mei et al., 2013), certainly depends on the air-sea fluxes (Mei & Pasquero, 2012): a reduced evaporation, for instance, can limit the buoyancy loss from the surface layer, effectively isolating the warm subsurface water from the cold surface and favoring its persistence. The magnitude of this effect has still to be quantified in order to understand whether or not a change in tropical cyclone characteristics could impact the storage of heat in the upper ocean.

Data Availability Statement

ERA5 single level monthly mean data are publicly available on the Copernicus Climate Data Store at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means.

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References

Chelton, D. B., Schlax, M. G., Freilich, M. H., & Milliff, R. F. (2004). Satellite measurements reveal persistent small-scale features in ocean winds. *Science*, *303*(5660), 978–983.

Chen, X., & Zhang, F. (2019). Development of a convection-permitting air–sea-coupled ensemble data assimilation system for tropical cyclone prediction. *Journal of Advances in Modeling Earth Systems*, *11*, 3474–3496. https://doi.org/10.1029/2019MS001795

Chiang, T.-L., Wu, C.-R., & Oey, L.-Y. (2011). Typhoon Kai-Tak: An ocean's perfect storm. *Journal of Physical Oceanography*, *41*(1), 221–233.

Courtney, J. B., Langlade, S., Sampson, C. R., Knaff, J. A., Birchard, T., Barlow, S., et al. (2019). Operational perspectives on tropical cyclone intensity change part 1: Recent advances in intensity guidance. *Tropical Cyclone Research and Review*, *8*(3), 123–133.

Cronin, M. F., Gentemann, C. L., Edson, J., Ueki, I., Bourassa, M., Brown, S., et al. (2019). Air-sea fluxes with a focus on heat and momentum. *Frontiers in Marine Science*, *6*, 430. https://doi.org/10.3389/fmars.2019.00430

Dare, R. A., & McBride, J. L. (2011). Sea surface temperature response to tropical cyclones. *Monthly Weather Review*, *139*(12), 3798–3808.

D'Asaro, E. A., Sanford, E. B., Niiler, P. P., & Terrill, E. J. (2007). Cold wake of hurricane Frances. *Geophysical Research Letters*, *34*, L15609. https://doi.org/10.1029/2007GL030160

Emanuel, K., DesAutels, C., Holloway, C., & Korty, R. (2004). Environmental control of tropical cyclone intensity. *Journal of the Atmospheric Sciences*, *61*(7), 843–858.

Foussard, A., Lapeyre, G., & Plougonven, R. (2019). Response of surface wind divergence to mesoscale SST anomalies under different wind conditions. *Journal of the Atmospheric Sciences*, *76*(7), 2065–2082.

Frenger, I., Gruber, N., Knutti, R., & Münnich, M. (2013). Imprint of southern ocean eddies on winds, clouds and rainfall. *Nature Geoscience*, *6*(8), 608–612.

Gaube, P., Chickadel, C., Branch, R., & Jessup, A. (2019). Satellite observations of SST-induced wind speed perturbation at the oceanic submesoscale. *Geophysical Research Letters*, *46*, 2690–2695. https://doi.org/10.1029/2018GL080807

Gentemann, C. L., Clayson, C. A., Brown, S., Lee, T., Parfitt, R., Farrar, J. T., et al. (2020). FluxSat: Measuring the ocean–atmosphere turbulent exchange of heat and moisture from space. *Remote Sensing*, *12*(11), 1796. https://doi.org/10.3390/rs12111796

Hayes, S. P., McPhaden, M. J., & Wallace, J. M. (1989). The influence of sea surface temperature on surface wind in the eastern equatorial Pacific. *Journal of Climate*, *2*, 1500–1506.

Jansen, M., & Ferrari, R. (2009). Impact of the latitudinal distribution of tropical cyclones on ocean heat transport. *Geophysical Research Letters*, *36*, L06604. https://doi.org/10.1029/2008GL036796

Korty, R. L., Emanuel, K. A., & Scott, J. R. (2008). Tropical cyclone–induced upper-ocean mixing and climate: Application to equable climates. *Journal of Climate*, *21*(4), 638–654.

Laurindo, L. C., Siqueira, L., Mariano, A. J., & Kirtman, B. P. (2019). Cross-spectral analysis of the SST/10-m wind speed coupling resolved by satellite products and climate model simulations. *Climate Dynamics*, *52*(9–10), 5071–5098.

Li, Y., & Carbone, R. (2012). Excitation of rainfall over the tropical western Pacific. *Journal of the Atmospheric Sciences*, *69*(10), 2983–2994.

Lin, I.-I., Black, P., Price, J. F., Yang, C.-Y., Chen, S. S., Lien, C.-C., et al. (2013). An ocean coupling potential intensity index for tropical cyclones. *Geophysical Research Letters*, *40*, 1878–1882. https://doi.org/10.1002/grl.50091

Lindzen, R. S., & Nigam, S. (1987). On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. *Journal of the Atmospheric Sciences*, *44*(17), 2418–2436.

Lin, I.-I., Liu, W. T., Wu, C.-C., Chiang, J. C. H., & Sui, C.-H. (2003). Satellite observations of modulation of surface winds by typhoon-induced upper ocean cooling. *Geophysical Research Letters*, *30*(3), 1131. https://doi.org/10.1029/2002GL015674

Ma, Z., Fei, J., Lin, Y., & Huang, X. (2020). Modulation of clouds and rainfall by tropical cyclone's cold wakes. *Geophysical Research Letters*, *47*, e2020GL088873. https://doi.org/10.1029/2020GL088873

Ma, J., Xu, H., Dong, C., Lin, P., & Liu, Y. (2015). Atmospheric responses to oceanic eddies in the Kuroshio extension region. *Journal of Geophysical Research: Atmospheres*, *120*, 6313–6330. https://doi.org/10.1002/2014JD022930

Mei, W., & Pasquero, C. (2012). Restratification of the upper ocean after the passage of a tropical cyclone: A numerical study. *Journal of Physical Oceanography*, *42*(9), 1377–1401.

Mei, W., & Pasquero, C. (2013). Spatial and temporal characterization of sea surface temperature response to tropical cyclones. *Journal of Climate*, *26*(11), 3745–3765.

Mei, W., Primeau, F., McWilliams, J. C., & Pasquero, C. (2013). Sea surface height evidence for long-term warming effects of tropical cyclones on the ocean. *Proceedings of the National Academy of Sciences*, *110*(38), 15207–15210.

Mei, W., Xie, S.-P., Primeau, F., McWilliams, J. C., & Pasquero, C. (2015). Northwestern Pacific typhoon intensity controlled by changes in ocean temperatures. *Science Advances*, *1*(4), e1500014.

Minobe, S., Kuwano-Yoshida, A., Komori, N., Xie, S.-P., & Small, R. J. (2008). Influence of the gulf stream on the troposphere. *Nature*, *452*(7184), 206–209.

Price, J. F. (1981). Upper ocean response to a hurricane. *Journal of Physical Oceanography*, *11*, 153–175. https://doi.org/10.1175/1520-0485(1981)011<0153:UORTAH>2.0.CO;2

Price, J. F., Morzel, J., & Niiler, P. P. (2008). Warming of SST in the cool wake of a moving hurricane. *Journal of Geophysical Research*, *113*, C07010. https://doi.org/10.1029/2007JC004393

Renault, L., Masson, S., Oerder, V., Jullien, S., & Colas, F. (2019). Disentangling the mesoscale ocean–atmosphere interactions. *Journal of Geophysical Research: Oceans*, *124*, 2164–2178. https://doi.org/10.1029/2018JC014628

Sanford, T. B., Price, J. F., Girton, J. B., & Webb, D. C. (2007). Highly resolved observations and simulations of the ocean response to a hurricane. *Geophysical Research Letters*, *34*, L13604. https://doi.org/10.1029/2007GL029679

Shao, M., Ortiz-Suslow, D. G., Haus, B. K., Lund, B., Williams, N. J., Özgökmen, T. M., et al. (2019). The variability of winds and fluxes observed near submesoscale fronts. *Journal of Geophysical Research: Oceans*, *124*, 7756–7780. https://doi.org/10.1029/2019JC015236

Skyllingstad, E. D., de Szoeke, S. P., & O'Neill, L. W. (2019). Modeling the transient response of tropical convection to mesoscale SST variations. *Journal of the Atmospheric Sciences*, *76*(5), 1227–1244. https://doi.org/10.1175/JAS-D-18-0079.1

Wallace, J. M., Mitchell, T. P., & Deser, C. (1989). The influence of sea surface temperature on surface wind in the eastern equatorial Pacific: Seasonal and interannual variability. *Journal of Climate*, *2*, 1492–1499.