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INTRODUCTION TO A SPECIAL SECTION

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Special Section:
Oceanic Responses and Feedbacks to Tropical Cyclones

Key Points:
- The special section on ocean-TC interaction in JGR-Oceans is introduced
- Papers in the special section are briefly reviewed and some papers are highlighted
- Challenges and suggestions for further studies in ocean-TC interactions are presented

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Introduction to Special Section on Oceanic Responses and Feedbacks to Tropical Cyclones

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Abstract Tropical cyclones (TCs) are among the most destructive natural hazards on Earth. The ocean can have dramatic responses to TCs and further imposes significant feedbacks to the atmosphere. A comprehensive understanding of the ocean-TC interaction is a challenging hindrance for improving the simulation and prediction of TCs and therefore avoidance of human and economic losses. A special section of *JGR-Oceans* was thus organized, in order to have a broad summary of latest progress in ocean-TC interactions. This introduction presents a brief overview of the contributions found in this collection. We hope it can also shed light on recent advance and future challenges in the studies on the oceanic responses and feedbacks to TCs.

Tropical cyclones (TCs) are one of the most extreme weather events, which cause tremendous disasters to nations across the globe including the heavily populated coastlines of Asia and North America. Improving the understanding, simulation, and forecast of TCs is a scientific and social imperative. It is well known that the upper ocean exhibits pronounced responses to TCs. However, many of the detailed processes and physical mechanisms governing such responses remain a mystery. In addition, the ocean has complicated feedbacks to TCs, which can leave clear fingerprints on the intensity, track, and the long-term variability of TCs. Therefore, a special collection in the *Journal of Geophysical Research: Oceans* on Oceanic Responses and Feedbacks to TCs was organized in 2016 and 2017. The special collection received more than 70 submissions and about 30 papers have been published so far. Papers included in this international special collection cover a broad topic of the ocean-TC interactions, such as, but not limited to, the physical mechanism for ocean-TC interactions, ocean-TC interactions in the context of climate change, the data assimilation techniques and TC prediction using coupled models, and other related interdisciplinary studies such as coastal environments (Seroka et al., 2017; Shen et al., 2017), biochemical (Xu et al., 2017; Zhao et al., 2017), and geological (Lin et al., 2018) processes associated with TCs. This introduction is not a comprehensive review of recent progress in ocean-TC interaction, but a brief introduction to some highlights in this special section.

Observations, especially those synchronized across the ocean and atmosphere, are still the major challenge for making breakthroughs on ocean-TC interactions due to the prohibitively harsh working environment associated with TCs. Data are gradually accumulated from isolated stations and individual TC events, such as the ones reported in Duan et al. (2017), Lee et al. (2017), and Blair et al. (2018) in this collection. Remote sensing has been a routine method to monitor TCs and oceanic variabilities, but technological limitations inhibit some satellite sensors from fully observing the ocean and atmosphere in TC conditions (heavy clouds and rainfall, high wind speeds, etc.). New techniques and algorithms are continuously proposed to improve the retrieval of TC properties from Earth orbiting satellites; for example, Shao et al. (2017) improved estimation of TC wind speeds by exploiting wind-generated waves extracted from spaceborne synthetic aperture radar (SAR). Intensive and well-organized projects are usually an auspice of significant progress in the ocean-TC studies, such as the Coupled Boundary Layer Air-Sea Transfer (CBLAST) experiment (Black et al., 2007) and the Impact of Typhoons on the Ocean in the Pacific (ITOP) project (Collins et al., 2018; D'Asaro et al., 2014; Potter et al., 2017). Recently, in order to collect a chronic and three-dimensional perspective on changes to the water column during TCs, a series of mooring/buoy arrays are deployed in the northern South China Sea (Zhang et al., 2016a) where historical statistics show that typhoon has the highest occurrence probability. A novel approach using rocket-deployed dropsondes is designed and tested to obtain vertical profiles in the atmosphere within a TC (Lei et al., 2017). Comparing with the aircraft platform, a rocket can fly higher (up to 15 km above the sea surface) and faster (traversing a TC in about 6 min), so that the vertical profiles are more complete and more simultaneous. Synthesizing the rocket-based observations and traditional mooring/buoy arrays in the ocean, it is expected to build up an observing system which can capture coherent variations across the ocean and atmosphere during TCs. Other adaptive technologies such as the Iridium Argos and glider arrays have already made the TC chase more flexible and agile over the ocean.

The ocean has complex responses to the passage of a TC. Near-inertial waves are a well-known consequence in the ocean due to TC forcing. However, since mesoscale eddies account for almost 90% kinetic energy in the upper ocean (Ferrari & Wunsch, 2009), the responses and feedbacks of oceanic eddies to TCs become the focus of the local ocean-TC interactions, which can be clearly seen from the papers in this collection. Although eddies apparently have a large variance in all properties, a universal structure can be established for the cyclonic and anticyclonic eddies separately, by normalizing the eddy properties against the background environment (Sun et al., 2017; Zhang et al., 2014). Cyclonic and anticyclonic ocean eddies have different behaviors during TCs. Usually, anticyclonic eddies carry warm sea surface temperature (SST) anomalies and are favorable for the rapid intensification of TCs (Mawren & Reason, 2017). In addition to the surface heat flux, the horizontal convergence/divergence induced by eddies are also large enough to modify the temperature and salinity anomalies induced by TCs (Liu et al., 2017), which indicates that a three-dimensional ocean structure and horizontal advection are inevitable to have a comprehensive understanding of the oceanic responses to TCs. Below the upper ocean mixed layer, cold water rises due to the Ekman pumping (Zhang et al., 2016a) and a secondary cooling center is found in both the cyclonic and anticyclonic eddies but at different depths. As a result, the stability of the upper ocean is modified and the ocean mixing can be significantly increased, which ultimately have feedbacks to TCs.

In addition to the local responses and feedbacks, the ocean also interacts with TCs at much larger and longer spatiotemporal scales. Strong disturbance during TCs is an efficient way to deluge the ocean interior with heat and kinetic energy. The energy input heavily depends on the oceanic and atmospheric environment (such as the barrier layer in the upper ocean and the moving speed of a TC; Yan et al., 2017) and the climate states (such as El Niño and La Niña; Huang et al., 2017). The TC-originated energy spreads over the ocean along with the general circulation, and subsequently modifies its vertical stratification and dynamics (Zhang et al., 2017b). On the other hand, the long-term statistical properties of TCs are subject to the upper ocean heat content (Fedorov et al., 2010; Sriver & Huber, 2007). The depth of 26°C isotherm is a commonly used proxy of the upper ocean heat content, as shown with the Ocean Observing System Simulation Experiments (Halliwell et al., 2017). A new genesis potential index (GPI) for TCs is established by explicitly involving the depth of 26°C isotherm, which represents the variance in the ocean interior (Zhang et al., 2016b). The new GPI provides a quantitative tool for the evaluation of the oceanic feedback to TCs at a low frequency.

Finally, the improvement of TC simulation in fully coupled Earth system models is a major challenge. Due to the close relations between the oceanic eddies and TCs, an eddy-resolving ocean model is necessary for further improvement of TC simulation. In this collection, Zhao and Chan (2018) evaluated the influences of oceanic eddies on the simulated TC intensity by comparing coupled and uncoupled models. Li and Sriver (2016) examined global ocean responses to TCs with different model resolutions and found that TCs can significantly contribute to global ocean heat and energy budgets. Similarly, Mogensen et al. (2017) tested the ocean simulations during TCs using a coupled European Centre for Medium-Range Weather Forecasts (ECMWF) model with different resolutions. They confirmed that the upper ocean stratification is critical for the oceanic feedbacks to TCs. Specifically, a strong (weak) coupled feedback is found when the ocean heat content of the upper layer is low (high). In addition to the high-resolution which can resolve eddies, some other small-scale processes also play important roles for the ocean-TC interactions, such as the sea surface waves and sea spray (Zhang et al., 2017a). Therefore, designing and adopting appropriate parameterizations for the subgrid processes, which have smaller scales than the state-of-the-art eddy-resolving models can capture, are critical for a vivid simulation of oceanic responses to TCs. For example, Aijaz et al. (2017) considered the turbulence generated by nonbreaking waves by adopting a new parameterization in an ocean-atmosphere-wave-coupled model and Blair et al. (2018) examined the influences of the state-dependent Langmuir turbulence by modifying the classical K-Profile parameterization scheme. Along with the improvement in TC simulation, TC forecast has also achieved much progress by using coupled models and advanced data assimilation technics (Wada & Kunii, 2017). For instance, in this collection, a three-dimensional adjoint targeting approach was applied to examine the impact of ocean observations on TC forecast errors in a coupled prediction system (Chen et al., 2017) and the results emphasized the necessity of targeted observations and ocean eddies for TC prediction.

In summary, ocean-TC interactions are of both scientific and socioeconomic importance, and the depth of this special section is a testament to the energy of the international scientific community addressing the challenge. Although much progress has been made, some key challenges still remain for understanding fundamental mechanisms, simulation and data assimilation technologies, and operational forecast systems. Papers in this special section provide an outline of the contemporary advance in ocean-TC interactions, and meanwhile raise many serious issues requiring more investigations in the future. Studies in this collection emphasize the necessities of both the fully coupled climate models with a high enough ocean resolution and better parameterizations for unresolved processes. Along with the fast increasing power of super computers (and probably cloud computing as well), until now, resolutions have become high enough to permit TCs in an atmosphere model (Zhao & Held, 2012) and to resolve mesoscale eddies in an ocean model. An eddy-resolving ocean model should be preferred if the computing resources allow. In addition, many processes (such as the ocean waves, mixing, and sea spray), which are critical for the oceanic feedbacks to TCs, are too small to be resolved given current computing ability. Thus, better parameterizations for such subgrid (even smaller than the eddy-resolving scale) processes are highly required based on delicate observations and careful analyses. With the continuous boost in computing power, it is for sure that model (including the atmosphere, ocean, wave components, and maybe others) resolutions will become higher and more processes will be directly resolved in the future. Nevertheless, since the ocean and TCs have inseparable interactions over very wide spatiotemporal scales, it is also very likely that the effects of more fine-scale processes (for example, the ones related to the air-sea fluxes and probably something that has not been well known to people so far) will be unveiled as a result of the in-depth process studies. Therefore, it is hardly doubtful that progress on parameterization will be still necessary for a long time. Hence, we believe a coupled model with high resolutions and advanced parameterizations should be a desired test bed for promoting the studies on ocean-TC interactions.

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References

Aijaz, S., Ghantous, M., Babanin, A. V., Ginis, I., Thomas, B., & Wake, G. (2017). Nonbreaking wave-induced mixing in upper ocean during tropical cyclones using coupled hurricane-ocean-wave modeling. *Journal of Geophysical Research: Oceans*, *122*, 3939–3963. https://doi.org/10.1002/2016JC012219

Black, P. G., D'Asaro, E. A., Sanford, T. B., Drennan, W. M., Zhang, J. A., French, J. R., et al. (2007). Air–sea exchange in hurricanes: Synthesis of observations from the coupled boundary layer air–sea transfer experiment. *Bulletin of the American Meteorological Society*, *88*, 357–374.

Blair, A., Ginis, I., Hara, T., & Ulhorn, E. (2018). Impact of Langmuir turbulence on upper ocean response to Hurricane Edouard: Model and observations. *Journal of Geophysical Research: Oceans*, *122*, 9712–9724. https://doi.org/10.1002/2017JC012956

Chen, S., Cummings, J. A., Schmidt, J. M., Sanabia, E. R., & Jayne, S. R. (2017). Targeted ocean sampling guidance for tropical cyclones. *Journal of Geophysical Research: Oceans*, *122*, 3505–3518. https://doi.org/10.1002/2017JC012727

Collins, C. O., Potter, H., Lund, B., Tamura, H., & Graber, H. C. (2018). Directional wave spectra observed during intense tropical cyclones. *Journal of Geophysical Research: Oceans*, *123*. https://doi.org/10.1002/2017JC012943

D'Asaro, E. A., Black, P. G., Centurioni, L. R., Chang, Y.-T., Chen, S. S., Foster, R. C., et al. (2014). Impact of Typhoons on the Ocean in the Pacific. *Bulletin of the American Meteorological Society*, *95*, 1405–1418.

Duan, Z., Yao, X., Li, Y., Lei, X., Fang, P., & Zhao, B. (2017). Investigation of turbulent momentum flux in the typhoon boundary layer. *Journal of Geophysical Research: Oceans*, *122*, 2259–2268. https://doi.org/10.1002/2016JC012169

Fedorov, A. V., Brierley, C. M., & Emanuel, K. (2010). Tropical cyclones and permanent El Niño in the early Pliocene epoch. *Nature*, *463*, 1066–1070.

Ferrari, R., & Wunsch, C. (2009). Ocean circulation kinetic energy: Reservoirs, sources, and sinks. *Annual Review of Fluid Mechanics*, *41*, 253–282.

Halliwell, G. R., Mehari, M., Shay, L. K., Kourafalou, V. H., Kang, H., Kim, H.-S., et al. (2017). OSSE quantitative assessment of rapid-response prestorm ocean surveys to improve coupled tropical cyclone prediction. *Journal of Geophysical Research: Oceans*, *122*, 5729–5748. https://doi.org/10.1002/2017JC012760

Huang, H.-C., Boucharel, J., Lin, I. I., Jin, F.-F., Lien, C.-C., & Pun, I.-F. (2017). Air-sea fluxes for Hurricane Patricia (2015): Comparison with supertyphoon Haiyan (2013) and under different ENSO conditions. *Journal of Geophysical Research: Oceans*, *122*, 6076–6089. https://doi.org/10.1002/2017JC012741

Lee, J. H., Moon, I.-J., Moon, J.-H., Kim, S.-H., Jeong, Y. Y., & Koo, J.-H. (2017). Impact of typhoons on the Changjiang plume extension in the Yellow and East China Seas. *Journal of Geophysical Research: Oceans*, *122*, 4962–4973. https://doi.org/10.1002/2017JC012754

Lei, X., Lei, M., Zhao, B. K., Wang, J., Tang, J., Gao, H. W., et al. (2017). New technology and experiment of rocket dropsondes for typhoon observation [in Chinese]. *Chinese Science Bulletin*, *62*, 3789–3796.

Li, H., & Sriver, R. L. (2016). Effects of ocean grid resolution on tropical cyclone-induced upper ocean responses using a global ocean general circulation model. *Journal of Geophysical Research: Oceans*, *121*, 8305–8319. https://doi.org/10.1002/2016JC011951

Lin, J., Lin, J., & Xu, M. (2018). Microseisms generated by Super Typhoon Megi in the Western Pacific Ocean. *Journal of Geophysical Research: Oceans*, *122*, 9518–9529. https://doi.org/10.1002/2017JC013310

Liu, S.-S., Sun, L., Wu, Q., & Yang, Y.-J. (2017). The responses of cyclonic and anticyclonic eddies to typhoon forcing: The vertical temperature-salinity structure changes associated with the horizontal convergence/divergence. *Journal of Geophysical Research: Oceans*, *122*, 4974–4989. https://doi.org/10.1002/2017JC012814

Mawren, D., & Reason, C. J. C. (2017). Variability of upper-ocean characteristics and tropical cyclones in the South West Indian Ocean. *Journal of Geophysical Research: Oceans*, *122*, 2012–2028. https://doi.org/10.1002/2016JC012028

Mogensen, K. S., Magnusson, L., & Bidlot, J.-R. (2017). Tropical cyclone sensitivity to ocean coupling in the ECMWF coupled model. *Journal of Geophysical Research: Oceans*, *122*, 4392–4412. https://doi.org/10.1002/2017JC012753

Potter, H., Drennan, W. M., & Graber, H. C. (2017). Upper ocean cooling and air-sea fluxes under typhoons: A case study. *Journal of Geophysical Research: Oceans*, *122*, 7237–7252. https://doi.org/10.1002/2017JC012954

Seroka, G., Miles, T., Xu, Y., Kohut, J., Schofield, O., & Glenn, S. (2017). Rapid shelf-wide cooling response of a stratified coastal ocean to hurricanes. *Journal of Geophysical Research: Oceans*, *122*, 4845–4867. https://doi.org/10.1002/2017JC012756

Shao, W., Li, X., Hwang, P., Zhang, B., & Yang, X. (2017). Bridging the gap between cyclone wind and wave by C-band SAR measurements. *Journal of Geophysical Research: Oceans*, *122*, 6714–6724. https://doi.org/10.1002/2017JC012908

Shen, J., Qiu, Y., Zhang, S., & Kuang, F. (2017). Observation of tropical cyclone-induced shallow water currents in Taiwan Strait. *Journal of Geophysical Research: Oceans*, *122*, 5005–5021. https://doi.org/10.1002/2017JC012737

Sriver, R. L., & Huber, M. (2007). Observational evidence for an ocean heat pump induced by tropical cyclones. *Nature*, *447*, 577–580.

Sun, W., Dong, C., Wang, R., Liu, Y., & Yu, K. (2017). Vertical structure anomalies of oceanic eddies in the Kuroshio Extension region. *Journal of Geophysical Research: Oceans*, *122*, 1476–1496. https://doi.org/10.1002/2016JC012226

Wada, A., & Kunii, M. (2017). The role of ocean-atmosphere interaction in Typhoon Sinlaku (2008) using a regional coupled data assimilation system. *Journal of Geophysical Research: Oceans*, *122*, 3675–3695. https://doi.org/10.1002/2017JC012750

Xu, F., Yao, Y., Oey, L., & Lin, Y. (2017). Impacts of pre-existing ocean cyclonic circulation on sea surface chlorophyll-a concentrations off northeastern Taiwan following episodic typhoon passages. *Journal of Geophysical Research: Oceans*, *122*, 6482–6497. https://doi.org/10.1002/2016JC012625

Yan, Y., Li, L., & Wang, C. (2017). The effects of oceanic barrier layer on the upper ocean response to tropical cyclones. *Journal of Geophysical Research: Oceans*, *122*, 4829–4844. https://doi.org/10.1002/2017JC012694

Zhang, H., Chen, D., Zhou, L., Liu, X., Ding, T., & Zhou, B. (2016a). Upper ocean response to typhoon Kalmaegi (2014). *Journal of Geophysical Research: Oceans*, *121*, 6520–6535. https://doi.org/10.1002/2016JC012064

Zhang, L., Zhang, X., Chu, P. C., Guan, C., Fu, H., Chao, G., et al. (2017a). Impact of sea spray on the Yellow and East China Seas thermal structure during the passage of Typhoon Rammasun (2002). *Journal of Geophysical Research: Oceans*, *122*, 7783–7802. https://doi.org/10.1002/2016JC012592

Zhang, M., Zhou, L., Chen, D., & Wang, C. (2016b). A genesis potential index for Western North Pacific tropical cyclones by using oceanic parameters. *Journal of Geophysical Research: Oceans*, *121*, 7176–7191. https://doi.org/10.1002/2016JC011851

Zhang, Z., Wang, W., & Qiu, B. (2014). Oceanic mass transport by mesoscale eddies. *Science*, *345*, 322–324.

Zhang, Z., Zhang, Y., & Wang, W. (2017b). Three-compartment structure of subsurface-intensified mesoscale eddies in the ocean. *Journal of Geophysical Research: Oceans*, *122*, 1653–1664. https://doi.org/10.1002/2016JC012376

Zhao, H., Pan, J., Han, G., Devlin, A. T., Zhang, S., & Hou, Y. (2017). Effect of a fast-moving tropical storm Washi on phytoplankton in the northwestern South China Sea. *Journal of Geophysical Research: Oceans*, *122*, 3404–3416. https://doi.org/10.1002/2016JC012286

Zhao, M., & Held, I. M. (2012). TC-permitting GCM simulations of hurricane frequency response to sea surface temperature anomalies projected for the late-twenty-first century. *Journal of Climate*, *25*, 2995–3009.

Zhao, X., & Chan, J. C. L. (2018). Effect of the initial vortex size on intensity change in the WRF-ROMS coupled model. *Journal of Geophysical Research: Oceans*, *122*, 9636–9648. https://doi.org/10.1002/2017JC013283