# Atmospheric Convection and Air-Sea Interactions over the Tropical Oceans: Scientific Progress, Challenges and Opportunities

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**Atmospheric Convection and Air-sea Interactions over the Tropical Oceans**

**What:** 90 observational and modeling experts met to review and document progress, identify outstanding issues, and propose approaches for future integrated process studies in atmospheric convection and air-sea interactions over the tropical oceans.

**When:** May 7-9 2019

**Where:** Boulder CO, USA

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## Introduction

Over the past thirty years, the scientific community has made considerable progress in understanding and predicting tropical convection and air-sea interactions, thanks to sustained investments in extensive in-situ and remote sensing observations, targeted field experiments, advances in numerical modeling, and vastly improved computational resources and observing technologies. Those investments would not have been fruitful as isolated advancements without the collaborative effort of the atmospheric convection and air-sea interaction research communities. In this spirit, a U.S. and International CLIVAR-sponsored workshop on "Atmospheric convection and air-sea interactions over the tropical oceans" was held May 7-9, 2019 in Boulder, CO. The 90 participants were observational and modeling experts from the atmospheric convection and air-sea interactions communities with varying degrees of experience, from early-career researchers and students to senior scientists. The presentations and discussions covered processes over the broad range of spatio-temporal scales (Fig. 1).

## Key Topics and Results

The workshop identified key areas where progress has been made over the last 30 years. There has been tremendous progress in our understanding of atmospheric convection and air-sea interaction, much more than can be summarized in this report. Therefore, this report will discuss only a sample of results most relevant to key science questions and recommendations. Through sustained observations and experiments with a hierarchy of models of varying complexity, the key dynamical processes underlying different flavors of the El Nino Southern Oscillation (ENSO) have been elucidated. In particular, vertical advection of subsurface temperature anomalies (i.e., thermocline feedback) has been identified as the key mechanism for sea surface temperature (SST)



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variations over the eastern equatorial Pacific, where the thermocline is normally shallower (Capatondi et al. 2015), whilezonal advection near the eastern edge of the warm pool appears to be most relevant to central Pacific warming. There has also been much progress in our understanding of the Madden-Julian Oscillation (MJO) propagation mechanisms. Specifically, it has been shown that horizontal advection of the background lower-tropospheric moisture by MJO circulation plays a critical role in driving the eastward propagation of the MJO (e.g., Kim et al. 2014; 2017). Furthermore, observational and modeling studies over the last 30 years have improved our quantitative understanding of the oceans and air-sea interactions associated with the MJO, such as their role in amplifying MJO variability and maintaining its strength (DeMott et al. 2015). Thanks to significant improvements in radar technology, observations of shallow clouds, cumulus congestus, deep clouds, and organized mesoscale convective systems have greatly advanced over the last 30 years (Houze et al. 2019). Progress also includes a better understanding of the three-dimensional structure of precipitation, mesoscale air motions, and hydrometeors in these clouds, and the spatial distribution and temporal variability of non-precipitating clouds. Similarly, technical advances in ocean observations have revealed that the vertical distributions of salinity and temperature in the upper ocean play important roles in air-sea fluxes and the MJO evolution. By suppressing vertical mixing and entrainment cooling from the subsurface, salinity-stratified barrier layers can trap heat and momentum in the upper oceans and amplify the effects of westerly wind bursts on surface currents (Cronin and McPhaden 2002). Through this mechanism, the barrier layer dynamics associated with rainfall, river outflow, and horizontal advection also play a critical role in tropical cyclone intensification and may affect SST and air-sea interactions during the MJO and El Nino onset (Maes et al. 2002, Balaguru et al. 2012, Moum et al. 2014, Maes et al., 2005) .



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In parallel with these advances in scientific understanding, much progress has been made regarding observational and modeling technologies. Modern technology has enabled measurements of the vertical structure of the ocean mixed layer and embedded turbulence, the atmospheric surface and boundary layer, and the troposphere as a whole, though at limited spatial and/or temporal resolution/coverage (Andreas et al. 2015). New remote atmospheric observing technologies include ground and space-borne dual polarization radars, lidars, and millimeter cloud radars. Autonomous sea-surface platforms (e.g., wavegliders, Saildrones, drifters) and unpiloted aerial vehicles (UAVs) equipped with various sensors have begun to collect research quality oceanic and atmospheric observations over an extended range of spatial and temporal scales. These vehicles can perform adaptive sampling to augment measurements from research ships, sometimes at a fraction of the cost. On the modeling front, innovations include convection- and eddy-resolving models, high-resolution regional atmosphere-wave-ocean coupled models, superparameterization, bulk representation of sea-state dependent surface fluxes, bin microphysics, microphysics coupled with aerosols, stochastic perturbation ensembles, and stochastic cloud population models.

Workshop participants highlighted several key gaps in scientific understanding and limitations in technology. The relative roles of momentum and thermodynamic feedbacks in the zonal movement of the western Pacific Ocean warm and fresh pool and their implications for the onset of El Nino need to be quantified. The multi-scale processes affecting variability and predictability of the MJO have yet to be thoroughly understood. Of particular interest for the MJO are its seasonality and relationships with ENSO and the Quasi-biennial Oscillation (QBO), the role of air-sea coupling in its onset and evolution, and the diurnal cycle of precipitation over the Indo-Pacific Maritime Continent. Advancements are needed to improve understanding of the net effect



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of small-scale phenomena (e.g., atmospheric boundary layer response to SST fronts and ocean mesoscale variability, atmospheric cold pools, precipitation- or river-induced surface freshening, cloud microphysics, the coupled atmosphere-wave boundary layer in the presence of swell and wind sea, and entrainment of environmental air into convection) on convection transitions, organization, and the formation of high clouds and their implications for the top of the atmosphere radiative balance. Other key knowledge gaps are the formation and evolution of ocean barrier layers and their potential effects on air-sea interactions at larger spatial scales or longer time scales and under extreme conditions (high winds and rain). In order to address these key science issues, participants noted technological challenges that must be met. For example, satellites still have limitations in observing the near-surface variables (e.g., temperature and humidity) required for accurate estimates of surface turbulent fluxes, a problem that is more exacerbated near coastal areas. The vertical and temporal resolutions of Argo floats are not sufficient to capture the near-surface stratification and diurnal warm layers and its variability. Current measurements of the atmospheric boundary layer structure are mainly from towers that are extremely limited in spatial coverage and from ships that are expensive and allow only short-duration sampling, leaving much of the tropical ocean unsampled.

In making the recommendations for accelerating our scientific understanding of atmospheric convection and air-sea interactions over the tropical oceans, workshop participants noted that the multi-scale nature of the aforementioned challenges requires an innovative and efficient integration between data from sustained observing systems and short and intensive field campaigns that often have a broader range of instrumentation and observing platforms. Furthermore, such integration needs to be informed by existing scientific understanding of the processes of interest and by modeling needs. Preliminary modeling activities and pilot



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observational impact studies are viewed as important requirements for successful integrated new observing systems. To that end, the following recommendations were made.

**Recommendations**

*A tropical observational and modeling "super-site"*

A sustained tropical observational and modeling "supersite" was proposed to facilitate multi-scale integrated modeling and observational studies, including analyses of atmospheric and oceanic heat, freshwater, salinity, and momentum budgets. Extensive data collected from such an integrated observational program would provide valuable input not only to high resolution coupled data assimilation systems and forecast models, but also be very valuable for process studies and model validation and improvement. The key components of this integrated measurement site would be the co-location of field campaign and pilot study instrumentation with the sustained observing system. The key requirements are: large-scale spatial coverage (such as matching satellite footprints and across portions of mooring arrays) in tandem with localized high spatio-temporal resolution measurements of temperature, salinity, and currents in the upper ocean; the measurements of surface winds, waves, and lower-tropospheric variables as well as direct covariance measurements of heat, moisture, and momentum fluxes at the air-sea interface; the 3-D dynamic and thermodynamic structures, cloud, radiation, and aerosol properties in the atmospheric boundary layer and throughout the troposphere, as well as precipitation.

*Investment in aerial and oceanic autonomous vehicles*

The development of properly equipped aerial and oceanic autonomous vehicles is critical for observations over remote tropical oceans. Such vehicles can be augmented by moored bases for power charging and data transfer. Future instruments and platforms could involve a combination of UAVs, surface ocean autonomous vehicles (e.g., wavegliders, Saildrones), and underwater



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gliders, which, as a coordinated autonomous group, could measure profiles of both the atmosphere and upper ocean as well as their interface. Deployment of such autonomous platforms can be optimized by virtual field campaigns that simulate sampling strategies through existing gridded numerical model and satellite products.

*Investment in data preservation, data quality and accessibility*

Significant national and international coordination and investment are required to maintain and curate the collected observational and coupled assimilation datasets. The datasets, including their history, uncertainty, and calibration of the instruments, should be well documented and easily accessible. Providing organized and easily accessible data from all previous tropical field campaigns would increase their use and impact for research and model improvement. It is recommended that a fully supported center or organization create and maintain a searchable database of measurements from previous field campaigns and a user interface that provides simple procedures for combining desired data based on chosen locations, time, instruments, and variables. As applications of machine learning (ML) and artificial intelligence (AI) in research and modeling development expand, the availability of easily accessible and comprehensible high-quality datasets for training and validation of ML and AI algorithms will be critical.

*Effective communication with the general public and policy makers*

Sustained financial investment on the part of the funding agencies will be critical to the success of such an integrated effort. To that end, the societal value of understanding atmospheric convection and air-sea interaction over the tropical oceans and the associated improvement in predictions of high impact weather and climate events at a broad range of time-scales need to be articulated in a way that is easily understandable by the general public and policy makers. The researchers' engagement with the local communities and schools where the measurements are to



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take place, and consideration for the communities' interests such as education and capacity development, are also critical factors for the long-term success of such an endeavor.

*Joint sessions in the broader geosciences society conferences*

The dialogue between the atmospheric convection and air-sea interaction communities needs to be promoted and sustained by holding "atmospheric convection and air-sea interactions over the tropical oceans" sessions and workshops during the regular meetings of scientific societies such as the American Geophysical Union, the American Meteorological Society, the European Geosciences Union, and the Asia-Oceania Geosciences Society. Such continued interactions could provide opportunities for students and early career researchers to engage in tackling potentially rewarding scientific problems at the interface of atmospheric and oceanic sciences.

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**References**

Andreas, E. L, L. Mahrt, and D. Vickers, 2015: An improved bulk air–sea surface flux algorithm, including spray-mediated transfer. *Quart. J. Roy. Meteor. Soc.*, **141**, 642–654

Balaguru, K., P. Chang, R. Saravanan, L. R. Leung, Z. Xu, M. K. Li, and J.-S. Hsieh, 2012: Ocean barrier layers' effect on tropical cyclone intensification. Proc. Nat. Acad. Sci. U.S.A., 109, 14,343-14,347.

Capotondi, A., and Coauthors, 2015: Understanding ENSO diversity. *Bull. Amer. Meteor. Soc.*, **96**, 921–938,

Cronin, M. F., and M. J. McPhaden, Barrier layer formation during westerly wind bursts,J. Geophys. Res.,107(C12), 8020,doi:10.1029/2001JC001171, 2002.



Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0261.1.

DeMott, C. A., N. P. Klingaman, and S. J. Woolnough, 2015: Atmosphere-ocean coupled processes in the Madden-Julian Oscillation. *Rev. Geophys.*, **53**, 1099-1154.

Houze, R. A., Jr., 2019: 100 years of research on mesoscale convective systems. *A Century of Progress in Atmospheric and Related Sciences: Celebrating the American Meteorological Society Centennial*, *Meteor. Monogr.*, No. 59, Amer. Meteor. Soc.,Kim, D., J.-S. Kug, and A. H. Sobel, 2014: Propagating versus non-propagating Madden–Julian oscillation events. J. Climate, 27, 111–125.

Maes, C., J. Picaut, and S. Belamari, 2002: Salinity barrier layer and onset of El Nino in a Pacific coupled model. Geophys. Res. Lett., 29, 2206, doi:10.1029/2002GL016029.

Maes, C., J. Picaut, and S. Belamari, 2005: Importance of the salinity barrier layer for the buildup of El Nino. J. Climate, 18, 104-118.

Moum, J. N., and Coauthors, 2014: Air–Sea Interactions from Westerly Wind Bursts During the November 2011 MJO in the Indian Ocean. *Bull. Am. Meteorol. Soc.*, **95**, 1185-1199.



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## Figures

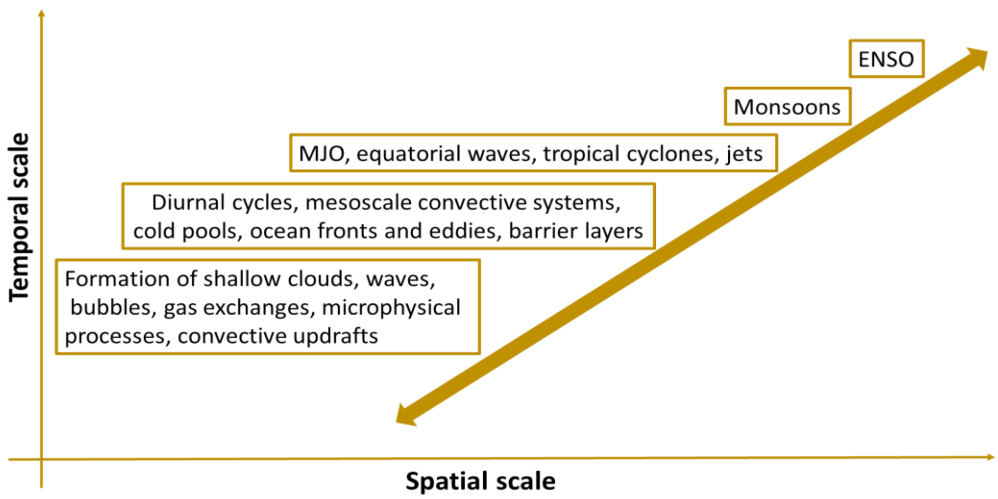


Fig. 1 A sampling of the phenomena discussed at the workshop demonstrates the broad range of spatial-temporal scales involved and the cross-scale interactions. The spatial scale ranges from <1 to >100,000 kilometers and the temporal scale covers from < 1 hour to multi-years.



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