Air–sea Interaction at the Dawn of the Global Cloud-system Resolving Era

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1 Introduction

Why do we continue to struggle with numerical weather prediction (NWP) at intraseasonal to seasonal time scales? Why are the uncertainties in regional precipitation change associated with global warming so large? Perhaps surprisingly, these two questions have a common answer: the representation of clouds, moist convection, and their feedback with the large-scale ocean and atmosphere remains a major challenge for numerical models (Dai 2006; Shepherd 2014; Bony et al. 2015). The essence of this challenge is in our endeavor to design all-encompassing cumulus parameterizations, as historically required, to account for the myriad unresolved interactions among clouds, air motions, and air–sea fluxes of enthalpy and momentum (Arakawa and Schubert 1974; Randall et al. 2003). Flaws in such parameterizations, and the resulting errors in air–sea feedback and radiative flux, lead to biases in the strength and location of climatological rain bands (e.g., the ITCZ) and storm tracks (Dai 2006; Stevens and Bony 2013). On shorter time scales, these problems manifest in severely inadequate representation of the Madden–Julian oscillation (MJO) and El Niño/Southern Oscillation (ENSO), and in turn, in missed opportunities for global weather prediction on intraseasonal (30–90-day) and interannual time scales (Waliser et al. 2003; Lau and Waliser 2012; Zhang 2013; Kim et al. 2014; Neena et al. 2014; Jiang et al. 2015). While cumulus parameterization will long remain necessary for extended climate prediction, the potential to explicitly represent clouds and convection is now at hand for NWP (Skamarock et al. 2012; Satoh et al. 2015; Klocke et al. 2017). Yet fully realizing the predictability offered by explicitly resolving convection will depend on bringing the treatment of air–sea interaction to a new level of realism. To this end, ***the overarching objective of this research is to investigate air–sea interaction at the scales of moist convection, and its upscale feedback onto climate at greater spatiotemporal scales.***

Experiments with traditional climate models (i.e., with cumulus parameterization) have revealed that the fidelity of the MJO – both its amplitude and eastward propagation – can be increased by invoking an ocean mixed-layer (OML) model to account for rapid changes in upper-ocean static stability, convection, and shear-driven mixing (Klingaman and Woolnough 2014; Seo et al. 2014; DeMott et al. 2015; Large and Caron 2015). Such OML models lead to more realistic diurnal upper-ocean warming, which leads to improved sea surface temperature (SST) variability at longer time scales through nonlinear rectification (Shinoda 2005). An important question is to what extent including an OML model can offset errors in air–sea feedback linked to the cumulus parameterization itself (Dai 2006; Shepherd 2014; DeMott et al. 2015). Cloud systems evolve and organize on fast time scales ($O(1\text{ h})$), producing downdrafts and cold pools that alter wind speed and thermodynamic variability in the atmospheric boundary layer (Feng et al. 2015; Rowe and Houze 2015; de Szoeke et al. 2017). Clouds additionally drive rapid changes in both solar and downwelling infrared radiative fluxes. No study to date has investigated the coupled impacts of such convective processes, and how they impact climate at longer time scales. The research proposed here will address this critical science gap. The specific objectives of the research are as follows:

Objective 1: Assess the feedback between tropical deep convective clouds, radiation, cold pools, and the ocean mixed layer;

Objective 2: Assess the influence of convective-scale air–sea feedback on the Walker cell;

Objective 3: Assess the role of convective-scale air–sea feedback in the MJO.

To fulfill these objectives, a convection-permitting model will be coupled to a vertical OML model, which will then be invoked to conduct a series of experiments. The expected outcomes of the research are critical insights into the nature of air–sea interaction at convective scales, and a new assessment of its role in weather and climate.

2 Background

Observations in the tropical warm pool region resulting from both COARE (the Coupled Ocean–Atmosphere Response Experiment) (Webster and Lukas 1992) and DYNAMO (Dynamics of the MJO) (Yoneyama et al. 2013) have shed new light on OML–atmosphere interaction and its changes with the convective state of the atmosphere. Under light winds ($0 \sim 6$ m s^{-1}) and suppressed large-scale cloudiness, strong solar heating stratifies the OML, concentrating the warming into shallow "diurnal warm layers" that typically penetrate down to only ≤ 3 m, with an exponentially decaying thermal signature (Fig. 1, upper). This accumulated warmth is then mixed downward into the deeper OML by nocturnal oceanic convection in response to the onset of surface cooling after sunset. This OML heat cycle can cause a diurnal cycle in SST with a range exceeding 3°C (Webster et al. 1996). Figure 2 depicts the response of clouds and cumulus moistening to this ocean warming through composites from two suppressed phases of DYNAMO MJO events. Surface sensible and latent heat fluxes increase in connection with SST during daytime, in turn promoting deeper convection and moistening of the midtroposphere each afternoon (Ruppert and Johnson 2015, 2016). Ruppert and Johnson (2015) and Ruppert (2016) argue that this local diurnal air–sea feedback is important for the onset of deep convection as the MJO active phase initiates in the equatorial Indian Ocean.

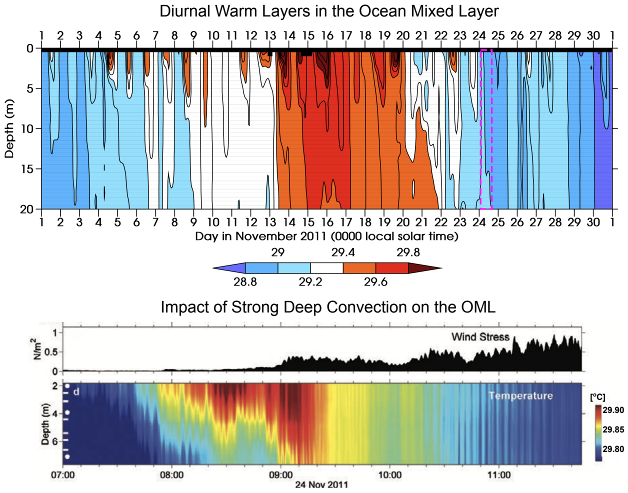

Figure 1: (upper) Time series of upper-ocean temperature (shaded, contoured every 0.2°C) through the progression of a DYNAMO MJO event (from Matthews et al. (2014)). (lower) Surface wind stress and temperature during the arrival of a strong deep-convective event on 24 Nov 2011 (from Moum et al. (2014)).

The diurnal interaction described above is characteristic of suppressed conditions – that is, the subsiding branch of the Hadley or Walker cell, or the suppressed or pre-onset phase of the MJO. In the context of the MJO, the OML first accumulates potential energy on a week$\sim$month time scale through this diurnal cycling and rectified warming (Bernie et al. 2005; Shinoda 2005), which is later removed by widespread deep convection during the active phase (Moum et al. 2014). The latter regime is well exemplified by the arrival of a strong convective event on 24 Nov, the cold pools from which bring a marked increase in surface wind stress, and rapid OML cooling and deepening (Fig. 1, lower) (Moum et al. 2014). The sensible and evaporative ocean cooling equates to the source of buoyancy and latent energy that supports the overlying cumulus convection. Eventually convection locally dissipates – likely aided by convectively-driven OML cooling – as the MJO convective envelope propagates eastward (DeMott et al. 2015). These observational examples reveal that feedback between the OML and moist convection manifests on both intraseasonal and much shorter time scales – namely, time scales set by the spatiotemporal scales of organized convection, and the diurnal cycle.

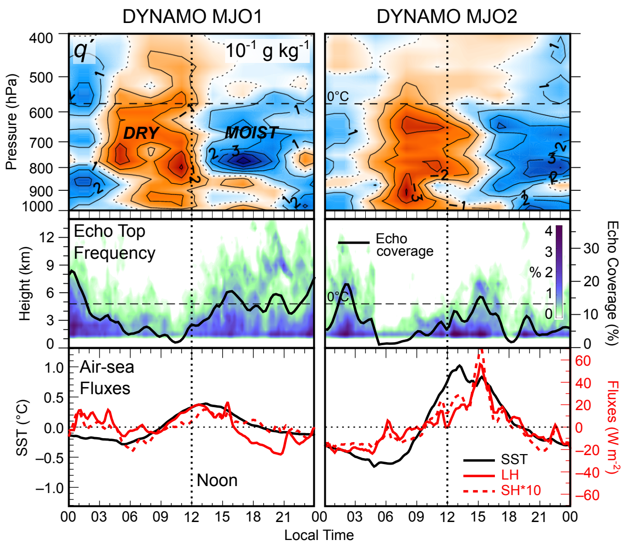

Figure 2: Diurnal composites in two DYNAMO MJO pre-onset periods (i.e., prior to the onset of strong deep convection), with (top) water specific humidity, (middle) cloud echo-top frequency (shading) and echo area coverage (line) measured by S-PolKa radar, and (bottom) SST anomaly (left y-axis) and sensible ($\times 10$) and latent heat flux anomalies (right y-axis) (modified from Ruppert and Johnson (2015)).

3 Hypotheses

Although highly simplified, interpretation of the interactions between convection and the OML can be conceptualized through the heat budget for a slab OML, shown here with only the most important terms (Weller and Anderson 1996):

$$C_s \frac{dT_s}{dt} = Q_{net} = (LW_{\downarrow} - LW_{\uparrow}) + SW - LH - SH.$$

C_s is the heat capacity of the slab layer, T_s its temperature, Q_{net} net heating, $LW_{\downarrow}$ and $LW_{\uparrow}$ downward and upward longwave flux, SW shortwave flux (very little is directed upward given the very low albedo of ocean water), and LH and SH turbulent latent and sensible heat flux. The effects of convection on these fluxes are schematically depicted in Fig. 3. In cloud-free regions where the wind is light, the cooling due to net longwave, sensible, and latent heat flux is more than offset by the warming due to shortwave. This is true of the daily mean, and especially so during daylight hours when shortwave flux commonly exceeds 1000 W m^{-2} (Weller and Anderson 1996; Bernie et al. 2005). With the local influence of clouds, shortwave heating is greatly reduced, while downwelling longwave radiation leads to reduced net longwave cooling. Finally, with increased SH and LH due to greater wind speeds in cold pools (de Szoeke et al. 2017), net cooling results. This spatial response of Q_{net} will eventually lead to a horizontal gradient in SST. Mesoscale SST gradients have been found to invigorate tropical convection by driving mesoscale circulations in the atmospheric mixed layer (Li and Carbone 2012; Hohenegger and Stevens 2016). Important open questions include: how strong are such SST gradients, and how rapidly do they form and dissipate?

Now assume the term C_s in the slab OML heat budget implicitly represents the depth, and hence the response time, of the OML. Reduced C_s yields a larger time-tendency of T_s for a given Q_{net}. Under light winds and strong shortwave heating, a rapid increase in stratification causes a rapid reduction of C_s, and hence rapid warming of the OML (Fig. 1). In typical ocean models, vertical spacing is $\geq$10 m in the upper ocean, which is far too coarse to resolve this stratification. This implies that C_s never approaches the low values achieved in nature, and that both the spatial and horizontal variability of SST is underestimated. Including a high-resolution vertical OML helps rectify this issue (Klingaman and Woolnough 2014); however, the sensitivity of OML stratification to mesoscale organized convection (Fig. 3) implies that, even with the inclusion of such an OML model, coarse climate models will miss much of the air–sea feedback that lives on the mesoscale (Li and Carbone 2012; Hohenegger and Stevens 2016). The following hypotheses are formulated based on these arguments:

Hypothesis 1: Changes in static stability in the upper 10 m of the ocean amplify the spatial and temporal variability of SST, in turn amplifying the variability of moist convection;

Hypothesis 2: The feedback between moist convection and the ocean mixed layer on the mesoscale amplifies SST variability, thereby increasing the variability of moist convection;

Hypothesis 3: Air–sea feedback at the mesoscale drives greater variability in SST and moist convection that rectifies onto larger space and time scales, thereby influencing patterns of large-scale circulation.

4 Research Plan

To conduct this research, two non-hydrostatic models will be employed to treat the atmosphere, coupled with a single-column OML model that represents rapid changes in stratification. The two atmosphere models are 1) the Advanced Research Weather Research and Forecasting (WRF) model, which will be employed in a regional framework to represent a subset of the tropical climate system (Objectives 1 and 2); and 2) the global Model for Prediction Across Scales – Atmosphere (MPAS), which will be invoked to investigate the role of air–sea coupling in the MJO (Objective 3). The fluid dynamics are implemented in both WRF and MPAS with explicit convection in mind (Skamarock et al. 2008, 2012), while both models include the same physics parameterizations. Each model implementation in this study will invoke a two-moment microphysics scheme (Morrison et al. 2009), RRTMG shortwave and longwave radiation, and Monon–Obukhov similarity theory for the surface layer. All model simulations will be conducted using the NCAR–UCAR Cheyenne supercomputer.

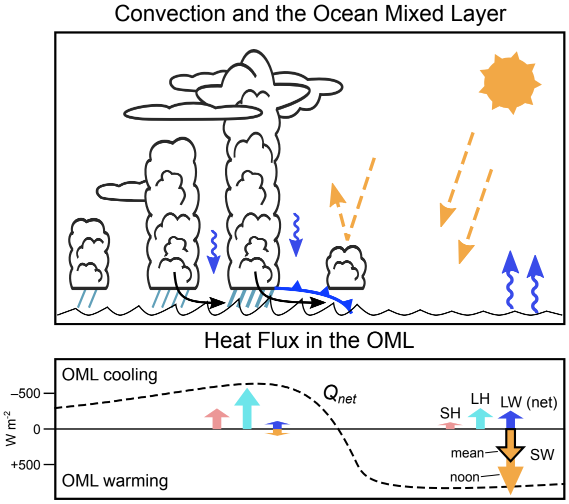

Figure 3: Schematic depiction of the influence of clouds, convection, and cold pools on heat flux in the ocean mixed layer. Dashed line shows net flux Q_{net} assuming midday shortwave heating.

Two OML models will be tested for use in this study: 1) the K-Profile Parameterization (KPP) first-order turbulence scheme based on similarity theory (Large et al. 1994; Bernie et al. 2005); and 2) a simplified, fast diurnal sea-surface cycling (DSC) scheme that parameterizes the effects of changing stratification in the upper ocean (Large and Caron 2015). Both OML models will be coupled to the WRF as part of the research for Objective 1 to compare results. Based on comparisons with observations, one OML model will be selected for the subsequent parts of the study. For both models, profiles of ocean temperature, salinity, and current representative of a background (and deep-ocean) state are required, which in this study are taken from observations and treated as fixed in time.

Objective 1

This part of the research will seek general insights into the feedback between the OML and convective-scale processes, including clouds, precipitation, cold pools, and cloud–radiation interaction. To do so, a set of limited-area convection-permitting experiments will be conducted by integrating out to radiative–convective equilibrium (RCE) from a horizontally homogeneous initial state. The RCE framework is highly useful for studying convection–radiation feedback in a setting that approximates the tropical climate system (Bretherton et al. 2005; Khairoutdinov and Emanuel 2013). The treatment of two-way air–sea feedback while resolving feedback with the OML will be a novel exploration of this framework.

To test the first hypothesis, the WRF model will be employed to conduct a coupled RCE experiment, where all simulations are integrated out to $\geq$100 days. A set of six simulations will be conducted on a grid of 1 000×1 000 km^2, discretized with 3-km spacing, each identical in their initial and background ocean and atmosphere states. In simulations denoted RCE-KPP and RCE-DSC, the WRF will be coupled to the KPP and DSC OML models. Comparison between these tests and tropical buoy observations will shed important light on a) the nature of air–sea interaction at convective scales, and b) the advantages, disadvantages, and potential biases of each OML model.

Next, in simulations RCE-S1, RCE-S5, RCE-S10, and RCE-S20, a simple slab ocean model will instead be invoked, with fixed C_s, by assuming four slab-layer depths: 1 m, 5 m, 10 m, and 20 m. Comparison of the above OML tests with these slab tests will reveal the major shortcomings of assuming fixed OML-depth, wherein changes in ocean stratification are neglected. The expectation is that the RCE-S* simulations will exhibit large biases in SST variability, with consequent biases in the variability and mean RCE states of domain-averaged precipitation and radiation.

Next, to test the second hypothesis, a simulation will be conducted (RCE-PARAM) in which the same model domain is discretized with 20-km spacing, coupled to the DSC OML, with moist convection parameterized using the Tiedke scheme (Tiedtke 1989). Expectation is that this test will exhibit severe biases in convection and radiation in comparison with the explicit-convection tests.

Objective 2

This research will investigate the effect of mesoscale air–sea feedback on the large-scale Walker cell, and will test Hypothesis 3. In this case, only one OML model will be employed. Instead of a square model grid, a grid of 200×10 000 km^{-2} will be employed with 3 km grid spacing, with the initial and background ocean states prescribed with a cosine function such that SST varies with a range of 3 K. This initial ocean state will establish a large-scale overturning Walker circulation with convection over the warmest SST.

WRF will be coupled to either the OML model in a control test denoted WALKER-OML. As in the above procedures, an additional three tests will be conducted. In WALKER-S5 and WALKER-S10, slab layers will again be assumed with depths 5 and 10 m. In WALKER-PARAM, this model grid will be discretized with a mesh of 20-km spacing, with convection parameterized using the Tiedke scheme. This will allow the testing of Hypotheses 1 and 2, as described above. Additional expectation is a substantial sensitivity of the transient patterns of convection and SST to both resolved convection and variable upper-ocean stratification – namely, as noted in Hypothesis 3. These results will shed critical insight on the impact of air–sea feedback with convective processes on the Bjerknes Feedback, in turn shedding important light on the maintenance of ENSO and interannual variability.

Objective 3

To test the sensitivity of the MJO to air–sea feedback at convective scales, the MPAS will take the place of the WRF from the above experiments. MPAS will be integrated globally on a mesh of 5-km spacing. Four tests will be conducted. For the first two, the initial and background ocean and atmosphere states will be prescribed as 1 September 2011, which marks the start of DYNAMO, and approximately one month prior to the active phase of the first MJO observed therein. For the test MJO1-OML, MPAS will be coupled to the OML, while for MJO1-FSST, MPAS will instead be integrated with observed daily SST. These tests will be integrated for 75 days to cover the during of the MJO over the warm pool region. MJO2-OML and MJO2-FSST are the same as the prior two tests, except integrated beginning at 31 October, in advance of the second observed DYNAMO MJO.

Expectation from these four tests is that both resolving moist convection and treating air–sea feedback at the scales of organized convection are critical to properly forecasting the large-scale circulation signal of the MJO. This argument is in line with Hypothesis 3.

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