particulate tracers in aquatic environments and forecast changing optical properties out to 24 hours.

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Probing the World's Greatest Source of Variability — Madden Julian Oscillation

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Introduction: The Madden–Julian Oscillation (MJO), named after Roland Madden and Paul Julian, who first described this phenomenon, is a primary mode of atmosphere/ocean variability. The MJO consists of a large, planetary-scale convective anomaly propagating eastward along the Equator over the Indo Pacific warm pool with a phase speed of about 5 to 8 m/s. It influences the atmosphere and ocean on various temporal and spatial scales — from tropical cyclones through monsoons and El Niño in the tropics, to mid-latitude, and even polar, atmosphere, and ocean circulation patterns. The effects of this tropical phenomenon can be observed as far away as ocean current anomalies in the Drake Passage.

MJO behavior depends on multiscale interactions between the global circulation and local convective patterns, as well as feedback between the atmosphere and the ocean. The MJO "cycle" consists of the dry (suppressed) phase, in which clear skies and large insolation allow for heating of the upper ocean and energy is accumulated in the atmosphere/ocean system, and the active phase, in which the energy is released in the form of atmospheric convection (precipitation). A synthesis of the MJO based on model simulations, field measurements, and a conceptual model is shown in Fig. 8(a-d).

MJO Forecast: From the forecasting point of view, the MJO represents a link between the weather and climate. Its relatively long time scale forms a base for extended weather prediction and, therefore, understanding of the MJO became a Holy Grail for the forecasting community. However, in spite of its importance, the MJO presents a formidable forecasting challenge, mostly because of its multiscale nature. The MJO system includes eastward and westward moving tropical disturbances with various spatial and temporal scales that interact with the large-scale "MJO envelope"; the air-sea interaction creates another level of complexity.

An interdisciplinary NRL team participated in an international effort, called Cooperative Indian Ocean Experiment on Intraseasonal Variability (CINDY) / Dynamics of Madden–Julian Oscillation (DYNAMO), directed toward understanding MJO dynamics, with the focus on MJO initiation in the Indian Ocean that appears to be especially difficult to predict. During the CINDY/DYNAMO field campaign (October to December 2011), three MJO episodes were observed, providing a wealth of data for MJO investigation. In this campaign, the NRL air-sea-ocean-wave Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) model was used, the first fully coupled high-resolution model run in real time. The model consists of the atmospheric regional model, ocean model Navy Coastal Ocean Model (NCOM), and wave model Simulating WAves Nearshore (SWAN) with the boundary forcing provided by Navy global models and data assimilation in the atmosphere and in the ocean. The model nested grid setup used for the DYNAMO forecasts, with the cloud resolving nest centered on the DYNAMO observational array, reflected the multi-scale nature of the MJO. With this model, combined with the atmospheric and ocean observations collected during the field program, we analyzed the transitions from the suppressed stage to the active stage of the

MJO. Our research was focused on the air–sea interaction between the atmospheric convectively coupled waves and the development of the temperature, surface current, and salinity anomalies in the upper ocean.

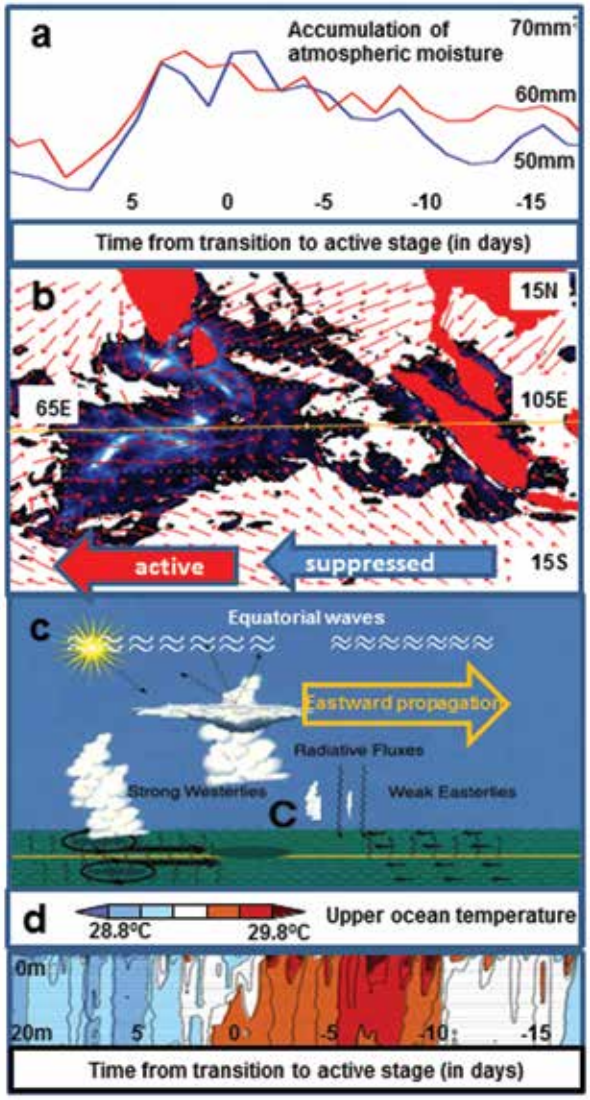

FIGURE 8
The synthesis of MJO transition from convectively supressed to active phase based on DYNAMO observations, COAMPS simulations, and conceptual model. Spatial patterns from the model and point observations from DYNAMO instruments are combined. (a) The buildup of atmospheric moisture in the supressed phase and the release during the active phase at 80E 0N, as observed in DYNAMO atmospheric soundings (courtesy of R. Johnson and P. Ciesielski) and COAMPS simulation adapted from Ref. 3. (b) The surface winds and precipitation from the COAMPS 11/23/2011 forecast of MJO. The area with strong winds and precipitation corresponds to the active phase, while the area to the east of the moving convection represents the supressed phase. (c) The conceptual model of air-sea interaction in MJO adapted from Ref. 4. (d) The time series of the ocean temperature in the upper 20 m of the ocean, measured by the Sea-Glider near 80E 2N (courtesy of A. Matthews and D. Baranowski). The high temperatures and large diurnal cycle develop during the supressed MJO phase.

Multiscale Air–Sea Interaction: Our research addressed the multiscale nature of the MJO, from equatorial waves in the atmosphere and the ocean to local air–sea interaction. Using satellite observation, we have shown the remote effects of the wind anomalies associated with MJOs observed during DYNAMO.[1] Satellite-derived precipitation patterns indicated also that atmospheric equatorial waves play a role in MJO initiation (Fig. 9). The role of atmospheric disturbances and their interaction with the ocean surface was further studied using COAMPS simulations that focused on the transition between the suppressed and active MJO phases.[2,3] Our model experiments indicate that during the MJO suppressed phase, equatorial waves and air–sea interaction are essential for the moisture buildup in the atmosphere shown in Fig. 8(a), preconditioning the atmosphere for the deep convection ahead of the active phase of MJO (Fig. 8(b)). The warm diurnal layer that develops in the upper ocean on clear days (Fig. 8(d)) appears to be particularly important for air-sea interaction, especially on short time scales.

The equatorial disturbances play an important role in the MJO active phase as well. We have shown that the interaction between the eastward and westward propagating waves (Fig. 8(c)) leads to rapid development of the deep convection observed during the MJO active phase. The enhanced equatorial winds in the active phase shown in Fig. 8(b) are the result of such interactions. COAMPS simulations indicate that air/sea interactions play a role at this stage of the MJO by strengthening the equatorial waves.

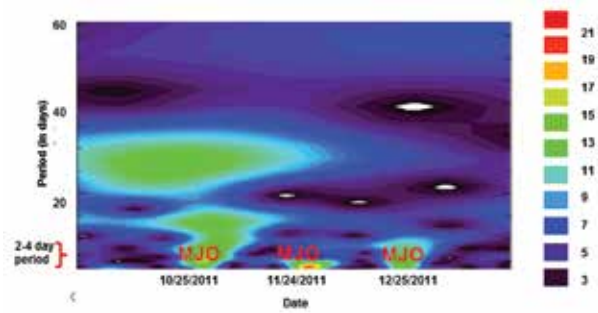

FIGURE 9
Multiscale character of MJO as shown by wavelet analysis of eastward propagating precipitation disturbances with small zonal scales (zonal wave numbers 9-40, corresponding to zonal wavelengths below 4000 km). The dominant period of large-scale (zonal numbers 1-8) perturbations was 30 days, corresponding to frequency of MJO episodes. However, each MJO initiation was accompanied by a burst of short, high-frequency perturbations with 2–4 day period. The precipitation data are obtained from NASA TRMM analysis.

Summary: Our research indicates that even though the MJO is mainly an atmospheric phenomenon, the interaction with the ocean surface plays an

important role in its evolution and it is critical for skillful forecasts. On the shorter time scales (1 to 2 weeks), local interactions with the upper ocean appear critical, demanding high vertical resolution near the ocean surface in the ocean model. On the longer time scales, the remote response of the ocean to atmospheric anomalies requires that the ocean dynamics are properly resolved. In the atmosphere, MJO forecasts depend on the simulation of the equatorially coupled convective waves and their interactions.

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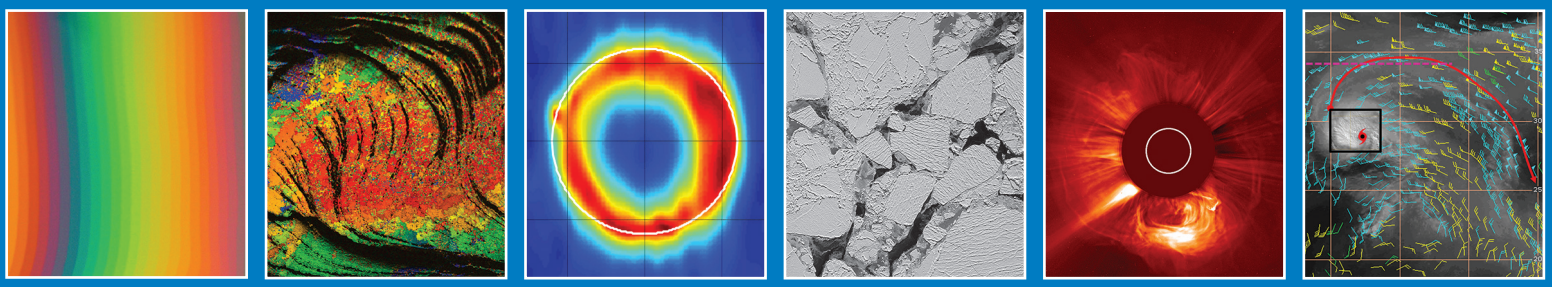

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