Large-Eddy Simulations of Tropical Convective Systems, the Boundary Layer, and Upper Ocean Coupling

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LONG-TERM GOAL

Improve operational numerical weather prediction (NWP) models to more accurately simulate the interaction of tropical deep convection and atmospheric and oceanic boundary layers.

OBJECTIVES

Investigate tropical convection and upper ocean circulations on scales from 100 m to 200 km. Elucidate specifically how the ocean mixed layer responds to forcing from atmospheric convection such as wind and precipitation, and thus how surface fluxes depend on the history of convective events. Perform high-resolution coupled atmosphere-ocean numerical model simulations, whose fidelity is a benchmark for operational models and parameterizations. Insights gained from these simulations will be used to improve parameterizations used in operational scale models, and to refine hypotheses in collaboration with investigators working on observational field studies in the Indian and West Pacific Oceans.

APPROACH

Intraseasonal variability in the tropics is dominated by the Madden-Julian Oscillation (MJO), which generates large-scale variability in the structure and organization of deep convective cloud systems. MJO events consist of multiple scales of convective activity, from single kilometer-sized cells to circulations encompassing half of the tropical Pacific. Key factors for tropical convection include sea-surface evaporation and large-scale atmospheric moisture convergence, which both depend on sea-surface temperature and wind speed. Most numerical models do not resolve turbulent and convective scales, nor do they simulate the MJO accurately. We plan to investigate how convection during the active phase of MJO affects and interacts with the ocean mixed layer. We will perform large eddy simulation (LES) of organized convective systems, which resolve boundary layer eddy scales to

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mesoscale convective towers. These numerical simulations will reveal how atmospheric convection alters air-sea fluxes and the ocean boundary layer, and will refine hypotheses on coupling between the ocean and atmospheric boundary layer during MJO events, to be tested during the field campaign. Processes on these scales are gaining importance in operational NWP models as the realism of convection increases along with model resolution.

WORK COMPLETED

Research during the third year of this project has focused on analyzing data from the DYNAMO cruise conducted in the fall of 2011 and performing large-eddy simulation (LES) experiments of tropical convection initialized using soundings derived from field program. We have extended the coupled LES model to include a column ocean model at each grid point using a modified version of the K-profile parameterization (KPP). Our version of KPP includes the effects of Langmuir circulation by enhancing a non-local vertical mixing term for momentum in the equation based on surface wind speed.

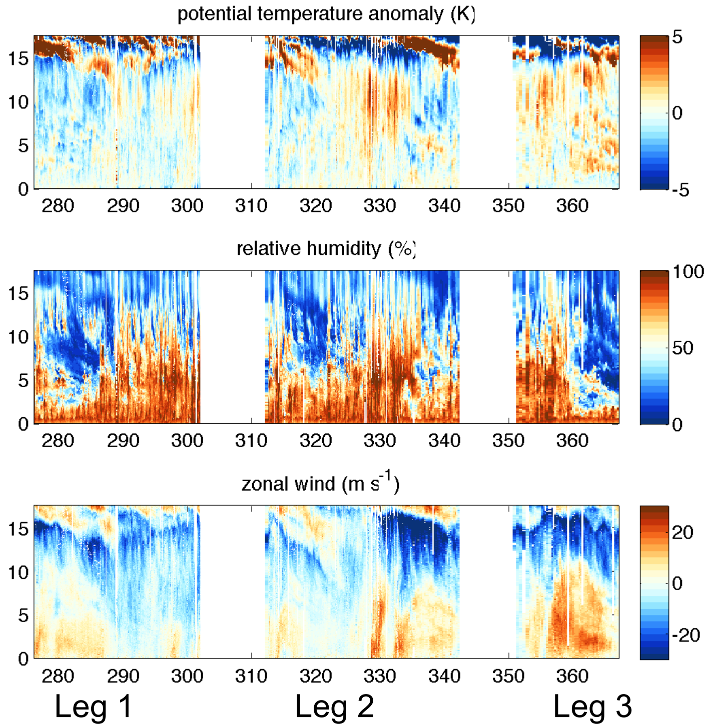

Figure 1. Upper air potential temperature (K), relative humidity (%), and zonal wind (m s^{-1}) measured from the RV Revelle October 2011 through early January 2012. Upper atmosphere dry periods on days 280-290, 315-325, and in early January preceded active convective periods indicated by strong westerlies and deep moisture.

RESULTS

Phenomena observed in DYNAMO

In 3 legs of observations aboard the *Revelle* (figure 1), we observed phenomena in the atmosphere and air-sea interface. Certain phenomena were unexpected, or our observing capability allows us to see it in new ways:

- warming of SST during sunny, calm inactive phase of the MJO.
- rapid transitions in atmospheric convection from inactive to active MJO phases, including wind intensification and multicellular storms.
- intense rain events.
- gusts and outflows associated with surface cold pools.
- sub-cloud turbulence: flux sensors and HRDL vertical velocity variance
- in-cloud turbulence: NOAA W-band cloud radar.
- NOAA Doppler cloud radar also observed sub cloud turbulence when the air was filled with stratiform rain particles.

Our research with models and observations addresses the LASP/DYNAMO hypothesis that mesoscale and cloud-scale *gusts associated with convection increase fluxes through the marine atmospheric boundary layer*. Wind bursts temporarily increase the wind stress and surface heat fluxes, generating turbulence in the ocean and supplying moist enthalpy and potential instability to the lower troposphere.

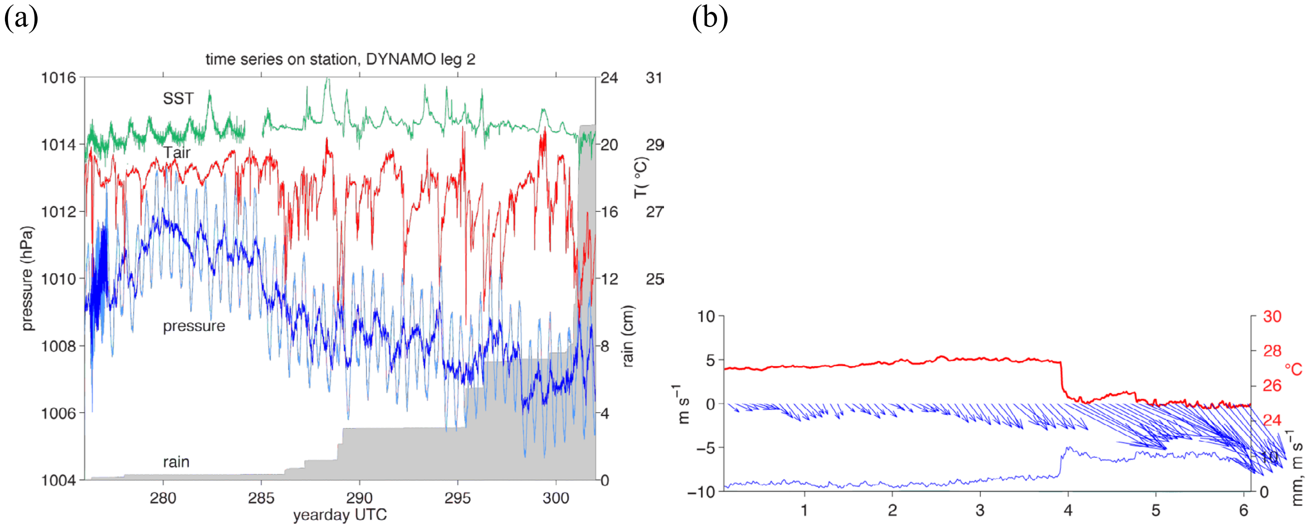

Figure 2. (a) Synthesis of temperature, pressure and cumulative rainfall measurements made during leg 2 and (b) rapid increase in wind following a nearly 1° C reduction in temperature presumed from the arrival of a cold pool.

In leg 2 we frequently observed rapid increases in wind speed and shifts in wind direction, accompanied by arrival of colder air. Figure 2a summarizes leg 2 SST, air temperature, rain, atmospheric surface pressure, and integrated rain. Figure 2b shows passage of a gust of stronger wind with cold air behind the gust. These gusts or outflows were a significant if not dominant source of wind variability for much of the SOP. The gusts are believed to be gravity currents from cold pools.

The hypothesis predicts increases in evaporation in such wind bursts. In a preliminary analysis from leg 2 we composited 42 events when the temperature had dropped by more than 7° C hour^{-1}. Temperature, wind speed, surface pressure, evaporation, and sensible heat flux were averaged for the hours leading up to and following the rapid temperature drop events. While wind speed increased 2 m s^{-1} at the crest of the front, composite air temperature dropped 1° C and stayed lower for 2 hours. Pressure also saw roughly a 0.1 hPa increase. A hydrostatic pressure perturbation of this size would result from a –1° C temperature anomaly of ~400 m thickness. Evaporation increases rapidly from 120 W m^{-2} to 180 W m^{-2} at the gust, resembling the composite wind speed. Sensible heat fluxes are 10 W m^{-2} before the gust, and reach 30 W m^{-2} in the gust. The temperature change results in sustained elevated sensible heat fluxes of 20 W m^{-2} for about 2 hours.

Large-eddy simulations

Observations from the DYNAMO field experiment (figure 2) showed that the atmospheric boundary layer structure is often affected by convectively forced “cold” outflows that lead increased surface winds and a slight decrease in the surface air temperature. This combination forced substantial changes in the latent heat flux that may have a significant impact on the formation and propagation of the MJO. To examine this hypothesis, we conducted a series of LES cases with identical initial conditions for atmospheric temperature and winds, but differing upper troposphere moisture content. Our goal in these experiments was to determine how the vertical moisture structure affects convective activity as MJO events evolve over the Indian Ocean.

Upper air measurements (Figure 1) suggest that MJO events begin with a period of dry upper troposphere conditions as shown by the low relative humidity on days 280-290 and 315-325. Initial conditions representing these dry periods, along with a case having average moisture, were constructed to examine the effects of tropospheric moisture on convective activity and cold pool formation.

Results from these two simulations are shown in figure 2 after 4 days of simulation. In general, the model shows that drier conditions lead to larger convective systems and cooler surface outflows. Clouds in the dry case are concentrated along the leading edge of outflow boundaries moving in the same direction as the initial zonal wind. As the outflow expands outward, the cool air region is reinforced by new downdrafts producing a long-lived convective squall line that persists for multiple hours.

In contrast, the moist case is characterized by multiple smaller scale convective elements that generate much smaller and weaker cold pools. In this case, organized squall line structures are rare and cloud systems tend to cycle through growth and decay over much shorter time intervals.

The difference between the low and high moisture cases appears to be the strength and scale of the cold air surface outflows, which are generated by evaporating rainfall in convective downdrafts. In the low moisture case, we believe that mid tropospheric air is entrained into the downdraft circulation, enhancing evaporative cooling. The net effect is a stronger, colder downdraft that leads to more intense outflow systems at the surface. Stronger outflows are also able to increase the surface latent and sensible heat flux, which will aid in the formation and growth of new convective systems along the outflow front.

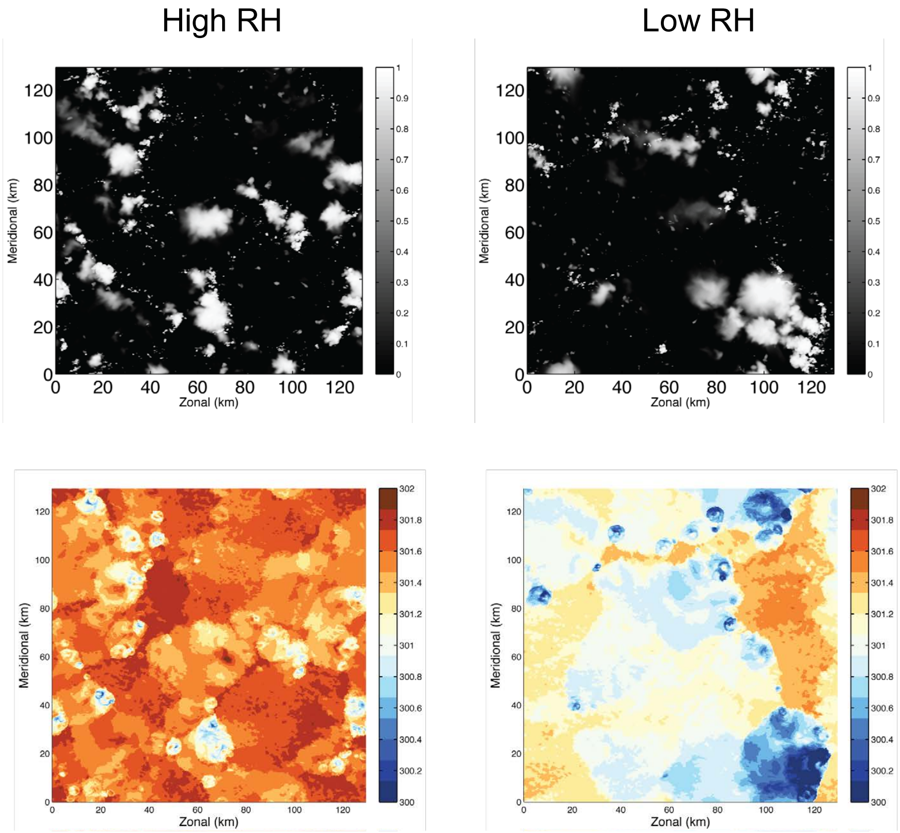

Figure 3. Top panel shows simulated cloud albedo and lower panel represents the surface temperature. Both plots are taken from hour 20 on day 5 from the average and low moisture cases. Cloud systems in the low RH case generate larger cold air outflow regions and frequently propagate along distinctive fronts at the leading edge of the cold air.

RELATED PROJECTS

This project is part of the Indian Ocean Air-Sea DRI and is a part of DYNAMO. A related DYNAMO National Science Foundation project entitled “DYNAmics of the Madden-Julian Oscillation / Analysis of subsurface fluxes with coupled large-eddy simulation models” will provide a significant ocean component not proposed in the current project.