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The Potential for Predictability in the North Pacific Due to Tropical Circulation Skill and Tropical-Extratropical Interactions in the Community Earth System Model (CESM)

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LONG-TERM GOALS

This project aims to achieve multi-week forecasts of utility using the global-domain Community Earth System Model (CESM, Hurrell et al., 2013) and at vertical and horizontal resolutions relevant to the atmosphere-ocean interface forecast problem. The end product will be a framework for rapid continual skill enhancements due to additions and improvements to the representation of key atmospheric processes. A whole system approach will thus be possible whereby the performance and skill of the model can be assessed from tropical circulations through tropical/extra-tropical interactions and ultimately to forecast skill within the North Pacific and North American regions.

OBJECTIVES

The objectives for achieving the long term goals are three-fold. First to demonstrate individually that tropical and extratropical climates, as simulated by CESM using the Community Atmopshere Model version 5, (CAM5, Neale et al., 2011), have sufficient realism to be considered useful in an initialized hindcast framework. In the tropics this includes the simulation of convectively-coupled, equatorial trapped wave modes such as the Madden Julian Oscillation (MJO), eastward propagating Kelvin waves and westward propagating Rossby waves. At higher-latitudes this includes the spectra of eastward propagating barocilinic wave activity, surface high pressure blocking statistics and the representation of the Arctic Oscillation. Second, to demonstrate that historical hindcasts have sufficient skill to be useful at the greater-than-weekly timescale. This includes examining current CESM configurations and evaluating the impact of modifications to atmospheric process representation on hindcast skill. Third, to evaluate the connections between tropical climate and North Pacific climate and the mechanims whereby high tropical skill on longer time-scales could propagate to influence and ultimately elevate the generally lower hindcast skill in the extra-tropical climate.

APPROACH

We use and analyze the CESM in both standard 'free-running' climate and in hindcast configurations. The free-running configuration consists of a fully coupled system with interactive ocean, atmosphere, sea-ice and land components. Existing CMIP-class experiments have been analyzed compared to observations and reanalyses to examine the model's performance for tropical climate, extra-tropical Pacific climate and the interactions between the two. They have shown CESM to be one of leading CMIP5 models in climate simulation skill. The hindcast configuration is based on the Cloud-Associated Parameterization Testbed (CAPT, Phillips et al., 2004) protocol. The setup is the same as in the Atmosphere Model Intercomparison Project (AMIP) protocols with interactive land, simplified sea ice and prescribed sea-surface temperatures (SSTs). Global simulations are performed with a simple initialization from the ECMWF Interim Reanalysis (ERAI) for the 3D prognostic quantities temperature, humidity and winds as well as surface pressure. Observed SSTs are prescribed during the hindcast period, but are know to have minimal impact over the course of each 25–day simulation. No traditional data-assimilation is performed. However, to minimize the impact of spin-up a period of nudging is applied to the model prognostic variables from 5 days prior to day 0 of the forecast period. Nudging is applied with a 6-hour relaxation timescale and the forcing are also updated every 6 hours.

WORK COMPLETED

Initial completed work has focused on establishing the nudging-hindcast framework used for the CESM hindcasts that form the major part of the current activities. This task has established the protocol for staging ERAI analysis products for a pre-hindcast nudging period, initialization of the hindcast and validation of the hindcast output. This framework has been utilized extensively to carry out hindcasts from multiple starting points during the most recent Year of Tropical Convection (YOTC) Dynamics of the MJO (DYNAMO) period of winter 2010-11 as part of an intercomparison project. It showed CESM to have superior skill at simulating observed MJOs compare to other models (Fig. 1). The period exhibited three very distinct MJOs (Fig. 2), each with genesis in the tropical western Indian ocean and propagation eastward to decay in the central Pacific. To date, our hindcast simulations have been performed starting on three spearate, but co-located days either prior to or at the peak of each of the three dominant MJO events of the DYNAMO period. Each of the set of three forecasts have been carried out using the quasi-uniform grid of the spectral element dynamical core for horizontal resolutions ne30 and ne120. These are nominally 1° and 0.25° resolutions, representing the standard CESM and prototype high-resolution versions of the model respectively. Hindcast output has been analyzed to identify the role of resolution, MJO phase and pre-hindcast nudging on the simulation and skill of hindcast skill.

Investigative work has also begun to configure CESM for use with a regionally refined grid. Initial prototype configurations have enabled a tropical area of regional refinement (up to 0.25°) to be embedded within a 1° global grid configuration. Testing is ongoing for focusing grid refinement over other regions of the globe and is ready for testing of the regional requirements and impacts of high resolution.

We have performed a comprehensive analysis of the structure and transience of extra-tropical climate features in free running version of CESM. This includes examination of mid-latitude wave activity in the upper-troposphere and the statistics of high-pressure blocking patterns.

RESULTS

Initial simulations performed using the CESM nudging-hindcast framework have led to a significant quantification and improved understanding of the role of horizontal resolution, initialization phase and spinup procedures in CESM hindcast skill. We have determined that tropical intraseasonal forecast skill is strongly dependent on the phase of event initialization (Fig 4). Hindcasts started during the peak of an MJO event, as determined by precipitation anomalies near the Maritime Continent, tend to have poorer skill scores beyond eight days than for events initialized earlier in the MJO event prior to its development in the central Indian Ocean.

We have determined that the optimal and most skillful evolution of the hindcasts is achieved using the simple nudging technique that enables the model's non-nudged condensed water quantities (ice and liquid, mass and number concentrations) to spin-up prior to releasing the hindcast. This is in contrast to simulations where the hindcast are started at day 0 without any nudging. In CAM5 there is a spin-up response to the initial state that involves a gradual increase in tropical rainfall over a few days. This is somewhat detrimental to the skill of the hindcast, particularly when it is initialized during the peak of an MJO when precipitation signals are the strongest. The nudging-hindcast framework represents a significant new capability using CESM and we intend to exploit this tool for the future of this project. Preliminary linkages between tropical modes of variability in the hindcast simulations and those of the Northern Pacific have been evaluated. This includes an analysis of the impact of tropical moisture supply to atmospheric river (AR) moisture plumes. Figure 5. demonstrates the utility of nudging prior to hindcasts, which are then allowed to free run. Resolution plays a significant role in this region as the nature of the ARs tend to be filamental and only the ne120/0.25° simulations are able to capture this structure. This is signficant as ARs have been shown to play a key role in the supply of moisture to strong spring-time frontal systems that hit the California coast and provide significant, sometimes extreme, precipitation totals (e.g., Ralph et al., 2004).

Results from the analysis of the free-running model's mid–latitude climate on weekly and greater timescales show that the model is able to represent wave-number frequency distributions of wave propagation similar to observations (Fig 3) with eastward propagation becoming faster at the smaller length scales, as well as the westwards propagation existing at planetary wave number five and scales between 10 and 30 days. In addition, to the transient, mostly baraclinic activity is the blocking frequency that exists in the North Pacific centered near the Aleutian islands. Although, blocking in climate models is generally underestimated CESM manages to maintain a reasonable winter-time blocking frequency. These results indicate that CESM has a robust Pacific climate, able to simulate accurately many modes of variability and provide a necessary representation that, given the correct variability signals from the tropical Pacific, will be able to propagate them to the limits of predictability.

Conclusions of the research so far center around the utility of the nudging/hindcast capability that has been built. It has enabled the initial analysis of model skill in different regions and on different timescales as part of 25-day forecasts. It has also enabled a examination of how model simulation errors grow and ultimately asymptote toward free-running climate simulation biases. In addition, analysis of existing climate simulations using CESM have shown its capability in reproducing key aspects of the equatorial and North Pacific climate critical for maintaining skill in multi-week hindcast simulations.

Plans for the near future will center on further demonstrating the utility of the nudging-hindcast framework. Additional simulations covering the entire DYNAMO 2010/2011 season at high resolution (0.25°) will increase the robustness of the current results with our limited set of experiments. Efforts to improve the representation of atmospheric physical processes will also be incorporated into the framework in order to evaluate changes to hindcast skill. This is expected to include alternatives to the convection parameterizations using the Unified Convection scheme (UNICON; Park, 2014) and the moist turbulence using the Cloud Layers Unified By Binormals scheme (CLUBB, Bogenschutz et al., 2013)

The free-running simulation analysis will shift focus to the Arctic Oscillation (AO) and Northern Annular Mode (NAM) relationships with the spectra of mid-latitude wave activity. In particular, evaluation will contrast standard low model top versions of the CESM, with a top at 40 km, against an extended version of CESM using the Whole Atmosphere Community Climate Model (WACCM, Marsh et al., 2013) with a top at around 110 km. This will then allow the potential simulated role of stratospheric control on both these modes of variability and their successive influence on mid-latitude wave propagation and surface blocking.

IMPACT/APPLICATIONS

As previously stated the nudging/hindcast framework under development has the potential to deliver a useful and accelerated procedure for evaluating skill due to wide a array of modeling aspects, including resolution, case study, initialization and parameterization dependencies.

RELATED PROJECTS

None currently, but it is expected that efforts will be compared with other 'Predictability of Seasonal and Intraseasonal Oscillations' projects led by Tim Li and Duane Waliser. They have foci on tropical intrasesaonal oscillation prediction and so have direct relevance to this project.

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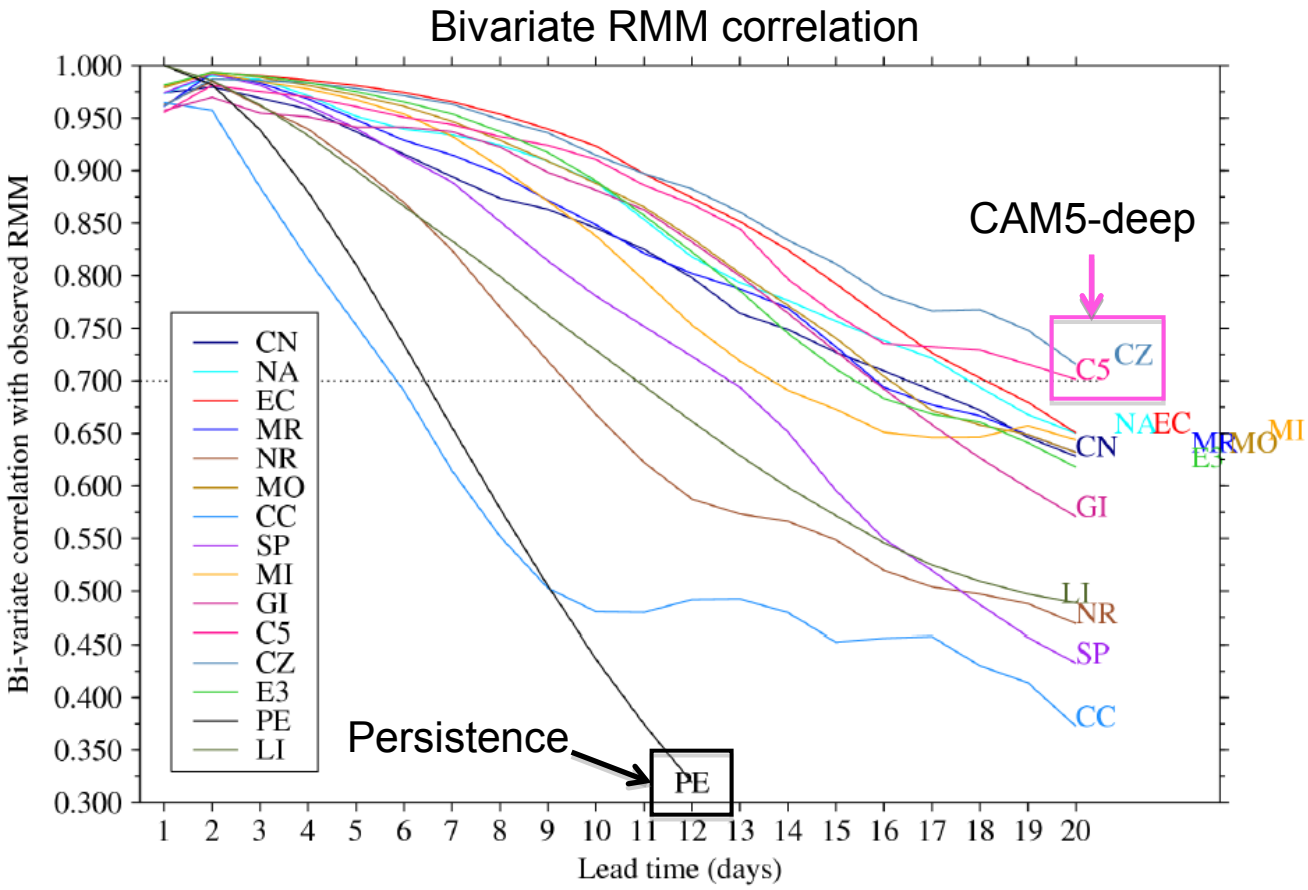

Figure 1: Hindcasts of RMM correlation (a standard measure of MJO activity) for contributing models to the DYNAMO Diabatic Heating project. Shown are the average of an ensemble set of hindcasts during the 2009-2010 Winter period. CESM variants that include the CAM5 deep convection parameterization exhibit the largest significant skill at by day 20.

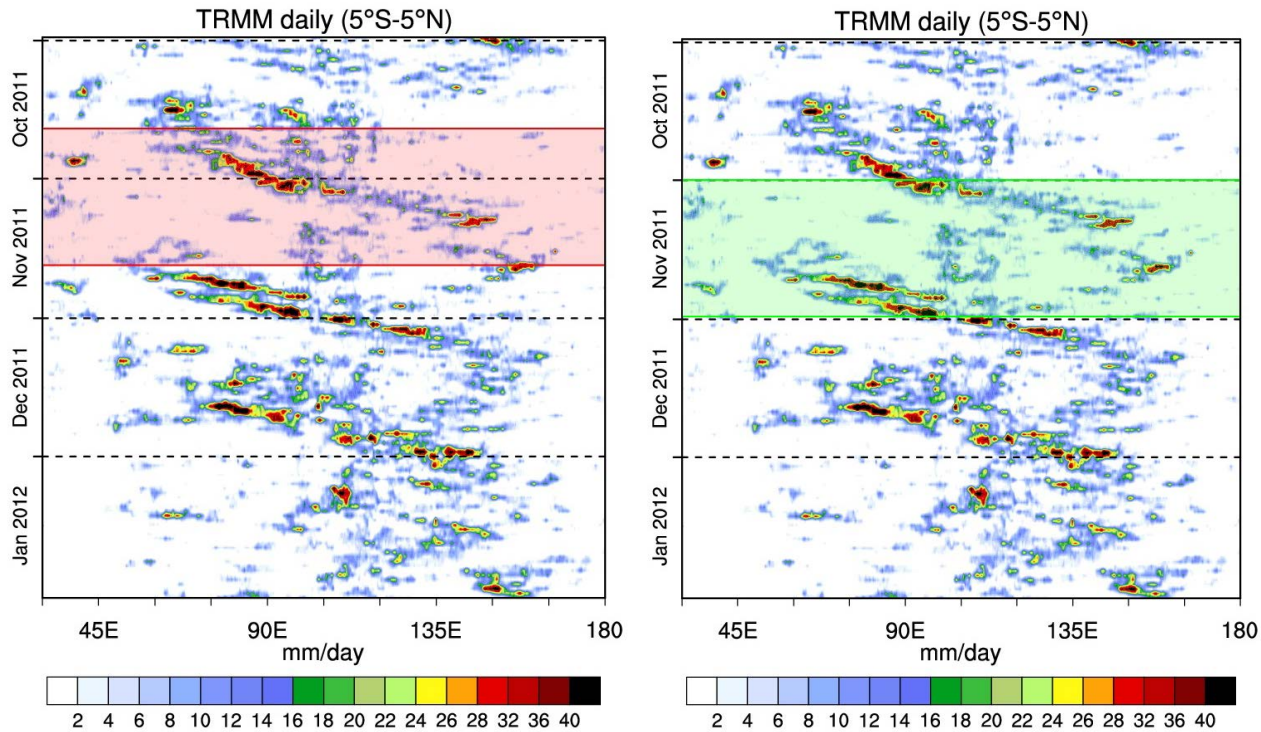

Figure 2. Hovmoller time-series of observed precipitation from the Tropical Rainfall Measuring Mission (TRMM) during the DYNAMO IOP period. Forecasts are performed during and prior to the peak of each of the three major MJO events. Examples are shown for event 1 with the forecast period started (a) prior to, and (b) during the peak of the MJO event.

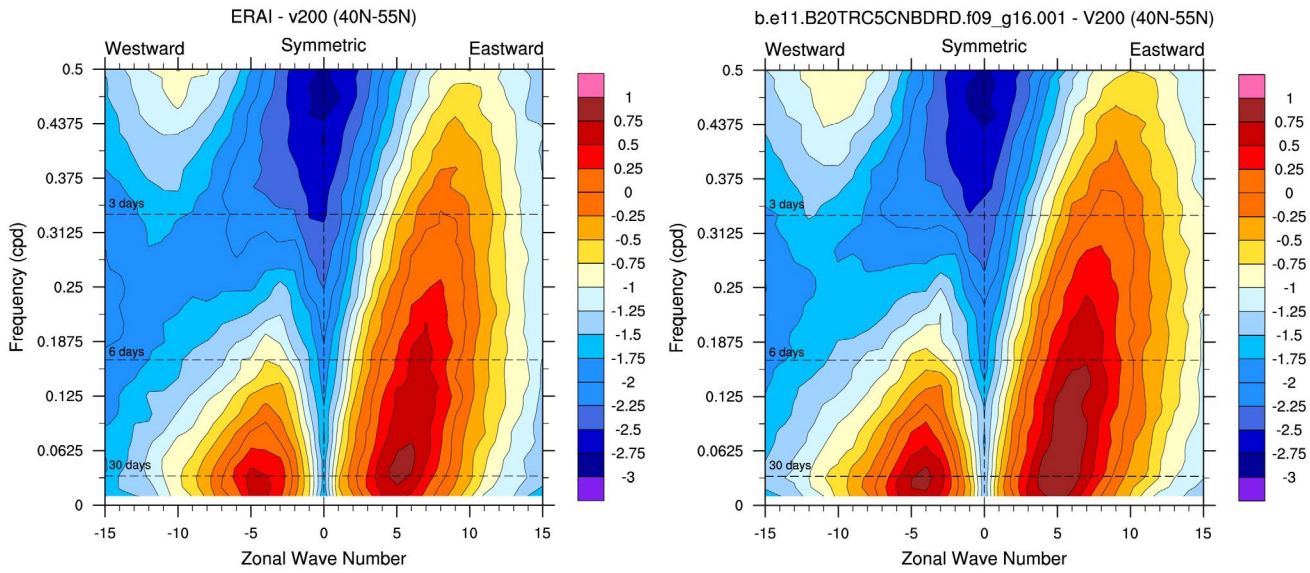

Figure 1. Zonal wavenumber, time frequency power spectra for 200-mb meridional wind velocity (averaged 40N to 55N) for the period 1991-2000 (a) ERA-Interim, and (b) CESM1 20th century simulation.

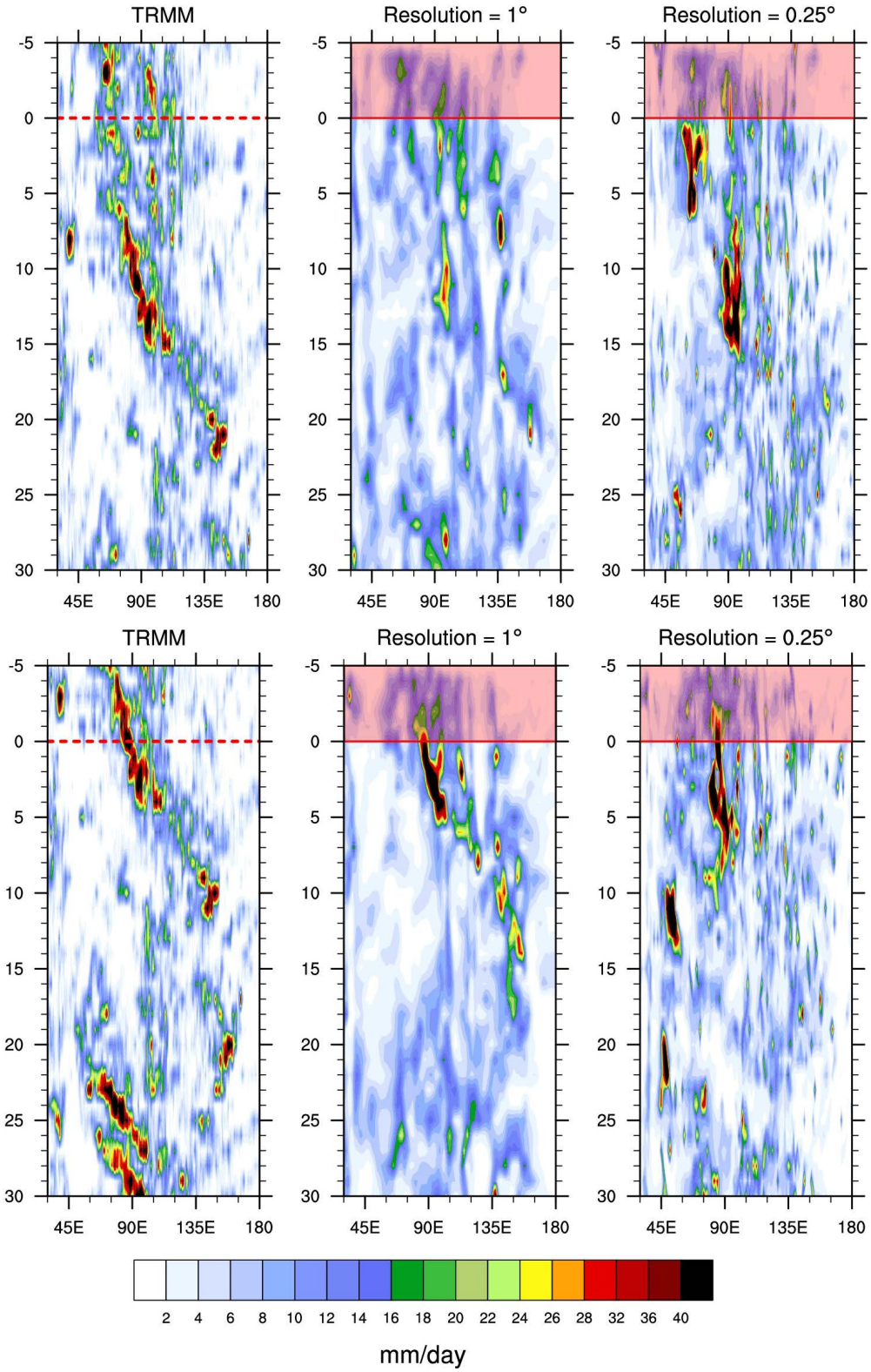

Figure 2. Hovmoller of precipitation for TRMM (left) low resolution (ne30/1°, center) and high resolution (ne120/0.25°, right) hindcasts. Top panel shows hindcast prior to start of the 1st MJO and bottom panel shows hindcasts during the peak of the 1st MJO. Shaded pink regions indicated the period of atmospheric nudging prior to the free-running hindcasts.

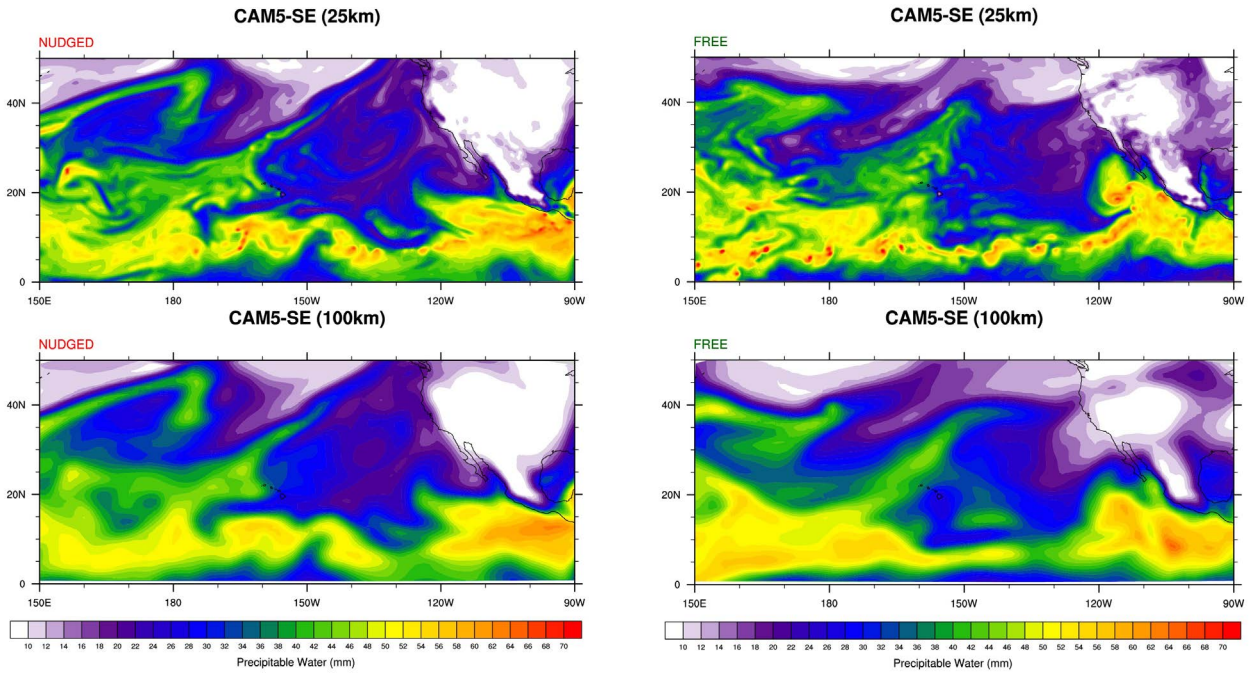

Figure 3. Snapshots of vertically integrated precipitable water (mm) for the high and low resolution hindcasts initialized at the center of MJO 1. The end of the nudging period is shown in the left panels and 5 days into the hindcast period is shown in the left panels.