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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 continues to target a capability for greater-than-weekly hindcasts as both a technical modeling framework using the Community Earth System Model (CESM) and as a resource for providing skillful projections. The framework will benefit from the research performed over the lifetime of this award. In particular there will be a capability for multiple hindcast simulations with a comprehensive diagnostic suite for assessing performance Ultimately, it is intended that the framework will enable assessment and testing of model skill in multiple locations for multiple time-periods. The greatest focus will of course be in regions of significant Navy interest and operations including the tropics, Arctic and Coastal US waters. The framework will also serve as a model validation and hindcast improvement tool with validations performed using proposed new CESM physical representations and scheme reconfigurations, since the configurations leading to the best climate of CESM may not be the same configuration that leads to the best hindcasts.

## OBJECTIVES

The technical objectives over the previous year were largely to automate the data acquisition, processing, application, simulation and diagnosis for the hindcasts that would enable us to run more efficiently and prepare the capability for a more extensive set of experiments in the future. The science objectives remain a comprehensive analysis of tropical and more specifically Madden Julian Oscillation (MJO) skill from the CINDY-DYNAMO period, including an understanding of the poorly performing processes in CESM (Hurrell et al., 2013) that limit skill. The focus will be an understanding of the relationships between resolution, phase and physical parameterization settings and hindcasts skill. As an extension we aim to understand the feasibility of examining extra-tropical skill on the two-week time frame and determine what the challenges would be to translating tropical skill into higher latitudes.

## APPROACH

We have continued our approach to the research from the previous year. Hsiaming Hsu (NCAR) has been the key technical point of contact. The research project uses versions of the Community Earth System Model (CESM) in 'climate' and 'hindcast' mode. A significant pool of existing climate simulations exist with CESM using the Community Atmosphere Model, version 5 (CAM5). These simulations are analyzed to examine the model biases that may in turn impact the hindcast simulation, ultimately limiting long-term skill.

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 known 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 forcings are also updated every 6 hours.

## WORK COMPLETED

In order to provide more robust conclusions from the initialized hindcast simulations a more comprehensive experiment set with Community Atmosphere Model version 5, (CAM5, Neale et al., 2011) was performed. This included running hindcasts that sample around the central day of the MJO maxima and minima of the CINDY-DYNAMO period for both the high resolution (25 km) and low resolution (100 km) versions previously run. With these simulations in place we have performed a comprehensive examination of the performance skill. In addition, we have performed simulations perturbing the most sensitive aspects of the parameterized physics that have emerged from previous climate-type simulations. Deep convection is the dominant process in the tropics and the most sensitive perturbed parameters relate to the imposed convective timescale and convective plume entrainment rate.

## RESULTS

The increased number of hindcast split-day ensembles and further analysis have revealed some significant emergent characteristics of the model simulations during the CIDY-DYNAMO period of 2011. Figure 1 shows the regional averaging areas for the skill characteristics to be discussed subsequently. The analysis aim was to understand the dependence of the hindcast skill on resolution, start time related to MJO skill, individual hindcast and model physics configurations.

The individual anomaly correlation (ACC) lead-time skill for different quantities in the tropical domain for all 36 hindcasts are shown in Fig. 2. It clearly shows different characteristics in the evolution of skill for different model fields. 500-mb height is a general large scale field and is largely a

function of surface pressure and temperature profiles. The hindcasts are able to maintain a generally high skill through day 5 and the ensemble average skill crosses the 0.4 threshold at day 9. However, the spread in hindcast skill is large with the 0.4 crossing point varying from 6 to 11 days. The dynamical fields have different characteristics relating to hindcast skill. They have high skill at short lead times and with a narrow spread, low-level wind has slightly higher spread than upper-levels. However, the skill reduces more quickly than for geopotential height even though all fields (temperature and surface pressure) are nudged prior to each hindcast. The poorest performance is for Outgoing Longwqave Radiation (OLR). This is not an initialized or nudged model field and so relies on the emergent properties of the parameterized cloud physics. As such it illustrates the difficulty the model has in representing the correct response of the cloud fields to the state variables. Furthermore, it illustrates the challenges of using a non-native reanalysis product in CESM. An improved response may be expected when using a native model initialization provided, for example, from the Data Assimilation Research Testbed (DART).

We also examined the sensitivity of the skill evolution according to hindcast resolution (100 km versus 25 km) and MJO phase hindcast start period (prior to and during the mature period). The resolution dependent skill evolution is shown in Figure 3. Somewhat surprisingly we can see that higher resolution does not lead to systematic improved hindcast skill at any lead time for either 500-mb height or OLR. If anything at longer lead times the 100-km hindcasts appear to perform better. The reason for this may lie in the fact the the 100-km model resolution is a much more tried and tested configuration with significant investment having been made in its performance for climate-type configurations. The 25-km version is much more experimental and hasn't been fully optimized for performance in climate-type simulations. We intend to investigate further whether more targetted measures of skill, such as measures of thermodynamical/dynamical coupling as part of the MJO can distinguish the high resolution model as being more skillful.

Figure 3 also show the dependence of skill on the hindcast start time as it relates to the MJO maturity phase. Here we see a distinct skill advantage when hindcasts are initialized during the mature phase of the MJO where observed precipitation and heating anomalies are greatest over the Maritime Continent region. For 500-mb height this improvement is significant at shorter lead times, but is lost at the longer lead times. More notable, even though skill is lower, is the higher OLR skill during the mature phase initialization. This may be explained as the model's greater difficult in initializing the non-nudged fields during the weakly forced periods prior to an MJO. Whereas in the mature phase the response to the stronger dynamical forcing has a greater chance at being more coherent with observations.

Referring to the regions in Fig 1. we have analyzed the the regional tropical skill performance in the major MJO propagation regions of the Indian and Pacific regions. In figure 4 skill evolution is broken out for the six different start periods (either prior to or during the MJO event) which includes both resolution and start-day dependent simulations. For the tropics the events are, somewhat surprisingly similarly simulated, the outliers are 'prior-to' event number one with the lowest skill and 'during' event number six with the greatest skill. In the individual basins this skill ordering of events varies significantly. Firstly the evolution of skill is not as continuous as in the whole tropical domain. For example, event number two is very poor in the Indian Ocean, but it has comparable skill to the other events in the Pacific basin. This may be a reflection of the mature MJO leaving behind a weakly forced state that is difficult to simulate in the Indian Ocean, but which is more strongly forced ahead of the event in the West and East Pacific. This is not true for all 'during' events. Event number six for example maintains similar skill among all the basins showing there are obviously different details for all the events. In general all events are most accurately simulated in the East Pacific, and apart from the

possibility of a locally more accurate hindcast, could be explained by the fact that all MJO events, whether initialized prior to or during the event maximum will extend into the East Pacific with a significant structure that is more easily represented.

A key aspect in the understand of predictability in the extra-tropics is the potential influence of tropical heating from convective processes. Much work has been done to understand the propagation of wave modes from the tropics to the extra-tropics. Chief among this work is the detailing of the emission of planetary Rossy waves in response to tropical heating (Karoly, 1981). Sardeshmukh and Hoskins (1988) show in an idealized framework that the global extra-tropical flow is forced by tropical divergent flow. We have extended this type of analysis to our tropical hindcasts. In Fig. 5 we can see that the divergent flow is much less predictable than the rotational flow. The skill is lower at short lead-times and the hindcast spread much lower. In contrast the rotational flow is much more skillful and the spread in the hindcasts much lower. This illustrates the understanding that the divergent flow in the tropics is much less predictable and more difficult that the rotational flow. The conclusion from this behavior is that the component of skill that could manifest from skill in the tropics (out to 20 days) may be largely dependent on the divergent part of the flow and this is much harder to predict that the rotational part of the flow.

Finally we have tested the sensitivity to parameter settings from the deep convection parameterization present in CESM (Neale et al., 2008). This hindcast set is focuses on only 'during' event number 2 and so is somewhat limited for interpretation. The parameter changes focus on the prescribed convection timescale and entrainment rate. From the default timescale value of 1 hour we increase it to 100 hours and also decrease it to 300 seconds. For the entrainment rate we decrease from the default value of 1/km to 0.2/km; a less entraining value. Figure 6 shows the response of the 500-mb height skill to these parameter changes. The preliminary conclusion is that the evolution of skill, even in the presence of these significant parameter changes, is more heavily dependent on forecast initialization day (given by the different line solid/dash/dot) than on the configuration of the model physics. This is certainly true for 500-mb height, but less so for OLR which may be because OLR is a more direct consequence of the parameterized physics and is therefore more impacted by the deep convection changes. These results are preliminary be we intend to experiment with more perturbed parameter experiments and also perform companion hindcasts with the new cloud physics options available in recent versions of CAM including the Cloud Layers Unified By Binormals scheme (CLUBB: Bogenschutz et al., 2013) and the Unified Convection scheme (UNICON: Park, 2014).

To extend this analysis we are planning a much more extensive suite of hindcast experiments using CESM. Utilizing computing time we hope to secure on the NCAR supercomputer (yellowstone) we will perform a range of experiments intended to analyze the tropical and extratropical climate more generally. All the experiments will now extend over a much longer time-frame than just the DYNAMO period. It will cover the period 2008-2012 which encompasses both the Year of Tropical Convection (YOTC) and DYNAMO periods. For each experiment during the whole period, hindcast simulations will be initialized every day. Then a comprehensive sub-division of start times can be constructed based on the phase of many tropical and extra-tropical phenomenon. The suite of experiments aim to address a number of research questions related to the role of resolution, physical parameterizations and aspects of simulation nudging. Resolution includes both global increases in vertical and horizontal resolutions as well as performing regional refinements of resolution in the tropical domain in order to understand the regional importance of high resolution. The proposed nudging experiments will address questions regarding the role of the atmospheric state in hindcast skill. In particular, what is the role of temperature, humidity and wind structures in maintaining the Madden Julian Oscillation (MJO) and

skill in general. Also how close to observations does the state have to be to see a significant maintenance of hindcast skill at longer lead time (>10-20 days).

## 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 a wide array of modeling aspects, including resolution, case study, initialization and parameterization dependencies

## RELATED PROJECTS

Similar non-ONR CESM Cloud Associated Paramaterization Testbed (CAPT) activities exist at NCAR as part of the DOE-NCAR cooperative agreement including projects led by Brian Medeiros and Julio Bacmeister. Also we are involved with hindcast activities at the Lawrence Livermore National Laboratory (LLNL) led by Steve Klein.

## REFERENCES


Bogenschutz, P. A., A. Gettelman, H. Morrison, V. E. Larson, C. Craig, and D. P. Schannen, 2013: Higher-order turbulence closure and it's impact on climate simulations in the Community Atmosphere Model. *J. Climate*, **26**, 9655-9676

Hoskins, B. J. and D. J. Karoly, 1981: The Steady Linear Response of a Spherical Atmosphere to Thermal and Orographic Forcing. *J. Atmos. Sci.,* **38**, 1179–1196. doi: http://dx.doi.org/10.1175/1520-0469(1981)038<1179:TSLROA>2.0.CO;2

Hurrell, J. W., and Co-authors, 2013: The Community Earth System Model: A Framework for Collaborative Research. *Bull. Amer. Meteor. Soc.*, **94**, 1339–1360.

Neale, R. B. and Co-authors, 2011: *Description of the NCAR Community Atmosphere Model (CAM5),* Technical Report NCAR/TN-486+STR, National Center for Atmospheric Research, Boulder, Colorado, 268 pp

Neale, R. B., J. H. Richter, and M. Jochum, 2008: The impact of convection on ENSO: From a delayed oscillator to a series of events. J. Climate, **21,** 5904-5924.

Park, S., 2014: A Unified Convection Scheme, UNICON. Part II. Simulation. *J. Atmos. Sci.* doi: http://dx.doi.org/10.1175/JAS-D-13-0233.1

Phillips, T.J., et al., 2004: Evaluating parameterizations in general circulation models: Climate simulation meets weather prediction *Bulletin of the American Meteorological Society*, **85**, 1903-1915.

Sardeshmukh, P. D. and B. J. Hoskins, 1988: The Generation of Global Rotational Flow by Steady Idealized Tropical Divergence. *J. Atmos. Sci.,* **45,** 1228–1251.doi: http://dx.doi.org/10.1175/1520-0469(1988)045<1228:TGOGRF>2.0.CO;2

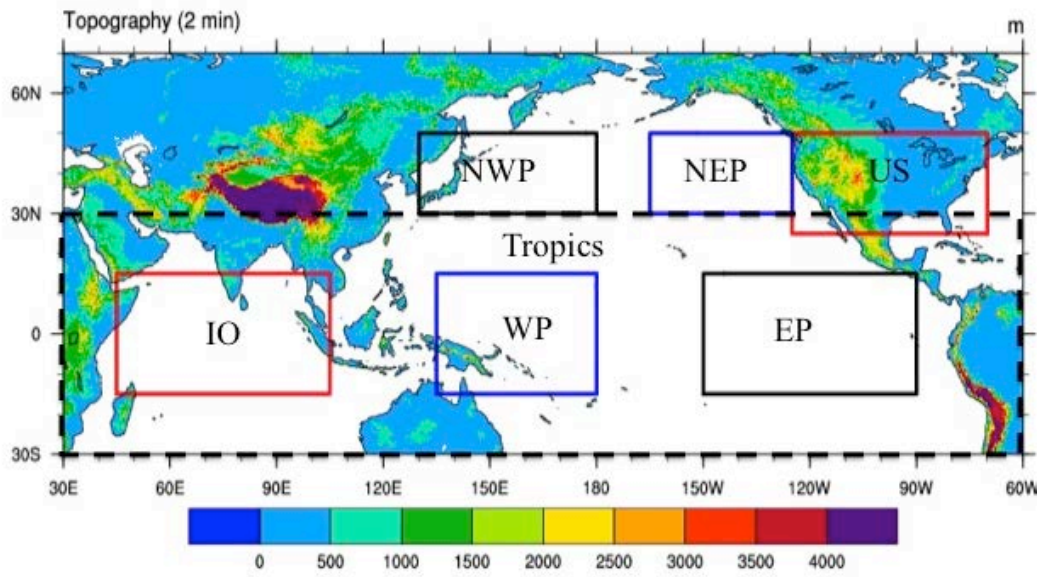


***Figure 1: Location of averaging regions for the hindcast composite skill analysis.***

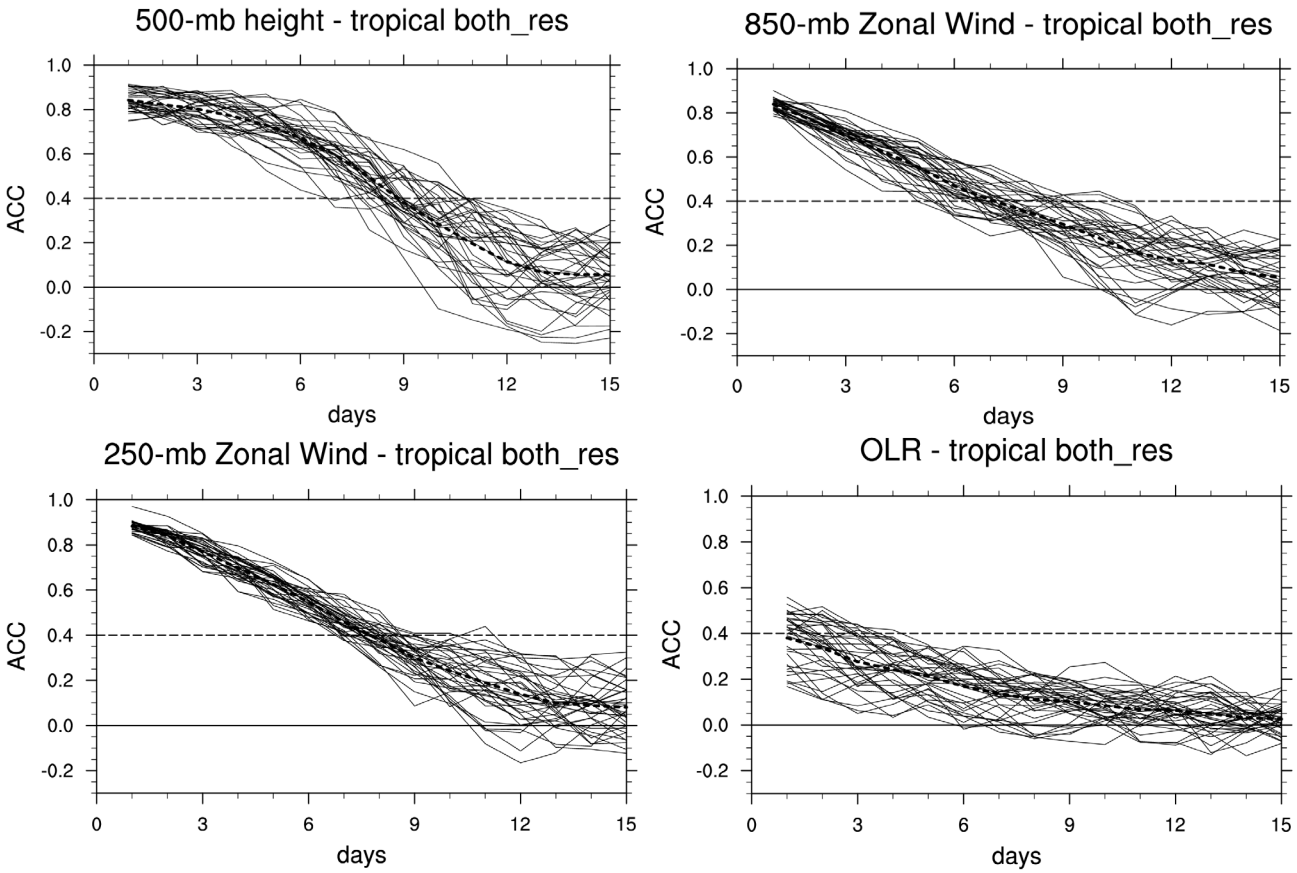


***Figure 2. Anomaly correlation coefficient skill score evolution for the ensemble of all 36 hindcasts incorporating 6 start periods each with 3 forecasts at high and low resolution. The analysis domain is the tropics (30N to 30S) and the fields are 500-mb height, 850-mb zonal wind, 250-mb zonal wind and outgoing longwave radiation (OLR).***

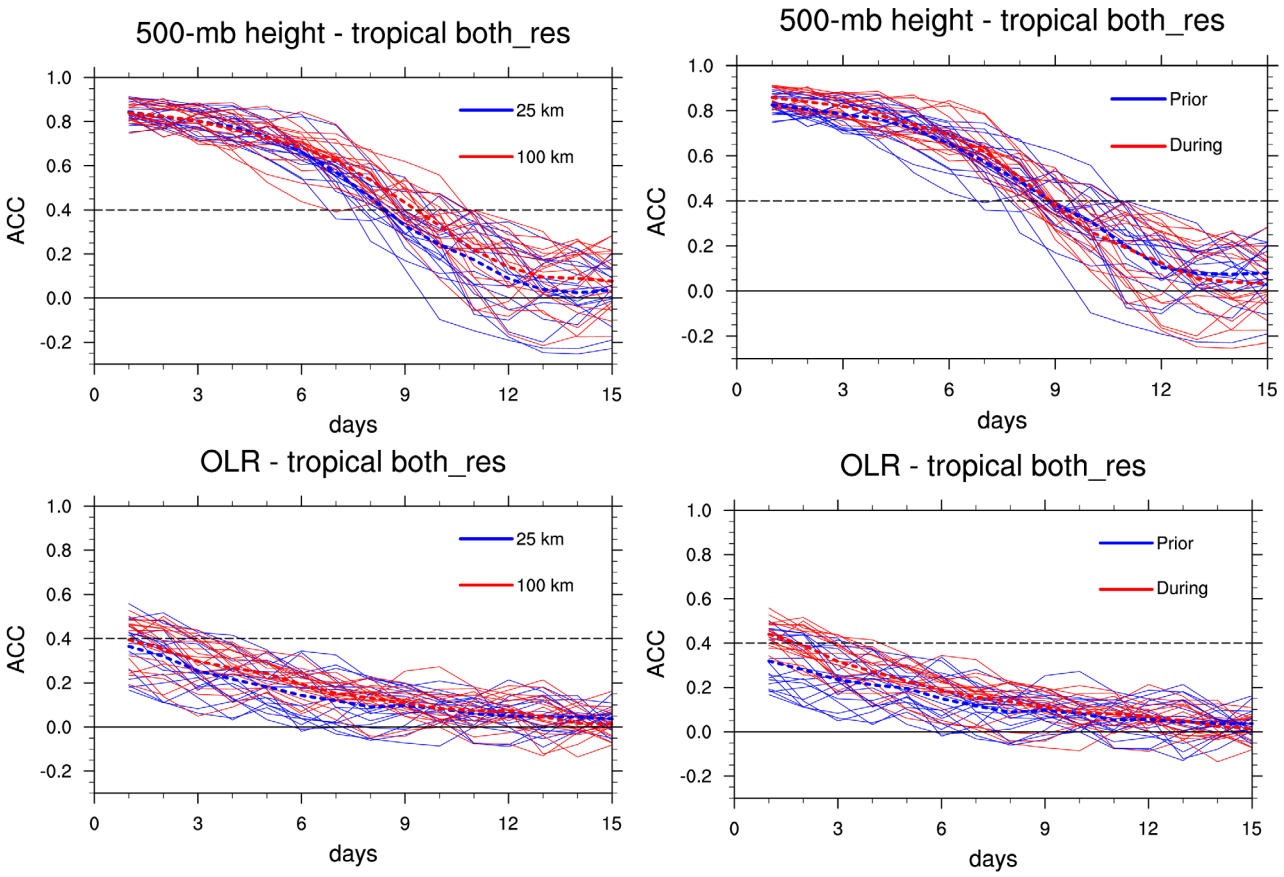


***Figure 3. Anomaly correlation coefficient (ACC) skill scores broken out according to resolution (left) and MJO dependent start period (right).***

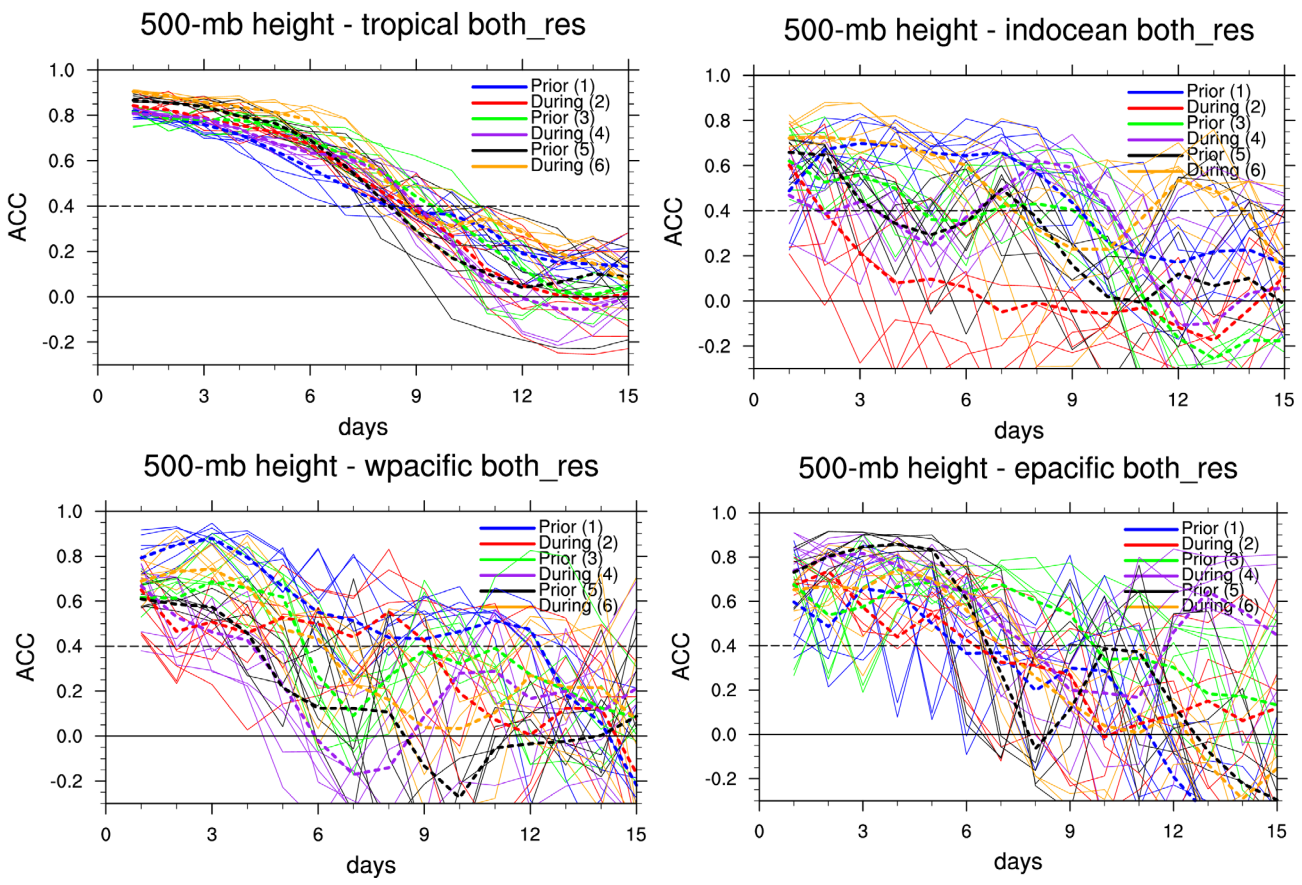


***Figure 4. Anomaly correlation coefficient (ACC) skill scores of 500-mb height for different tropical regions (top-left: Tropics top-right: Indian Ocean, bottom-left: West Pacific, bottom-right: East Pacific). Domains are shown in Fig. 1.***

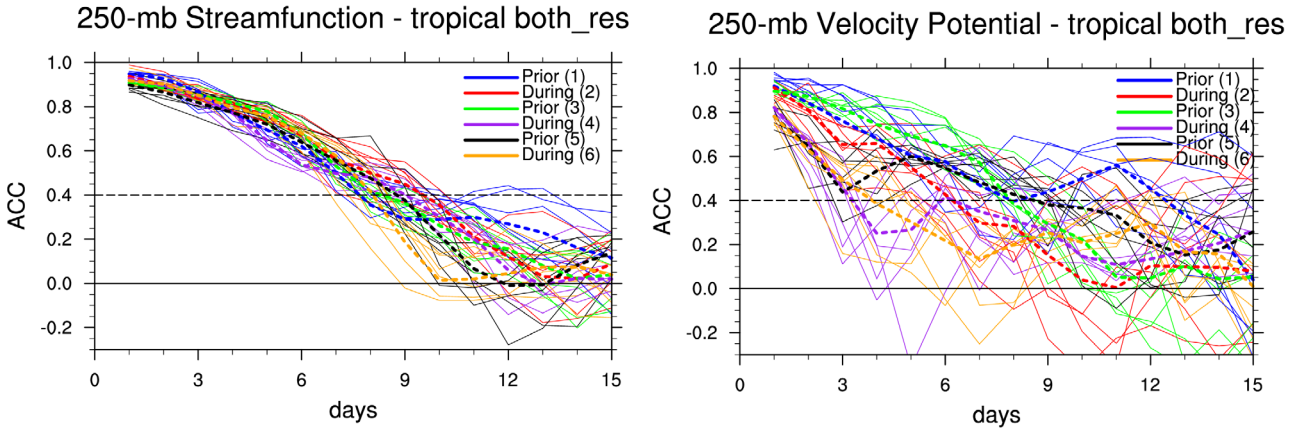


***Figure 5. Hindcast anomaly correlation coefficient (ACC) for the tropical rotational flow (streamfunction, left) and divergent flow (velocity potential, right).***

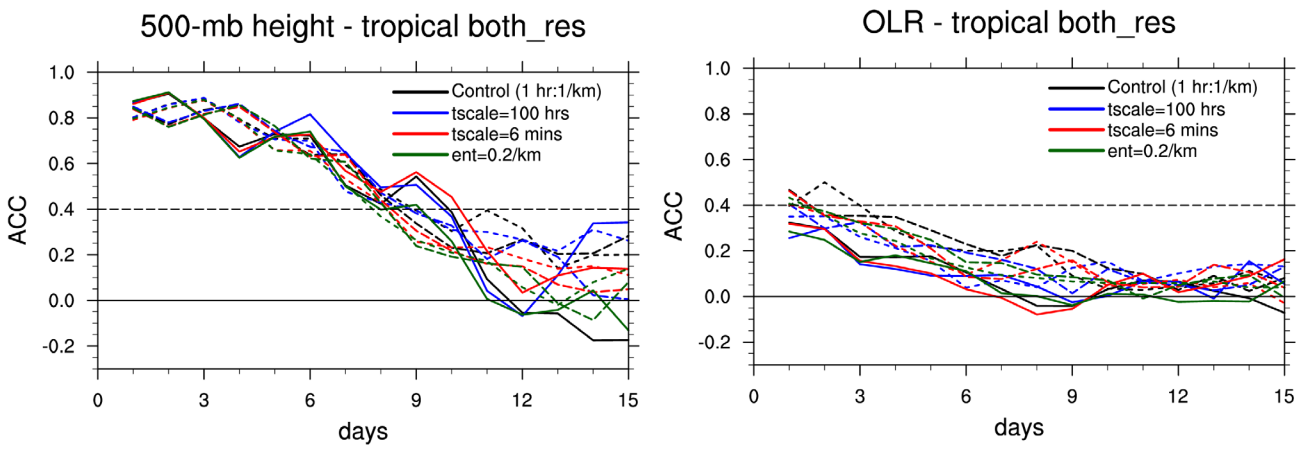


***Figure 6. Evolution of ACC for 500-mb height (left) and OLR (right) for event 2. Color lines show convection modifications. Different line dash patterns (solid/dash/dotted) correspond to the 3 different start dates at the peak of MJO event 2.***