# Propagation of the MJO and Associated Moist Dynamics, and the Advantages of Enhanced Resolution in NASA's GEOS-S2S Forecast System

Young-Kwon Lim[1,2], Andrea Molod[1], and Nathan Arnold[1]

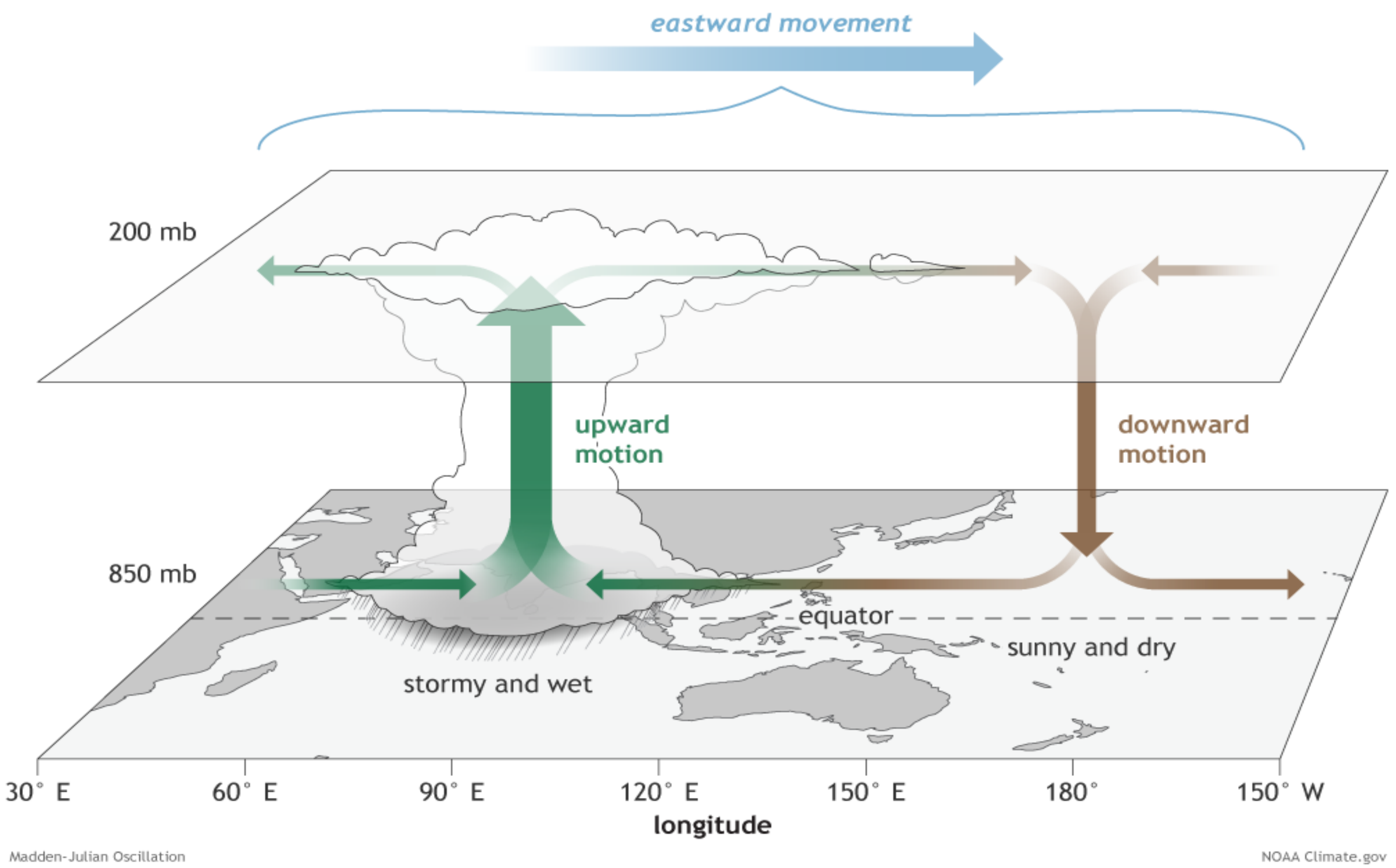
[1]NASA Goddard Space Flight Center, Global Modeling and Assimilation Office,
[2]GESTAR II, University of Maryland, Baltimore County

GMAO
Global Modeling & Assimilation Office
NASA
GODDARD EARTH SCIENCES
GESTAR II

# Introduction (Background and Objective)

- S2S models have enhanced the MJO prediction skill over the recent decades. NASA's GEOS-S2S forecast system, in particular, exhibits a correlation of 0.5 based on the Real-time Multivariate MJO (RMM) at a forecast lead time of 28 days (Lim et al. 2021).

- However, further enhancing the prediction skill faces ongoing challenges with the Maritime Continent barrier effect (e.g., Vitart and Molteni 2010)).




- Many agree that accurately depicting MJO events as they traverse the MC region and extend into the W Pacific has the potential to advance the MJO prediction skill (e.g., Abhik et al. 2023).

- This presentation covers two main points: it 1) presents the performance of the GEOS-S2S forecast system in predicting MJO propagation and 2) explores the advantages of higher resolution in capturing air-sea coupled effects, resulting in improved representation of MJO propagation across the MC.

GODDARD EARTH SCIENCES

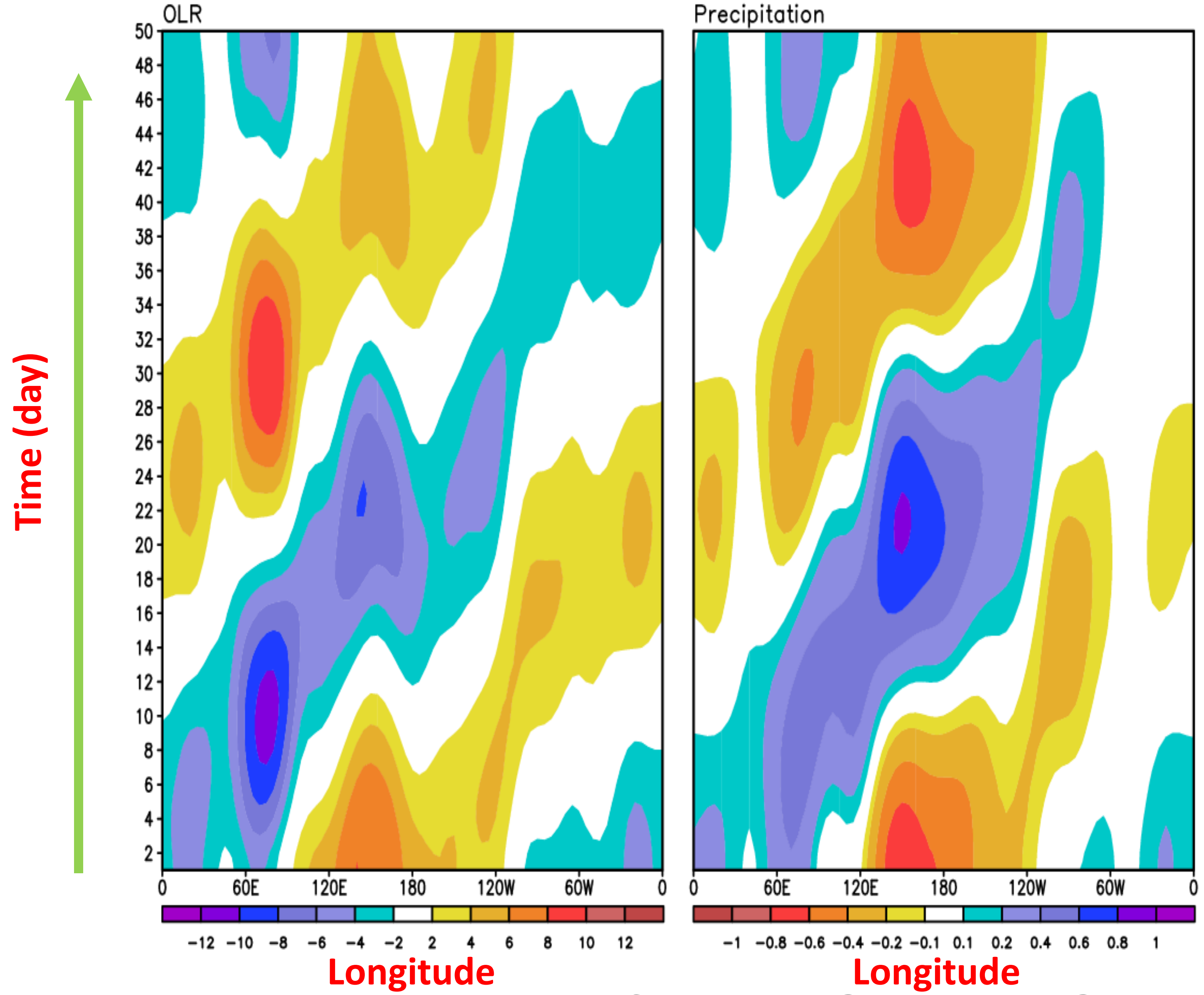
# GEOS-S2S model and experiment

NASA

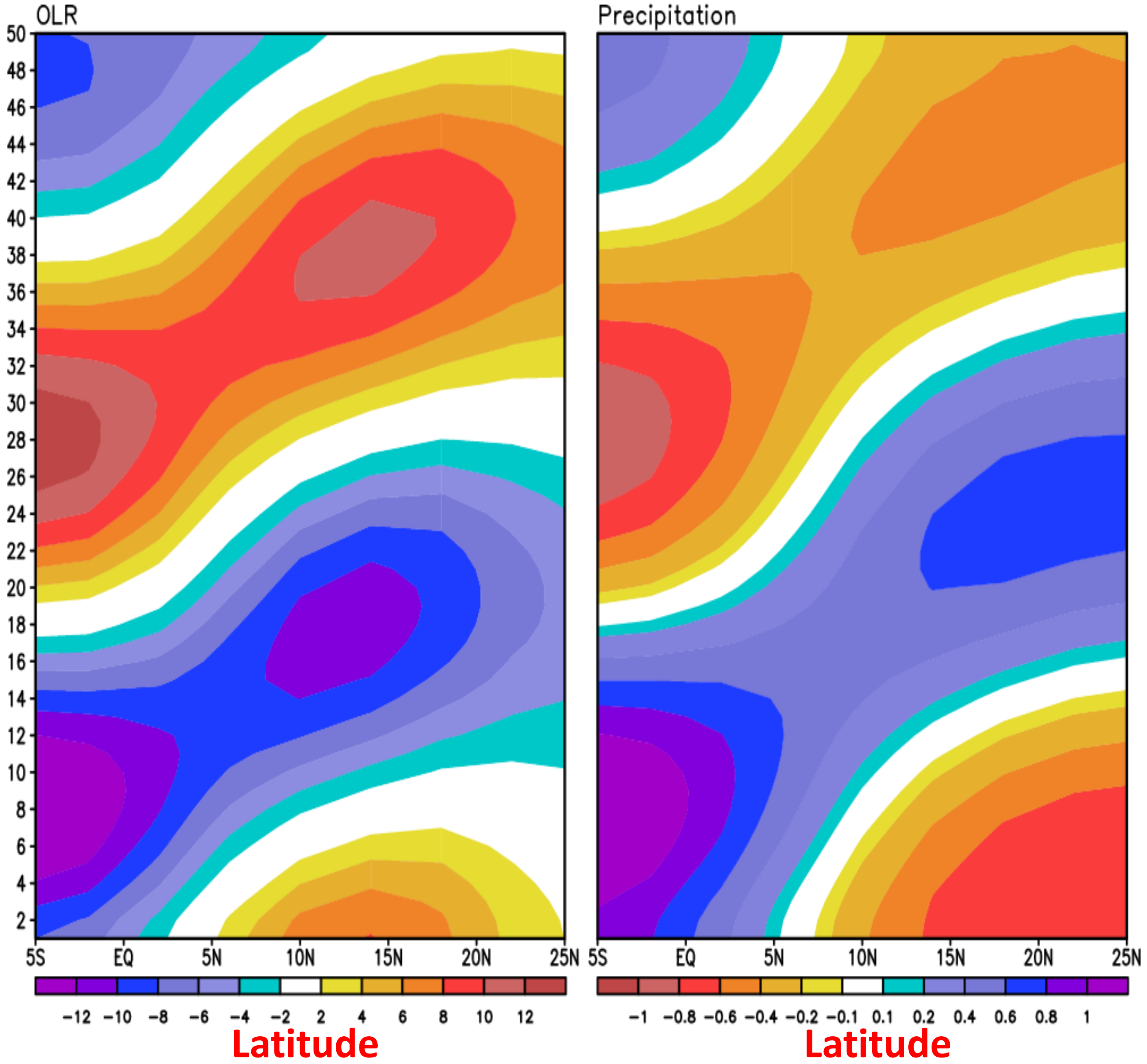
- Fully coupled global model: GEOS AGCM, land model, MOM5 ocean model (50 levels), and CICE-4
- Two-moment cloud microphysics (aerosol cloud interaction)
- New atmosphere-ocean interface layer – diurnal warm and cool-skin layer, to better represent surface fluxes (radiation, heat, turbulence…)
- Improved icesheet runoff to proper location
- Resolution: ~0.5 degree for atmosphere and ~0.25 degree for ocean
- Experiments: 200-yr "perpetual" simulations with atmospheric $CO_2$ and TOA radiative condition as in Y2000 annual cycle. (This condition is fixed over 200-yr run period)

# Eastward and northward propagation of the MJO-driven OLR and precipitation (MJO composite)

## Eastward propagation (*OLR (left) and precip. (right)*) along the equator




## Northward propagation (BSISO) over the Indian Ocean sector in summer




Eastward propagation of the MJO-driven OLR and precipitation along the equator is reliably represented. The model also captures the Boreal Summer Intraseasonal Oscillation (BSISO) propagating northward over the Indian Ocean Sector. But some of the BSISO appears to have a northward jump, rather than a continuous northward progression (this is not consistent with the observed behavior).

# Moist static energy (MSE) growth and premoistening ahead of MJO convection

GODDARD EARTH SCIENCES

NASA

## Moist static energy (MSE) budget (e.g., Arnold et al., Adames et al., Maloney et al., DeMott et al., Sobel et al. etc.)

The positive MSE tendency to the east of the MJO convection is associated with the premoistening process that promotes the eastward MJO propagation.

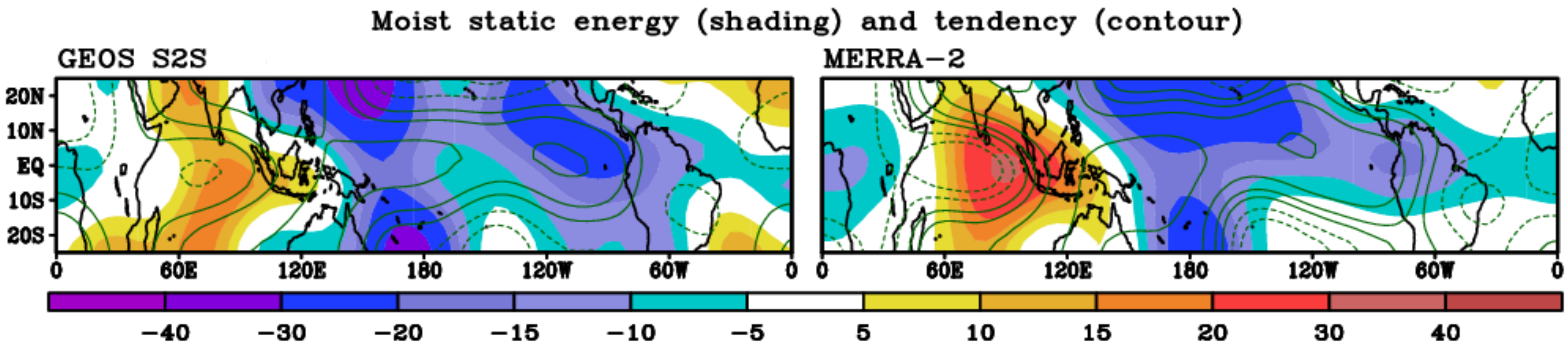
$$\langle\frac{\partial m}{\partial t}\rangle = -\langle V\cdot\nabla m\rangle - \langle\omega\frac{\partial m}{\partial p}\rangle + \langle LW\rangle + \langle SW\rangle + LH + SH + \langle\frac{\partial m}{\partial t}\rangle ANA$$

Angle brackets denote a pressure-weighted vertical integral.

(For reanalysis only)

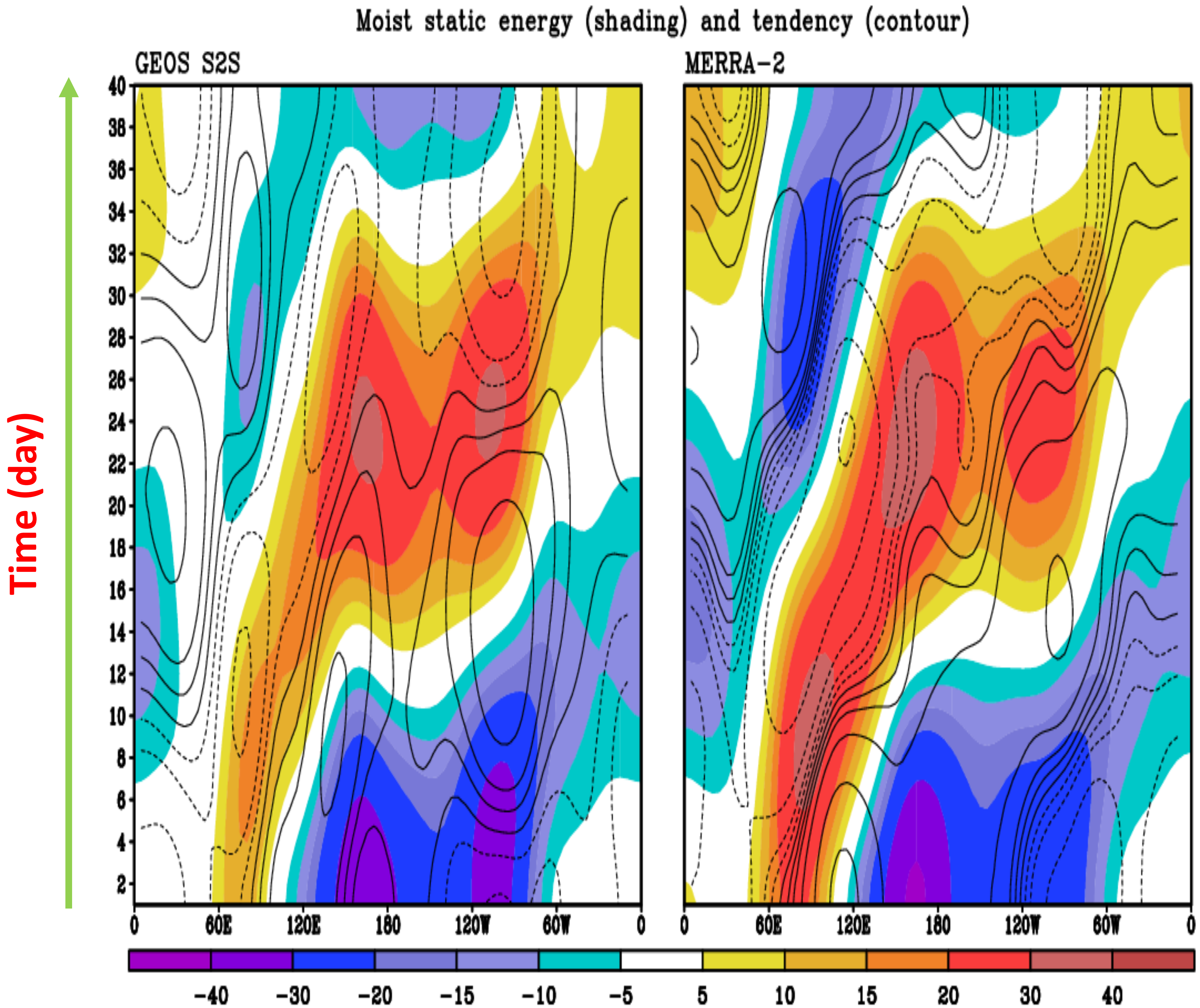
MSE ($m$) $m = c_pT + gZ + L_vq$, and the MSE tendency is controlled by advection, longwave (LW) and shortwave (SW) radiative heating, latent heat flux (LH), and sensible heat flux (SH), and for reanalysis (MERRA-2) only, the analysis increment of MSE.

MSE (shaded), MSE growth (contoured)



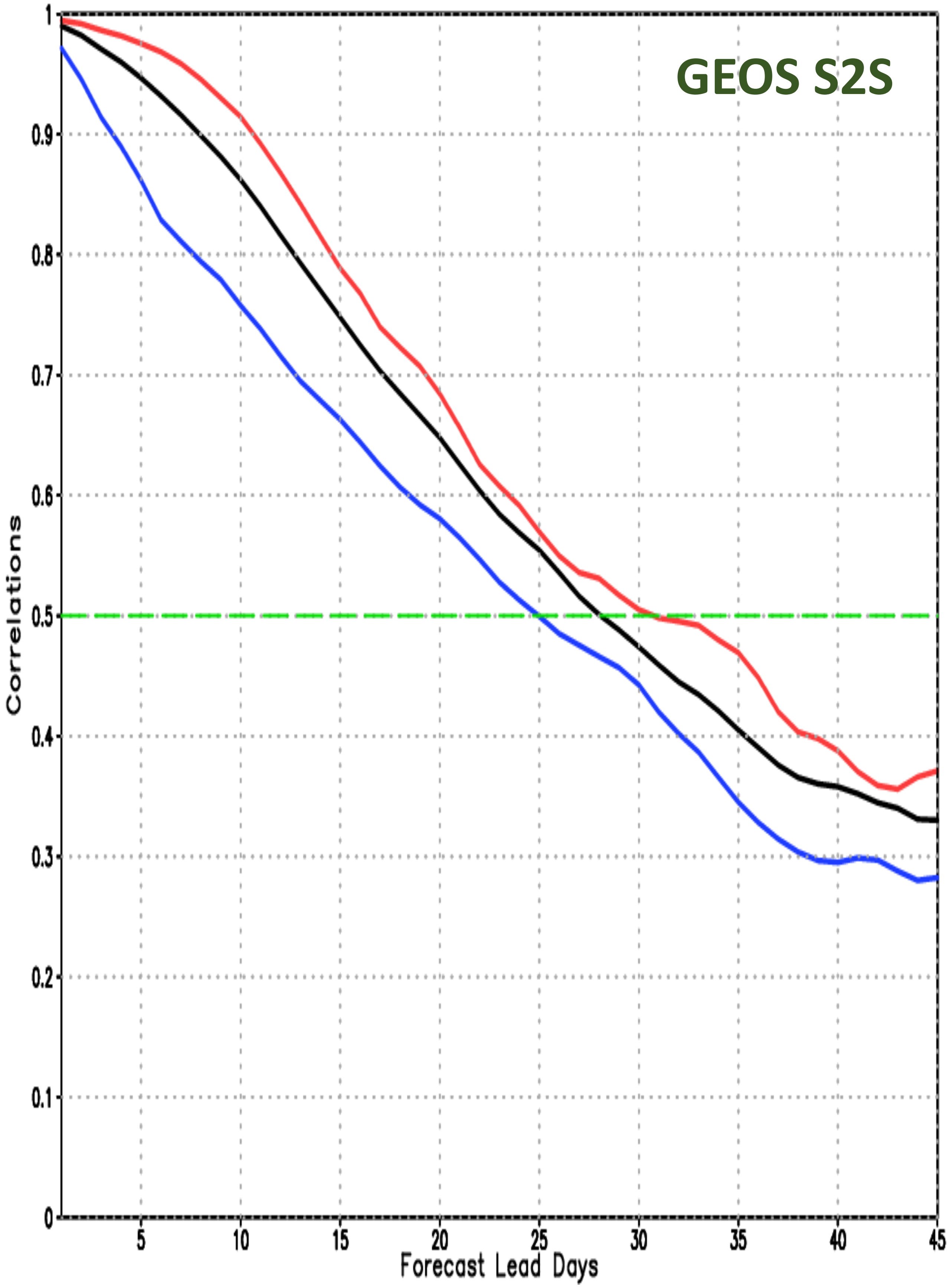

MSE is growing to the east of the current MJO convection (positive contours), helping eastward propagation of the MJO.

# Eastward propagation of the MSE and its tendency




MSE tendency that denotes the MSE growth (suppression) is located 90º ahead of (behind) of the red-shaded positive MSE anomaly, which indicates the current MJO convection. The model reproduces this phase relation and eastward progression of MSE and MSE tendency, with speed comparable to MERRA-2.

# MJO prediction skill (bivariate corr.) by the current operational GEOS S2S forecast model

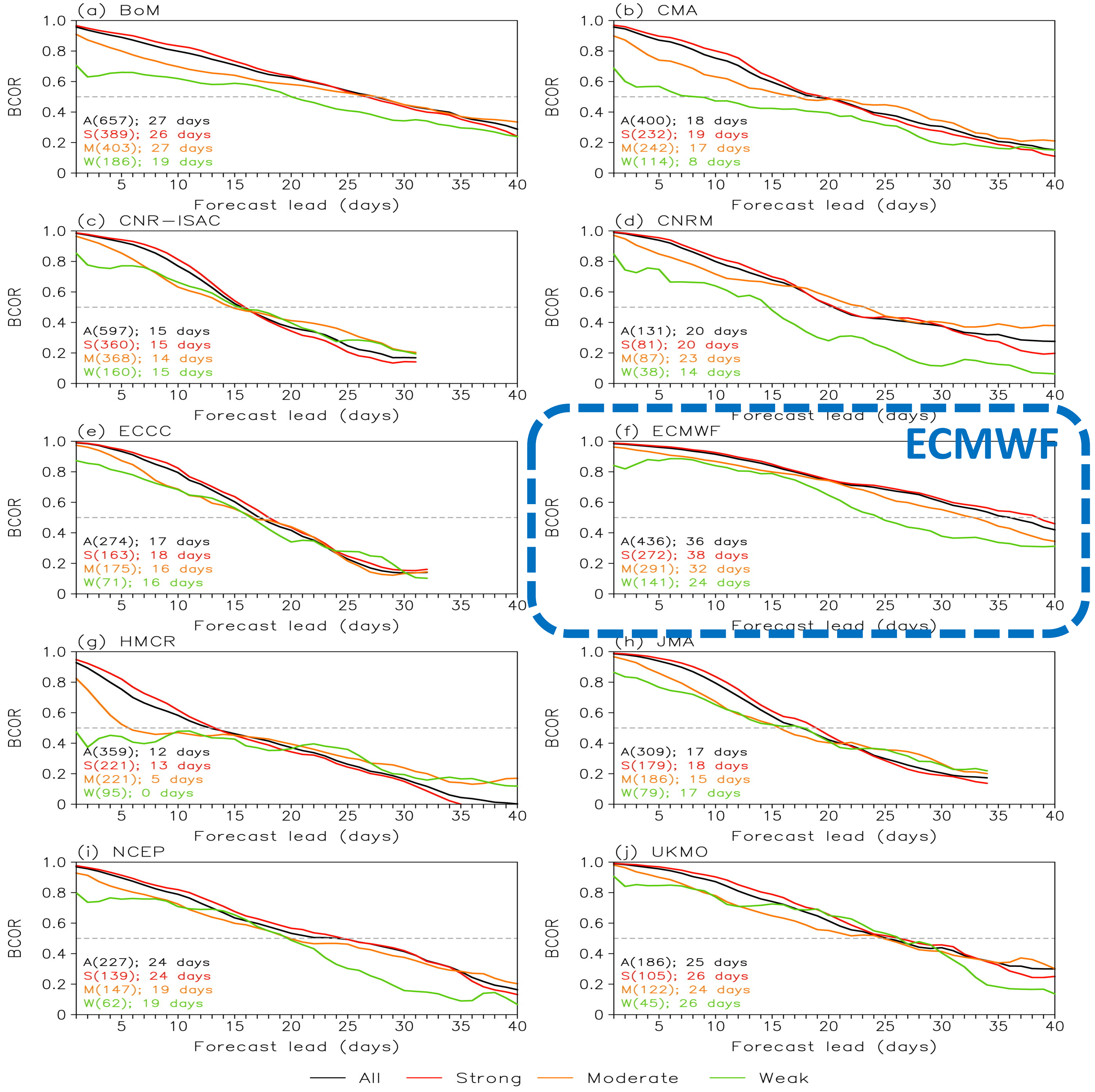



Bivariate correlations of Real-time Multivariate MJO (RMM1 and RMM2) time series between observation and prediction

Red: strong MJOs (RMM ≥ 1),
blue: weak MJOs (RMM < 1),
black: all MJOs

Correlations for all MJOs are greater than 0.7, 0.6, and 0.5 at 15-, 20- and 25-day lead. Correlation is near 0.5 at 28-day lead.

## Skills by other S2S forecast models (Y-N Lim et al)



GODDARD EARTH SCIENCES

# Part II: Experiments with higher horizontal resolution

NASA

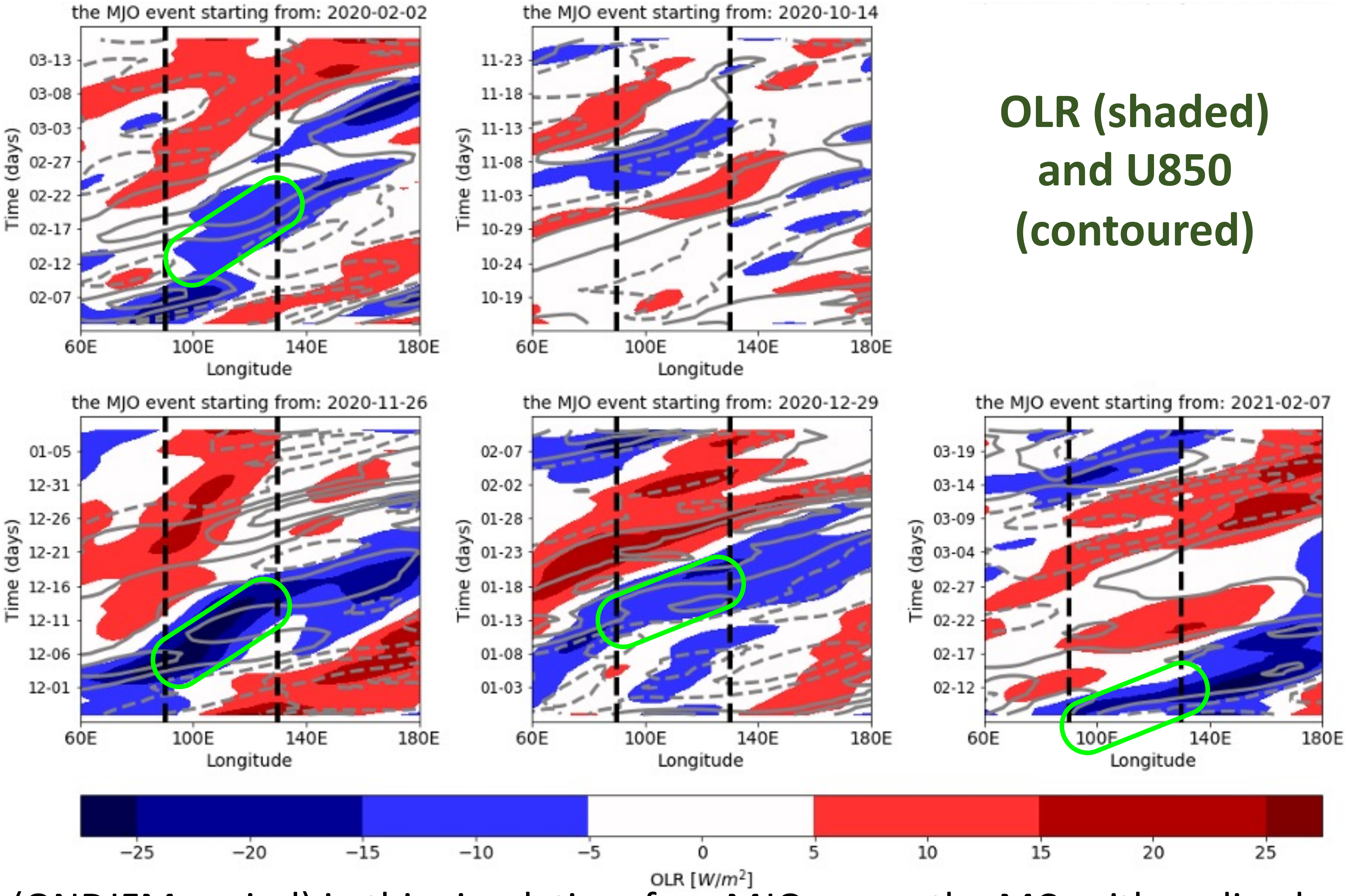
- How substantially can higher resolution enhance the eastward propagation of MJO across the MC? This experiment aims to investigate the impact of higher horizontal resolution (cloud-resolving scale) on depicting MJO-related surface features with a focus on air-sea coupled processes (*More effective air-sea coupled process at higher resolution (e.g., Crueger et al. 2013) OR skill insensitive to the resolution change (e.g., Zhu et al. 2017)?* )

- NASA's GEOS ECCO simulations (NASA GEOS AGCM coupled with MIT OGCM): Higher-resolution global storm- and eddy-resolving simulations that explicitly resolve atmospheric convection, cloud/precip., ocean turbulence/currents, fluxes at the interfaces of the Ocean-Atmosphere, etc. (ECCO: Estimating the Circulation and Climate of the Ocean)

- Resolution: ~7km, 72 level atmosphere and 2~4km, 90 level ocean
- Simulation period : 14 month (late January 2020 – late March 2021)

- Results are compared with coarser-resolution version (1 deg lat.-lon.) multi-decadal runs

# MJO propagation across the Maritime Continent in higher-resolution model




**OLR (shaded) and U850 (contoured)**

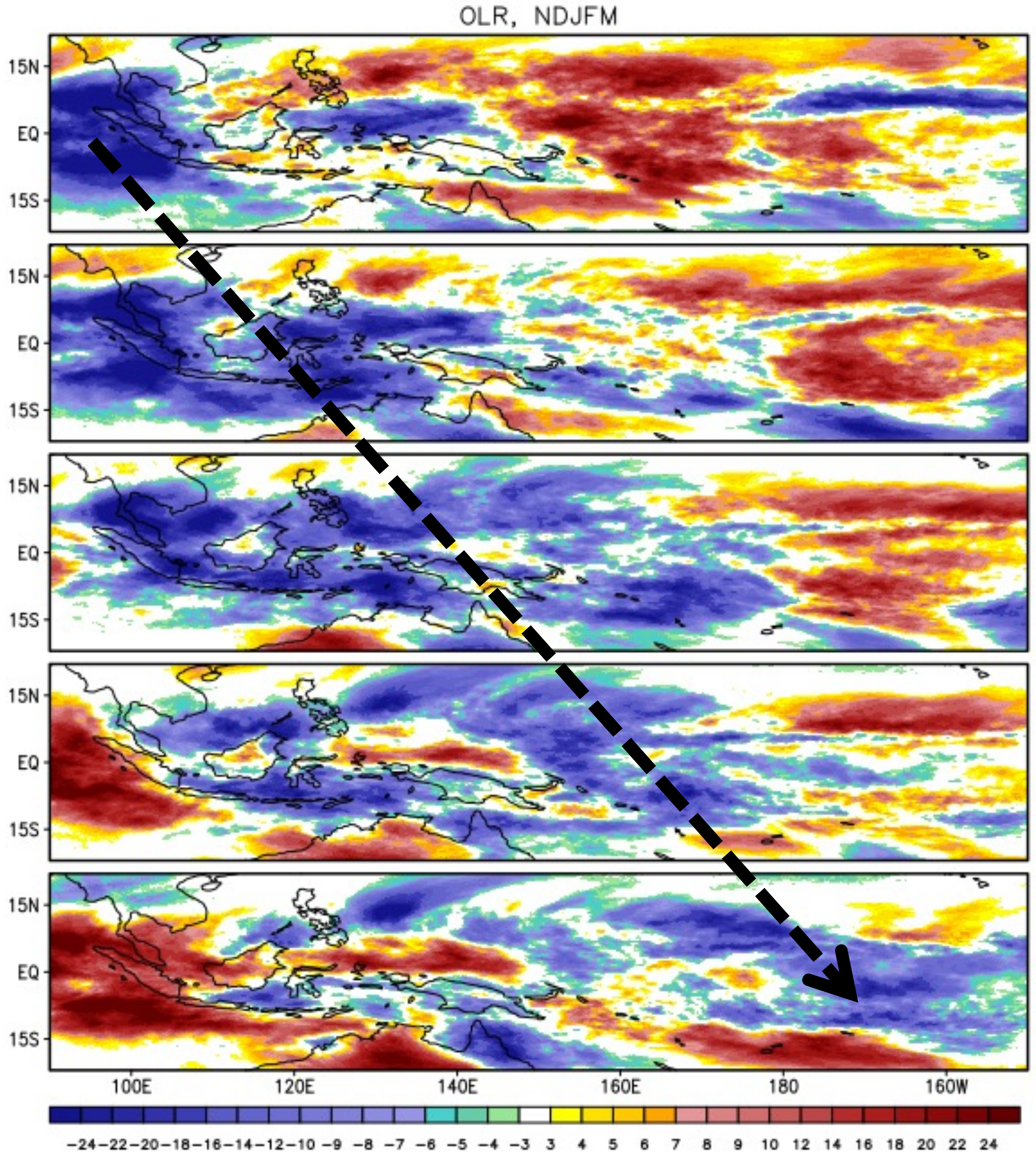
Courtesy of Danni Du

Of the 5 MJOs detected (ONDJFM period) in this simulation, four MJOs cross the MC, with ending longitudes east of ~150E. The same model run at coarser resolution (1˚ lat.-lon.) over two-decades exhibits ~35% of the MJOs cross the MC (composite on the next slide).

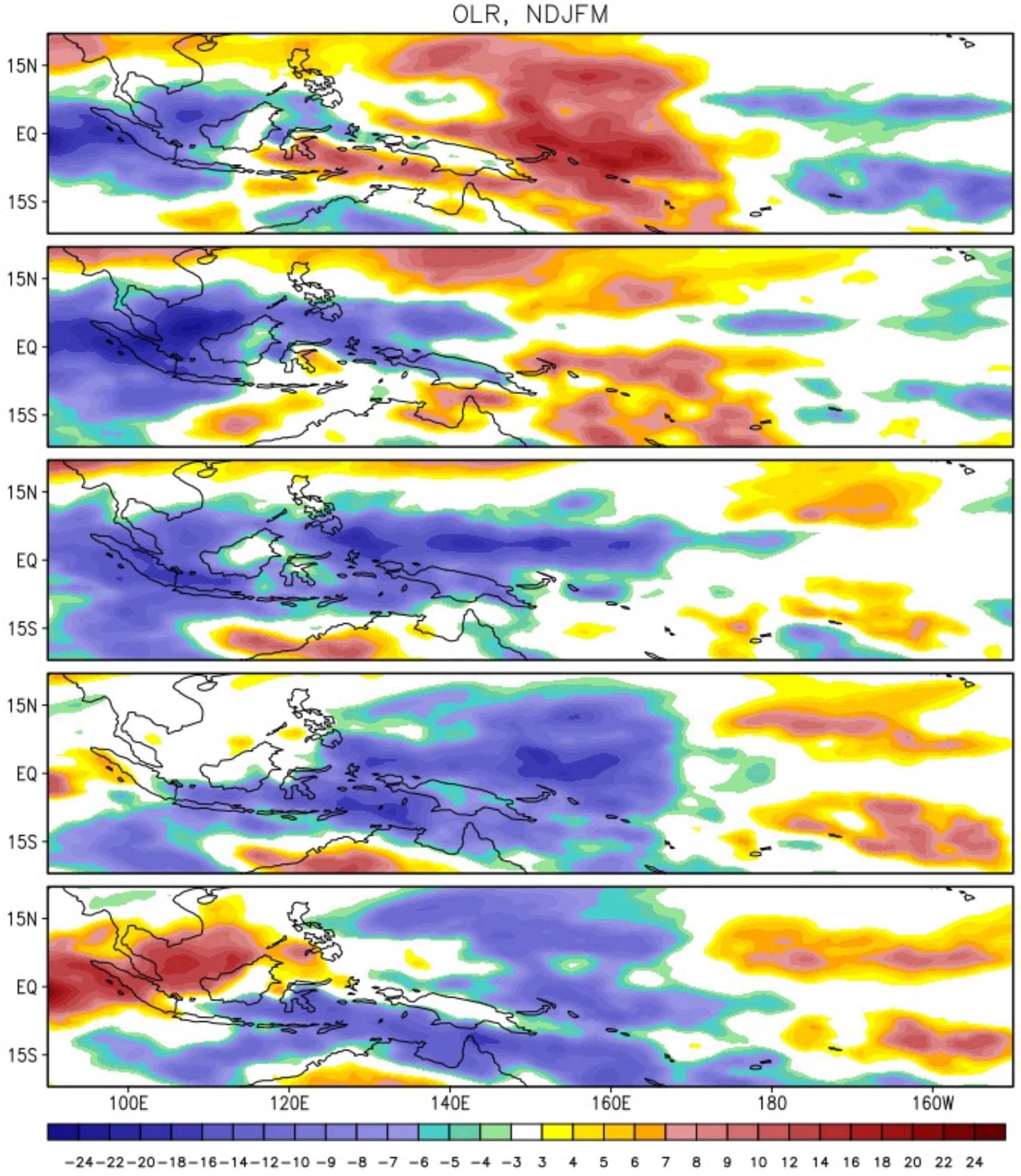
GODDARD EARTH SCIENCES

# MJO propagation across the MC in low resolution model (comparison with high-resolution)

**OLR, NDJFM (high resolution)**

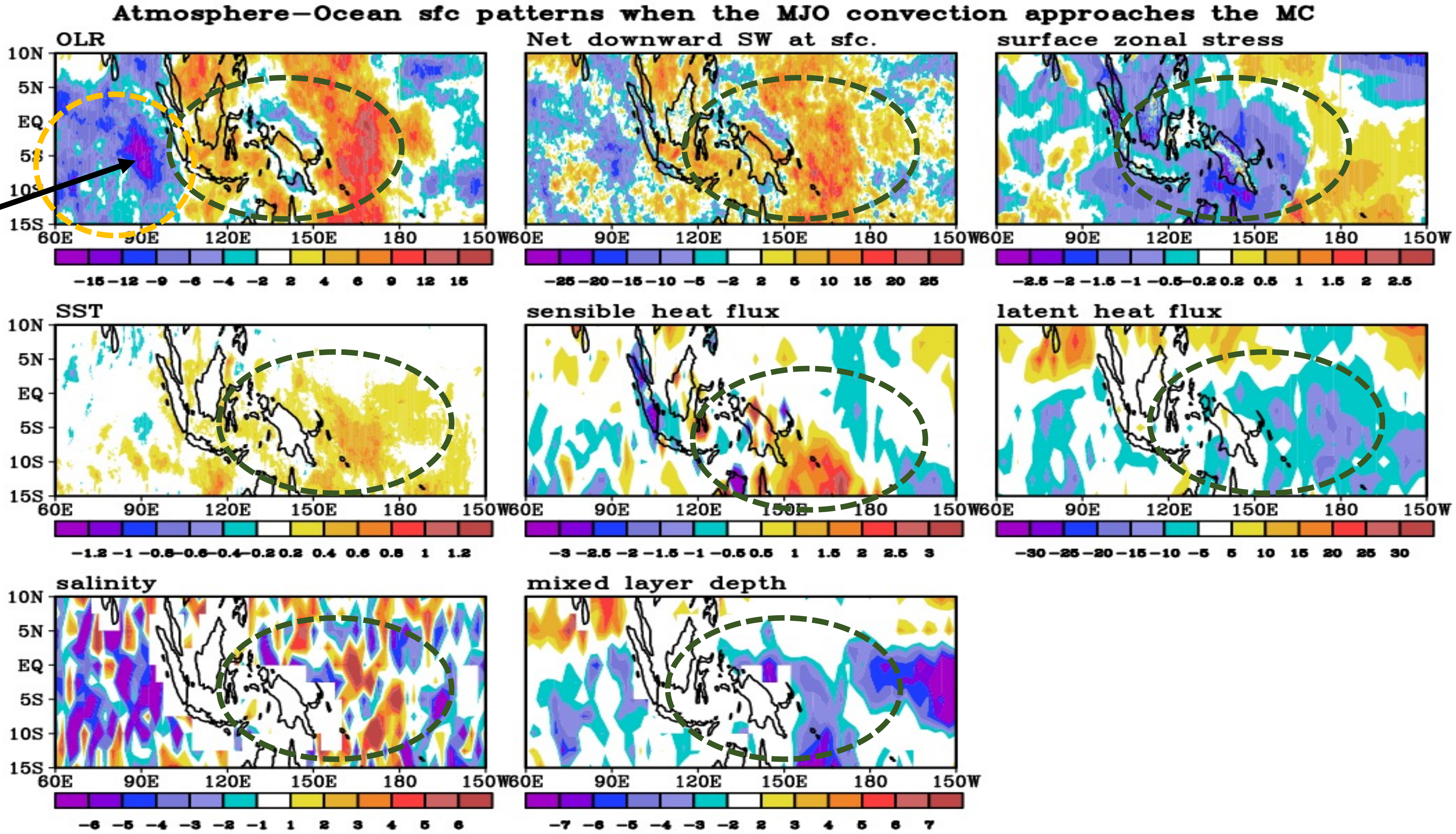



**OLR, NDJFM (low resolution)**




Cloud resolving high-resolution run exhibits the development of local convections over the seas in the MC and better represent the eastward MJO propagation into the western Pacific, with larger amplitude of anomalies than the coarser resolution run.

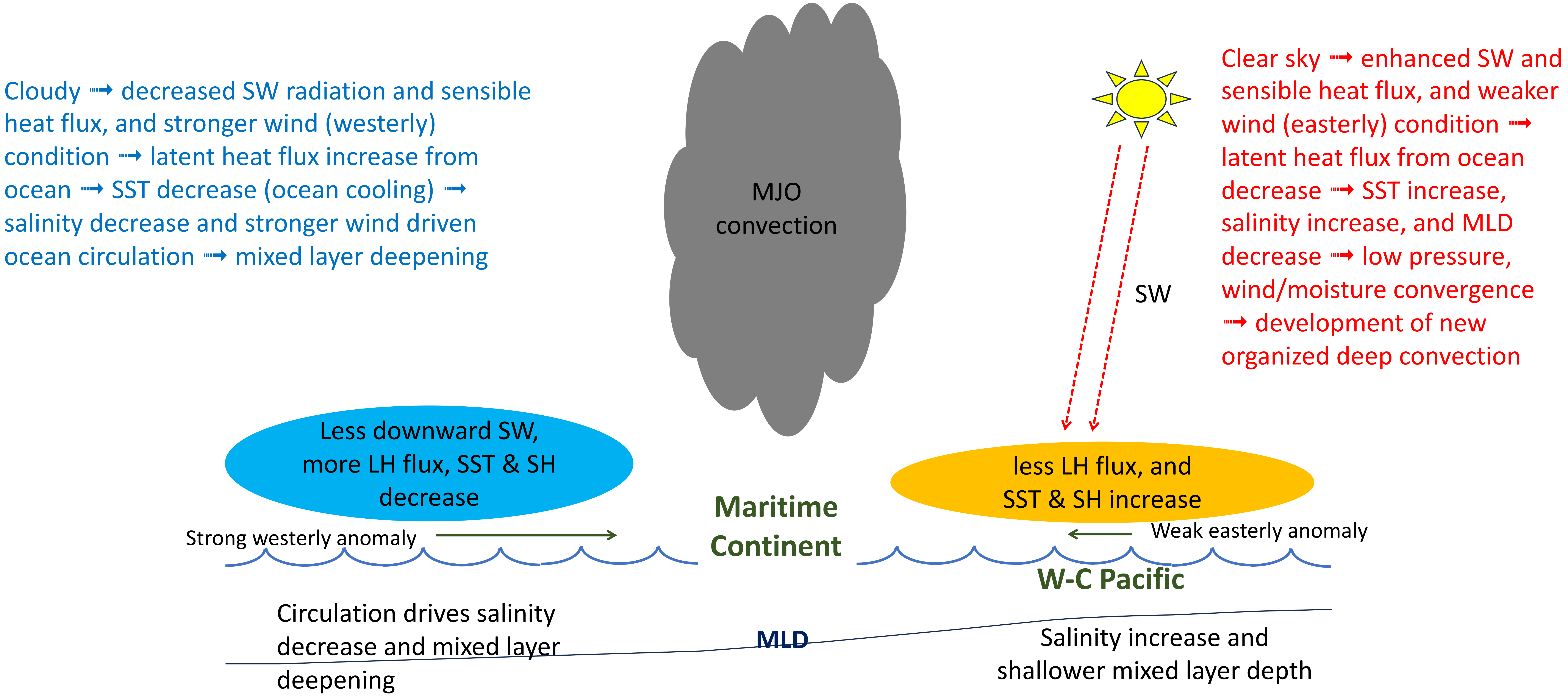
# Sfc patterns east of current MJO convection approaching the MC (higher resolution run)



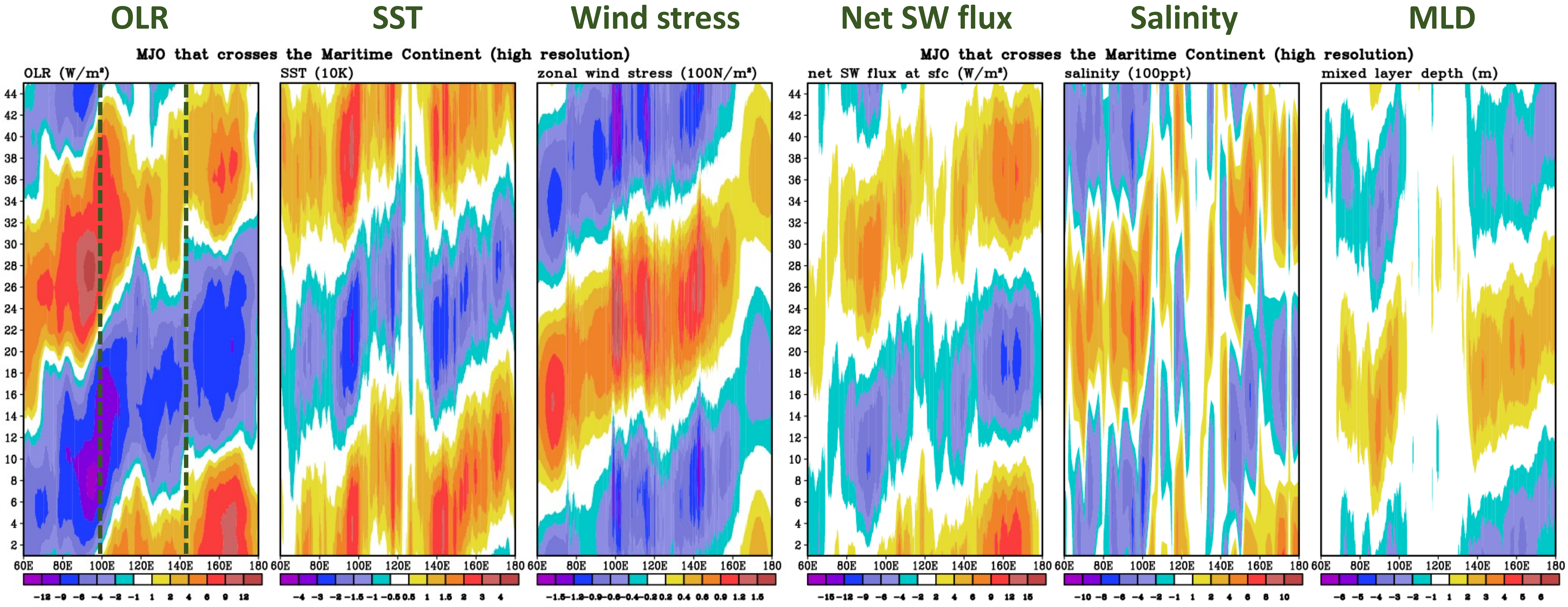

Current MJO convection

Over the region to the east of MJO convection: Net downward SW flux ⇧, Easterly stress ⇧, SST ⇧, Sensible heat flux ⇧, Latent heat flux ⇩, Salinity ⇧, and mixed layer depth ⇩

# Eastward MJO propagation associated with air-sea coupled process



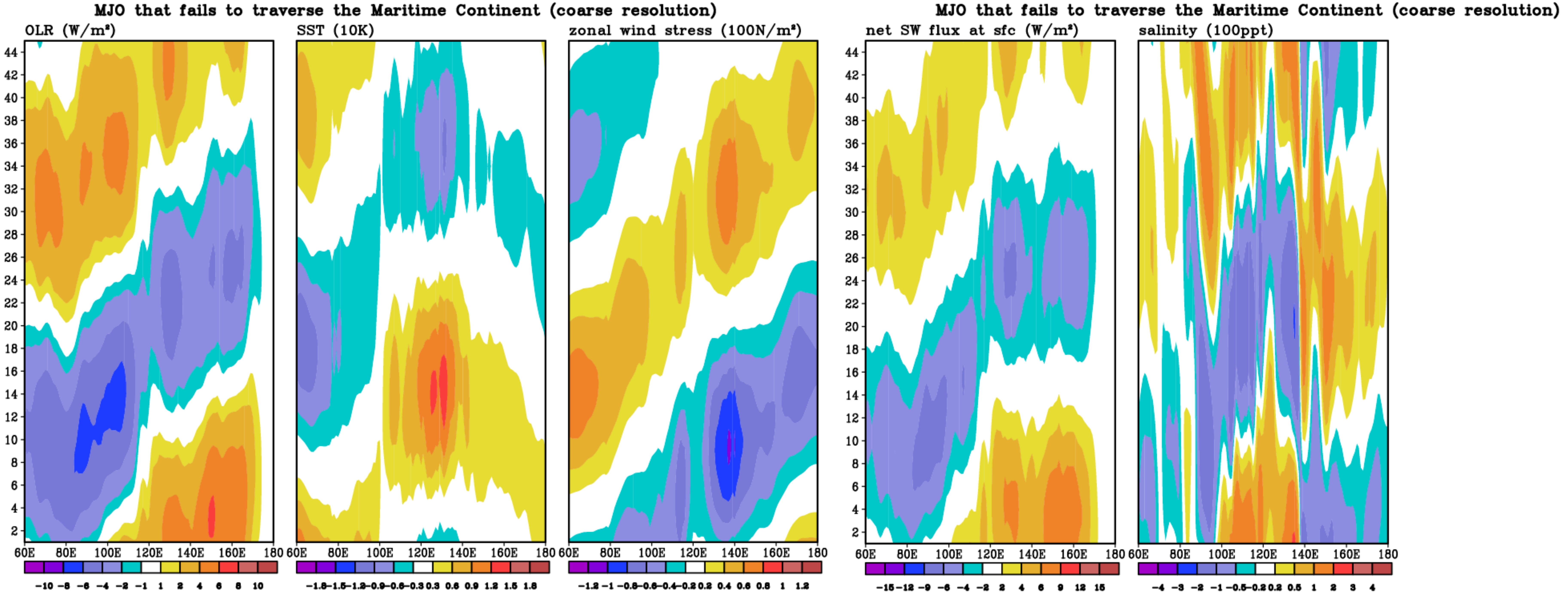
# Evolution of ocean-atmosphere sfc variables along the equator in association with MJO (higher resolution run)




Higher resolution run: Anomalies to the east of MJO evolve with time propagating eastward, enabling the MJO convection to traverse the MC and propagate further into the W Pacific.

# Evolution of ocean-atmosphere sfc variables along the equator in association with MJO (lower resolution run)

**OLR** | **SST** | **Wind stress** | **Net SW flux** | **Salinity**




Lower resolution run: The MJO OLR indicates eastward propagation but stalls around 160-170 E. Wind stress and SW flux show eastward propagation across the MC. However, ocean variables of SST and salinity peak at MC longitudes and do not extend further to the east.

GODDARD EARTH SCIENCES

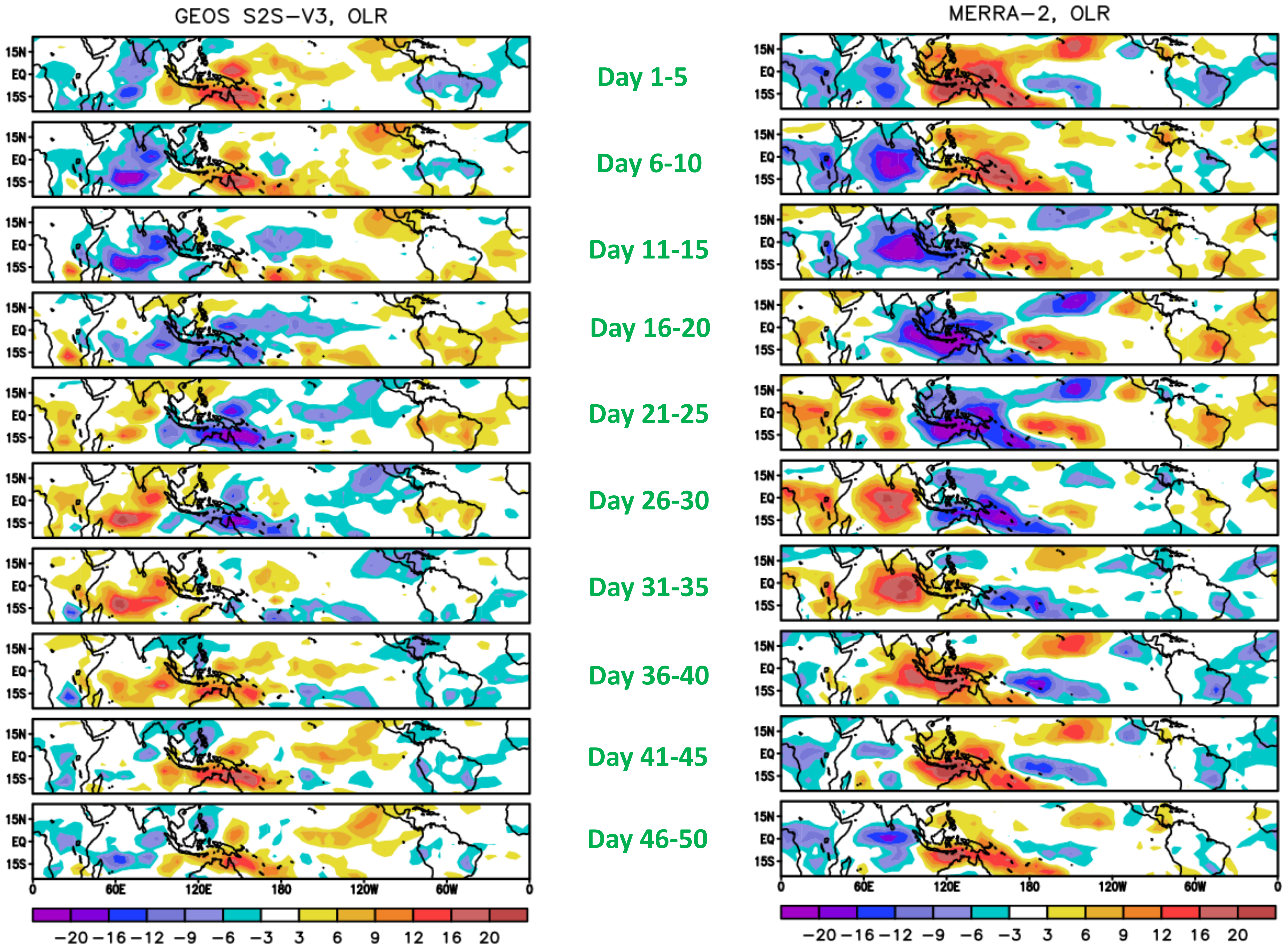
# Concluding remarks

- The new GEOS S2S forecast system reliably represents the eastward & northward propagation of the MJO, propagation speed, moist static energy growth and advection to the east of the MJO convection anomaly (a crucial premoistening process for MJO propagation).

- NASA's current operational system demonstrates a strong predictive capability for the MJO, achieving a correlation of 0.5 based on Realtime Multivariate MJO (RMM) at ~28 forecast lead days.

- However, there are still many MJOs that fail to traverse the MC in the forecast system. Experimental study using a cloud-resolving higher resolution coupled model (~7 km atm. and 2-4 km ocean) indicate that increased resolution benefits the realistic representation of the MJO propagation across the MC and further into the western Pacific, with larger amplitude of anomalies than the coarser resolution run. Specifically, the higher resolution model better captures the feedback from SST and salinity linked to air-sea coupling particularly in the W-C Pacific, facilitating the eastward MJO propagation into the Pacific.

# MJO evolution in the tropics




Both GEOS S2S and MERRA-2 show the MJO propagation that takes about 45 days to complete one cycle along the equator. 45 days => 5 m/s: typical MJO speed

# Moist static energy growth and premoistening ahead of MJO convection

## Moist static energy budget

***The positive MSE tendency to the east of the MJO convection is associated with the premoistening process that promotes the eastward MJO propagation.***

$$\langle\frac{\partial m}{\partial t}\rangle = -\langle V \cdot \nabla m\rangle - \langle \omega \frac{\partial m}{\partial p}\rangle + \langle LW\rangle + \langle SW\rangle + LH + SH + \langle\frac{\partial m}{\partial t}\rangle ANA$$

(For reanalysis only)

Where angle brackets denote a pressure-weighted vertical integral

$$\langle A\rangle = \frac{1}{g}\int_{p(bottom)}^{p(top)} A\, dp$$

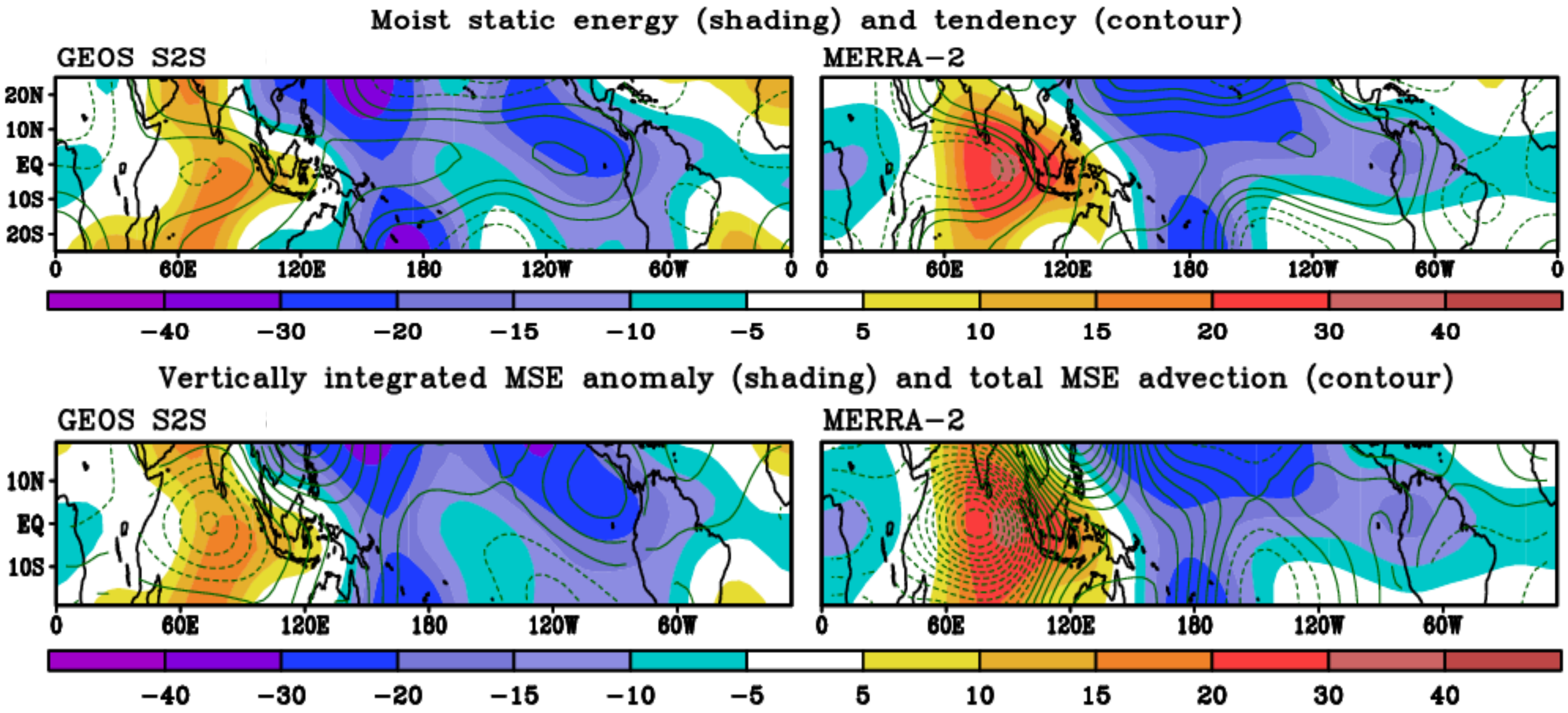
MSE ($m$) $m = c_p T + gZ + L_v q$, and the MSE tendency is controlled by advection, longwave (LW) and shortwave (SW) radiative heating, latent heat flux (LH), and sensible heat flux (SH), and for reanalysis (MERRA-2) only, the analysis increment of MSE.

# MSE growth and MSE advection to the east of MJO convection located near the Maritime Continent

**GEOS S2S** **MERRA-2**

**MSE (shaded), MSE growth (contoured)**

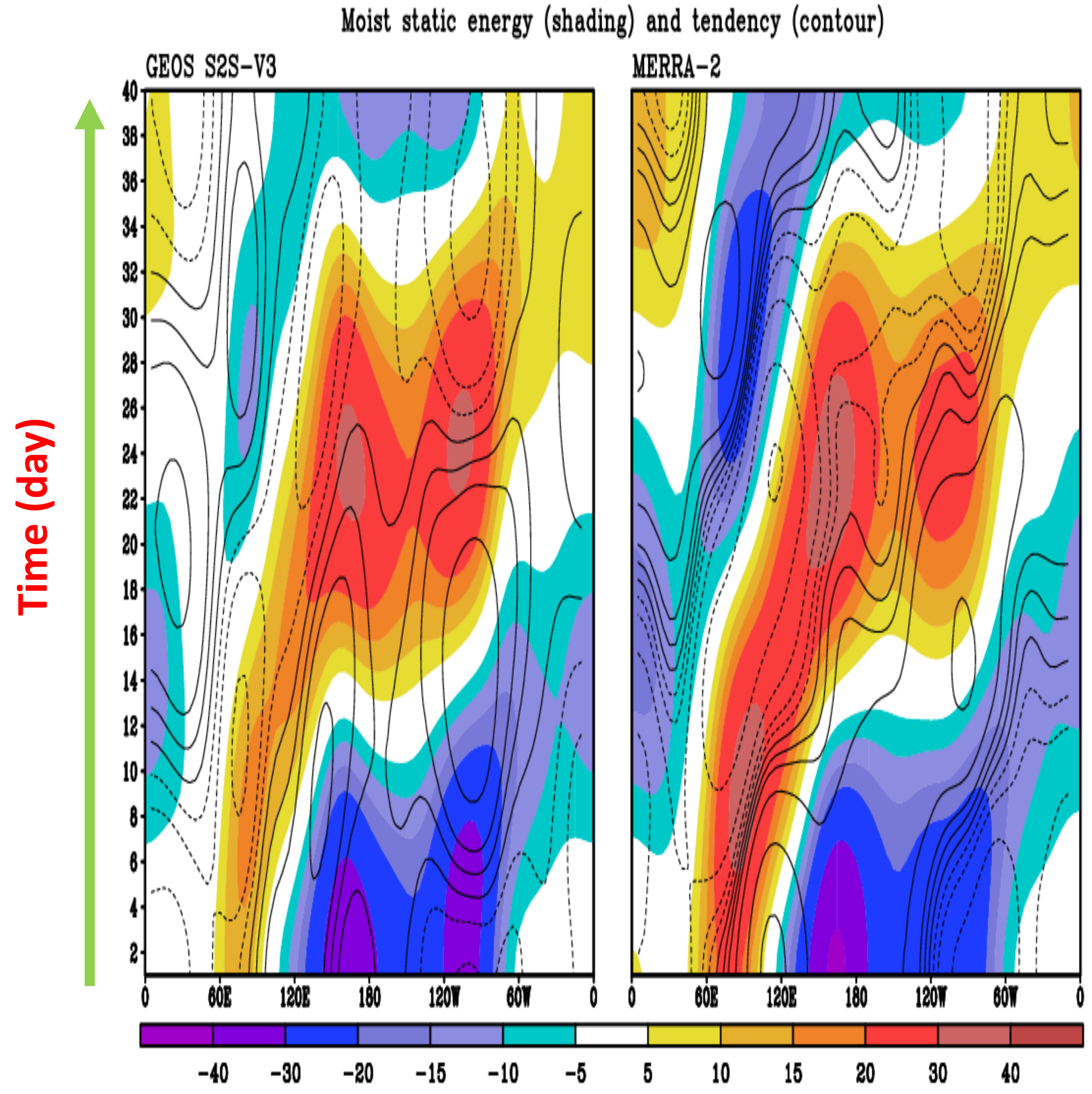
**MSE advection (contoured)**



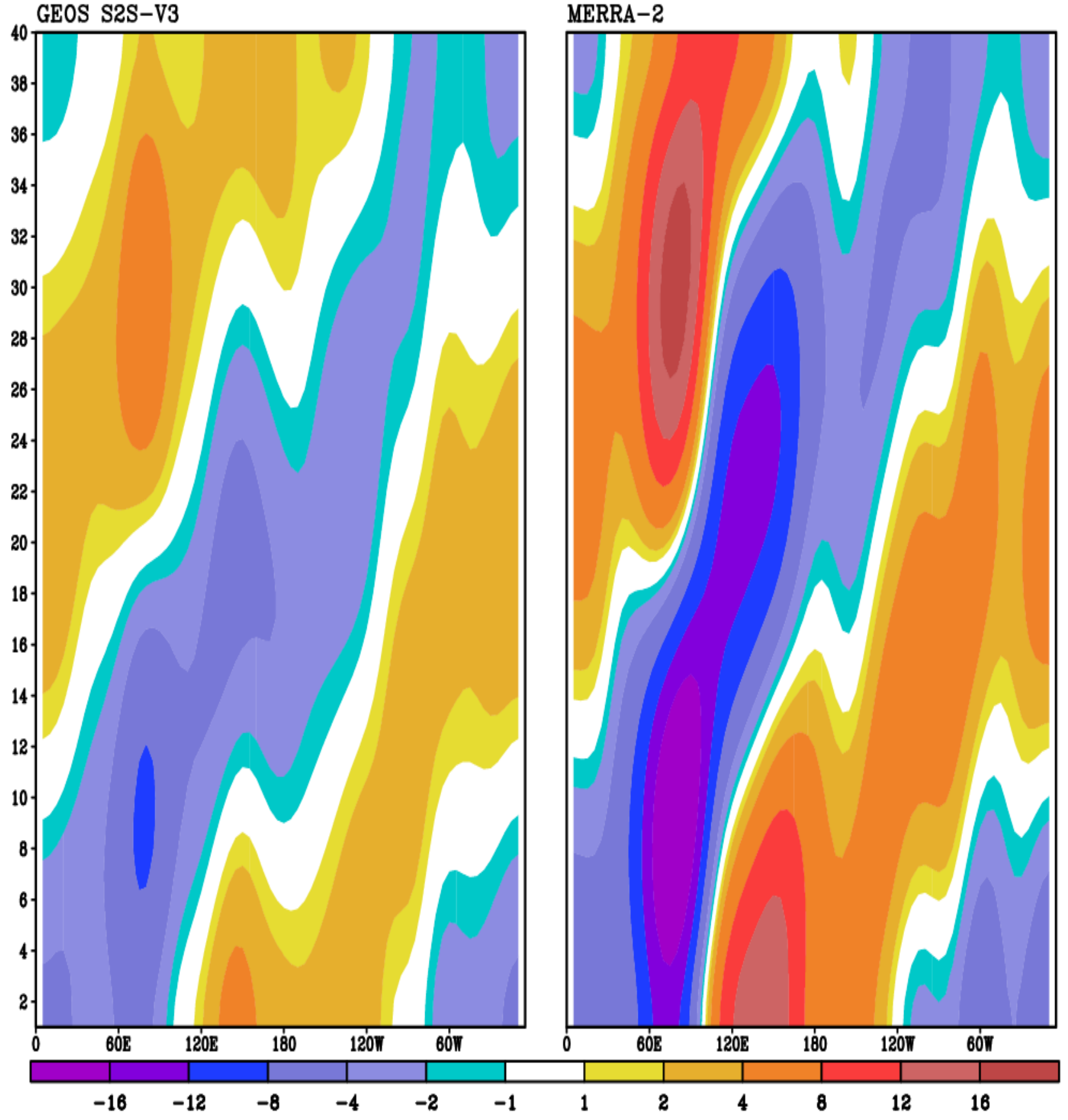

MSE is growing to the east of the current MJO convection, helping eastward propagation of the MJO. Positive (negative) MSE advection also grows over the region to the east (west) of MJO convection.

# Eastward propagation of the MSE tendency, MSE advection, and radiative heating

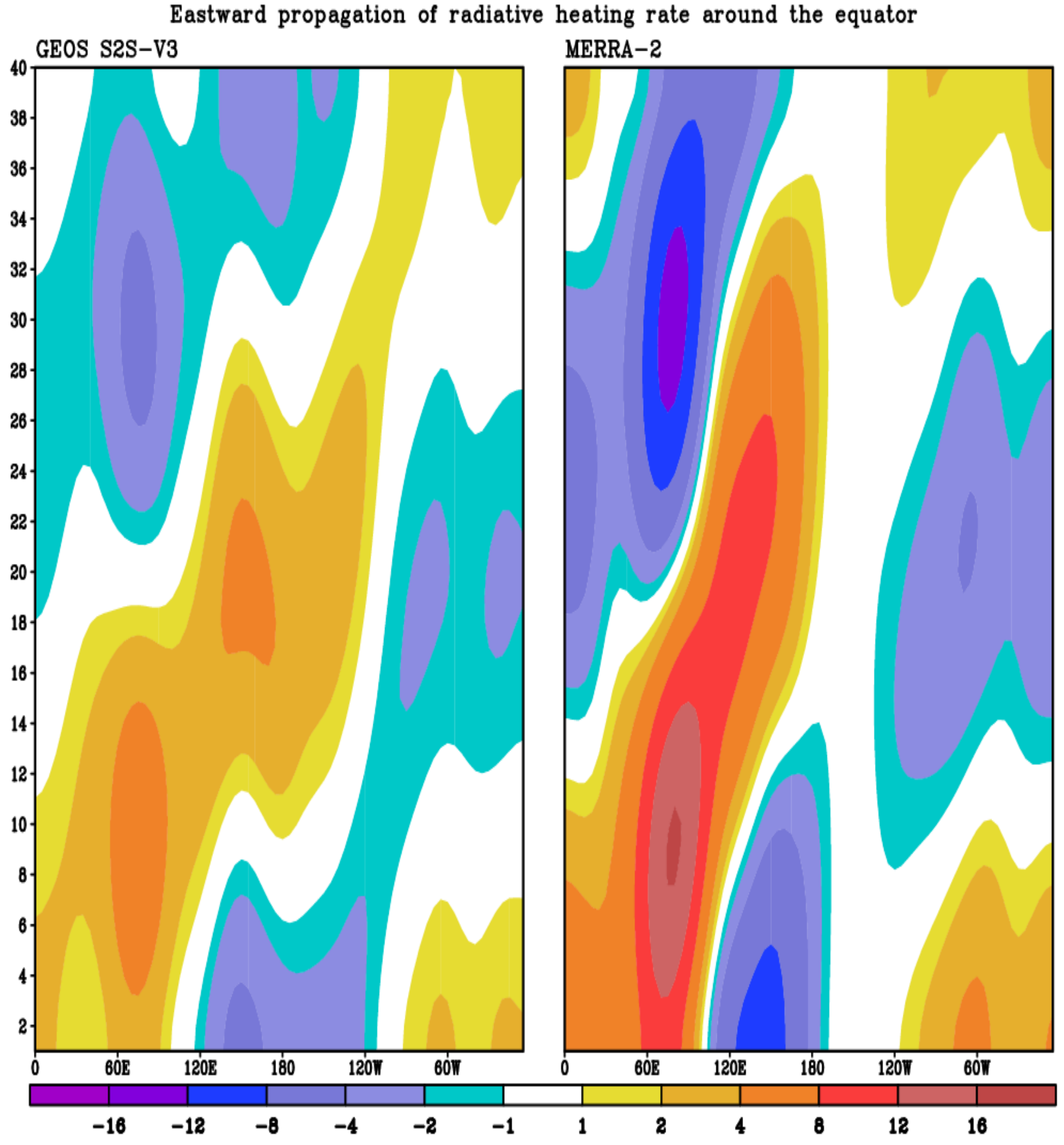
## MSE and tendency (*left: model, right: MERRA-2*)




## MSE advection




## Radiative heating




MSE tendency that denotes the MSE growth (suppression) is located 90º to the east (west) of the positive MSE anomaly, which indicates the current MJO convection. The model reproduces this phase relation and eastward progression of MSE and MSE tendency, with speed comparable to MERRA-2. Observed MSE advection is also faithfully represented in the model, in terms of its eastward propagation and speed.