Ocean-Atmosphere Coupled Feedbacks in the South Asian Monsoon

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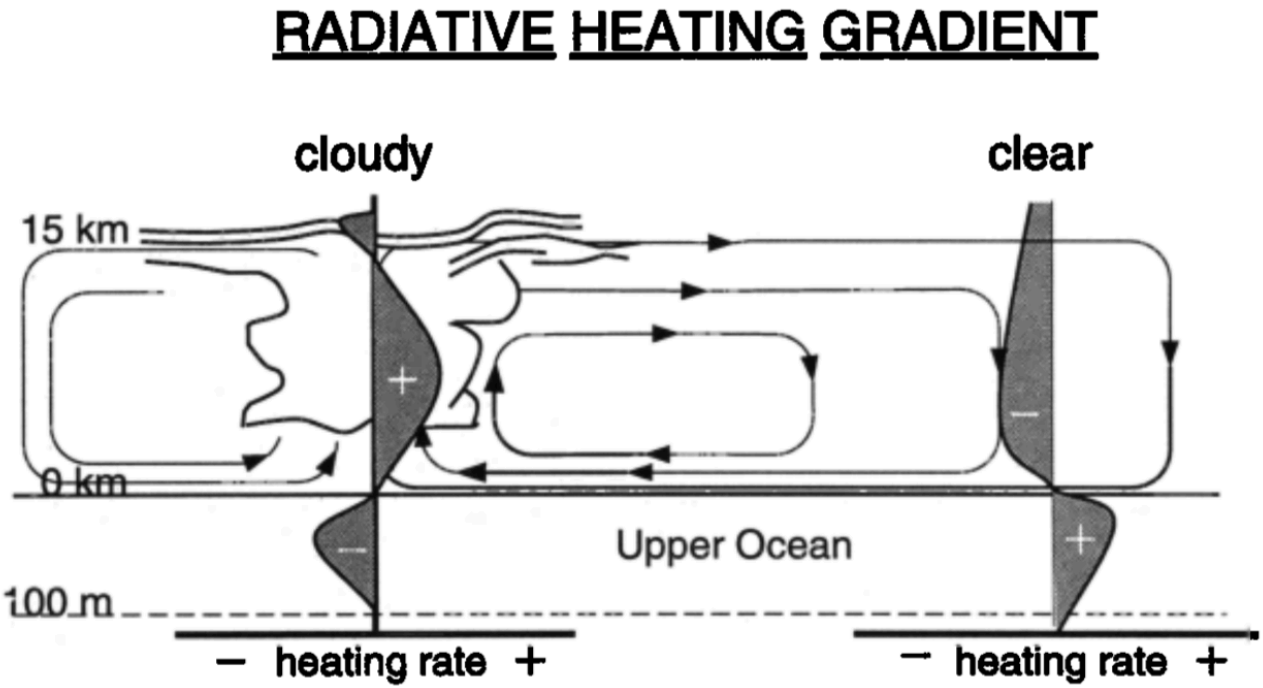
Topics covered in this talk

- Single-figure illustration of ocean-atmosphere coupling
- Mean state O-A coupling
- Intraseasonal O-A coupling
- O-A contributions to monsoon propagation

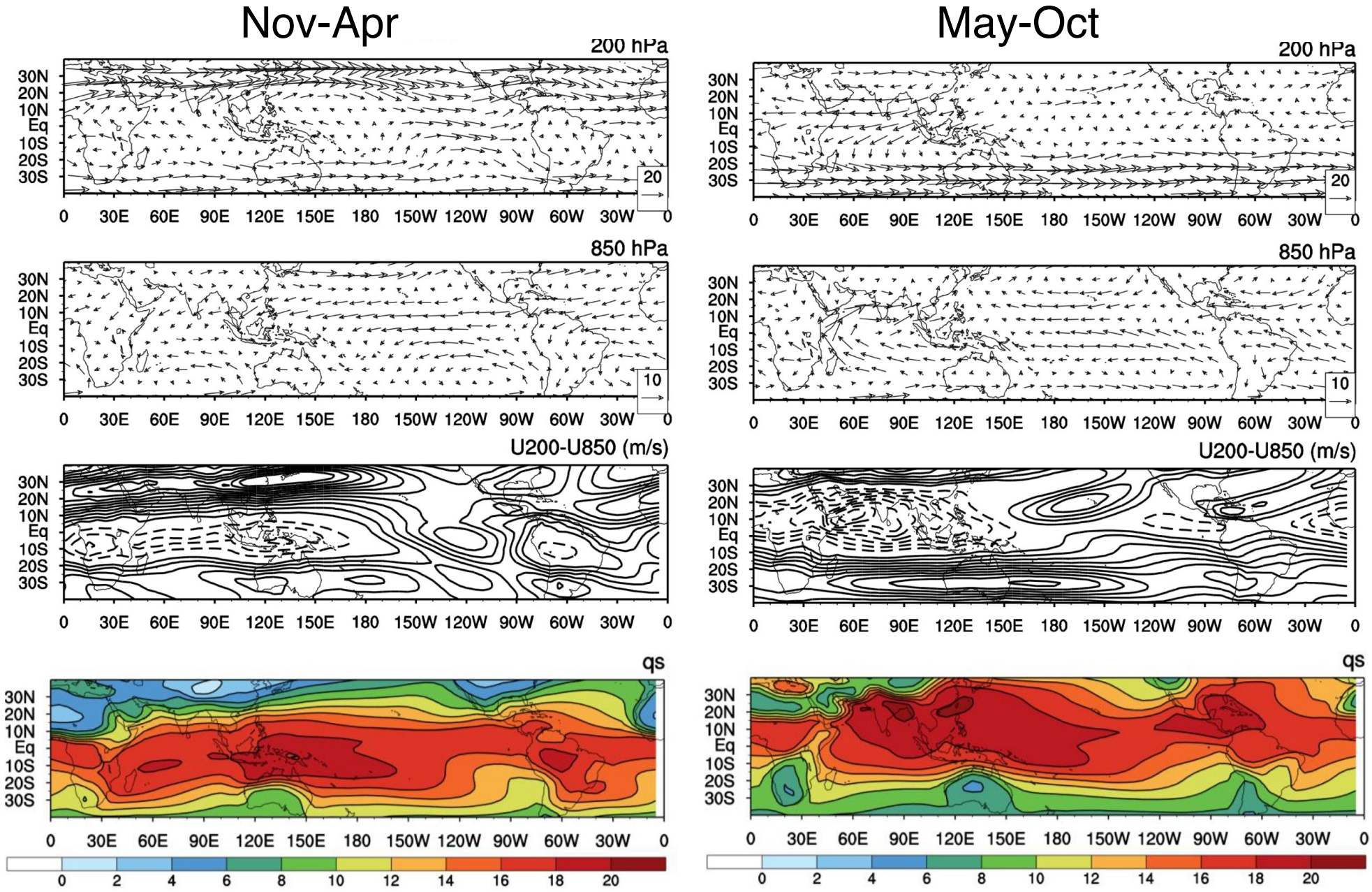
Ocean-atmosphere coupling



Webster (1994)

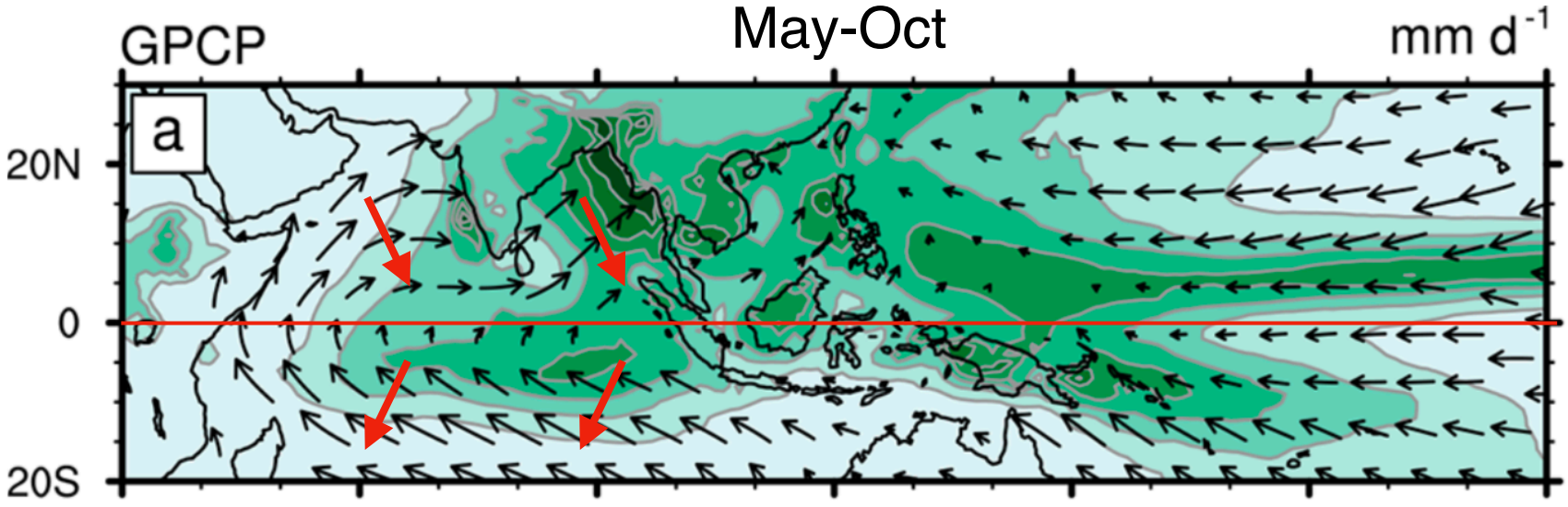
- Clouds warm atmosphere, cool ocean
- Near-surface ocean stratification regulates SST response
- Cloud migration can change sign of local ocean heating
  - interannual, seasonal, intraseasonal
- Ocean-to-atmosphere heat fluxes can influence convection

Mean state atmosphere



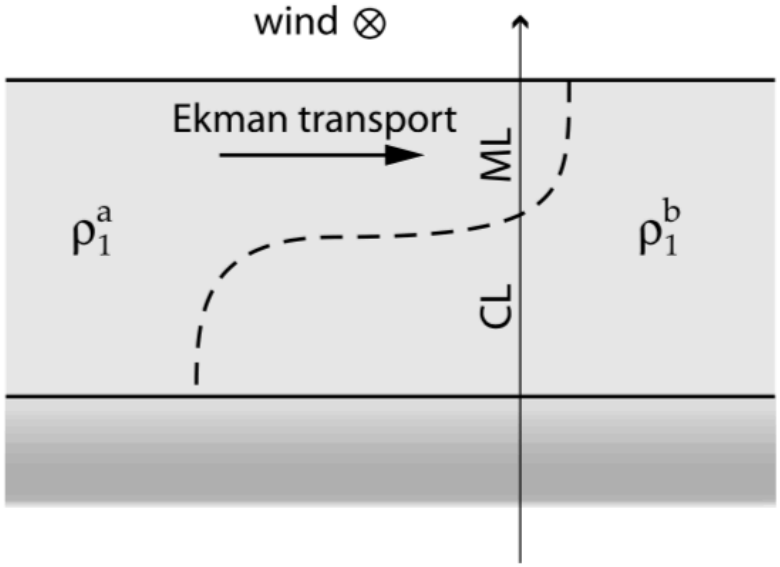
Wang and Chen (2017; doi.org/10.1016/j.dynatmoce.2016.11.002)

Ocean response to mean state atmosphere



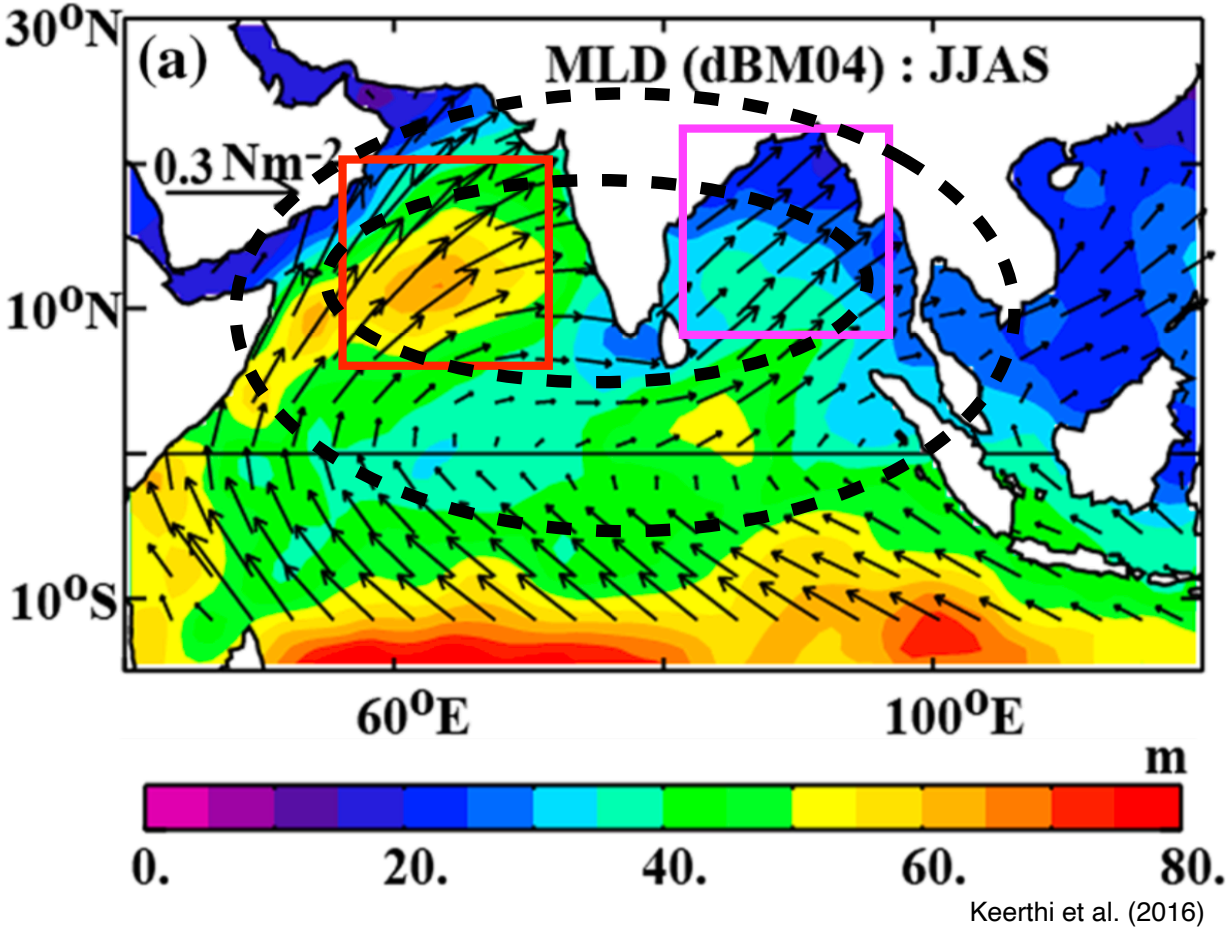
Gao et al. (2020)

- mean state winds drive southward Ekman transport



de Boyer Montégut (2004)

Ocean response to mean state atmosphere



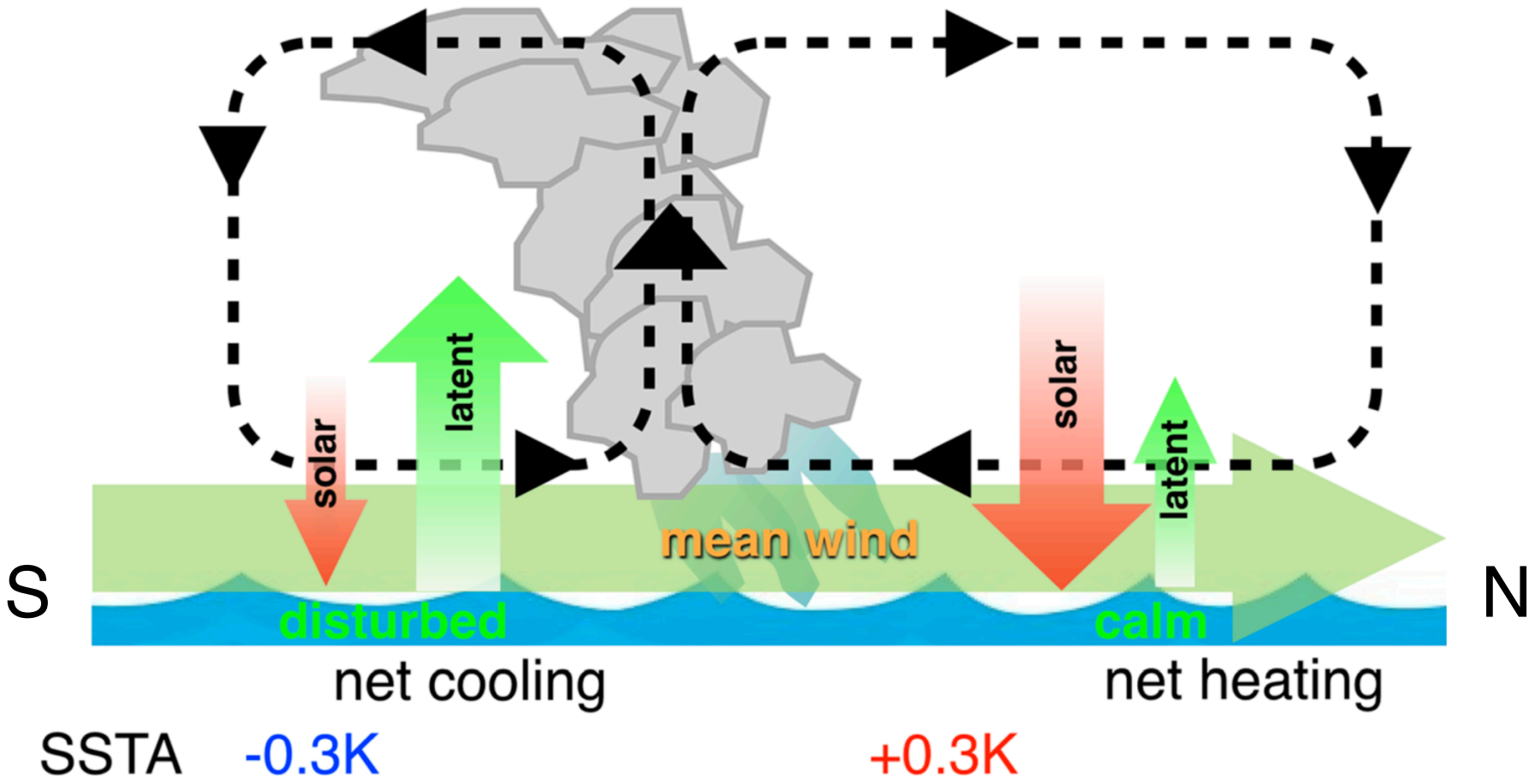
Keerthi et al. (2016)

$$\frac{\partial SST}{\partial t} = \frac{Q_{net}}{\rho C_p H} - \nabla(V \cdot T)$$

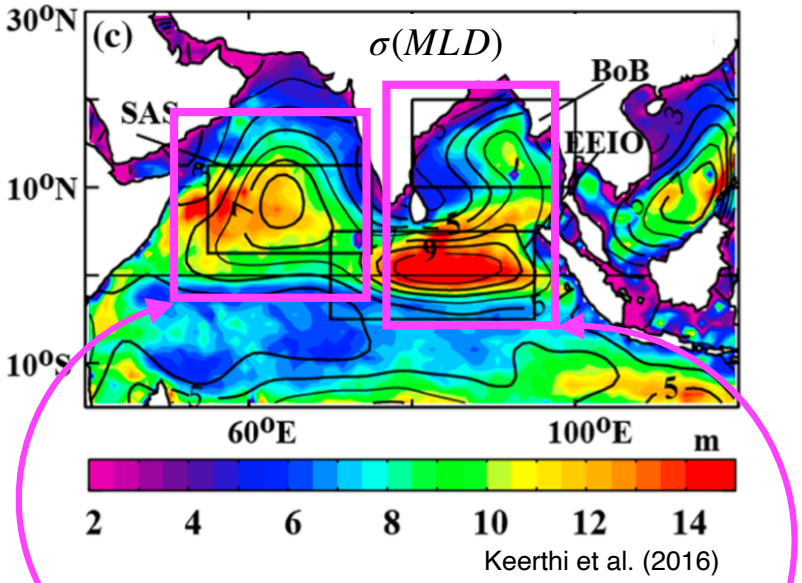
$$MLD = H$$

- Ekman convergence induces deeper ML in Arabian Sea
- River discharge, rain freshening induce shallower ML in Bay of Bengal

Intraseasonal forcing of upper ocean



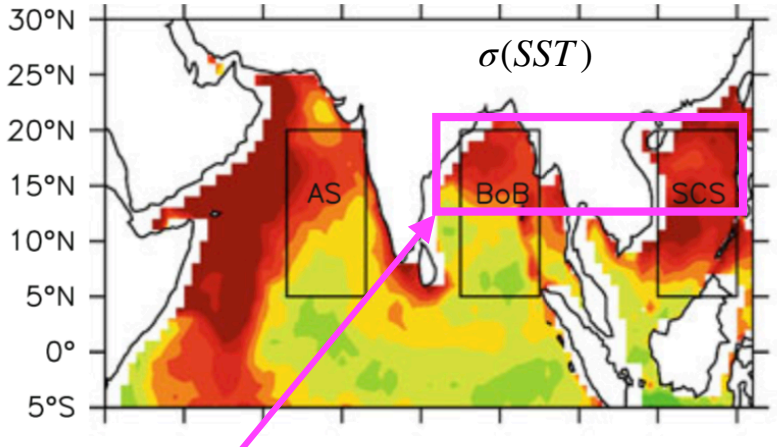
Ocean response to intraseasonal forcing



Keerthi et al. (2016)

ocean dynamics

monsoon forcing

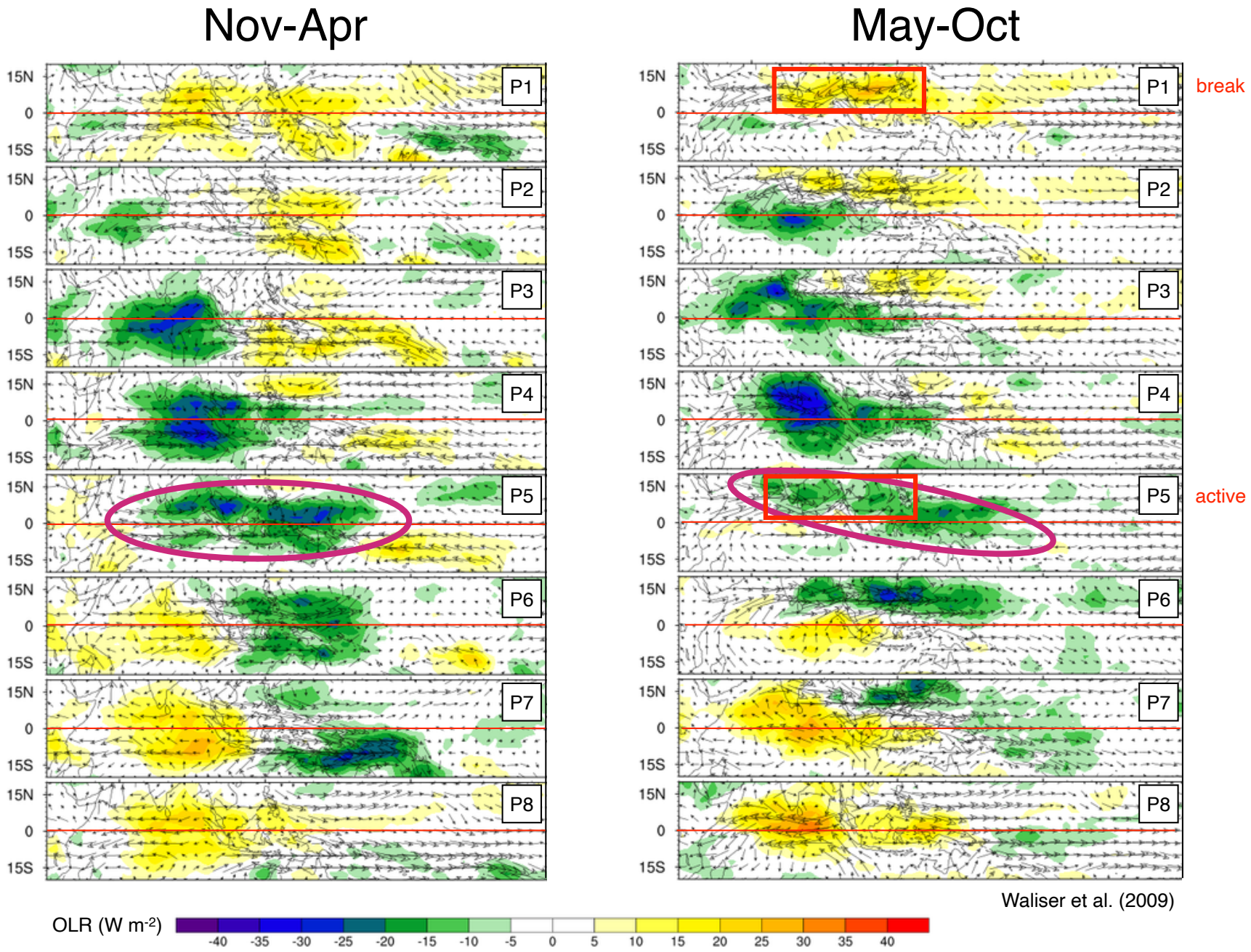


Roxy et al. (2013)

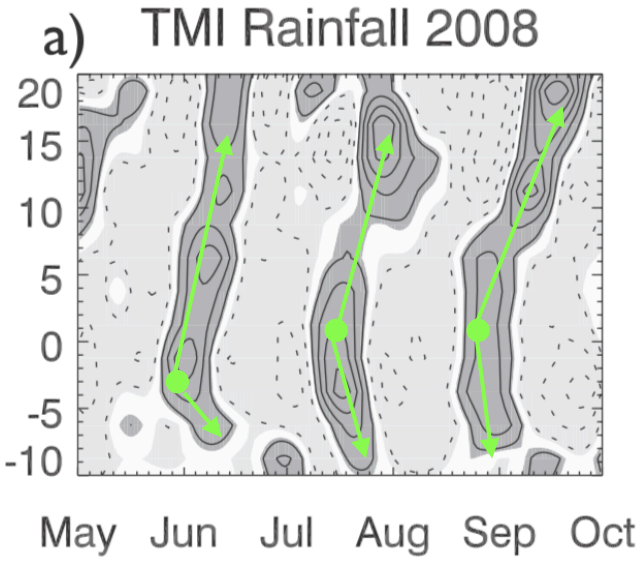
what role might large SST variability play in monsoon northward propagation?

"What are the relative roles of atmospheric dynamics and ocean feedbacks to the northward propagation?"

Intraseasonal variability

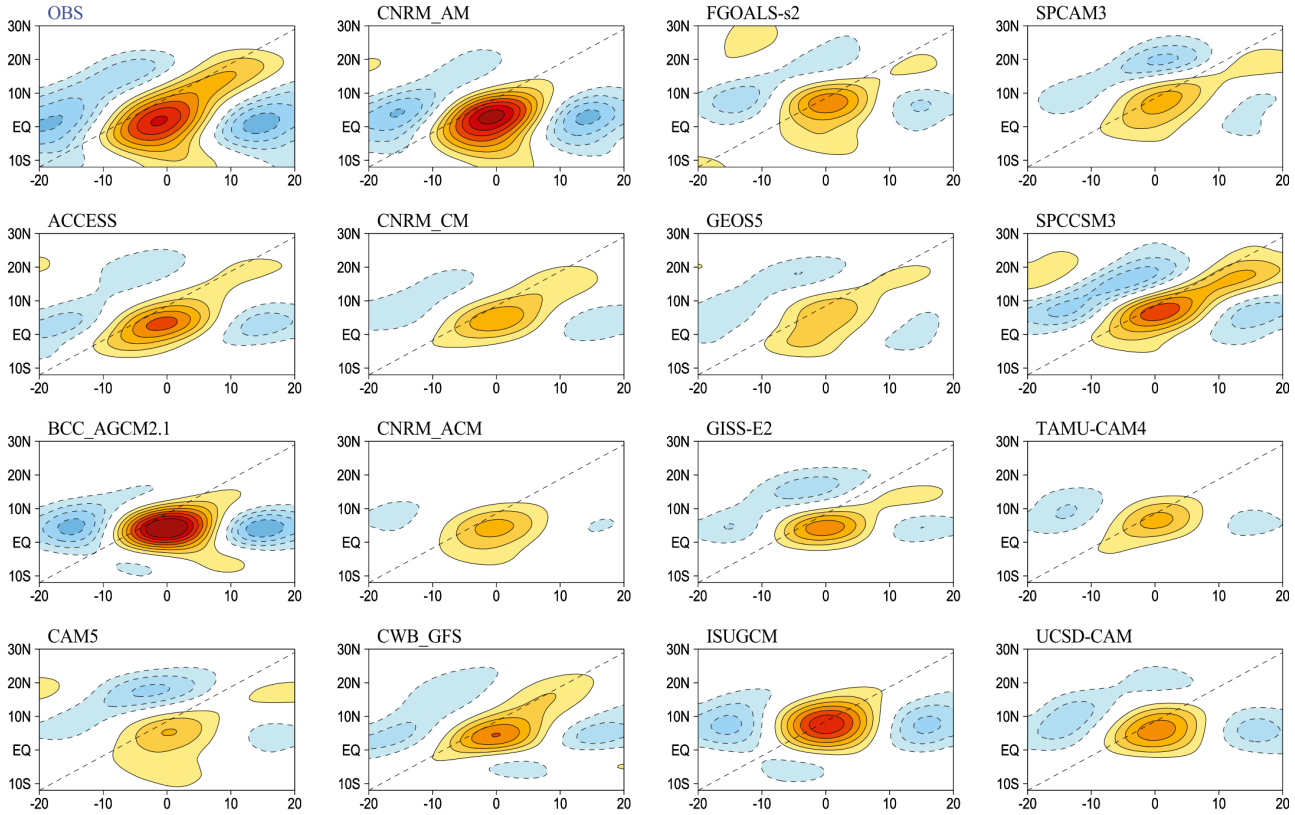


Intraseasonal variability



DeMott et al. (2013)

individual events

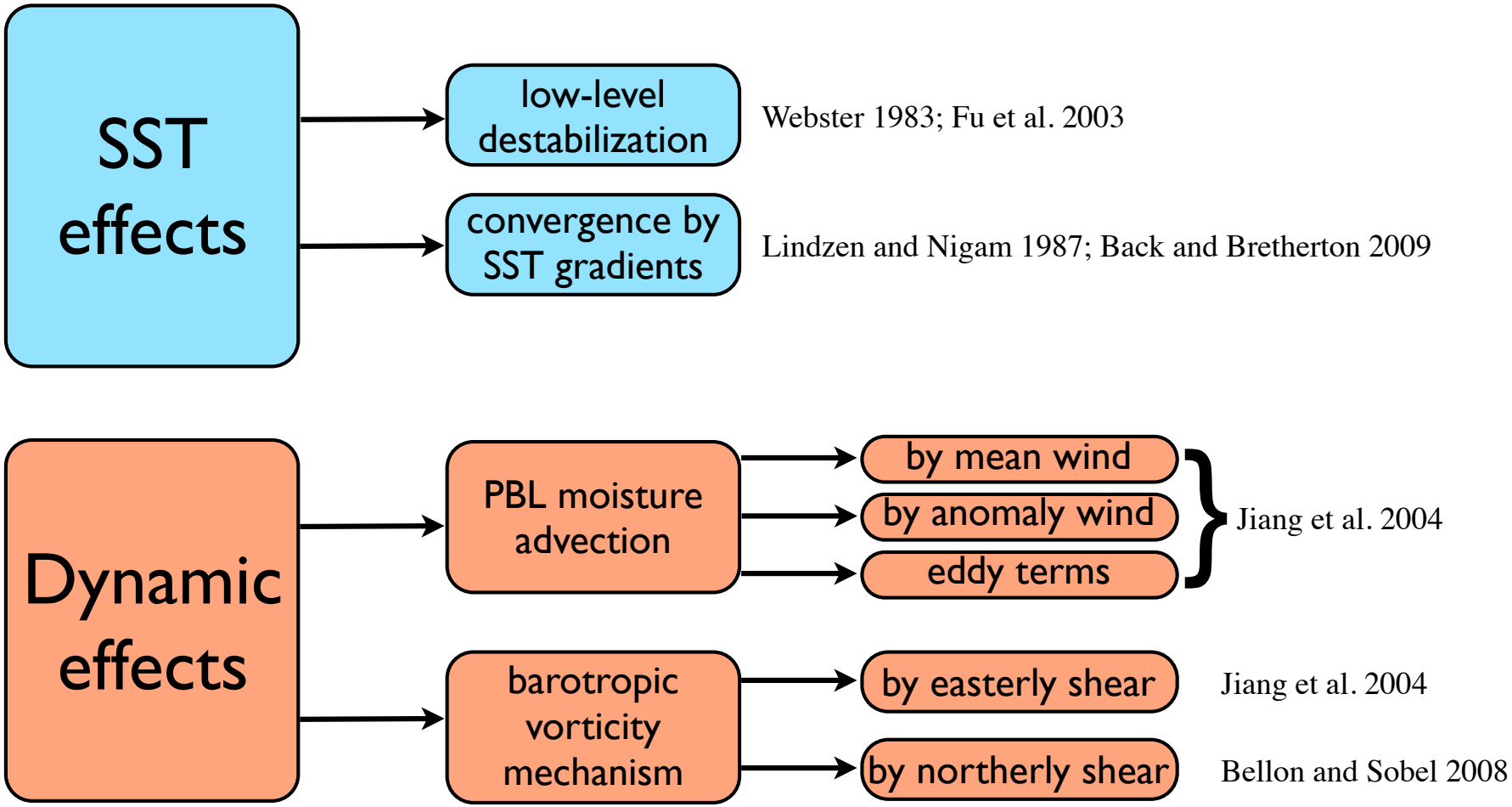


Jiang et al. (2018)

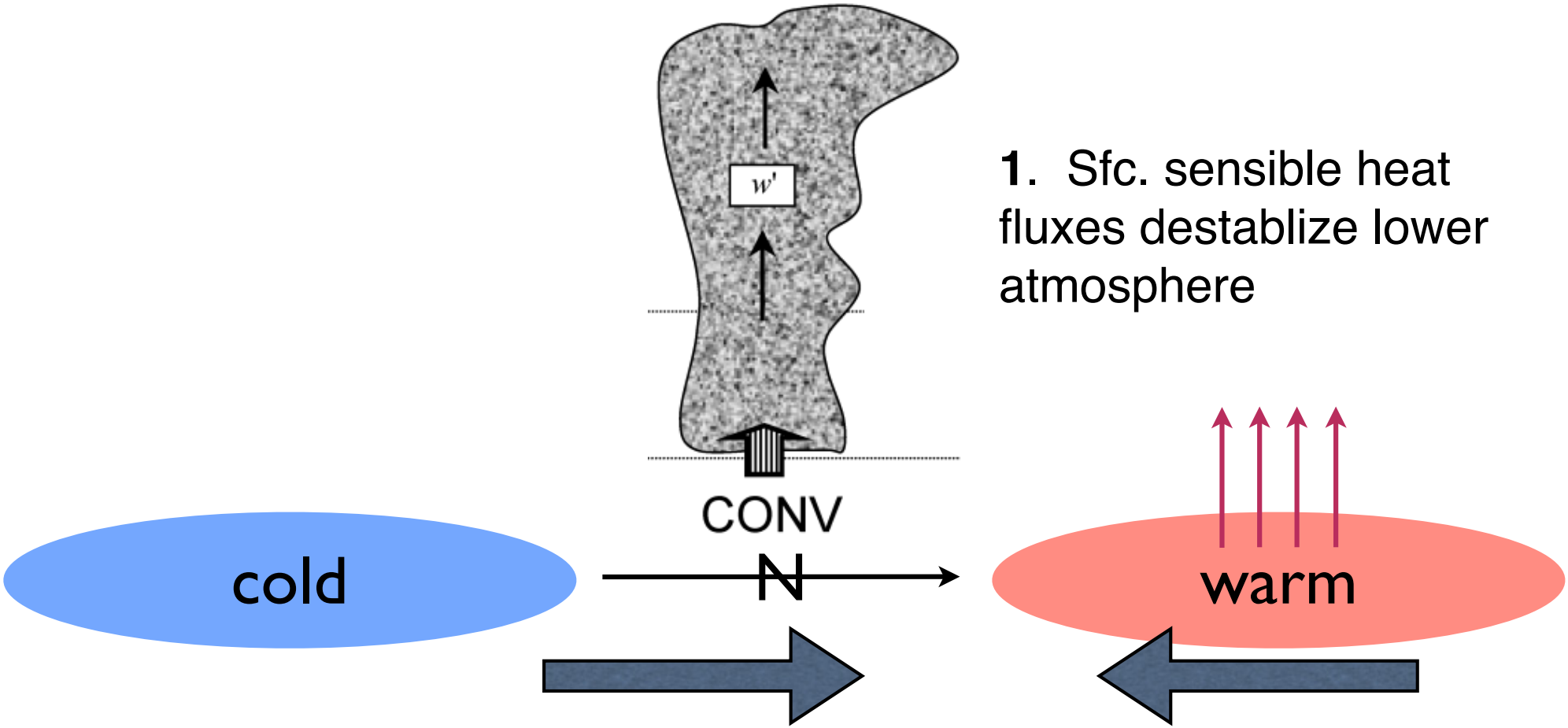
multi-event composite

- what drives northward propagation of monsoon rainfall?
- do model biases arise from dynamics or coupling biases?

Northward Propagation Mechanisms (ca. 2013)



Northward propagation: Surface temperature effects



1. Sfc. sensible heat fluxes destablize lower atmosphere

2. SST gradient (Laplacian) induces boundary layer convergence

Northward propagation: Dynamic effects

Boundary layer moisture advection (*Jiang et al. 2004*)

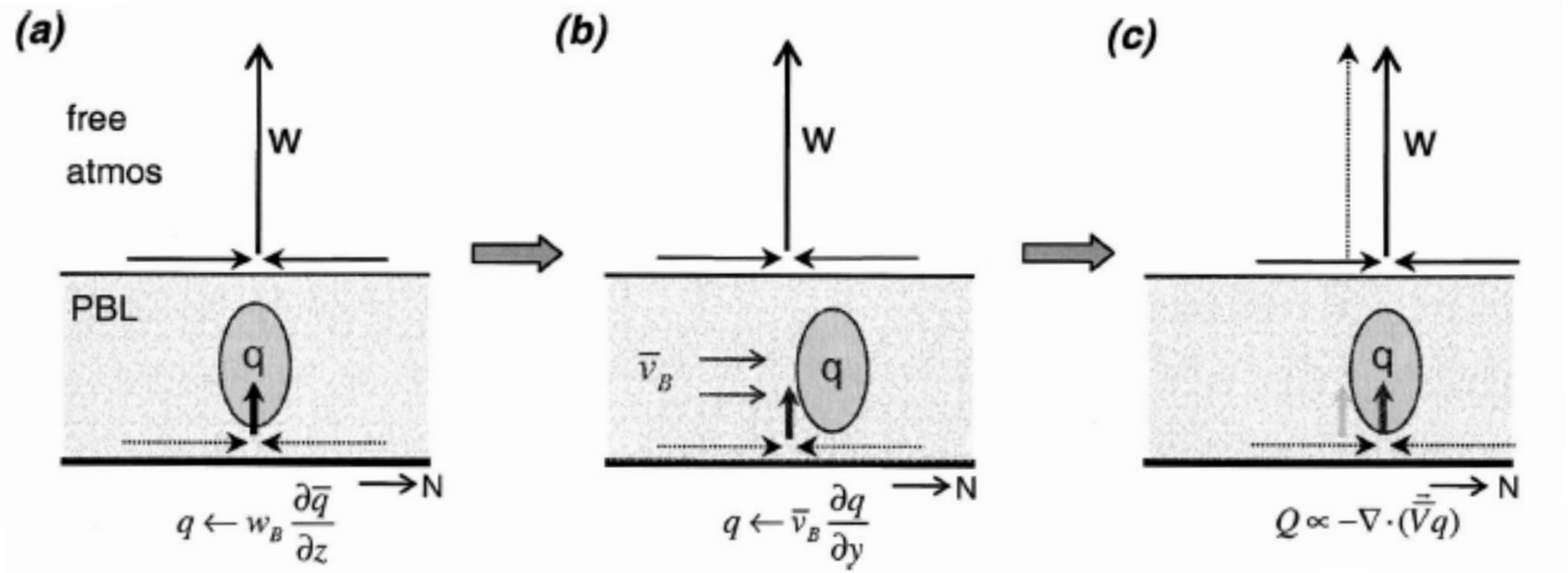
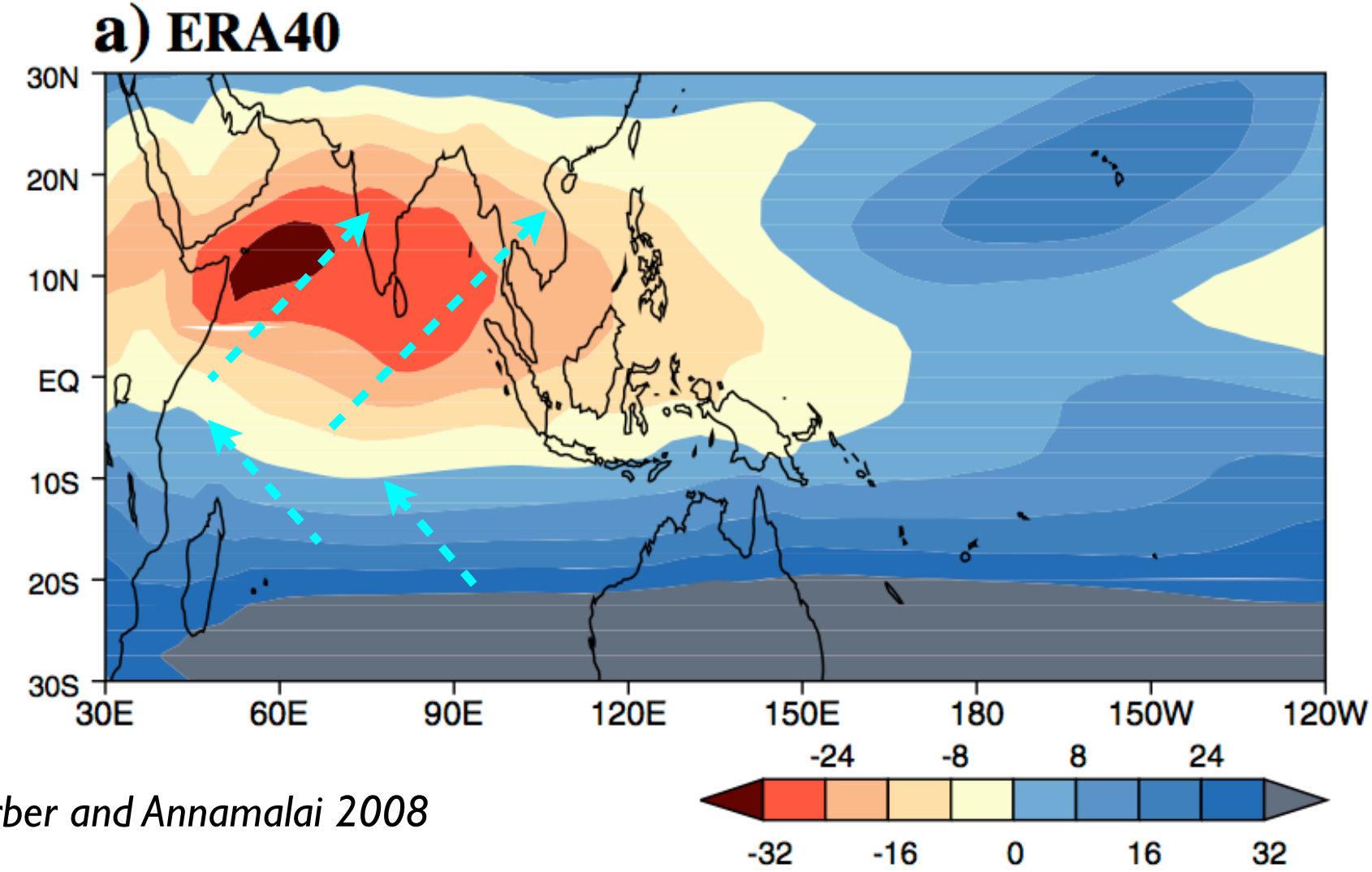


FIG. 12. Schematic diagram for the mechanism of moisture advection by mean flow. (a) The specific humidity perturbation caused by Ekman pumping is advected (b) by the mean northward meridional wind in the PBL, (c) which leads to the northward shift of moisture convergence and thus convective heating to the convection center.

Northward propagation: Dynamic effects

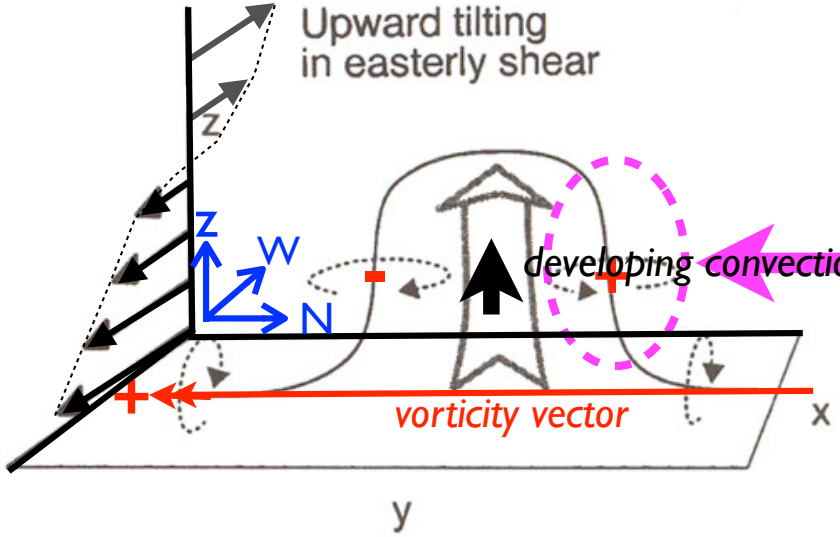
Seasonal onset of easterly shear is critical!



Sperber and Annamalai 2008

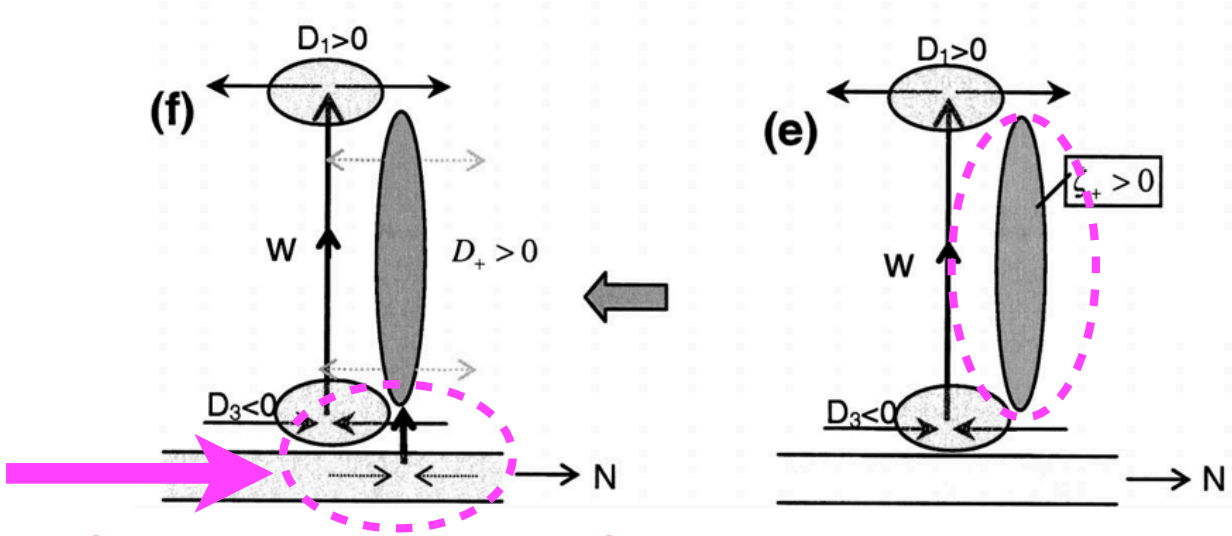
Northward propagation: Dynamic effects

Easterly shear mechanism (*Jiang et al. 2004*)



after Weisman and Davis (1998)

+ vorticity anomaly
north of convection



from Jiang et al. (2004)

barotropic vorticity induces
boundary layer convergence

How to assess NP mechanisms from data?

- Create a normalized index for each mechanism that can be regressed onto OLR or precipitation anomalies.
- Index with the largest regression coefficient is the winner!

Mechanism Indices

SST effects

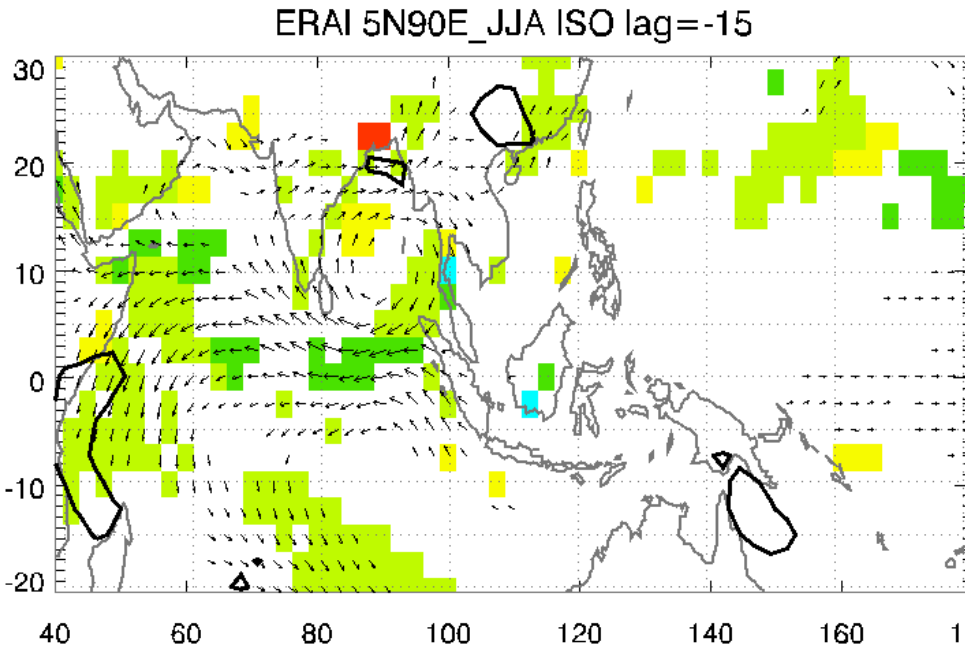
- Tsfc destabilization: Avg. normalized T_{sfc} (>0), lower tropospheric stability (<0)
- SST gradient effect: Avg. normalized SST Laplacian (>0), PBL convergence

Dynamic effects

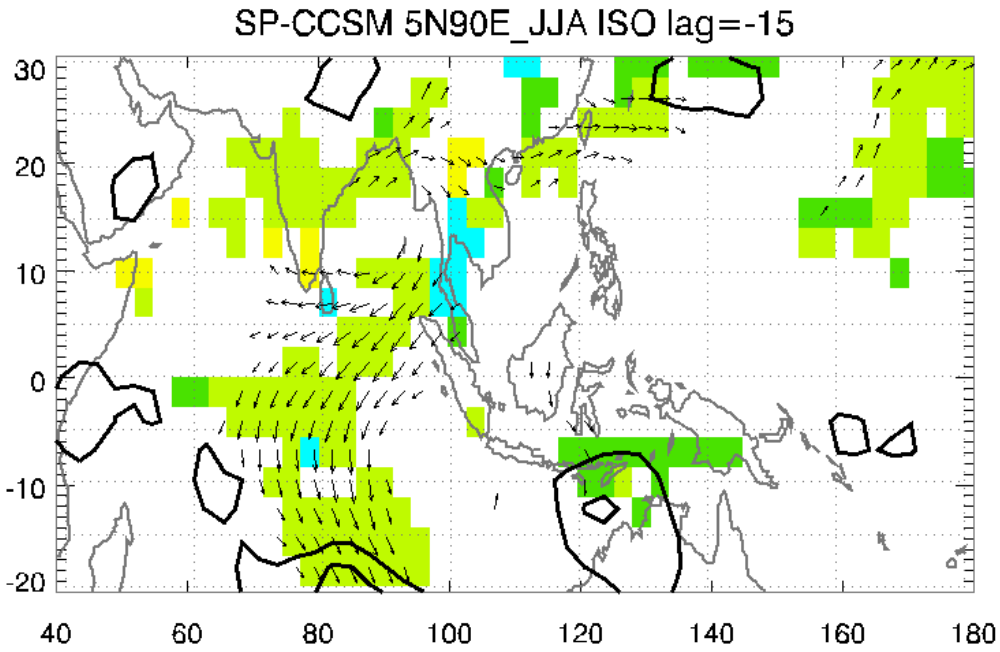
- $\left(-v'\frac{\delta q'}{\delta y}\right)_{1000}$ anomalous PBL q advection by anomalous winds
- $\left(-v'\frac{\partial \bar{q}}{\partial y}\right)_{1000}$ mean PBL q advection by anomalous winds
- $\left(-\bar{v}\frac{\partial q'}{\partial y}\right)_{1000}$ anomalous PBL q advection by mean winds
- ζ + effect: Avg. normalized ζ + (>0), PBL convergence

Northward Propagation Mechanisms for ISO

ERA-Interim



SP-CCSM



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SST gradient effect

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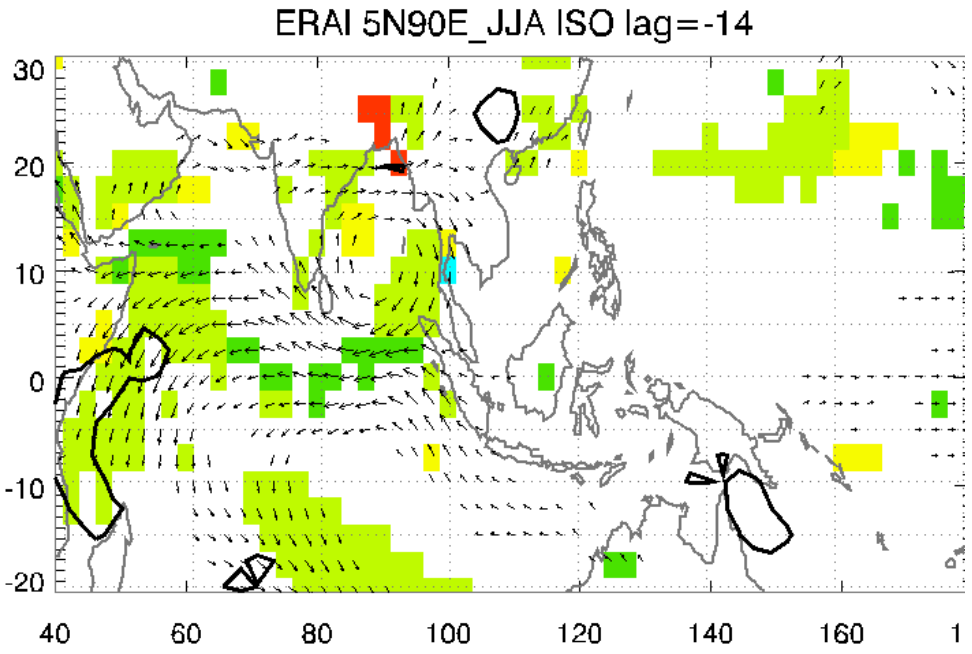

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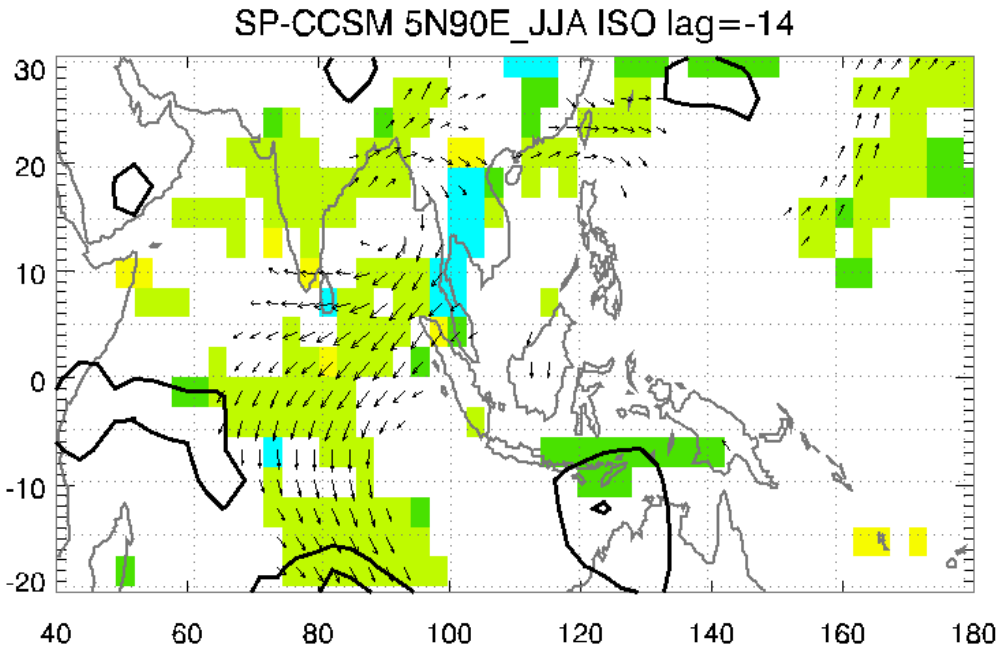

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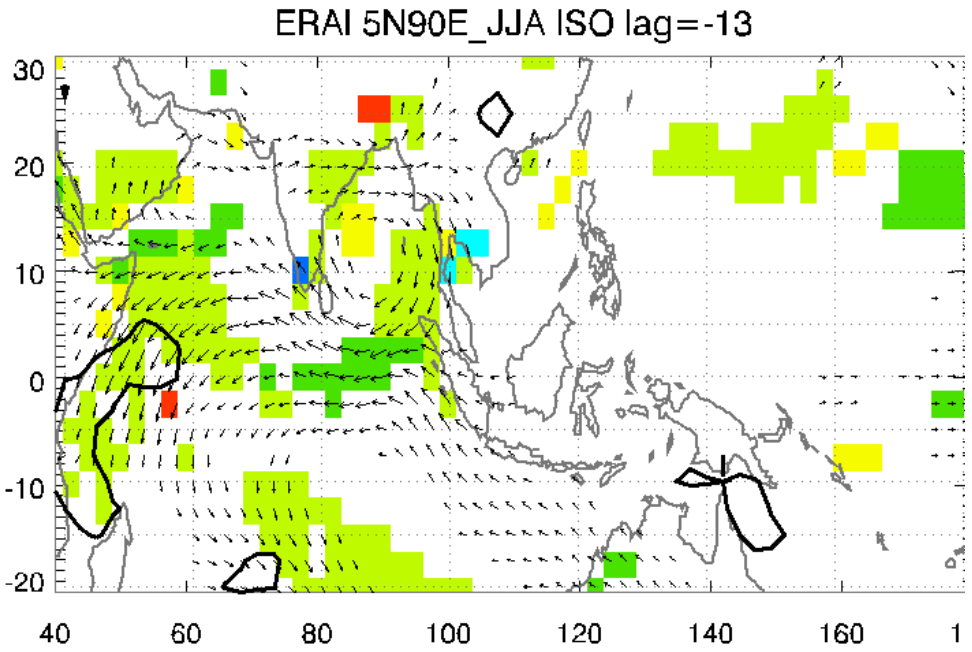

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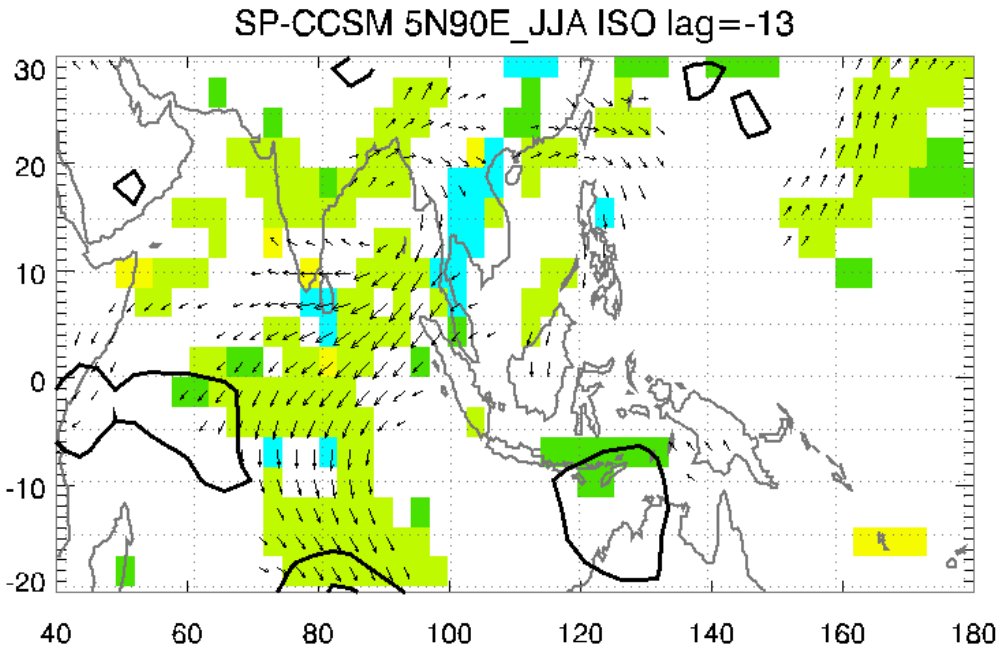

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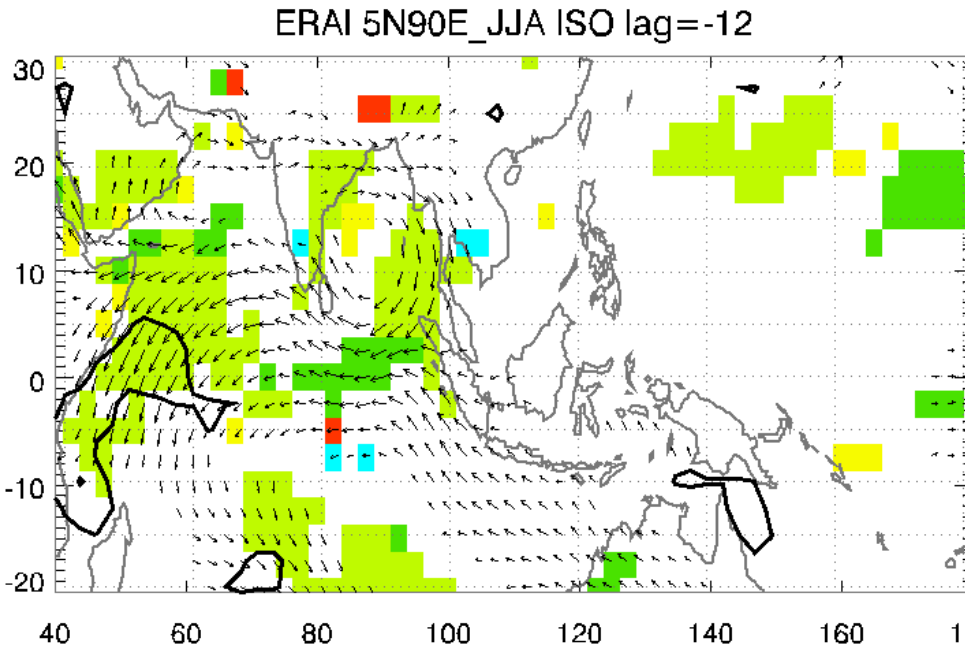

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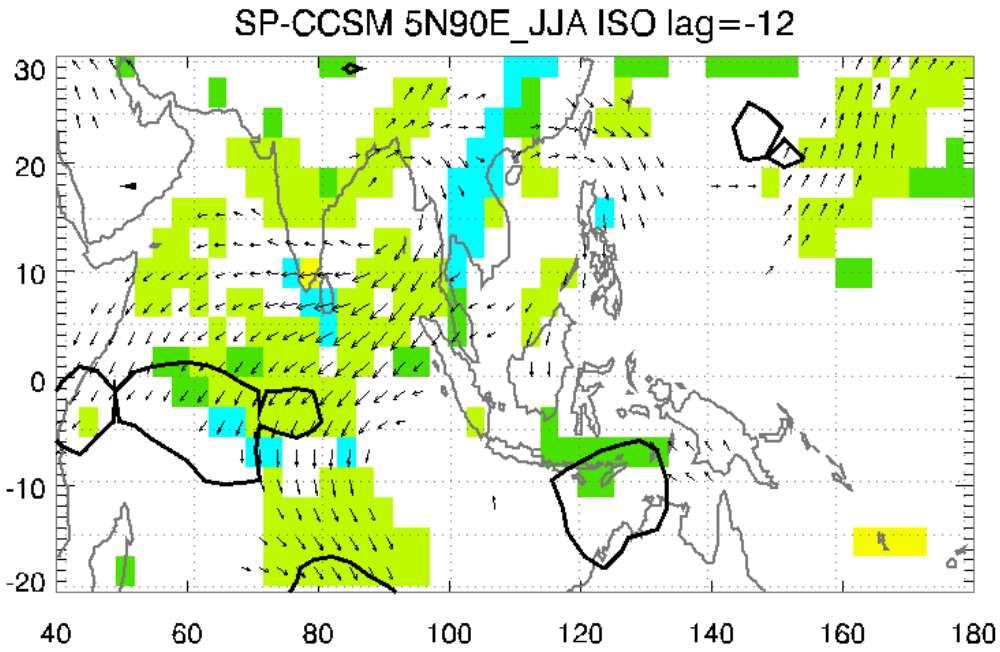

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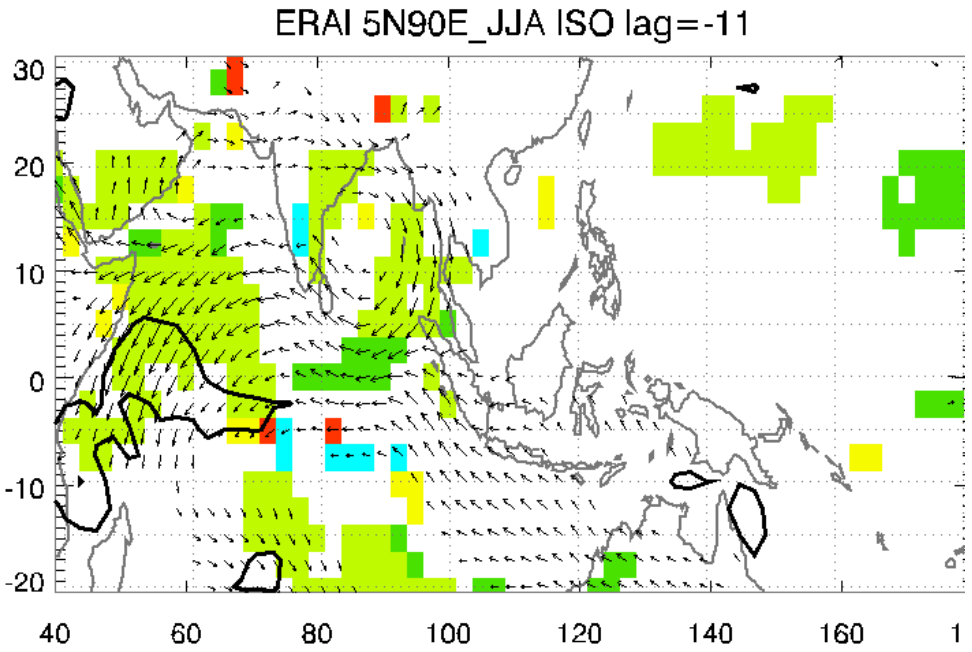

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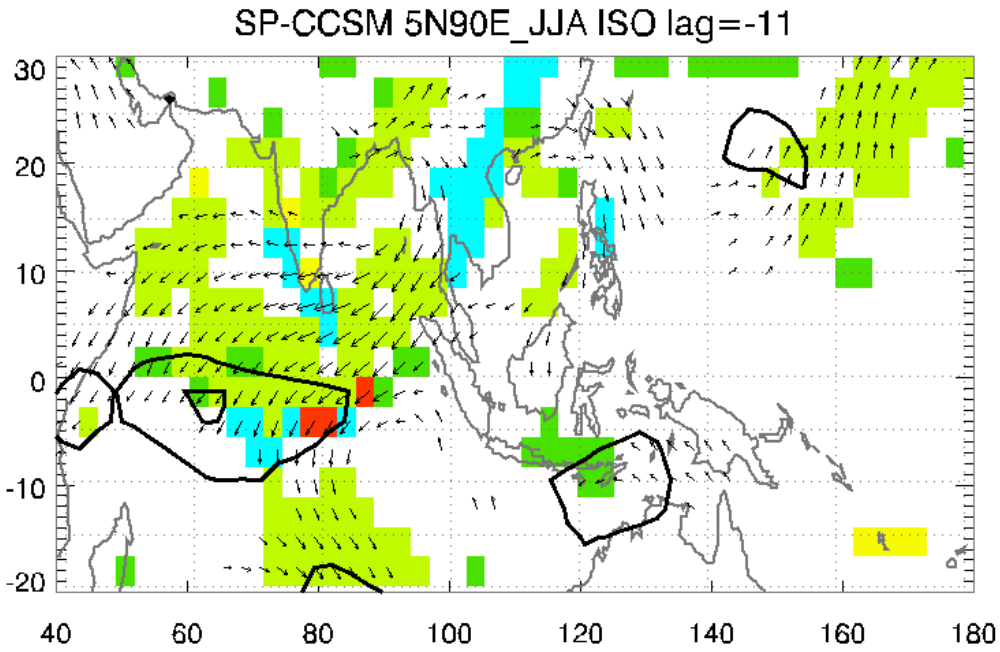

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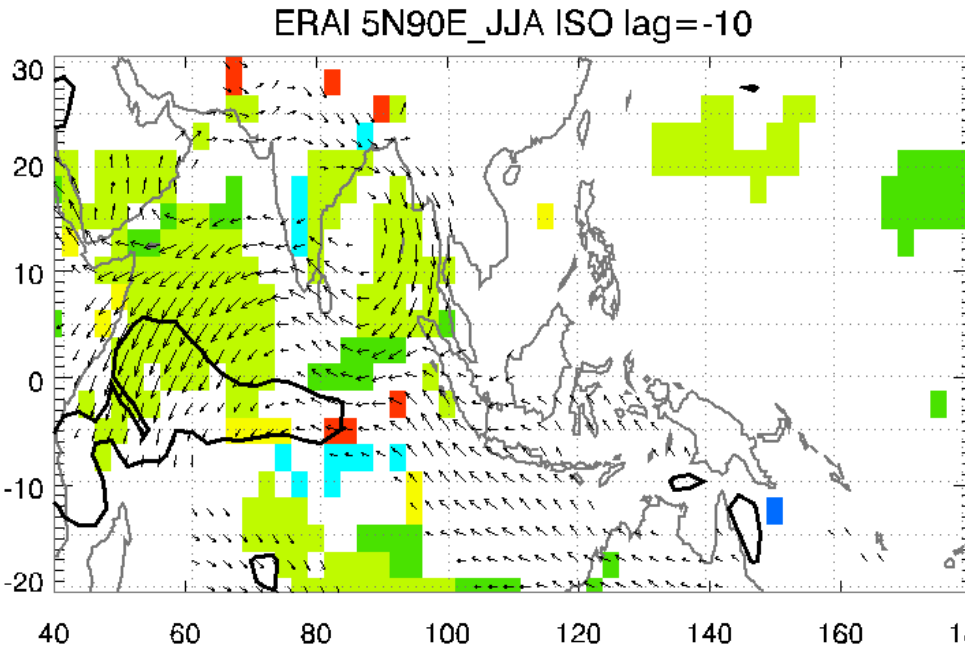

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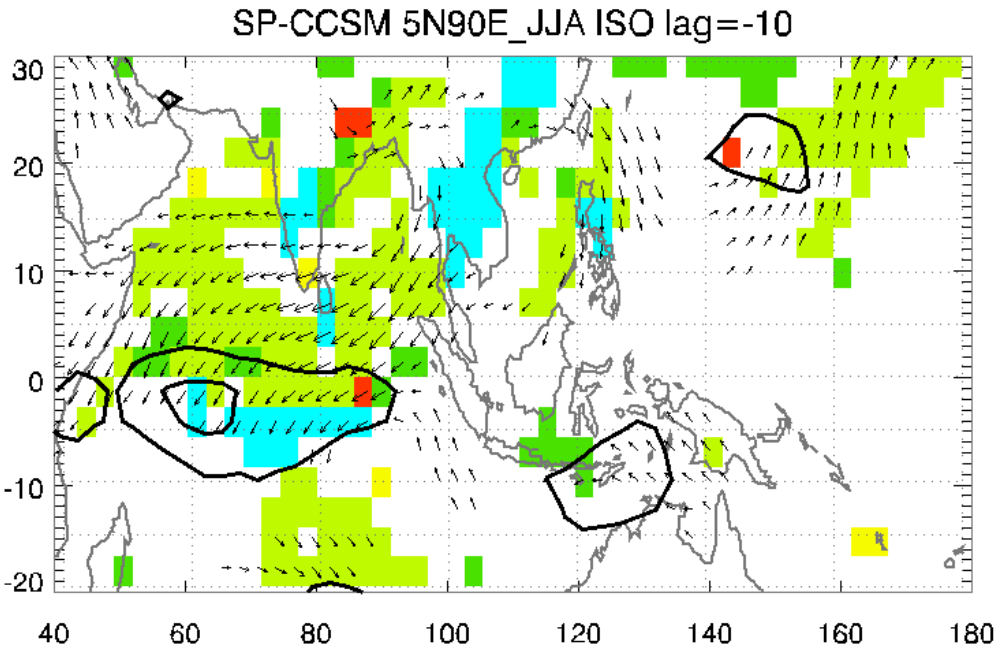

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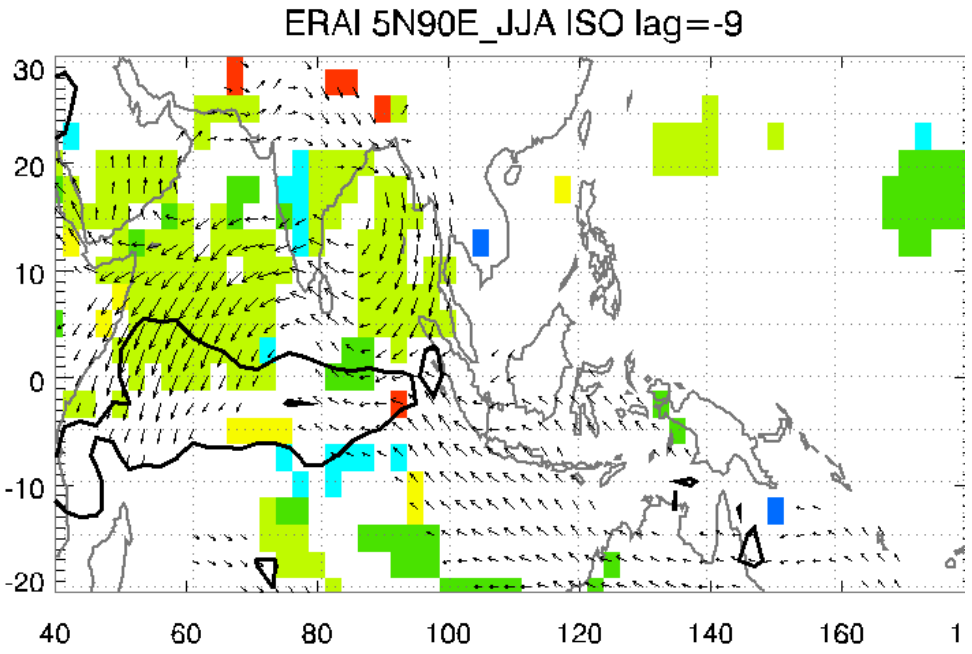

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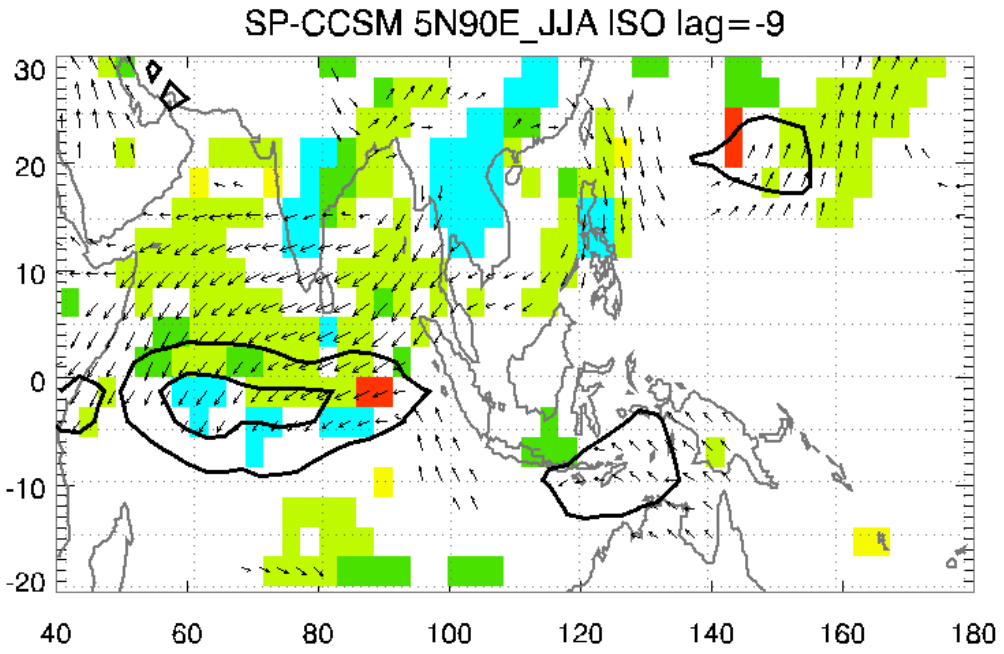

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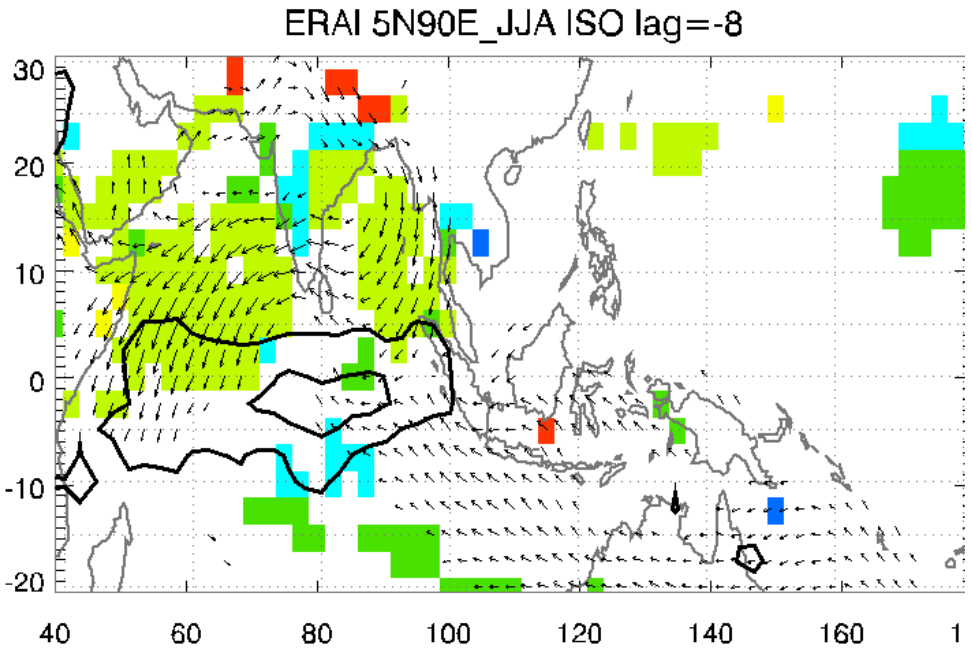

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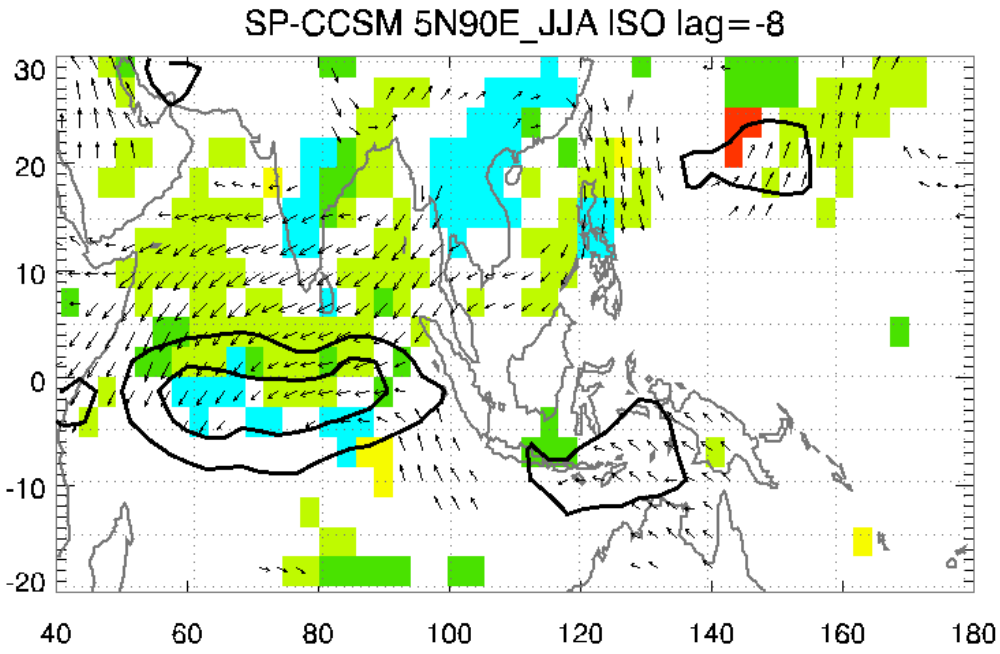

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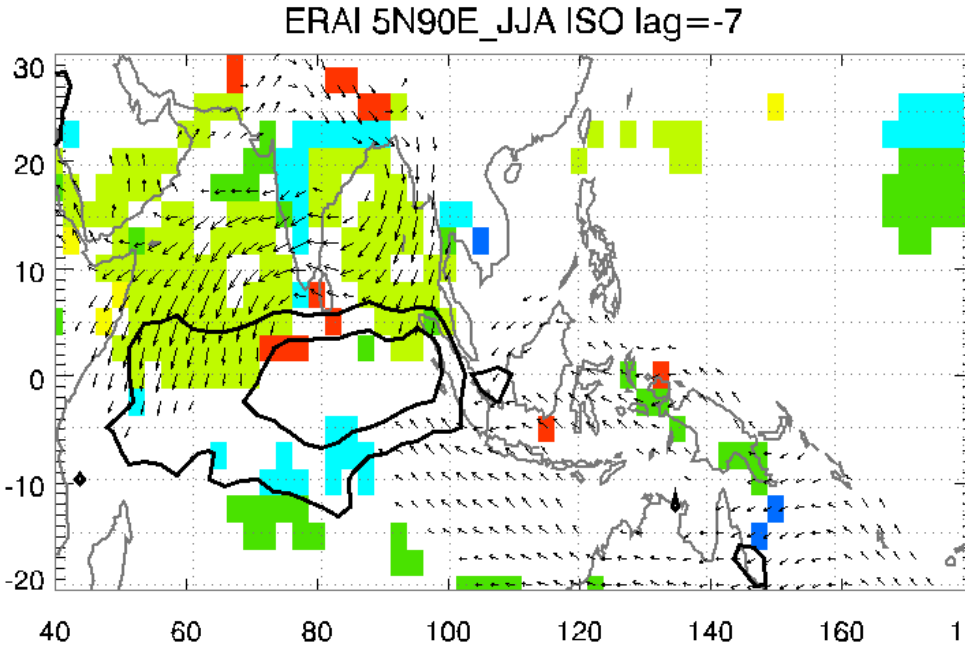

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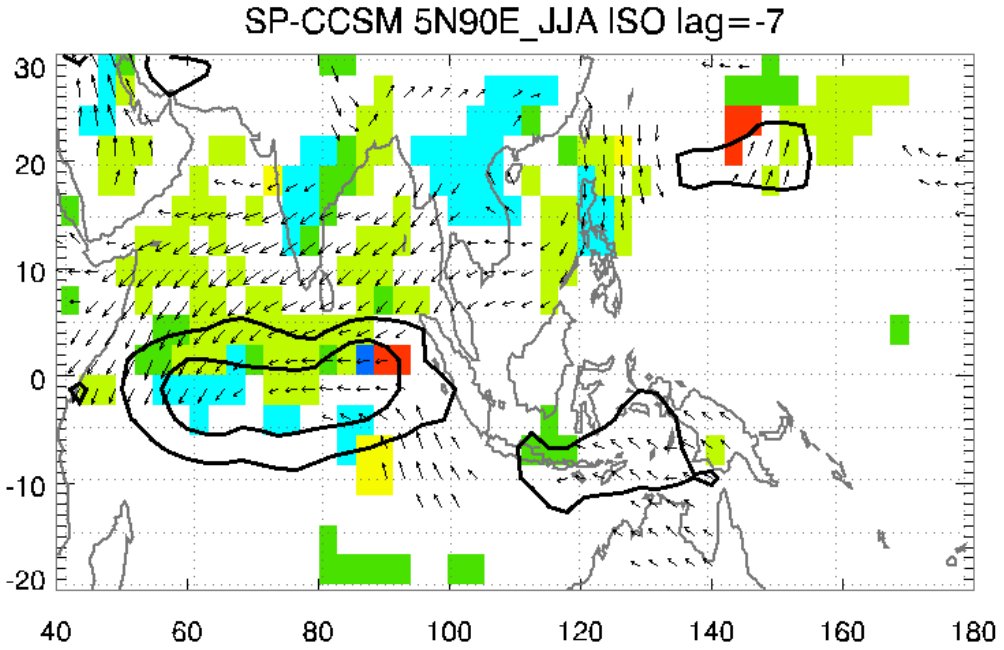

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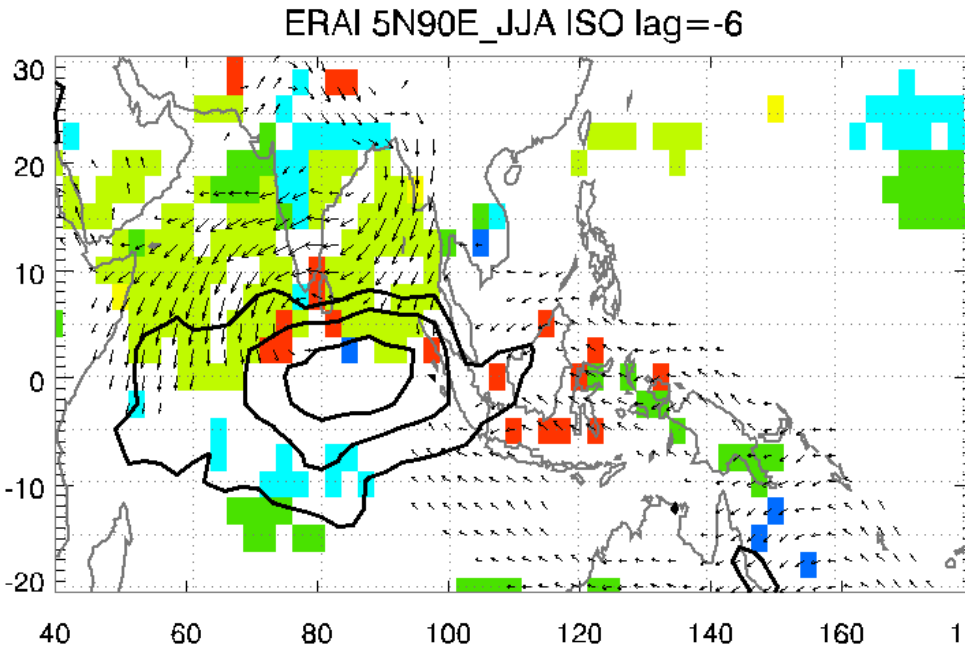

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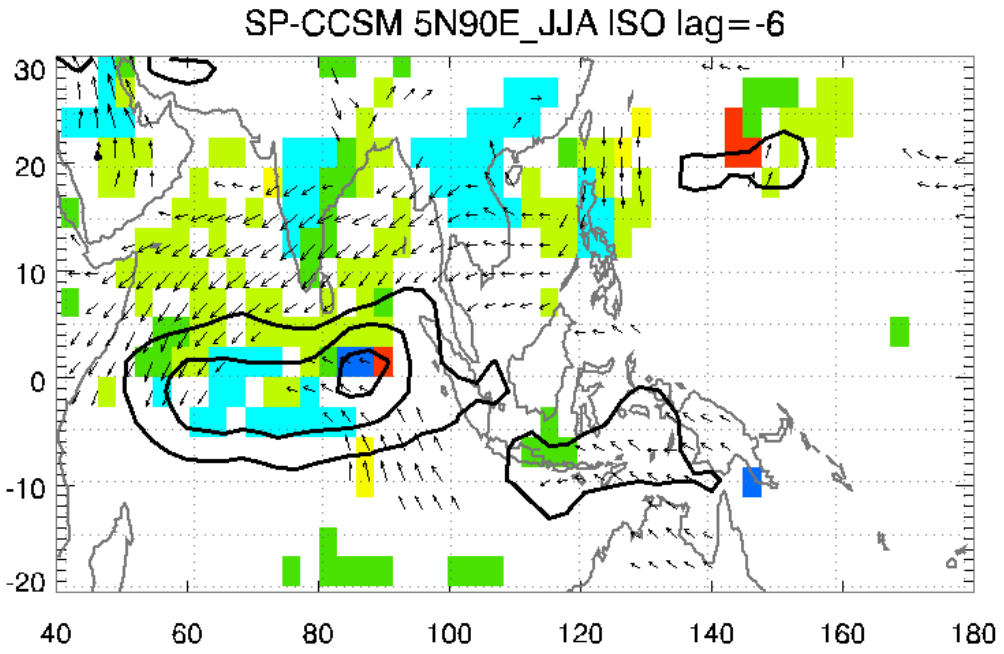

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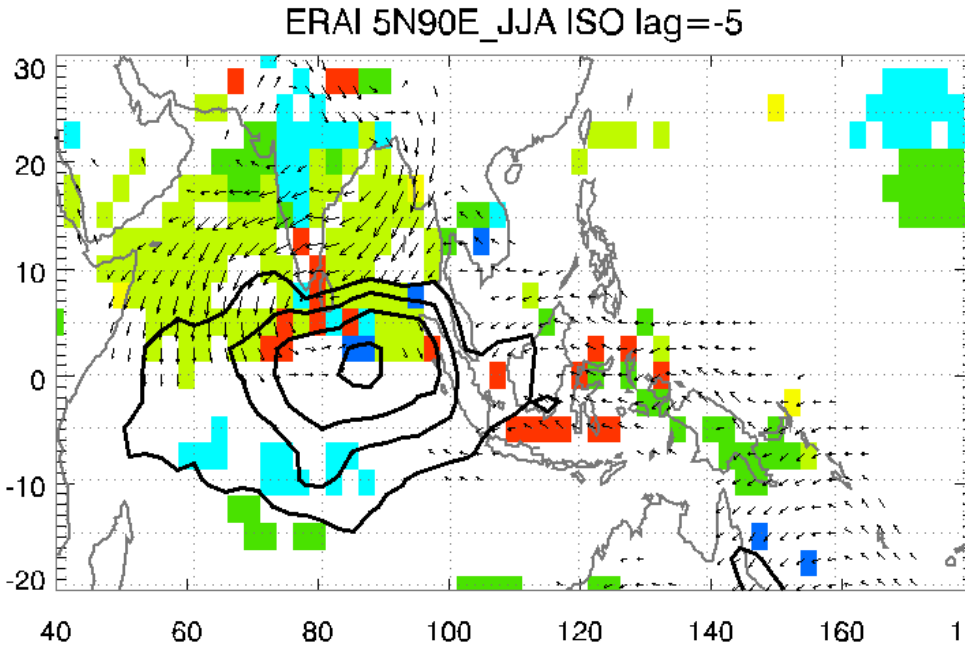

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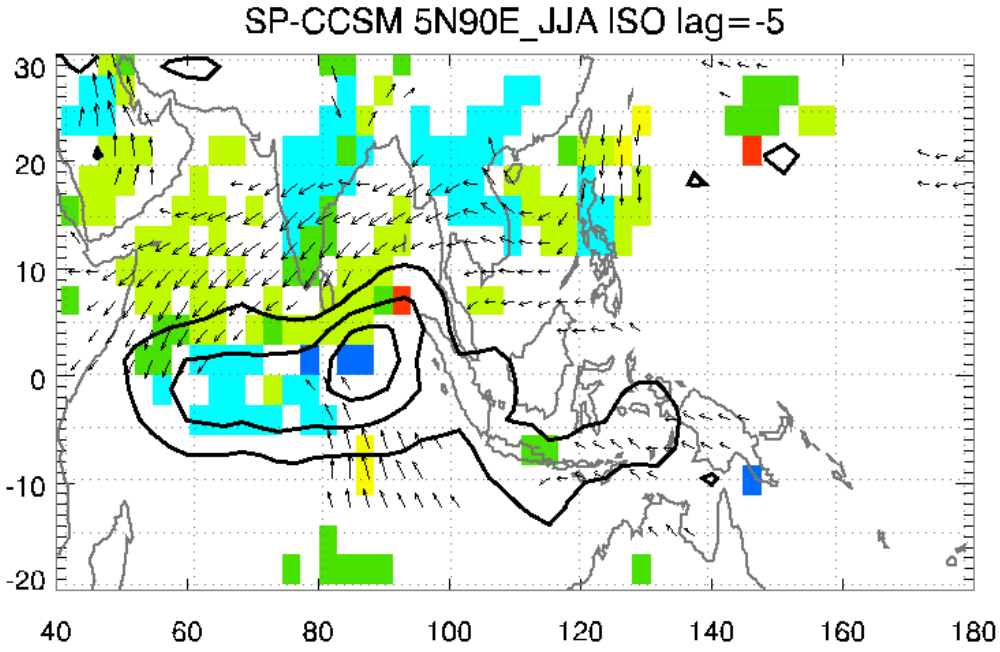

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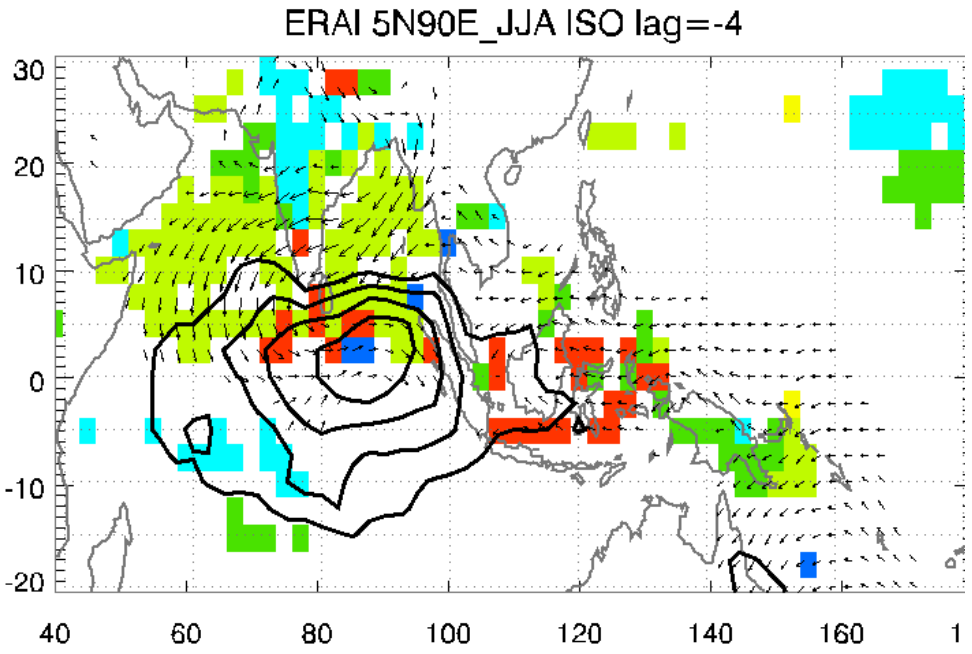

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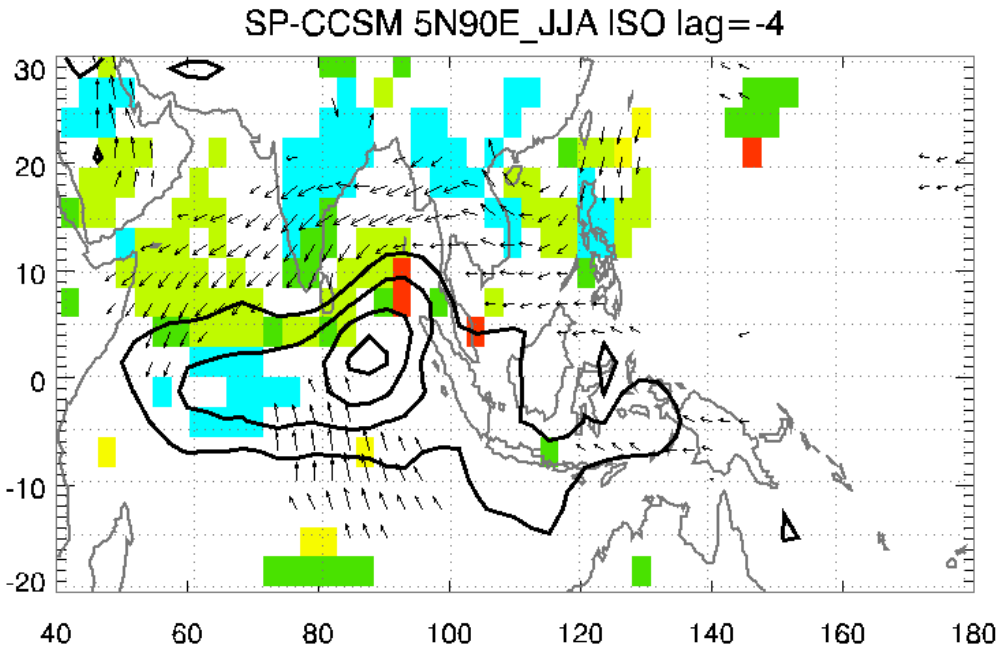

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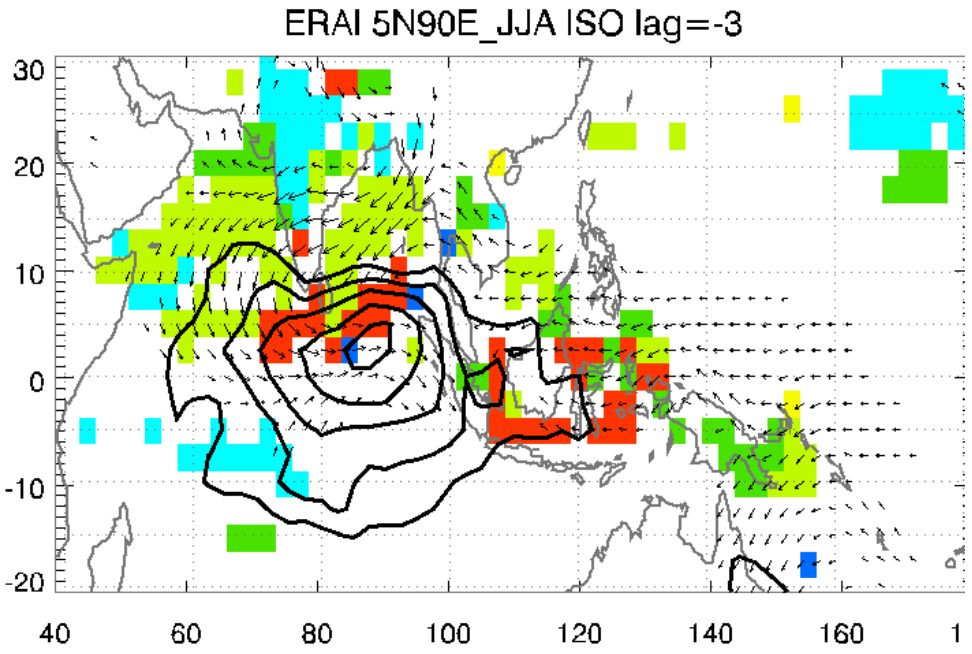

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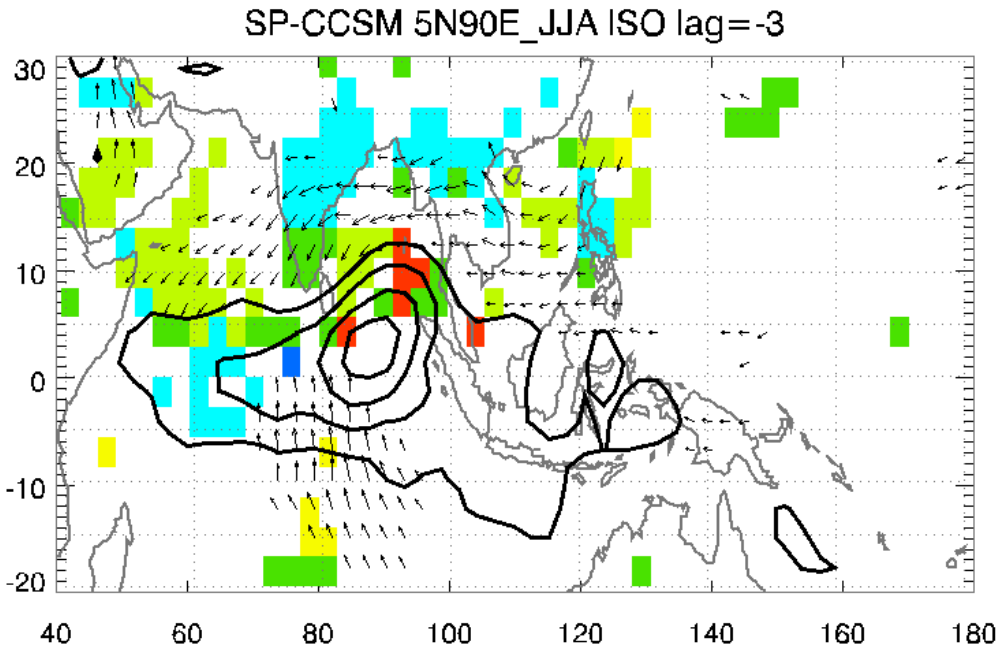

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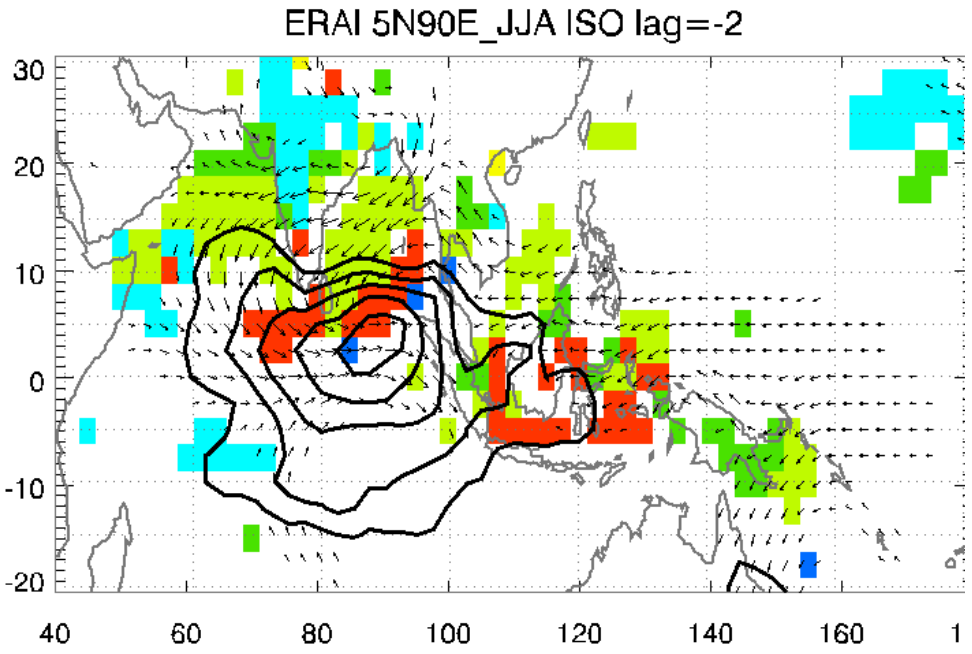

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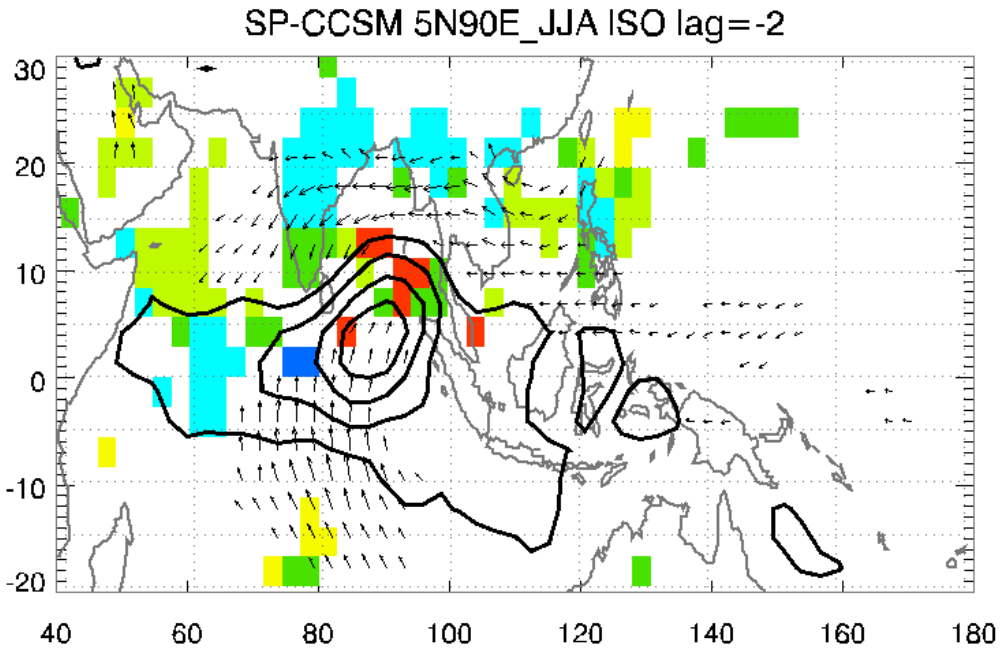

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Tsfc destabilization

SST gradient effect

Z+ effect

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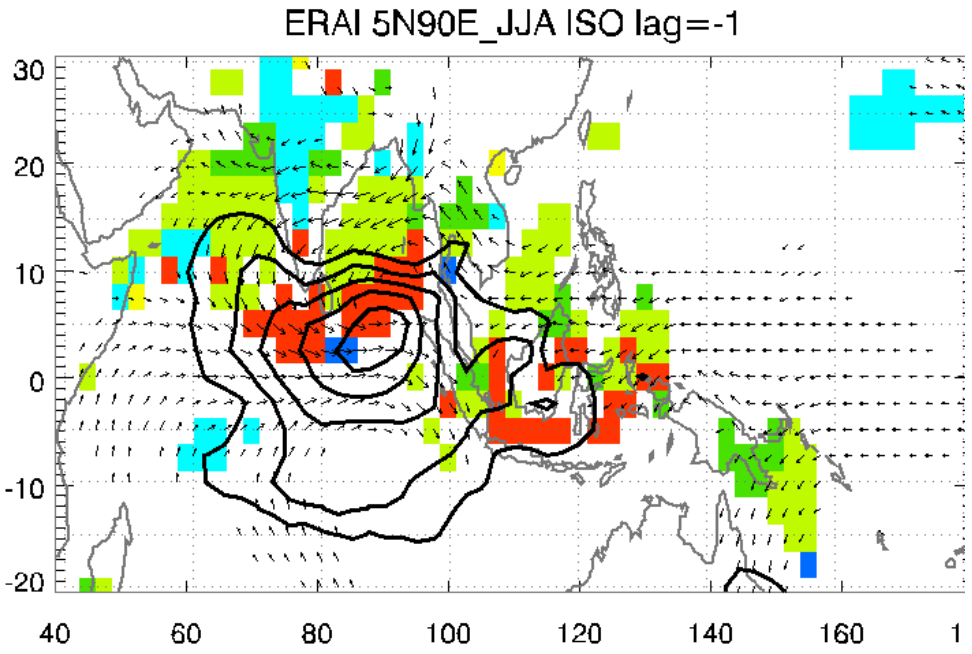

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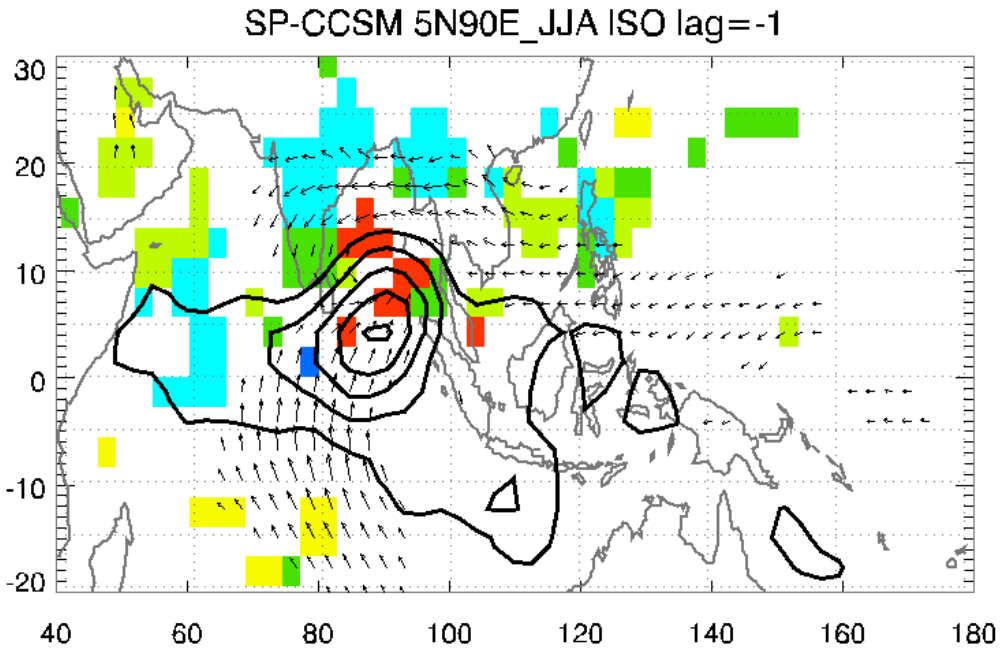

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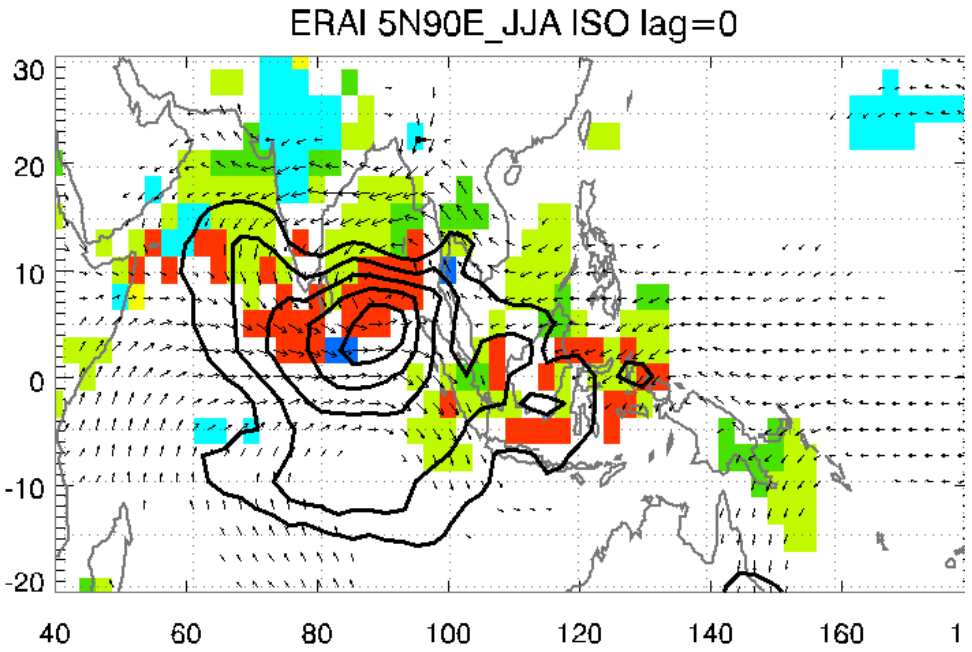

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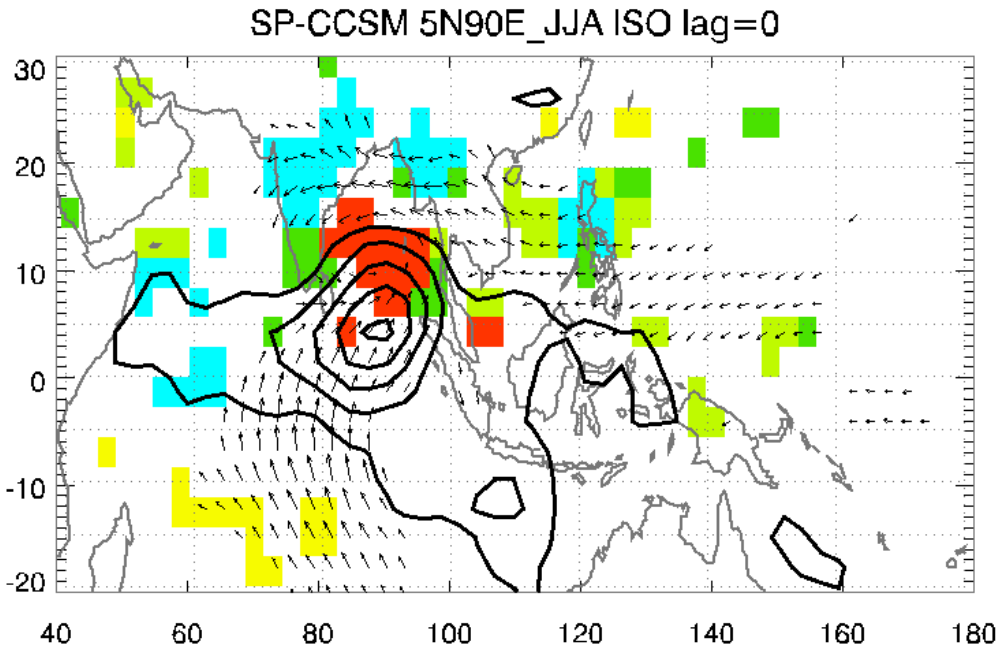

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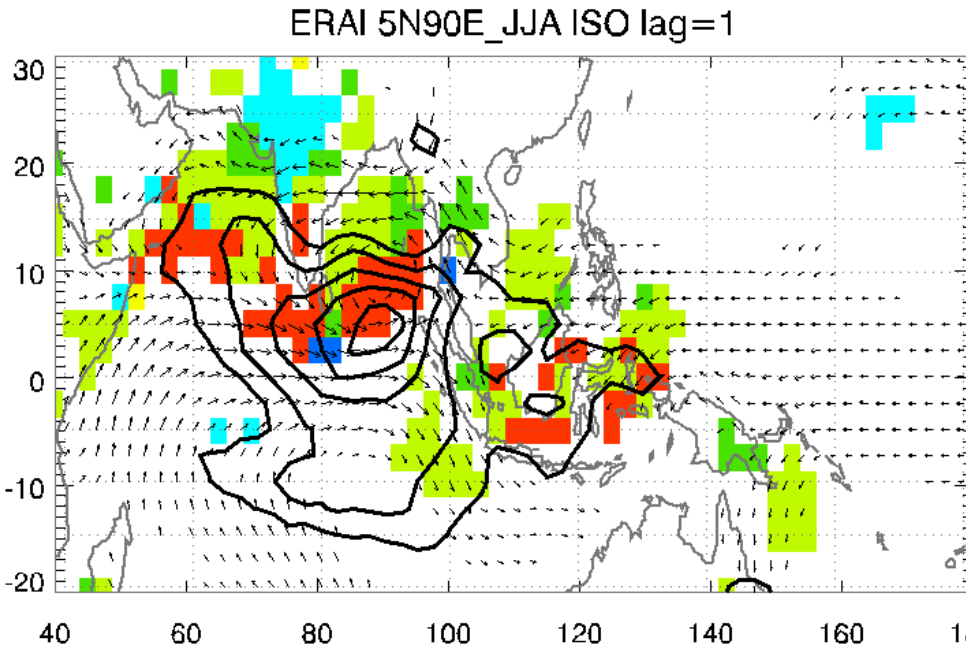

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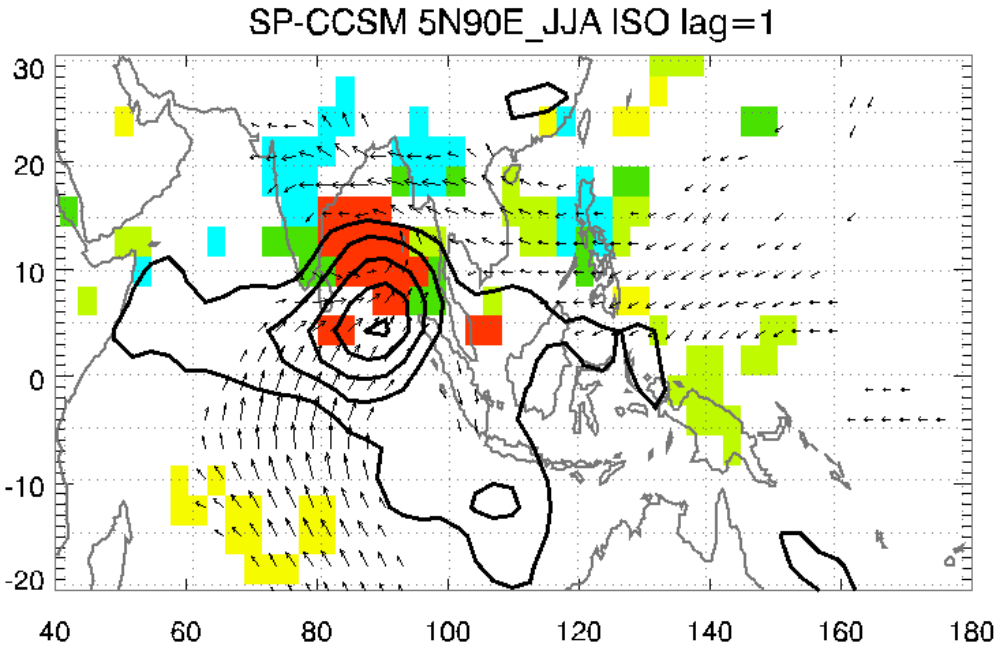

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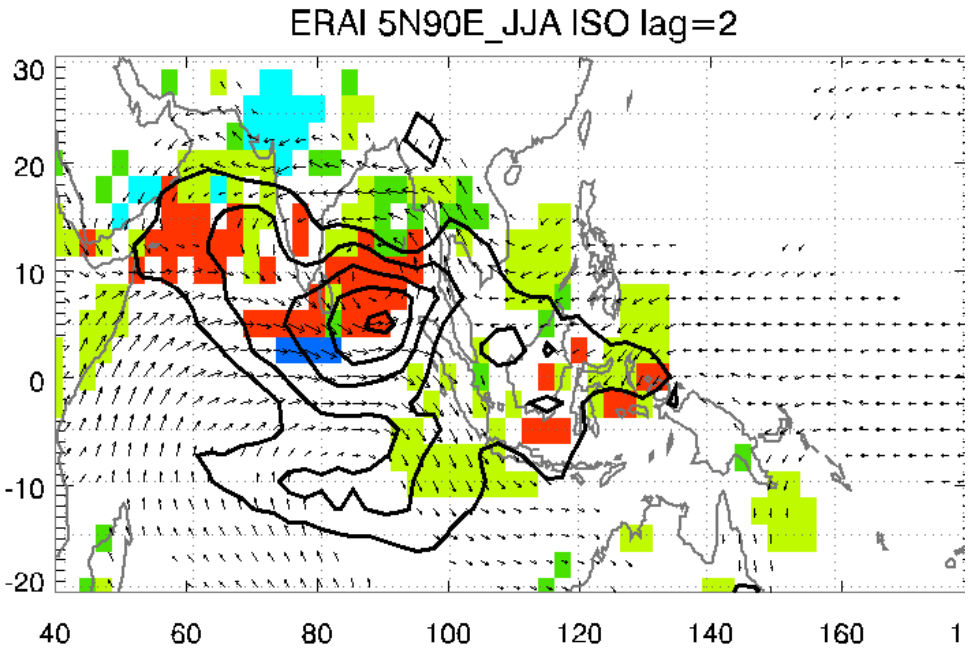

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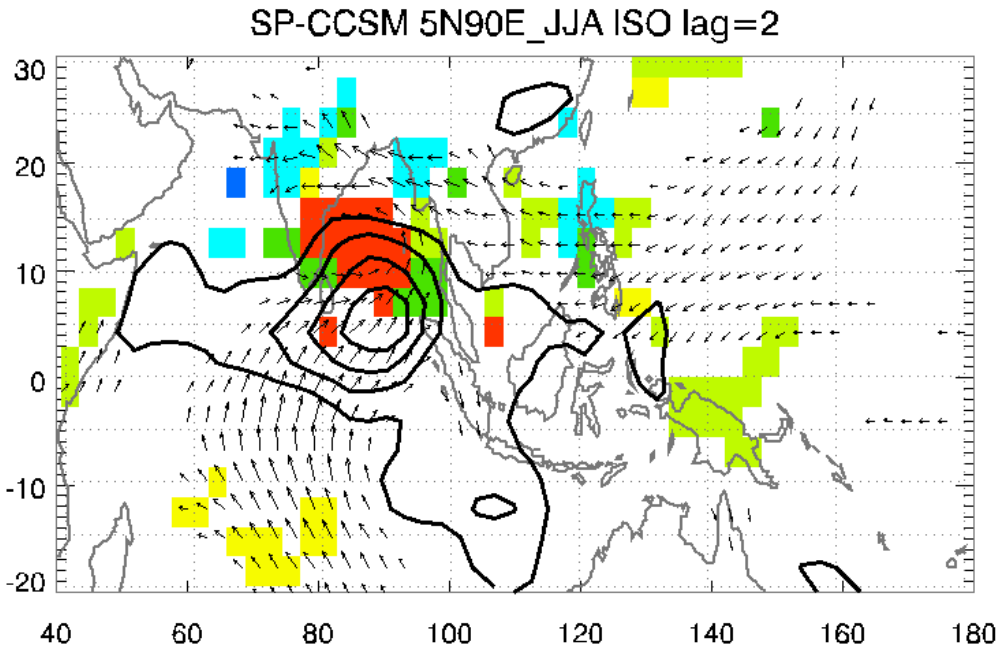

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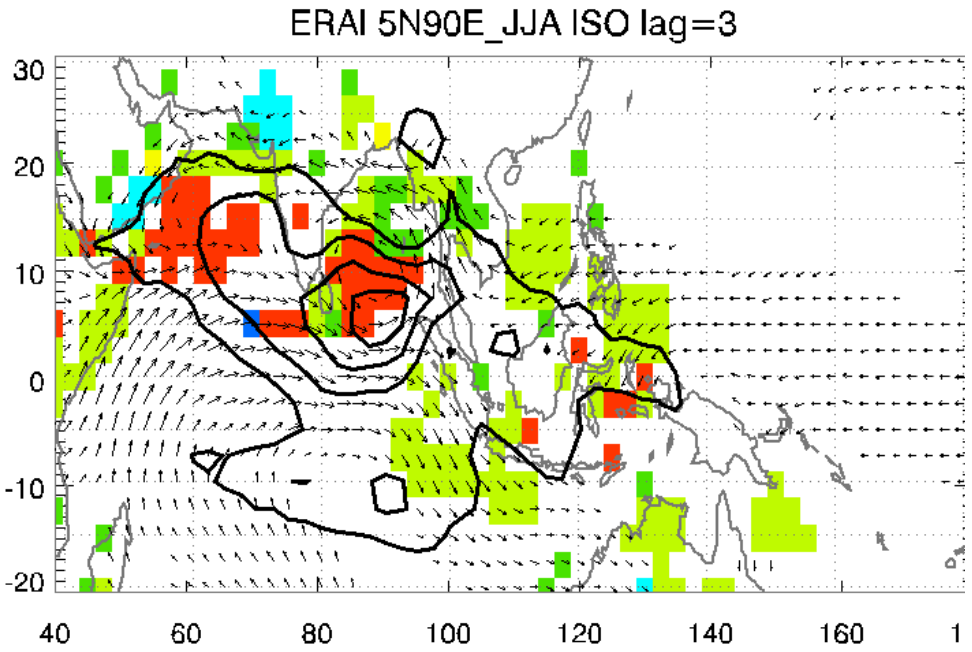

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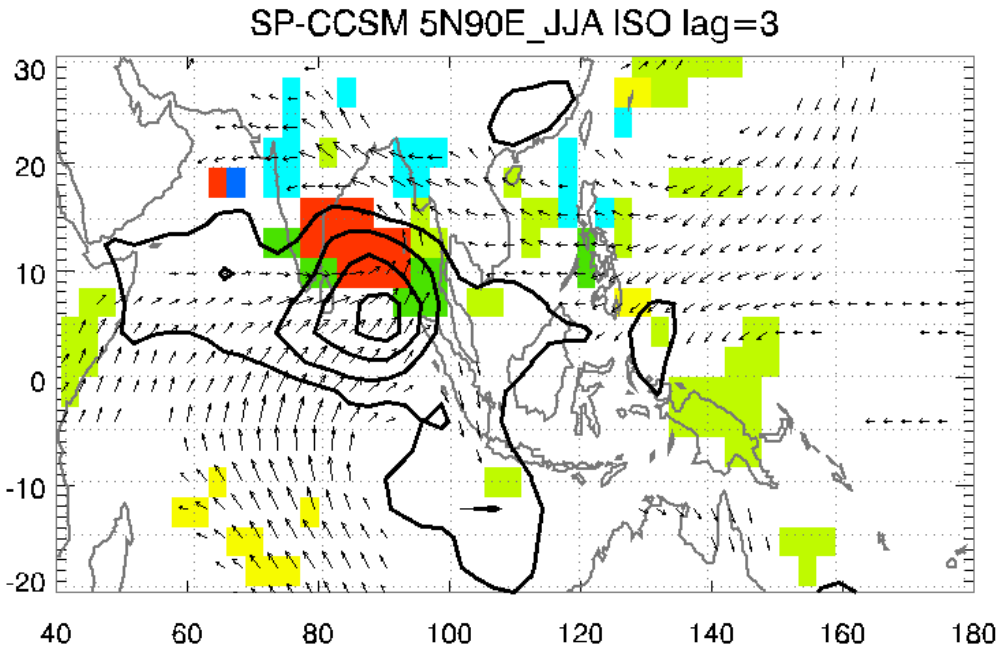

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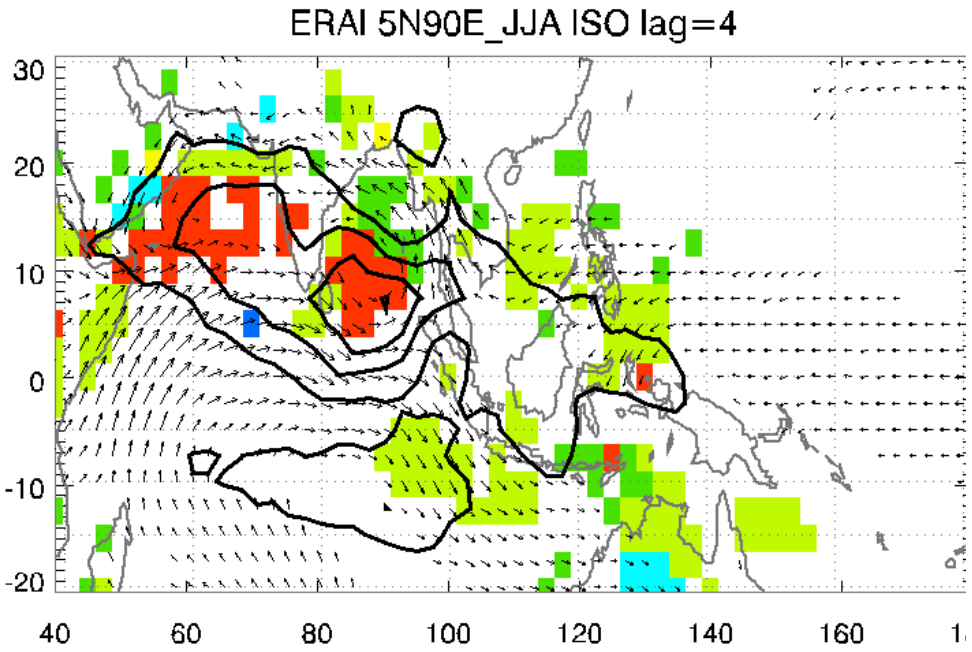

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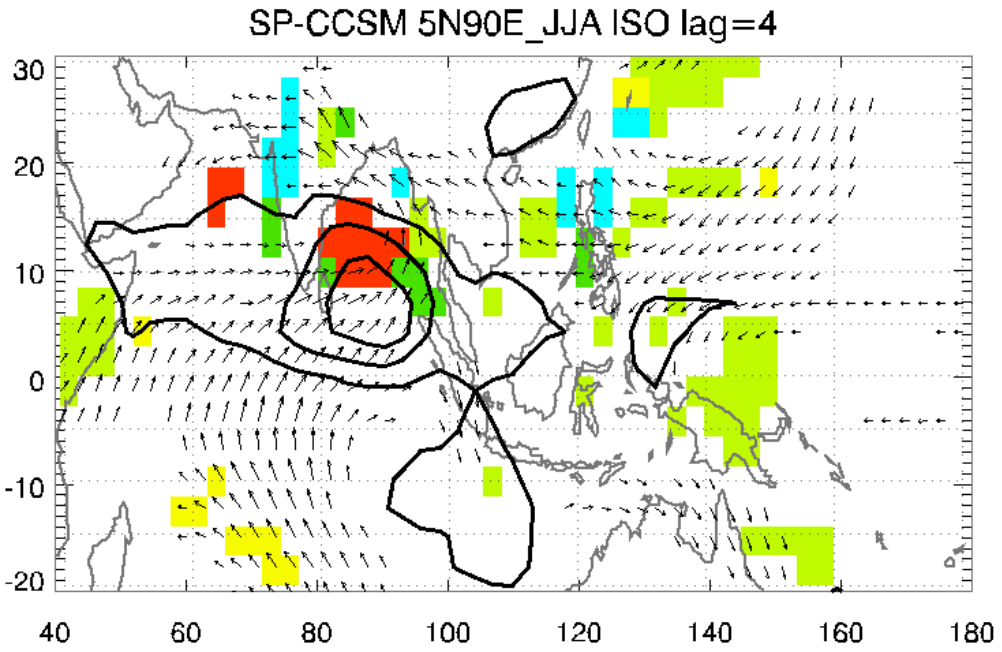

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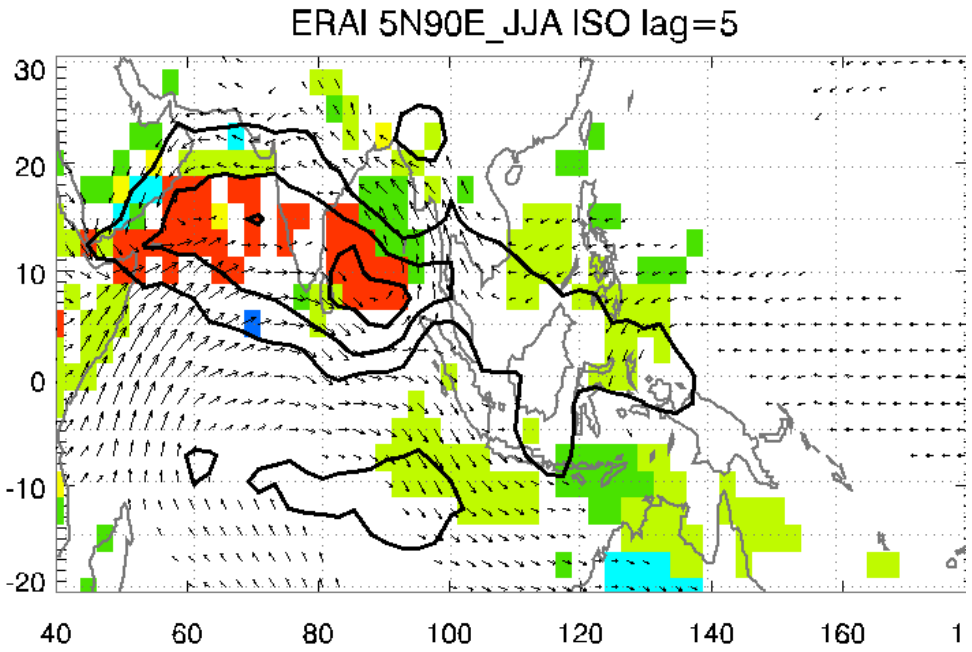

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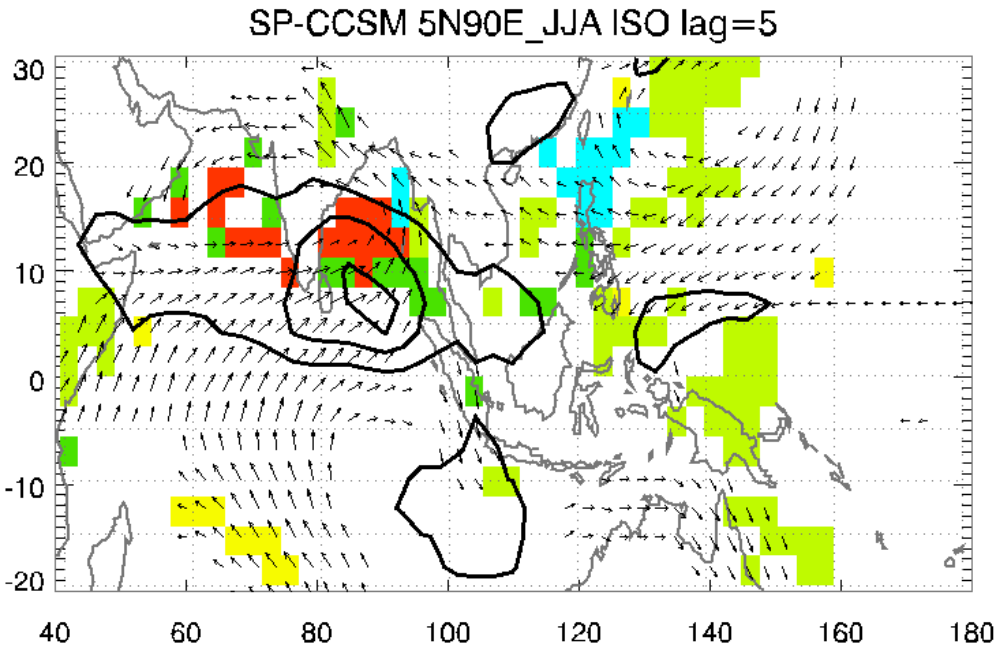

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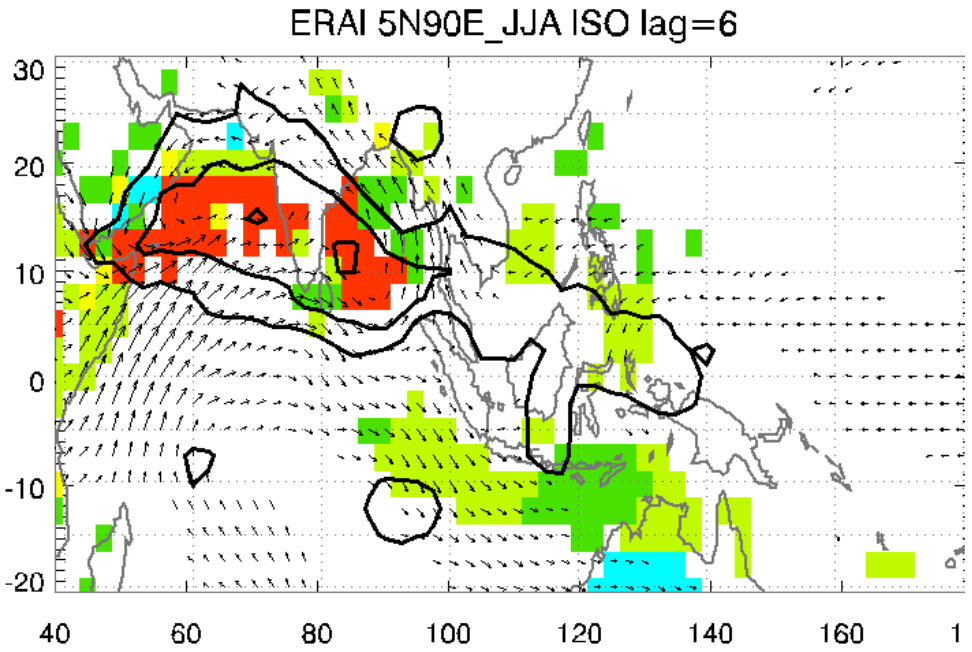

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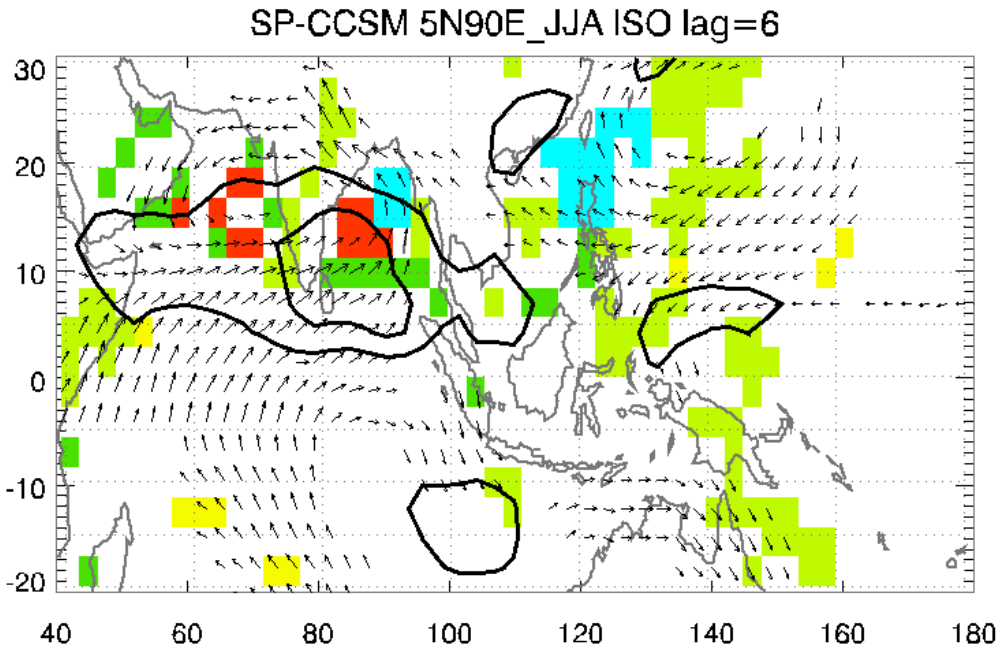

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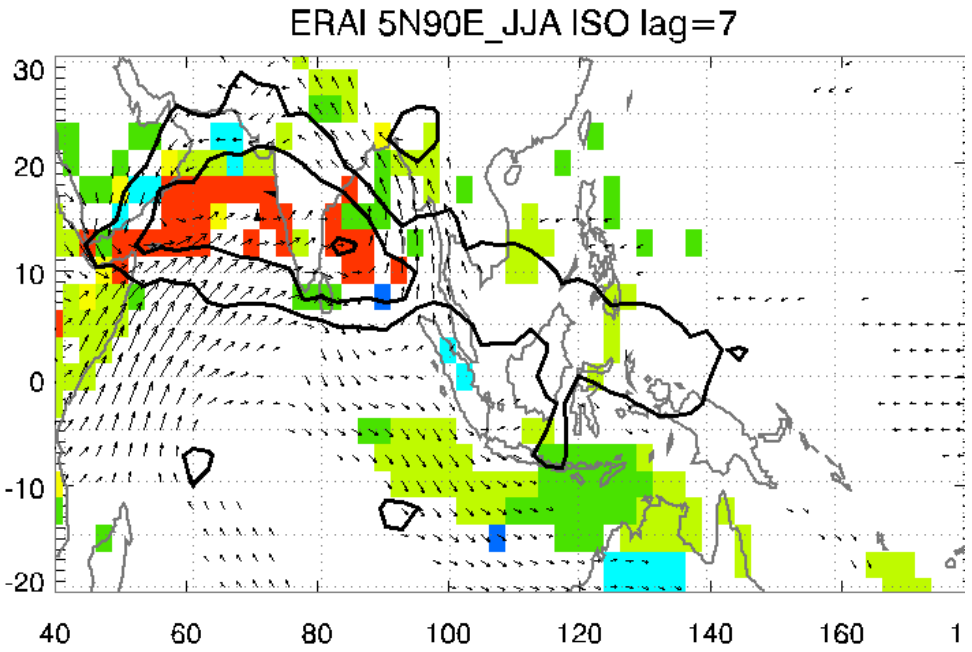

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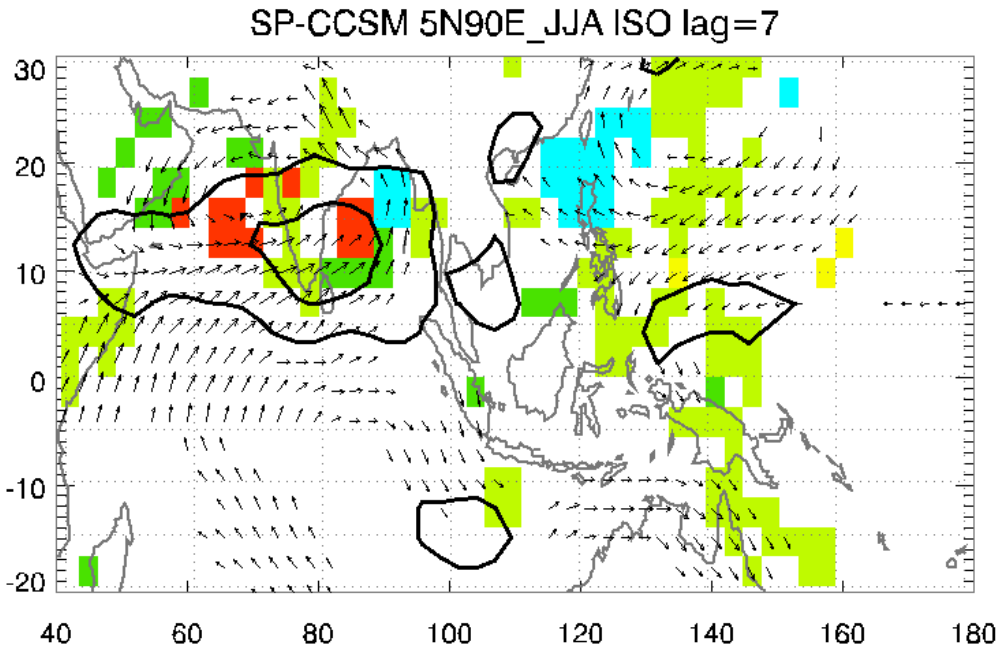

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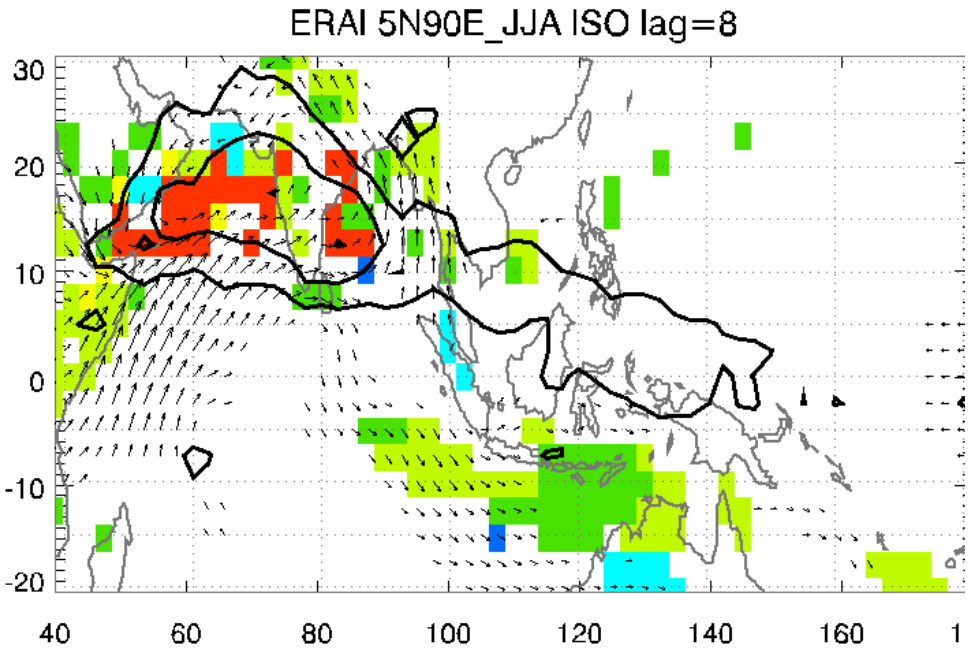

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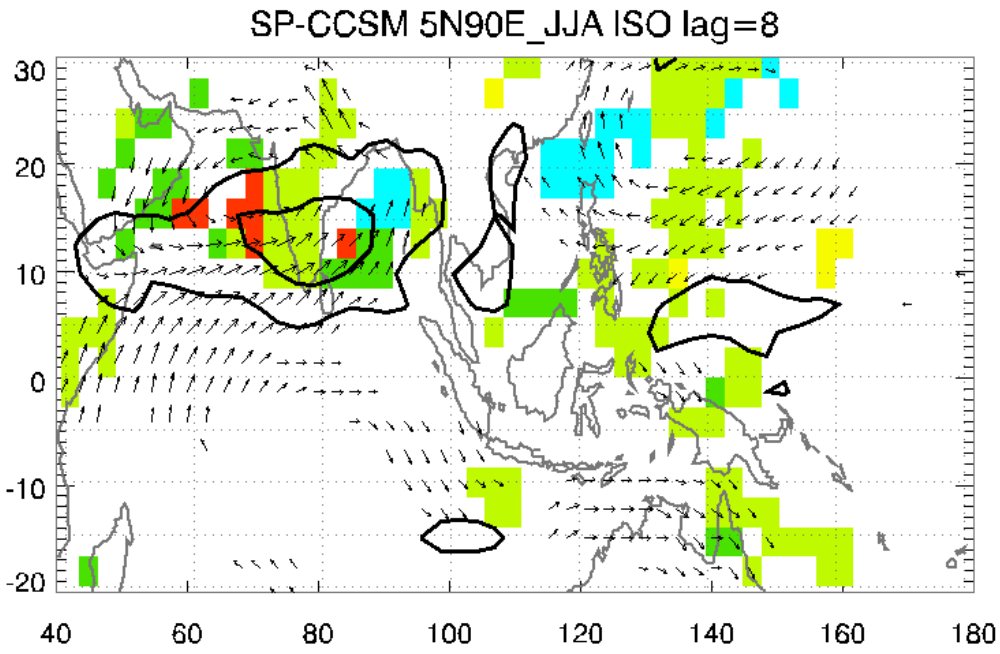

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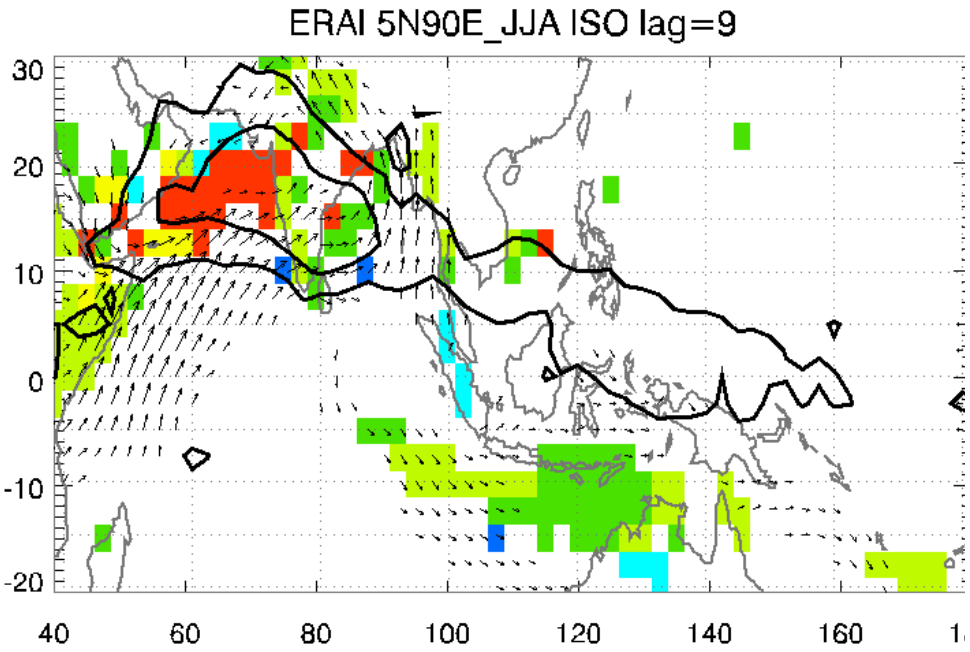

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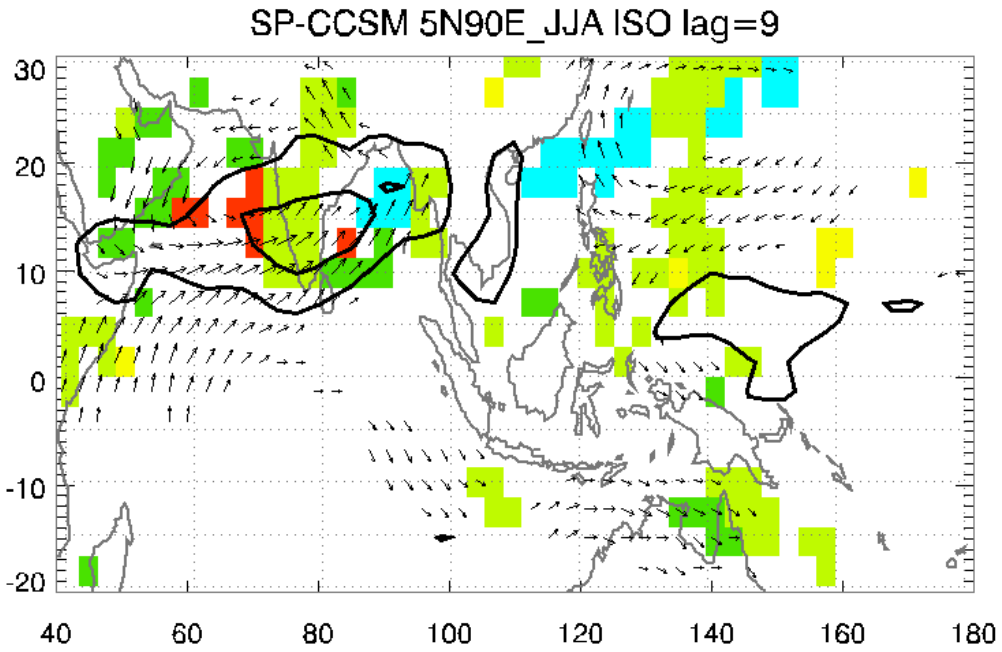

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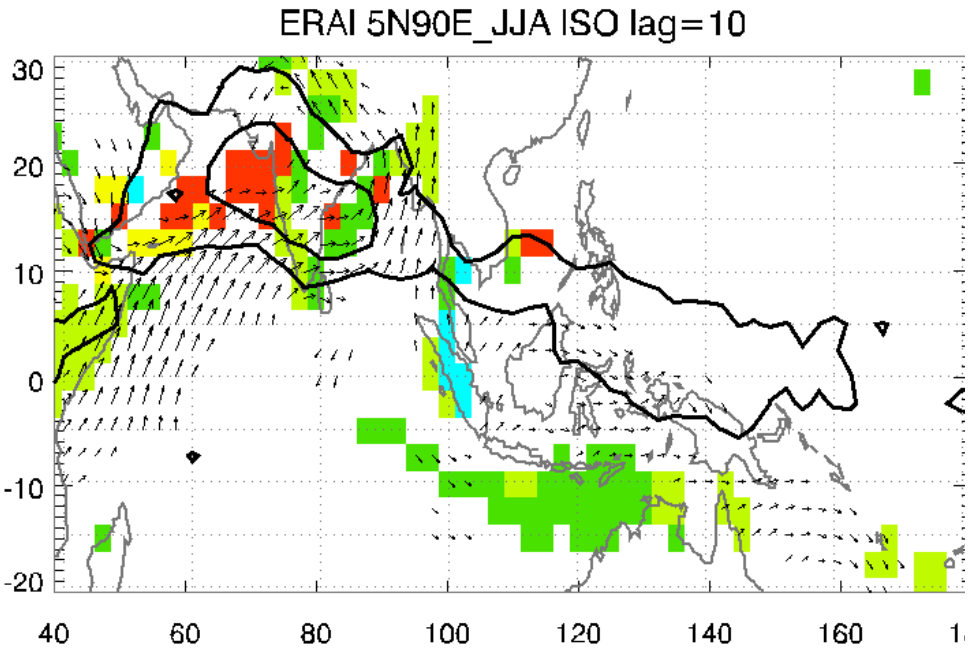

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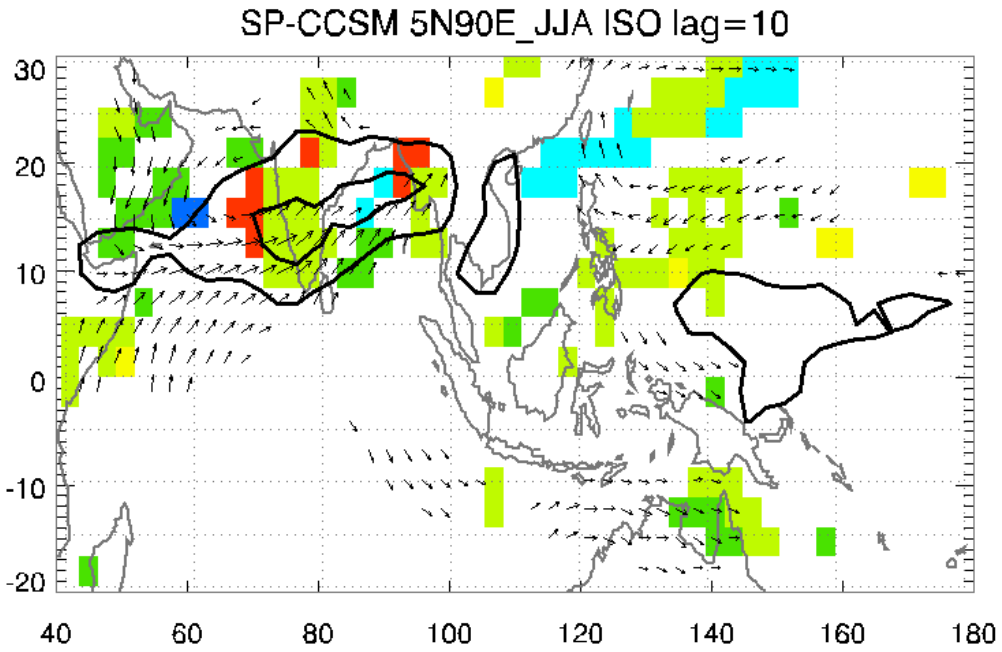

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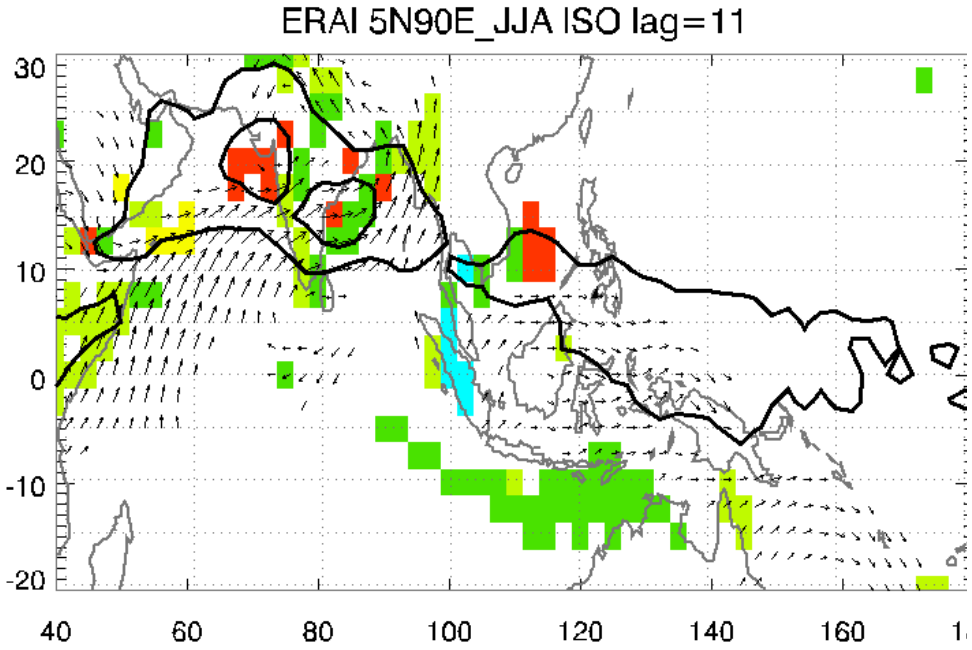

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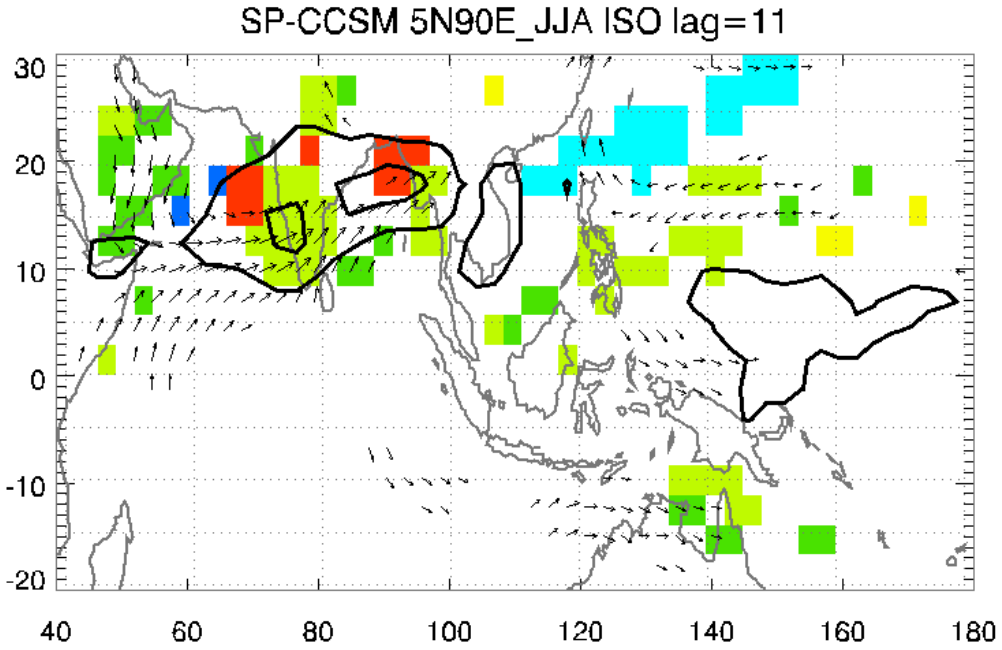

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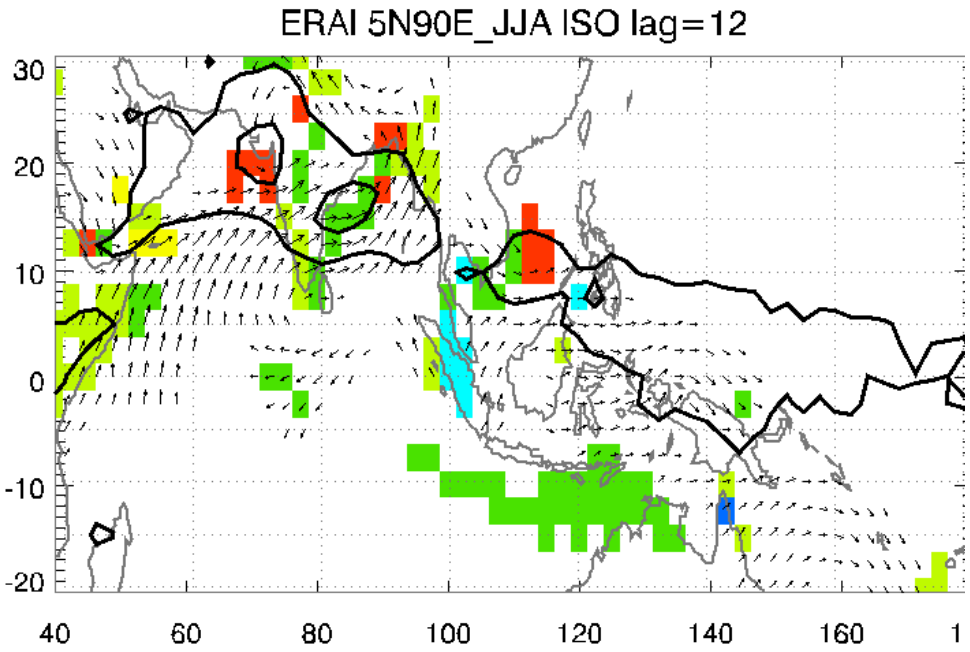

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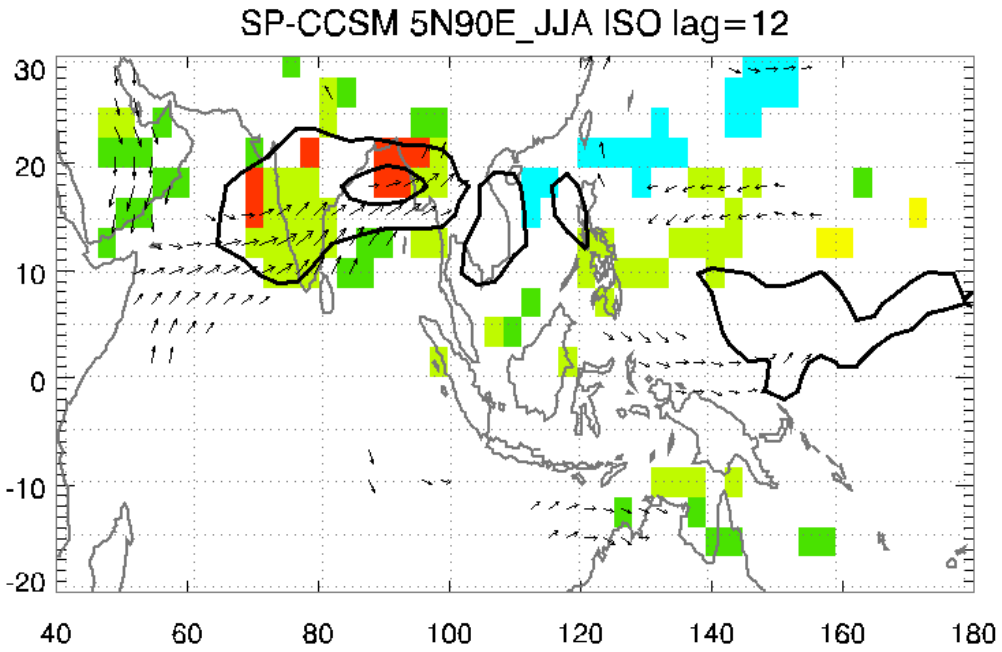

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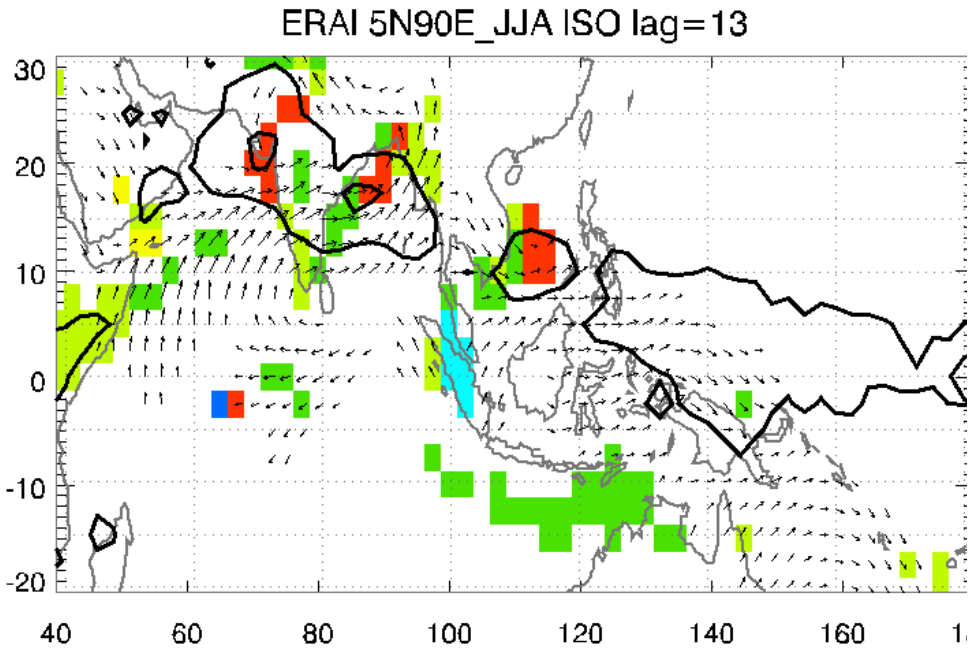

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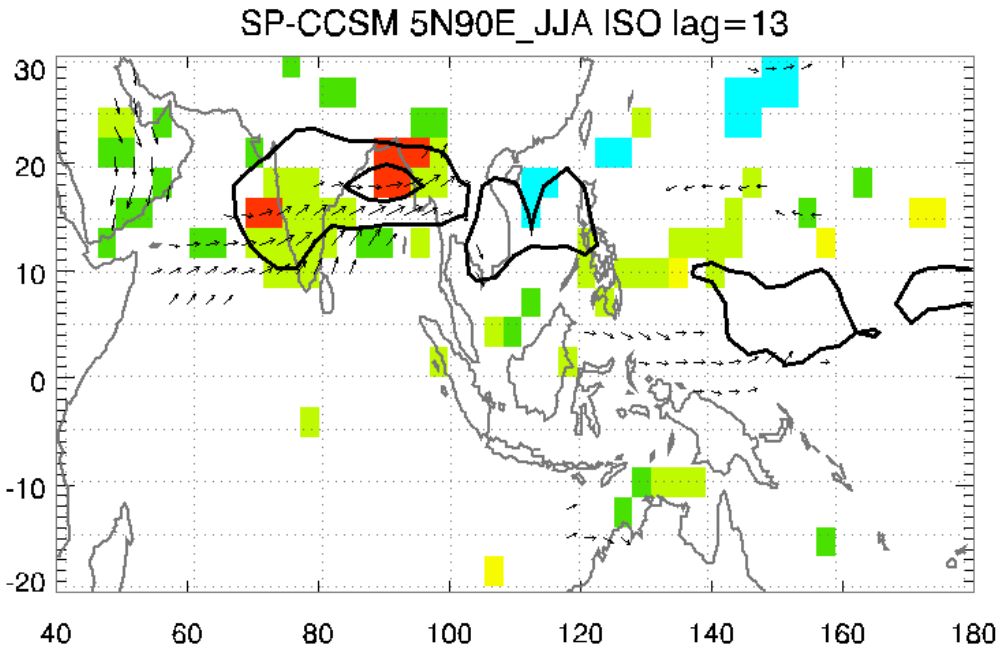

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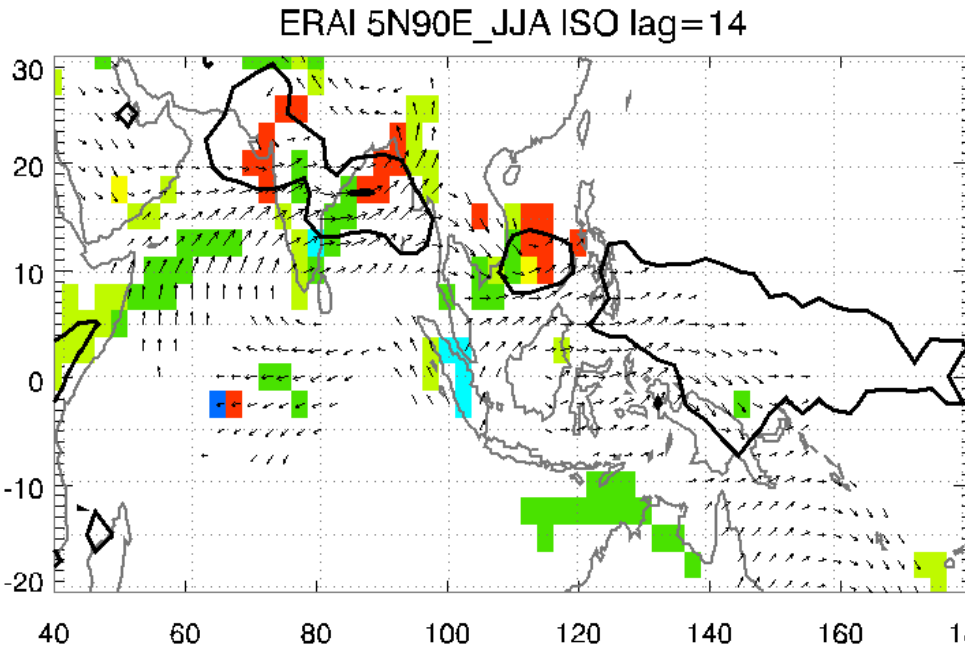

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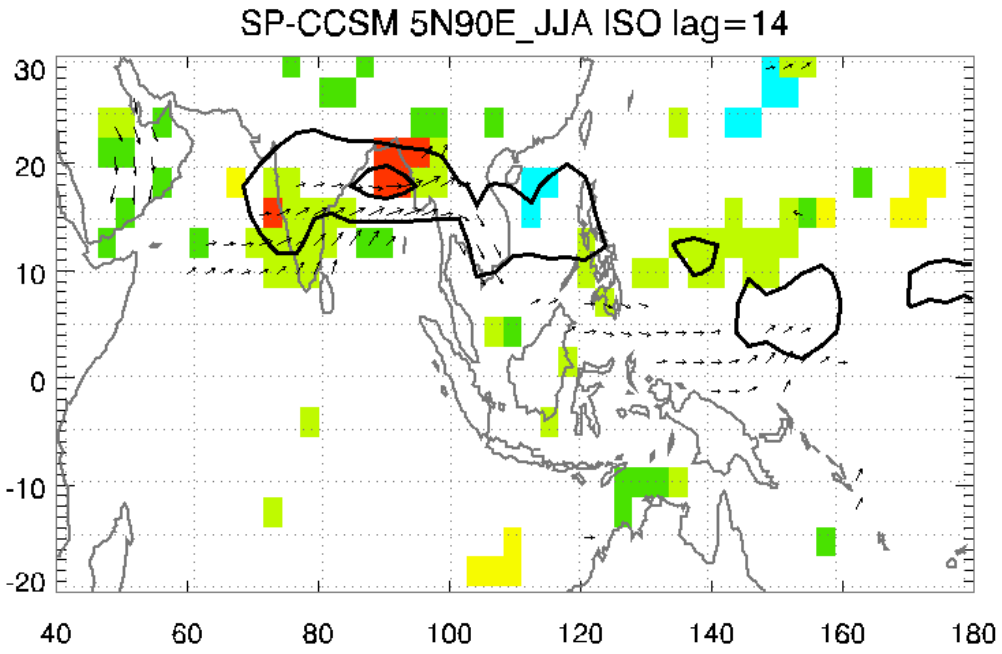

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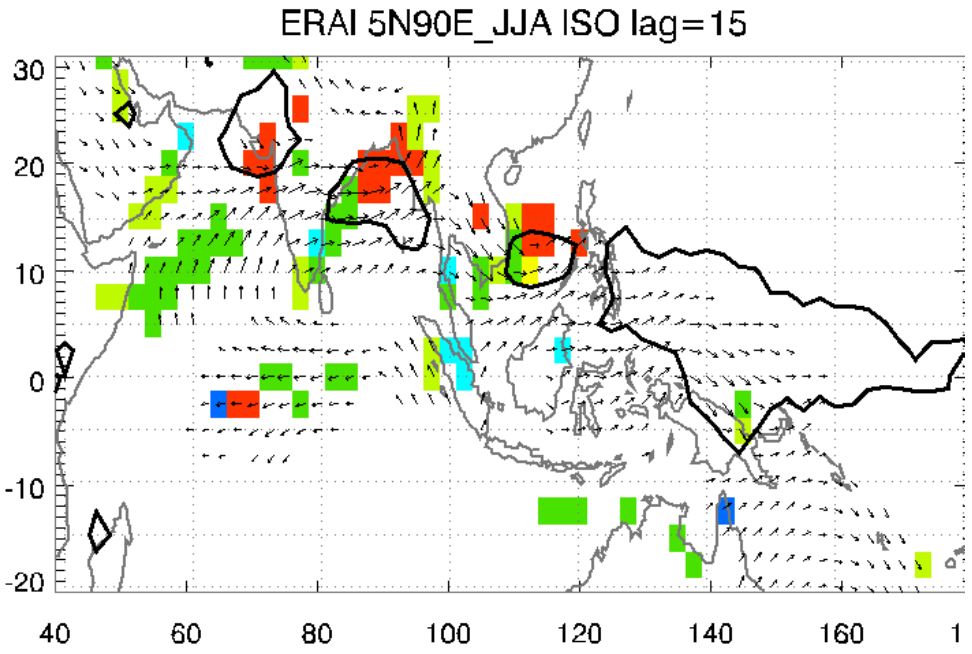

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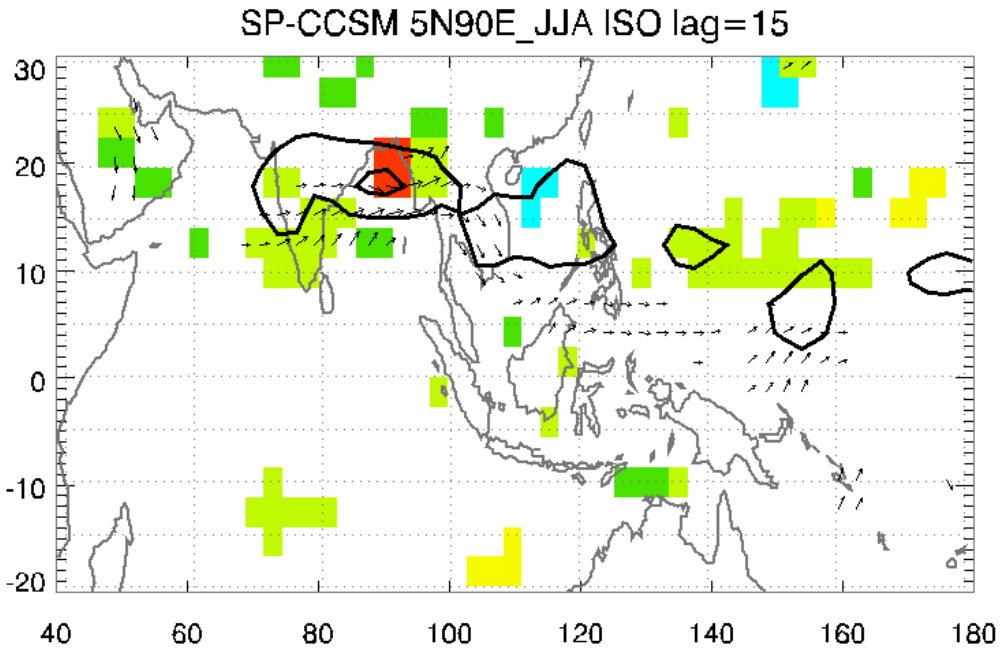

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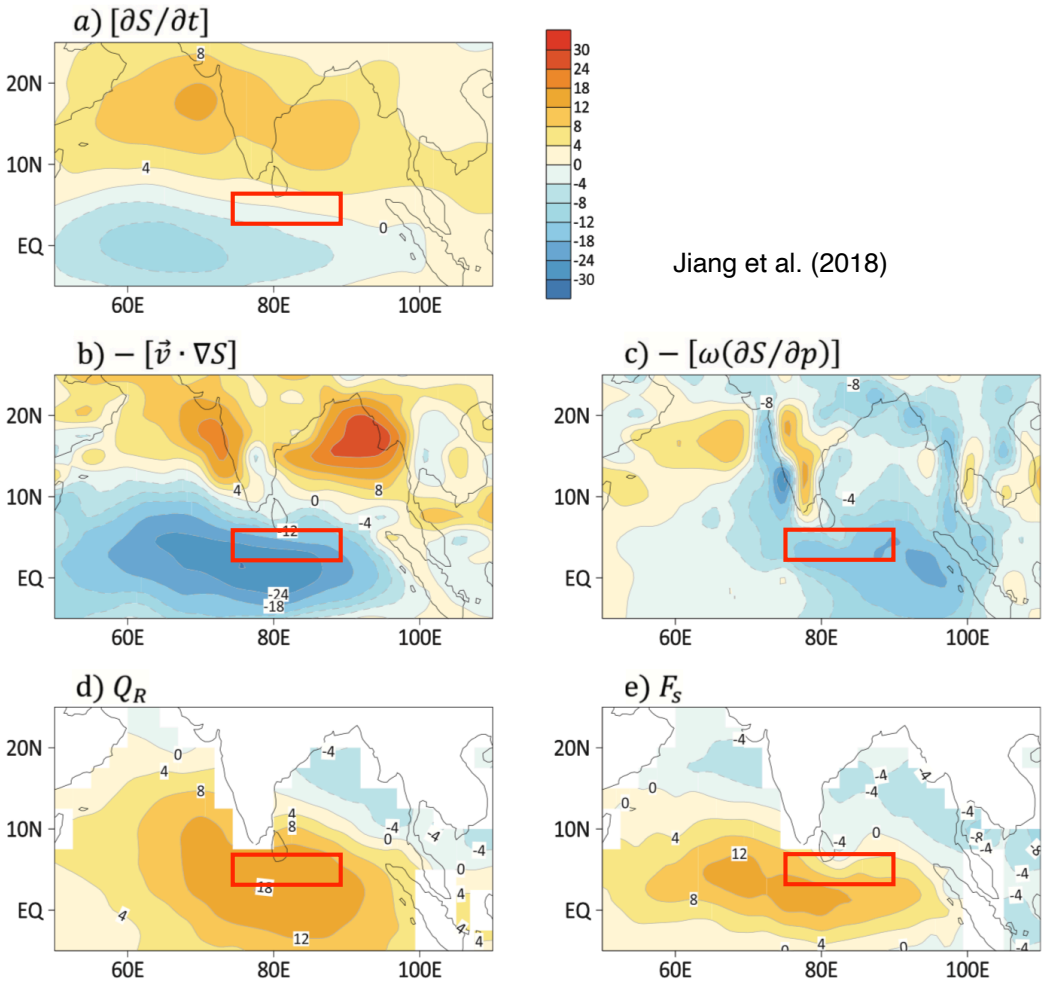
Monsoon northward-propagation mechanisms (ca. 2013)

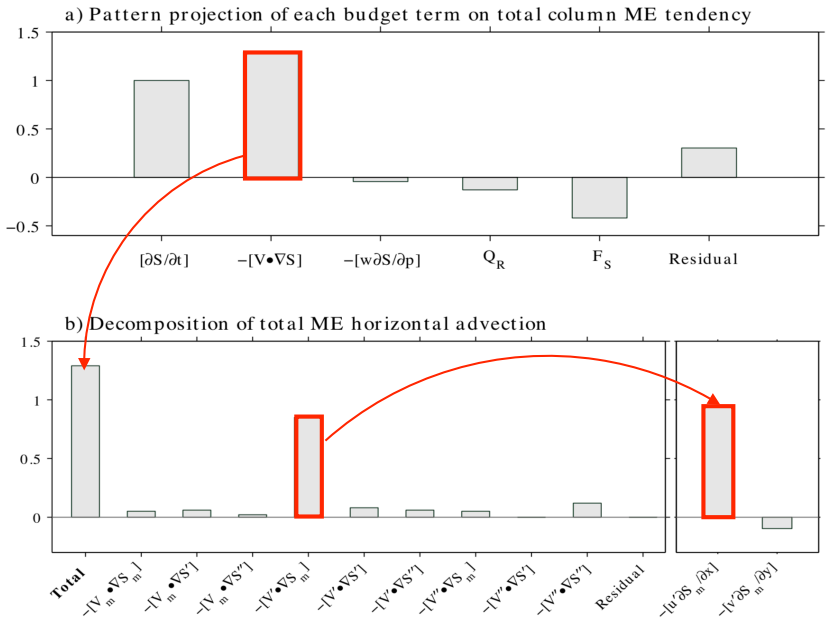
- Many mechanisms are active at any given time.
- Boundary layer moisture advection dominates when convection is near equator.
- Barotropic vorticity mechanism is dominant for convection poleward of ~5N.
- SP-CCSM is most lacking in Arabian Sea--both moisture advection, and barotropic vorticity mechanism.
- Simulated convection ***must*** respond appropriately to potential NP mechanisms!
  - convection-boundary layer interaction may be critical

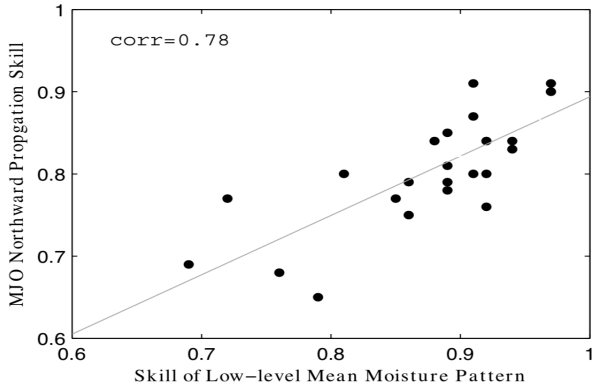
Monsoon northward-propagation mechanisms (post-2013)

- Moisture mode theory for tropical ISV
- Moist enthalpy (ME) budget analysis of ISV
- Mean-state moisture patterns are critical!



Jiang et al. (2018)





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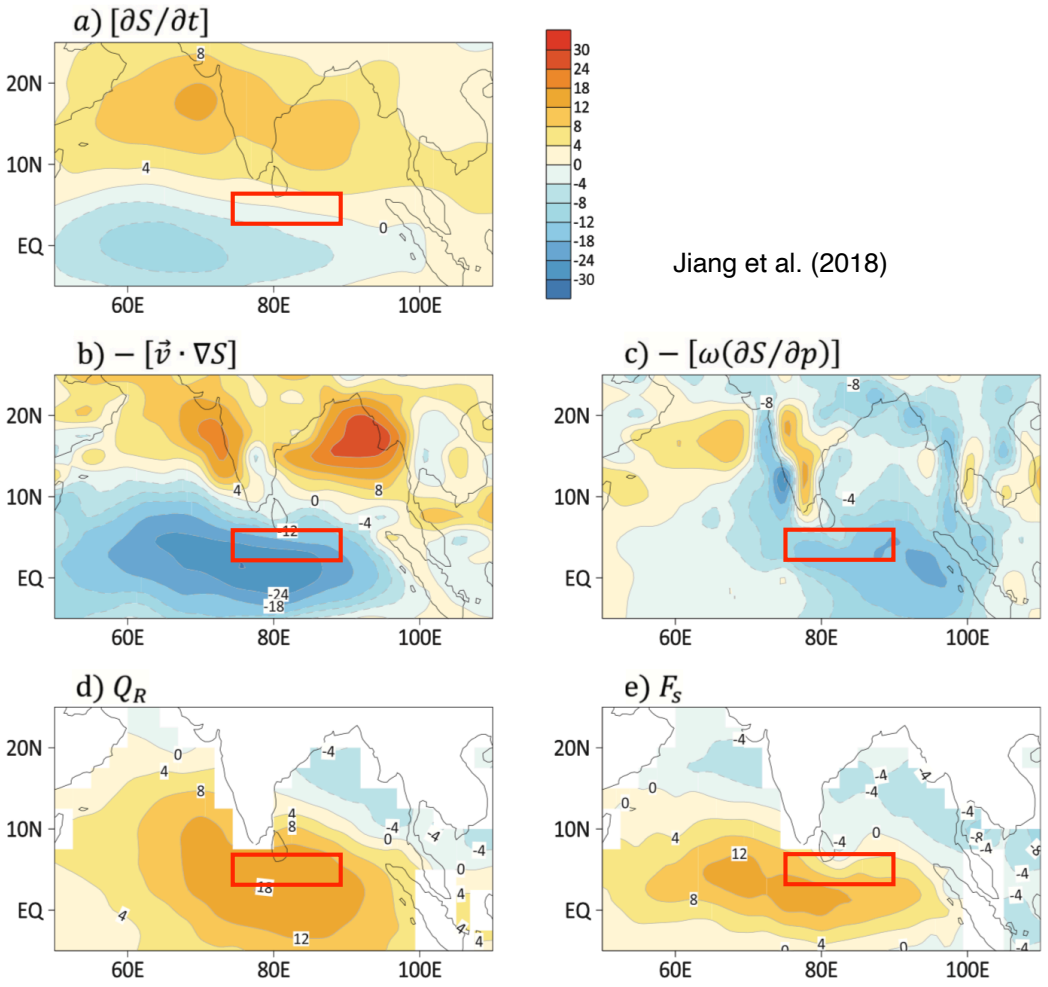

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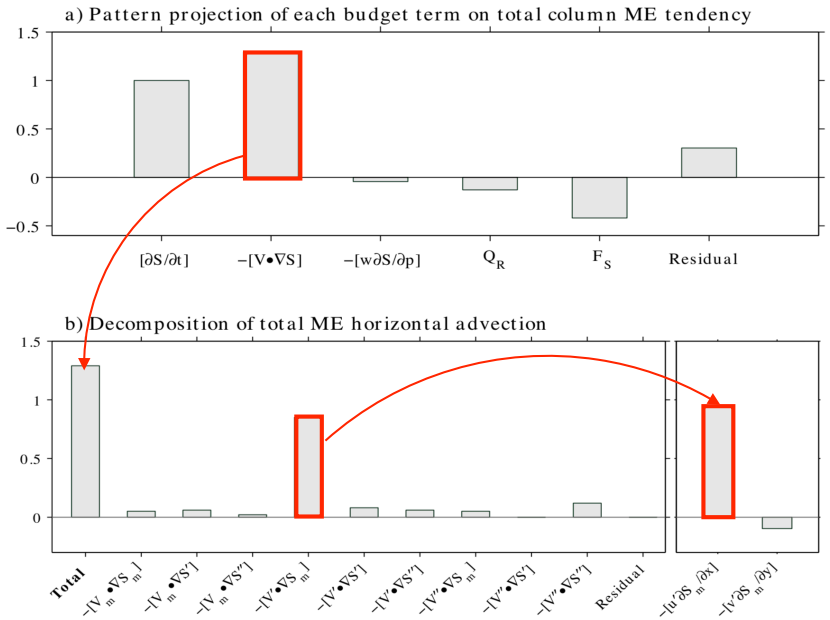
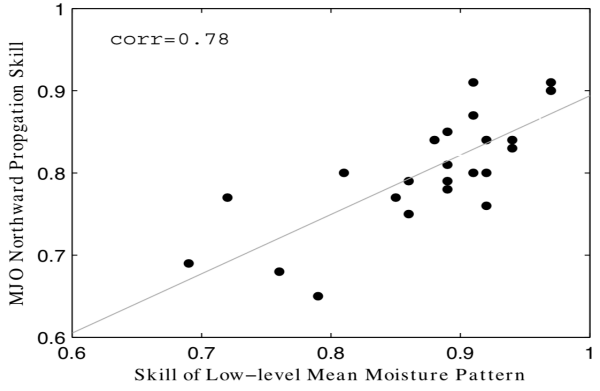
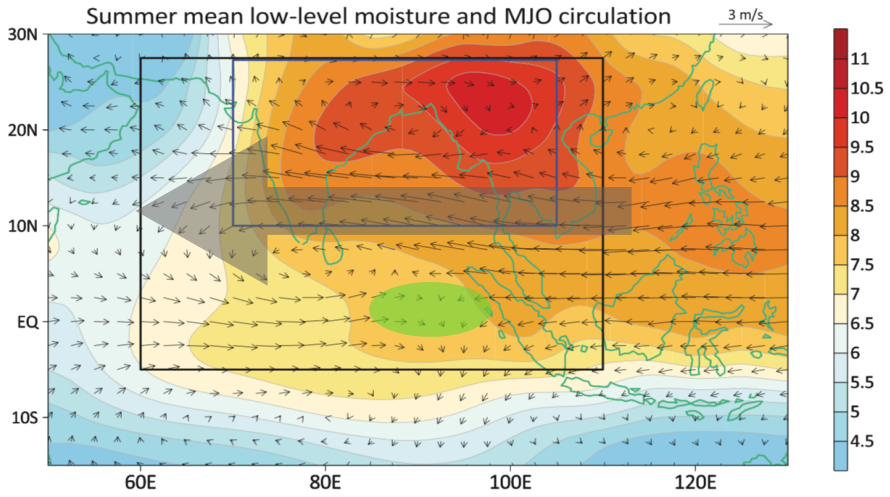


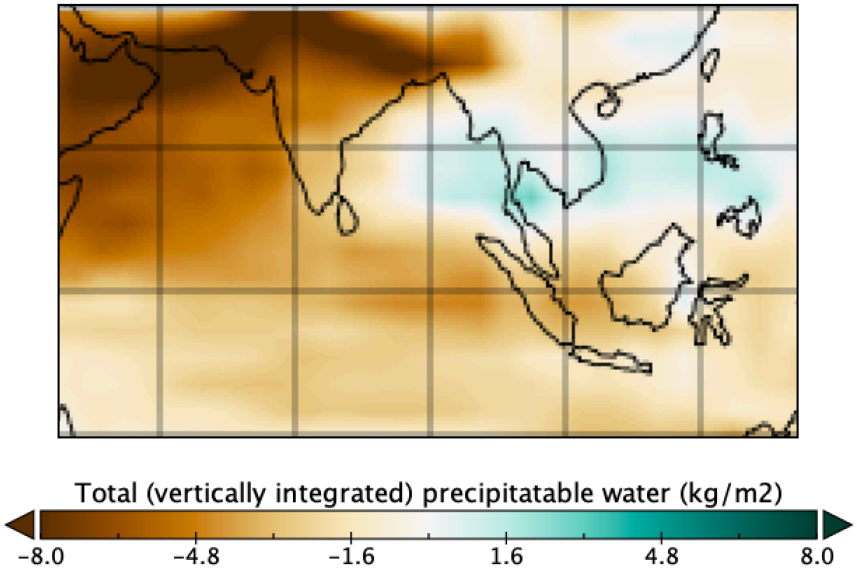


Ocean feedbacks to mean state moisture



Jiang et al. (2018)

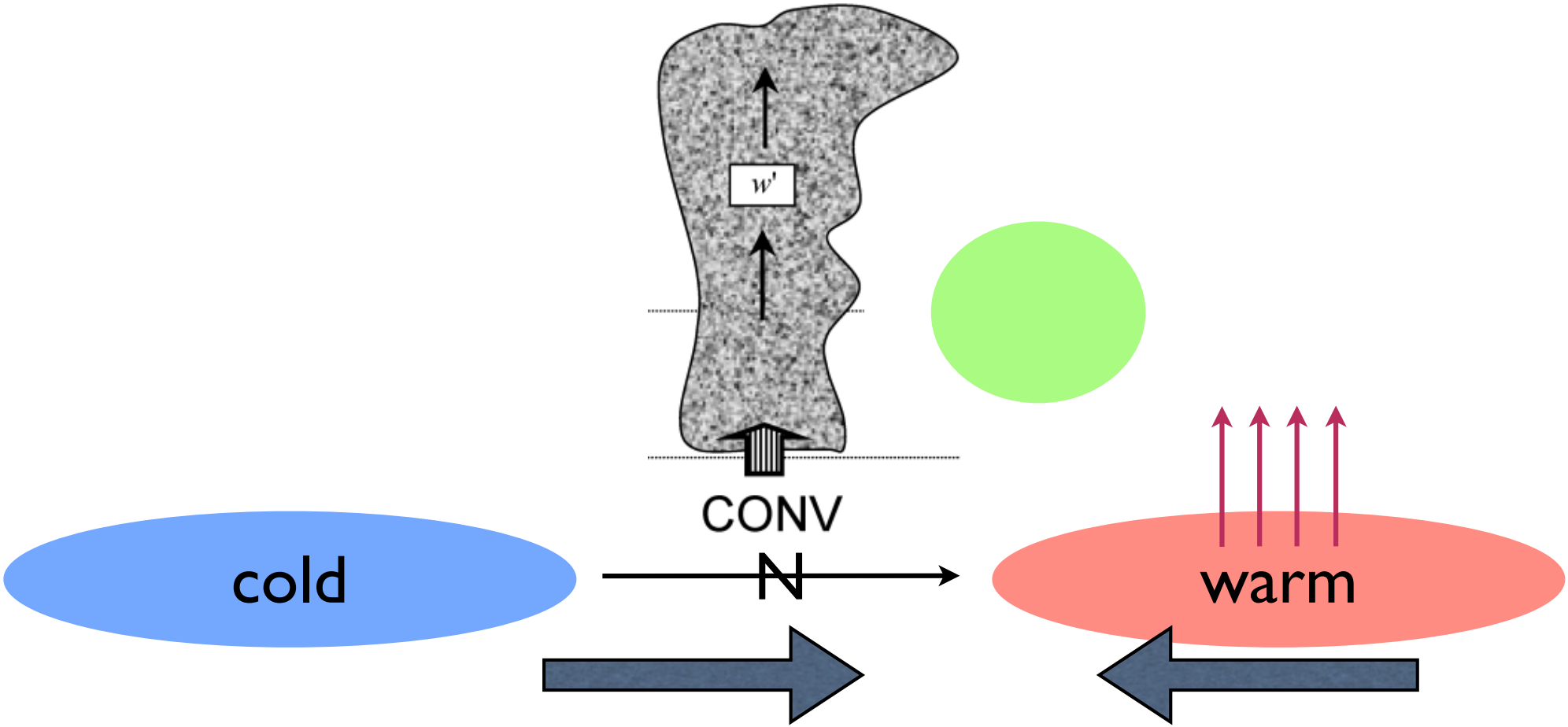
SPCCSM TPW change:
coupled - uncoupled (May-Oct)



from analysis of DeMott et al. (2019)

- sub-monthly ocean coupling enhances zonal moisture gradients
- stronger moisture gradient enhances zonal moisture advection, improved northward propagation
- scale interaction: convective moistening in response to SST ISV changes the mean state

MBL processes or mid-level moistening?



- scale interactions may be important: daily convection —> mean state moisture —> monsoon northward propagation
- MBL processes regulate convective initiation, intensity
- free-atmosphere moisture regulates convection growth rate, propagation speed

Summary

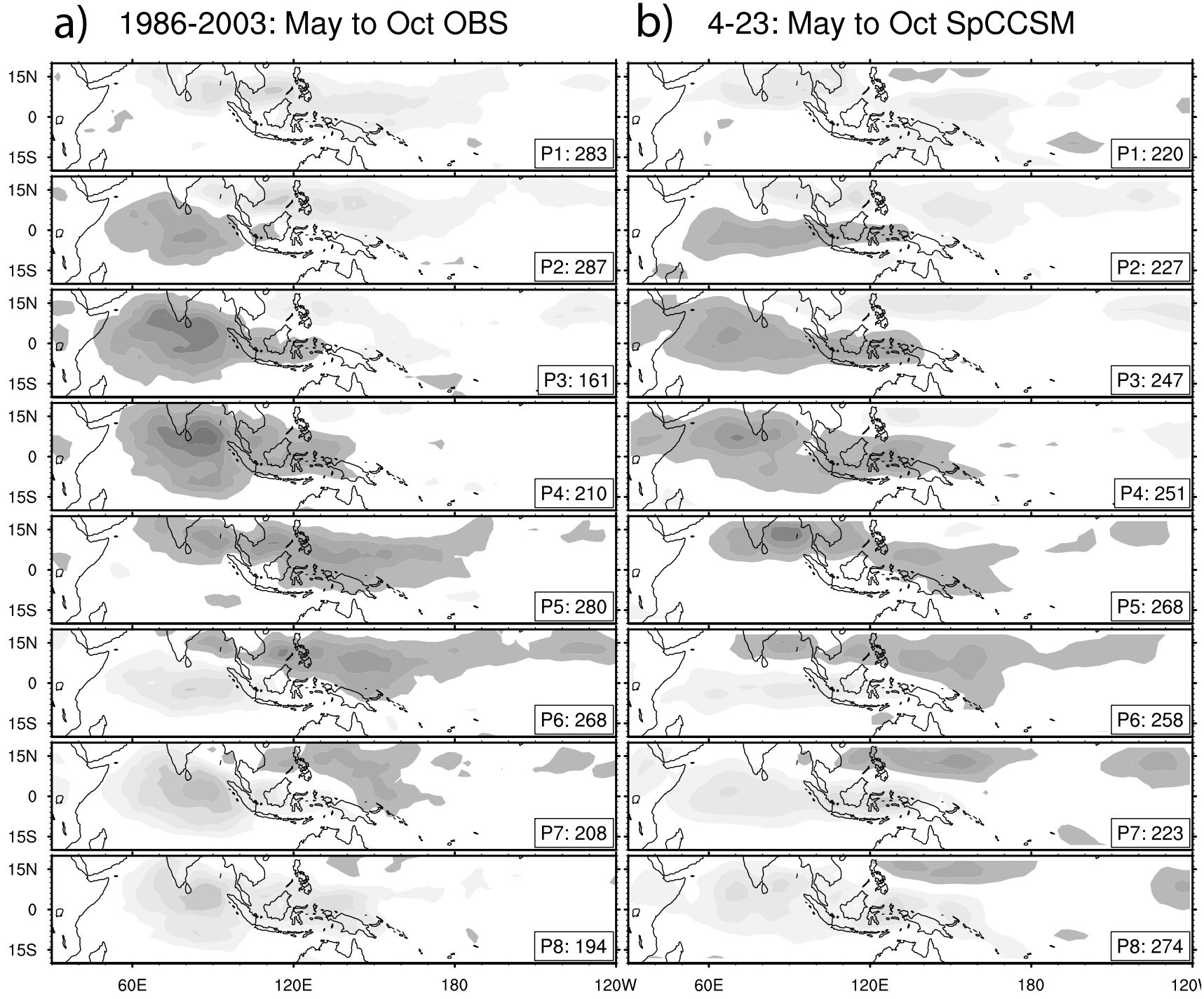
- boreal summer ISV more complex than boreal winter ISV
  - convection-easterly shear interactions
  - eastward and northward propagating convection

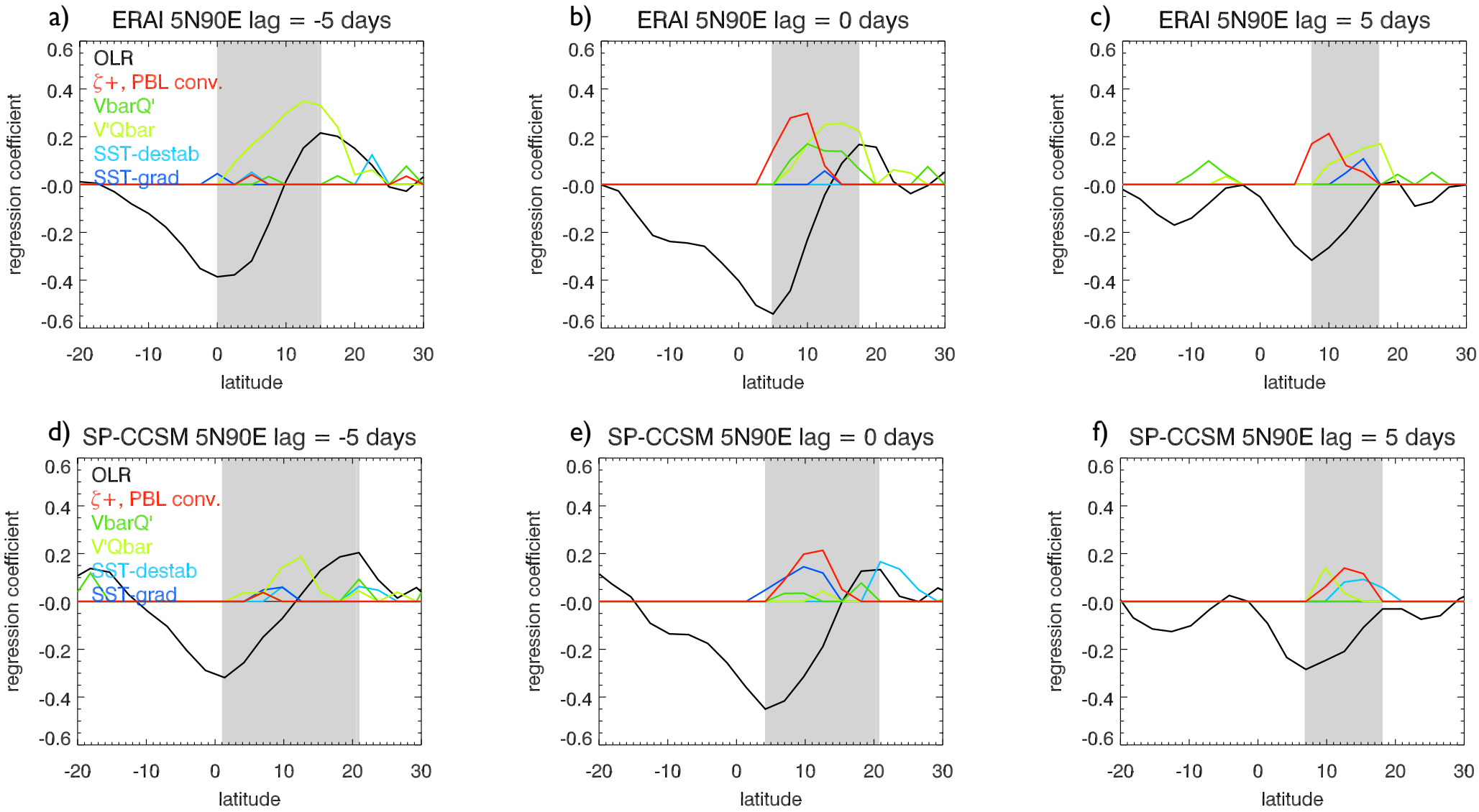
- ocean response to atmospheric forcing promotes large SST ISV in northern Indian Ocean
  - suggests ocean role for monsoon northward propagation

- MBL perspective:
  - dynamic processes, and not SST destabilization, contribute to northward propagation

- Moisture mode perspective:
  - free atmosphere low-level horizontal moisture gradients and moisture advection regulate northward propagation

- Convection links MBL processes to mean state moisture and monsoon northward propagation


a) 1986-2003: May to Oct OBS
b) 4-23: May to Oct SpCCSM
15N
0
15S
P1: 283
P2: 287
P3: 161
P4: 210
P5: 280
P6: 268
P7: 208
P8: 194
P1: 220
P2: 227
P3: 247
P4: 251
P5: 268
P6: 258
P7: 223
P8: 274
60E
120E
180
120W


a) ERAI 5N90E lag = -5 days
b) ERAI 5N90E lag = 0 days
c) ERAI 5N90E lag = 5 days
d) SP-CCSM 5N90E lag = -5 days
e) SP-CCSM 5N90E lag = 0 days
f) SP-CCSM 5N90E lag = 5 days
OLR
ζ+, PBL conv.
VbarQ'
V'Qbar
SST-destab
SST-grad
regression coefficient
latitude
0.6
0.4
0.2
-0.0
-0.2
-0.4
-0.6
-20
-10
0
10
20
30