Development of processes oriented metrics for ENSO-related precipitation anomalies along the equatorial Pacific in climate models

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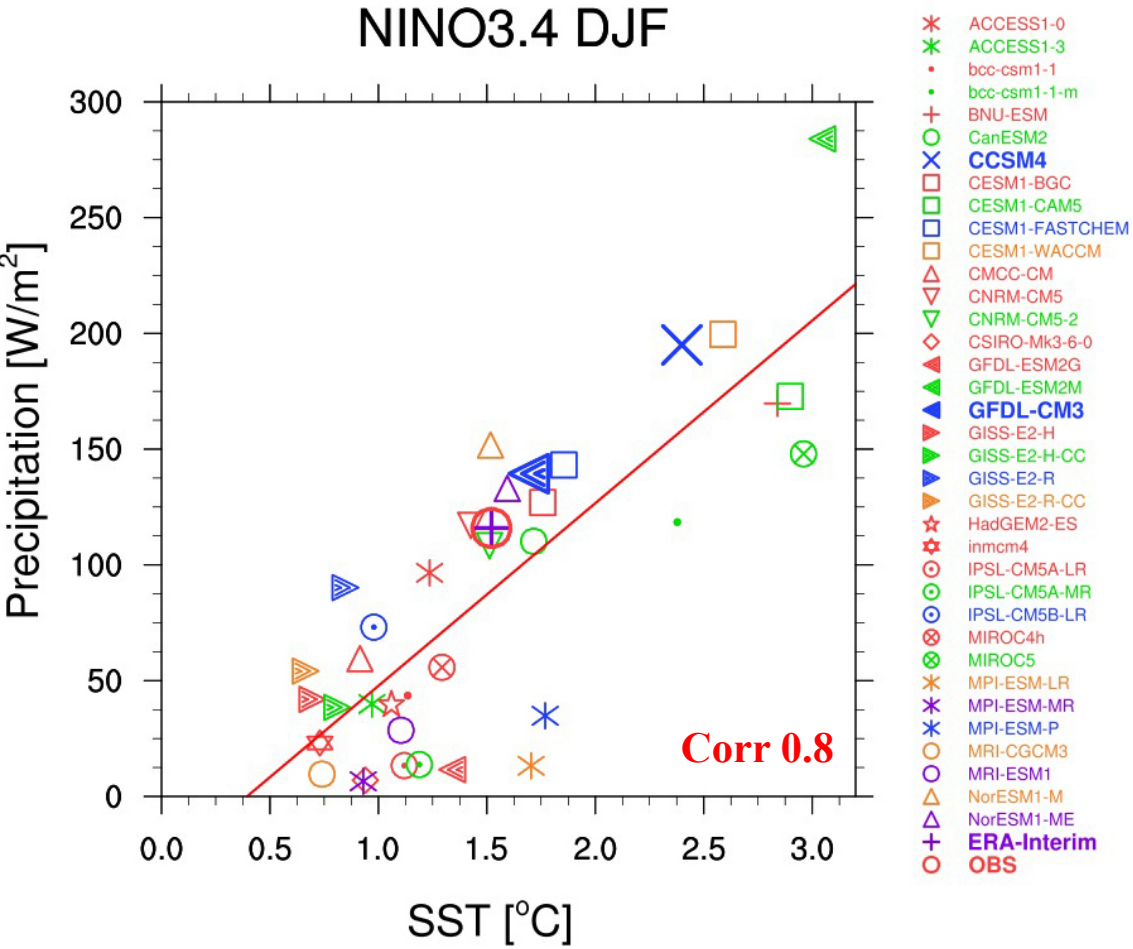
MAPP
Modeling, Analysis, Predictions, and Projections



SST anomalies translate to precip anomalies depend on model physical parameterizations

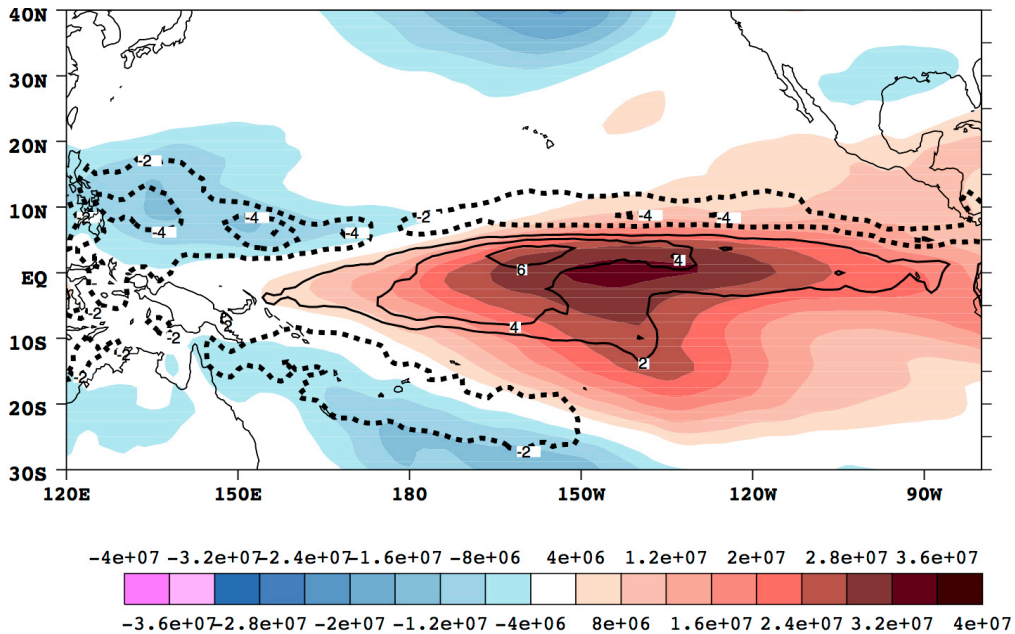
NOT concerned about generation of SST anomalies!!

Red line – best fit regression

- CMIP5 models diagnosed – historical run (1951-2005) – ENSO composite
- Multiple reanalysis products (ERA-I, JRA-25 and MERRA)
- MSE budget and its variance diagnostics
- Metrics (scatter plots)
- Conclusions and future work

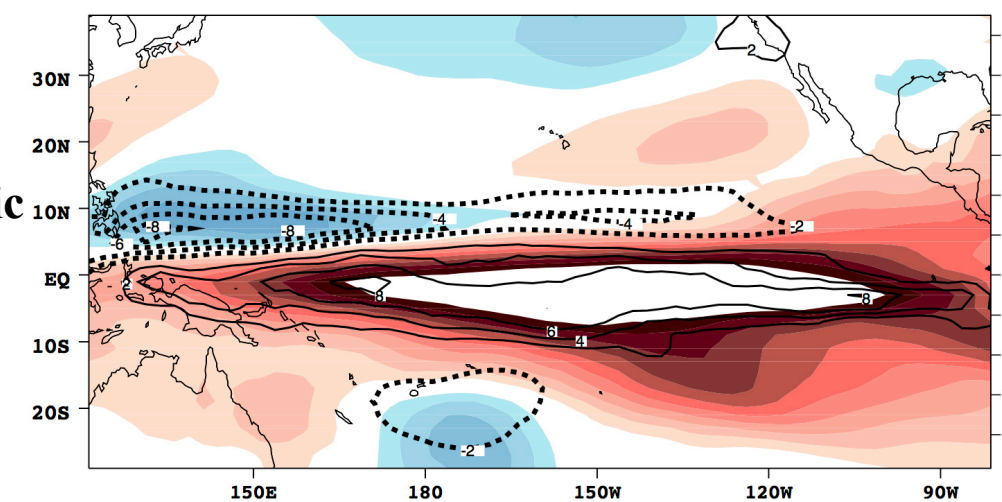
El Nino (DJF) composite

JRA-25



MSE anomalies (shaded)
Precip anomalies (contour)

GFDL_CM3



Focus: +ve Precip anomalies along Eq. Pacific

Deep Tropics – MSE ~ Moisture

Vertically integrated MSE tendency is approximately given by

$$\left\langle \frac{\partial m}{\partial t} \right\rangle = -\left\langle \overline{V} \bullet \nabla m \right\rangle - \left\langle \omega \frac{\partial m}{\partial p} \right\rangle + LH + SH + \langle LW \rangle + \langle SW \rangle$$

"storage" "adiabatic terms" "diabatic terms"

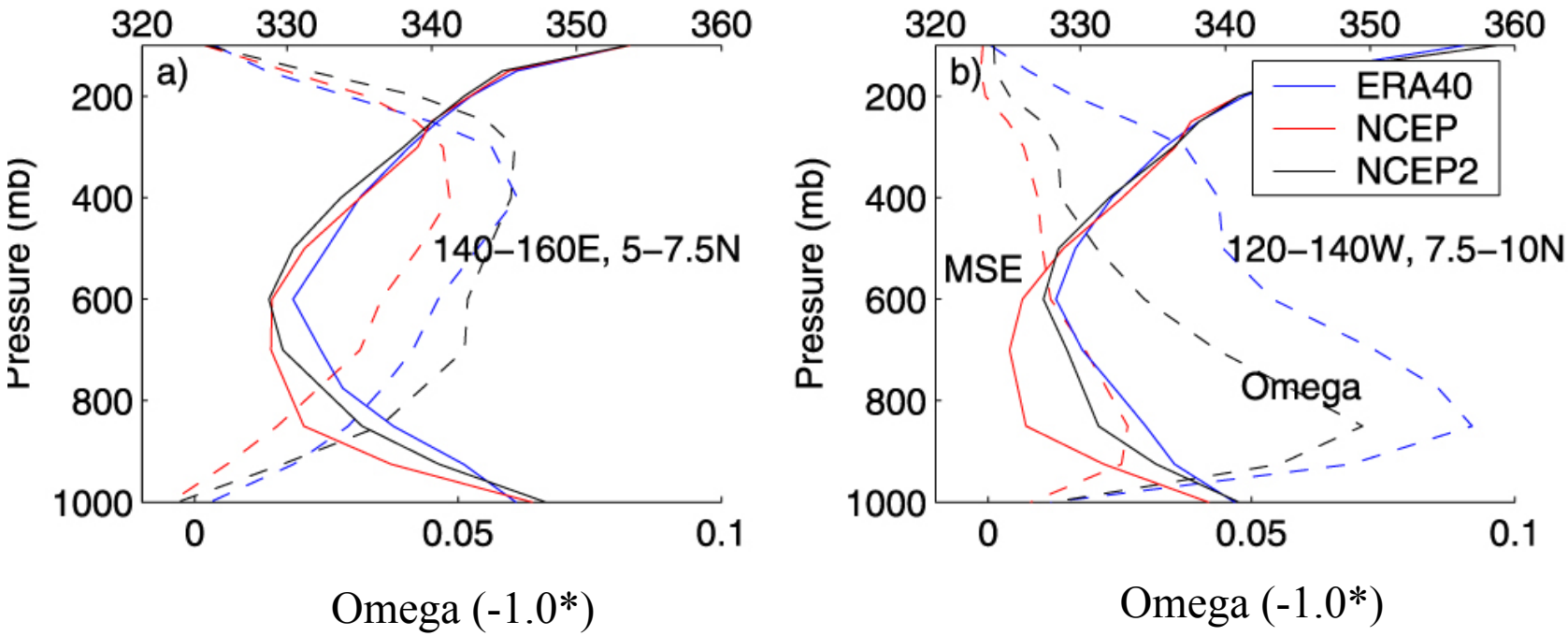
1. Deep tropics – above PBL – no horizontal T variations (WTG)
2. Entropy forcing: LH, SH, LW, SW, moisture variations
3. Strong feedbacks between adiabatic and diabatic terms

Infer: moisture-convection, cloud-radiation feedbacks

Neelin and Held 1987
Raymond et al. 2009
Bretherton et al. 2005
Su and Neelin 2005
Maloney 2009
Brethernton et al. 2015
Raymond et al. 2009
Holloway and Woolnough 2016
Alison and Emanuel 2015; 2016
Arnold and Randall 2016
*****and many more*****

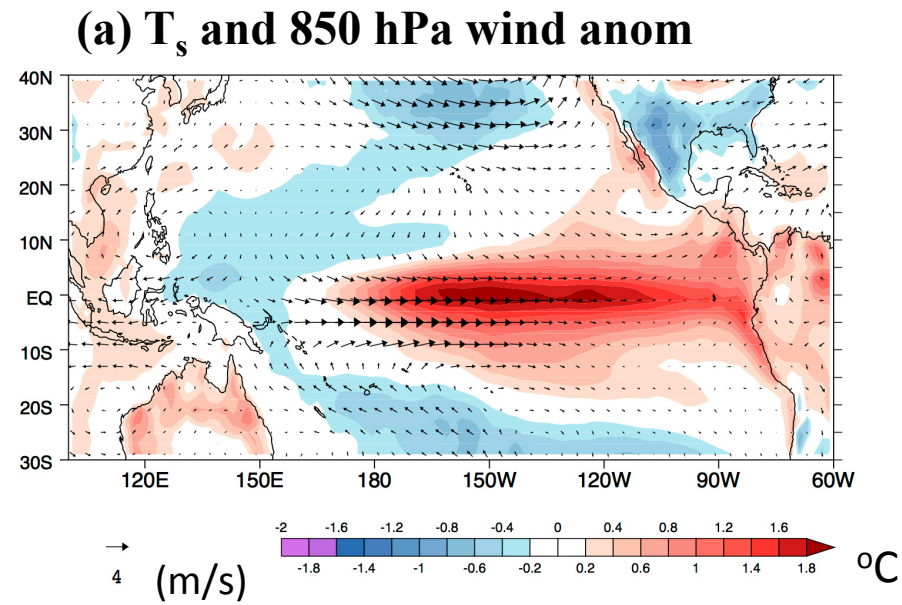
MSE export/import characteristics by the vertical motion

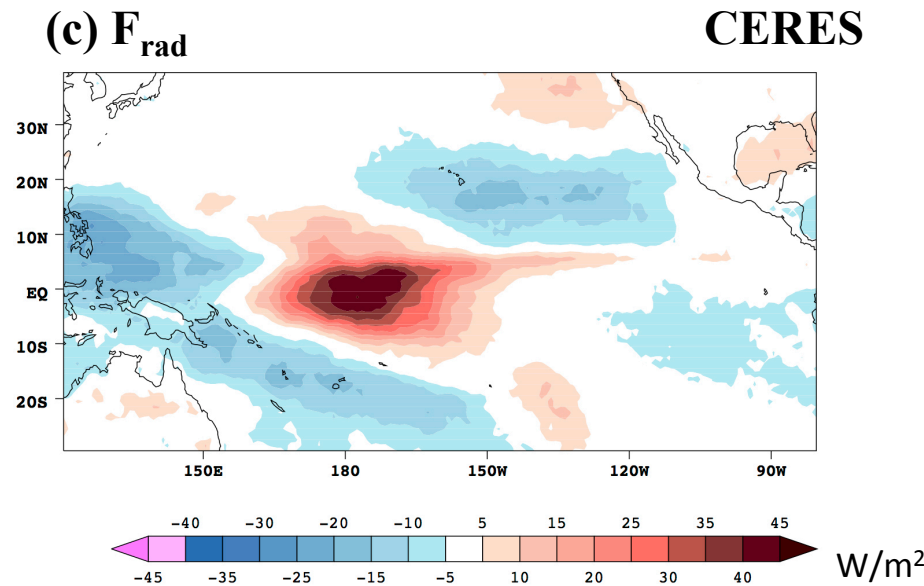
Western Pacific **Eastern Pacific**

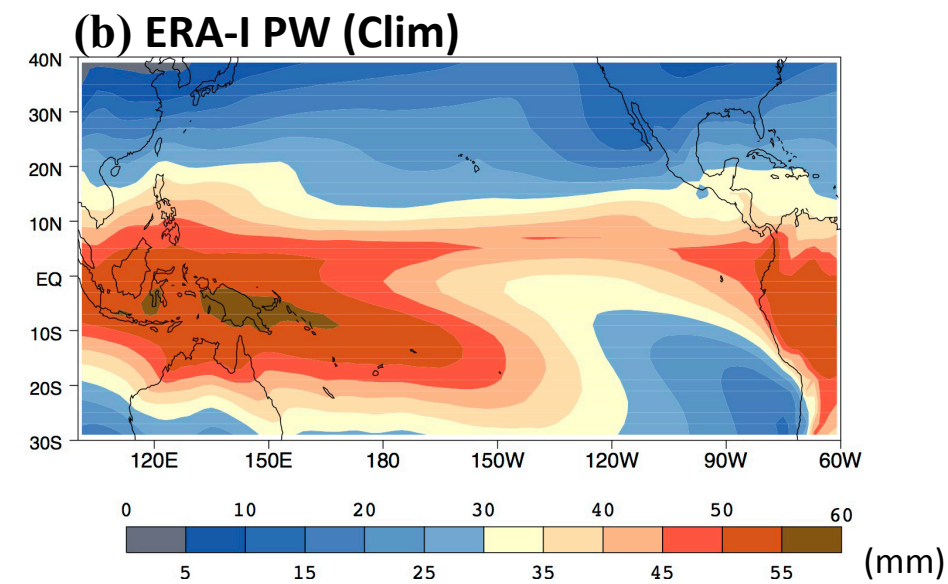


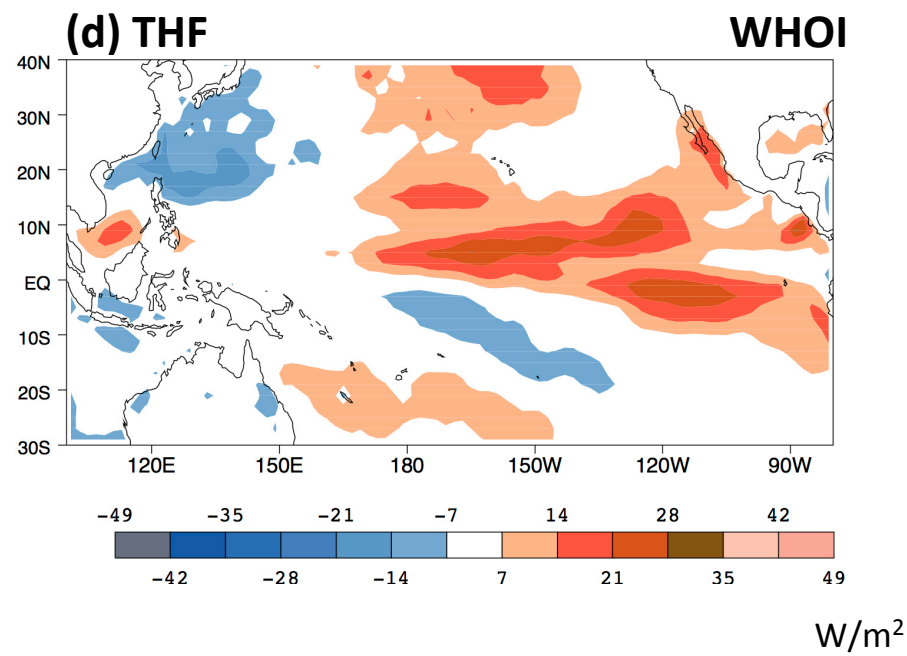
1. Similar MSE profiles and significant changes in vertical motion
2. Detraining air has higher MSE over **W Pacific** - **exports MSE**
3. Detraining air ~ 800 hPa over **E Pacific** - **imports MSE**

Back and Bretherton (2006, GRL)









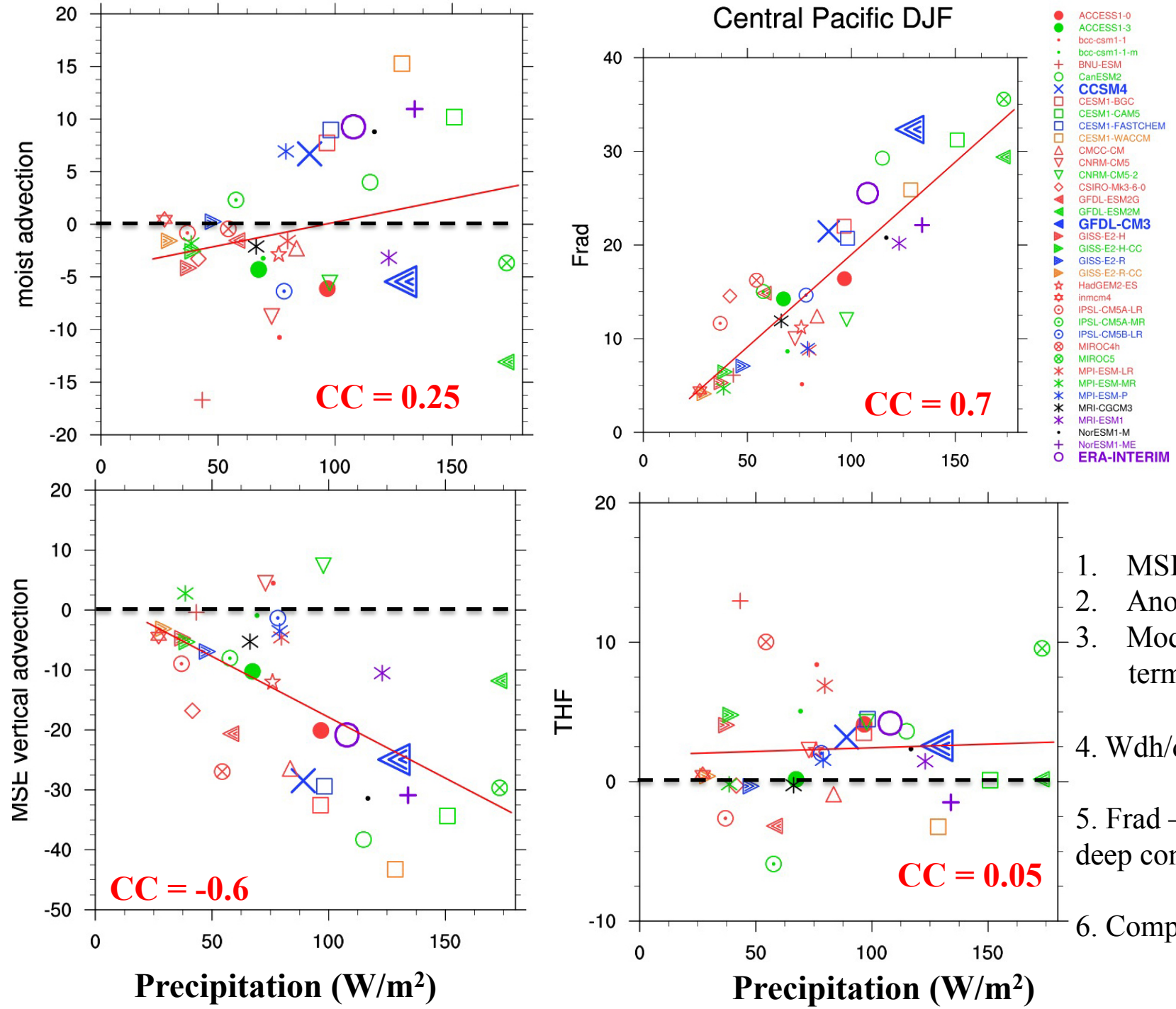
1. E-W and N-S circulations (adiabatic)
2. F_{rad} – consequence of convection
3. Central vs East Pac: THF vs F_{rad}

Su and Neelin (2002); Annamalai et al. (2014)

MSE budget diagnostics

$$\cancel{\left\langle \frac{\partial m}{\partial t} \right\rangle} = -\left\langle V \bullet \nabla m \right\rangle - \left\langle \omega \frac{\partial m}{\partial p} \right\rangle + \underbrace{LH + SH}_{\mathbf{THF}} + \underbrace{\left\langle LW \right\rangle + \left\langle SW \right\rangle}_{\mathbf{F_{rad}}}$$

"adiabatic and diabatic terms cancel out each other"

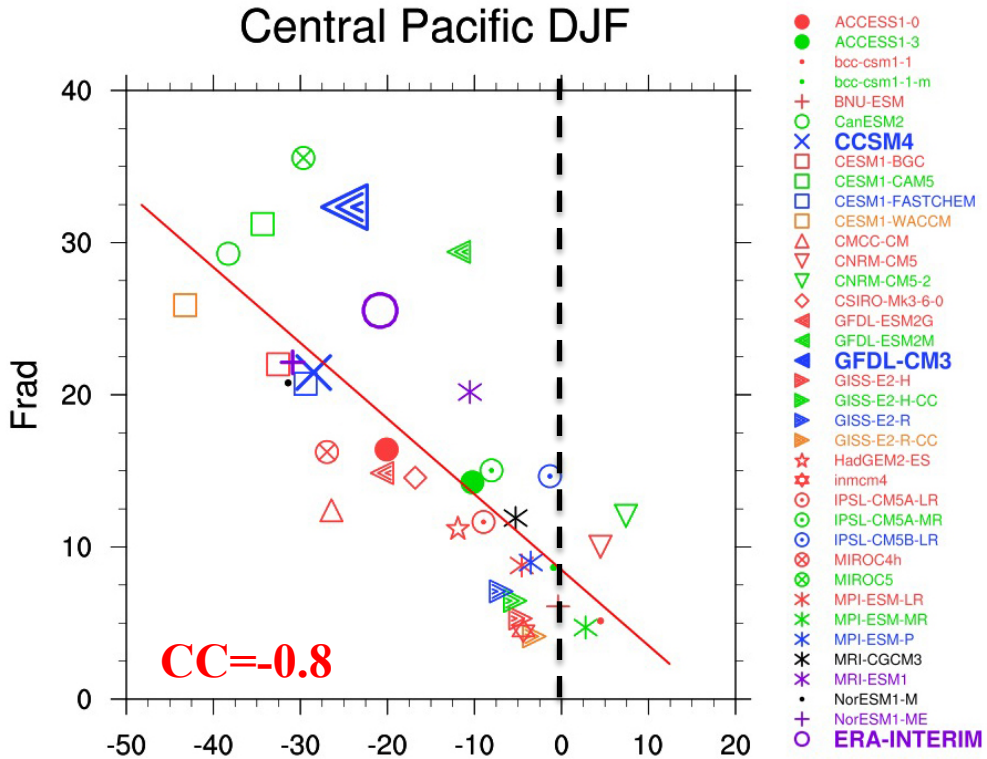


1. MSE clim models
2. Anom circulation
3. Modest moistening terms – limitations

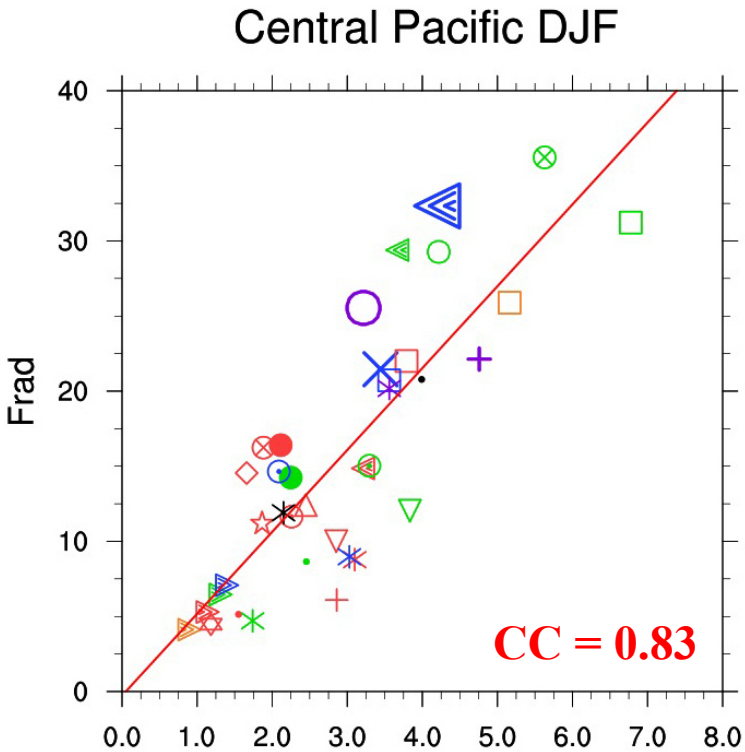
4. Wdh/dp – limitations

5. Frad – "large range" deep convection region

6. Compensating errors



MSE vertical advection

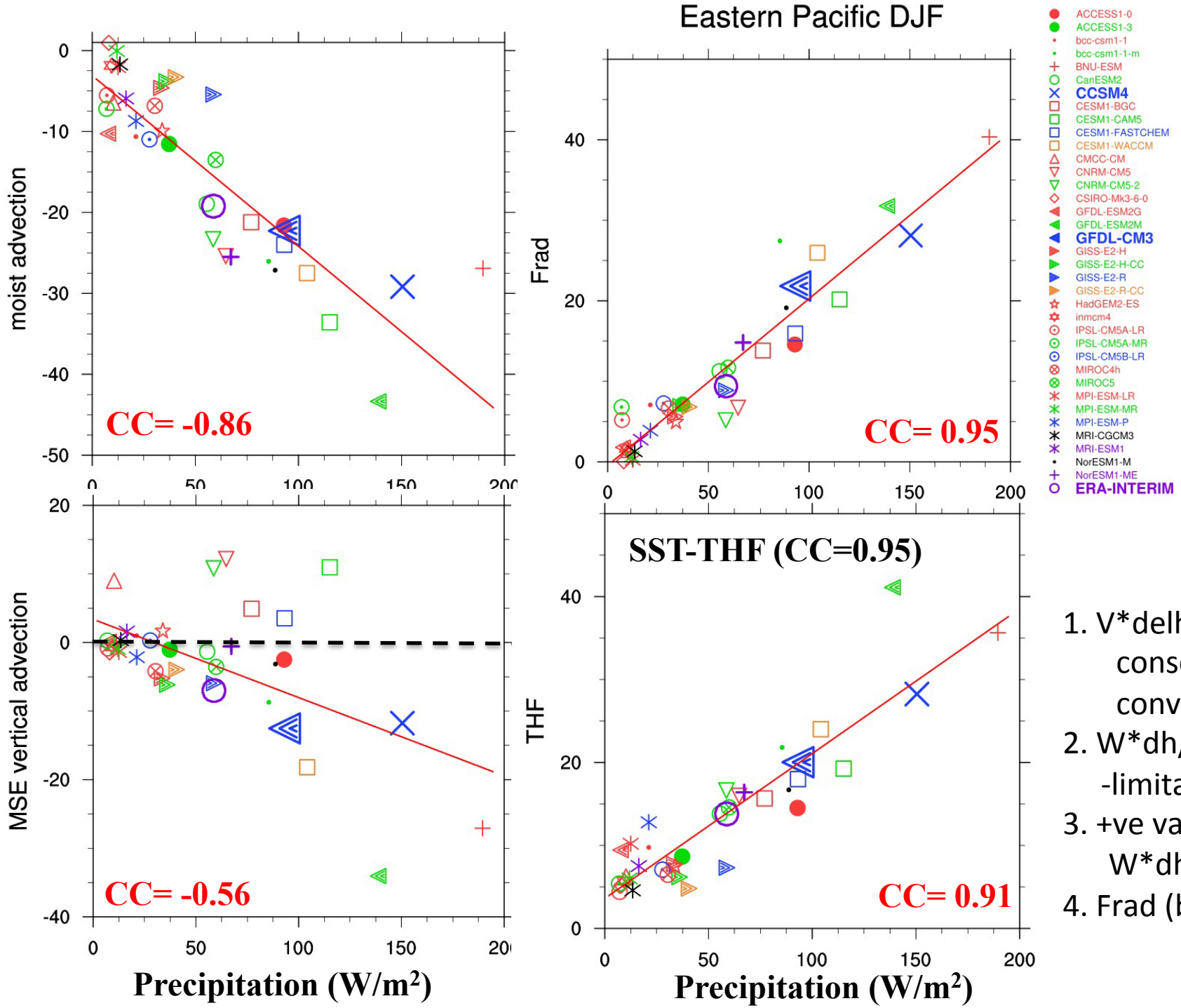


Sp. Humidity (700-400 hPa)

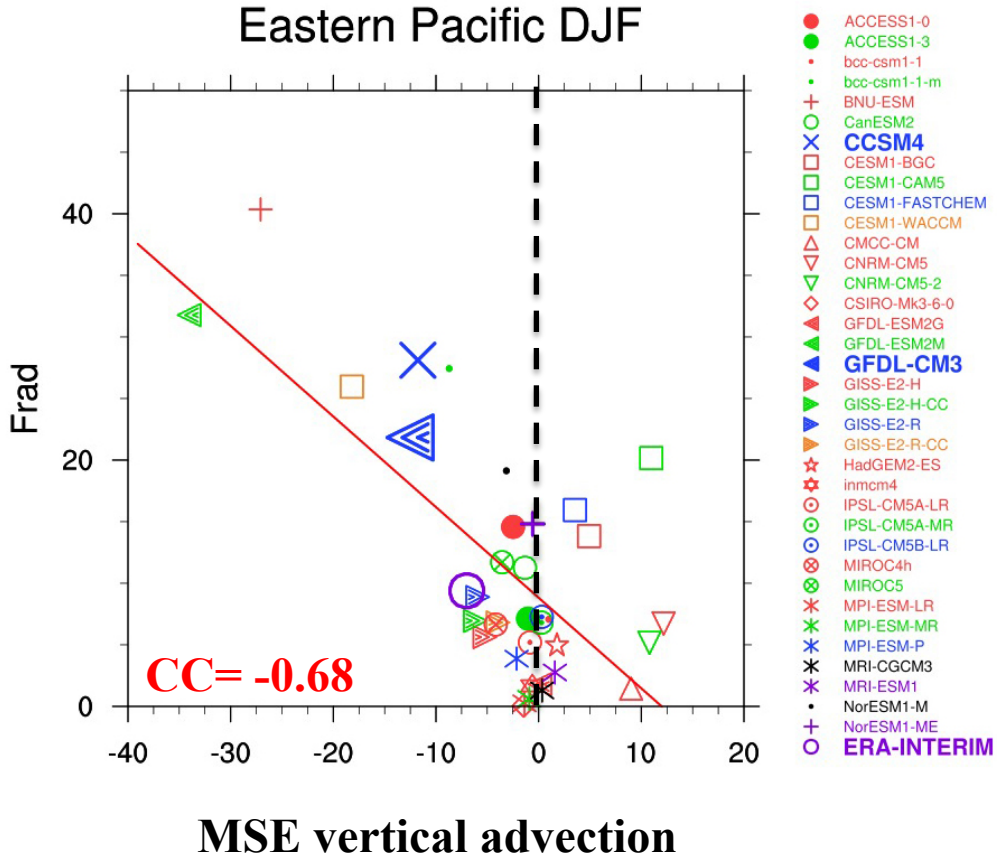
1. Strong feedbacks between adiabatic and diabatic terms
2. Higher values of W*dh/dp – models depict a "top-heavy" vertical velocity profile
3. Higher values of FT moisture- higher Frad values – top-heavy profile

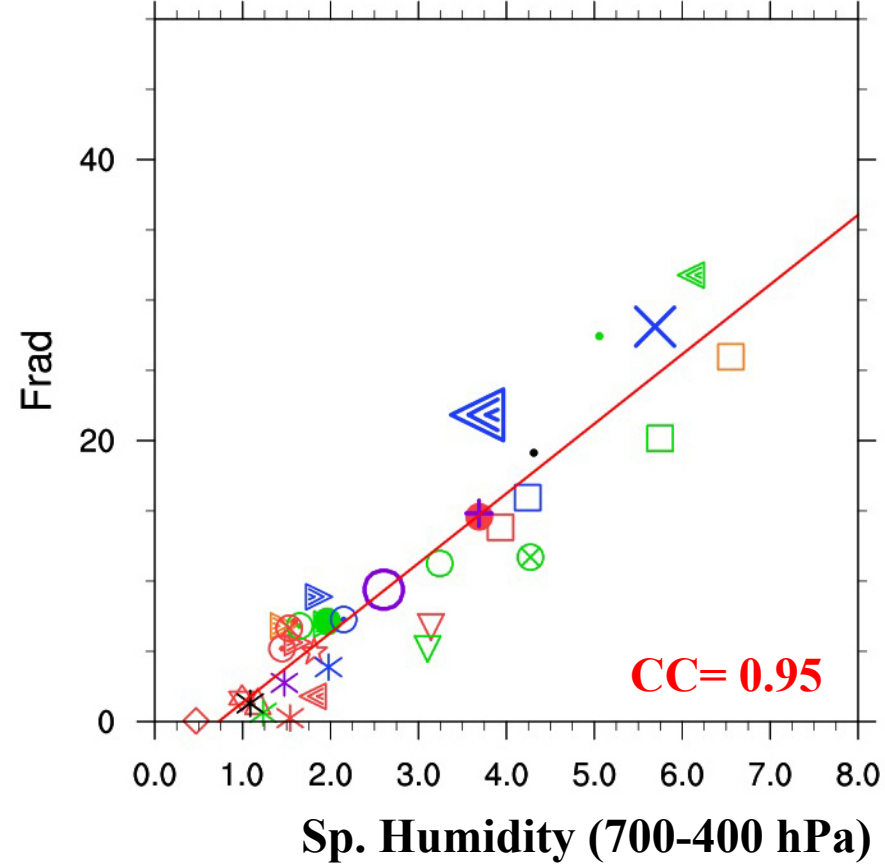
Moisture-convection (or lack of entrainment) and cloud-radiation feedbacks

GFDL_CM3 versus CCSM4: F_{rad} or LW feedback stronger in CM3



1. V*delh (N-S circ; consequence of convection)
2. W*dh/dp (small) -limitations
3. +ve values of W*dh/dp
4. Frad (bias)





1. Unlike obs/reanalysis, cloud-radiation feedback term dominates
2. Moisture-convection (or lack of entrainment) and cloud-radiation feedbacks
3. Over central and eastern Pacific, models' limitations in representing vertical advection

Similar SST forcing East Pacific – different precipitation response (CCSM4/CAM5/CM3)

CM3 versus CCSM4: Similar MSE export – but more FT moisture and stronger F_{rad} in CCSM4

MSE variance diagnostics

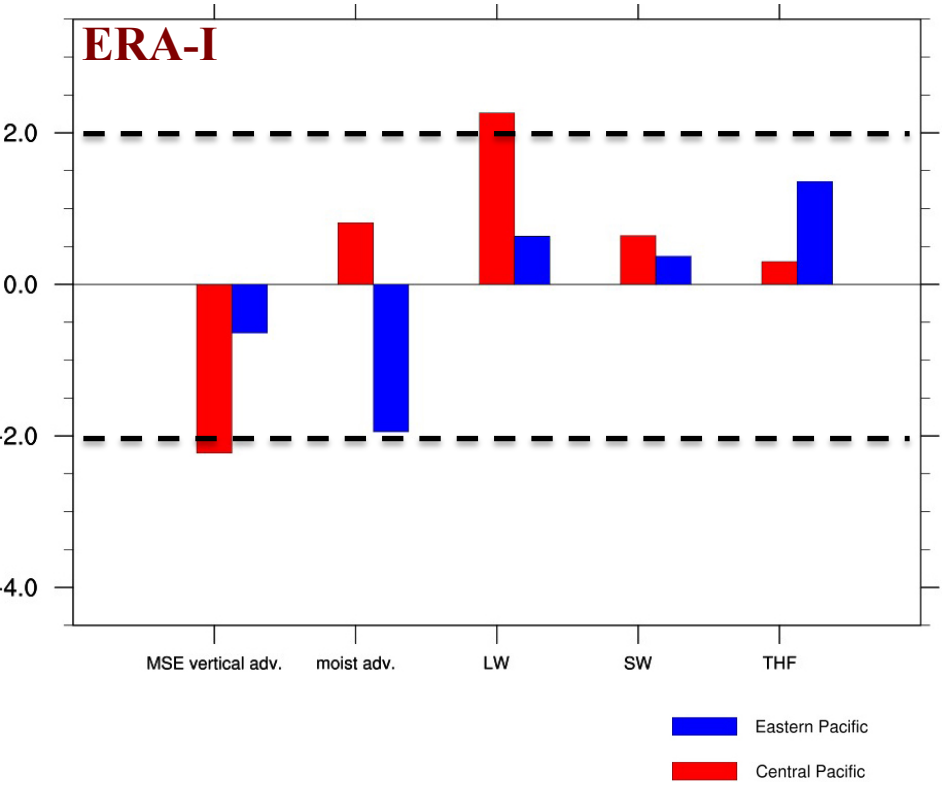
$$S_x = \frac{\left\| x \cdot \langle h \rangle \right\|}{\left\| \langle h \rangle^2 \right\|}$$

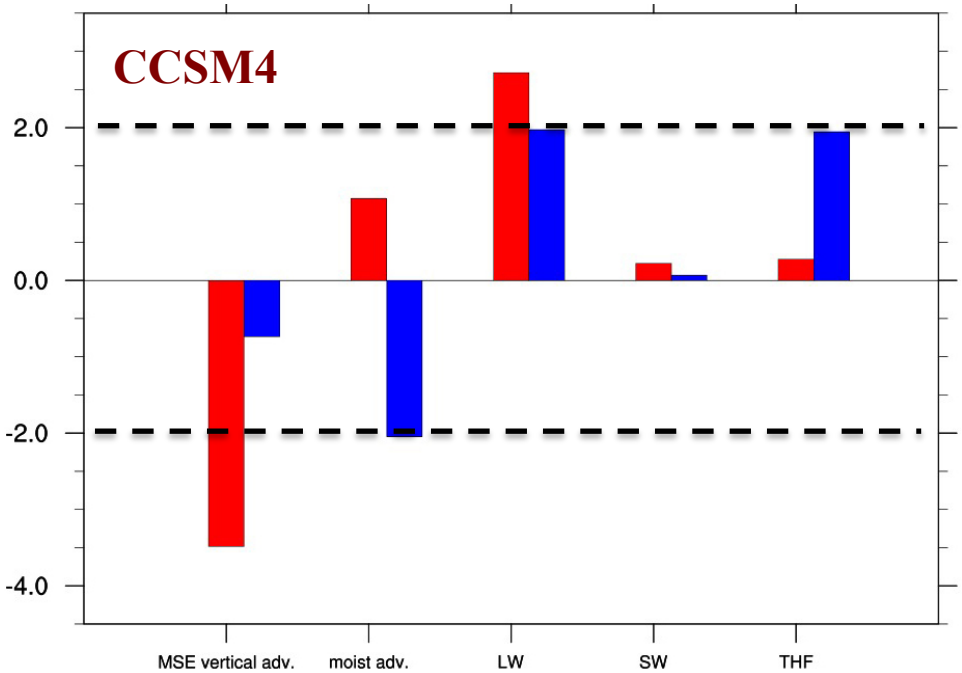
"relative contributions of MSE terms to the maintenance of column MSE anomaly"

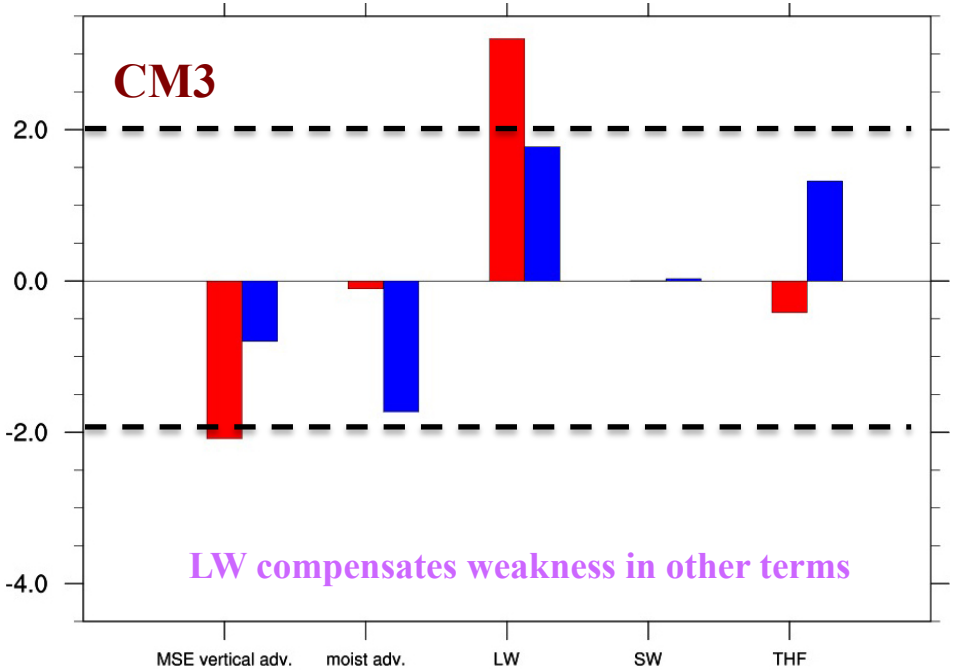
Anderson and Kuang (2012); Bretherton et al. (2015); Alison and Emanuel (2015;2016)

Central Pacific:

LW dominant MSE source followed by V*delh
Vertical advection MSE sink



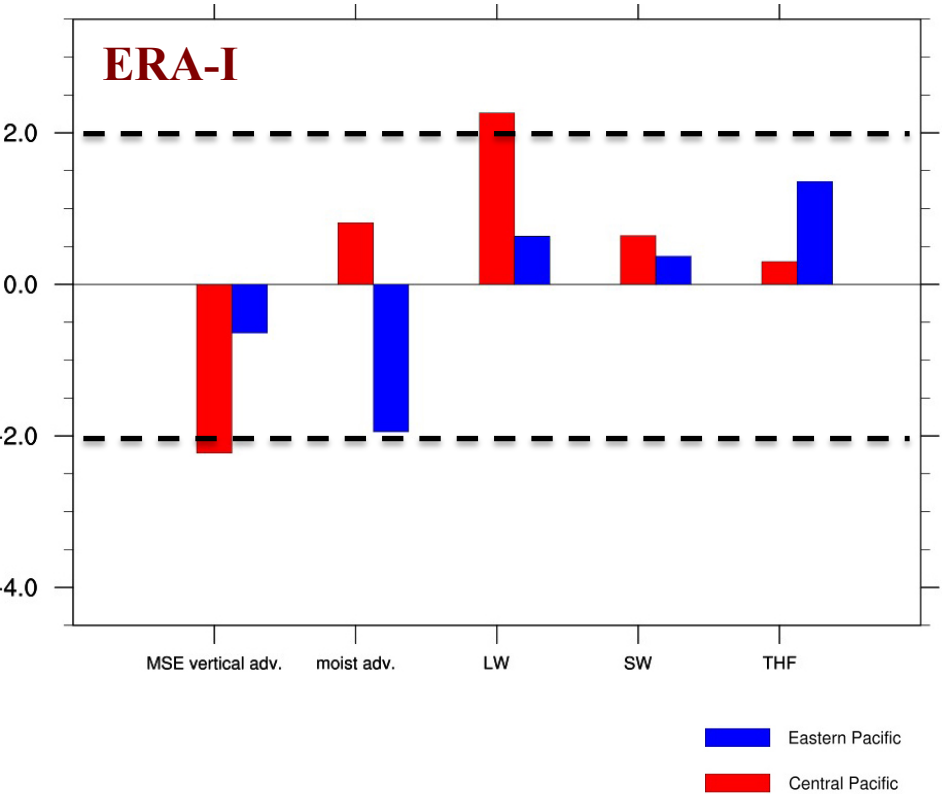


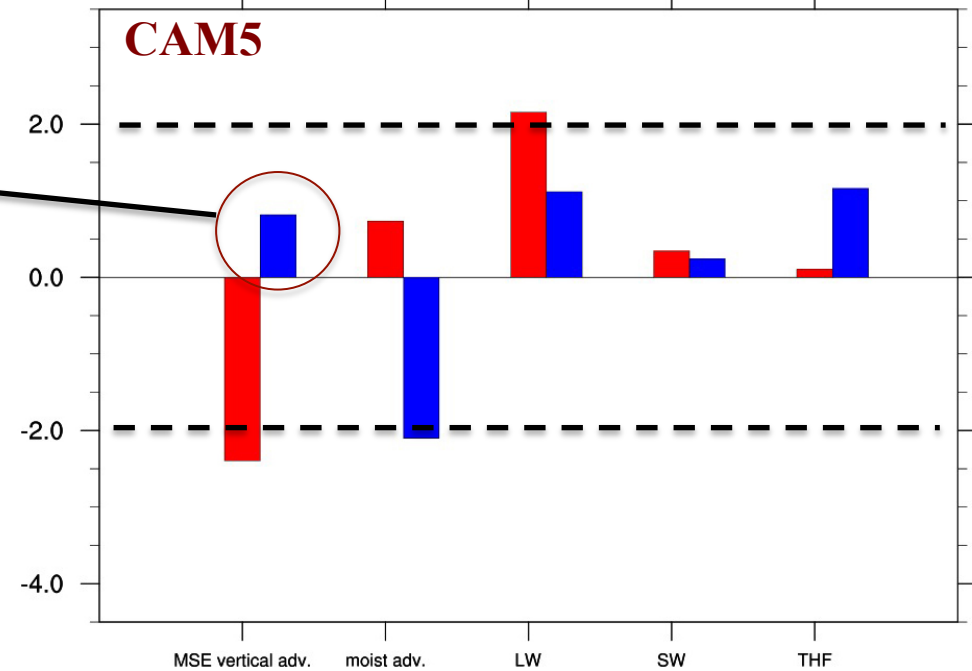


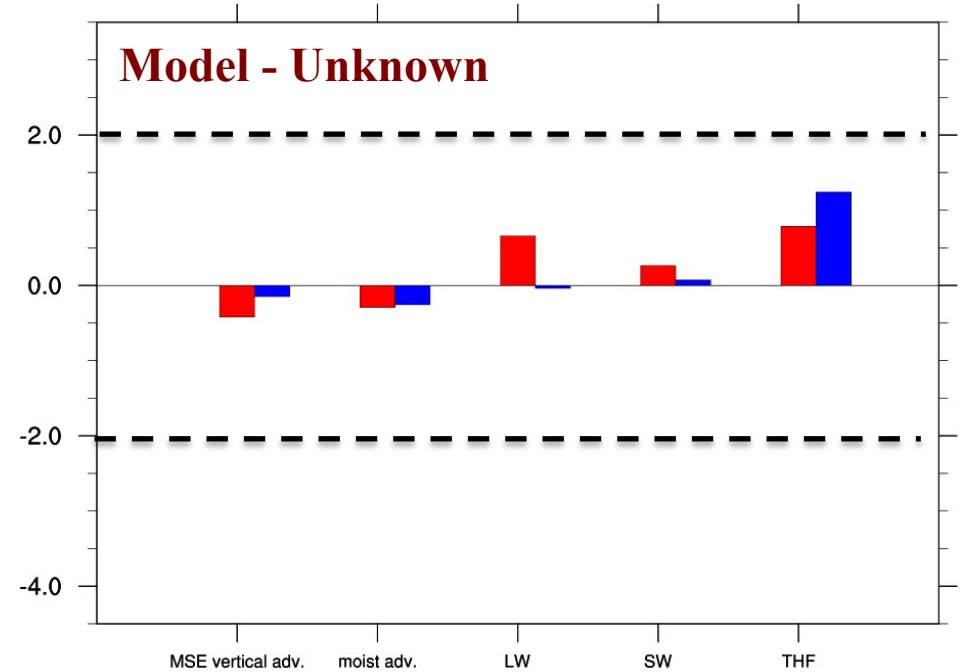
Eastern Pacific:

THF dominant MSE source followed by LW
V*delh dominant MSE sink

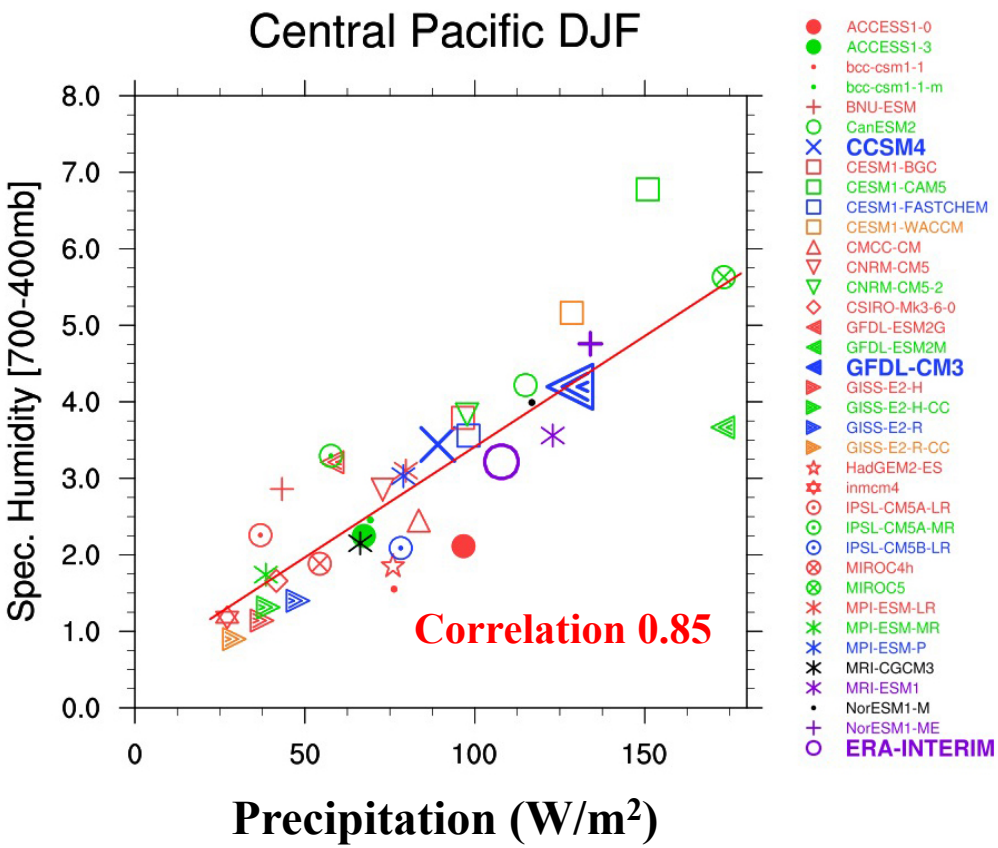
"Import MSE energy"

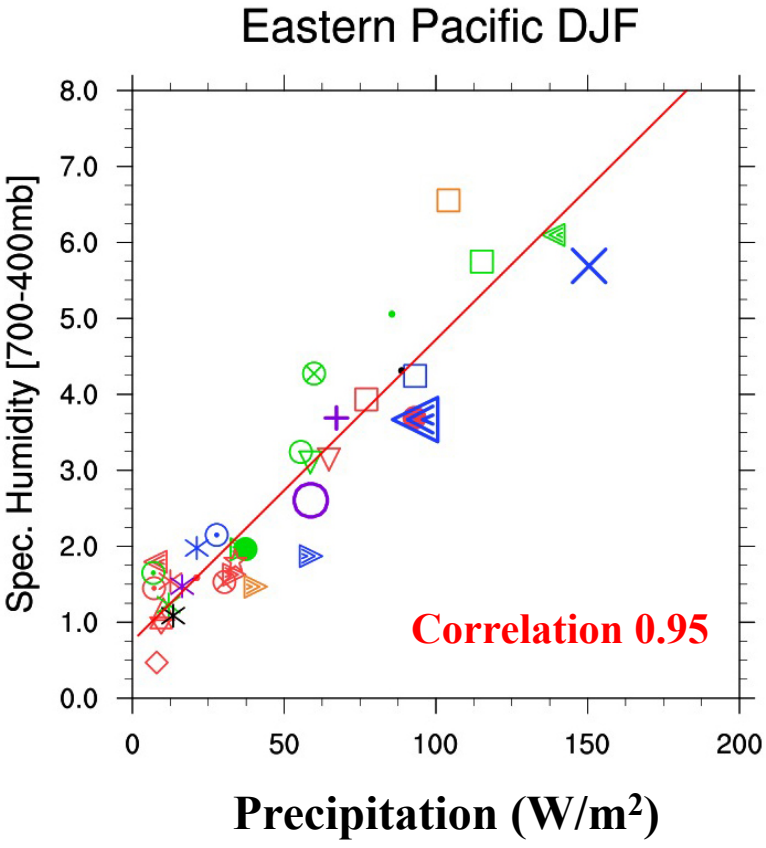






"very strong SST anom forcing but climatological descent over both regions"





"Precip anomalies are largely determined by free-troposphere moisture anomalies"

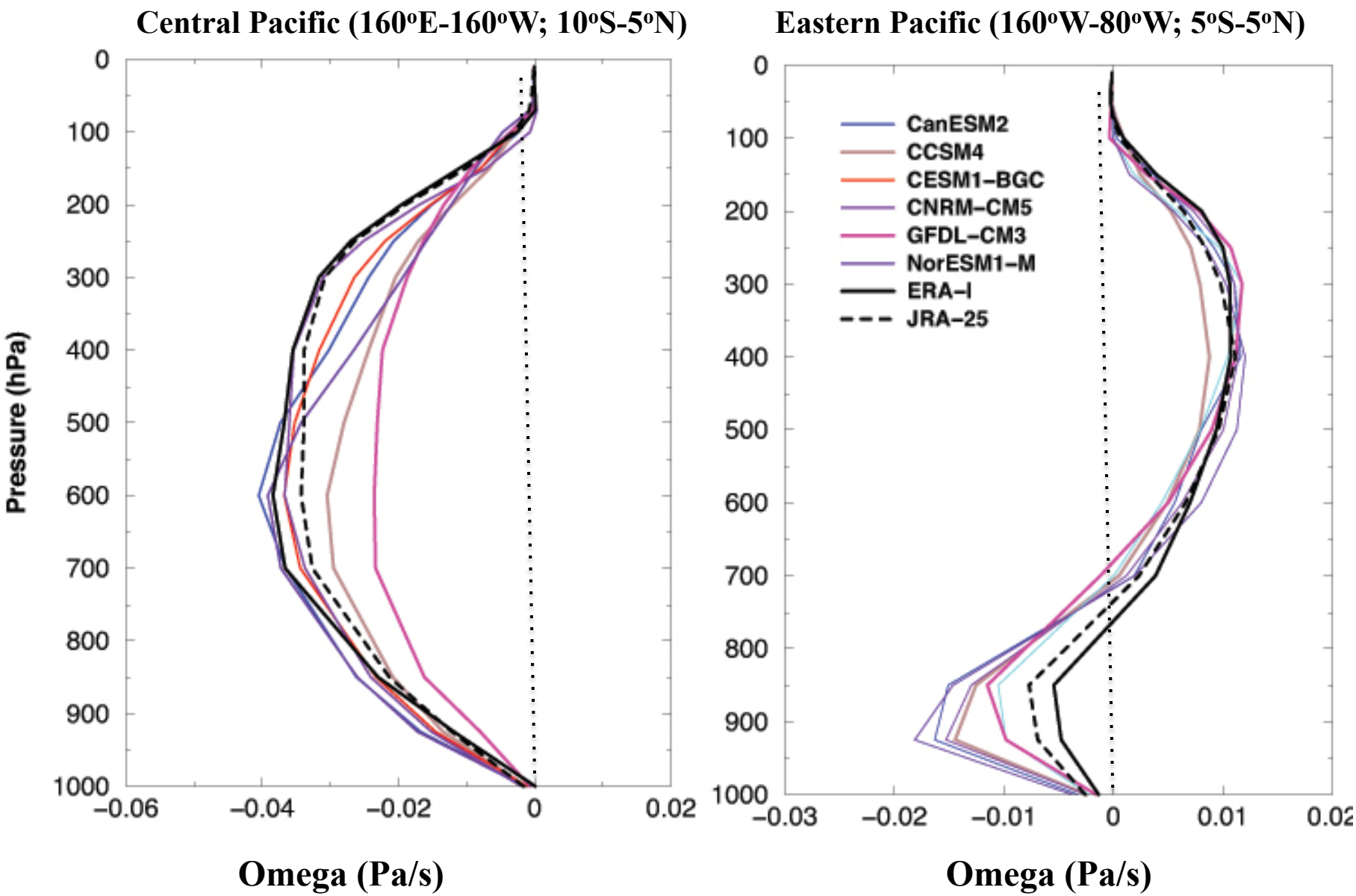
Consistent with observations (Holloway and Neelin 2009)

Convection schemes like to place the moisture anomalies in the FT?

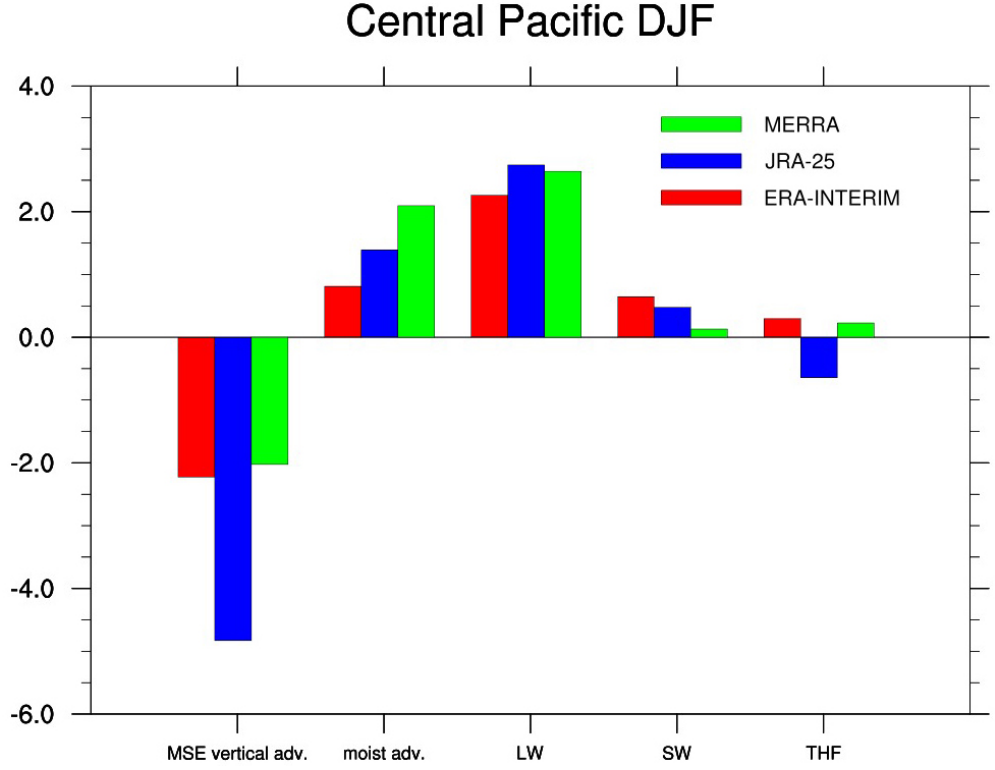
Summary

- THF – Precip (Eastern Pacific) : well-represented across all models
- Vertical advection of MSE – limitations across all models
- Modest MSE terms – limitations across most models
- LW feedback compensates errors
- FT moisture *vs* precipitation in the models: correct reasons?

Extra slides

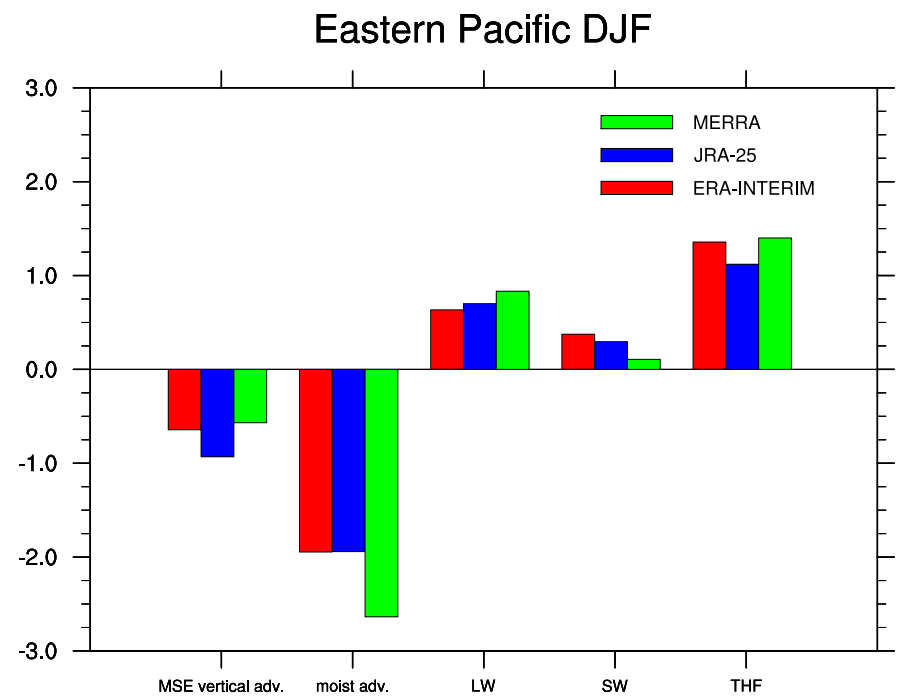


Regions correspond to +ve precipitation anomalies along the equatorial Pacific



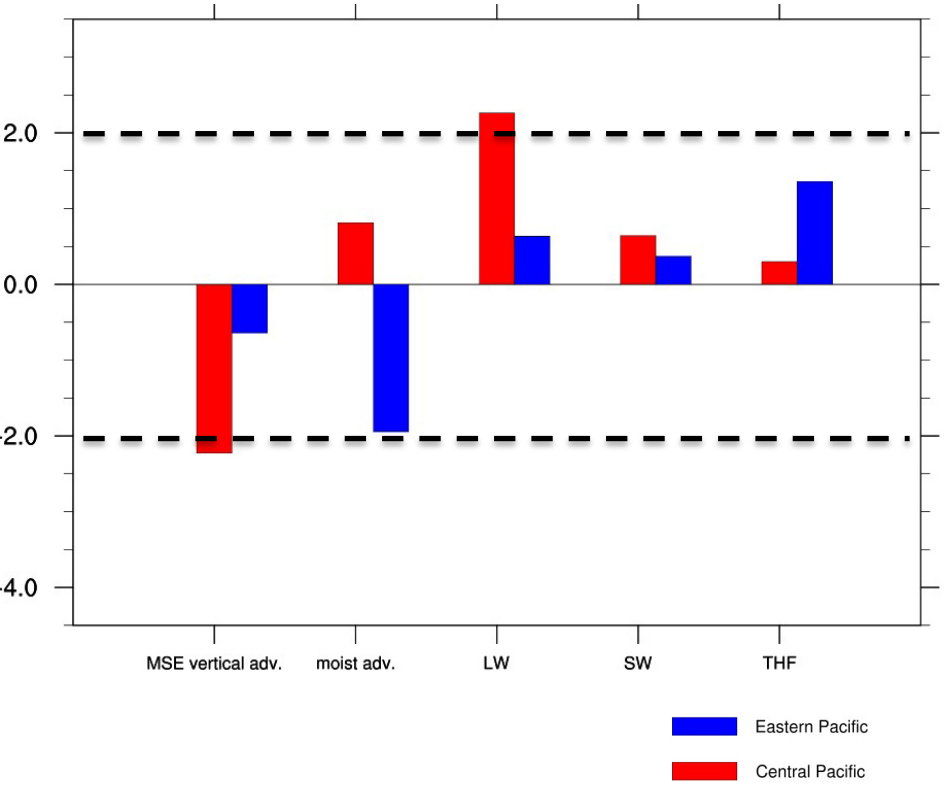
Central Pacific:

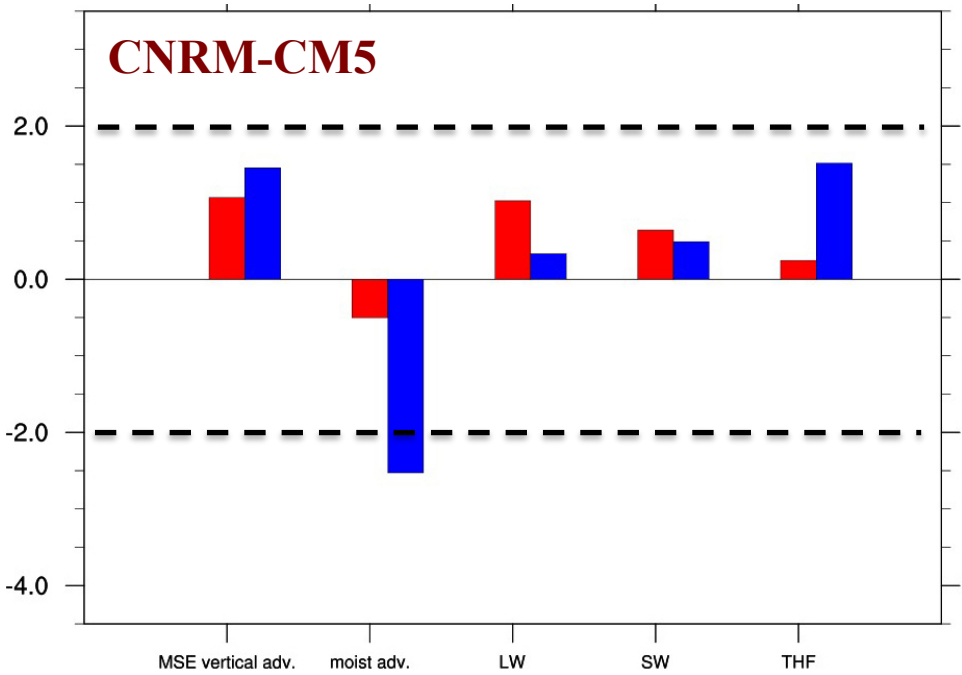
LW dominant MSE source followed by V*delh
Vertical advection MSE sink
Uncertainty in THF

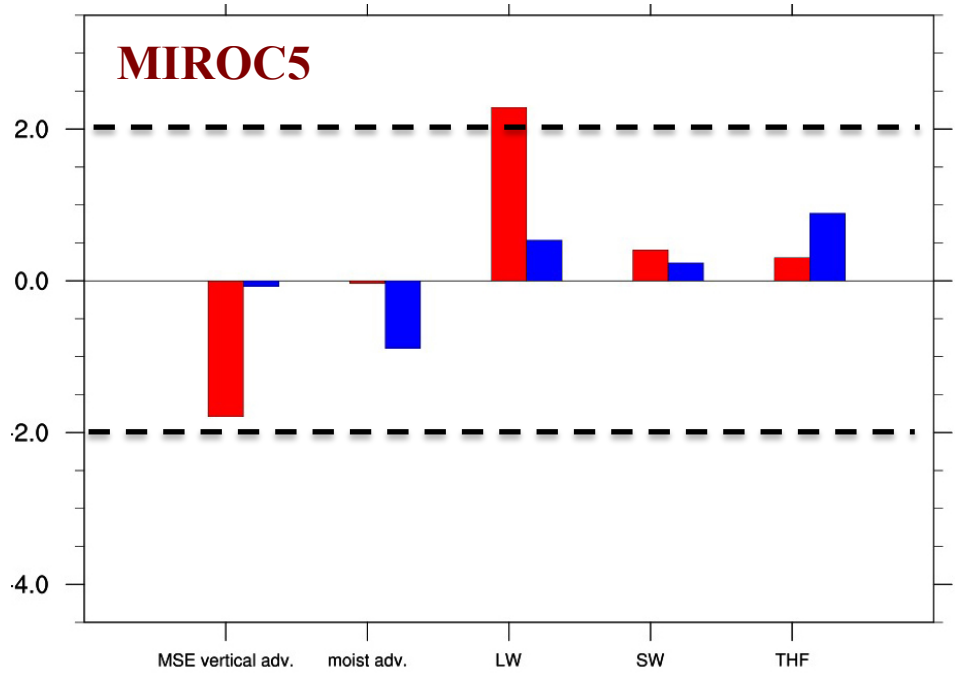


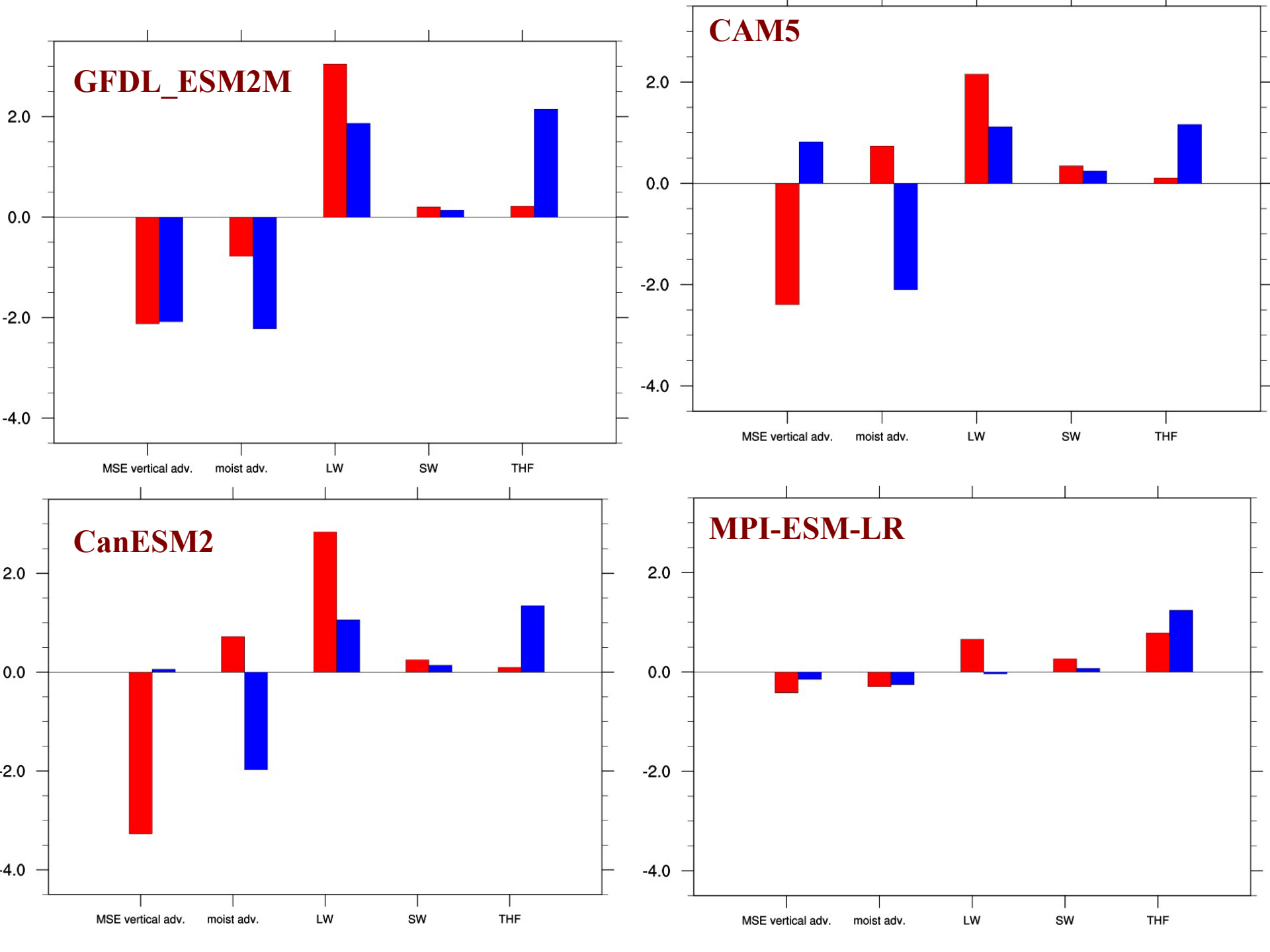
Eastern Pacific:

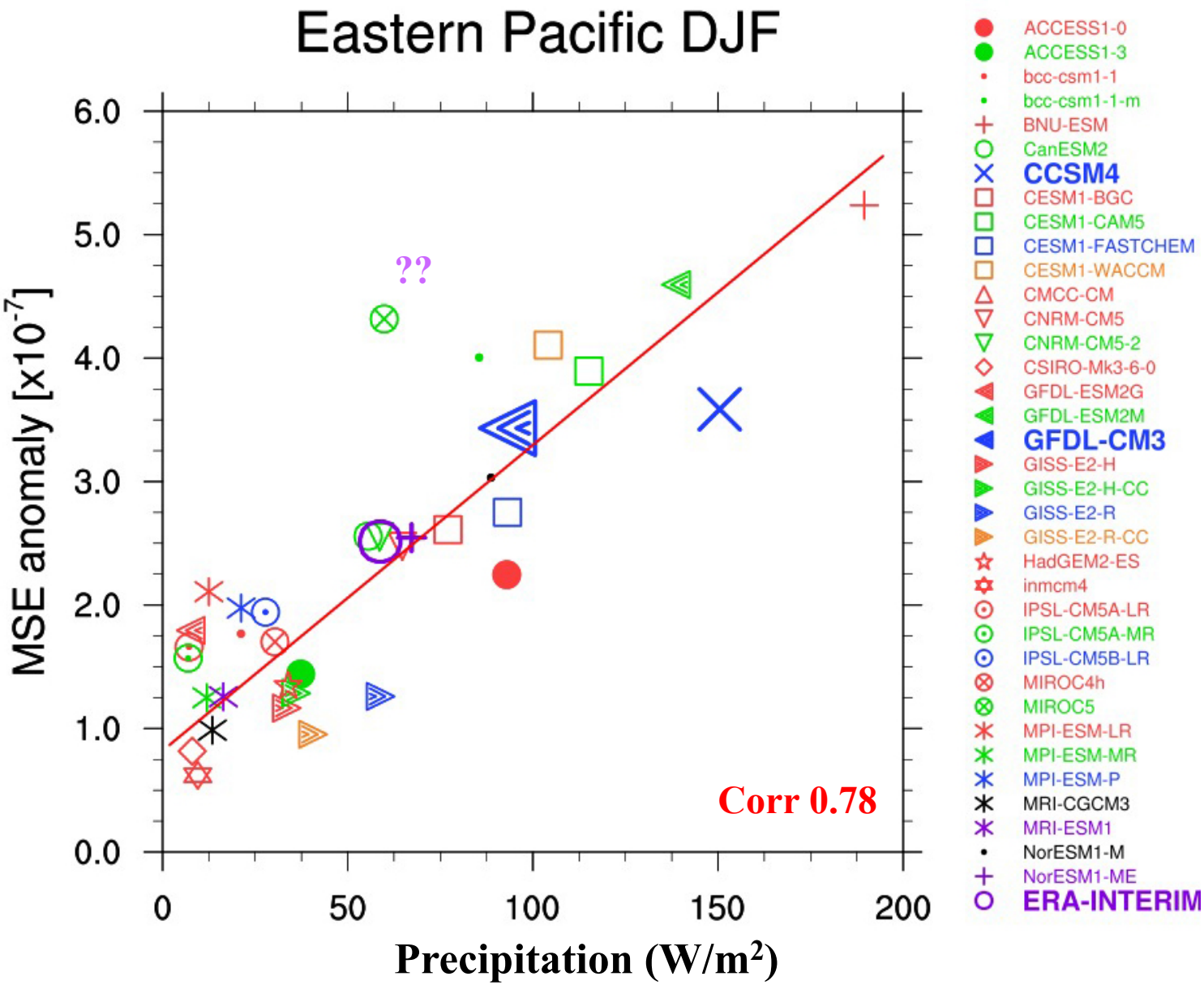
THF dominant MSE source followed by LW
V*delh dominant MSE sink

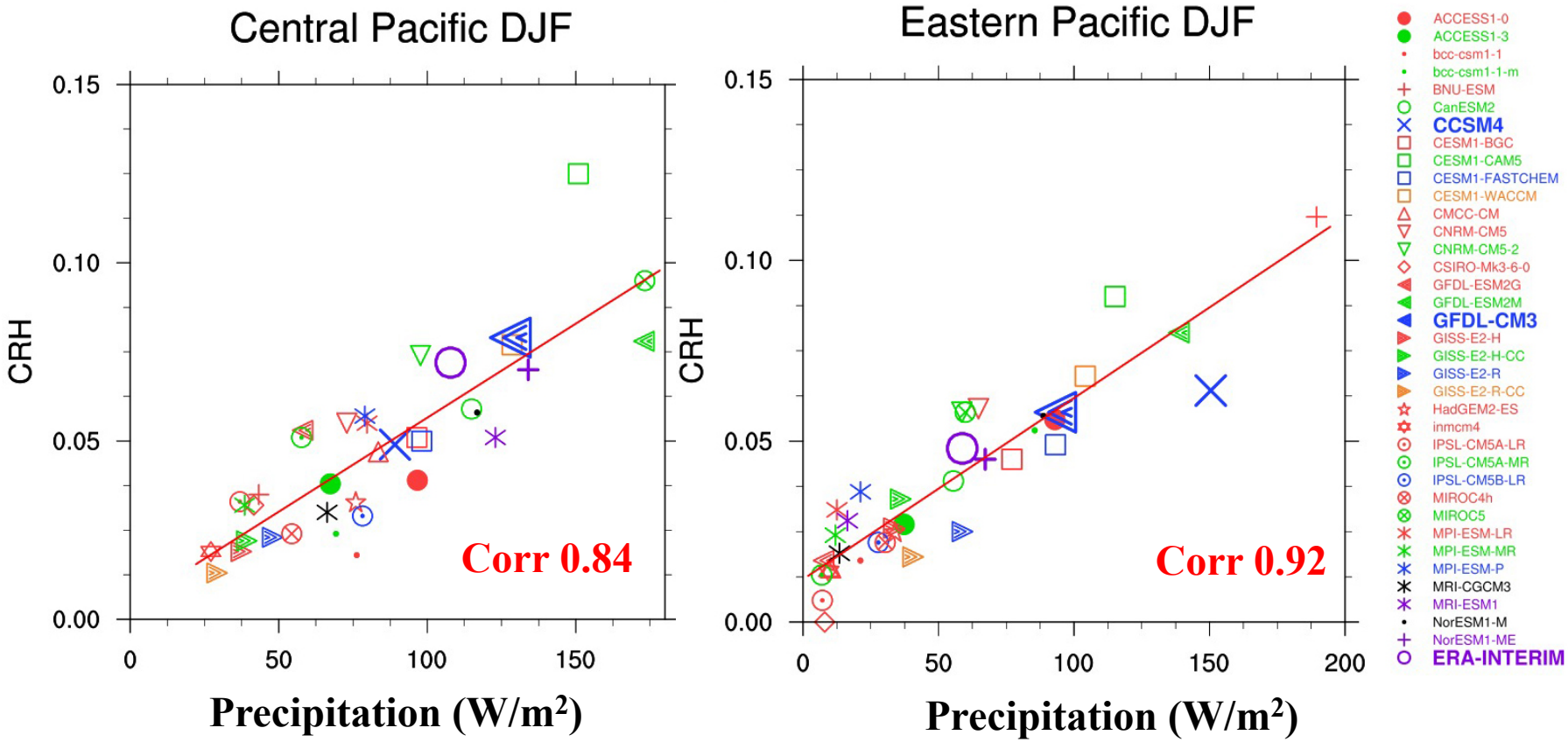

2.0
0.0
-2.0
-4.0
MSE vertical adv.
moist adv.
LW
SW
THF
Eastern Pacific
Central Pacific


CNRM-CM5
2.0
0.0
-2.0
-4.0
MSE vertical adv.
moist adv.
LW
SW
THF


MIROC5
2.0
0.0
-2.0
-4.0
MSE vertical adv.
moist adv.
LW
SW
THF


GFDL_ESM2M
CAM5
CanESM2
MPI-ESM-LR
2.0
0.0
-2.0
-4.0
MSE vertical adv.
moist adv.
LW
SW
THF


Eastern Pacific DJF
MSE anomaly [x10^-7]
Precipitation (W/m²)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200
??
Corr 0.78
ACCESS1-0
ACCESS1-3
bcc-csm1-1
bcc-csm1-1-m
BNU-ESM
CanESM2
CCSM4
CESM1-BGC
CESM1-CAM5
CESM1-FASTCHEM
CESM1-WACCM
CMCC-CM
CNRM-CM5
CNRM-CM5-2
CSIRO-Mk3-6-0
GFDL-ESM2G
GFDL-ESM2M
GFDL-CM3
GISS-E2-H
GISS-E2-H-CC
GISS-E2-R
GISS-E2-R-CC
HadGEM2-ES
inmcm4
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC4h
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MPI-ESM-P
MRI-CGCM3
MRI-ESM1
NorESM1-M
NorESM1-ME
ERA-INTERIM



"Positive precip anomalies are largely determined by anomalous increase in CRH"

Many models under (over) estimate precip anomalies over central (eastern) Pacific

Bretherton et al. (2004); Neelin et al (2007)

Moisture at all levels covaries with rain, but variability is mostly above always-moist PBL (PW is area under the curve)

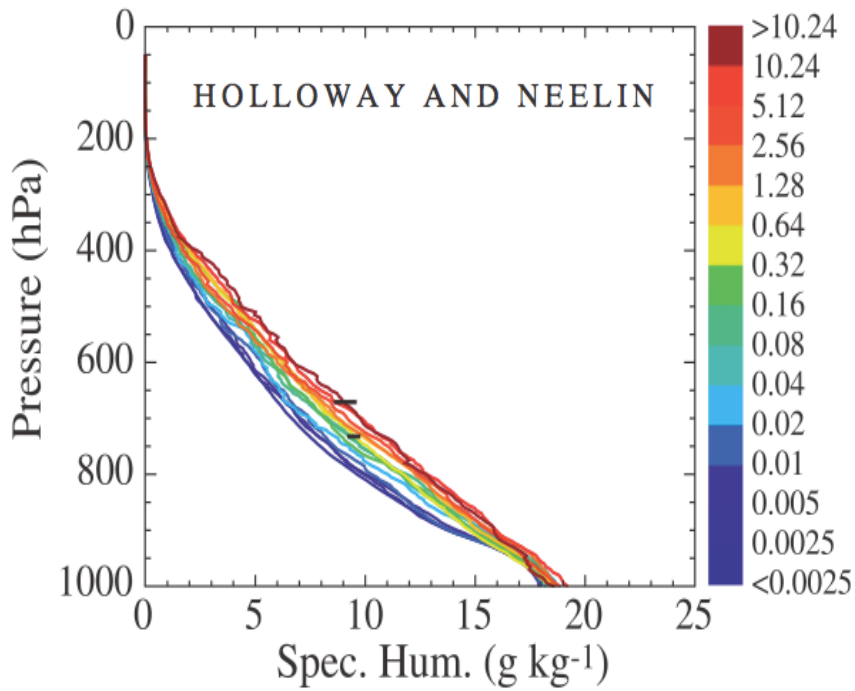
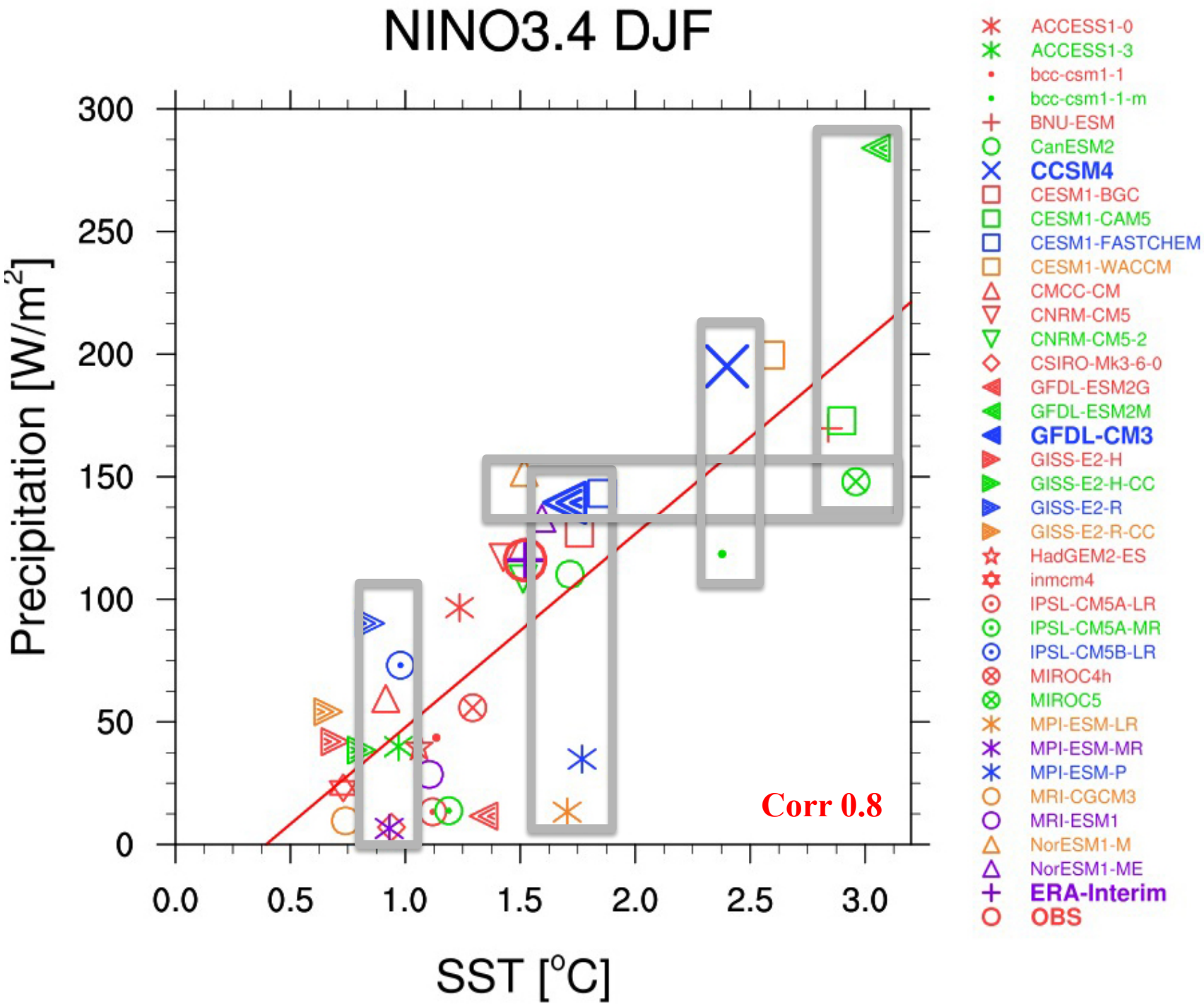


FIG. 1. Specific humidity (g kg^{-1}) profiles conditionally averaged on 1-h average precipitation rate in mm h^{-1} (color bar). Bin counts from the lowest to highest precipitation range are 2805, 93, 90, 59, 32, 40, 36, 49, 47, 43, 44, 30, 21, and 11. Horizontal bars indicate the maximum, as well as a representative, ±1 standard error of the mean (standard deviation divided by the square root of the sample number) range.

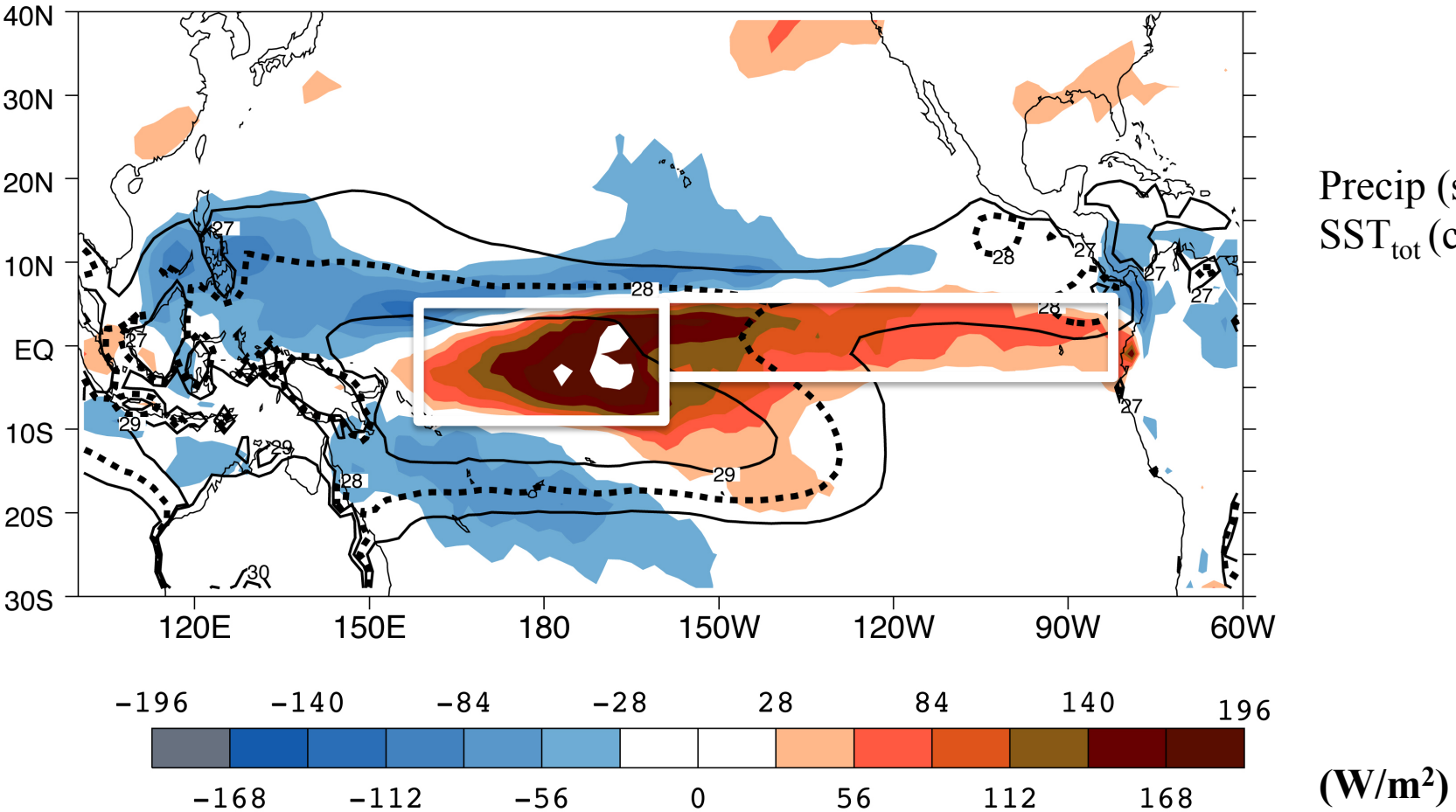
Moisture (water vapor, cloud)

Moisture-convection

Cloud - radiation

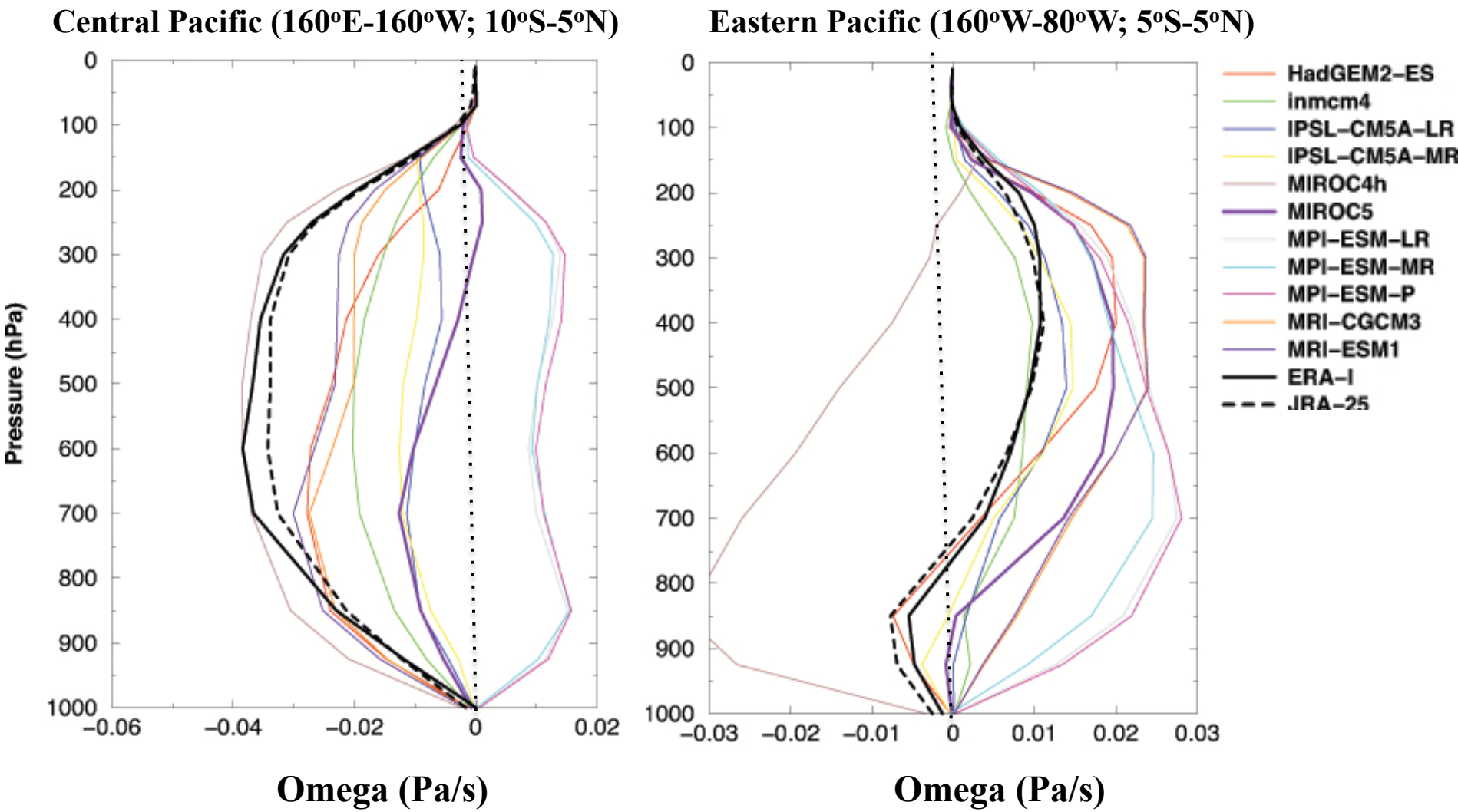

NINO3.4 DJF
Precipitation [W/m^2]
SST [^{o}C]
0
50
100
150
200
250
300
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Corr 0.8
ACCESS1-0
ACCESS1-3
bcc-csm1-1
bcc-csm1-1-m
BNU-ESM
CanESM2
CCSM4
CESM1-BGC
CESM1-CAM5
CESM1-FASTCHEM
CESM1-WACCM
CMCC-CM
CNRM-CM5
CNRM-CM5-2
CSIRO-Mk3-6-0
GFDL-ESM2G
GFDL-ESM2M
GFDL-CM3
GISS-E2-H
GISS-E2-H-CC
GISS-E2-R
GISS-E2-R-CC
HadGEM2-ES
inmcm4
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC4h
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MPI-ESM-P
MRI-CGCM3
MRI-ESM1
NorESM1-M
NorESM1-ME
ERA-Interim
OBS

El Nino (DJF) composite



Precip (shaded)
SST_{tot} (contour)

Central Pacific (10°S-5°N; 160°E-160°W)
Eastern Pacific (5°S-5°N; 160°W-80°W)



"MPI-ESM-LR Climatological descent over both regions"

- Dominant processes that are involved in column MSE moistening
- Processes that maintain convection and precipitation during El Nino winter

Neelin and Held; Su and Neelin; Raymond et al. ;

- Basic statistics (physically-based)
- Vertically integrated MSE budget diagnostics
- Vertically integrated MSE variance budget diagnostics
- Horizontal versus vertical advection - contribution

Similar SST forcing (bcc-csm1-1-m; CCSM4);
MIROC5; CESM-CAM5; GFDL-ESM2M
MPI-ESM-P; CanESM2; GFLD-CM3)
Similar Precip response (GFDL-CM3; MIROC5
bcc-csm1-1-m; CNRM-CM5)

Precipitation and associated diabatic heating anomalies – tropical-extratropical teleconnection

- Systematic errors in the representation of physical processes across all CMIP5 models
- Models capture precipitation anomalies but compensating physical processes
- Similar SST anomalies (but what about total SST) range of precip response

  Take TWO models that depict the maximum differences in MSE terms

- Similar precip response for a range of SST forcing (again, check the total SST)

  Take TWO models that depict the maximum differences in MSE terms

- Basic-state changes in MSE characteristics across the equatorial Pacific

  Two broad groups of models

- Systematic errors in the physical processes – pathways for model improvement
- Models over-emphasizing meridional dry/cold air advection (local Hadley vs Walker)

Scatter plots among …variables that are physically-linked

Precip anomalies vs THF; -V*delh; -w*dh/dp; Frad; LW

Precip anom vs BL moisture; FT moisture;
FT moisture vs –w*dh/dp; Frad
Frad vs –w*dh/dp (feedback between diabatic/adiabatic)

MSE budget (project all variables onto –w*dh/dp)

MSE variance budget (area-averaged over central and eastern Pacific)

Group I vs Group II (projections of MSE terms on vertical advection…)

Diagnostics identify systematic errors and suggest pathways for model improvement

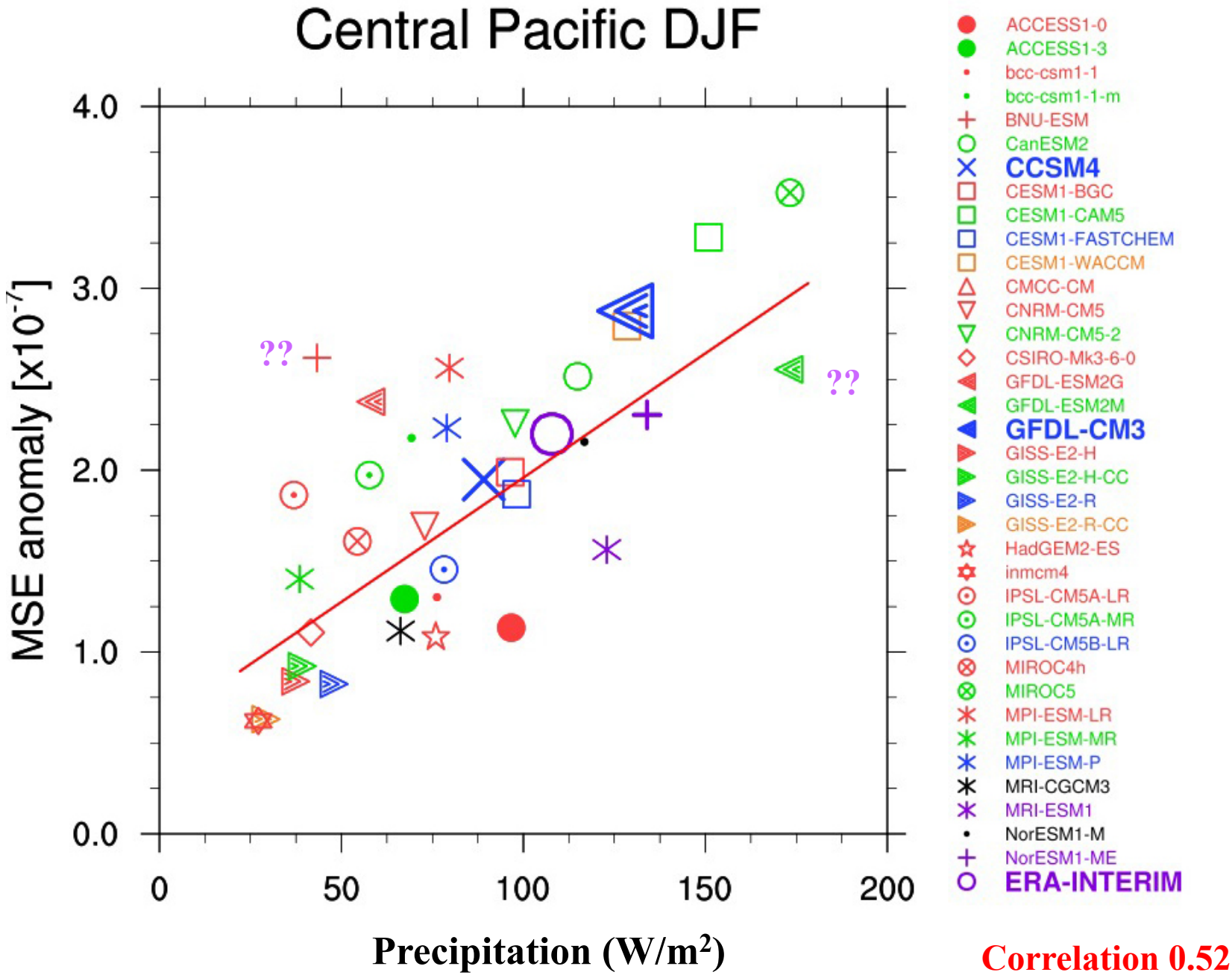
Basic-state
Excess moisture through out the column (entrainment)
Frad – cloud-radiative feedbacks; FT moisture implies moisture-convection feedbacks
-v*delh – Central Pacific
-wdh/dp – difficult for models to represent

$$S_x = \frac{\left\| x \cdot \langle h \rangle \right\|}{\left\| \langle h \rangle^2 \right\|}$$

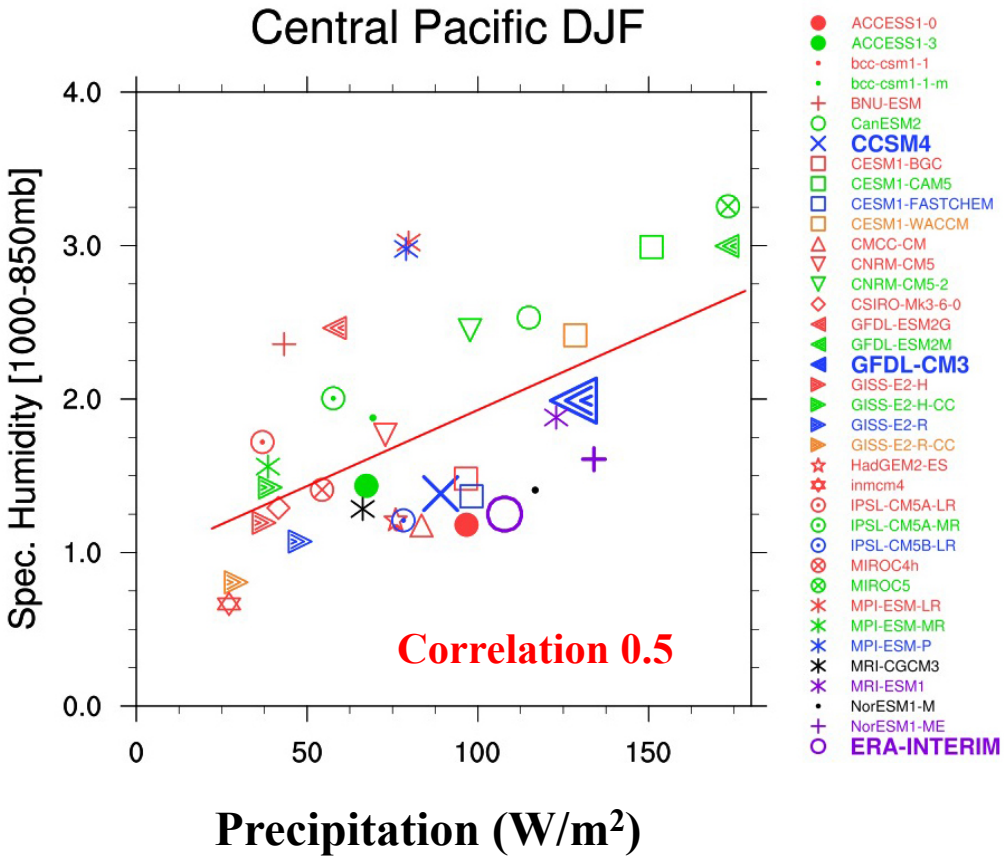
(MIROC5) – Clim. descent too strong

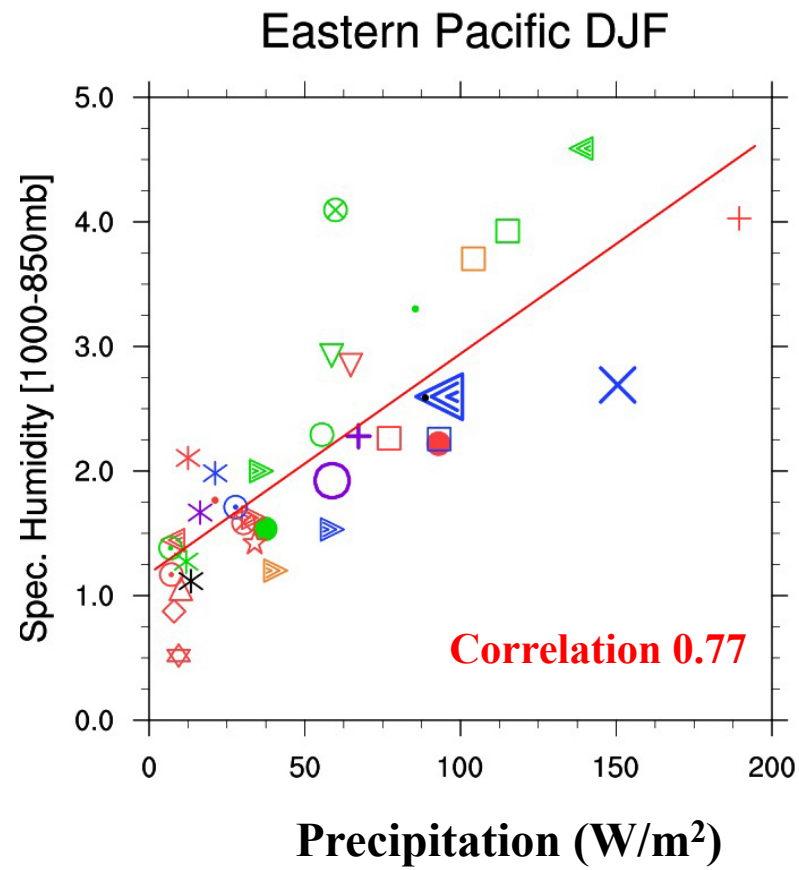
(CanESM2/NorESM1-M/CCSM4/CAM5)

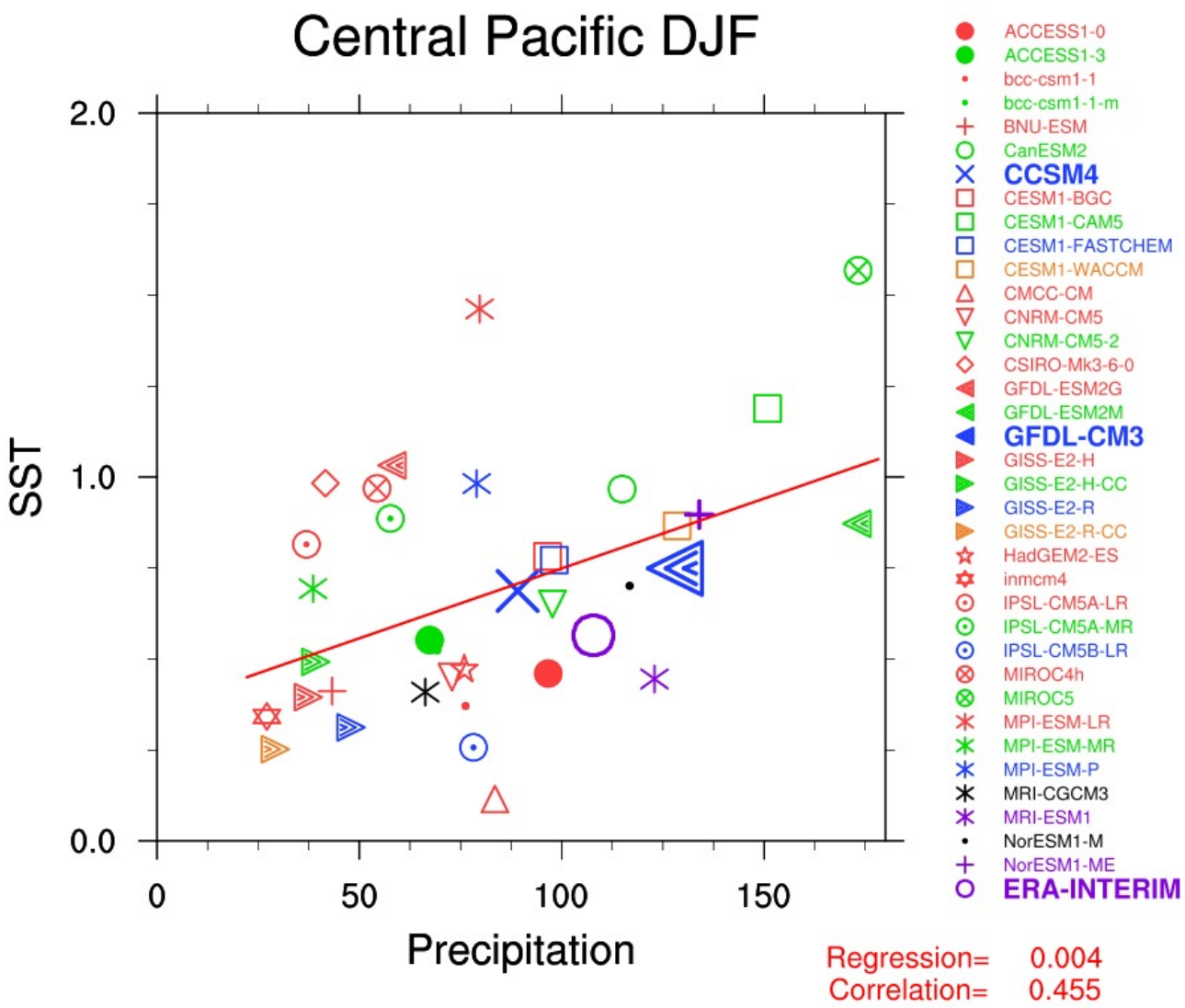
Composite of variance budget terms: (i) Similar SST but different precip response
(ii) Similar precip response but different SST forcing



Correlation 0.52

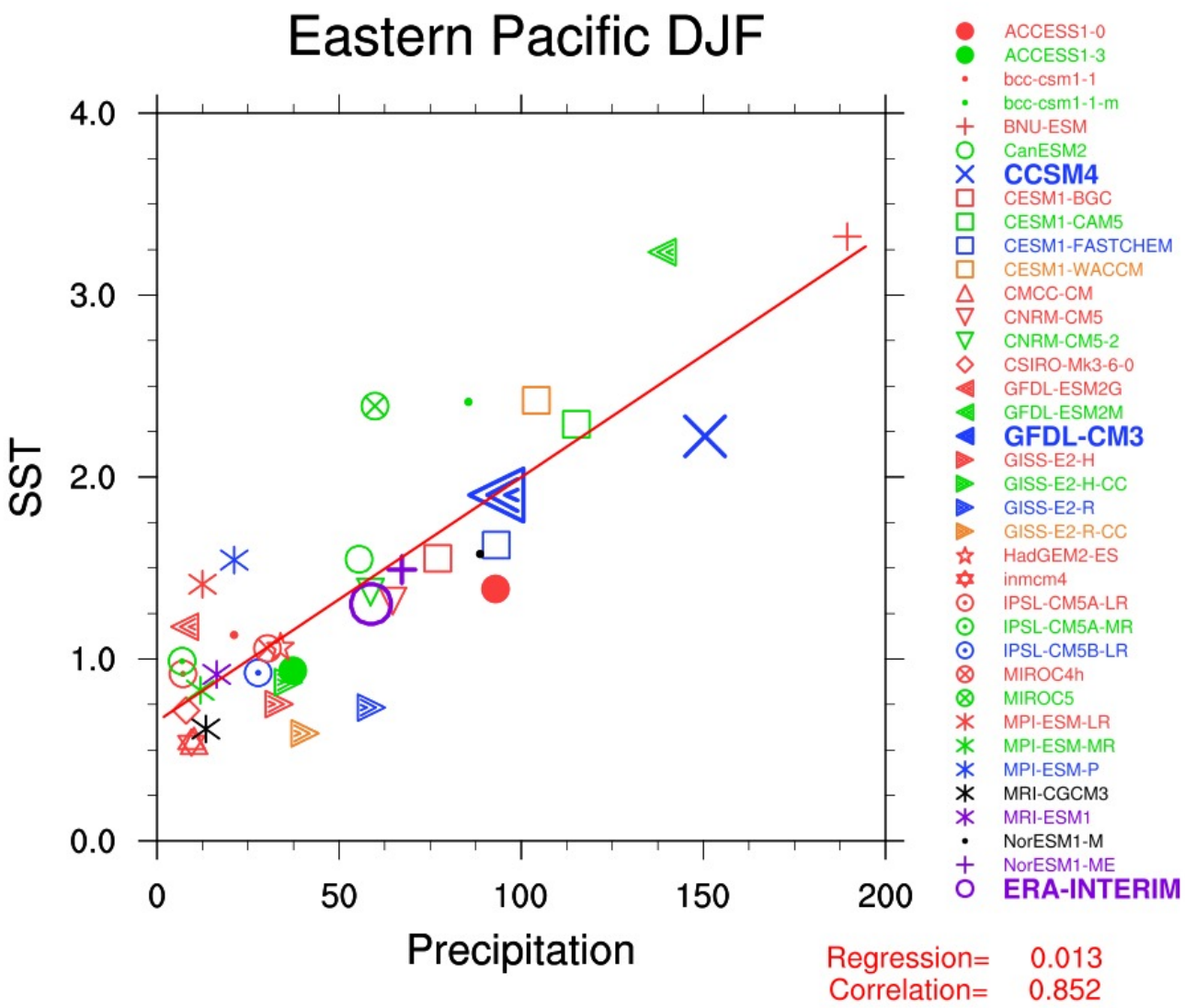

Central Pacific DJF
Spec. Humidity [1000-850mb]
Precipitation (W/m²)
Correlation 0.5
4.0
3.0
2.0
1.0
0.0
0
50
100
150
ACCESS1-0
ACCESS1-3
bcc-csm1-1
bcc-csm1-1-m
BNU-ESM
CanESM2
CCSM4
CESM1-BGC
CESM1-CAM5
CESM1-FASTCHEM
CESM1-WACCM
CMCC-CM
CNRM-CM5
CNRM-CM5-2
CSIRO-Mk3-6-0
GFDL-ESM2G
GFDL-ESM2M
GFDL-CM3
GISS-E2-H
GISS-E2-H-CC
GISS-E2-R
GISS-E2-R-CC
HadGEM2-ES
inmcm4
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC4h
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MPI-ESM-P
MRI-CGCM3
MRI-ESM1
NorESM1-M
NorESM1-ME
ERA-INTERIM


Eastern Pacific DJF
Spec. Humidity [1000-850mb]
Precipitation (W/m²)
Correlation 0.77
5.0
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200



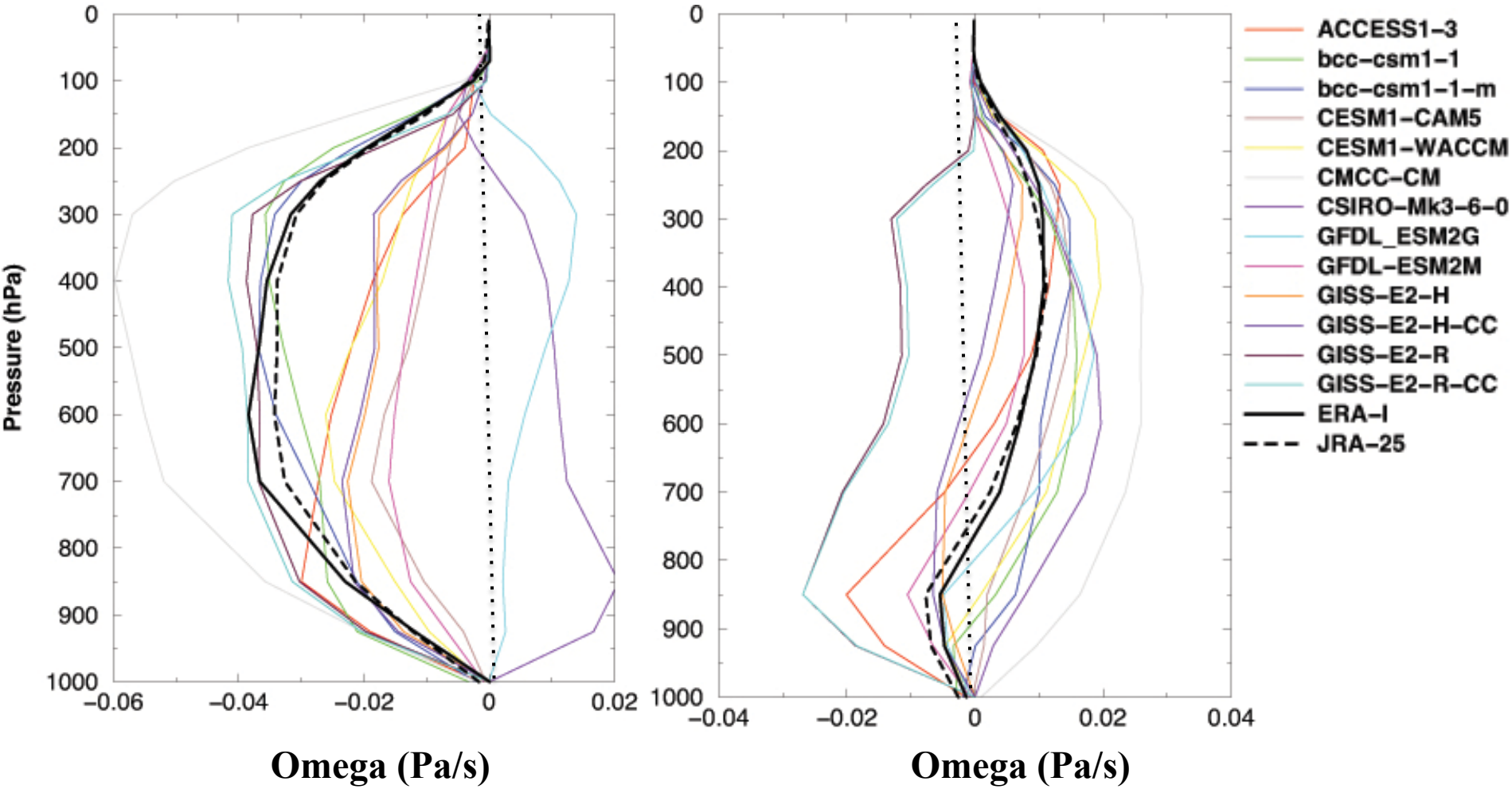
GFDL-family models – stronger LW feedbacks over the Central Pacific

Created: Fri Jun 16 11:46:45 HST 2017

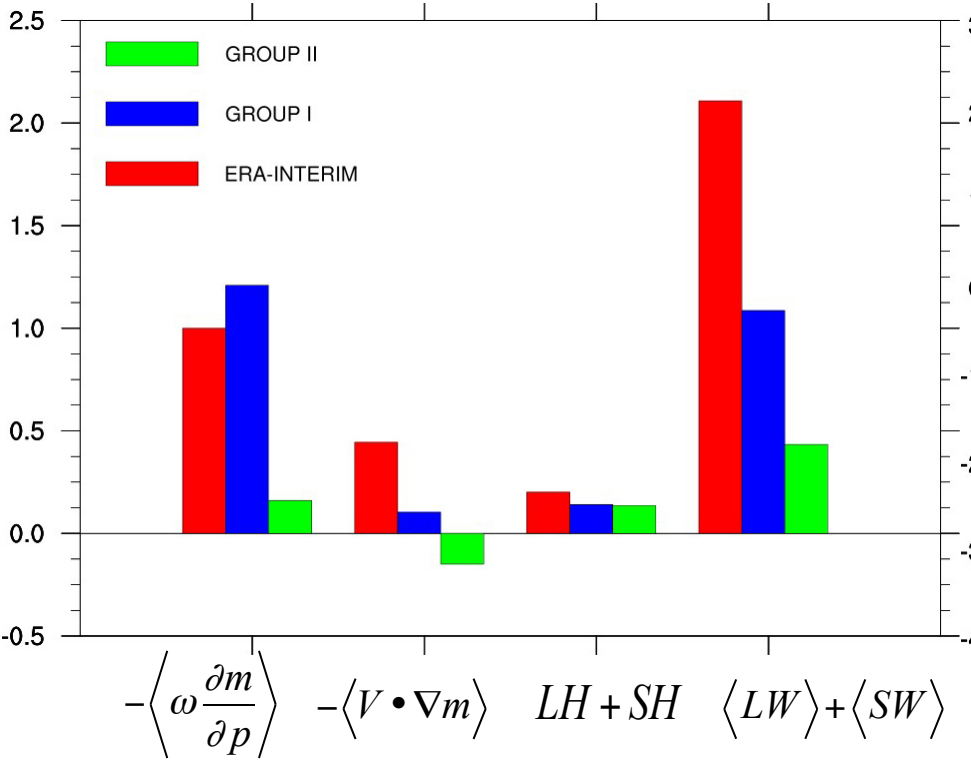


Created: Fri Jun 16 12:15:43 HST 2017

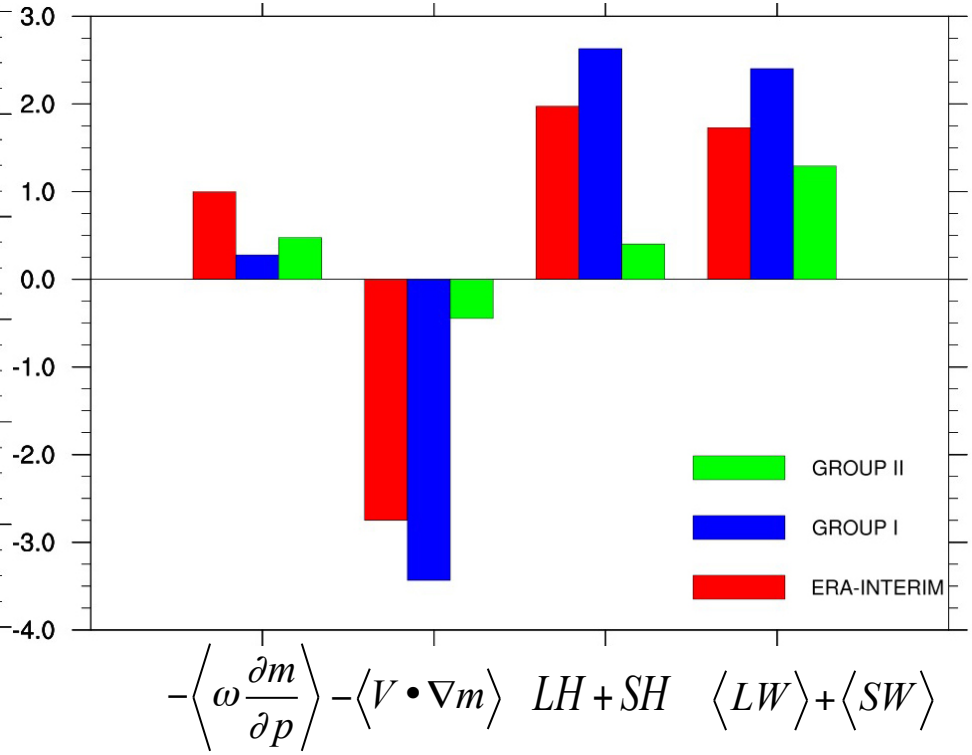
Central Pacific (160°E-160°W; 10°S-5°N) **Eastern Pacific (160°W-80°W; 5°S-5°N)**



Central Pacific (160°E-160°W; 10°S-5°N)

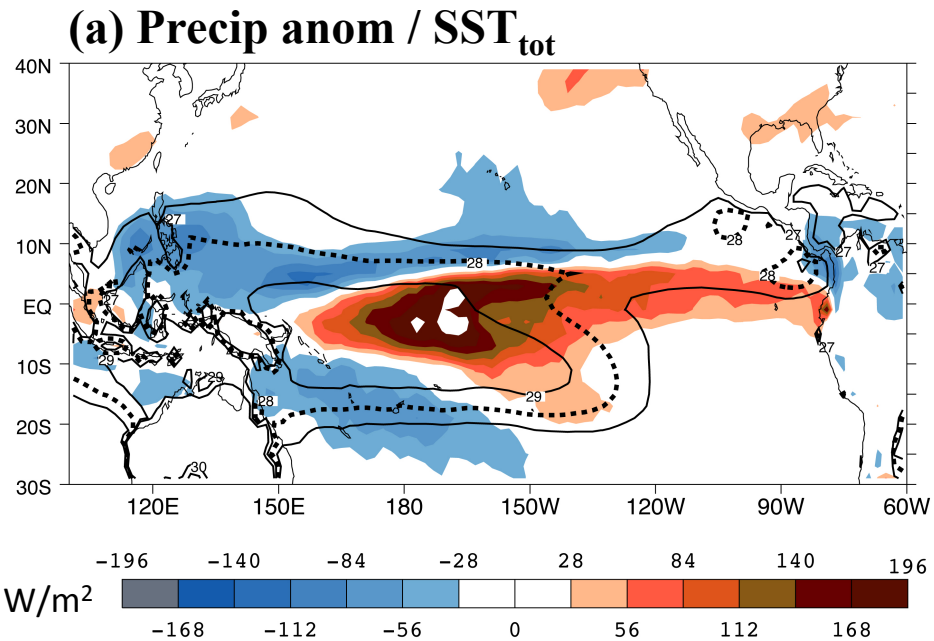


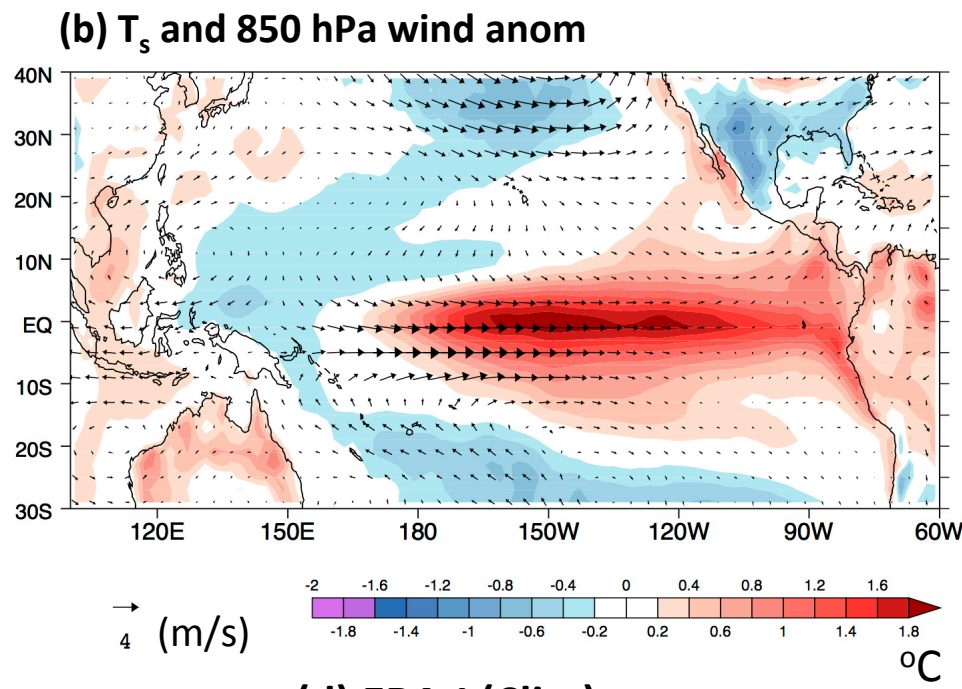
Eastern Pacific (160°W-80°W; 5°S-5°N))

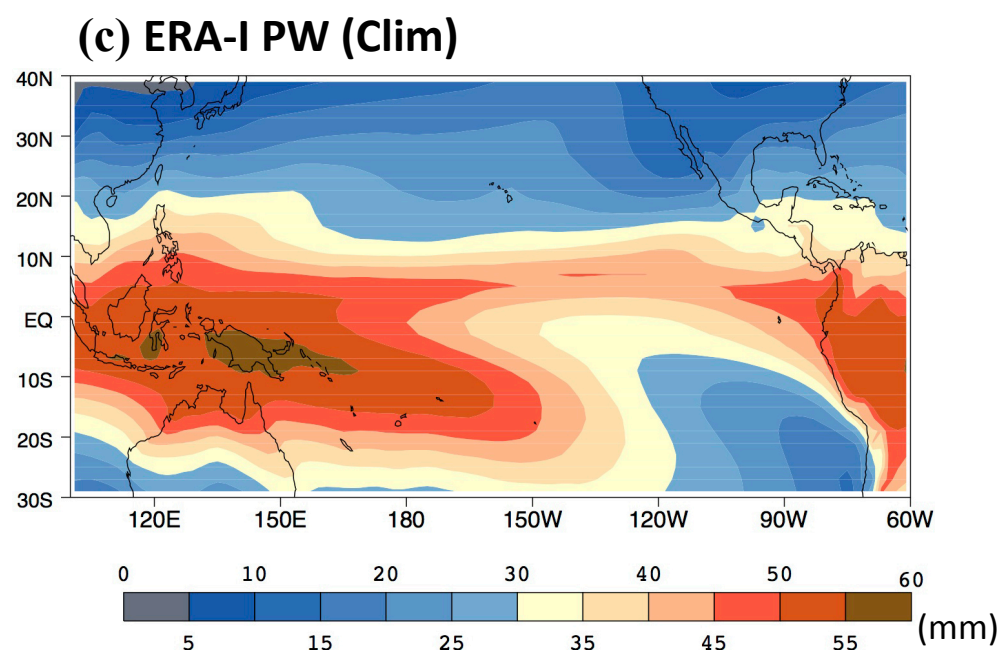


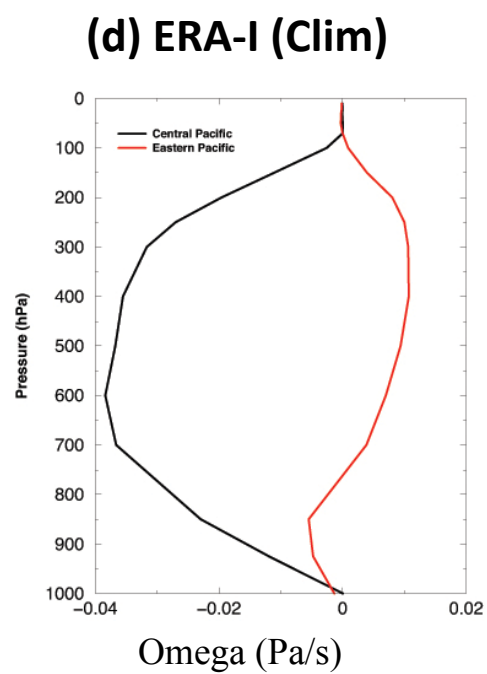
All the individual terms are projected onto $-\left\langle \omega \frac{\partial m}{\partial p} \right\rangle$ ERA-Interim

$$\cancel{\left\langle \frac{\partial m}{\partial t} \right\rangle} = -\langle V \bullet \nabla m \rangle - \left\langle \omega \frac{\partial m}{\partial p} \right\rangle + LH + SH + \langle LW \rangle + \langle SW \rangle$$


(a) Precip anom / SST$_{tot}$
40N
30N
20N
10N
EQ
10S
20S
30S
120E
150E
180
150W
120W
90W
60W
W/m^2
−196 −140 −84 −28 28 84 140 196
−168 −112 −56 0 56 112 168


(b) T$_s$ and 850 hPa wind anom
40N
30N
20N
10N
EQ
10S
20S
30S
120E
150E
180
150W
120W
90W
60W
4 (m/s)
-2 -1.6 -1.2 -0.8 -0.4 0 0.4 0.8 1.2 1.6
-1.8 -1.4 -1 -0.6 -0.2 0.2 0.6 1 1.4 1.8
^{o}C


(c) ERA-I PW (Clim)
40N
30N
20N
10N
EQ
10S
20S
30S
120E
150E
180
150W
120W
90W
60W
0 10 20 30 40 50 60
5 15 25 35 45 55
(mm)


(d) ERA-I (Clim)
Central Pacific
Eastern Pacific
Pressure (hPa)
0
100
200
300
400
500
600
700
800
900
1000
−0.04
−0.02
0
0.02
Omega (Pa/s)

Steady-state, vertically integrated MSE tendency is approximately given by

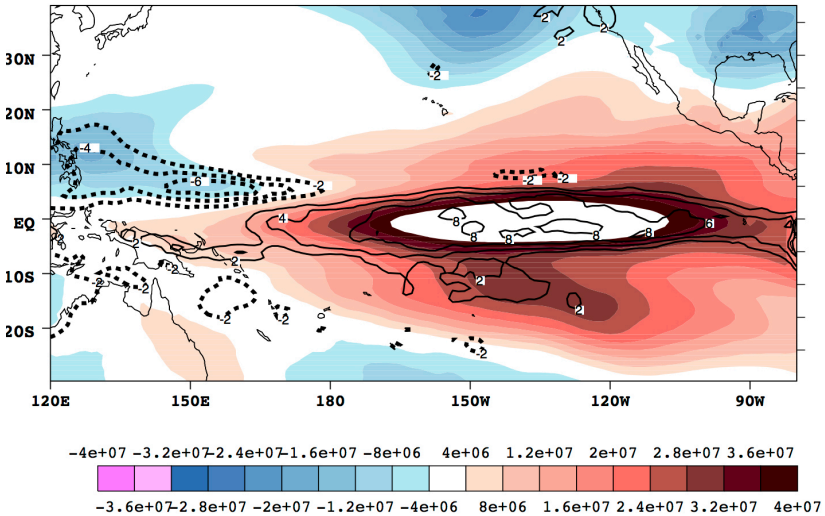
$$\cancel{\left\langle \frac{\partial m}{\partial t} \right\rangle} = -\left\langle V \bullet \nabla m \right\rangle - \left\langle \omega \frac{\partial m}{\partial p} \right\rangle + LH + SH + \left\langle LW \right\rangle + \left\langle SW \right\rangle$$

"storage" "adiabatic terms" "diabatic terms"

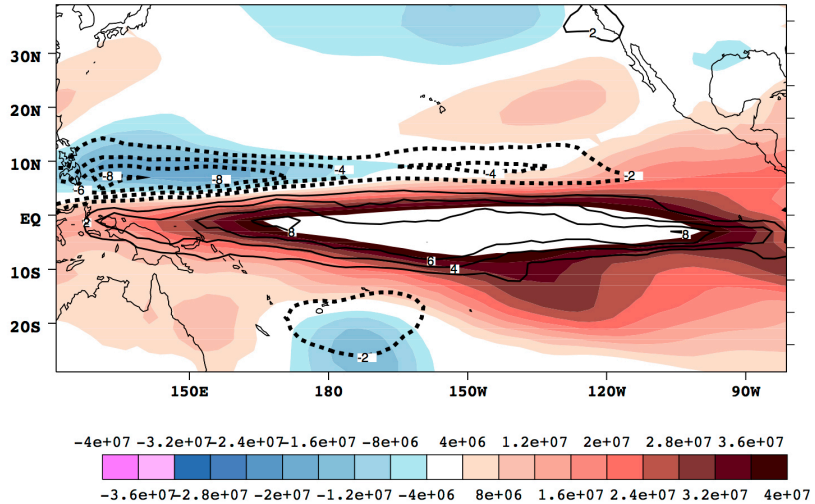
where V is the horizontal velocity vector, ∇ is the gradient operator, ω is vertical pressure velocity, LH and SH are surface fluxes of latent and sensible heat, and $\langle LW \rangle + \langle SW \rangle$ are net column integrated longwave and shortwave heating rates, and their sum represents net radiative flux (F_{rad}). The symbols $\langle \ \rangle$ represent vertical integral.

El Nino (DJF) composite

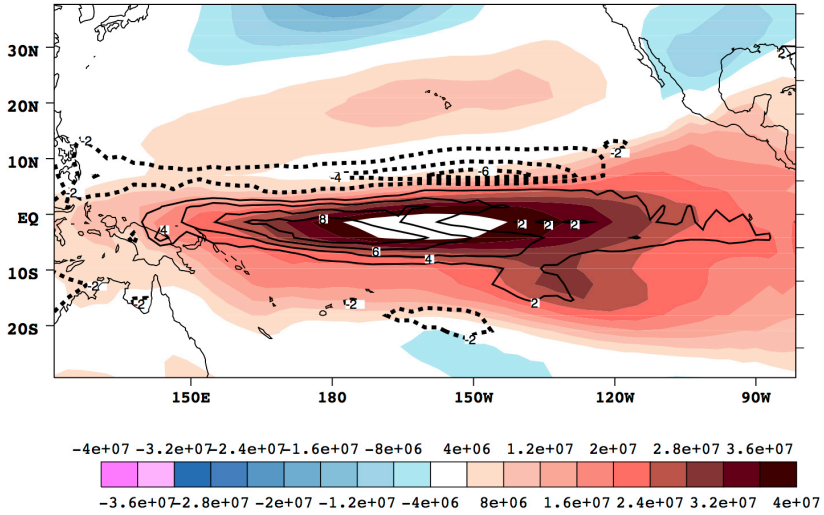
CCSM4



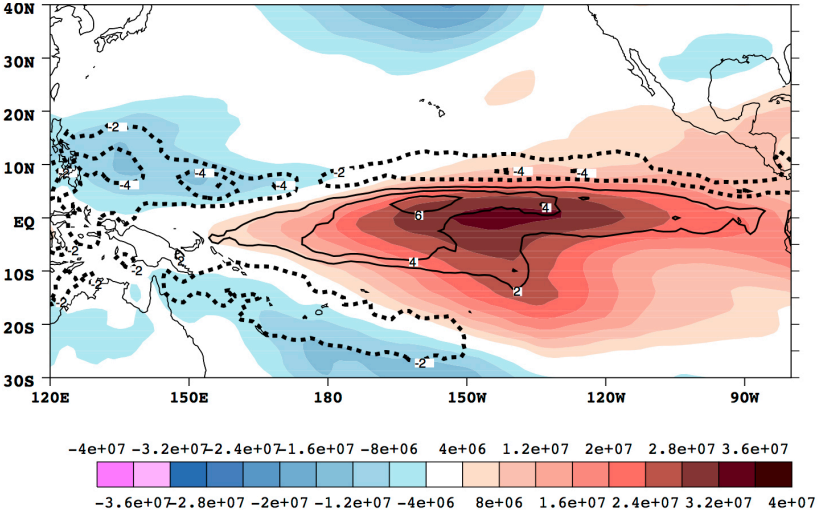
CM3



CanESM2



JRA-25



MSE anomalies (shaded)
Precip anomalies (contour)

Basic-state Vertical profile of vertical velocity (depends on cumulus parameterizations)

Central Pacific – “dispersion” is large – climatological ascent region – Frad dominates

Eastern Pacific – “dispersion” is small – climatological descent region – THF/Frad

Models that have strong Frad (cloud-radiative feedbacks) – larger moisture-convection

Feedbacks – results in higher intensity of precipitation

(1) Moisture-convection feedbacks – select the appropriate slides/scatters
(2) Cloud-radiative feedbacks – select the appropriate scatter plots
(3) Systematic errors across all models
(4) Errors in models that have similar SST forcing but different precip response
(5) Errors in models that have similar precip response but different SST forcing
(6) Models that depict too weak SST and precip – MSE processes are still correct!

- ENSO-related SST anomalies (processes that maintain column MSE anomalies)

- THF anomalies (due to SST and wind speed anomalies – physics – BL moistening due to turbulence; convective triggering and CAPE)

- V *del h (East-west circulation anomalies; North-south circulation anomalies anomalous winds advect climatological moisture gradient; moistening or drying the lower troposphere MSE anomalies)

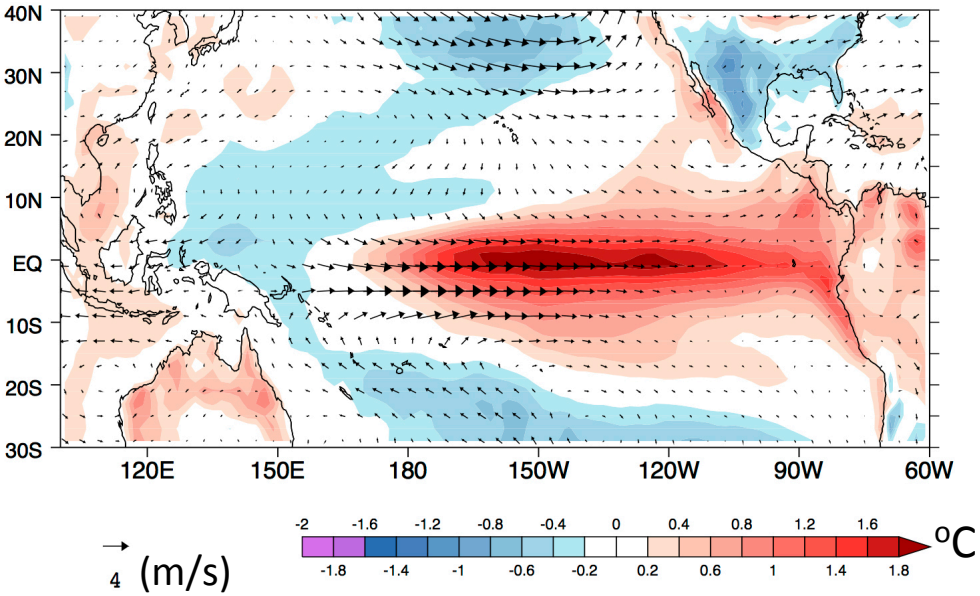
- Omega * dh/dp (proportional to precip anomalies; act as moisture sink proxy for convective forcing; very small term – too difficult for models to represent; vertical advection – promotes moisture-convection feedbacks FT moisture and temperature anomalies – LW heating anomalies)

- Frad (LW + SW anomalies – physics – consequence of convection)

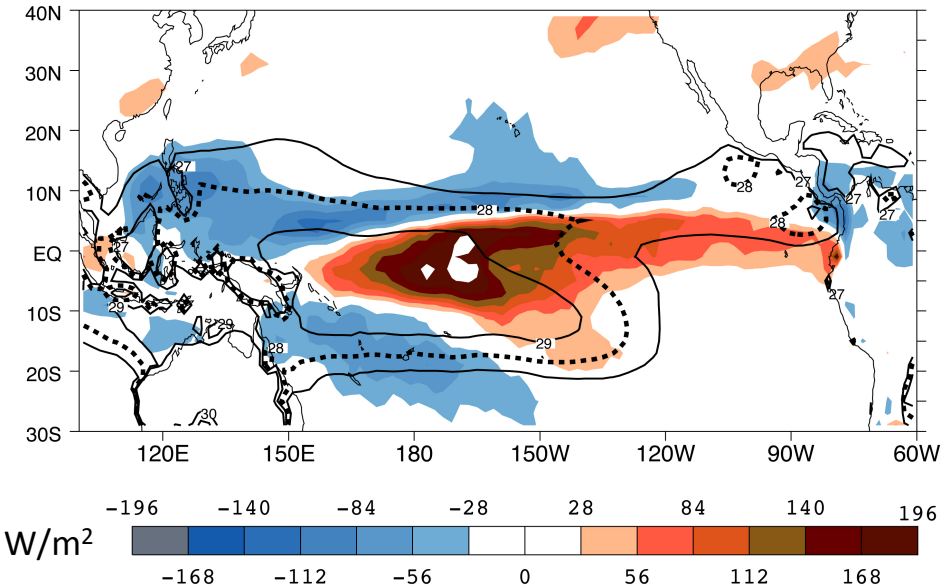
- All these processes anchor meso-scale circulation anomalies fluxing MSE out and feeding convection

SHOW COMPOSITES OF SST/winds/precip/MSE and MSE terms from reanalysis

(a) T_s and 850 hPa wind anom



(b) Precip anom / SST_{tot}



Based on preliminary diagnostics:

- Realistic contributions of MSE terms that accounts for vertical advection of MSE (a quantity that is proportional to precipitation anomalies) are noted in climate models that "realistically" represent the basic-state (omega profile, PW etc).

- vertical advection of anomalous MSE is largely balanced by anomalous F_{rad} (cloud radiative heating/cloud-radiative feedbacks)

- free-tropospheric moisture variations (moisture-convection feedbacks) determine precipitation variations.

- Diagnostics identify systematic errors in physics across most models