The role of the Western North Pacific (WNP) precursor in development of El Niño–Southern Oscillation (ENSO) in a warming climate

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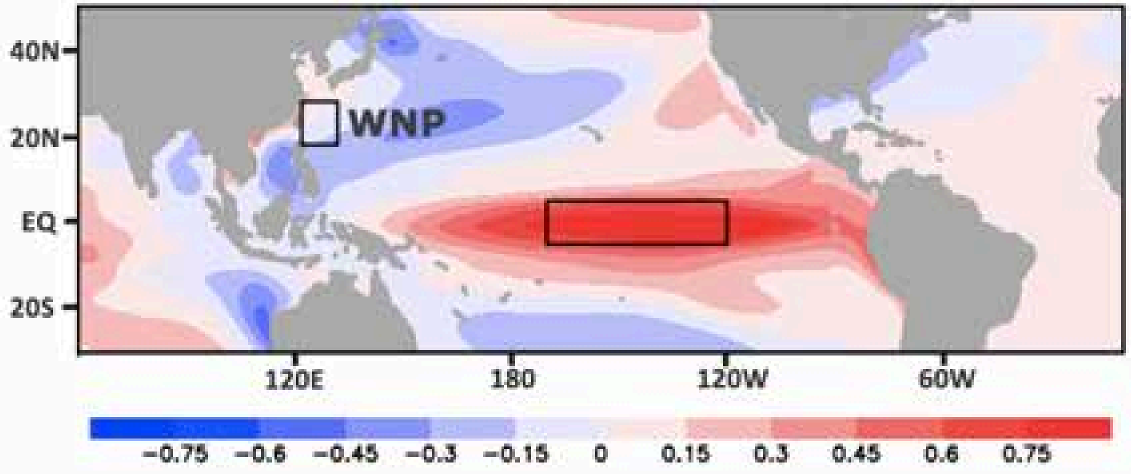
Sea Surface Temperature (SST) anomalies (DJF) →



Progress so far...

Bjerknes feedback (Bjerknes 1966; 1969)

Oscillator mechanisms (Suarez and Schopf 1988; Jin et al. 1997; Weisberg and Wang 1997; Picaut et al. 1996)

First successful prediction of ENSO (Cane et al., 1986)

Precursors used earlier in history:

- Warm Water Volume in tropical Pacific
- Westerly Wind Events/Easterly Wind Surges along tropical Pacific

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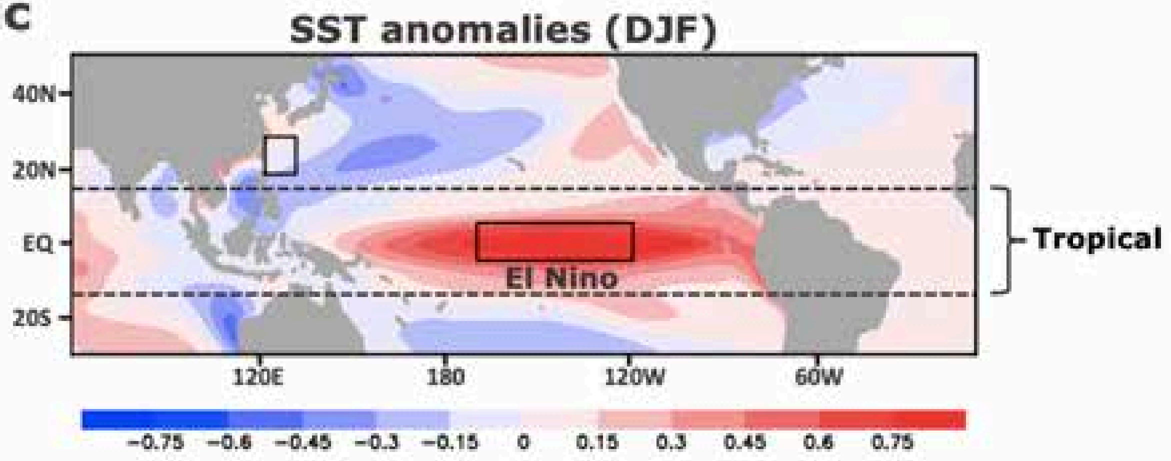
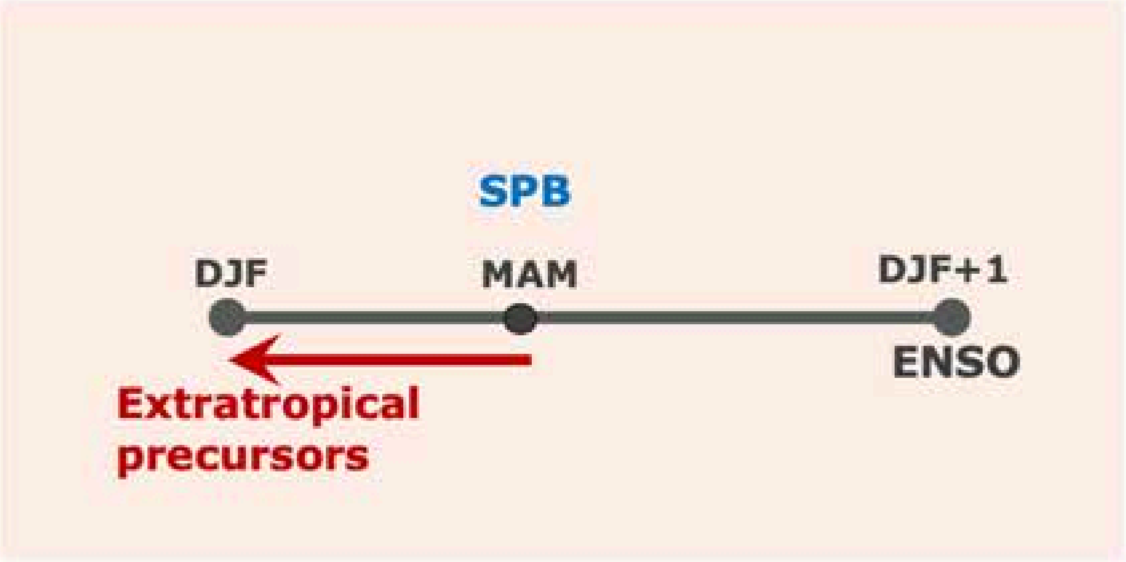
- Restricted to the Tropical Pacific



Extratropical Precursors

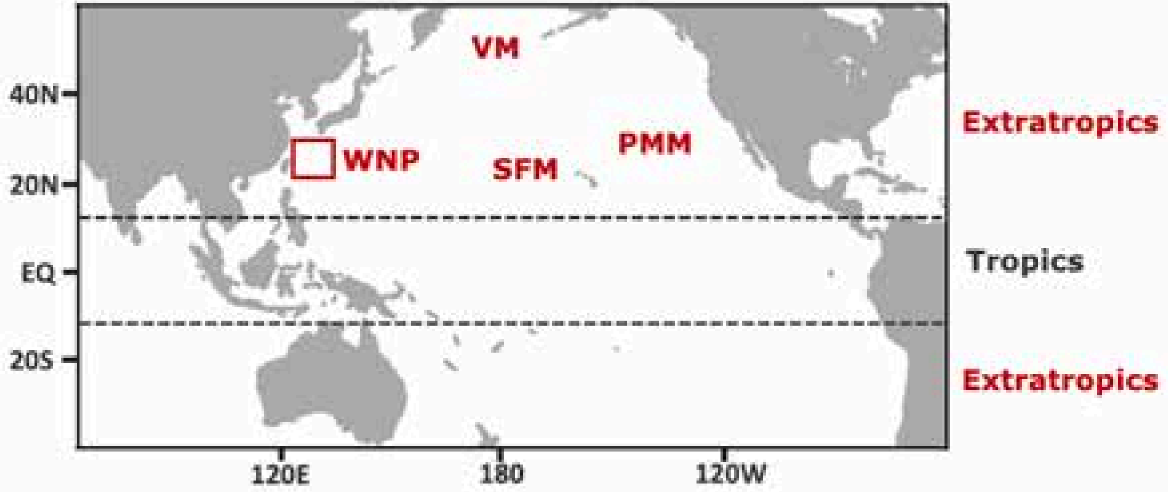
Decrease in prediction skill when ENSO prediction after 2000…

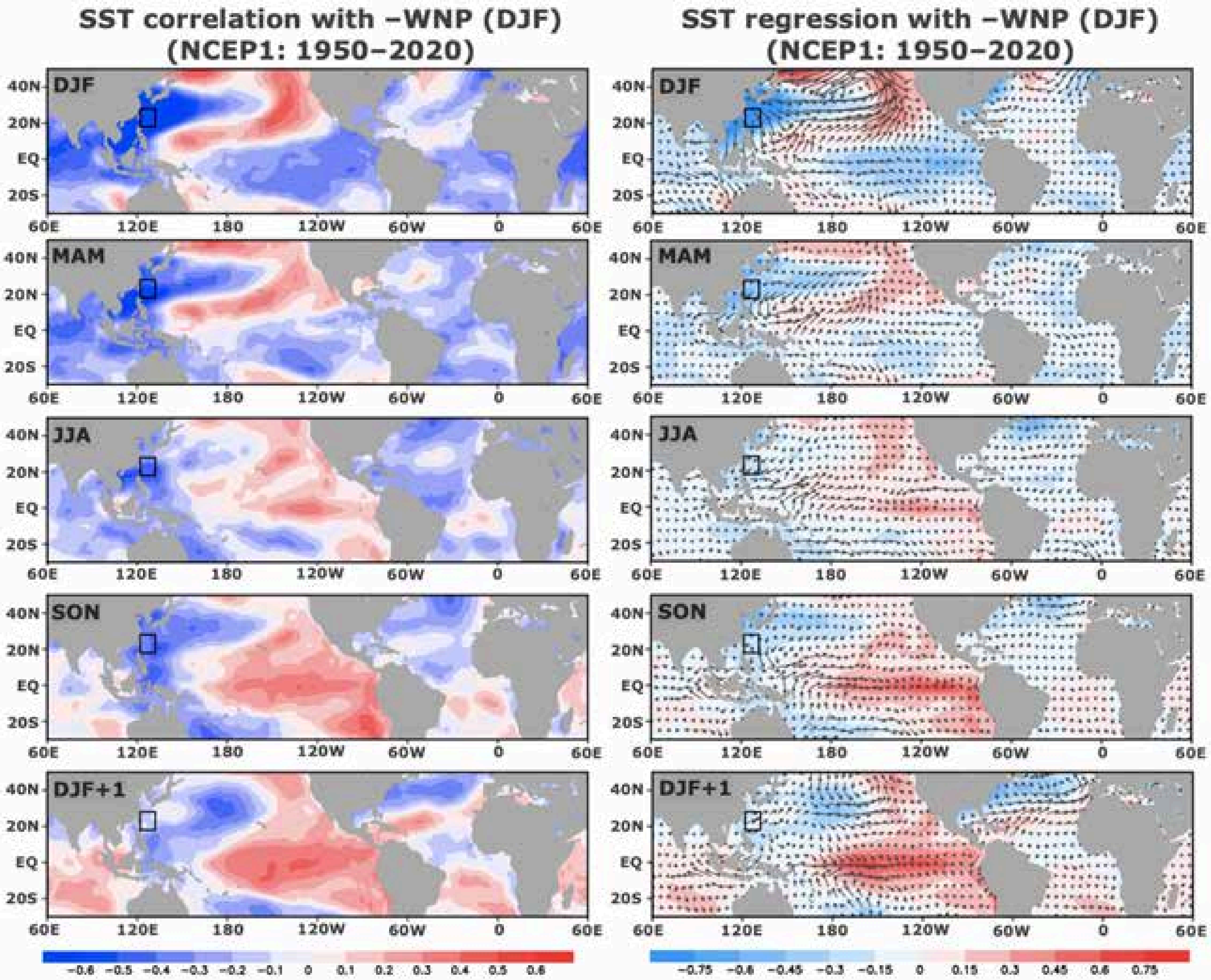
Spring Predictability Barrier (SPB): sharp decrease in prediction skill when ENSO prediction is made through Spring



- Extratropical Precursors
  - Pacific Meridional Mode (PMM),
  - Trade Wind Charging (TWC),
  - Victoria Mode (VM),
  - Seasonal Footprinting Mechanism (SFM),
  - **Western North Pacific (WNP)**

(e.g., Wang et. 2012; 2013; Fosu et al. 2020)





Cold WNP waters --> SST temperature gradient --> Anomalous winds

Eastward propagating Kelvin waves near the western equatorial Pacific

ENSO (El Nino) one year later.

CONDITIONAL PROBABLITY APPROACH:

For each ensemble e = 1, 2, … 86 of CMIP6, or e = 1, 2, … 50 of CESM2-LE:

$$(DJF+1)SST_{\mathrm{SSP}_e} - (DJF+1)SST_{\mathrm{HIST}_e} = \left[\frac{1}{n_e}\sum_{j=1}^{n_e}(DJF+1)\mathrm{SST}_j\right] - \left[\frac{1}{m_e}\sum_{i=1}^{m_e}(DJF+1)\mathrm{SST}_i\right] \quad \ldots (1)$$

An event is defined as a year with > 0.5°C cooling in the western North Pacific in DJF followed by > 1.0°C warming in Niño 3.4 in DJF+1. Equation (1) can be decomposed as follows:

$(DJF+1)\mathrm{SST}_i$ is the $(DJF+1)SST$ of the i^{th} event of the e^{th} ensemble of historical runs,
$(DJF+1)\mathrm{SST}_j$ is the $(DJF+1)SST$ of the j^{th} event of the e^{th} ensemble of ssp370 runs,
m_e is the frequency of historical events of the e^{th} ensemble,
n_e is the frequency of ssp370 events of the e^{th} ensemble,
$(DJF+1)SST_{\mathrm{HIST}_e}$ is the average $(DJF+1)SST$ of the m_e historical events, and
$(DJF+1)SST_{\mathrm{SSP}_e}$ is the average $(DJF+1)SST$ of the n_e ssp370 events.

CONDITIONAL PROBABLITY APPROACH:

For each ensemble e = 1, 2, … 86 of CMIP6, or e = 1, 2, … 50 of CESM2-LE:

$$(DJF+1)SST_{\mathrm{SSP}_e} - (DJF+1)SST_{\mathrm{HIST}_e} = \left[\frac{1}{n_e}\sum_{j=1}^{n_e}(DJF+1)\mathrm{SST}_j\right] - \left[\frac{1}{m_e}\sum_{i=1}^{m_e}(DJF+1)\mathrm{SST}_i\right] \quad \ldots (1)$$

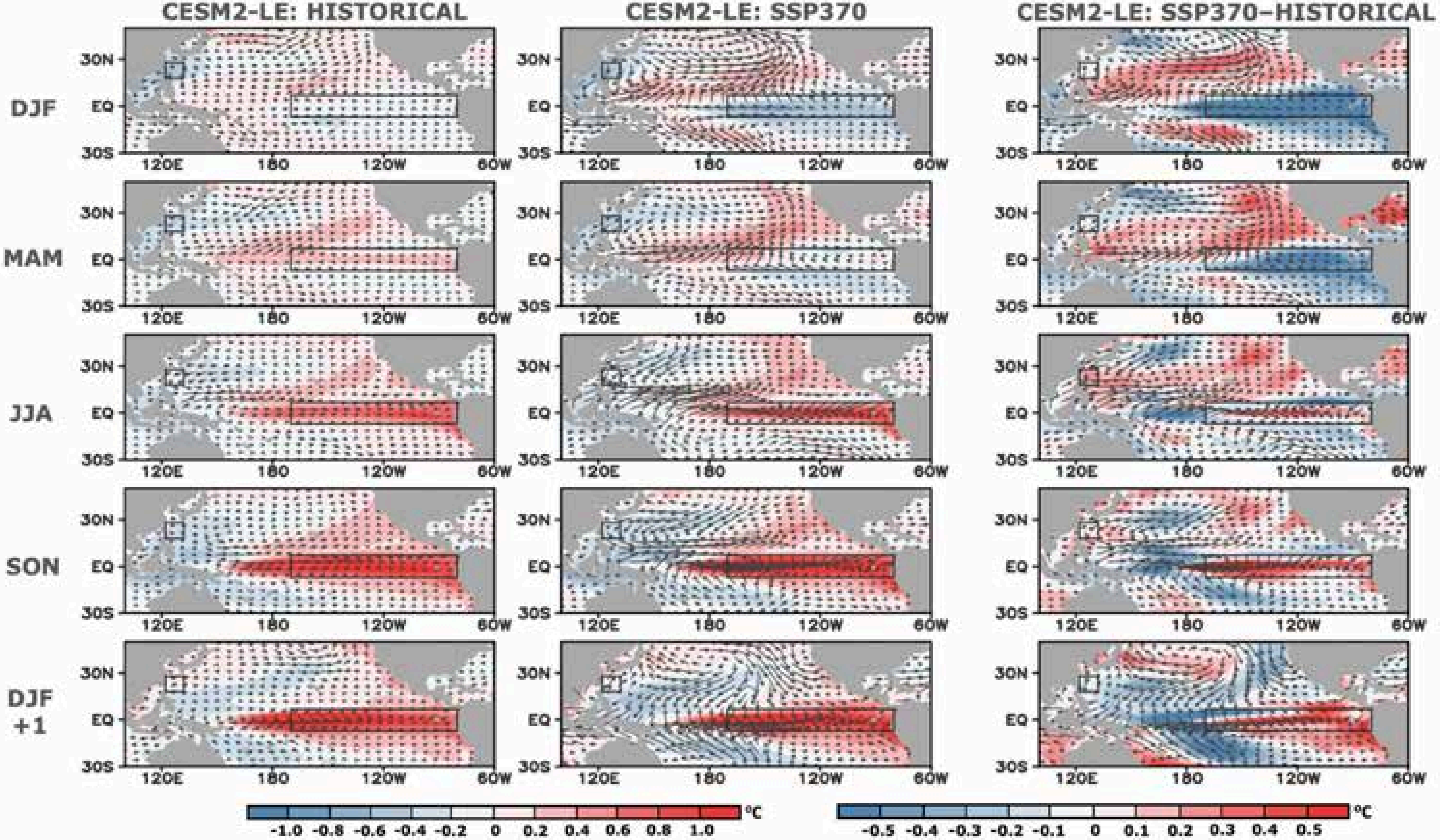
An event is defined as a year with > 0.5°C cooling in the western North Pacific in DJF followed by > 1.0°C warming in Niño 3.4 in DJF+1.

(In the central to eastern equatorial Pacific:)

$(DJF+1)SST_{\mathrm{SSP}_e} - (DJF+1)SST_{\mathrm{HIST}_e} > 0$ "WARM events" i.e., stronger future El Nino

$(DJF+1)SST_{\mathrm{SSP}_e} - (DJF+1)SST_{\mathrm{HIST}_e} < 0$ "COLD events" i.e., weaker future El Nino

SST and surface wind anomaly composites for "WARM events"



With SSP370 warming:

Stronger SST dipole

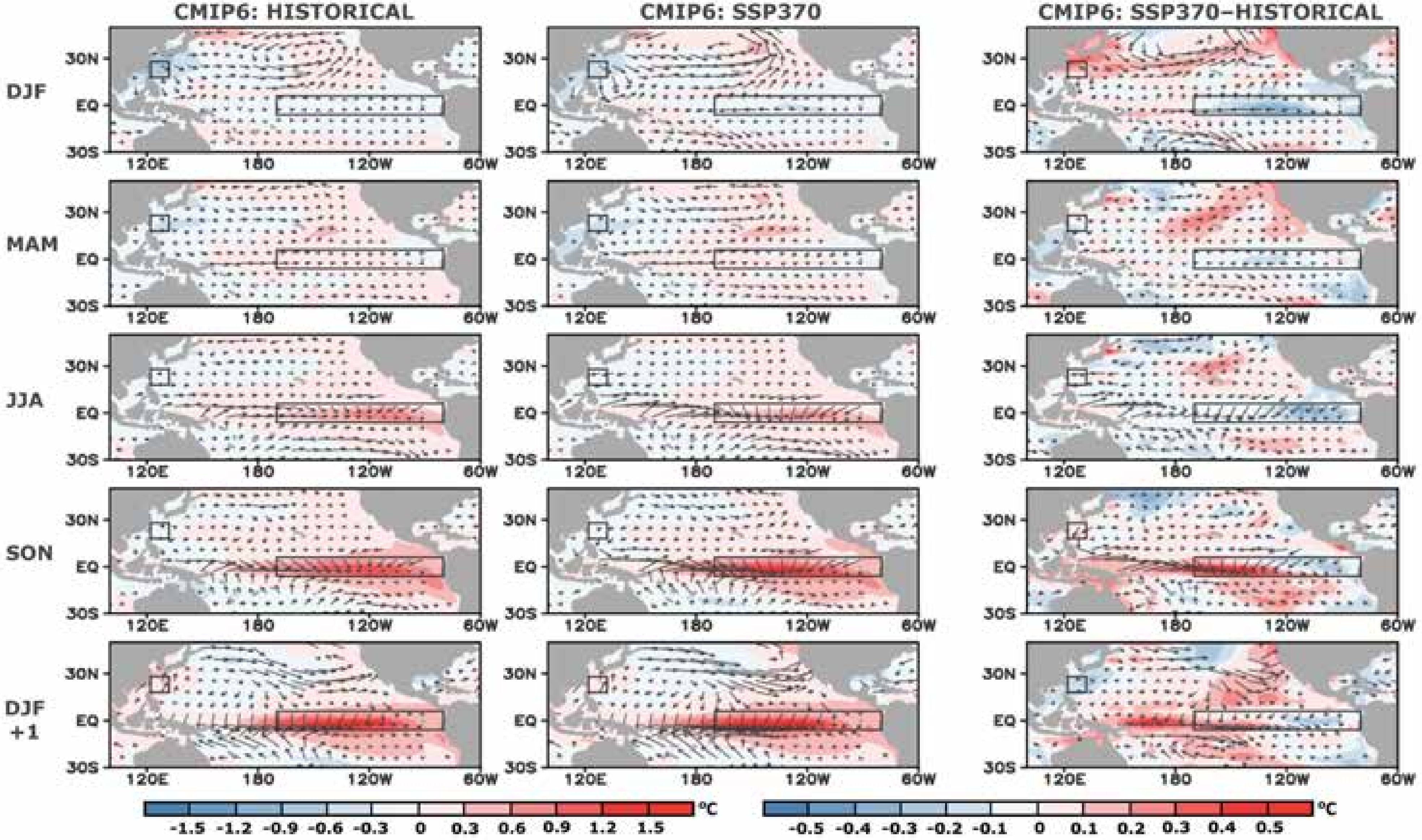
Stronger PMM southwesterlies in western Pacific

Stronger western Pacific westerlies

Stronger centers of central Pacific SST and surface convergence

EP type El Nino

SST and surface wind anomaly composites for "WARM events"

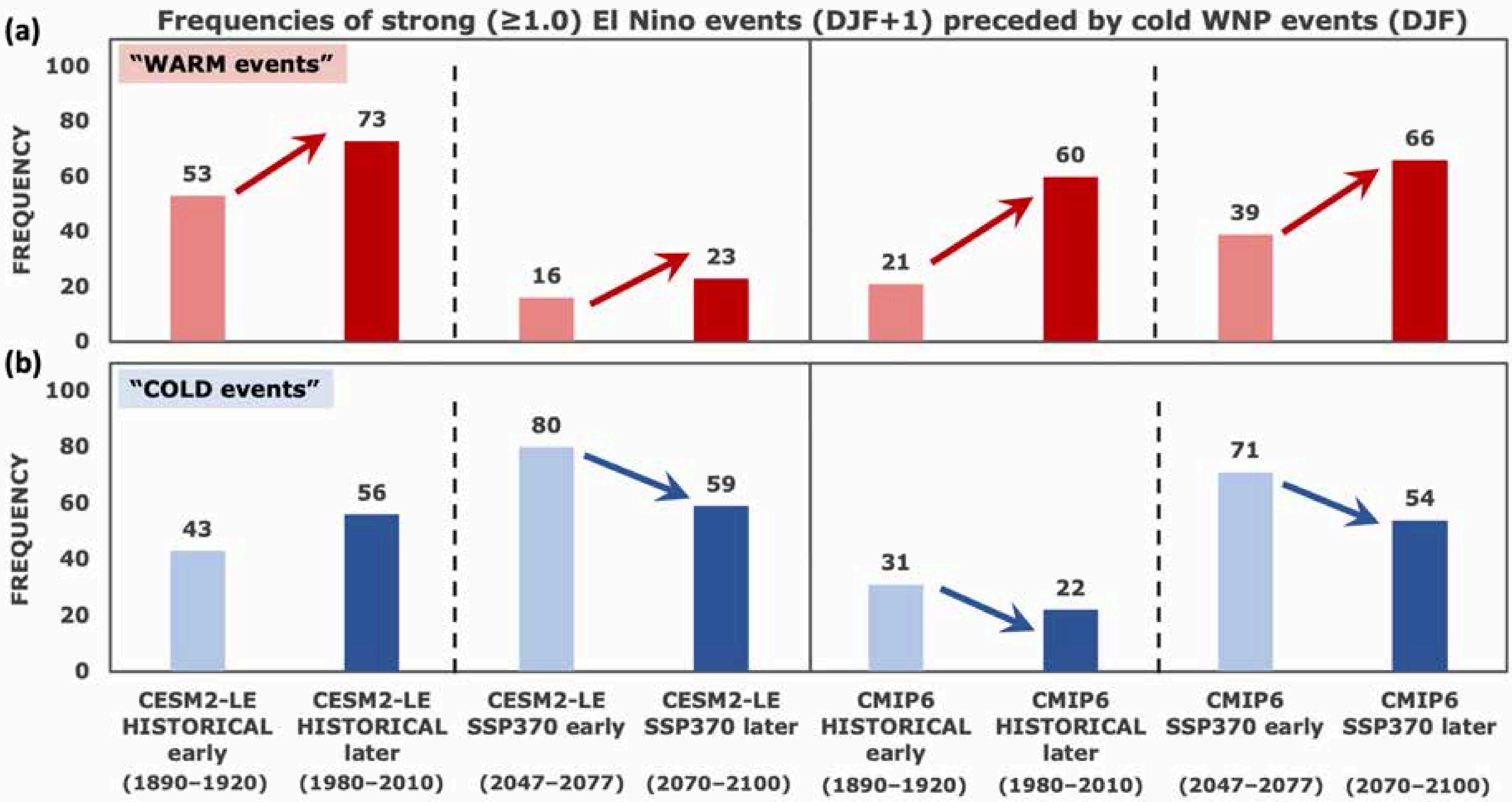


With SSP370 warming:

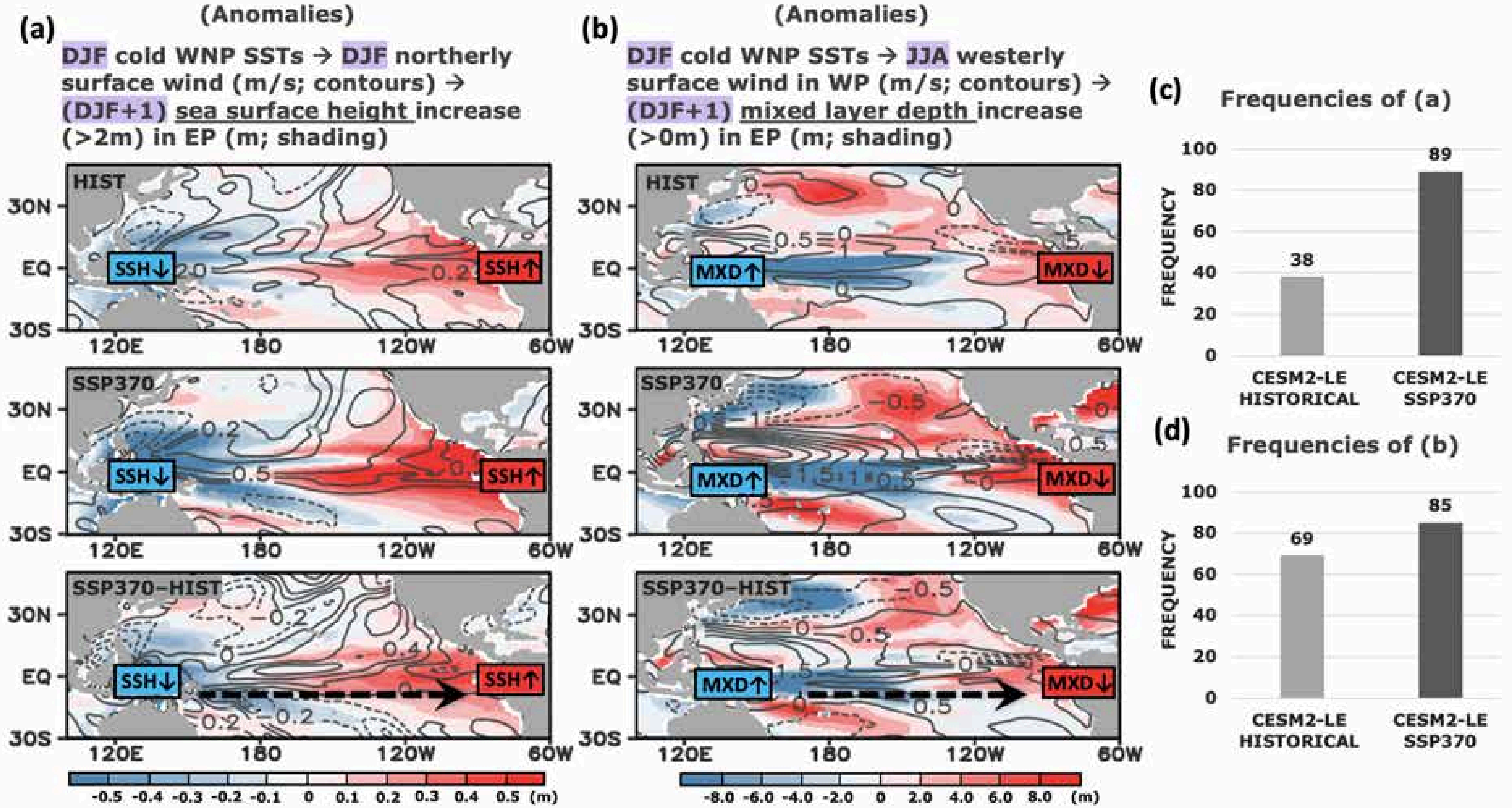
Stronger western Pacific westerlies

Stronger centers of central Pacific SST and surface convergence

Strengthened western Pacific warm pool



CESM2 reference: Danabasoglu et al. (2020)


(a)
(Anomalies)
DJF cold WNP SSTs → DJF northerly surface wind (m/s; contours) → (DJF+1) sea surface height increase (>2m) in EP (m; shading)
(b)
(Anomalies)
DJF cold WNP SSTs → JJA westerly surface wind in WP (m/s; contours) → (DJF+1) mixed layer depth increase (>0m) in EP (m; shading)
HIST
SSP370
SSP370-HIST
SSH↓
SSH↑
MXD↑
MXD↓
30N
EQ
30S
120E
180
120W
60W
-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 (m)
-8.0 -6.0 -4.0 -2.0 0 2.0 4.0 6.0 8.0 (m)
(c)
Frequencies of (a)
FREQUENCY
0
20
40
60
80
100
38
89
CESM2-LE HISTORICAL
CESM2-LE SSP370
(d)
Frequencies of (b)
FREQUENCY
0
20
40
60
80
100
69
85
CESM2-LE HISTORICAL
CESM2-LE SSP370

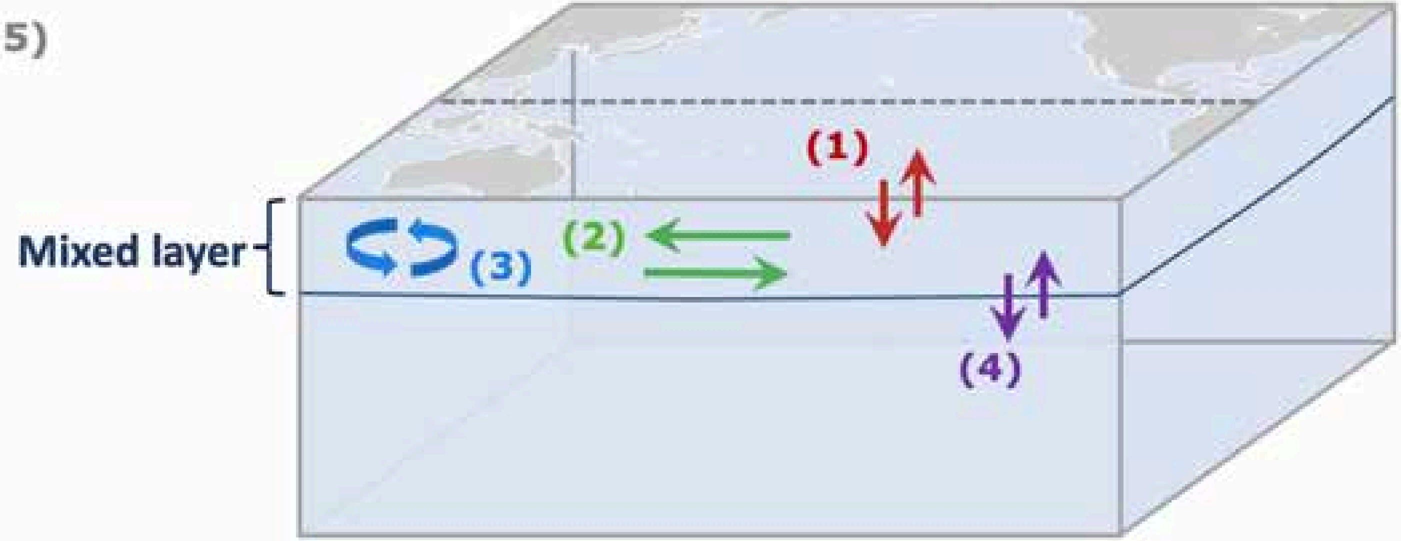
SST budget equation:

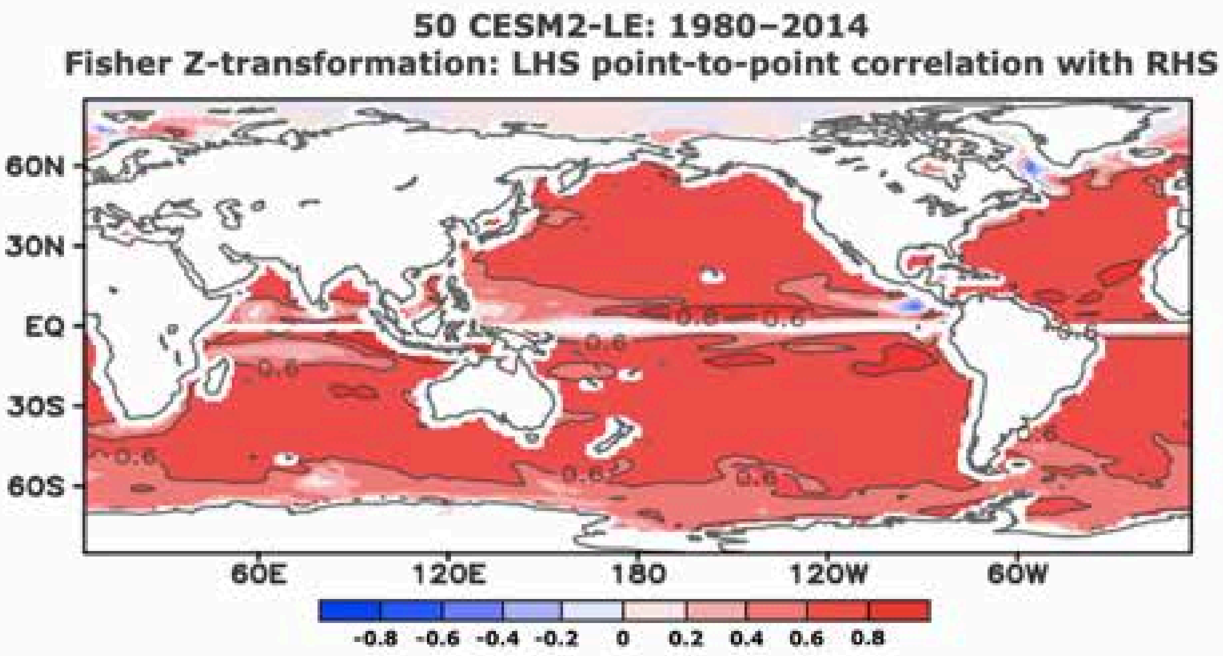
Temperature tendency of the ocean mixed layer

$$\frac{\partial T_m}{\partial t} = \frac{Q_{net} - q(-d_m)}{\rho_o c_p d_m} - u_m . \nabla T_m + \nabla^2 T_m - \frac{w_e \Delta T}{d_m}$$

Temperature Tendency Term (6) | **Air-Sea Heat Flux (1)** | **Advection (2)** → **Geostrophic + Ekman** | **Diffusion (3)** | **Entrainment (4)**

LHS (6) | **RHS (5)**





$$\underbrace{\frac{\partial T_m}{\partial t}}_{\text{Temperature Tendency Term (6)}} = \underbrace{\frac{Q_{net} - q(-d_m)}{\rho_o c_p d_m}}_{\text{Air-Sea Heat Flux (1)}} \underbrace{- u_m . \nabla T_m}_{\text{Advection (2)}} + \underbrace{\nabla^2 T_m}_{\text{Diffusion (3)}} \underbrace{- \frac{w_e \Delta T}{d_m}}_{\text{Entrainment (4)}}$$

Temperature Tendency Term (6)

Air-Sea Heat Flux (1)

Advection (2)

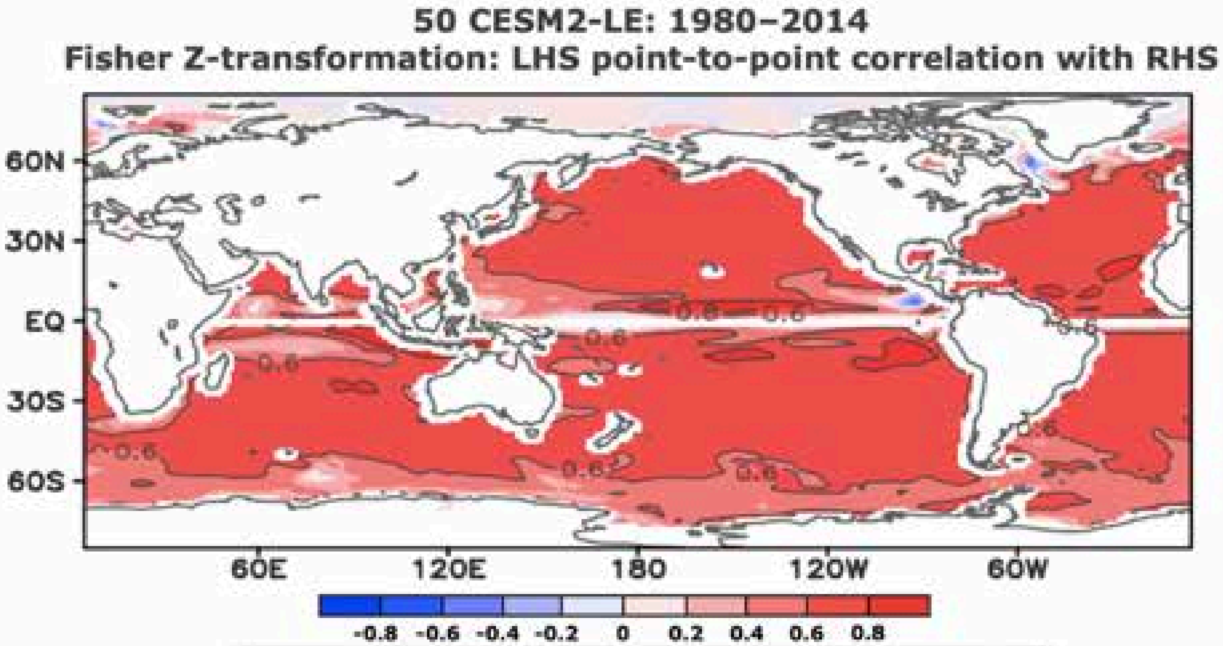
Geostrophic + Ekman

Diffusion (3)

Entrainment (4)

LHS (6)

RHS (5)



$$Z_{\text{ave}} = \frac{1}{2n}\sum_{i=1}^{n} \ln\left[\frac{1+r_i}{1-r_i}\right]$$

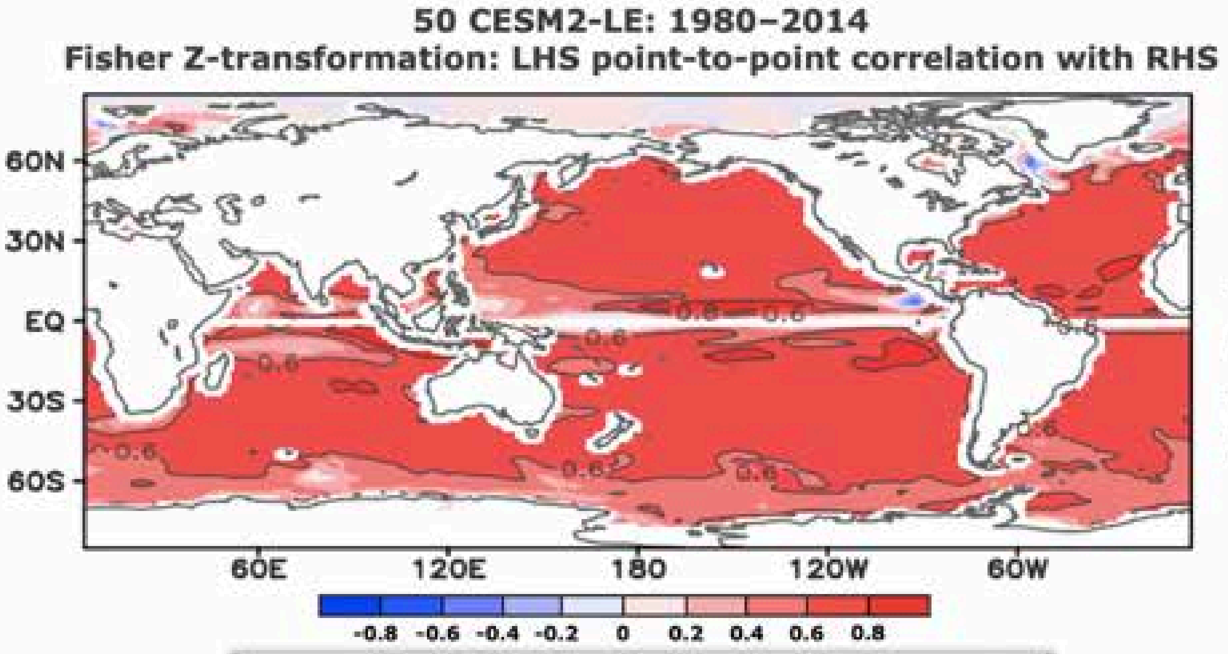
$$r_{\text{ave}} = \tanh(Z_{\text{ave}}) = \left[\frac{e^{Z_{\text{ave}}} - e^{-Z_{\text{ave}}}}{e^{Z_{\text{ave}}} + e^{-Z_{\text{ave}}}}\right]$$

$$\frac{\partial T_m}{\partial t} = \frac{Q_{net} - q(-d_m)}{\rho_o c_p d_m} - u_m . \nabla T_m + \nabla^2 T_m - \frac{w_e \Delta T}{d_m}$$

Temperature Tendency Term (6) | Air-Sea Heat Flux (1) | Advection (2) | Diffusion (3) | Entrainment (4)

Advection (2) → Geostrophic + Ekman

LHS (6) | RHS (5)



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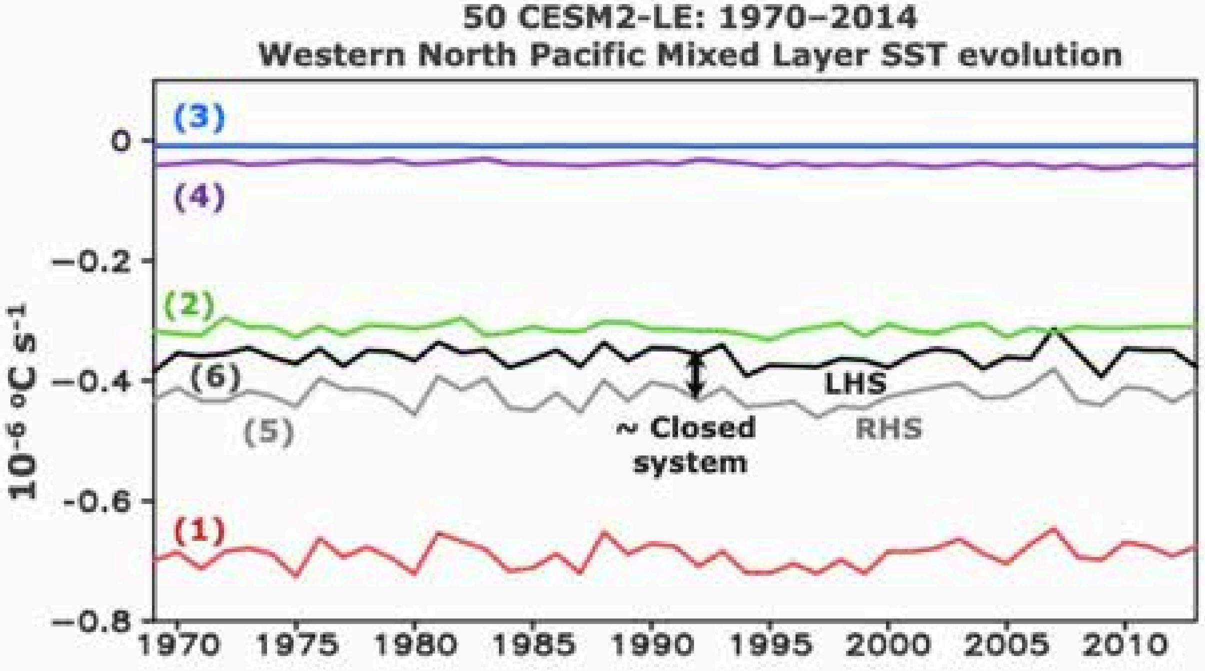
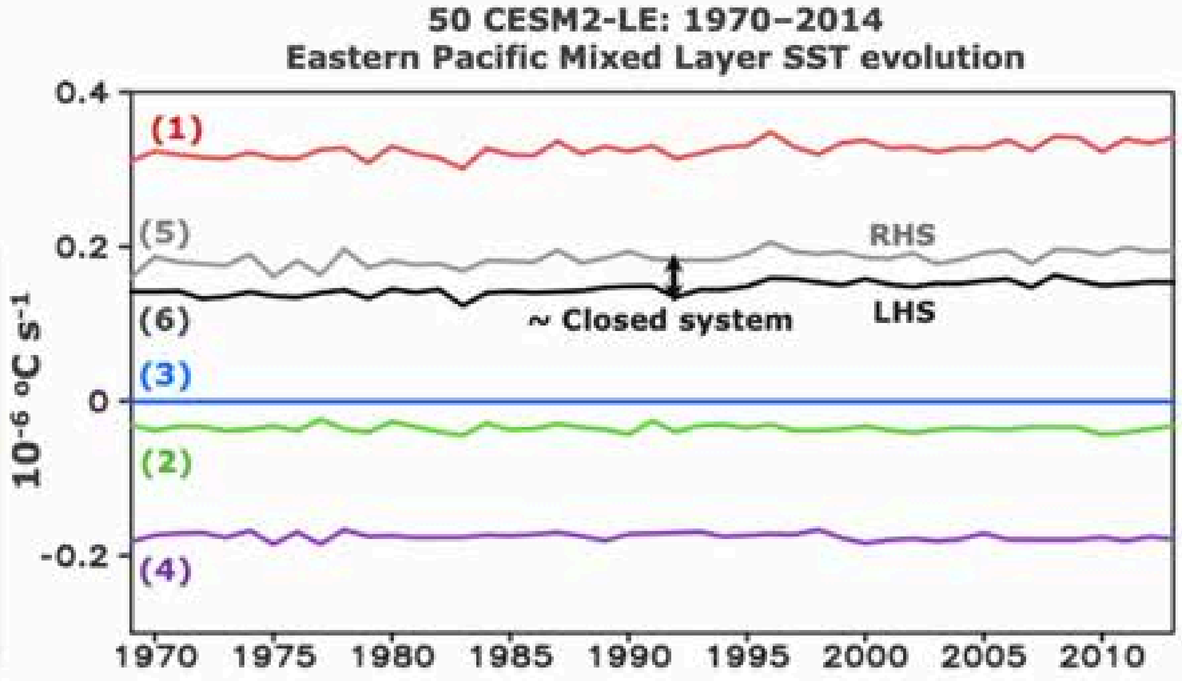
$$\frac{\partial T_m}{\partial t} = \frac{Q_{net} - q(-d_m)}{\rho_o c_p d_m} - u_m . \nabla T_m + \nabla^2 T_m - \frac{w_e \Delta T}{d_m}$$

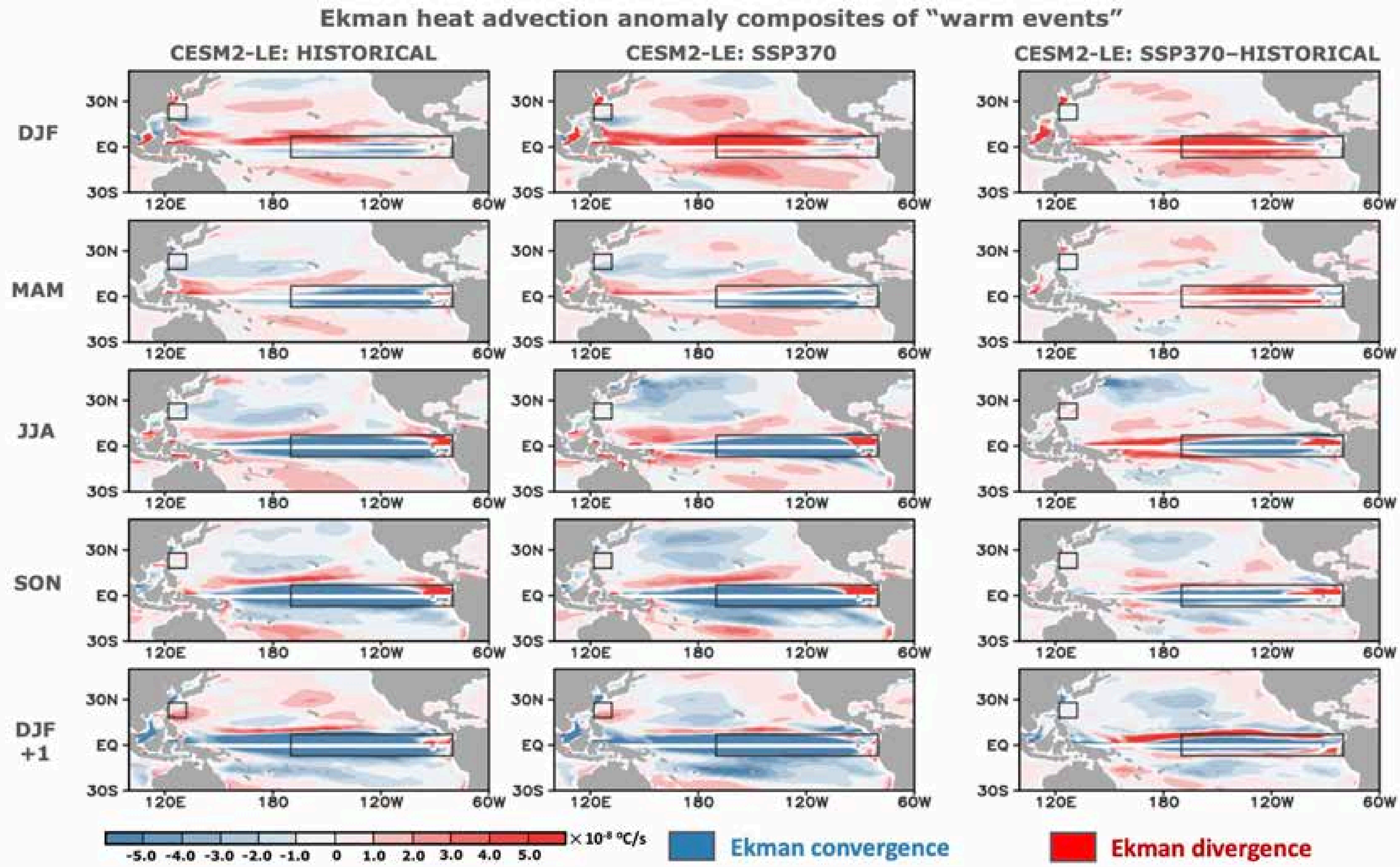
Temperature Tendency Term (6) | Air-Sea Heat Flux (1) | Advection (2) | Diffusion (3) | Entrainment (4)

Advection → Geostrophic + Ekman

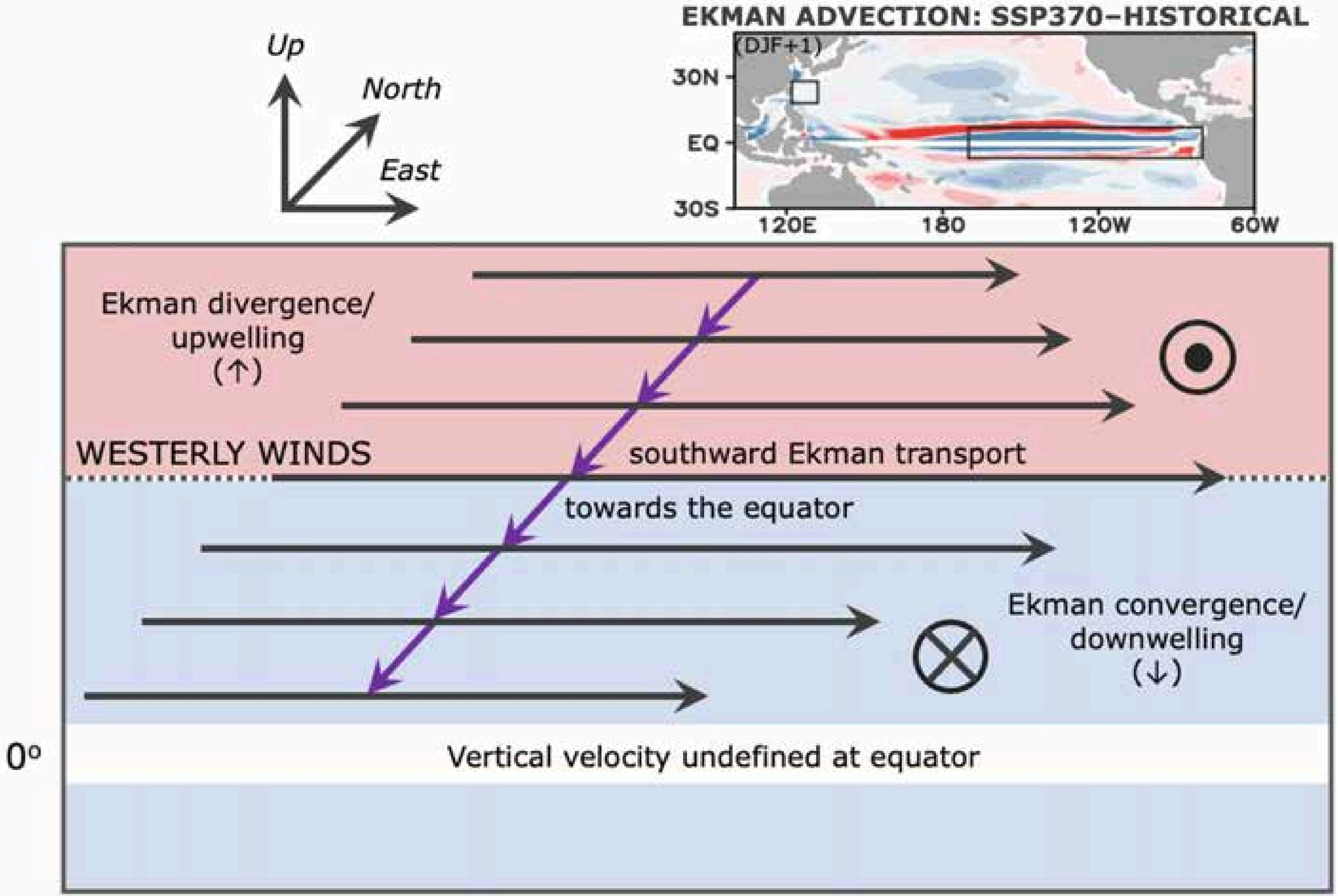
LHS (6) | RHS (5)

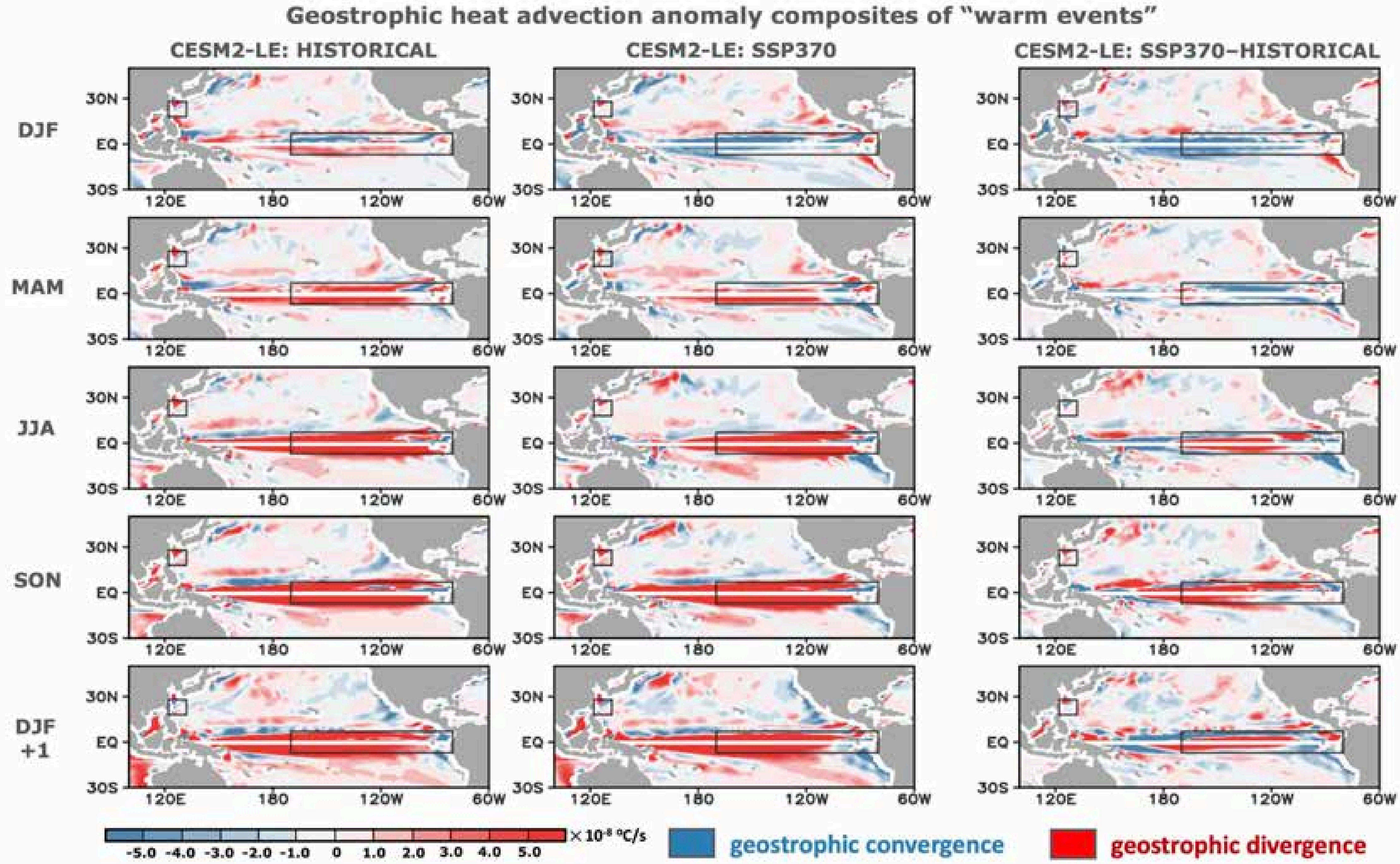




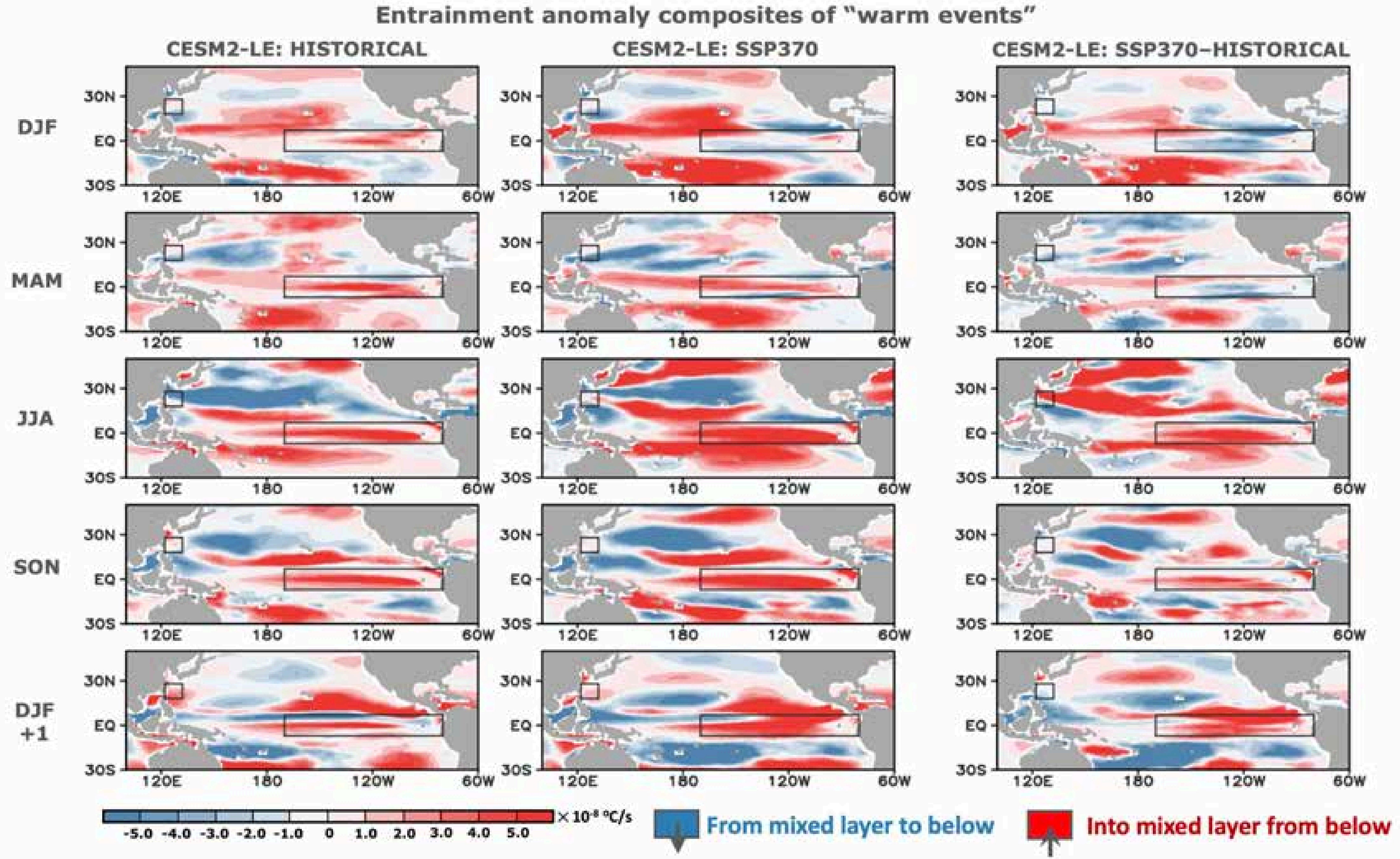


Ekman heat advection anomaly composites of "warm events"
CESM2-LE: HISTORICAL
CESM2-LE: SSP370
CESM2-LE: SSP370–HISTORICAL
DJF
MAM
JJA
SON
DJF +1
30N
EQ
30S
120E
180
120W
60W
-5.0 -4.0 -3.0 -2.0 -1.0 0 1.0 2.0 3.0 4.0 5.0
× 10⁻⁸ °C/s
Ekman convergence
Ekman divergence

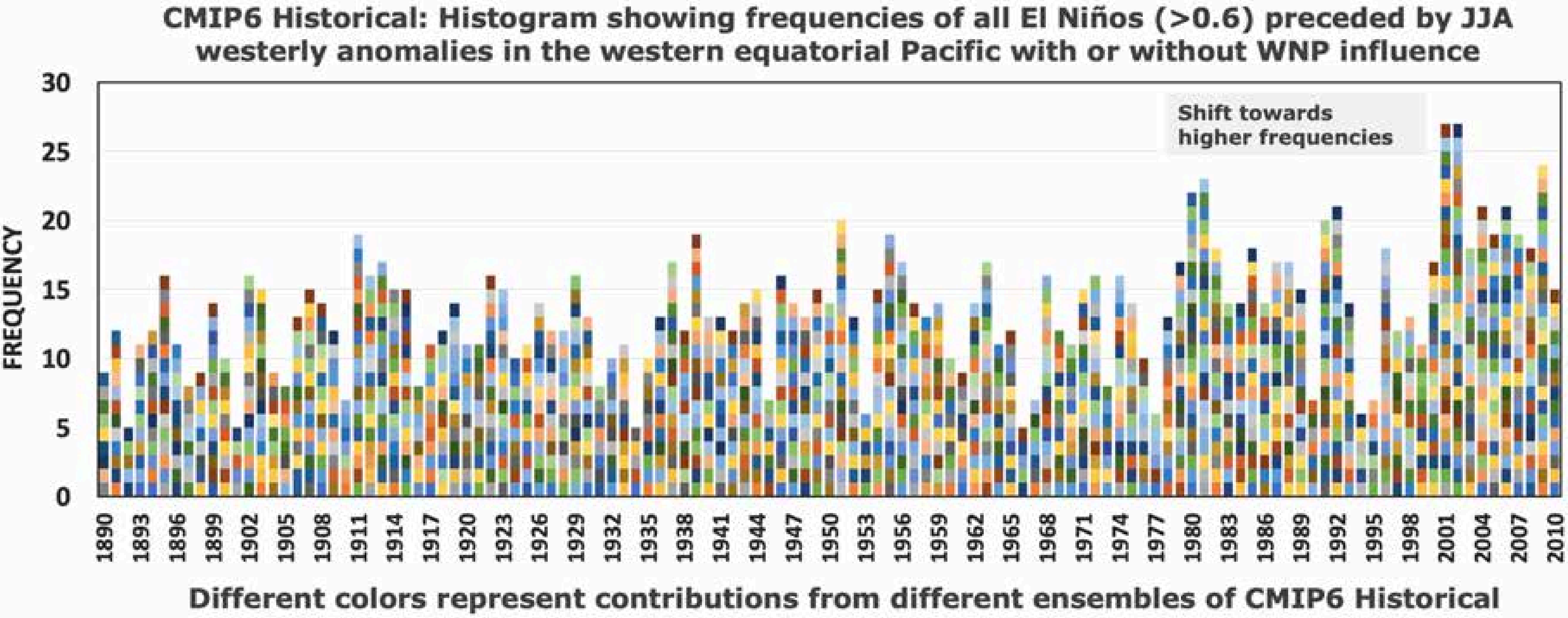

Up
North
East
EKMAN ADVECTION: SSP370–HISTORICAL
(DJF+1)
30N
EQ
30S
120E
180
120W
60W
Ekman divergence/
upwelling
(↑)
WESTERLY WINDS
southward Ekman transport
towards the equator
Ekman convergence/
downwelling
(↓)
0°
Vertical velocity undefined at equator

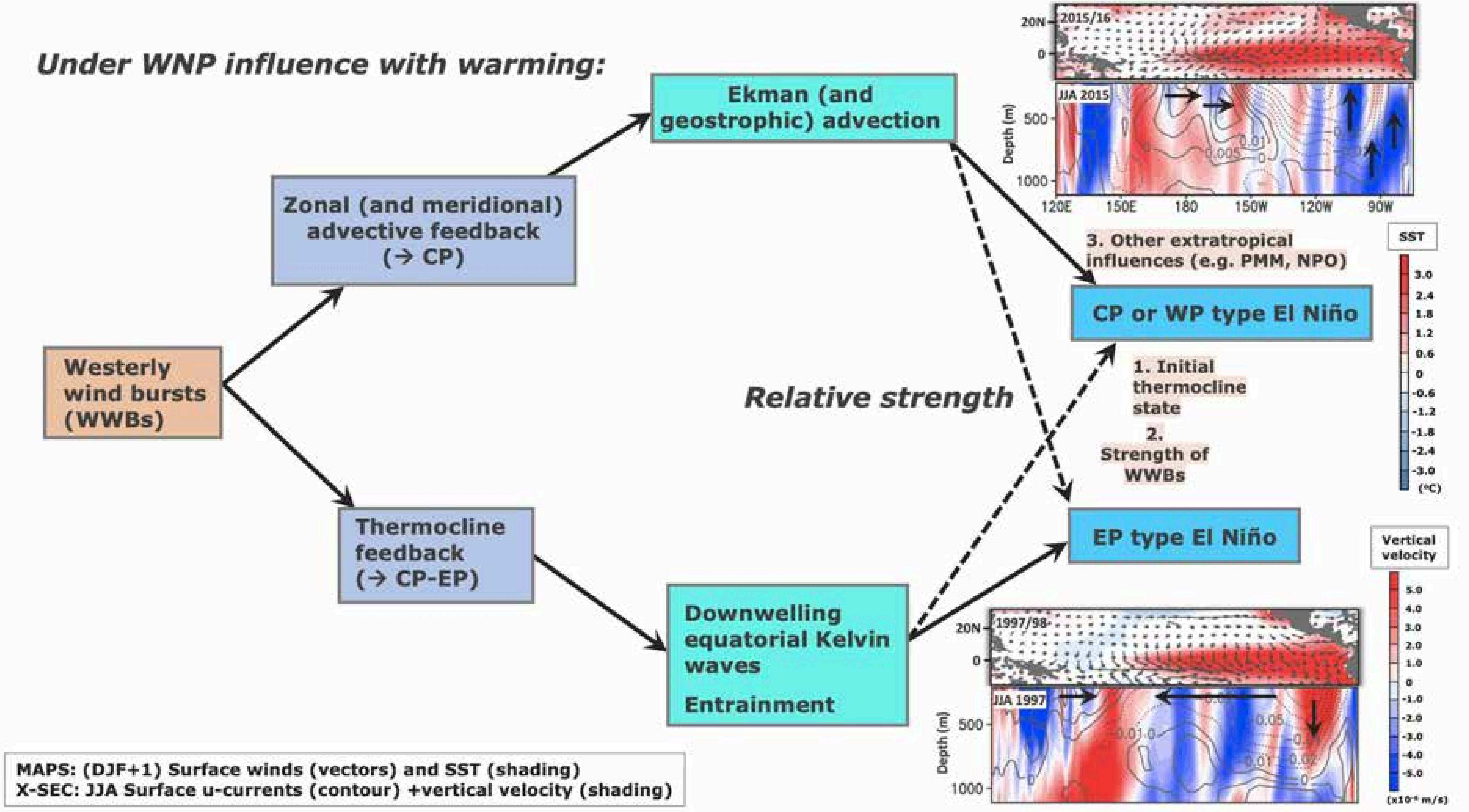


Geostrophic heat advection anomaly composites of "warm events"
CESM2-LE: HISTORICAL
CESM2-LE: SSP370
CESM2-LE: SSP370–HISTORICAL
DJF
MAM
JJA
SON
DJF +1
30N
EQ
30S
120E
180
120W
60W
-5.0 -4.0 -3.0 -2.0 -1.0 0 1.0 2.0 3.0 4.0 5.0
× 10⁻⁸ °C/s
geostrophic convergence
geostrophic divergence



Entrainment anomaly composites of "warm events"
CESM2-LE: HISTORICAL
CESM2-LE: SSP370
CESM2-LE: SSP370–HISTORICAL
DJF
MAM
JJA
SON
DJF +1
30N
EQ
30S
120E
180
120W
60W
-5.0 -4.0 -3.0 -2.0 -1.0 0 1.0 2.0 3.0 4.0 5.0
× 10⁻⁸ °C/s
From mixed layer to below
Into mixed layer from below


CMIP6 Historical: Histogram showing frequencies of all El Niños (>0.6) preceded by JJA westerly anomalies in the western equatorial Pacific with or without WNP influence
FREQUENCY
0
5
10
15
20
25
30
Shift towards higher frequencies
1890
1893
1896
1899
1902
1905
1908
1911
1914
1917
1920
1923
1926
1929
1932
1935
1938
1941
1944
1947
1950
1953
1956
1959
1962
1965
1968
1971
1974
1977
1980
1983
1986
1989
1992
1995
1998
2001
2004
2007
2010
Different colors represent contributions from different ensembles of CMIP6 Historical


Under WNP influence with warming:
Westerly wind bursts (WWBs)
Zonal (and meridional) advective feedback (→ CP)
Thermocline feedback (→ CP-EP)
Ekman (and geostrophic) advection
Downwelling equatorial Kelvin waves
Entrainment
Relative strength
3. Other extratropical influences (e.g. PMM, NPO)
CP or WP type El Niño
1. Initial thermocline state
2. Strength of WWBs
EP type El Niño
2015/16
JJA 2015
1997/98
JJA 1997
Depth (m)
120E
150E
180
150W
120W
90W
SST
(°C)
Vertical velocity
MAPS: (DJF+1) Surface winds (vectors) and SST (shading)
X-SEC: JJA Surface u-currents (contour) +vertical velocity (shading)

Conclusions

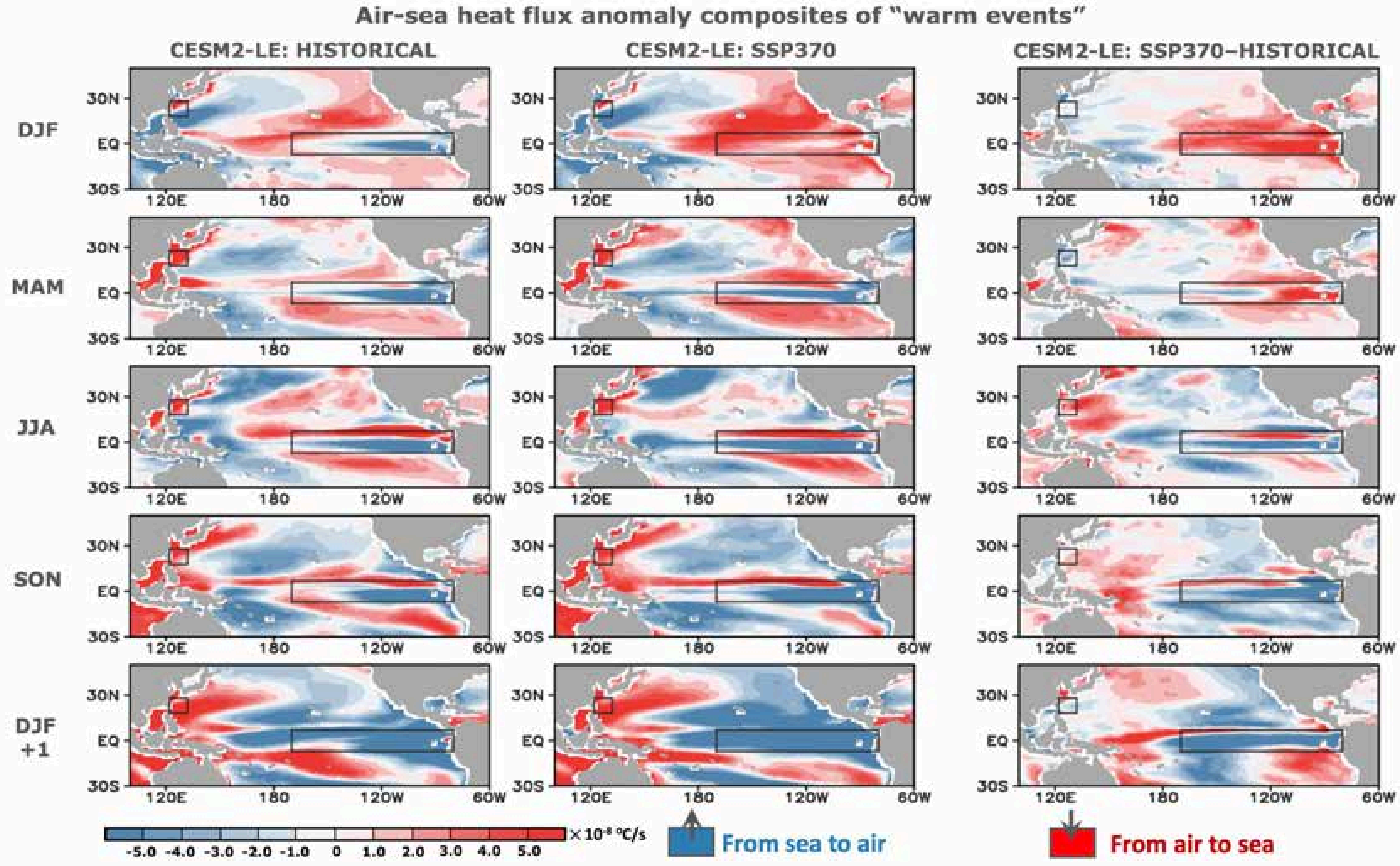
Under WNP influence with warming:

1. **Strengthened conditions leading up to an El Nino → Stronger amplitude and increased frequency of El Nino**

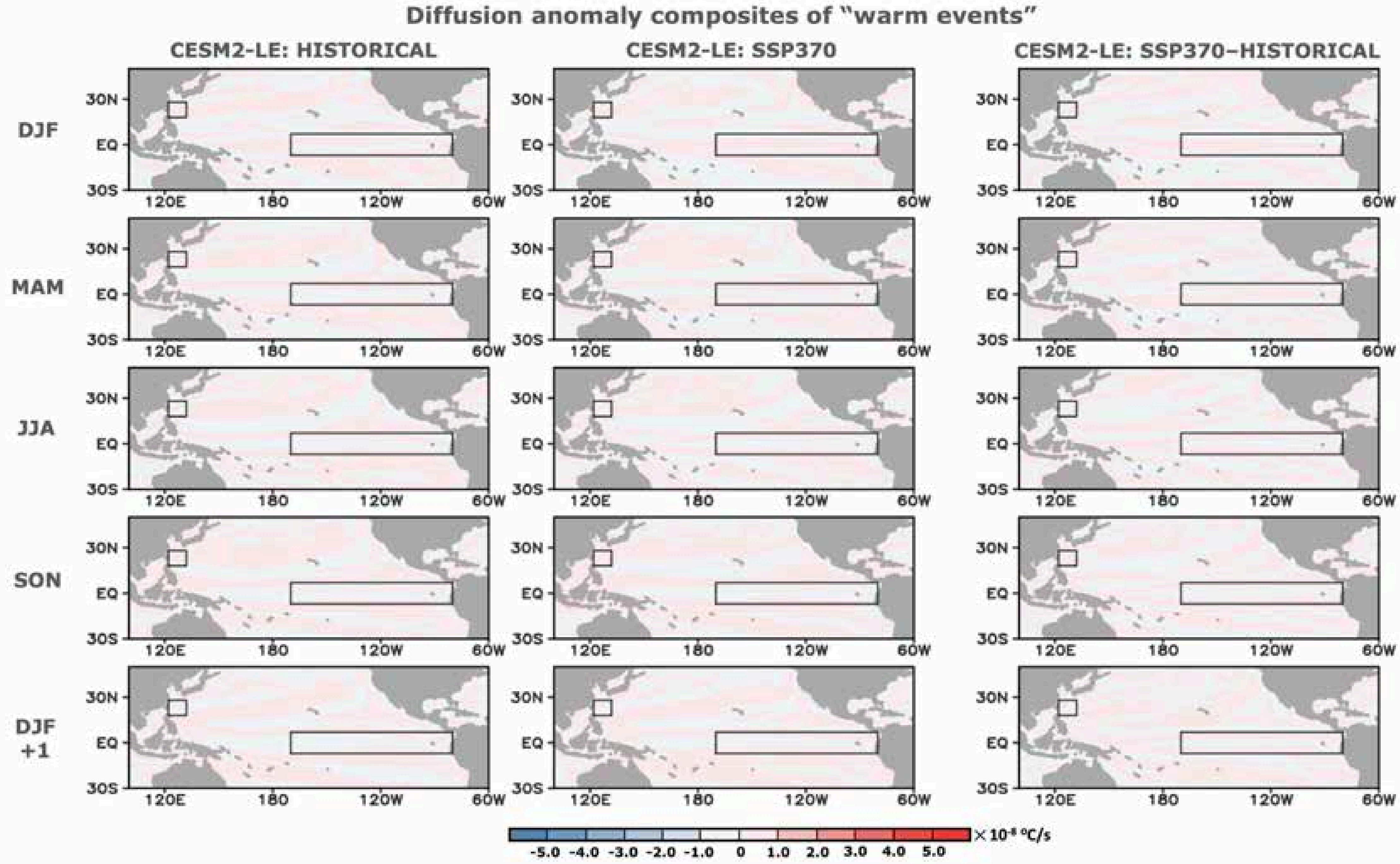
2. **Strengthened Ekman convergence (geostrophic divergence) in central Pacific promote advective feedback and positive entrainment anomalies from the central to eastern Pacific promote thermocline feedback**

3. **ENSO Diversity varies depending on the *relative strength* of advective feedback vs. thermocline feedback**
    - **Initial thermocline state**
    - **Strength of westerly anomalies**
    - **Other extratropical influence (PMM)**

Supplementary Materials



Air-sea heat flux anomaly composites of "warm events"
CESM2-LE: HISTORICAL
CESM2-LE: SSP370
CESM2-LE: SSP370–HISTORICAL
DJF
MAM
JJA
SON
DJF +1
30N
EQ
30S
120E
180
120W
60W
-5.0 -4.0 -3.0 -2.0 -1.0 0 1.0 2.0 3.0 4.0 5.0
× 10⁻⁸ °C/s
From sea to air
From air to sea



Diffusion anomaly composites of "warm events"
CESM2-LE: HISTORICAL
CESM2-LE: SSP370
CESM2-LE: SSP370–HISTORICAL
DJF
MAM
JJA
SON
DJF +1
30N
EQ
30S
120E
180
120W
60W
-5.0 -4.0 -3.0 -2.0 -1.0 0 1.0 2.0 3.0 4.0 5.0
× 10⁻⁸ °C/s