Improved predictions for ENSO diversities using a nonlinear forcing singular vector assimilation

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- 3. Prediction for ENSO diversities
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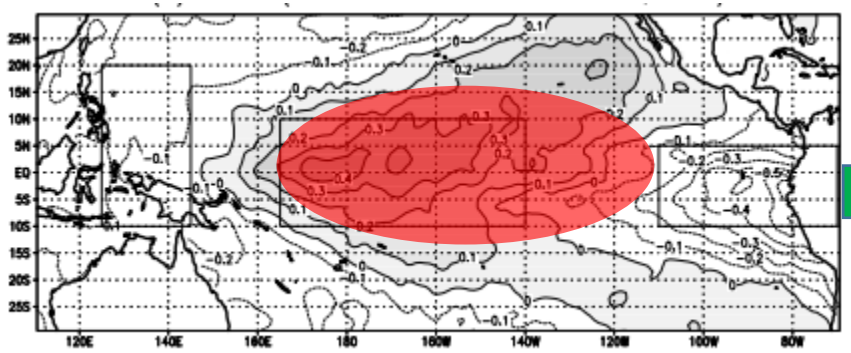
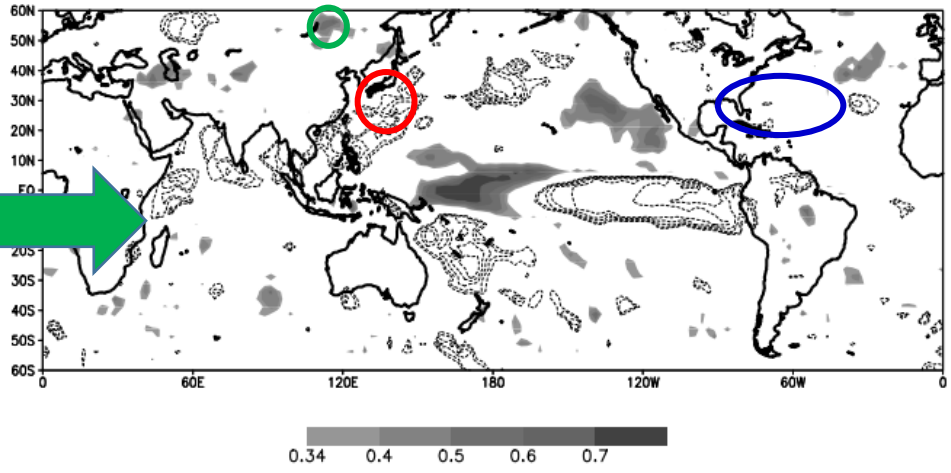
1. Motivation

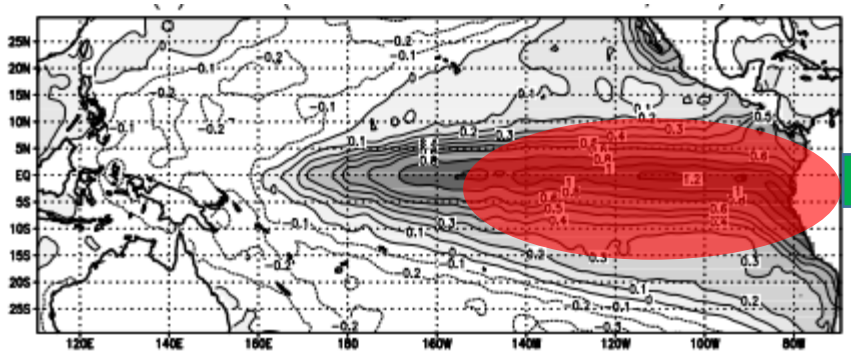
CP El Niño

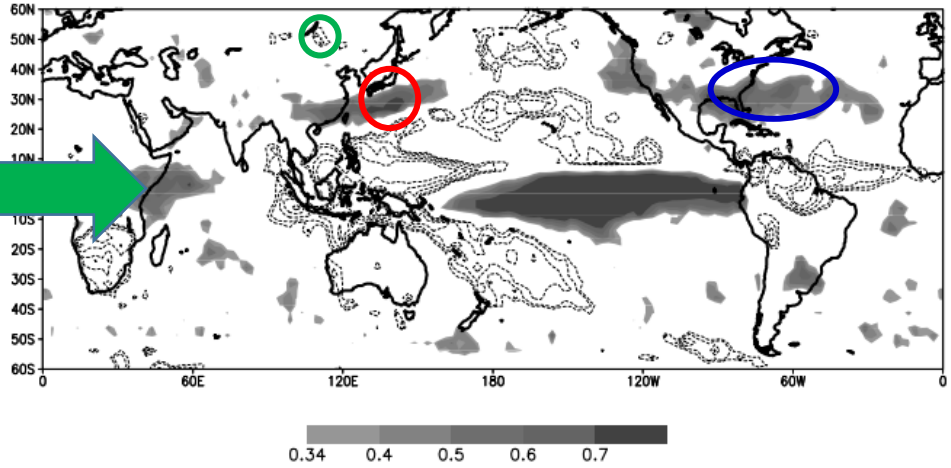




(b)

EP El Niño

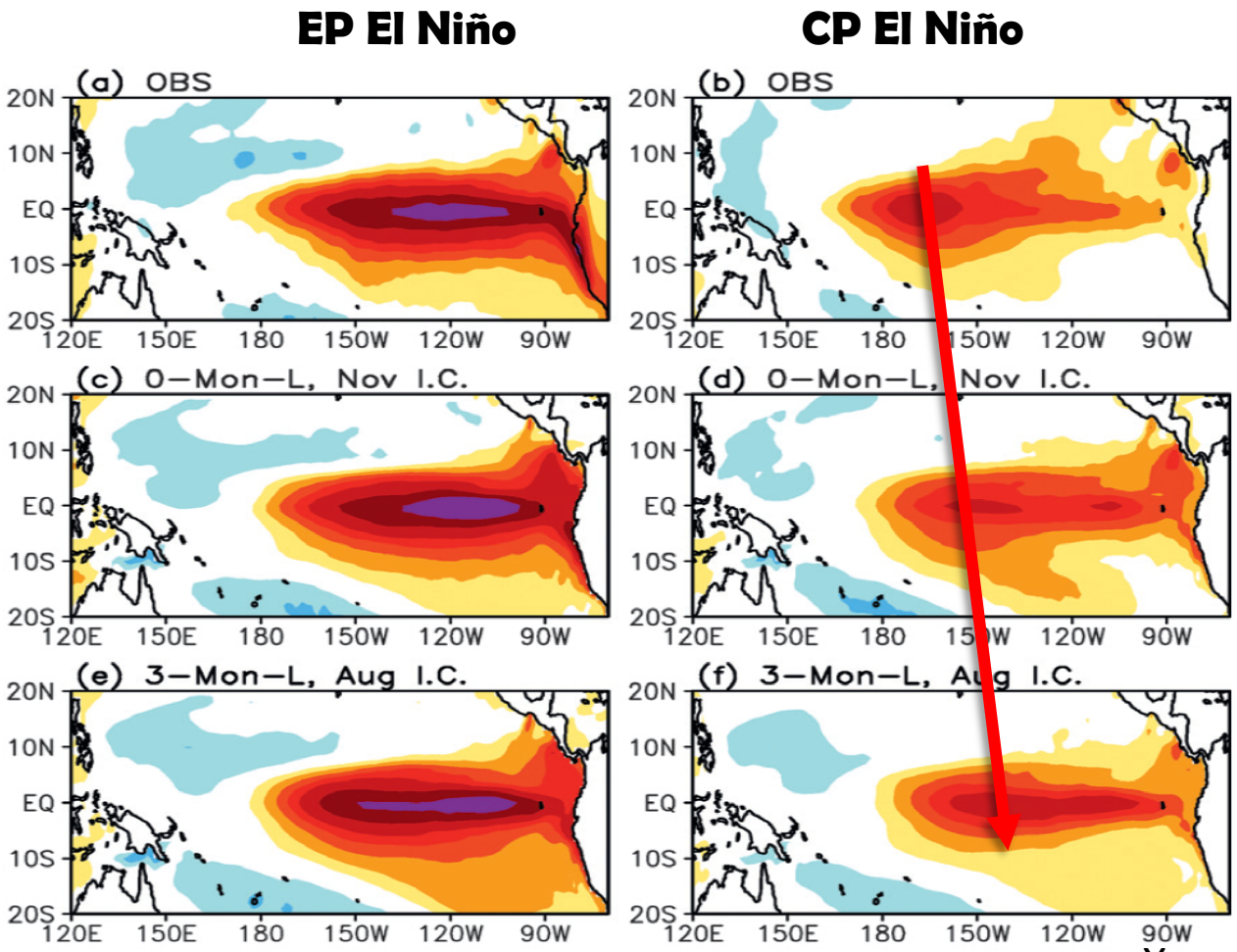




Ashork et al., *JGR*, 2007

- **The CP- and EP-El Nino induced climate effects are different and even opposite somewhere**

1. Motivation



Xue et al., 2013, JC

- **Most models can only distinguish/predict two types of El Niño at 3-month lead time even 1-month in some models** (e.g., Hendon et al., 2009; Jeong et al.,2012; Yang and Jiang, 2014; Zheng and Yu, 2017; Ren et al., 2017)

To improve the prediction skills regarding to ENSO diversities…

To improve the initial conditions

- More observations
- EnKF
- 4D-Var
- Hybrid data assimilation, e.g., 4DEnVar

BUT…

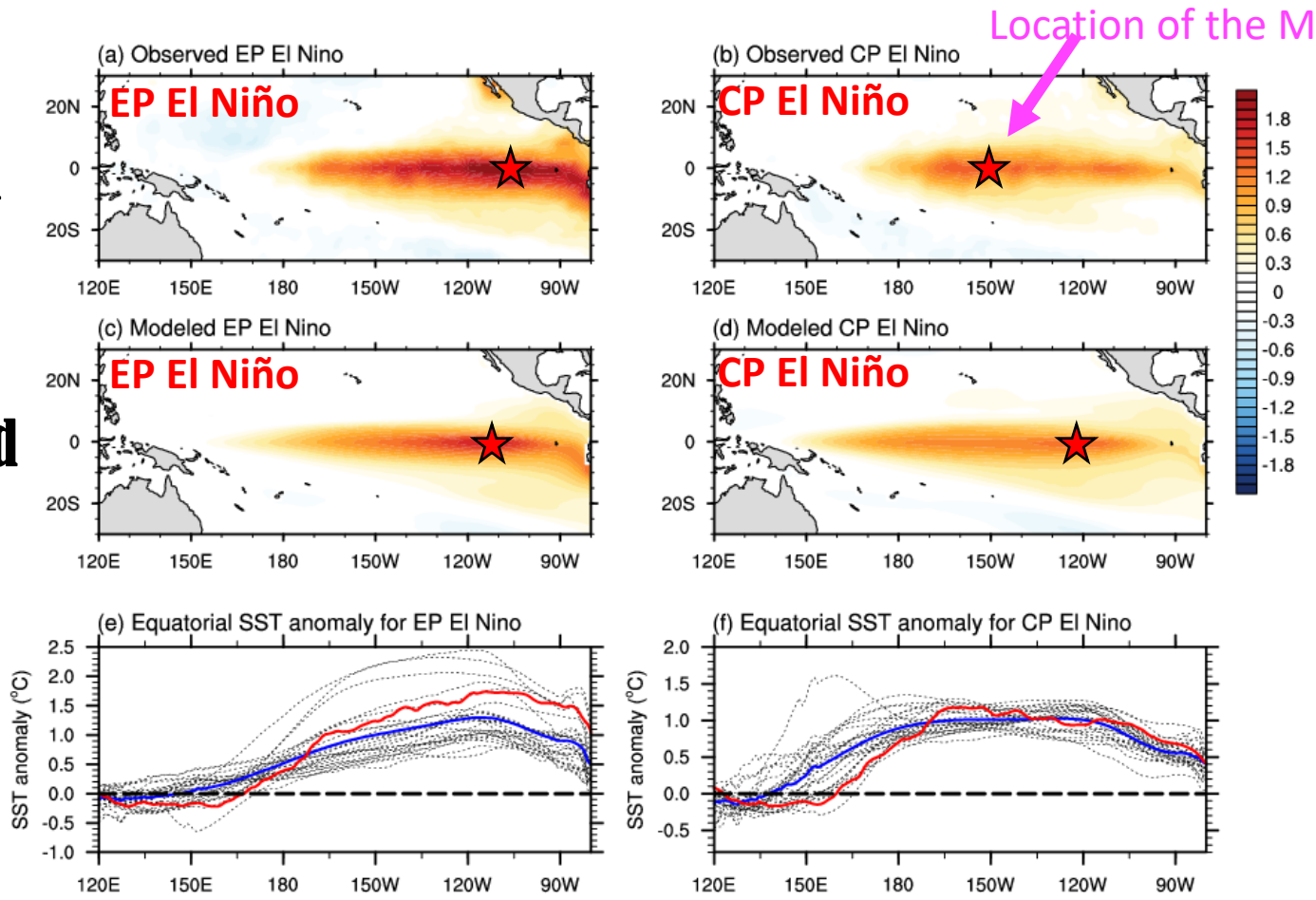
- The persistent barrier for EP El Niño is larger than CP El Niño (Zhang et al., 2014; Ren et al., 2016)
- Initial error-induced error growth during CP El Niño prediction is less than during EP El Niño prediction (Tian and Duan, 2016).

The CP El Niño is not as sensitive to initial condition as EP El Niño

1. Motivation

Observed

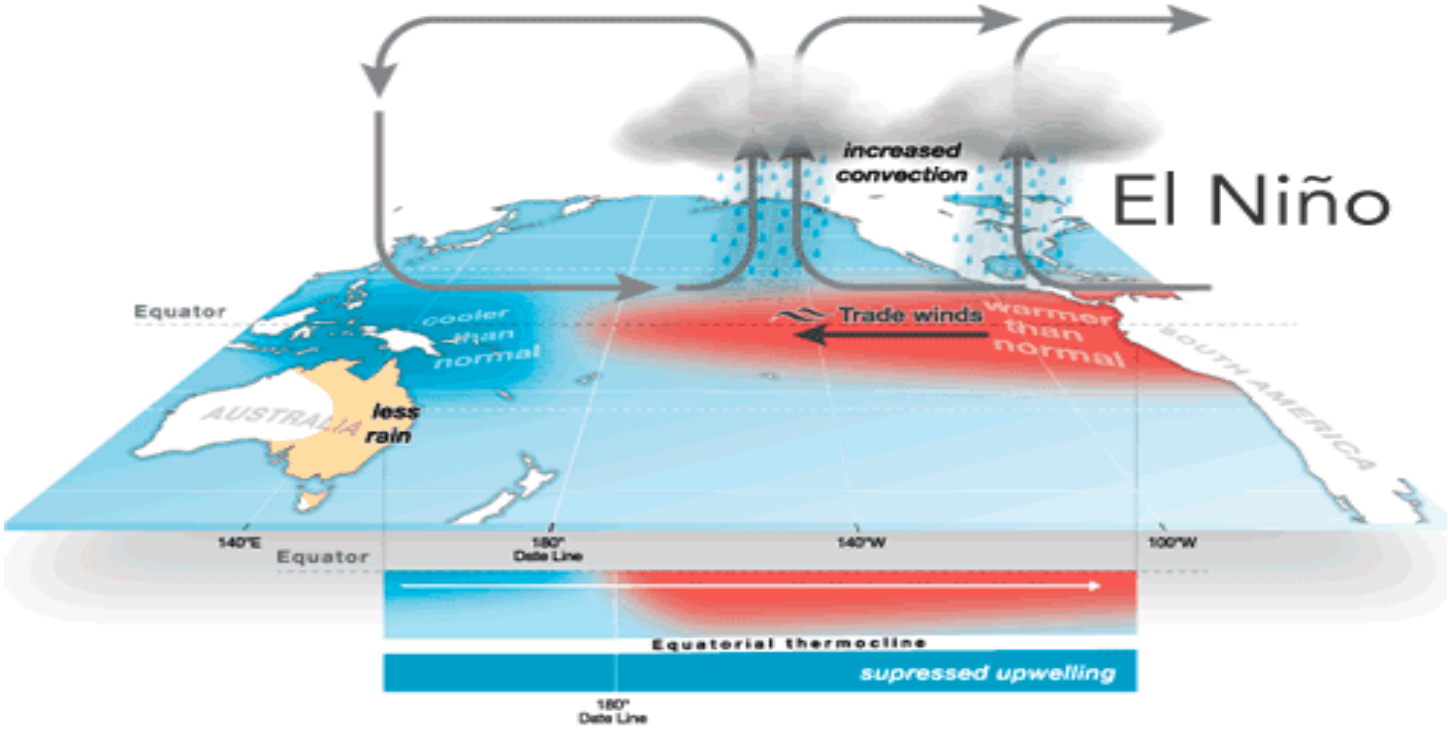
Simulated



- **CMIP3 and CMIP5 models still have large bias in CP El Niño simulation** (e.g., Kug et al., 2010; Yu and Kim, 2011; Ham and Kug, 2002; Capotondi, 2013; Ham and Kug, 2012; Taschetto et al., 2014, Xu et al., 2017)
- **Improving model will effectively improve the CP El Niño prediction**

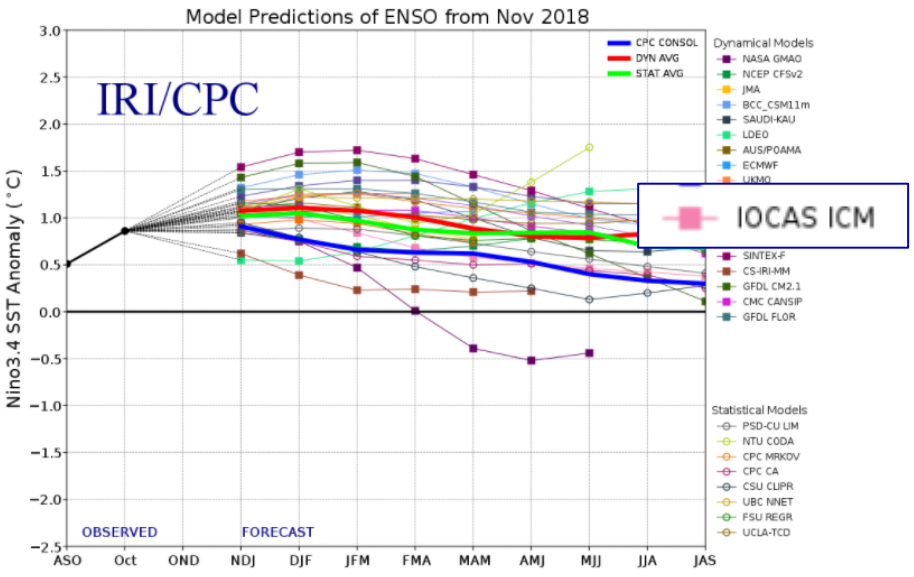
1. Motivation

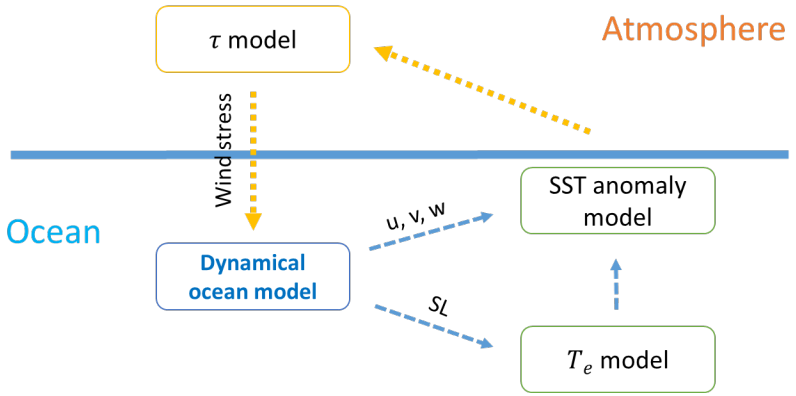
Source of model errors



- Air-sea coupling
- Convection and cloud
- Ocean mixing
- Extra-tropical forcing
- Subgrid scale parameterization
- ...

2.1 IOCAS ICM





ICM (Zhang et al., 2003; Zheng et al., 2010)

Simplified or missing processes in the ICM

- Air-sea heat interaction
- The stochastic atmospheric forcing (i.e., MJO)
- The fresh water flux (FWF) and salinity
- Tropical instability waves (TIW)
- Subtropical-tropical teleconnection
- Interaction between multi oceanic basins
- Ocean ecological/biological feedback

Model uncertainties are complicated and diverse

- **How to give a comprehensive consideration to model errors and correct the model?**
  - **Nonlinear forcing singular vector-assimilation (Duan et al., 2014)**

2.2 NFSV-assimilation

Control prediction

Forecast model:

$$\begin{cases} \dfrac{\partial \mathbf{u}}{\partial t} = \mathbf{F}(\mathbf{u}, t) \\ \mathbf{u}\big|_{t=0} = \mathbf{u}_0 \end{cases}$$

Prediction:

$$\mathbf{u}(\mathbf{x}, \tau) = \mathbf{M}_\tau(\mathbf{u}_0)$$

Prediction error:

$$E = \sum_{t=t_0}^{\tau} \left\| \mathbf{u}^p(\mathbf{x}, t) - \mathbf{u}^{obs}(\mathbf{x}, t) \right\| \gg \varepsilon$$

NFSV-assimilation

Duan et al., 2014, *Clim Dyn*

Forecast model with forcing vector $\mathbf{f}$:

$$\begin{cases} \dfrac{\partial \mathbf{u}}{\partial t} = \mathbf{F}(\mathbf{u}, t) + \mathbf{f}(\mathbf{x}, t) \\ \mathbf{u}\big|_{t=0} = \mathbf{u}_0 \end{cases}$$

Prediction:

$$\mathbf{u}(\mathbf{x}, \tau) = \mathbf{M}_\tau(\mathbf{f}_\tau)(\mathbf{u}_0)$$

Prediction error:

$$E(\mathbf{f}_t^*) = \min \sum_{t=t_0}^{\tau} \left\| \boldsymbol{M}_t(\mathbf{f}_t, \mathbf{u}_0) - \mathbf{u}^{obs}(\mathbf{x}, t) \right\| \approx 0$$

$\mathbf{f}_t^*$ **is the NFSV-tendency error, which represents the combined effect of kinds of model errors**

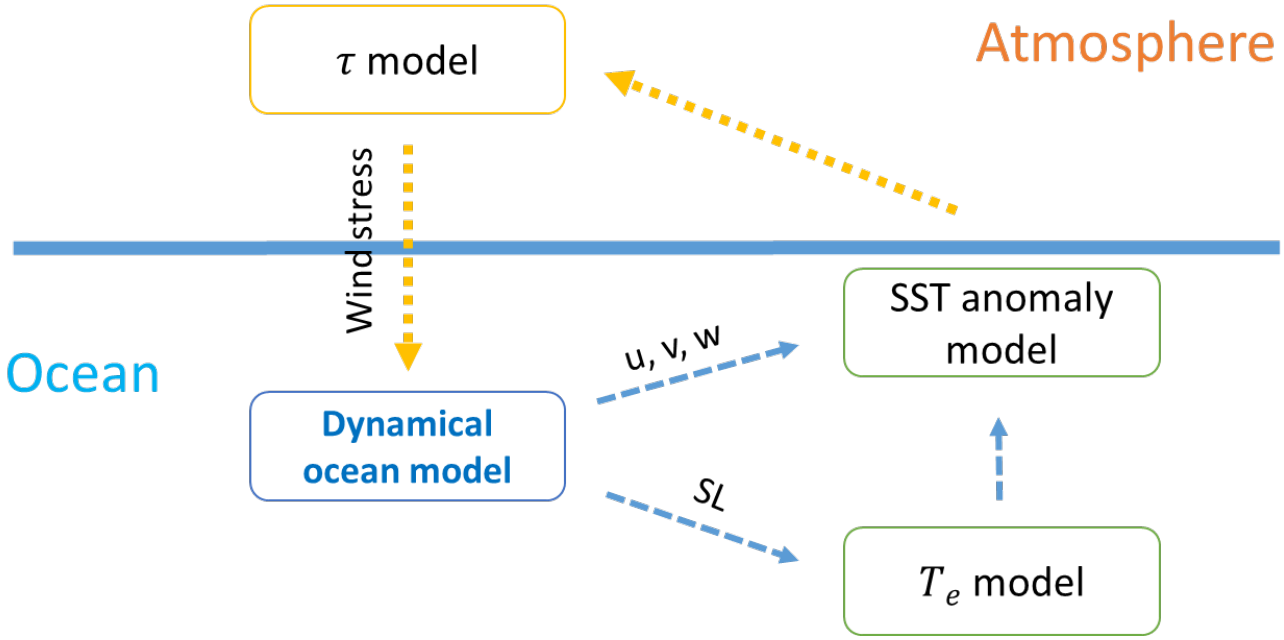
2.2 NFSV-assimilation

$$E\left(\mathbf{f}_t^*\right) = \min \sum_{t=t_0}^{\tau} \left\| \boldsymbol{M}_t\left(\mathbf{f}_t, \mathbf{u}_0\right) - \mathbf{u}^{obs}\left(\mathbf{x}, t\right) \right\|$$

- **SST data: ERSSTv3b (1854 - now)**

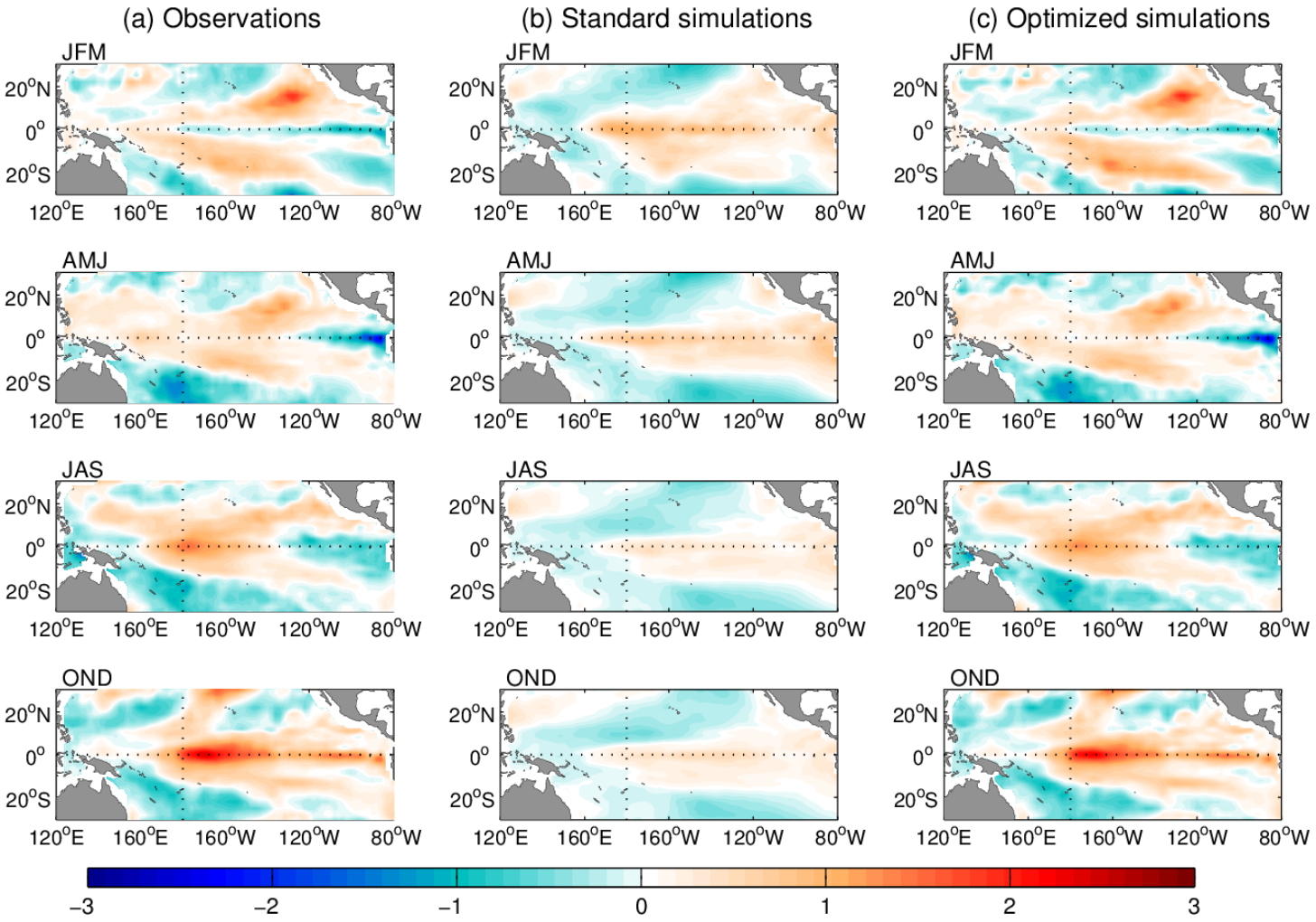
SST model

$$\frac{\partial T}{\partial t} = G(T, u, v, h, p) + \mathbf{F}$$

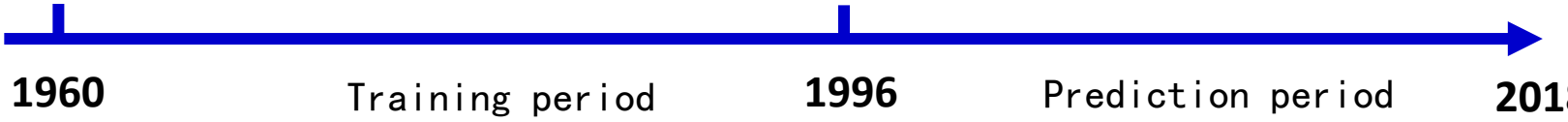


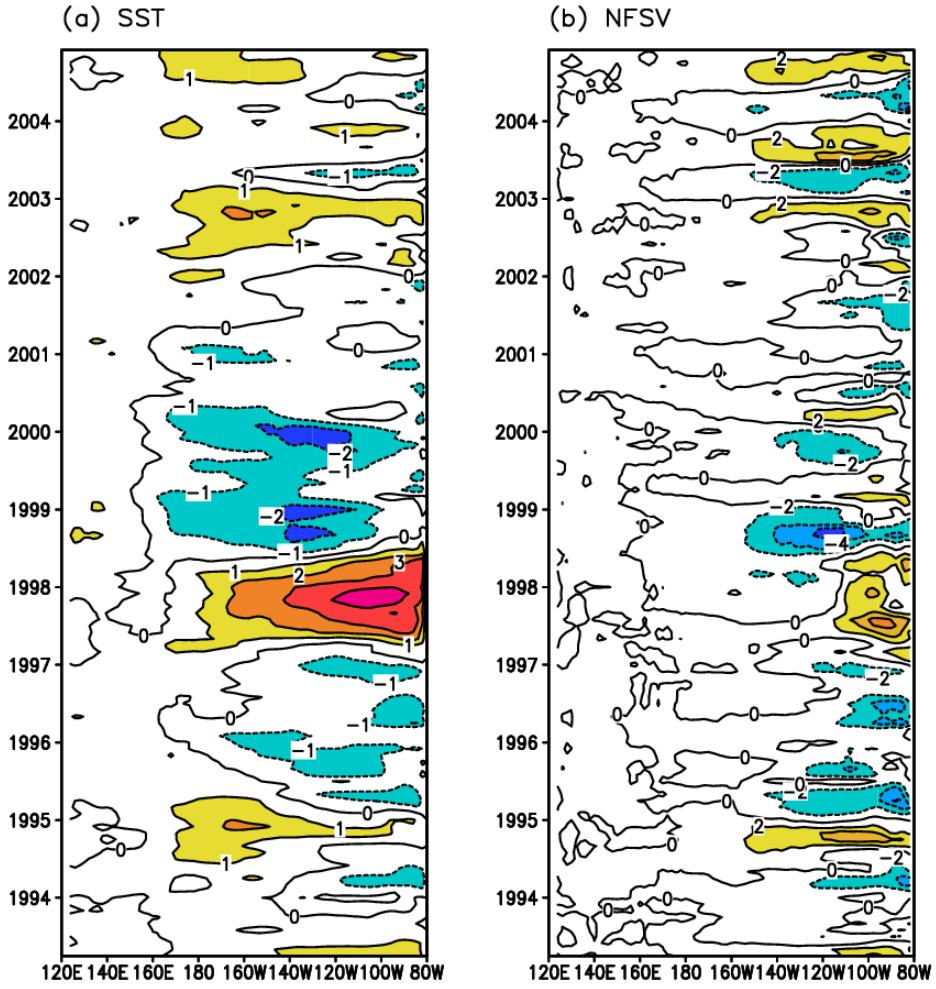
2.2 NFSV-assimilation: ENSO simulation

CP El Niño: 1994/1995



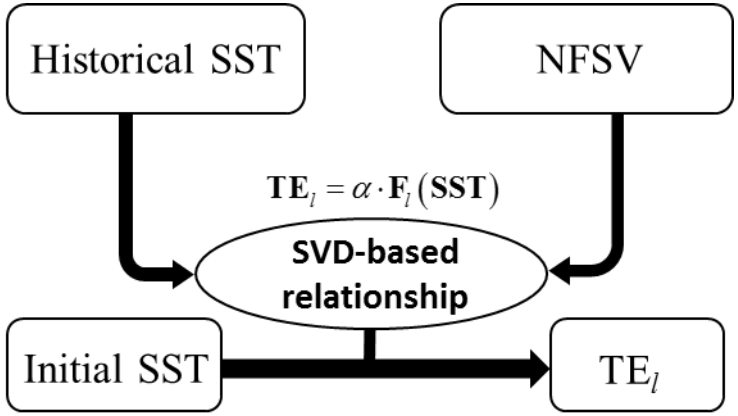
2.3 NFSV-tendency error forecast model





$$E\left(\mathbf{f}_t^*\right)=\min\sum_{t=t_0}^{\tau}\left\|\boldsymbol{M}_t\left(\mathbf{f}_t,\mathbf{u}_0\right)-\mathbf{u}^{obs}\left(\mathbf{x},t\right)\right\|$$

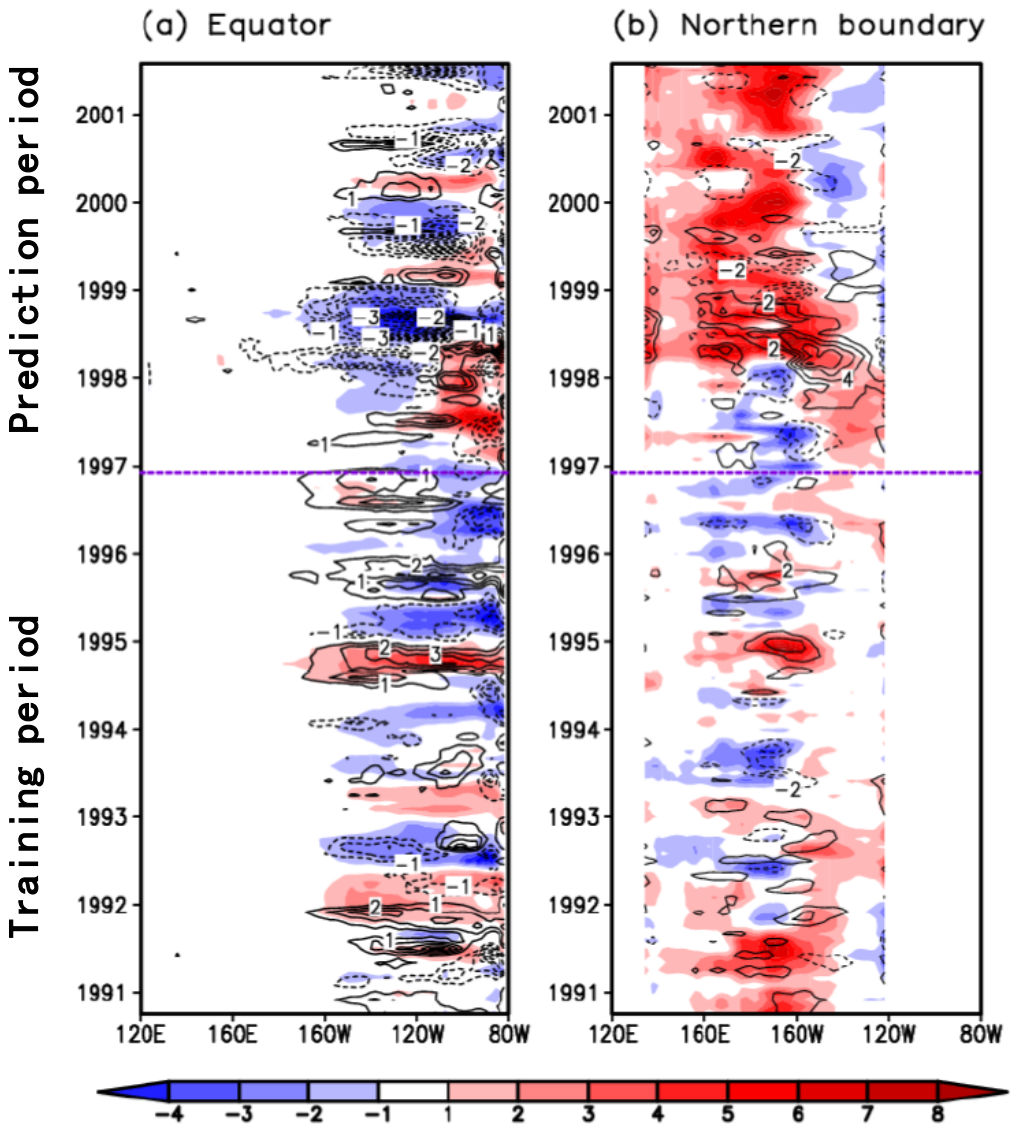
- **SST data:** **ERSSTv3b (1854 - now)**
- **Training period:** **1960-1996**
- **Relationship:** **SST-NFSV**



NFSV-tendency error forecast model

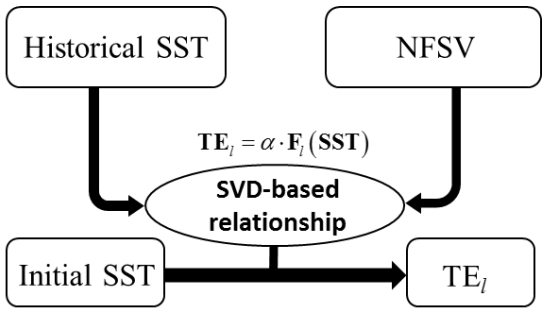
2.4 NFSV-ICM

Estimated NFSV-error at 6-month lead time



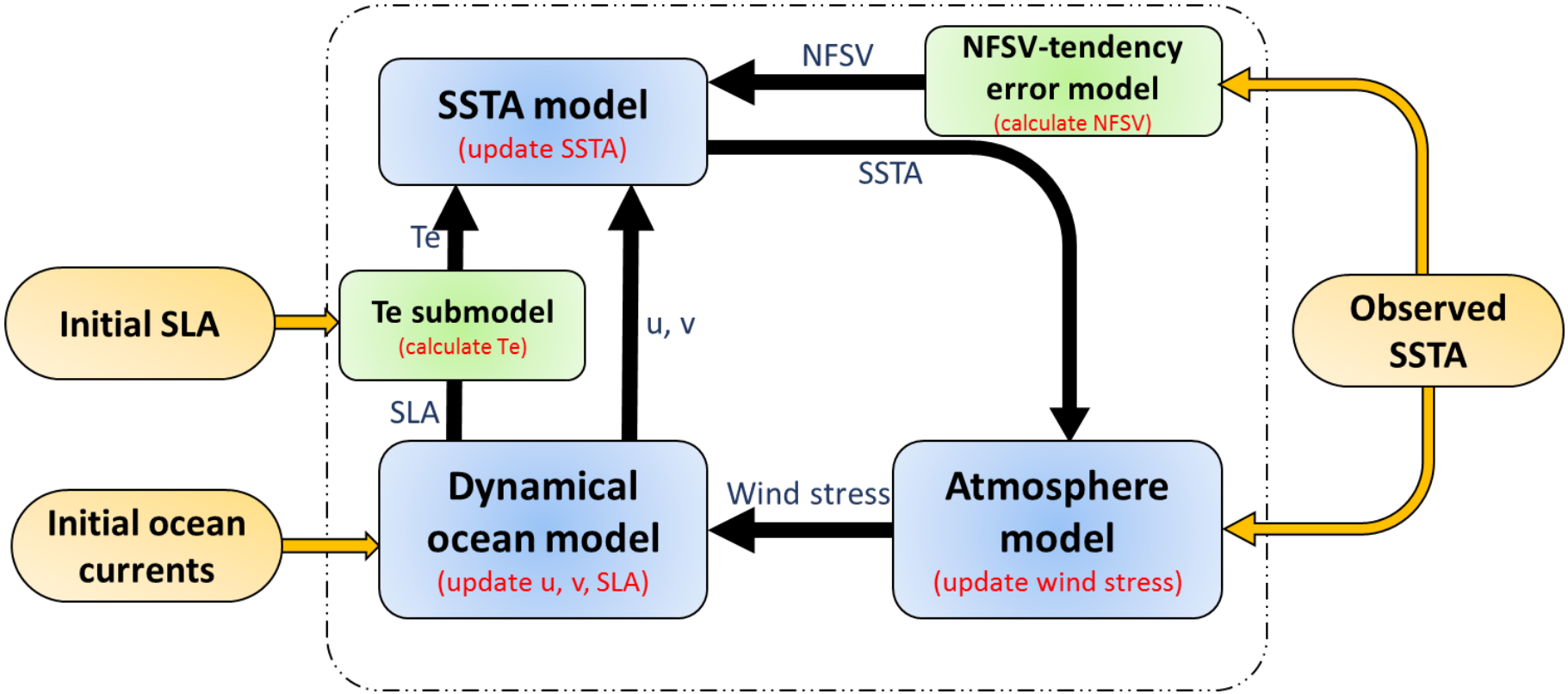
Shaded: NFSV-tendency error determined by the NFSV-assimilation

Contours: NFSV-tendency error determined by the constructed error model



Error forecast model

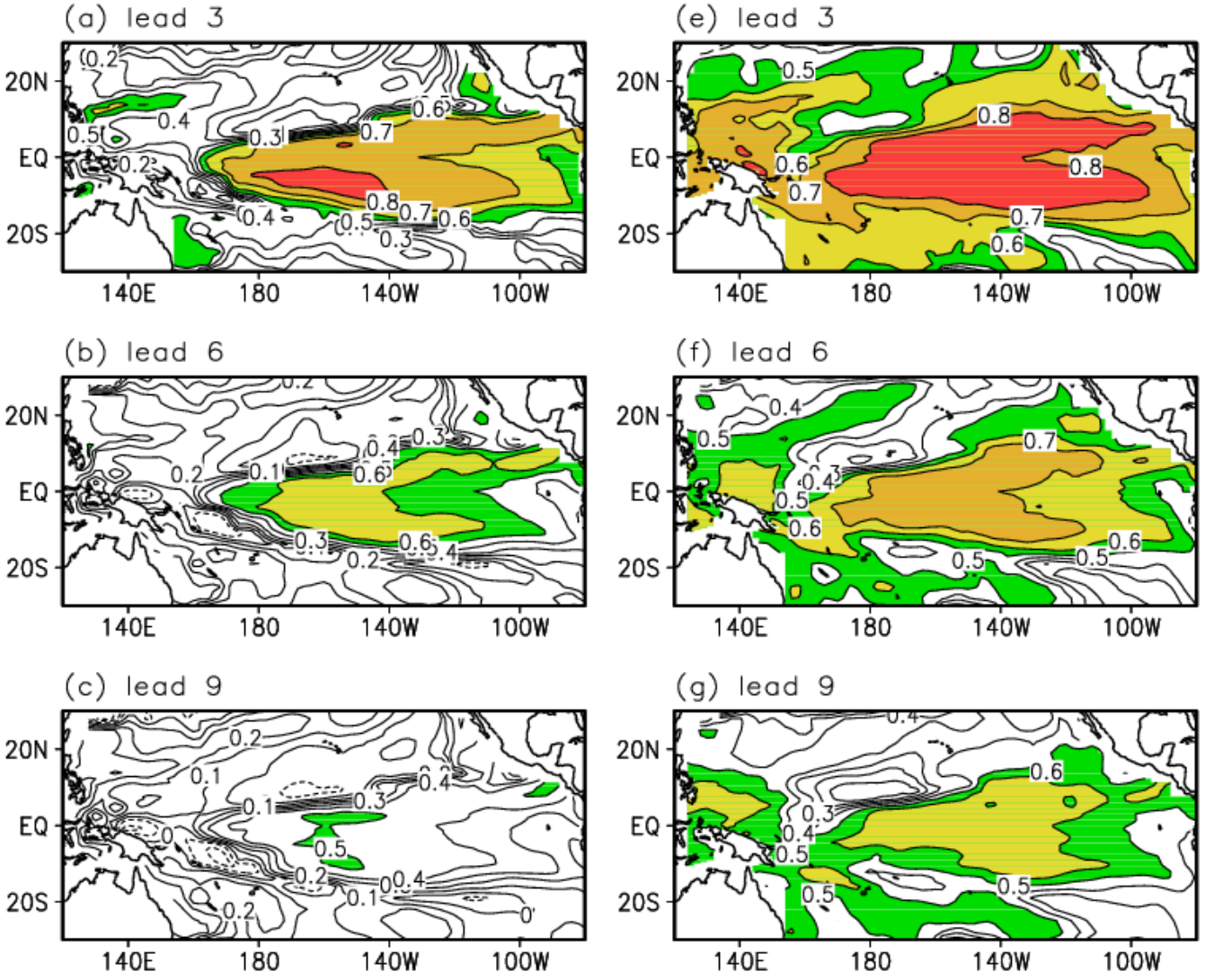
2.4 NFSV-ICM



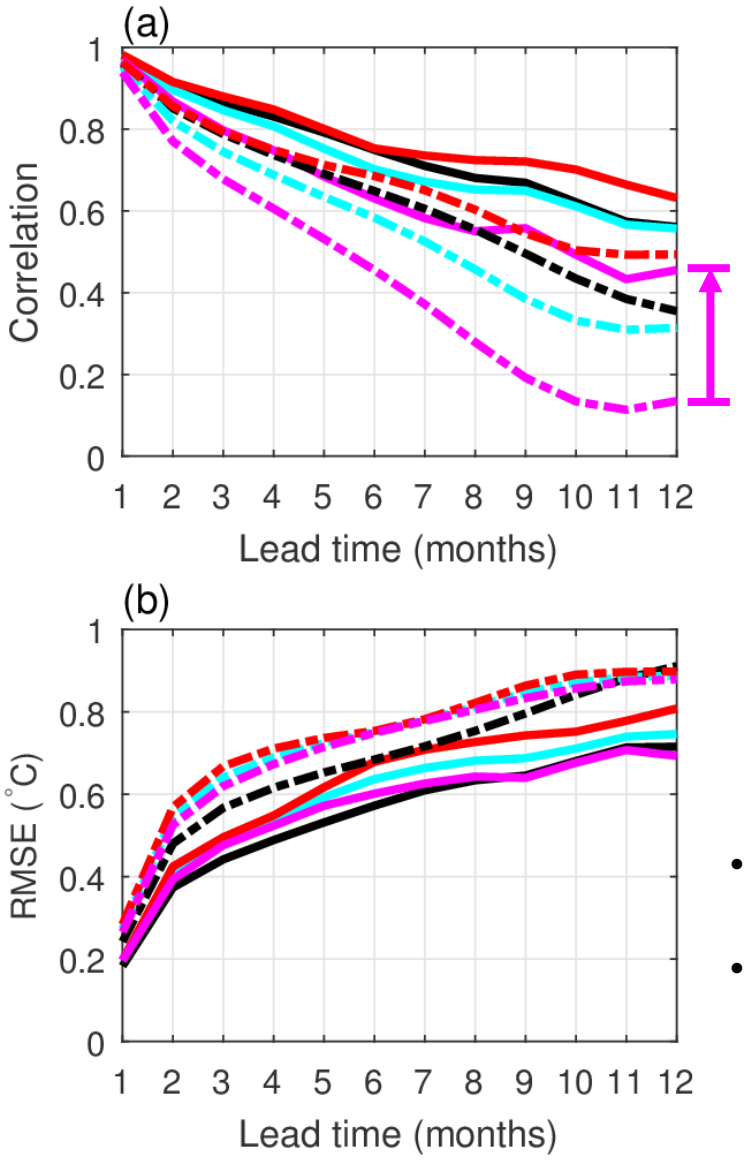
A new ENSO forecast system (NFSV-ICM)

3.1 Mean prediction skill

ICM **NFSV-ICM**



3.2 ENSO diversity predictions



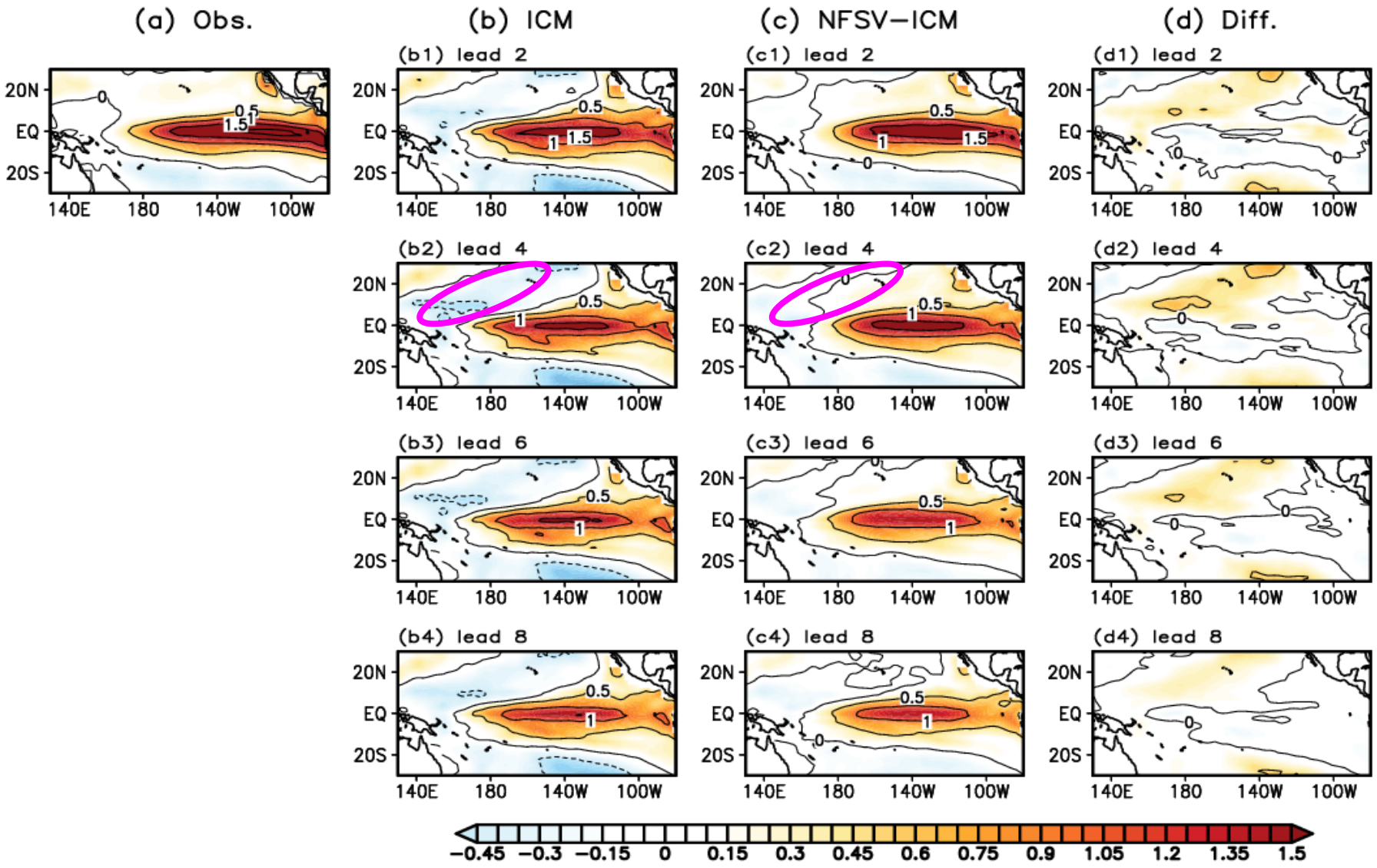
NFSV-ICM: 1960-2016
NFSV-ICM: All ENSO events
NFSV-ICM: EP events
NFSV-ICM: CP events
ICM: 1960-2016
ICM: All ENSO events
ICM: EP events
ICM: CP events

SSTA: 7 months => 10 months
ENSO: 5 months => 10 months
EP ENSO: 8 months => 12 months
CP ENSO: 4 months => 7 months

- The prediction skills for ENSO-related SSTA is significantly improved.
- The improvement of ENSO prediction skills **is attributed to the high performance for the CP ENSO**: lower RMSE and higher correlation coefficient

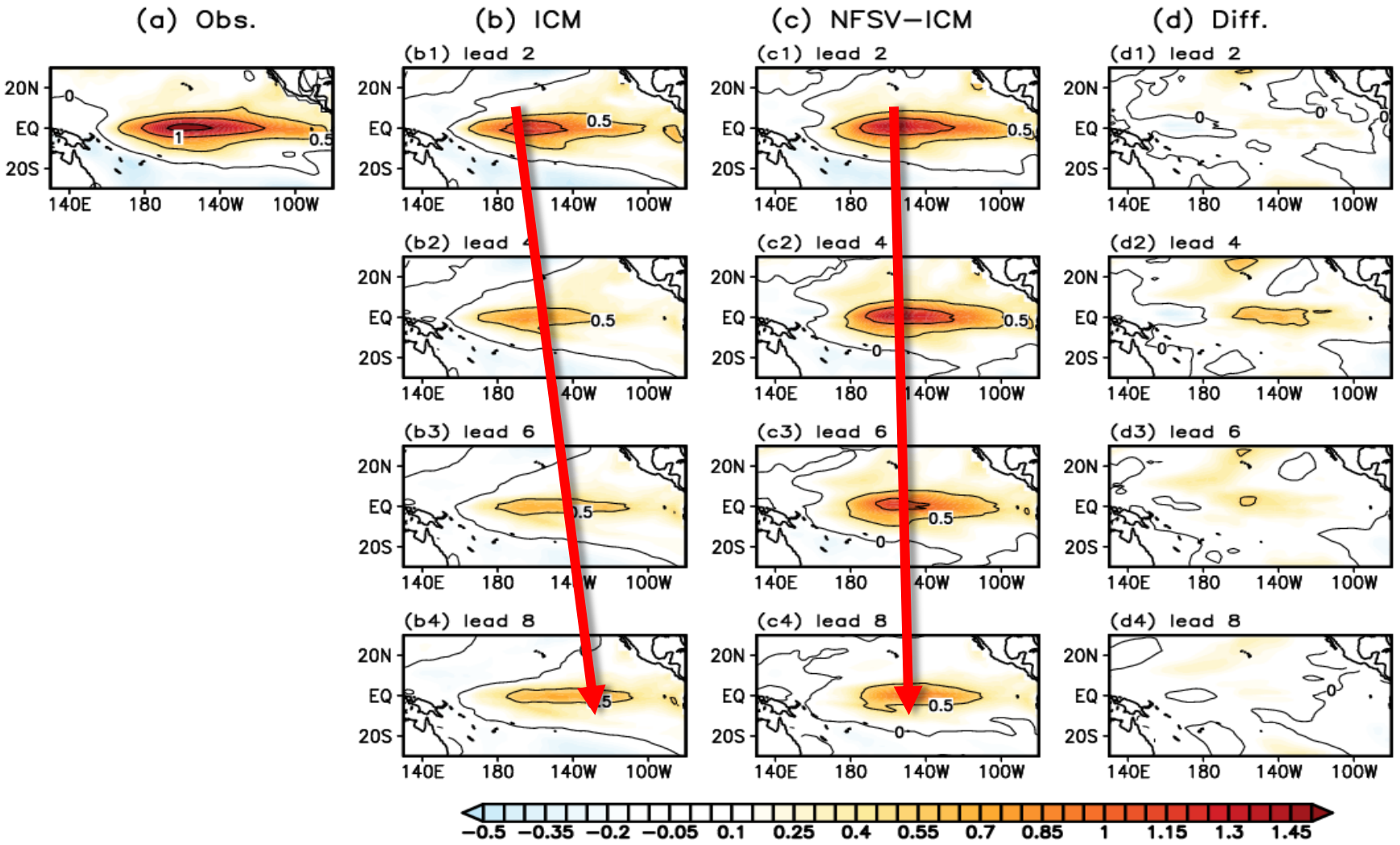
3.2 ENSO diversity predictions

Composite EP El Niño event

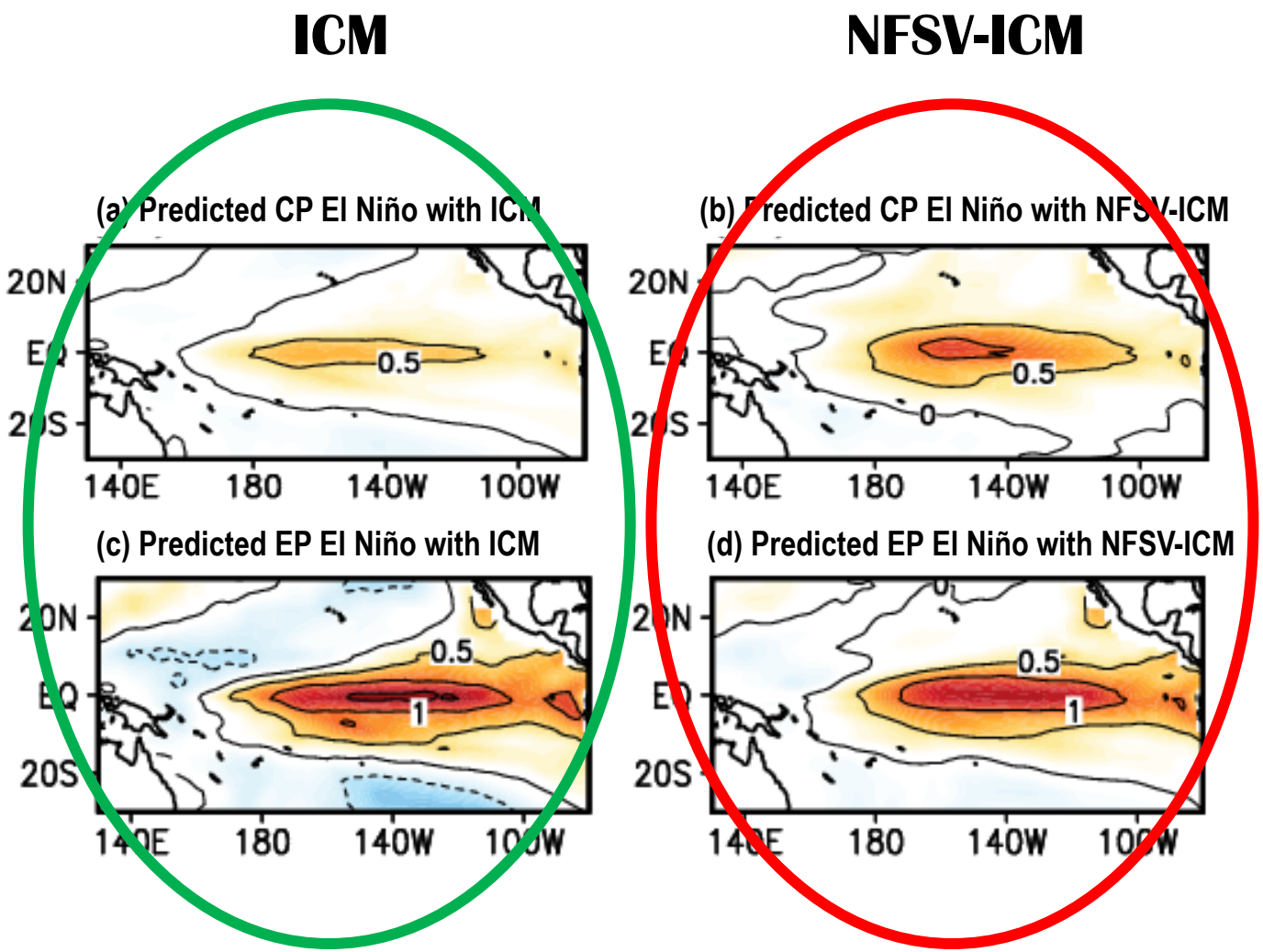


3.2 ENSO diversity predictions

Composite CP El Niño event



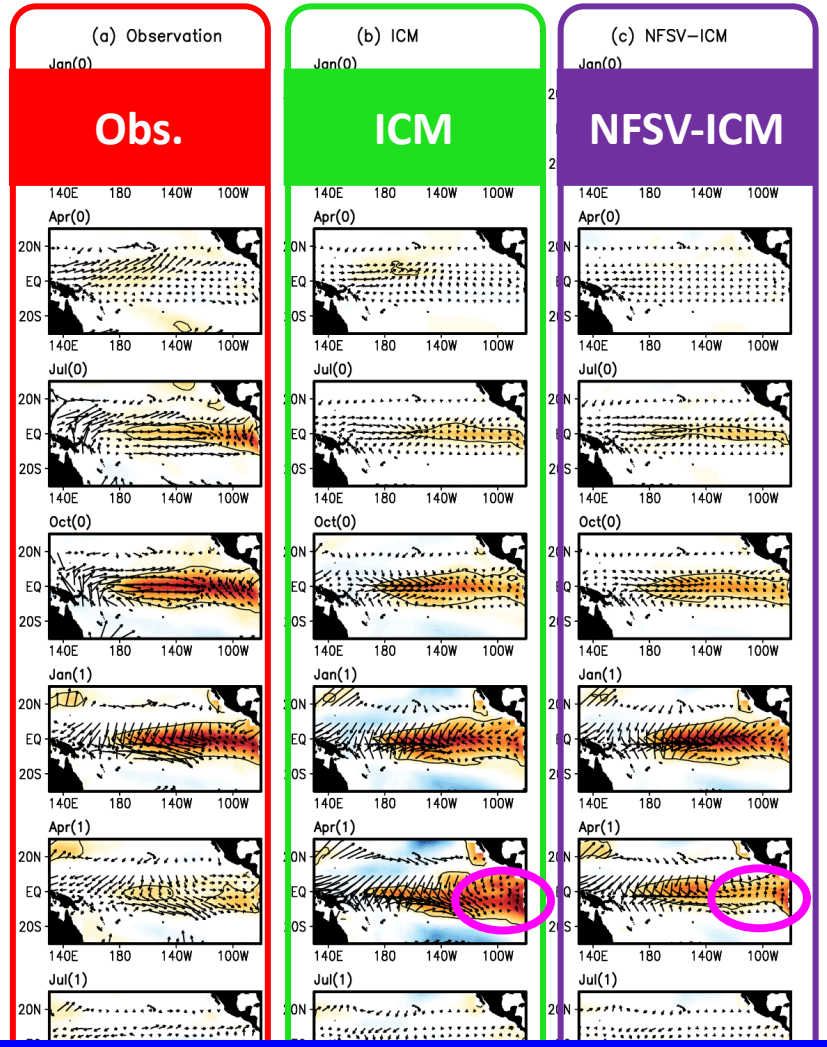
3.2 ENSO diversity predictions



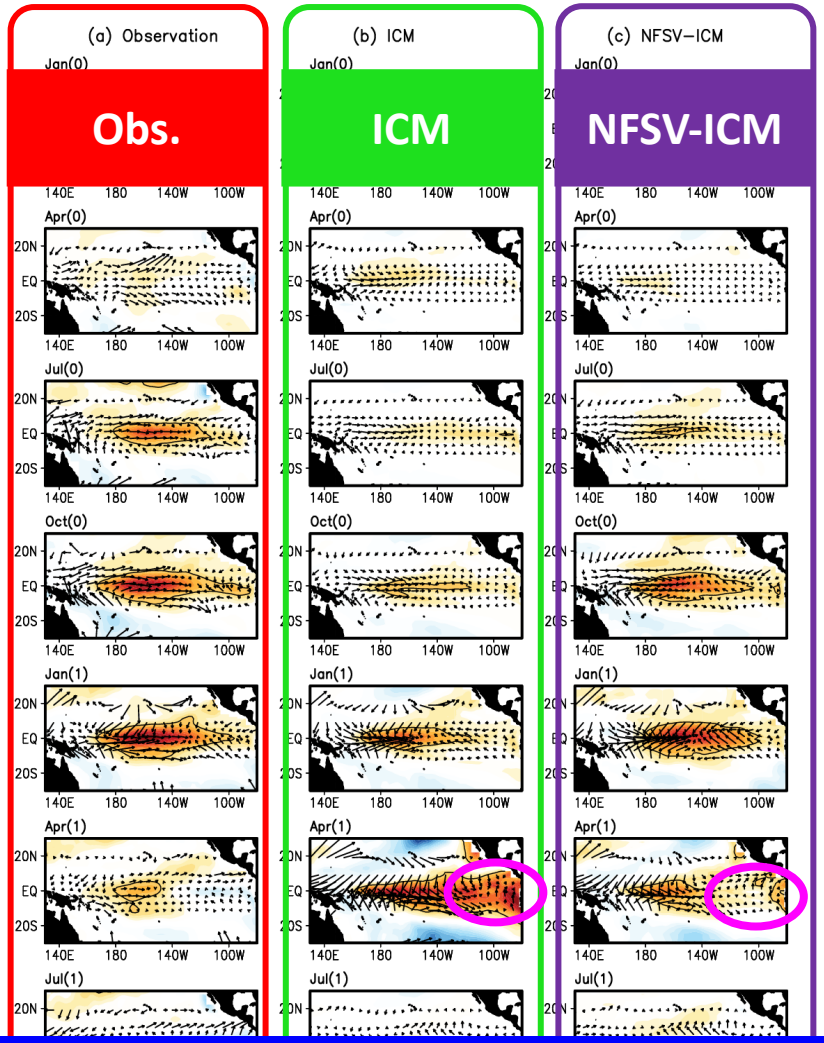
- Prediction of the major differences in pattern of SSTA between two types of El Niño is extended to larger than 2-season lead time.

3.2 ENSO diversity predictions

EP El Niño



CP El Niño

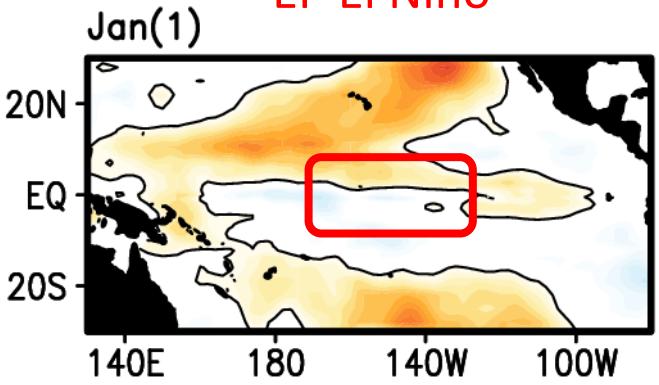


- NFSV-ICM can not only improve the identification to the El Niño diversities but also their evolutions

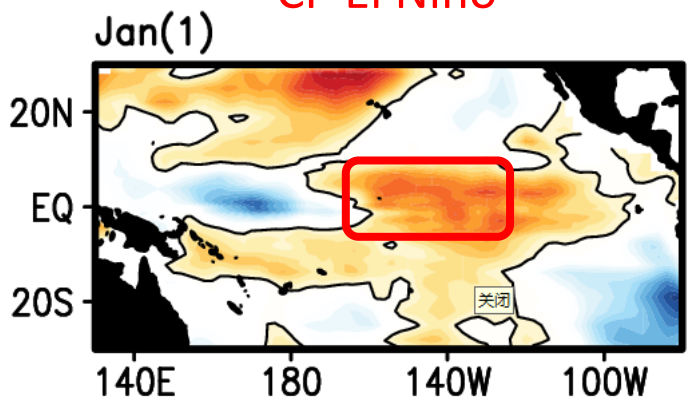
4. Dynamics of NFSV-tendency error: CP El Niño

NFSV-tendency perturbation effect on SST predictions

EP El Niño



CP El Niño



$$\frac{\partial T'}{\partial \mathrm{t}} = -u'\frac{\partial \overline{T}}{\partial x} - \overline{u}\frac{\partial T'}{\partial y} - u'\frac{\partial T'}{\partial y}$$

Zonal advection terms

$$-v'\frac{\partial \overline{T}}{\partial y} - \overline{v}\frac{\partial T'}{\partial y} - v'\frac{\partial T'}{\partial y}$$

Meridional advection terms

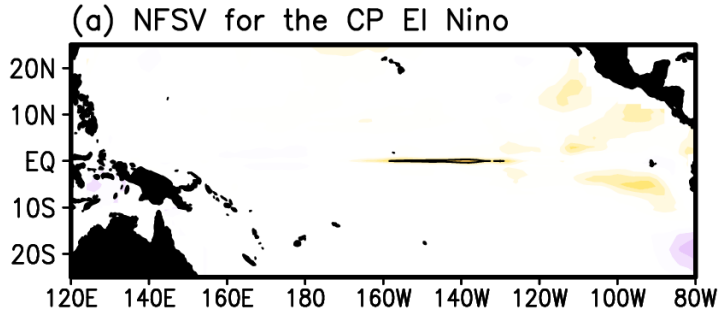
$$-w'\frac{\partial \overline{T}}{\partial z} - \overline{w}\frac{\partial T'}{\partial z} - w'\frac{\partial T'}{\partial z}$$

Vertical advection terms

$$+Q$$

4. Dynamics of NFSV-tendency error: CP El Niño

NFSV in CP El Niño prediction



$-\overline{v}\cdot\frac{\partial T'}{\partial y}$: Meridional heat transport

$-\overline{u}\cdot\frac{\partial T'}{\partial x}$: SSTA transport by SEC

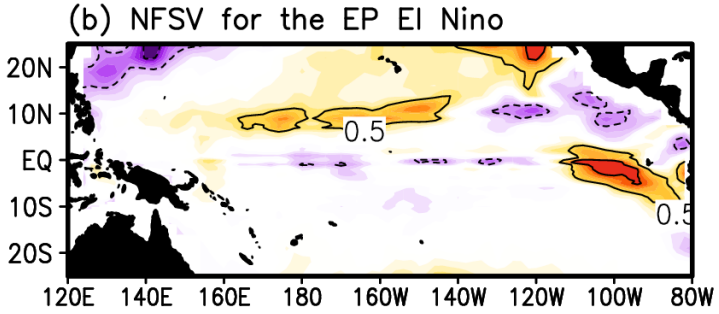
Changes of the heat budget

	$-\overline{u}\cdot\frac{\partial T'}{\partial x}$	$-u'\cdot\frac{\partial \overline{T}}{\partial x}$	$-u'\cdot\frac{\partial T'}{\partial x}$	total
Zonal advection terms	**1.40**	**3.17**	-1.32	3.25
Meridional advection terms	**5.09**	0.19	0.01	5.10
Vertical advection terms	**-10.56**	0.13	-0.11	-10.54
dT/dt				9.5

$-\mathbf{u}'\cdot\frac{\partial \overline{T}}{\partial x}$: **Zonal advection feedback**

$-\overline{w}\cdot\frac{\partial T'}{\partial z}$: **Thermocline feedback**

NFSV in EP El Niño prediction



$-\overline{v}\cdot\frac{\partial T'}{\partial y}$: Meridional heat transport

$-\overline{u}\cdot\frac{\partial T'}{\partial x}$: SSTA transport by SEC

Changes of the heat budget

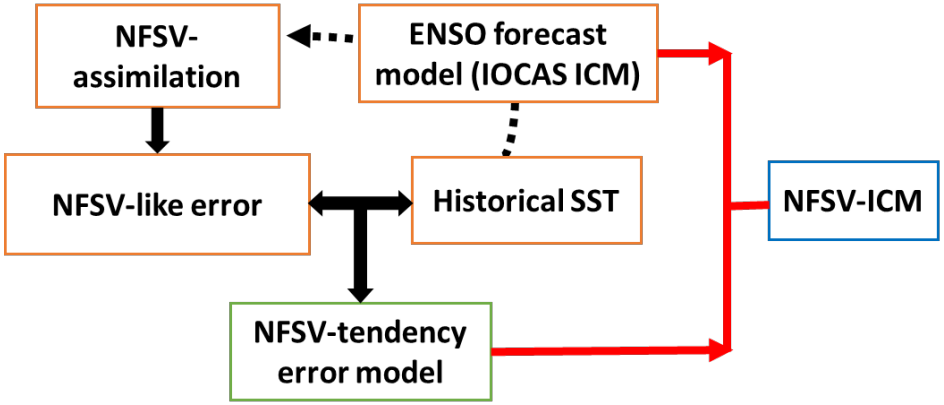
	$-\overline{u}\cdot\frac{\partial T'}{\partial x}$	$-u'\cdot\frac{\partial \overline{T}}{\partial x}$	$-u'\cdot\frac{\partial T'}{\partial x}$	total
Zonal advection terms	**1.25**	**-2.67**	0.80	-0.61
Meridional advection terms	**-5.50**	-0.20	3.04	-2.75
Vertical advection terms	**1.81**	0.03	-0.17	1.61
dT/dt				-2.60

$-\mathbf{u}'\cdot\frac{\partial \overline{T}}{\partial x}$: **Zonal advection feedback**

$-\overline{w}\cdot\frac{\partial T'}{\partial z}$: **Thermocline feedback**

5. Summary

- **How to use NFSV in correcting the ENSO model during predictions?**



- **The NFSV-ICM can successfully identify CP- and EP- El Niño at least 6-month lead time**

- **Additional to the local effect by the NFSV-tendency perturbation, it can enhance the thermocline feedback in the EP El Niño prediction but enhance the zonal advection feedback in the CP El Niño prediction.**

Reference:

1. Tao, L. J., and W. S., Duan, 2019: Using a Nonlinear Forcing Singular Vector Approach to Reduce Model Error Effects in ENSO Forecasting. *Weather and Forecasting,* **34**, 1321-1342.
2. Tao, L. J., W. S., Duan, and S. Vannitsem, 2019: Improving the forecast skill of El Niño diversity: A nonlinear forcing singular vector approach. *Clim Dynm,* Under Review.

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Thank you!

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