Can we predict NH land monsoon rainfall a decade in advance?

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Acknowledge contributions from

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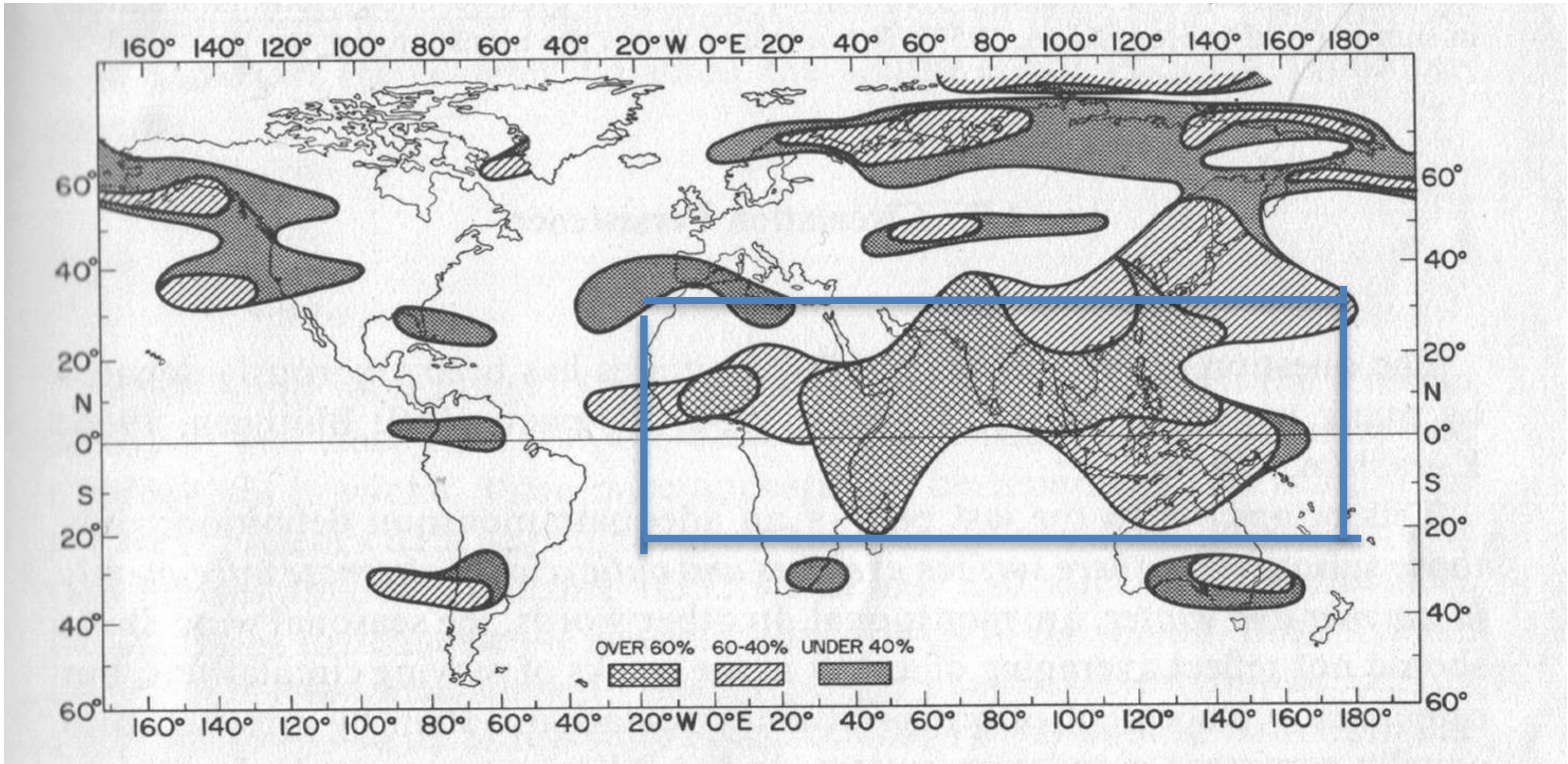
Where is Land monsoon rainfall (LMR)?

Monsoon domain by annual reversal of winds

Hann (1908) , Khromov (1957) and Ramage (1971) map,

Mid-20th century debate: annual march of westerlies



Annual reversal of surface winds

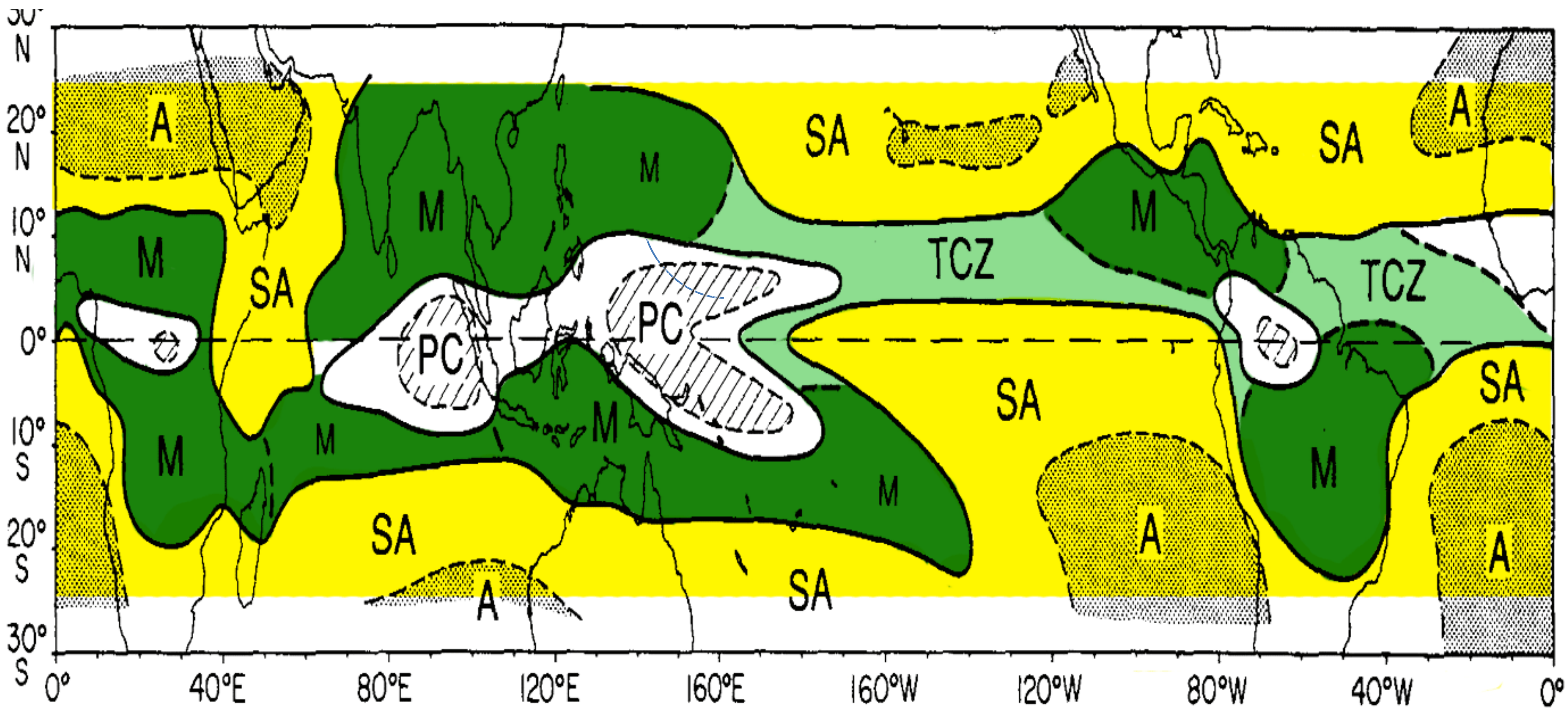
Ramage (1971) added Strength and Steadiness criteria

- Prevailing wind direction shifts at least 120 degree between January and July
- Average frequencies of the prevailing wind direction in January and July >40%

Defining Tropical Monsoon from Rainfall Perspective:

Extension to western hemisphere

Monsoons entail substantial oceanic regions

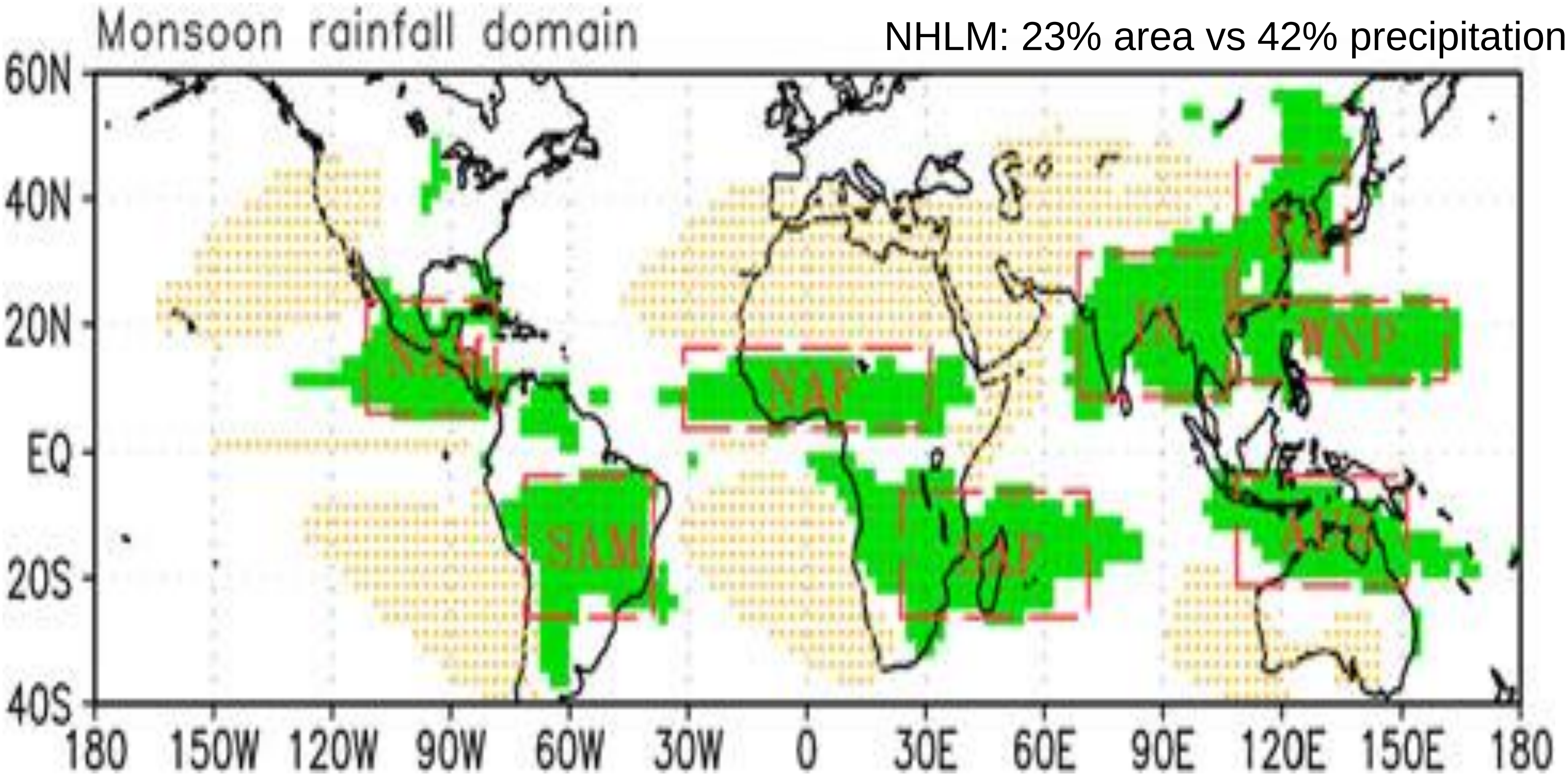


M: Monson; SA: Semi-Arid; A: Arid; PC: perennial; TCZ: Trades convergence Zone

The availability of remote sensing techniques since late 1970s has extended monsoon observations from continental into data-scarce oceanic regions.

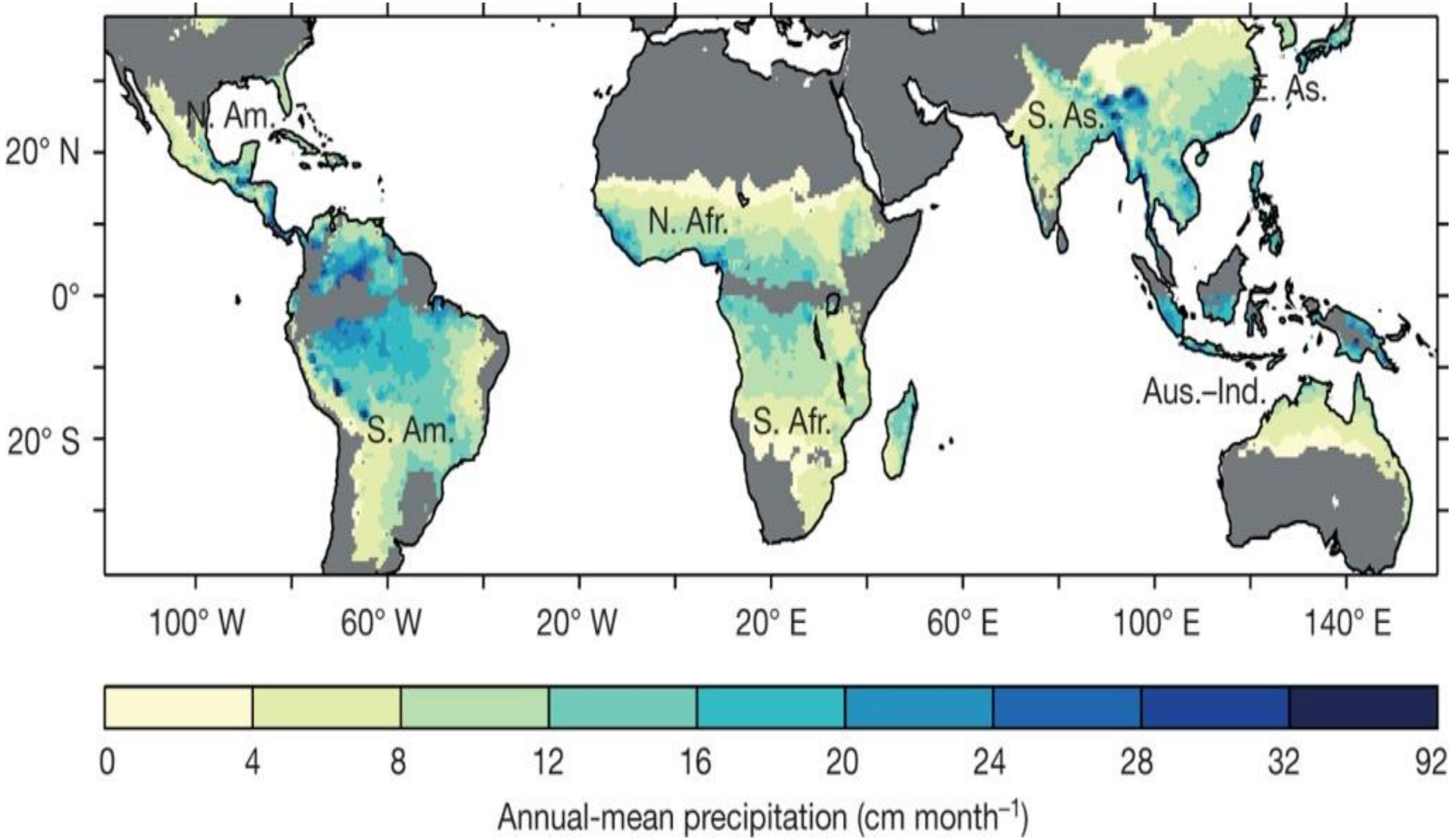
Reproduced from Wang 1994, J. Climate

GM domain defined by *rainy summer vs. dry winter*



Monsoon criteria by rainfall: (1) Annual range exceeds 300 mm (or 2mm/day) ; (2) Local summer precipitation exceeds 55% of the annual total precipitation (Wang and Ding 2008); **Arid regions**: Local summer precipitation rate is below 1 mm/day

Global monsoon domain (coloured regions) as defined by the seasonality (summer winter difference) in rainfall



M Mohtadi *et al. Nature* **533,** 191–199 (2016) doi:10.1038/nature17450

Wang and Ding (2008)

NH LMR

- NH LM occupies 23% of the total NH land area, but the NH LMR is about 42% of the total NH land precipitation.
- NH LMR provide water resources for about 70% of the world population.
- Global LM area is 28% of the total land area but the global LMR is about ~48% of the total land precipitation.

Why study the decadal prediction of the NHLMR?

A societal concern:
How much will LMR change in the coming decades (near future)?

- Predictions of changes of the LMR in the coming decades are vitally important for infrastructure planning, water resource management, disaster mitigation, and sustainable development.
- The NH LMR profoundly impact some two-thirds of the global population, particularly in less-developed countries that are often stressed by water shortages.

To what extent can we predict NH LMR change a decade in advance?

Scientific reasons for this study

- The current global climate models have little skill in the direct prediction of decadal LMR.
- Mechanisms responsible for the natural decadal variability of LMR, which often overwhelms the anthropogenic trend on decadal time scales, remain elusive.
- Physical basis and predictability for decadal prediction of LMR remain largely unexplored.

Current status of decadal prediction of precipitation

- Direct decadal predictions of precipitation in some CMIP5 models have skill over the Sahel, mid-latitude Eurasia and parts of North America and southern South America (Bellucci et al. 2013; Gaetani and Mohino 2013; Martin and Thorncroft 2014; Meehl et al. 2014; Bellucci et al. 2015; Otero et al. 2015), but part of the positive skill found after 1980 can be attributed largely to specified atmospheric greenhouse gas concentration variations (Doblas-Reyes et al. 2013).
- Multi-year predictions of 4-year mean Sahel rainfall with lead times of 2-5 year has no statistically significant skill ($p \approx 0.2$) (van Oldenborgh et al. 2012).

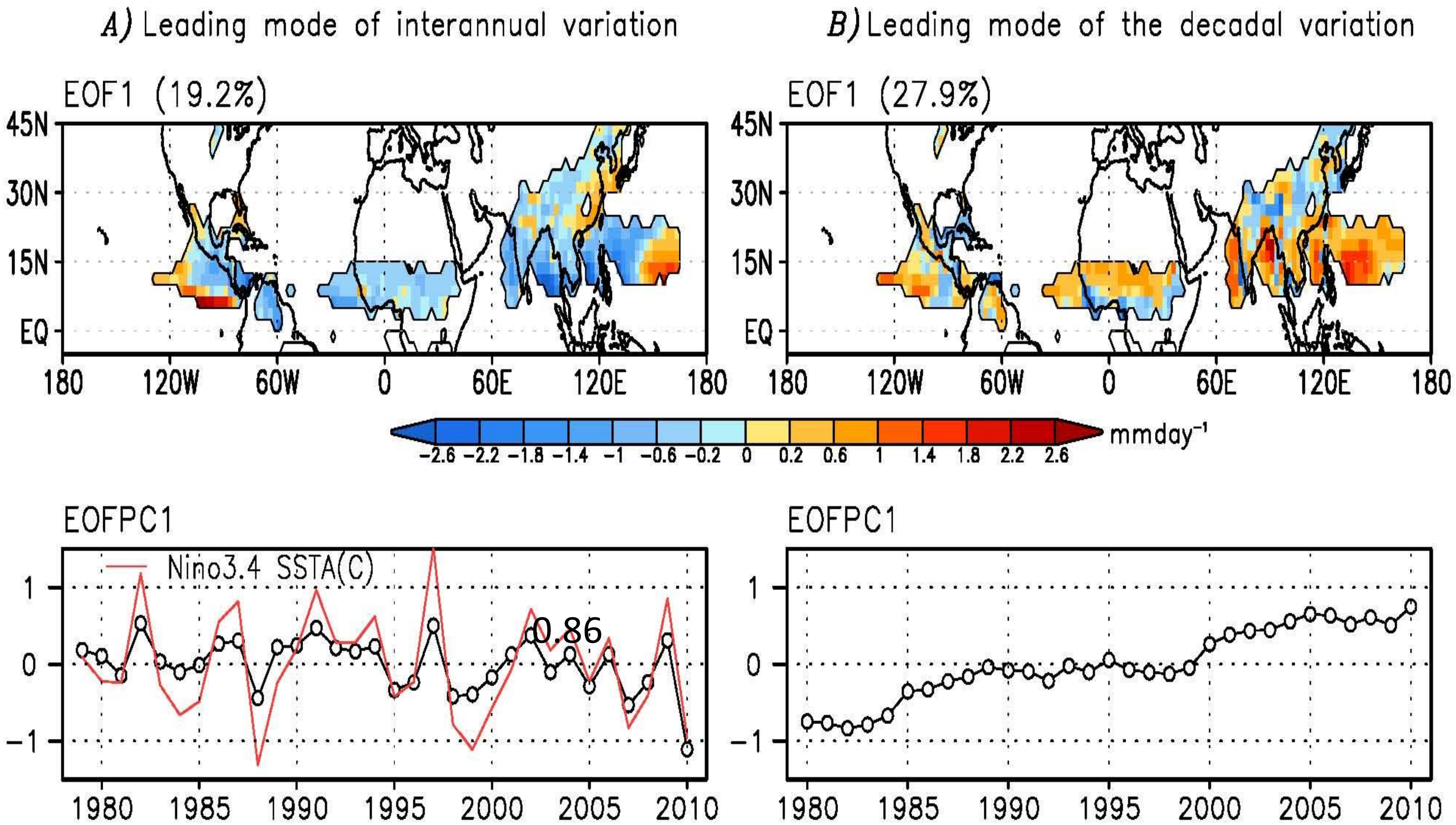
This presentation focuses on NHLMR, will

- Show coherent decadal variability of NH LMR and define a NHLMR index.
- Explore origins of decadal variability of NHLMR.
- Explain physical basis for decadal prediction of NHLMR through numerical experiments.
- Establish a Hybrid Dynamic-Conceptual (HDC) model for Independent Forward-Rolling (IFR) decadal prediction of NHLMR.
- Demonstrate the NHLMR change can be predicted a decade ahead.

Coherent Variability in NH LM Regions

- Leading mode of NH LMR variability
- NHLMR index
- What does NHLMR index represent?

Coherent interannual and decadal variations of NHSM rainfall

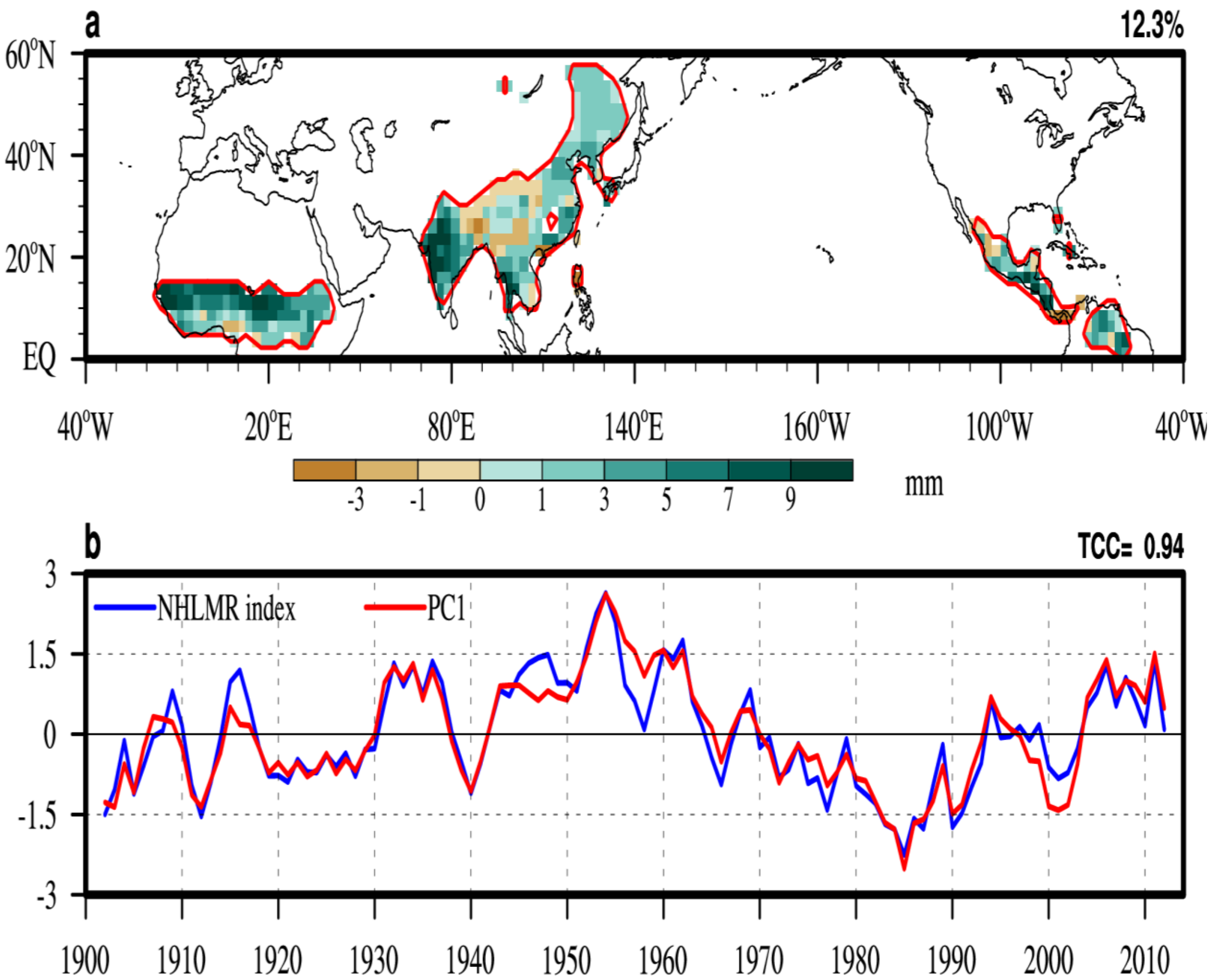


NH Land monsoon rainfall and Nino 3.4 correlation (monsoon year) is 0.73 (1979-2012)

Representation of decadal variation

- Four-year running mean time series were widely used to identify decadal variability (Kim et al. 2012; van Oldenborgh et al. 2012; Goddard et al. 2013).
- In the 4-year running mean time series, the yearly mark represents the second year of the four-year running mean.
- All statistical tests for correlation coefficients are determined by the effective degrees of freedom by taking into account of autocorrelations (Livezey and Chen 1983).

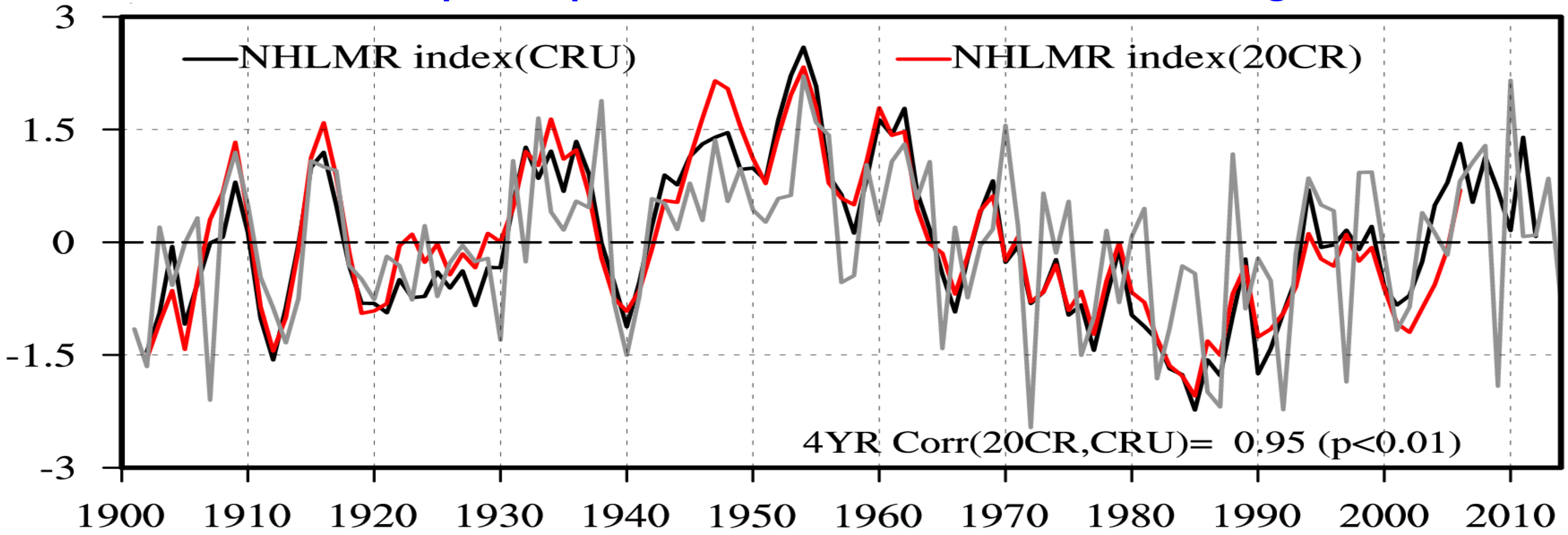
Does the NH LMR have coherent decadal Variability ?



The NHLMR is the area-weighted average of the summer precipitation within the NH land monsoon domains (outlined by the red contours).

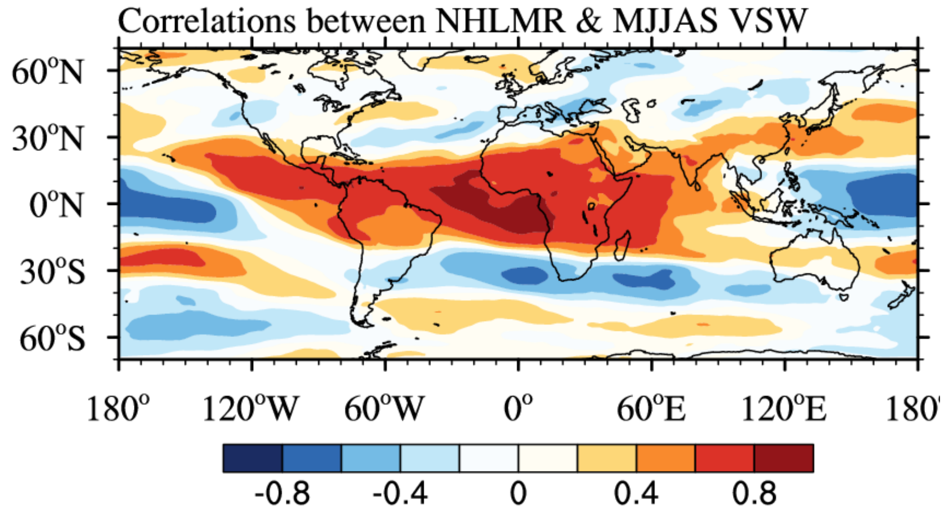
Leading decadal mode of NH land summer monsoon rainfall variability (1901-2014).

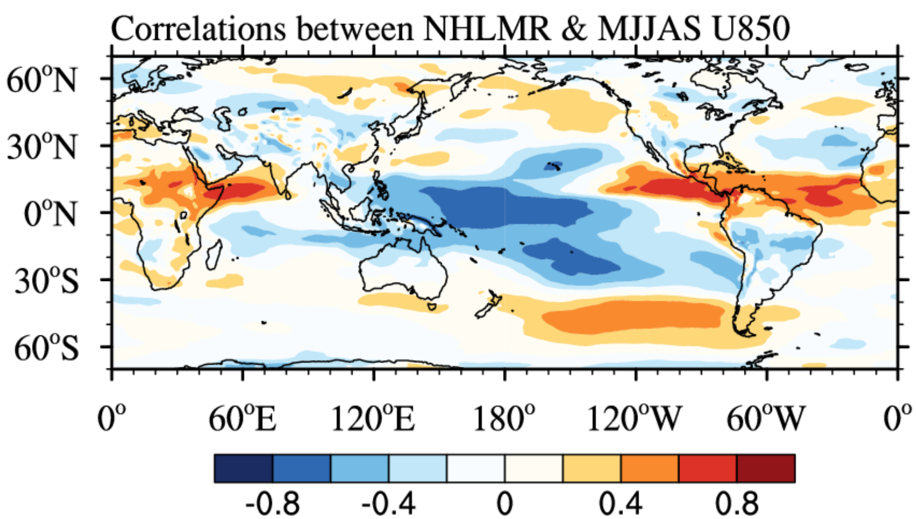
NHLMR Index: area-weighted average of May-Sept mean precipitation over the NH LM regions



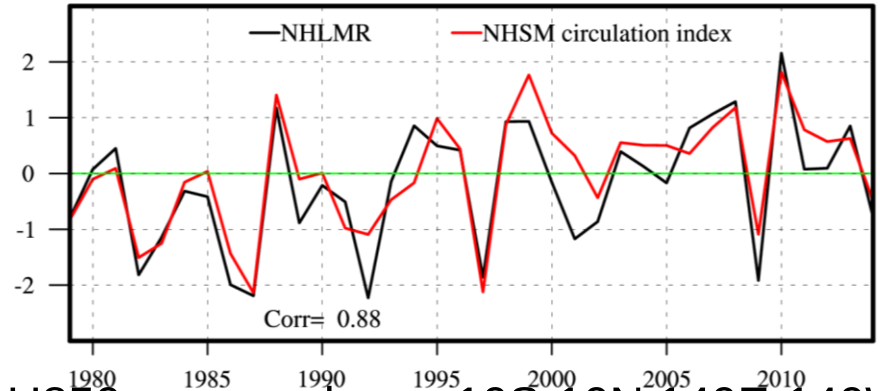
- The NHLMR index represents the annual precipitation, (r=0.96).
- The decadal NHLMR displays large-amplitude fluctuations (3.6% per decade), much larger than the corresponding trend induced by anthropogenic forcing (only approximately 0.5% per decade) (Lee and Wang 2014).
- <u>Decadal variation might have a major contribution to the total precipitation change in a time scale of 2-3 decades.</u>

ERA-interim

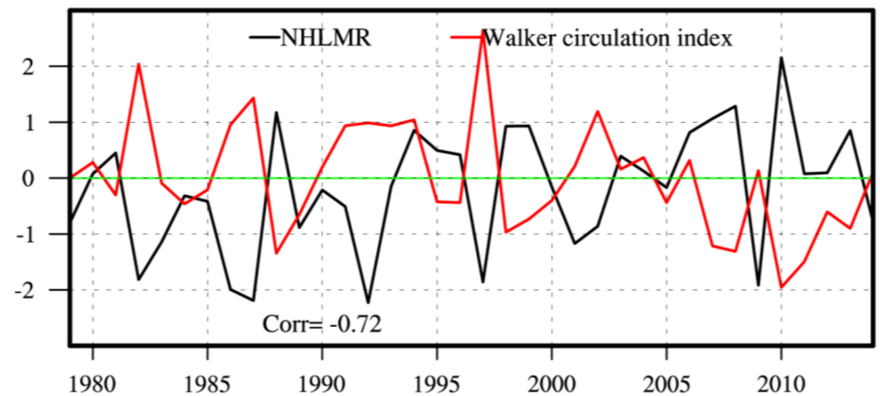




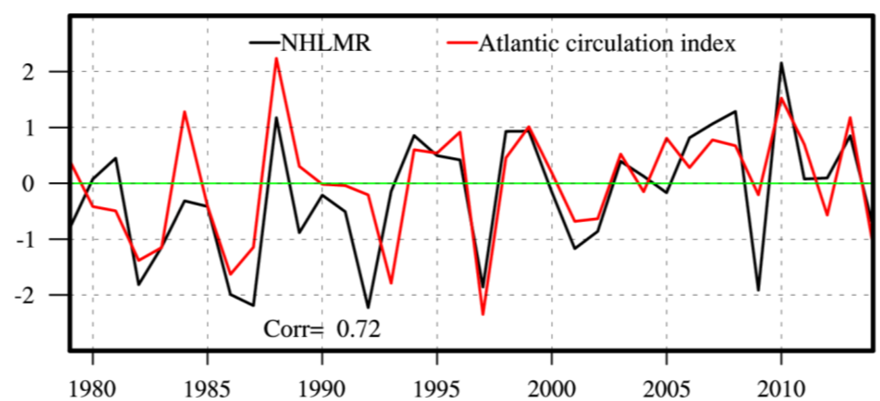
VWS averaged over 0-20N,120W-100E



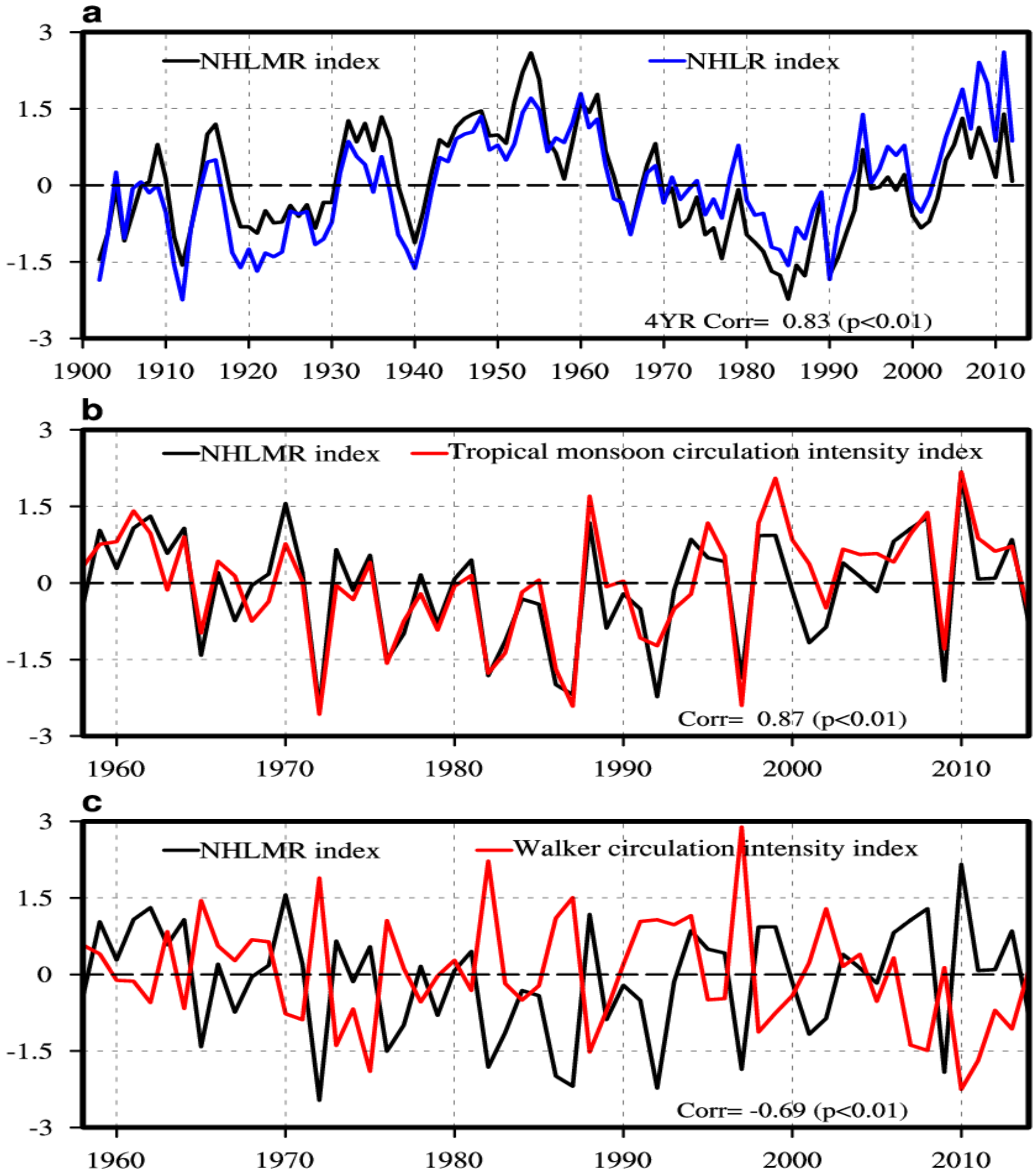
U850 averaged over 10S-10N,140E-140W



U850 (0-20N,70W-10W)- U850 (20N-40N,70W-10W)



What does the NHLMR index represent?



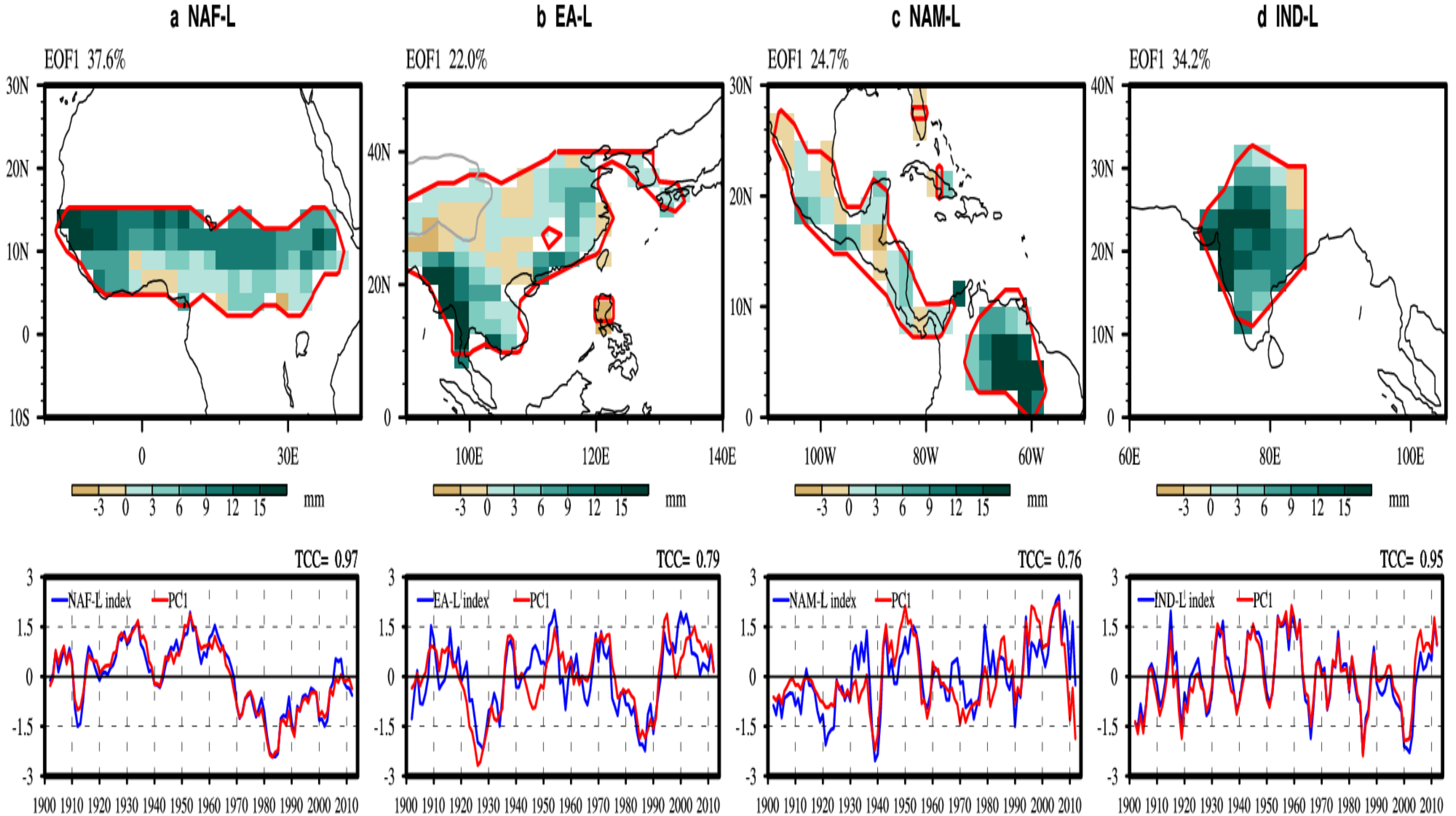
A. Total NH Land precipitation (r=0.83)

B. Tropical monsoon circulation intensity (r=0.87) measured by the vertical shear of zonal wind (U850 hPa minus U200 hPa) averaged over 0° –20° N, 120° W–90° E.

C. Walker circulation intensity (r=-0.69) measured by the U850 averaged over the (10° S–10° N, 140° E–140° W).

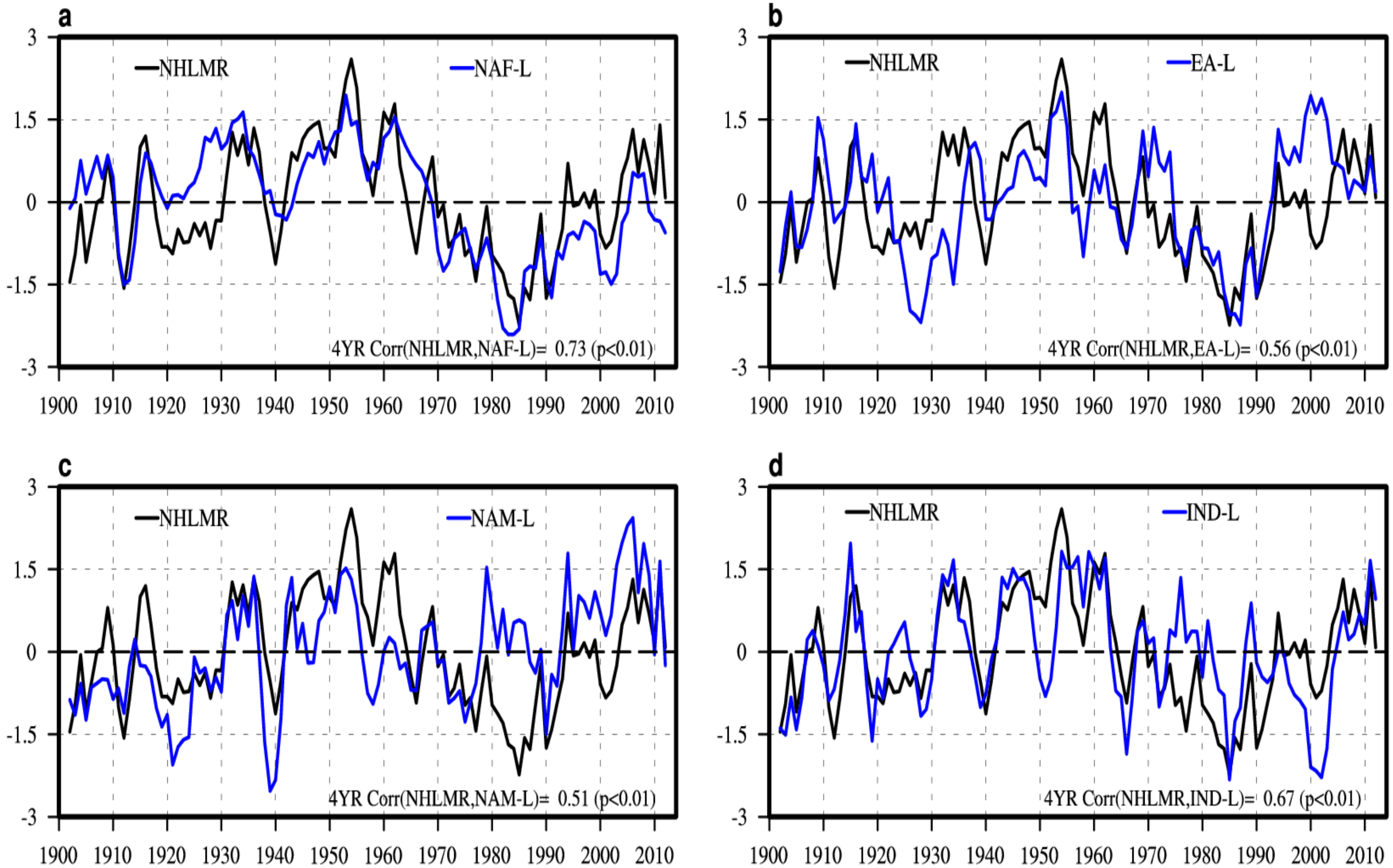
All indices are normalized

Regional LMR indices (decadal variation)



The leading EOF modes of regional summer (May-September) LMR decadal variability during 1901-2014 after 4-year running average. Blue curves in PC diagram show regional LMR indices.

Relationships between NHLMR and Regional LMR indices



TCC	NAF-L index	EA-L index	NAM-L index	IND-L index
NHLMR index	0.73	0.56	0.51 (0.68)	0.67

Intensity change of the NHLMR reflects

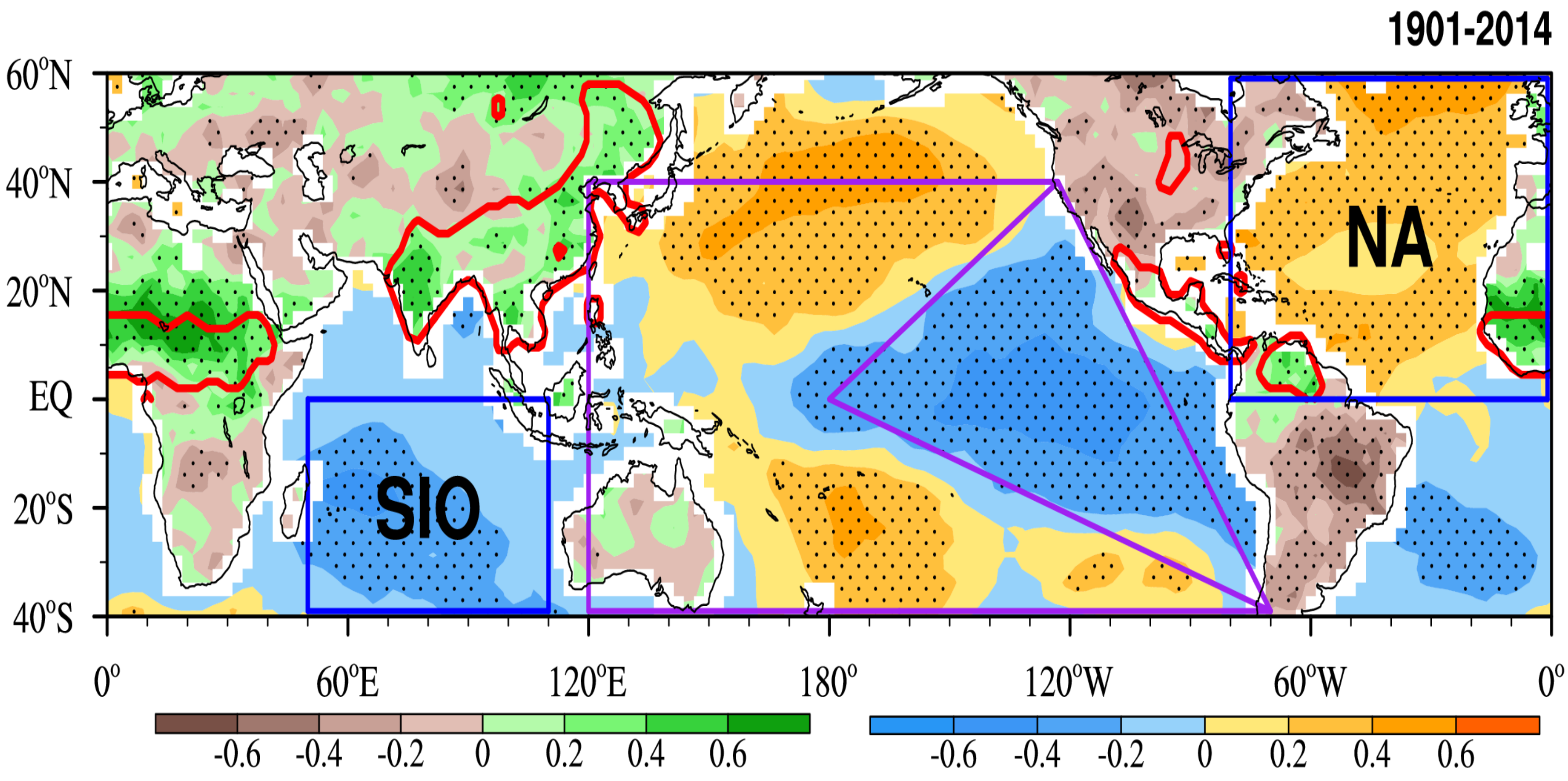
- Changes in total NH land rainfall, thus related to decadal variations of the global hydrology.
- Changes in tropical general circulation (monsoon circulation system and Walker circulation),
- Changes in the regional land monsoon rainfall indices over northern Africa, India, East Asia, and North America.

Let us focus on prediction of the NHLMR index first

What are the sources of the decadal variability of NHLMR?

- SST anomalies associated with the decadal NHLMR
- Global SST modes: NAID and Mega-ENSO
- Physical linkage between NAID and NHLMR and between Mega-ENSO and NHLMR
- Stationary relationship between NHLMR and the two global SST modes.

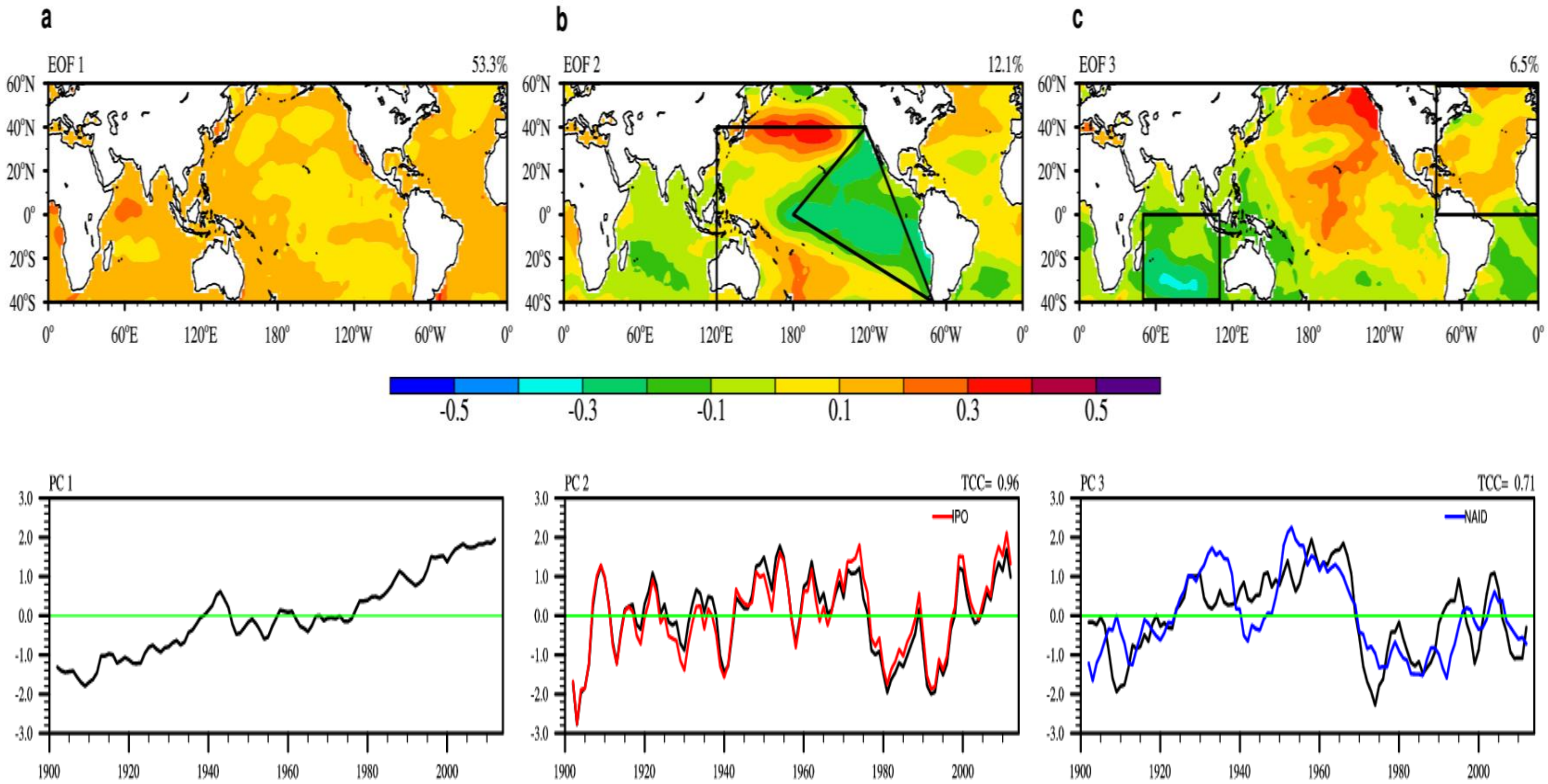
SST anomalies associated with the decadal NHLMR



NAID index = SSTA [North Atlantic-South Indian Ocean]

Extended ENSO (XEN) index=

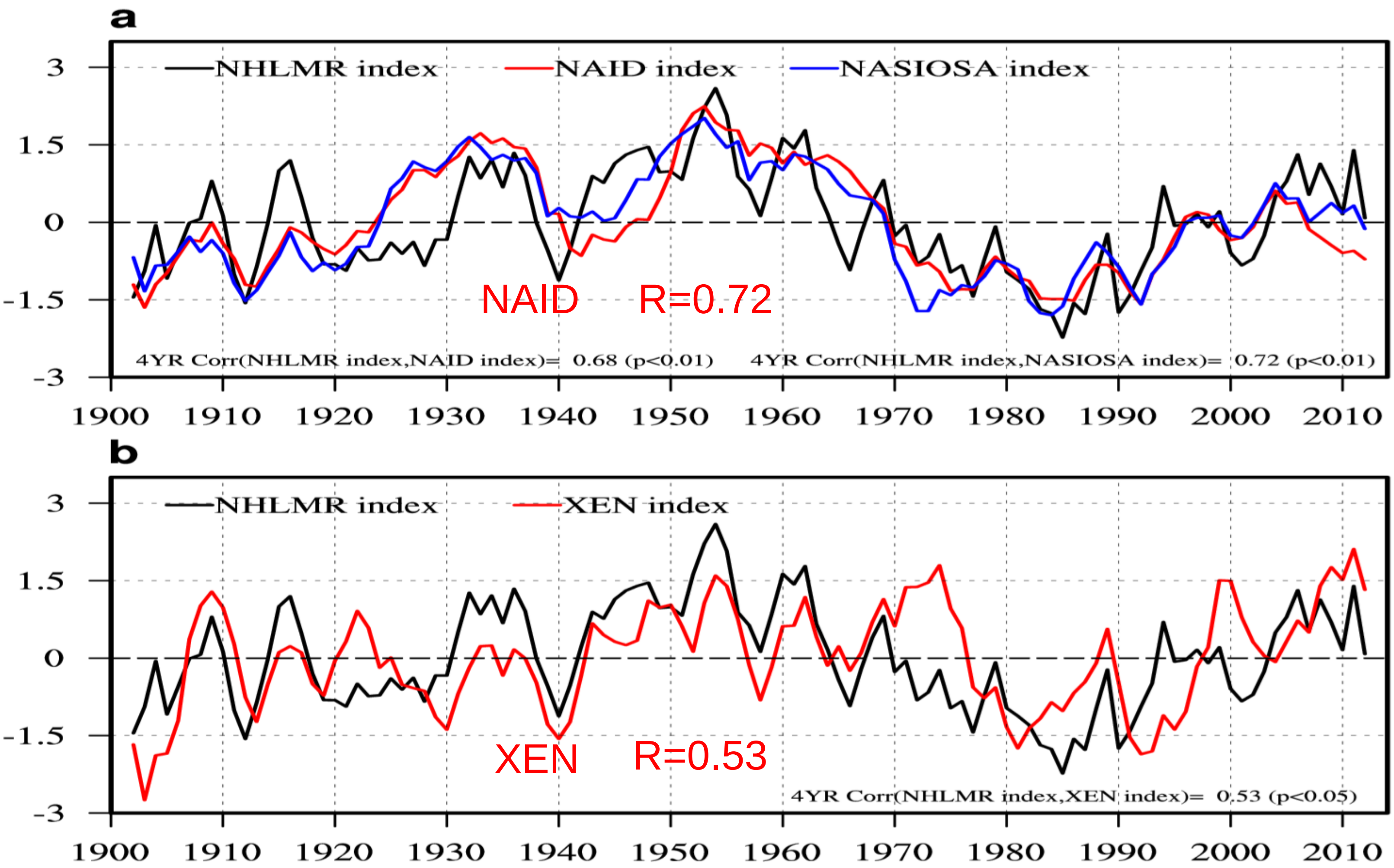
SSTA [(W. Pac K-shape)-(E. Pacific triangle)]



First three EOF modes of the global SST in MJJAS for the period of 1901-2014. The upper panels are spatial patterns, and the lower panels are corresponding principal components. The 4-year running mean blended HadISST and ERSST data were used. For comparison, the 4-year running mean IPO index (red) is shown in (**b**) and the 4-year running mean NAID index (blue) is shown in (**c**) with the TCC indicated.

Wang et al. 2013

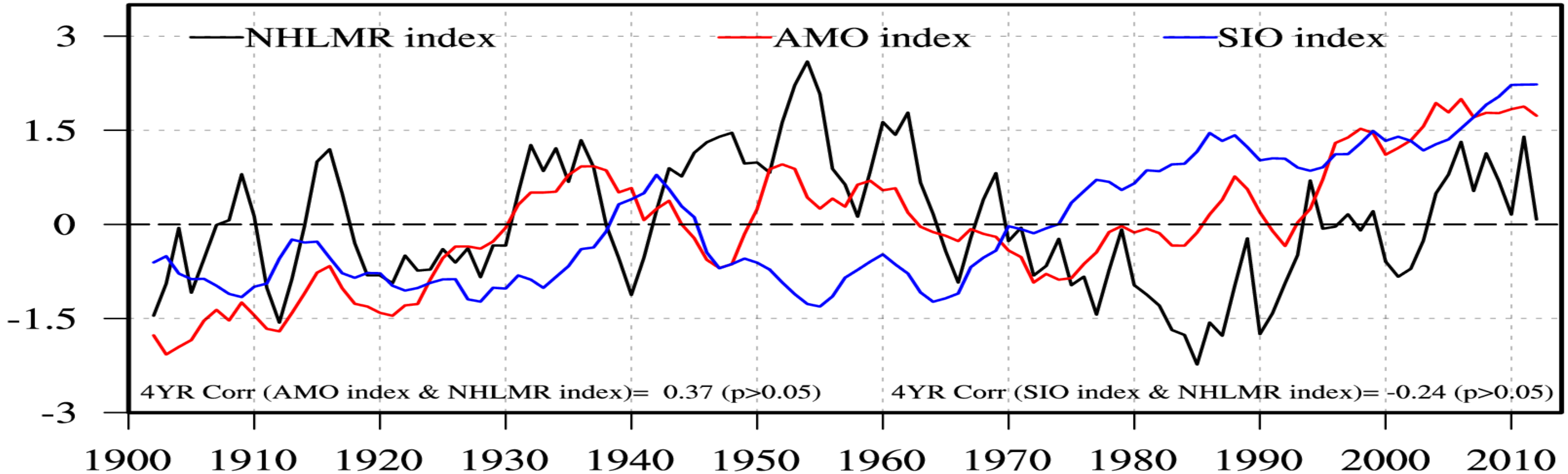
Decadal NHLMR is linked to two modes of Global SST Variations

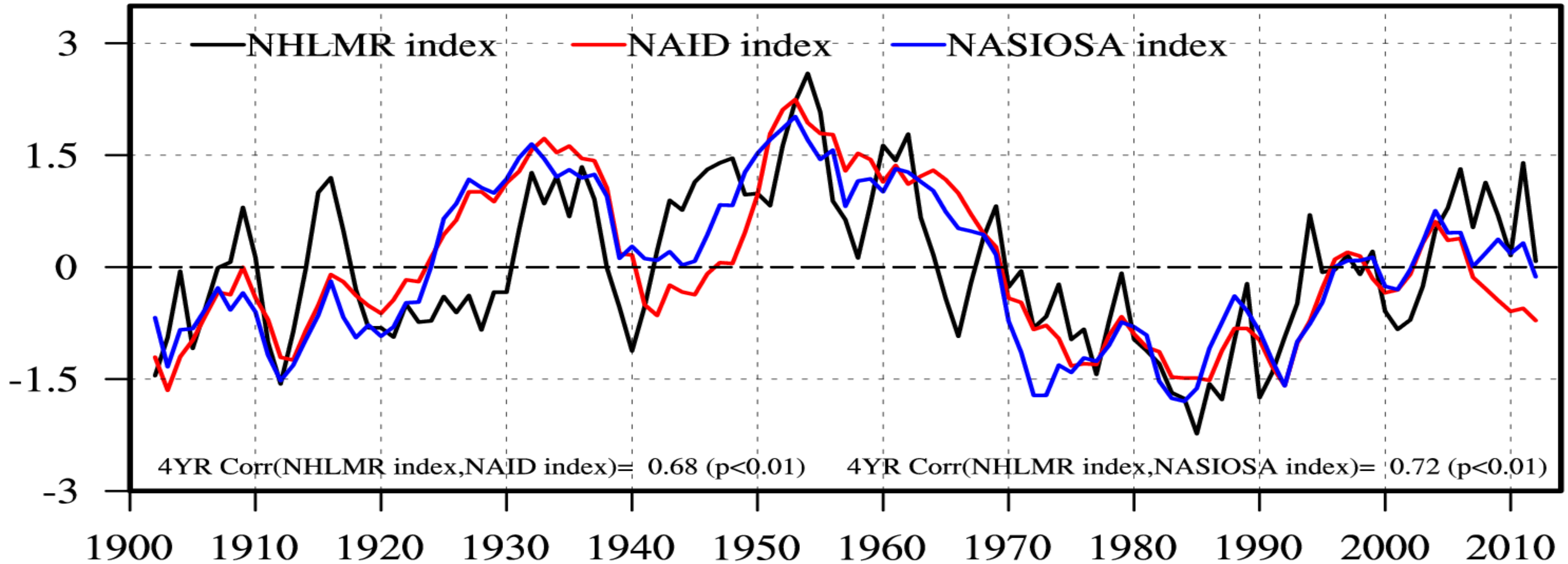


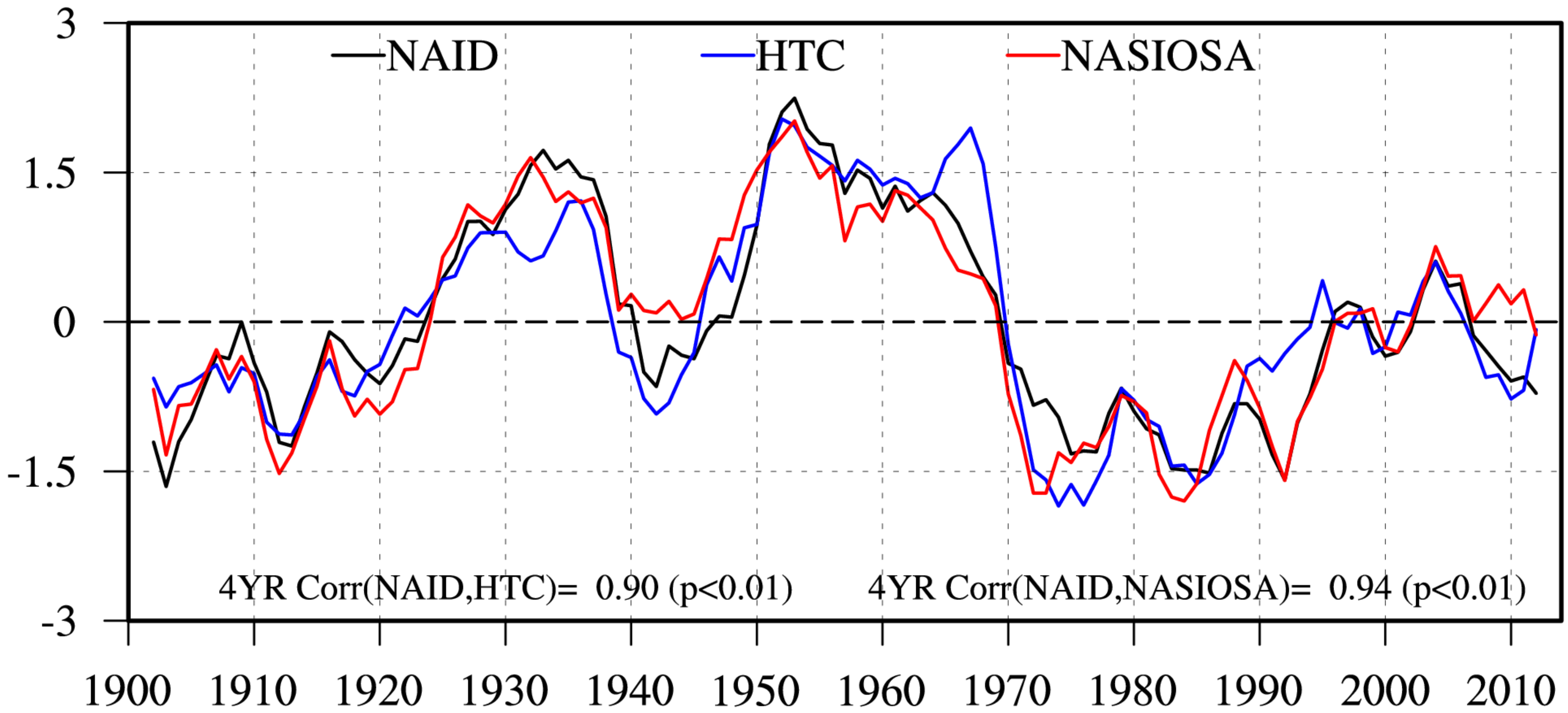
NHLMR index = 0.59*NAID +0.37*XEN,

NAID and XEN explains 35% and 14% of the total NHLMR variance

NAID: NH-SH SSTA contrast in Atlantic-Indian Ocean sector







Previous Extended Data Figure 5 | Decadal variation of Hemispheric SST contrast (HTC). HTC is measured by SST over NH (0-60ºN) minus that over SH (0-40ºS) oceans. For comparison, the 4-year running mean time series of NAID and NASIOSA (2x NA SSTA - SIO SSTA - SA SSTA) are also shown. The correlation coefficients and the corresponding statistical significance levels are shown in the bottom of each panels.

Physical linkage (1):

To what extent the SSTA associated with NAID and IPO can reproduce the NHLMR anomalies?

Pace-maker experiments with the coupled model
(a) Nudging SST anomalies in tropical Pacific (30S-30N)
(b) Nudging SSTA in tropical North Atlantic (0-30N) and southern Indian Ocean (0-30S)
The rest of the ocean is fully coupled with atmosphere; external forcing fixed at 1990 condition.
To simulate the steady response of the monsoon precipitation and circulation to a given SSTA forcing.

NUIST-ESM V3

Atmosphere
ECHAM v6.3 (T63L47/T31L31)

JSBACH
Dyn. Veg.

	AGCM	OGCM	CICE
V3_SR	T63L47	ORCA1	Gx1(1^{o} x 0.5^{o})
V3_LR	T31L31	ORCA2	Gx1(1^{o} x 0.5^{o})

Ocean
NEMO v3.4

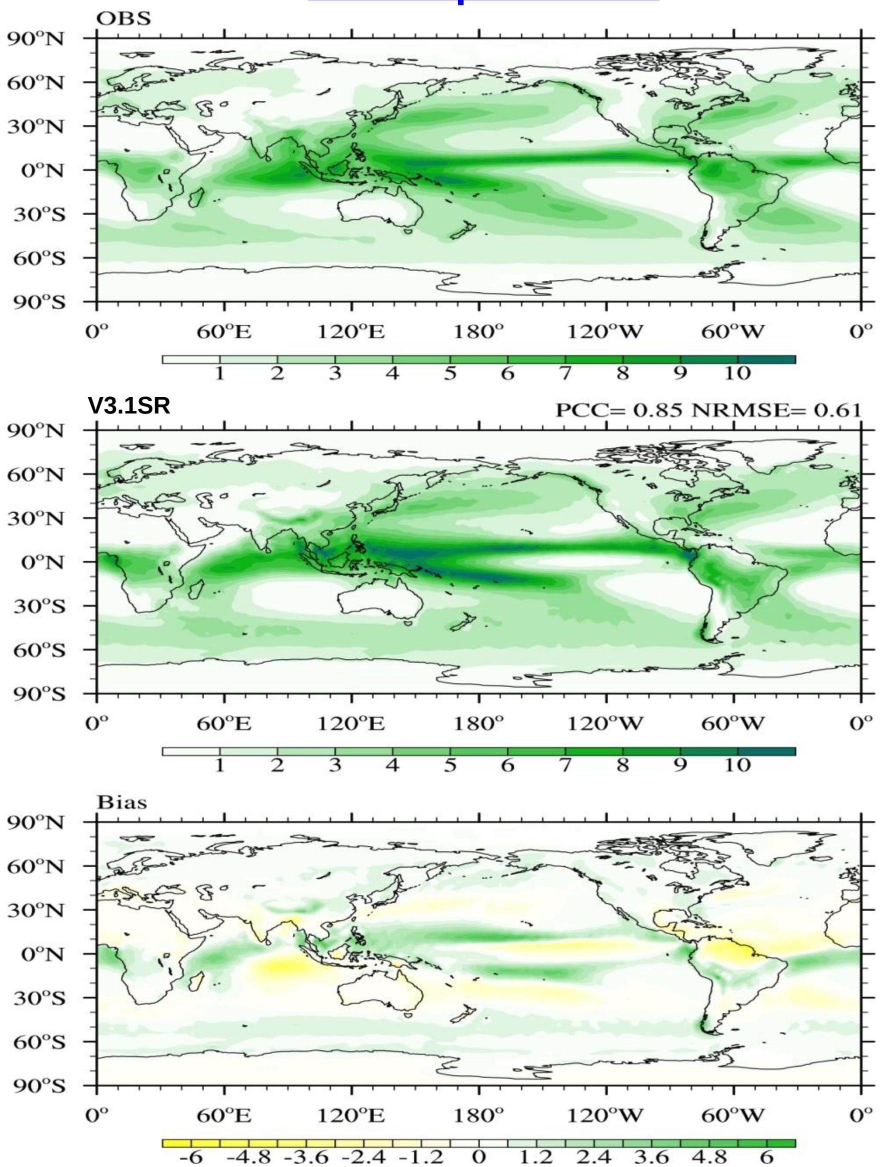
Sea Ice
CICE v4.1

Dec. 2016

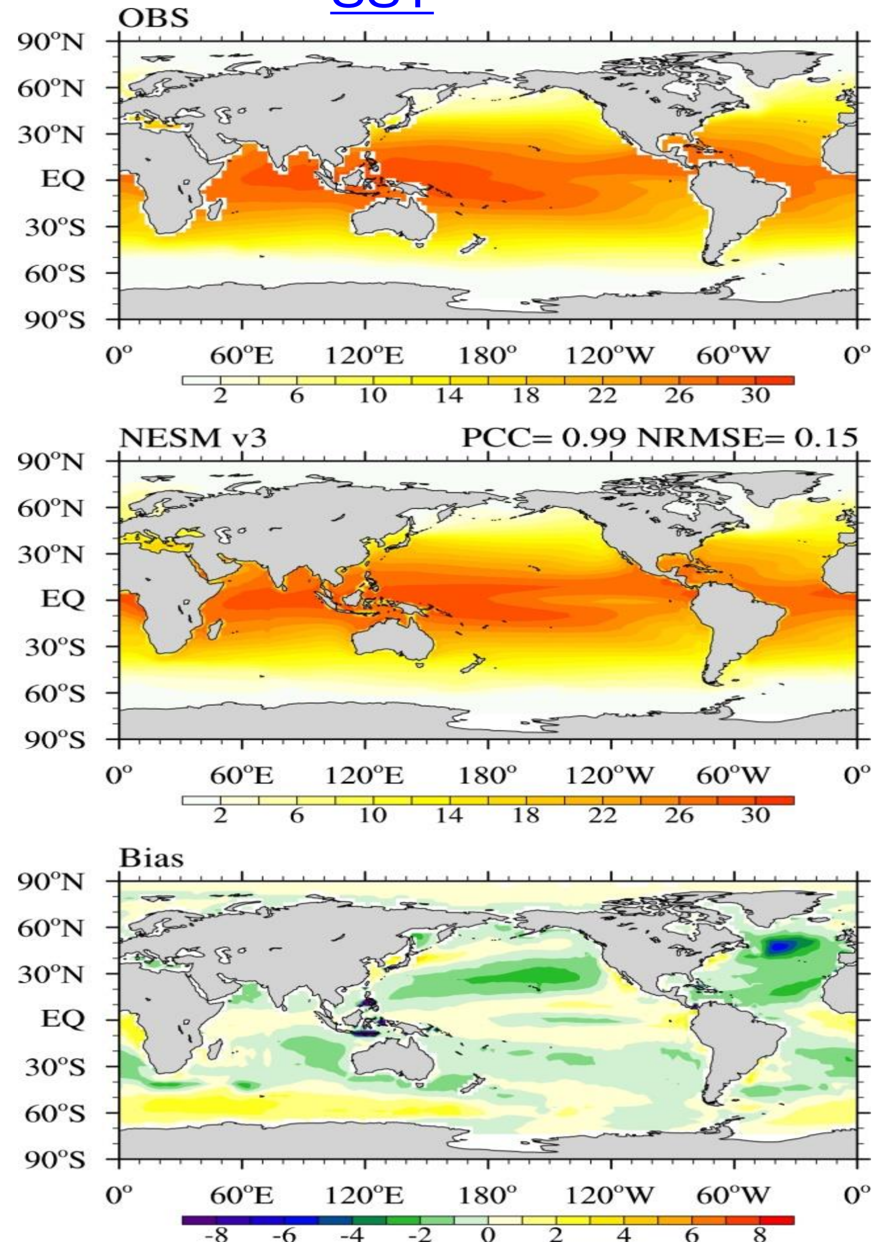
Cao, Wang, Yang et al. 2015, 2018

Historical run – Precipitation Climatology

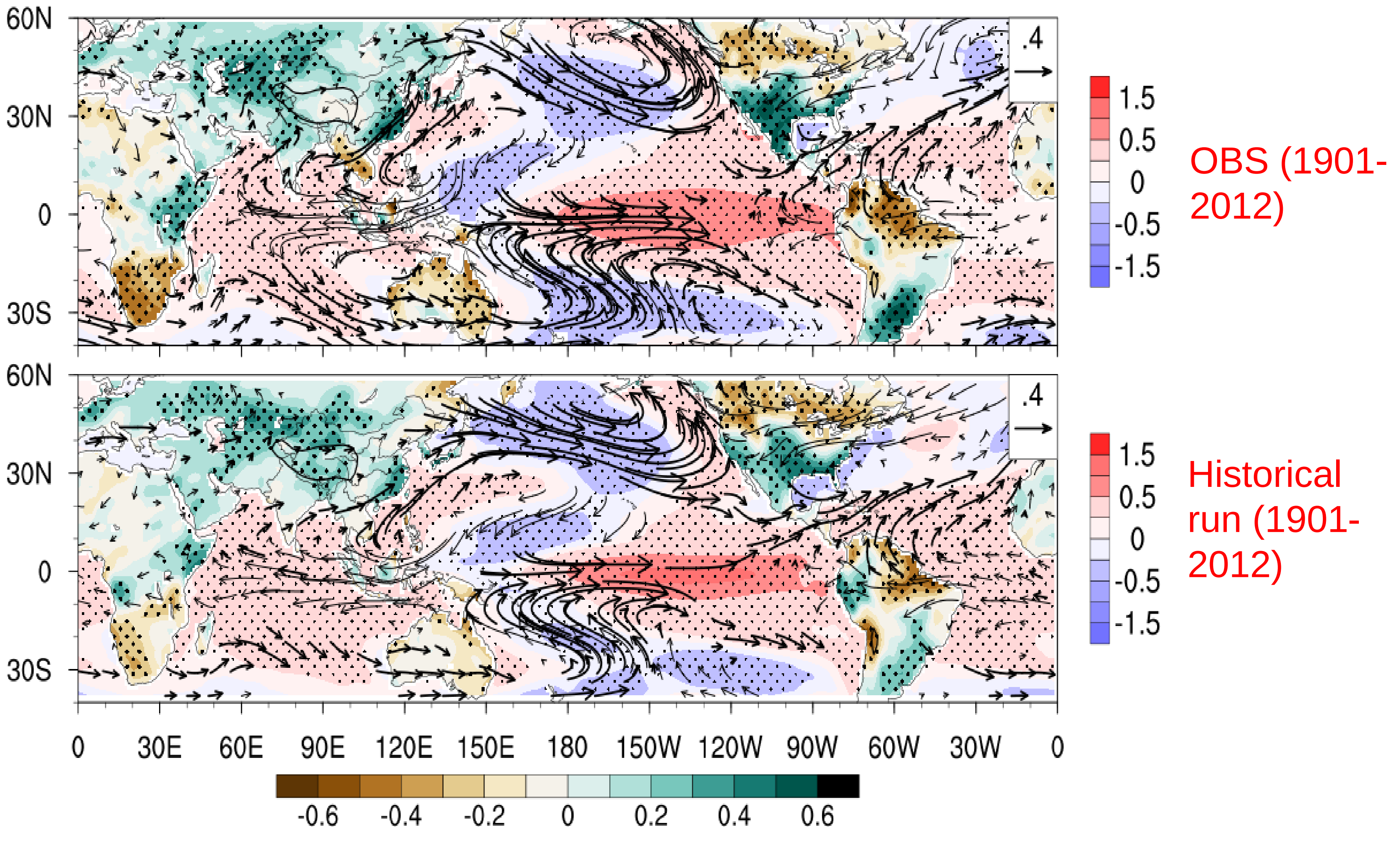
Precipitation



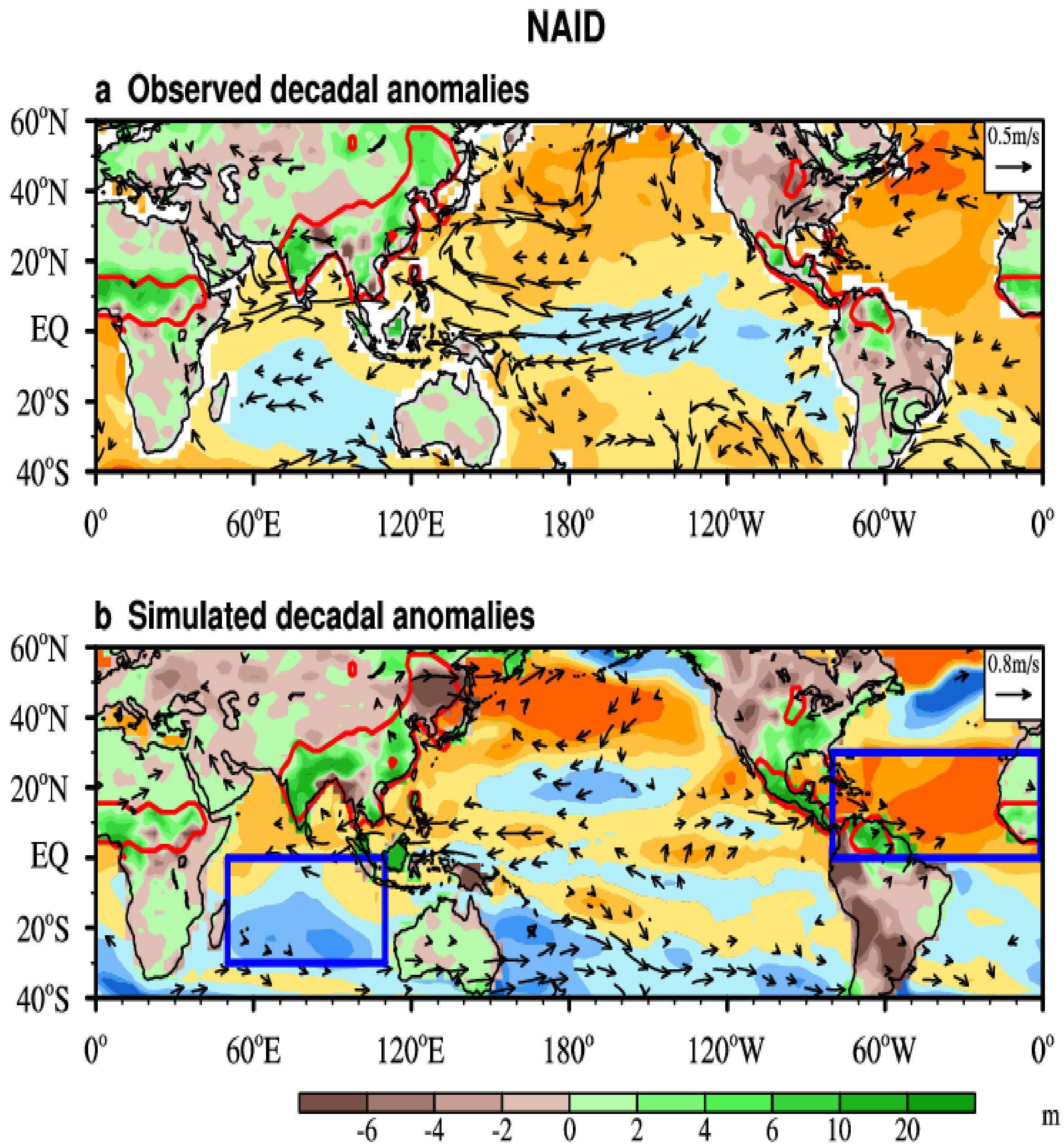
SST



Correlation map of Land precipitation, SSTA and 850 hPa wind anomalies wrt DJF Nino-3.4 SSTA



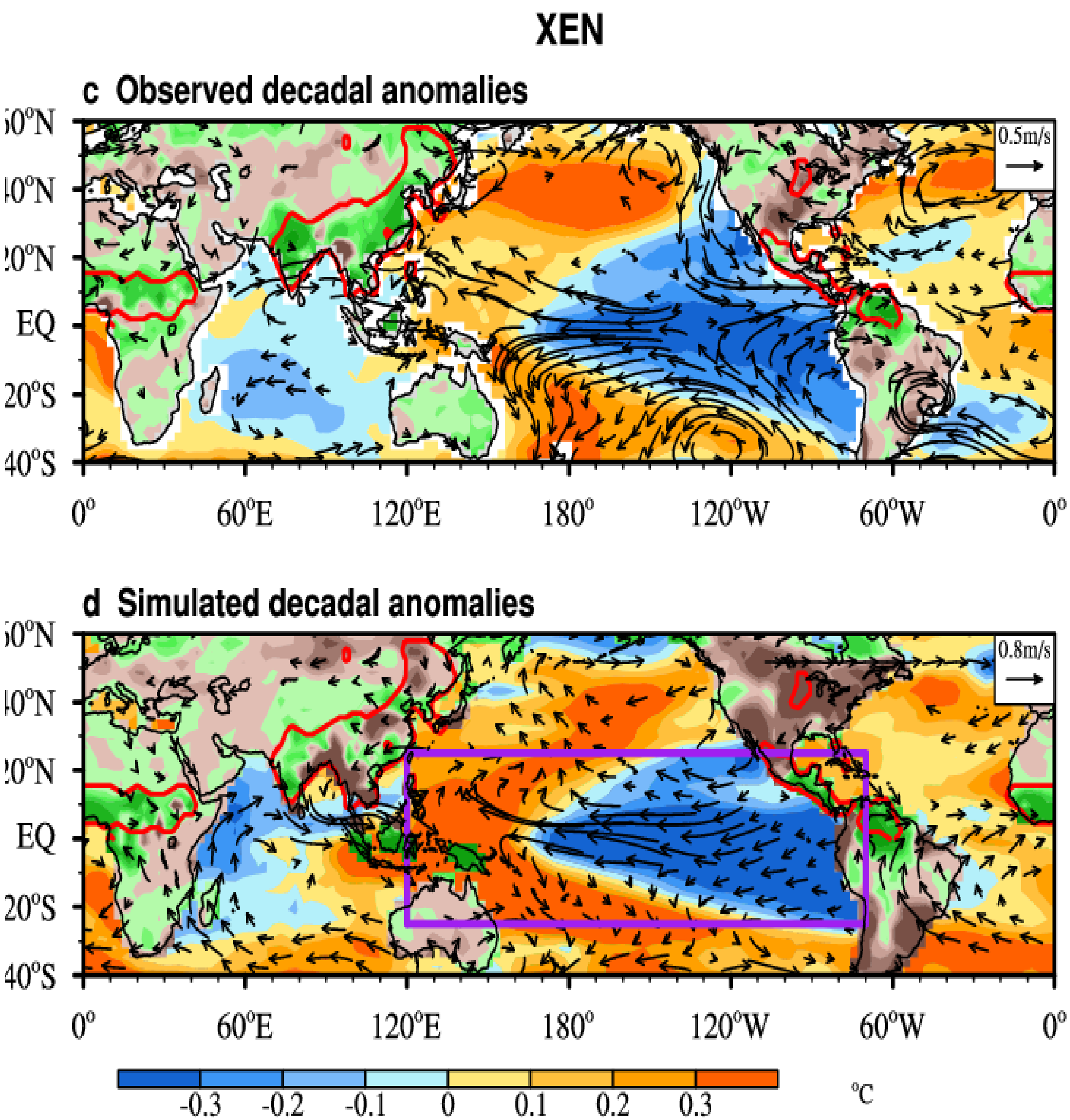
Response to NAID SSTA



The NH-SH SST gradients-induced low-level, northward cross-equatorial flows (Liu et al. 2009; Liu et al. 2012; Wang et al. 2013).

A warm NA can shift the ITCZ northward (Schneider et al. 2014), enhancing NAM (Sutton and Hodson 2005; Meehl and Hu 2006), NAF monsoon, (Gaetani and Mohino 2013; Martin and Thorncroft 2014; Otero et al. 2015) and Asian rainfalls (Lu et al. 2006; Meehl and Hu 2006; Zhang and Delworth 2006); A cold SIO can enhance the northward temperature gradient between the Indian Ocean and Asian continent, strengthening the Asian monsoon rainfall (Webster et al. 1998).

Response to IPO SSTA



The eastern Pacific cooling and western Pacific warming are consistent with a strengthening of the two Pacific subtropical highs in the NH and SH and their associated trade winds, causing moisture to converge into the Asian and African monsoon regions and thus contributing to the intensification of NHSM rainfall.

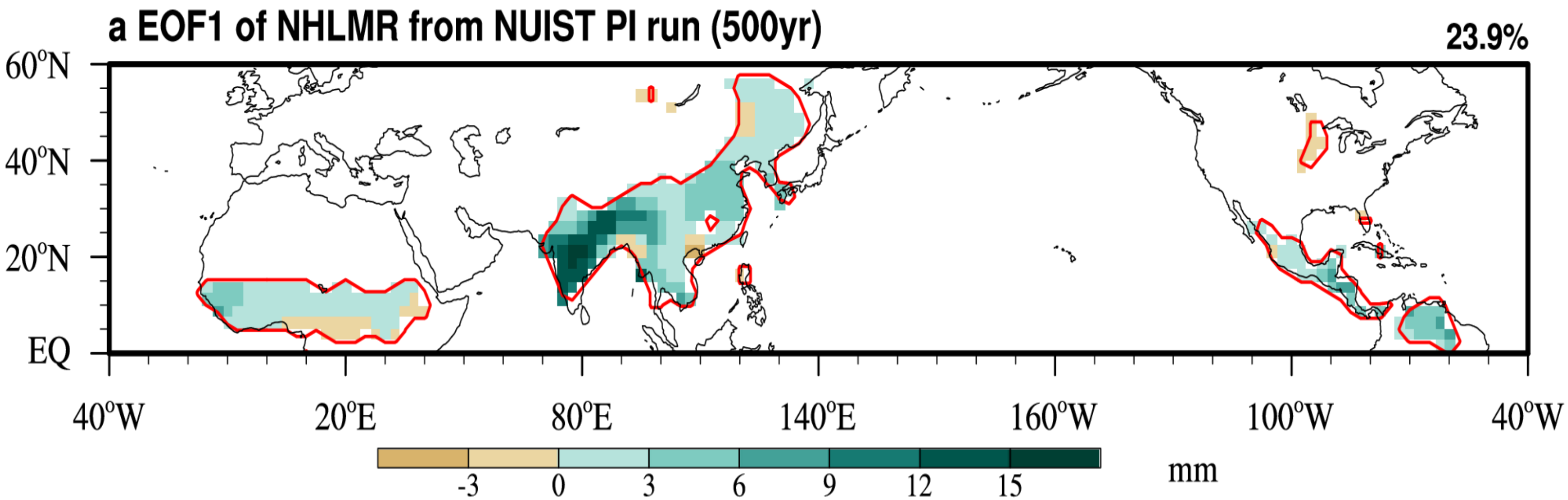
Physical linkage (2):

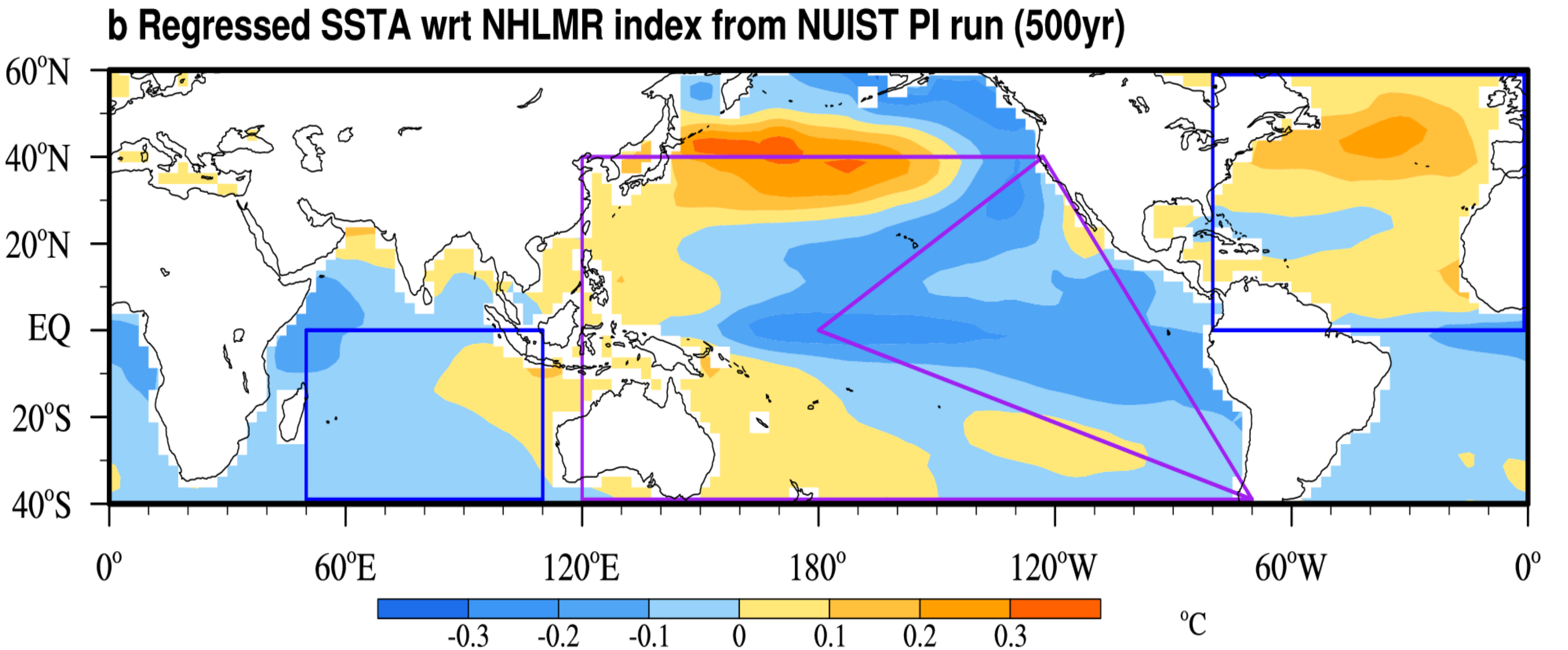
Are the decadal variability of the NHLMR driven by external forcing or internal variability?

A 500-year uninitialized Pre-Industrial experiment with fixed external forcing at 1850 condition.

To identify the internal modes of the coupled climate system.

Results from 500-y Preindustrial Exp.





The results of numerical experiments suggest

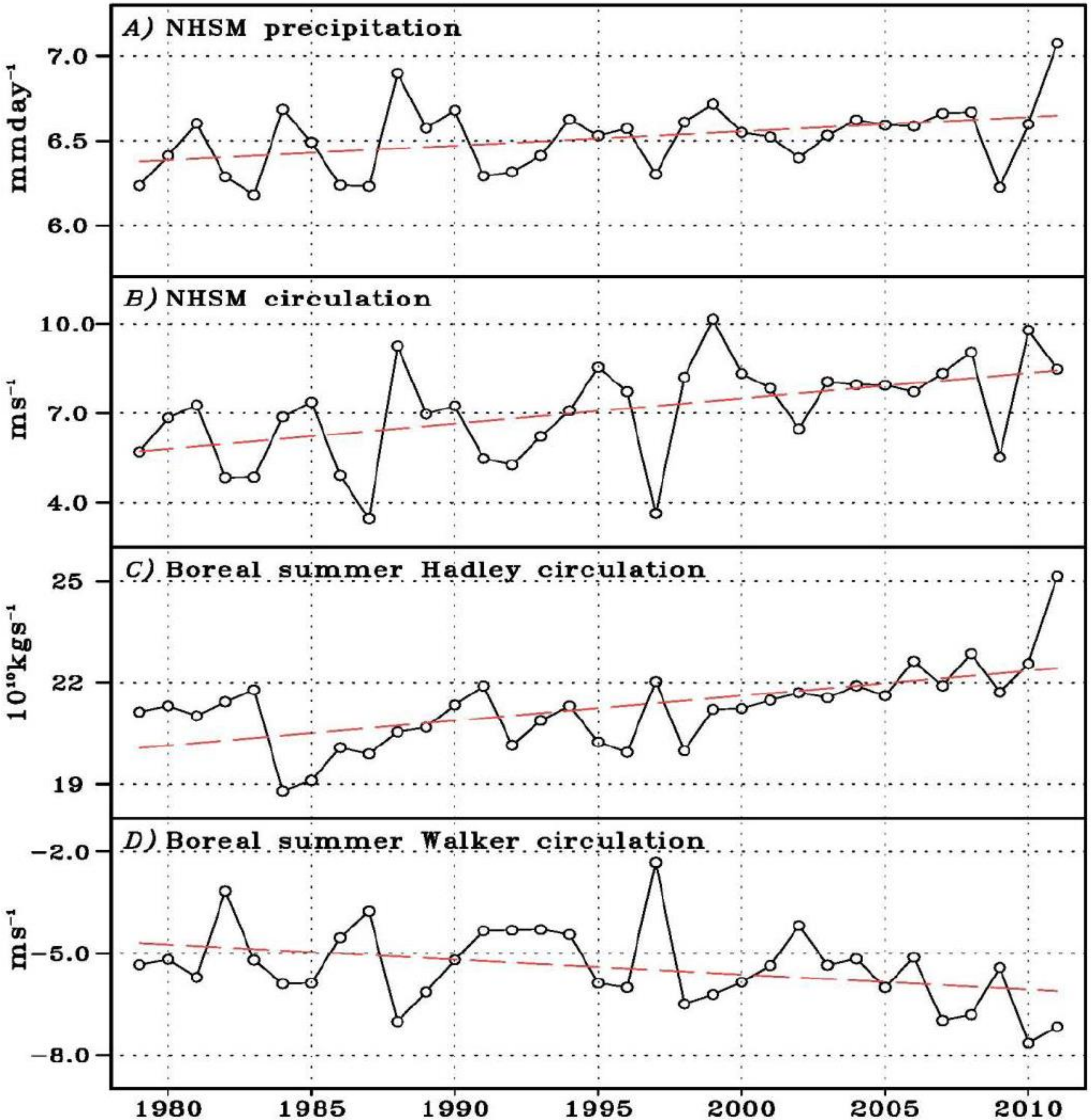
- The decadal variability of the NHLMR is likely a result of the global SST anomalies associated with the NAID and IPO.
- The observed decadal variability of the NHLMR in the past century may be a result of the internal feedback processes within the coupled climate system, possibly modified by the external forcing in the twentieth century.

Physical Linkagae (3):
What is the role of anthropogenic forcing and global warming?

How much the LMR change isdue to global warming resulted from increased greenhouse gases?
How much such a change is due to natural variations?

Wang, B., Liu J., Kim HJ, Webster PJ, Yim SY, and Xiang B., 2013: Northern Hemisphere Summer Monsoon Intensified by Mega-El Nino-Southern Oscillation and Atlantic multidecadal Oscillation, PNAS.

Interannual variation and TRENDS (1979-2011)



(A) NHSM precipitation intensity trend: A 9.5% increase per 1K warming

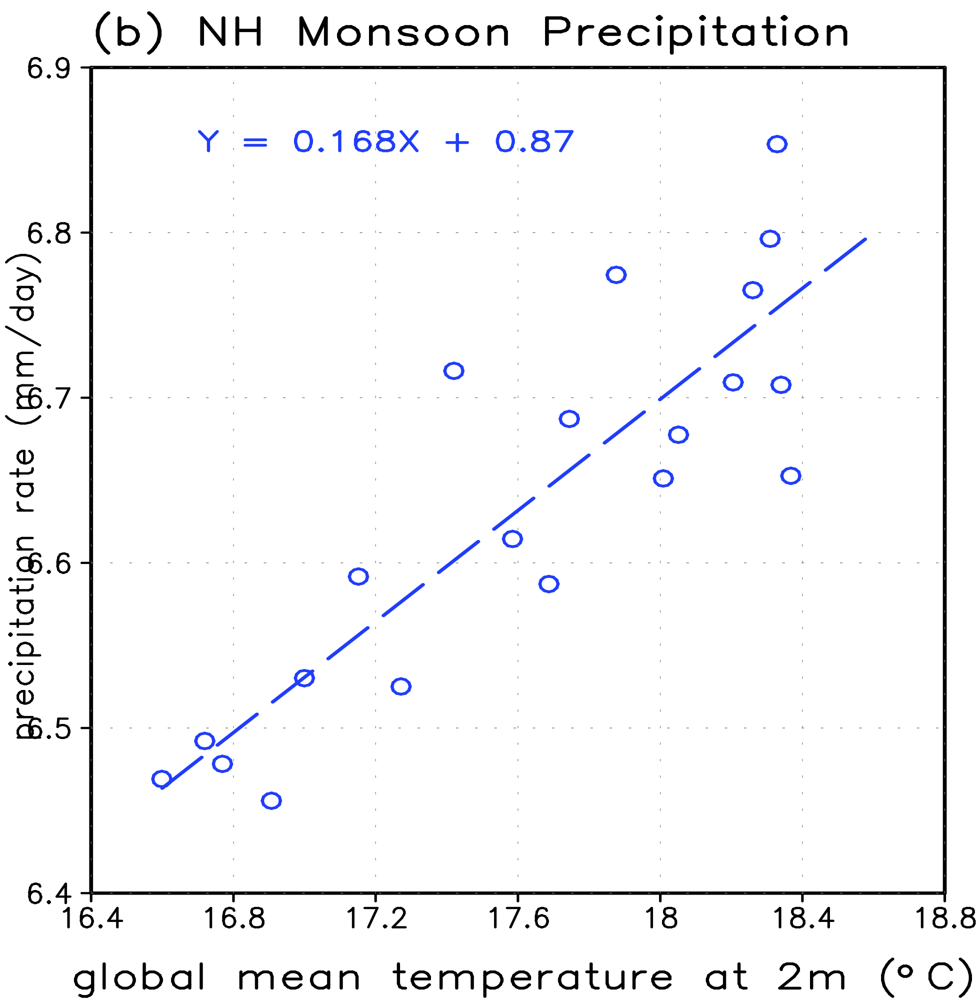
(B) NHSM circulation intensity VWS

(C) Hadley circulation intensity

(D) Walker circulation intensity (925 hPa equatorial westerly)

Wang et al. 2013 PNAS

Anthropogenic forcing can only explain 30% of the recent trend (1979-2013)



MJJAS

Results from CMIP 5 RC4.5 projection by 5 best model MME

NH Summer Monsoon Precipitation: 2.6% per 1K GMT

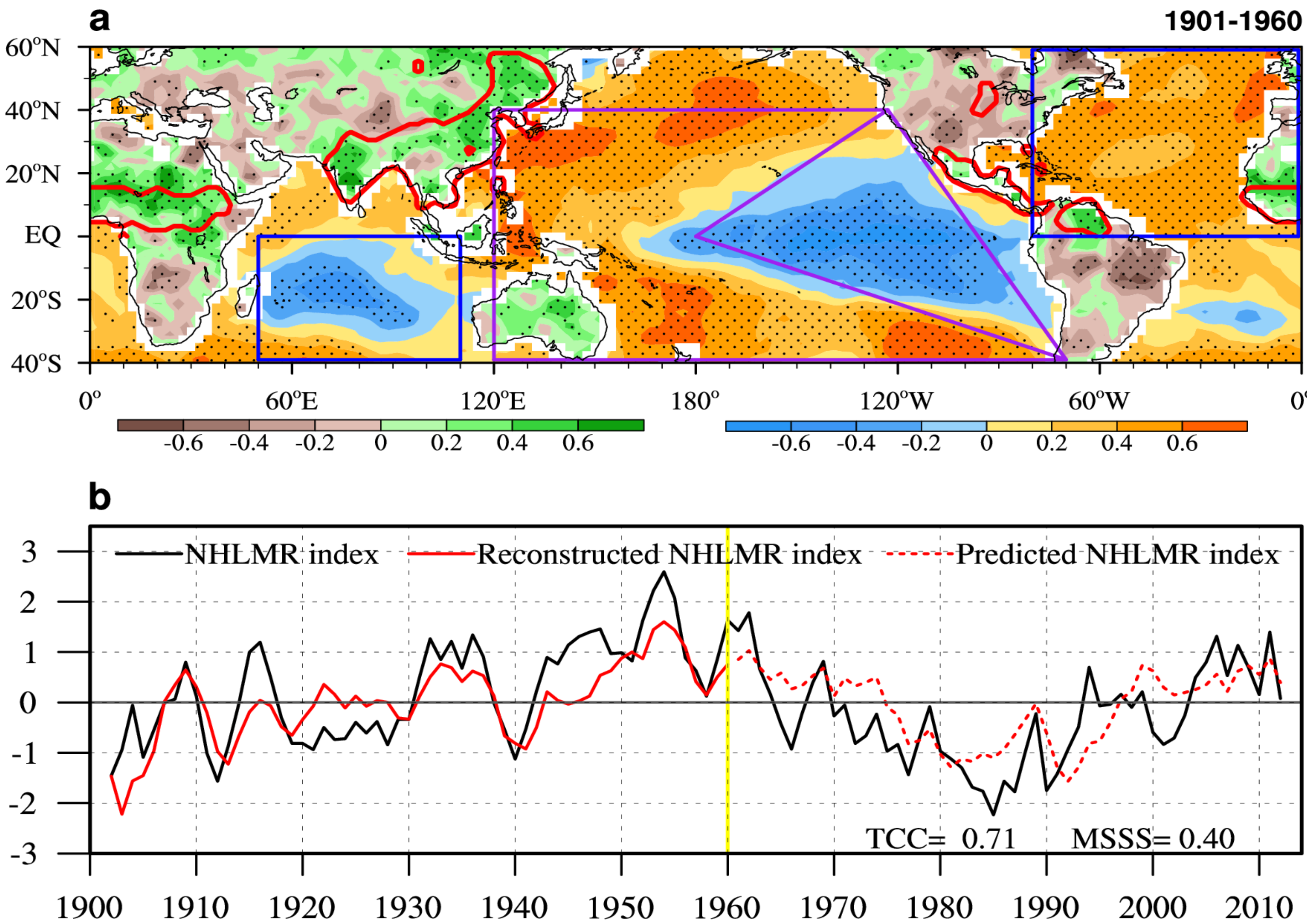
How can we predict Decadal change of the NHLMR ?

Hybrid dynamical-conceptual model

Two-tier conceptual forecast model

- Dynamic models' MME predicts NAID index
- Conceptual model (derived from observation) predict NHLMR index

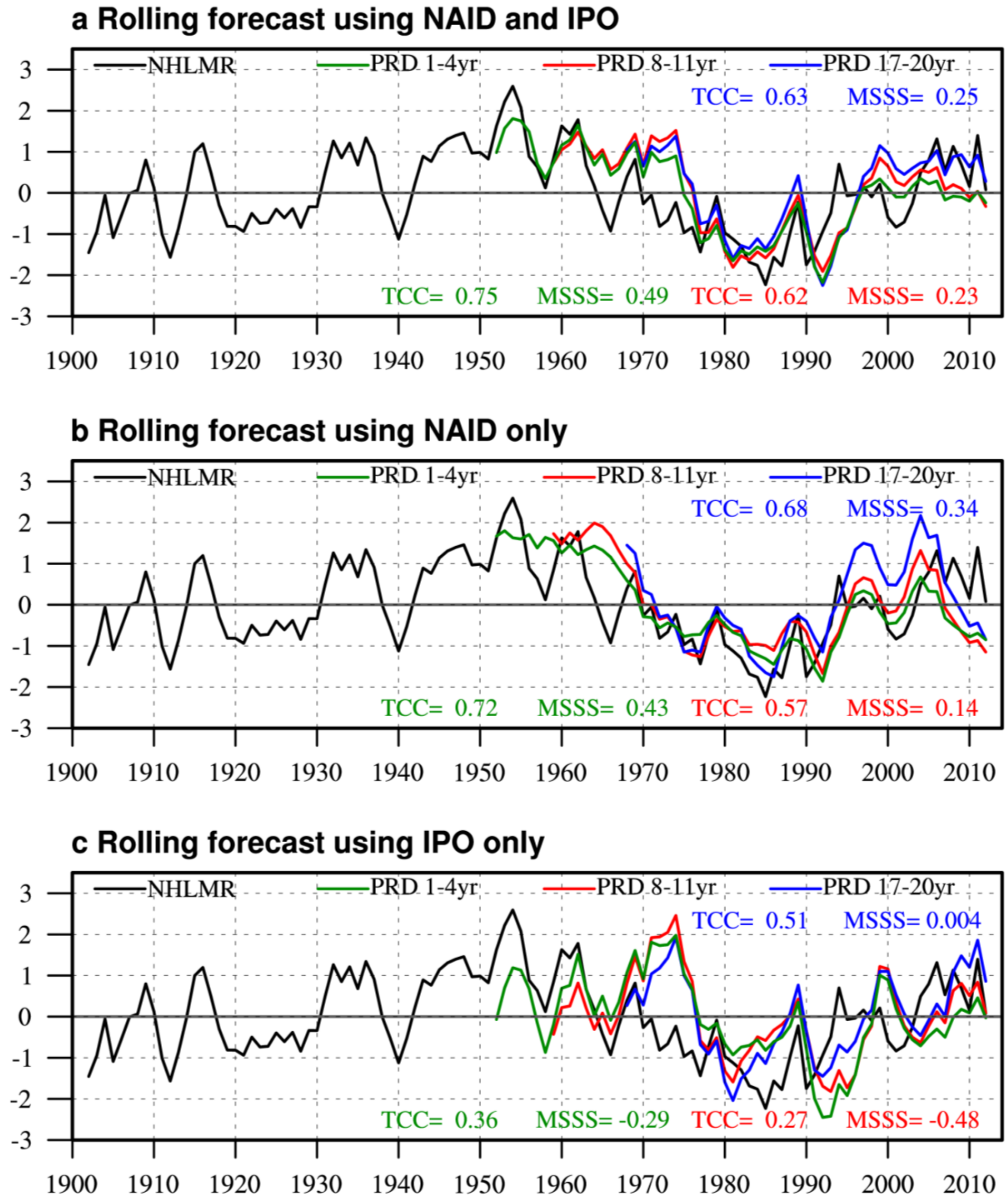
Stationarity of the relationship across 20th century



Conceptual model

Independent Forward-Rolling (IFR) prediction method

A “60 year-10 year” IFR means the conceptual model was derived using only the 60 years of data prior to the initial date of the dynamical prediction; and the forecast is made for the ensuing 10 years using the dynamical models-predicted NAID. Free of artificially built-in skill.



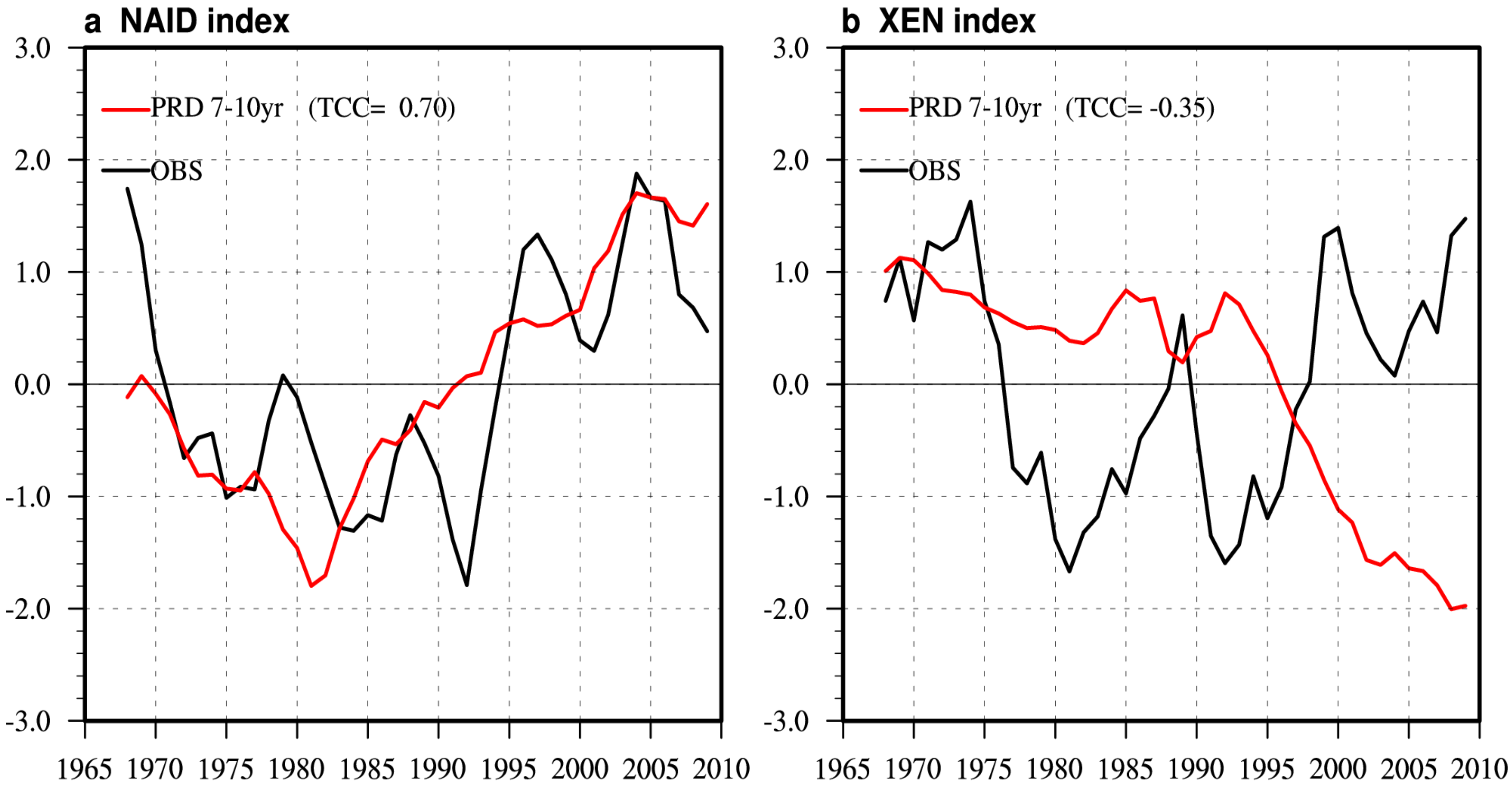
Extended Data Figure 8 | Comparison of the independent rolling-forecast at 1-4, 8-11 and 17-20 year lead times using the observed **a**, NAID and IPO indices, **b**, NAID only, and **c**, IPO only, respectively. The prediction skills are calculated during 4-year mean period of 1952-2012 for 1-4 year lead time, 1959-2012 for 8-11 year lead time and 1968-2012 for 17-20 year lead time.

Comparison (A) and (B) suggests improvement made by adding IPO during 1960s and after 2000.

Can CMIP5 models predict the two multi-decadal modes of global SST:

NAID and IPO modes?

CMP5 models can predict decadal NAID but not XEN



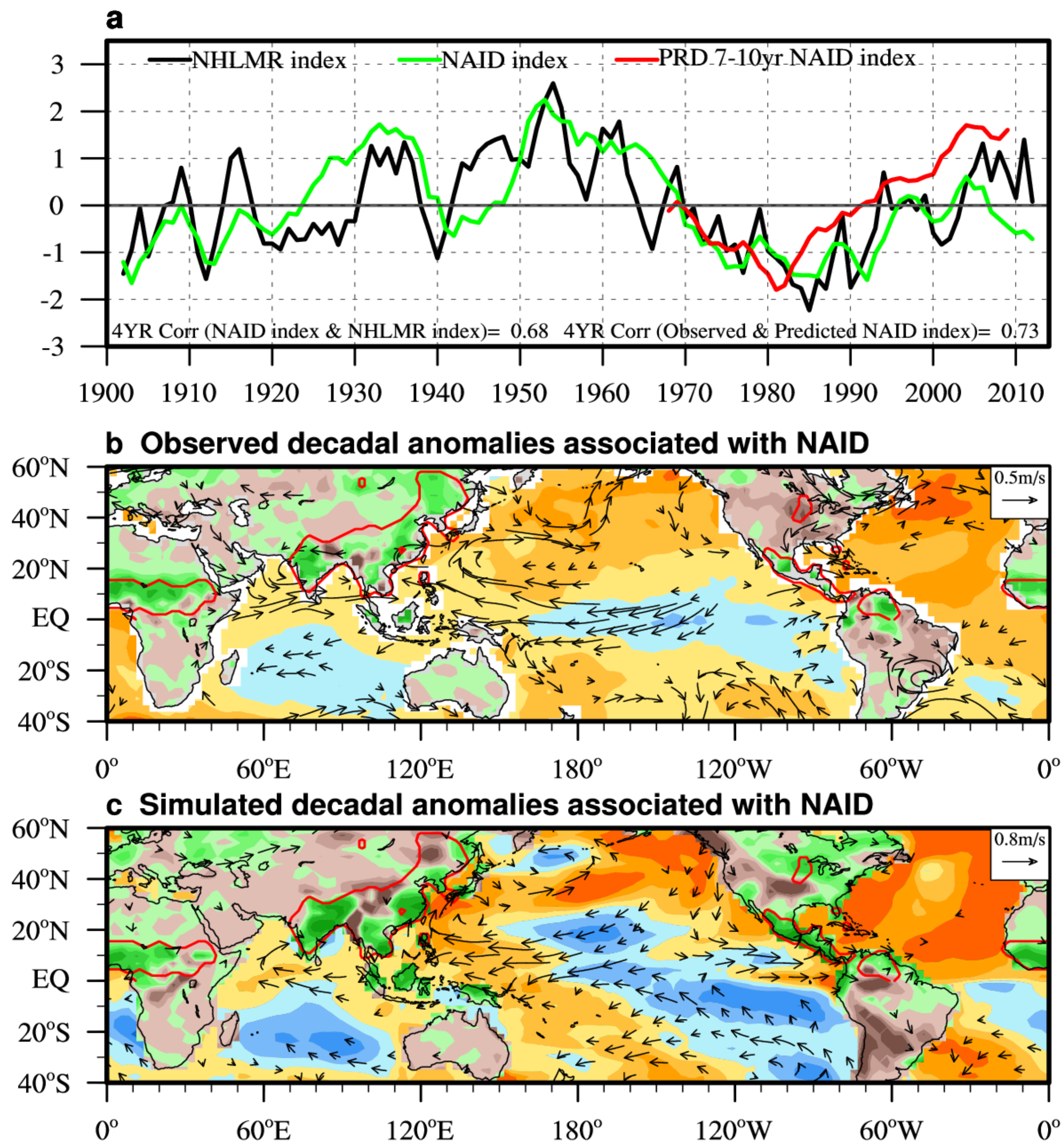
Three models MME was used (CMIP 5 Decadal hindcast 1961-2011):

UKMO Decadal Prediction System (HadCM3), 10 .members (1961-2005)

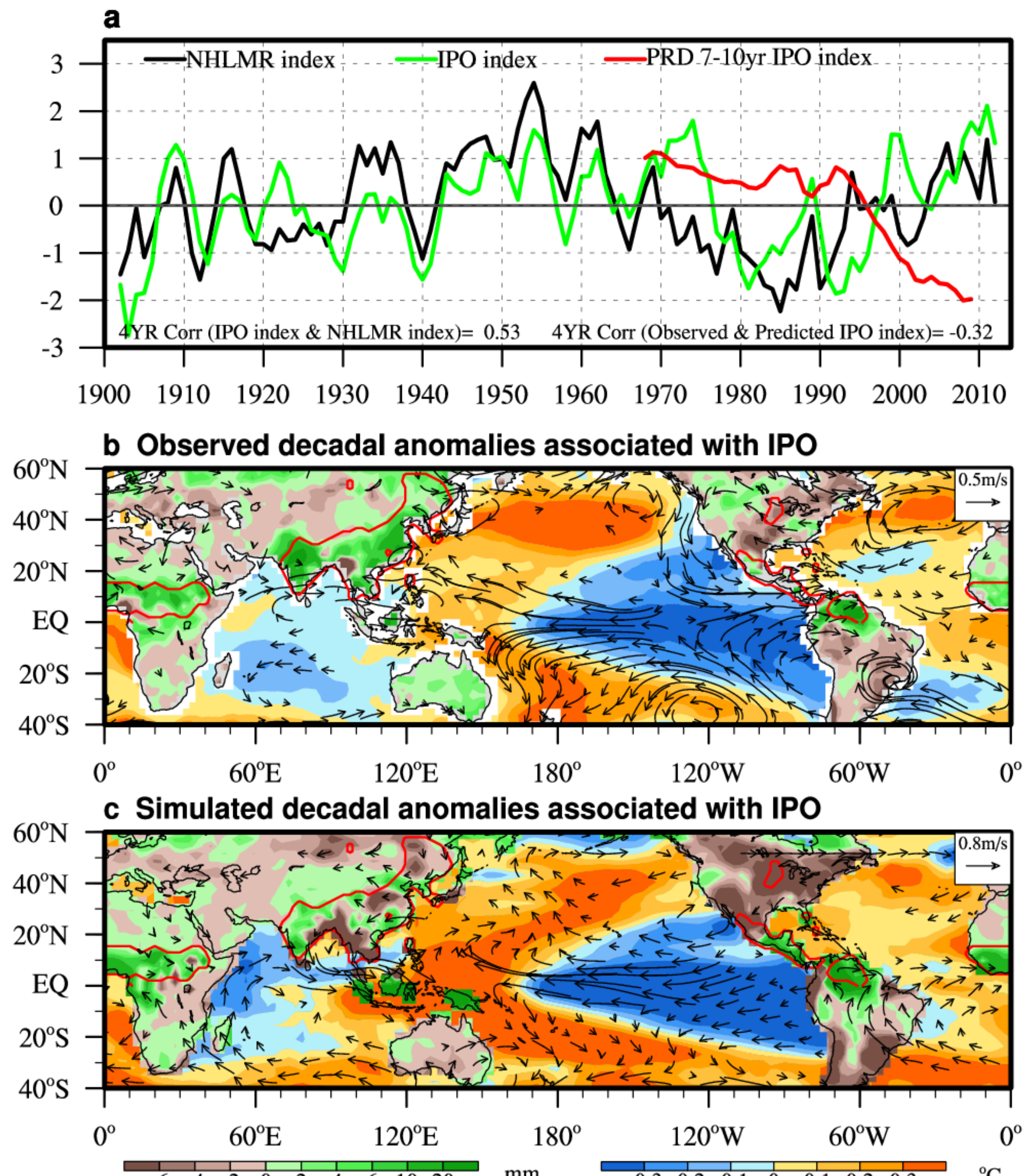
GFDL Climate Model version 2.1 (GFDL-CM2.1), 10 members

MPI ESM Low Resolution (MPI-ESM-LR), 3 members.

Prediction skill for NAID



Prediction skill for Mega-ENSO



Measure of deterministic forecast skill

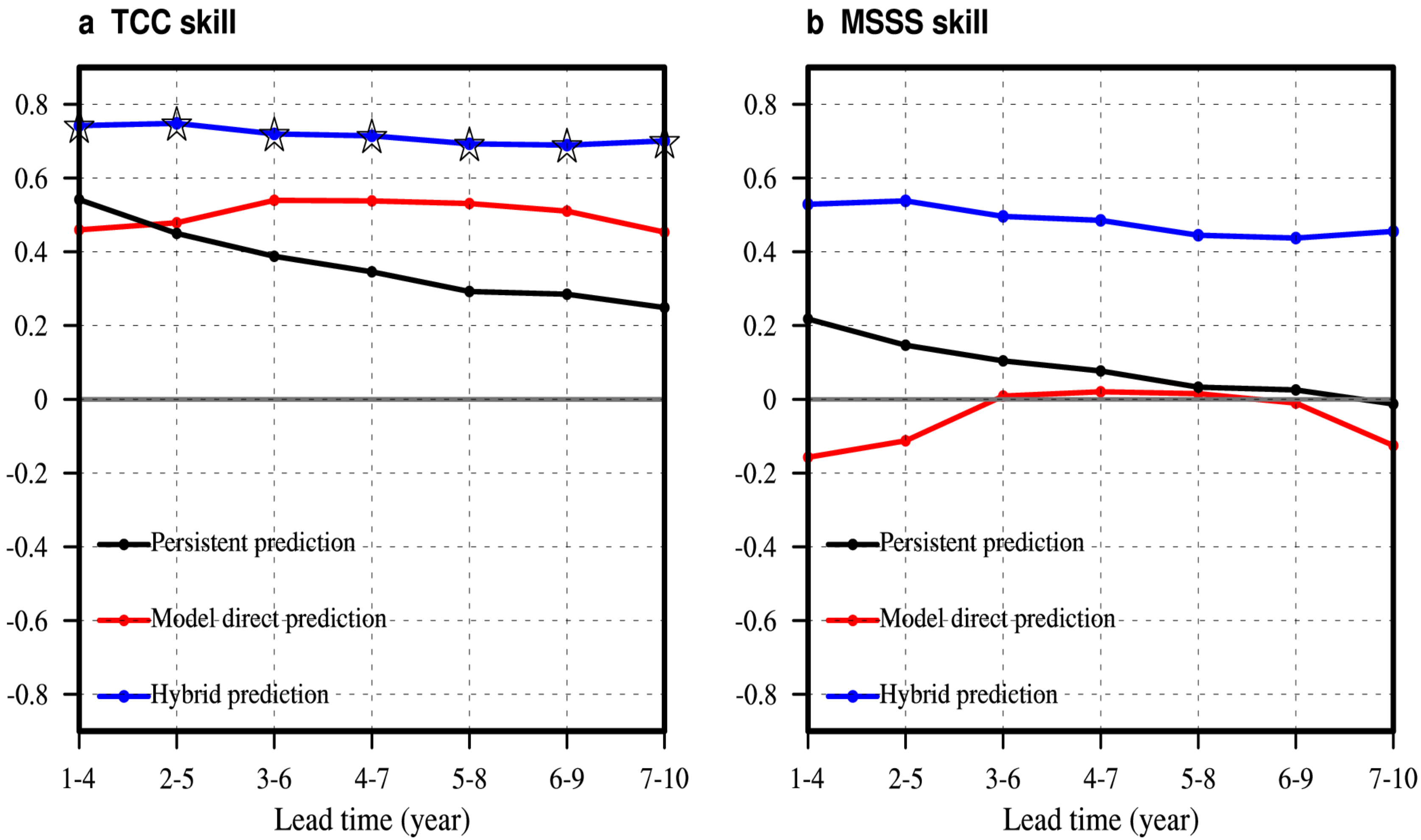
Correlation skill and the Mean Square Skill Score (MSSS) (Murphy 1988; Goddard et al. 2013) were used.

The MSSS reflects the percentage reduction in the mean square error (MSE) of the model forecast (MSE-F) compared to the MSE of climatological “forecast” (MSE-C).

MSSS=1-MSE-F/MSE-C

Positive (negative) skill indicates the model forecast is better (worse) than the climatological “forecast” .

Independent Decadal Hindcast for NHLMR(1967-2011)



The hybrid forecast used the model-predicted NAID index only. Stars indicate that the TCC is significant at a 95% confidence level taking serial autocorrelation into account.

$$\text{MSSS}=1-\frac{MSE}{MSE_c},$$

Concluding remarks

- Decadal predictability of the NHLMR is rooted in the SSTA contrast between NH and SH in Atlantic and Indian Ocean (NAID) and augmented by an east-west thermal contrast in the Pacific (mega-ENSO).
- The decadal NHLMR and associated two global SST modes are mainly due to internal feedback processes, possibly modified by natural and anthropogenic external forcing.
- A 51-year, independent decadal hindcast made by hybrid dynamic-conceptual model shows decadal changes in the NHLMR may be predicted approximately a decade in advance with significant skills.
- The results here open a promising way forward for decadal predictions of regional land monsoon rainfall worldwide.

How important is the IPO factor?

In the hybrid model prediction, the IPO index was not used because the models could not predict its decadal variation (Fig. S4). If dynamical models can capture IPO realistically, the prediction might be better. This speculation is tested by additional potential predictability experiments. Comparison of the potential predictability estimated by using NAID and IPO (Fig. S5A) and by using NAID only (Fig. S5B) suggests that use of IPO does improve the prediction during some decades, such as the 1960s and after the late 1990s, but becomes worse in 1970s.

In addition, use of IPO alone does not yield significant skill (Fig. S5C), suggesting that use of IPO may not be ciritical for NHLMR forecast.

Remaining issues

Prediction of regional LMR: regional LMR intensities are not solely driven by the NAID and IPO. Exploration and implementation of SST predictors that reflect distinct sources of predictability of individual regional monsoons are imperative. A detailed regional approach to LMR prediction is underway.

Physical processes determining NAID:

The North Atlantic SST is likely driven by atmospheric noise and affected by radiative forcing (greenhouse gases and aerosols) (Bellomo et al. 2017; Cane et al. 2017; Murphy et al. 2017, Bellucci et al. 2017).

The north-south thermal contrast in the Atlantic is suggested to be related to fluctuations in the AMOC (Liu 2011; McCarthy et al. 2015), although this mechanism remains subject to considerable debate (Knudsen et al. 2014).

The physical link between the South Atlantic and SIO SST variability is an open issue.

Other external forcing: volcanic eruptions (Liu et al. 2016); anthropogenic aerosol emissions (Polson et al. 2014; Guo et al. 2015).

END

Origins of the decadal predictability of East Asian land summer monsoon rainfall

Li, J., B. Wang, 2018: **Origins of the decadal predictability of East Asian land summer monsoon rainfall.** *J. Climate, 31 6229-*.

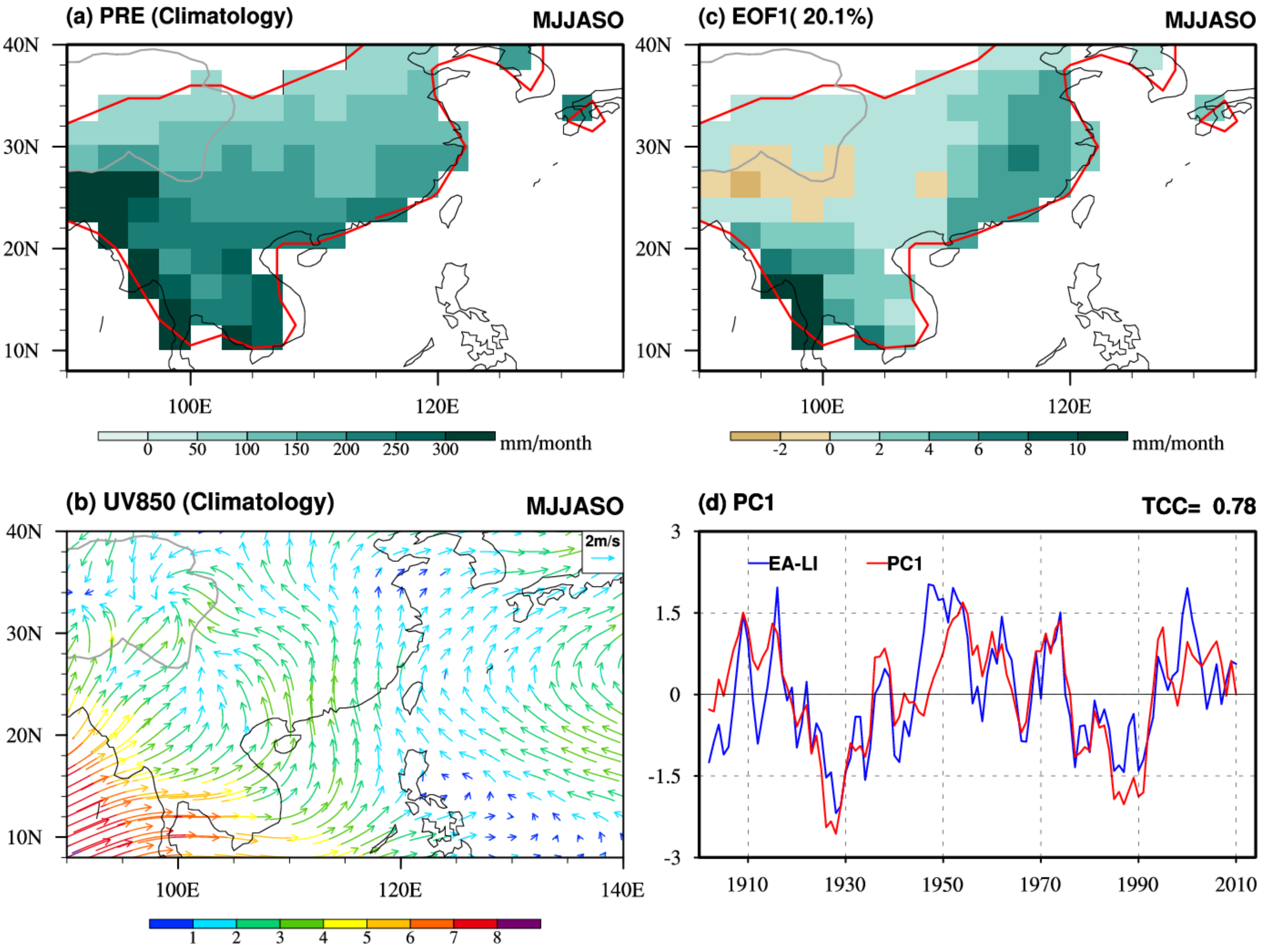


Figure 1. The detrended data are used to perform EOF analysis. 4-year running mean is applied in (c)-(d). The year in panel (d) represents the second year of the four-year running mean. For example, the value for 1902 is the average for the period of 1901-1904.

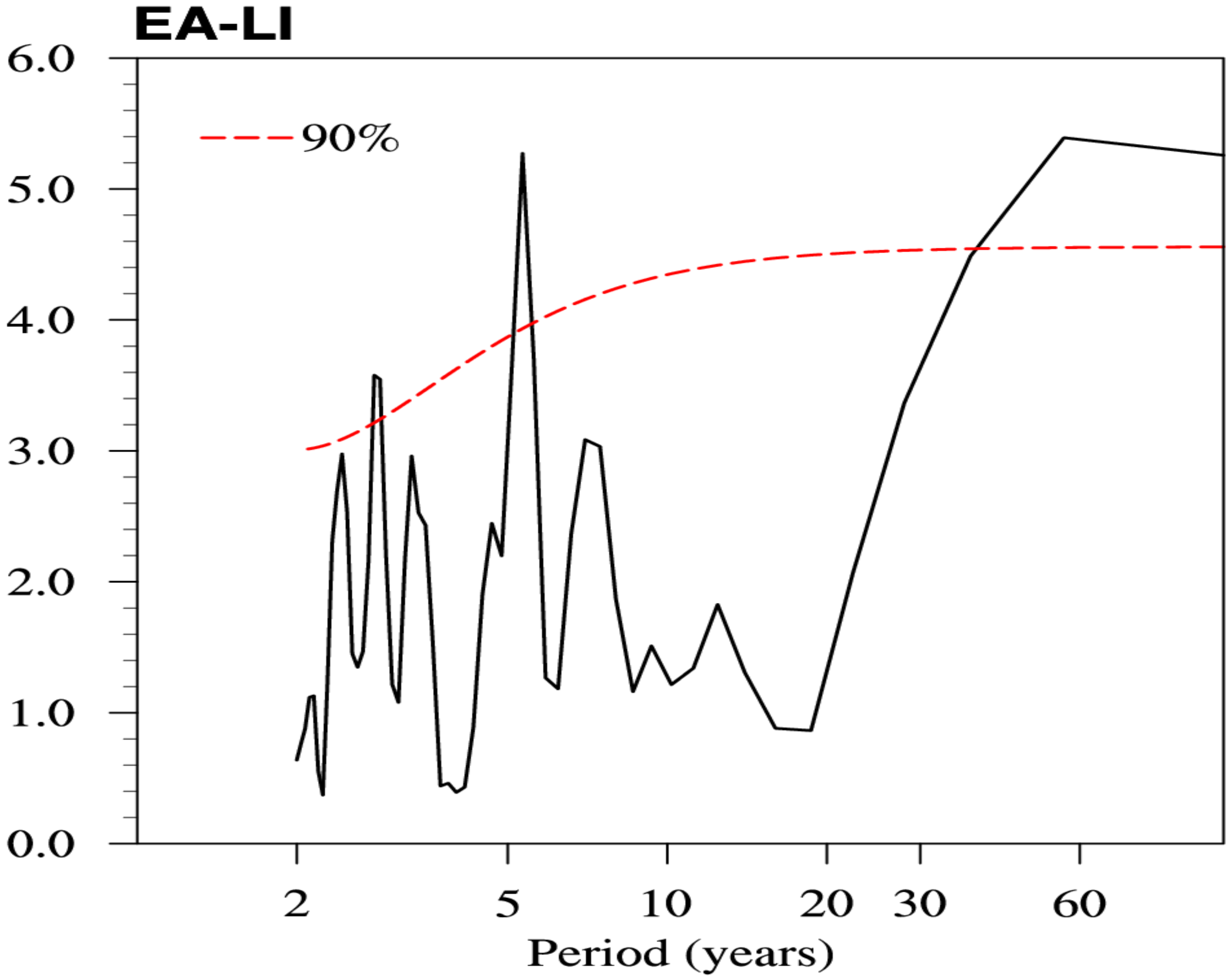


Figure 2. Spectra of yearly summer (MJJASO) mean EA-LI obtained with averaging three periodogram bins (bandwidth: 40)

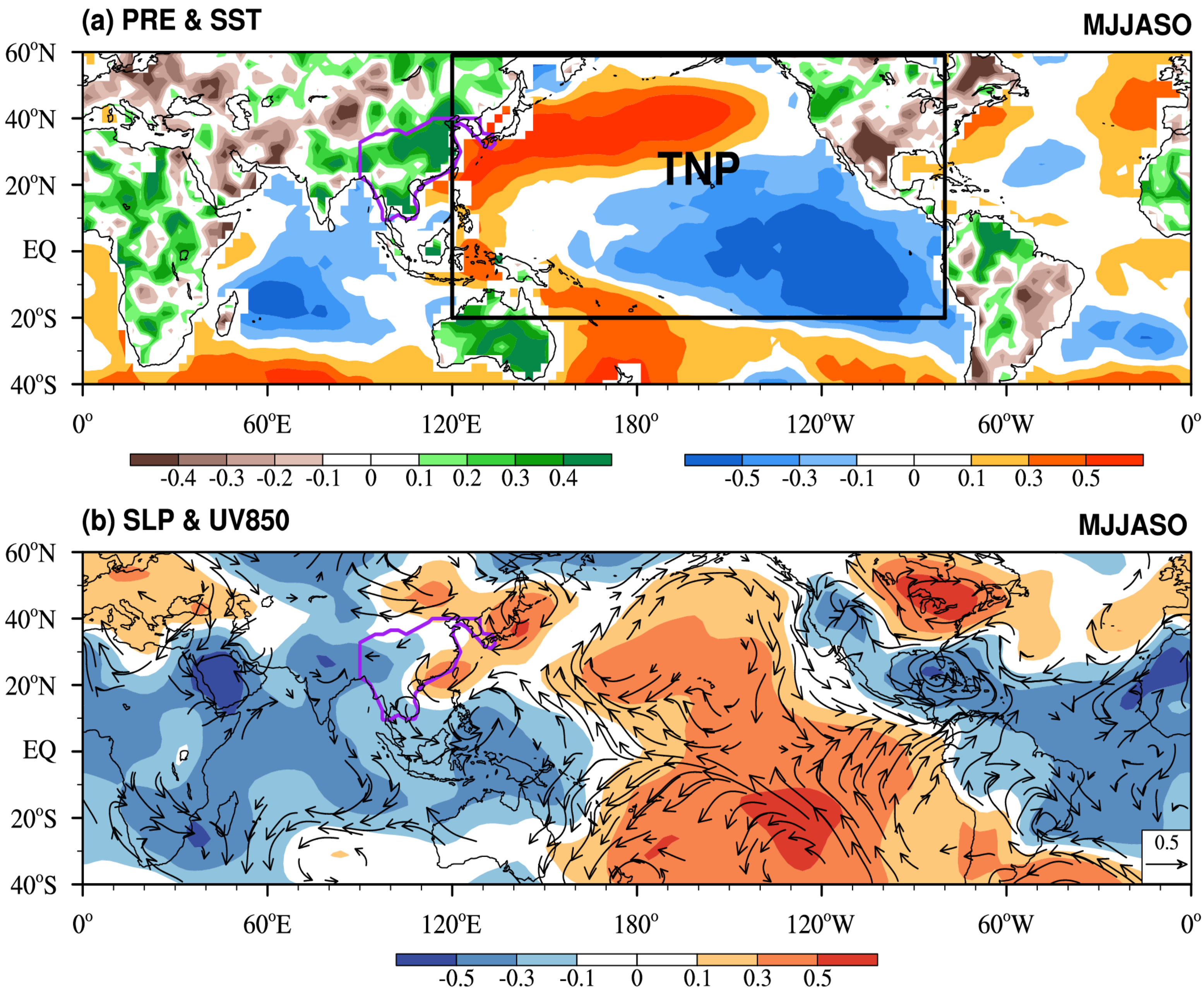
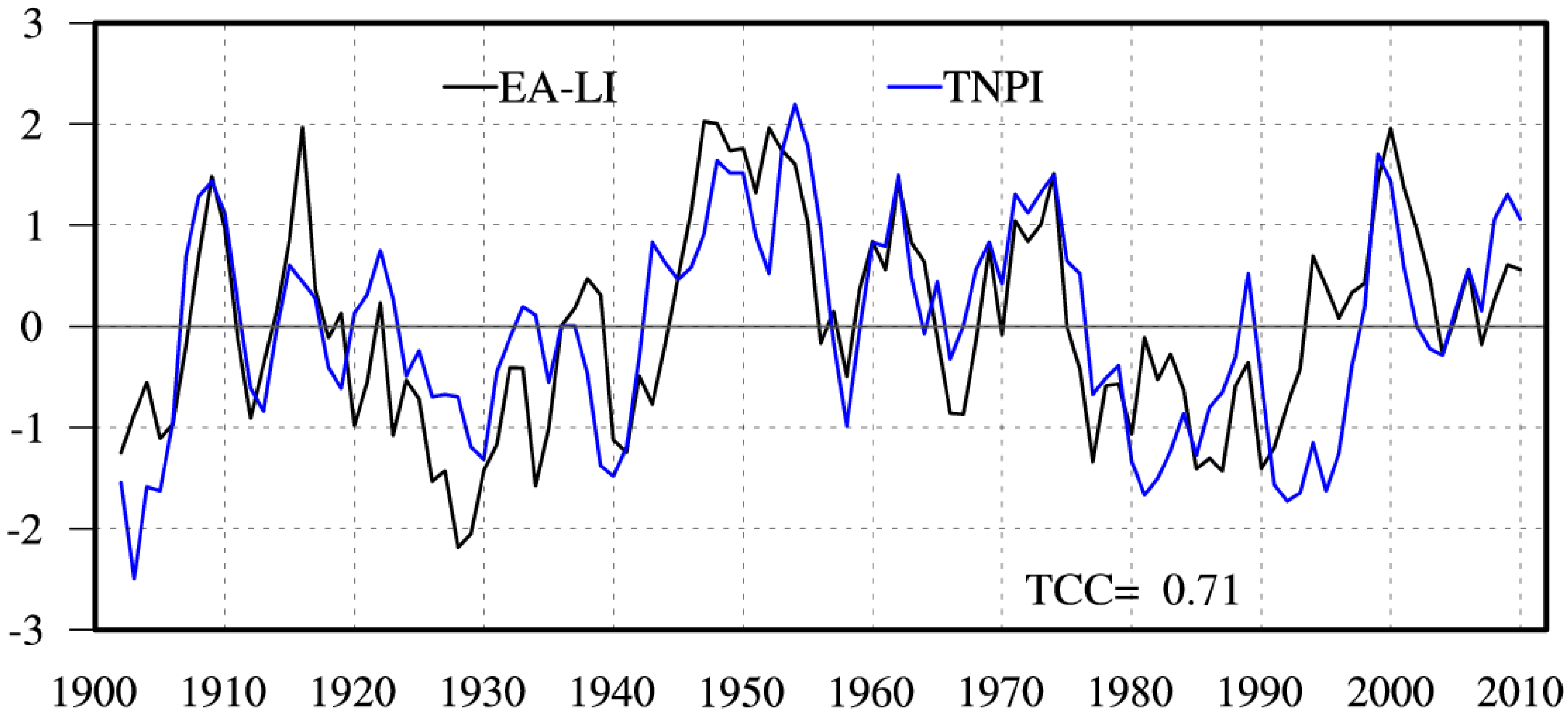


Figure 3. 1901 to 1960. Four-year running mean is applied. The black box indicate the region for TNP. EA-LR domain is outlined by purple curves.



TNPI(t)=[SST(t,lat,lon) *TCC(lat,lon)]

TCC: temporal correlation coefficient between the EA-LI and SST values during training period (1901-1960),
Square bracket is the areal mean over (20S-60N, 120E-80W).

Figure.4 Time series of observed decadal EA-LI and predictor TNPI.

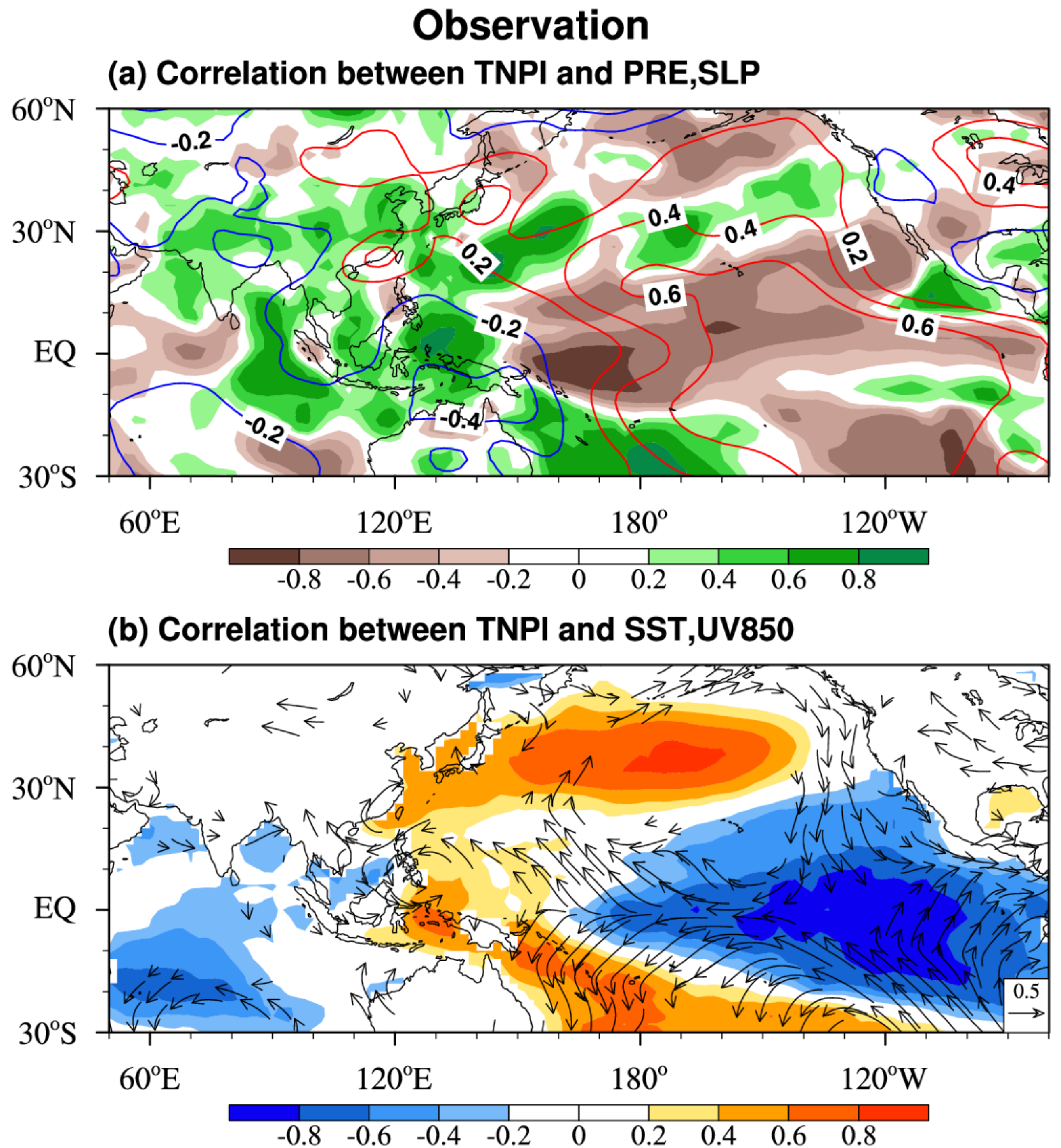
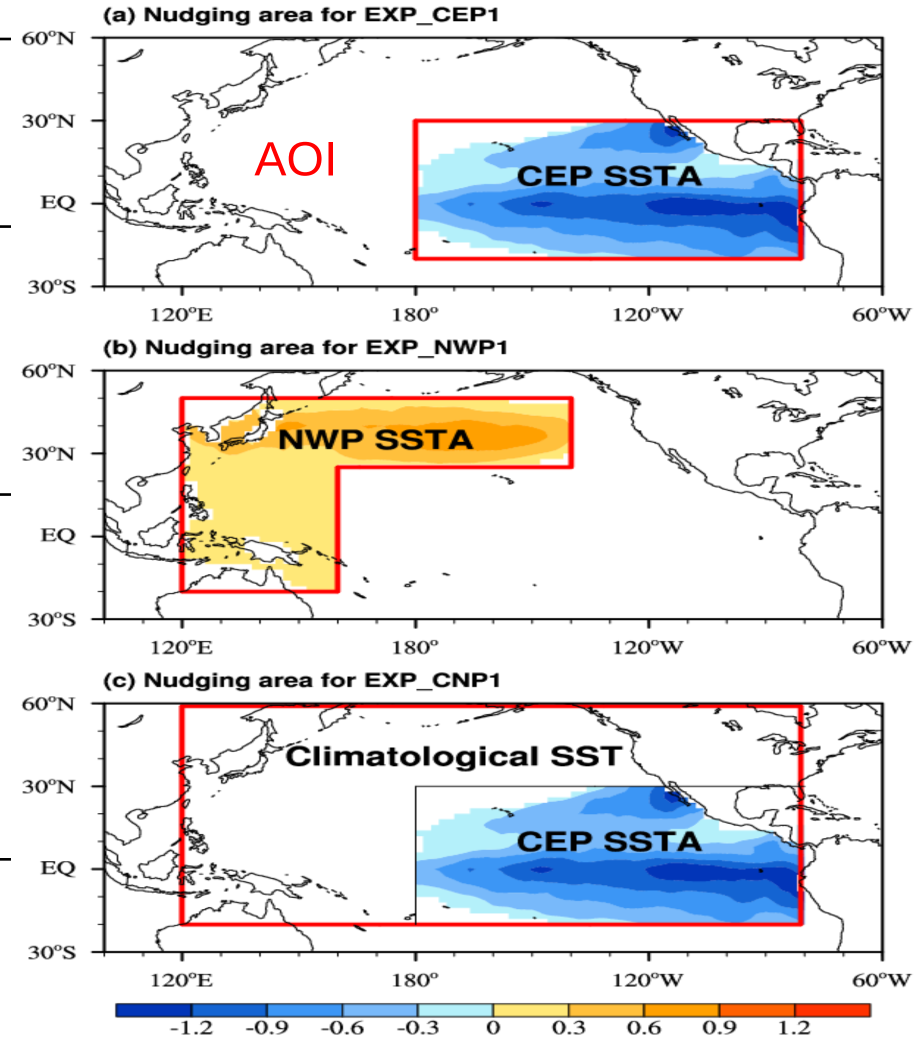


Figure 5. Observed correlations maps of MJJASO anomalies with reference to TNPI using data from 1901 to 1960. Four-year running mean is applied.

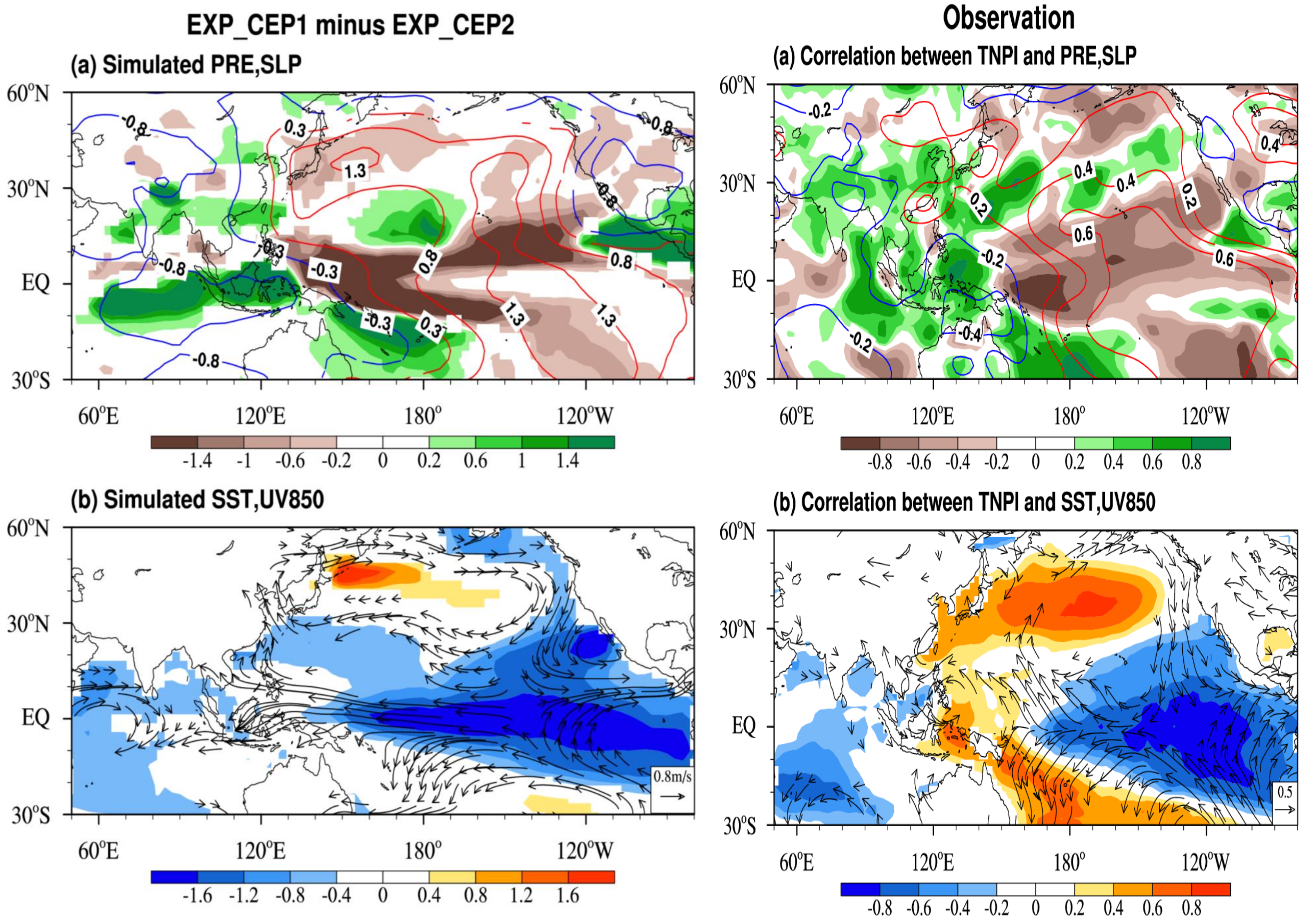
Numerical experiments with NUIST CSM v.1

Each experiment contains 30 ensemble members.
Control run (CTRL) is free coupled run.

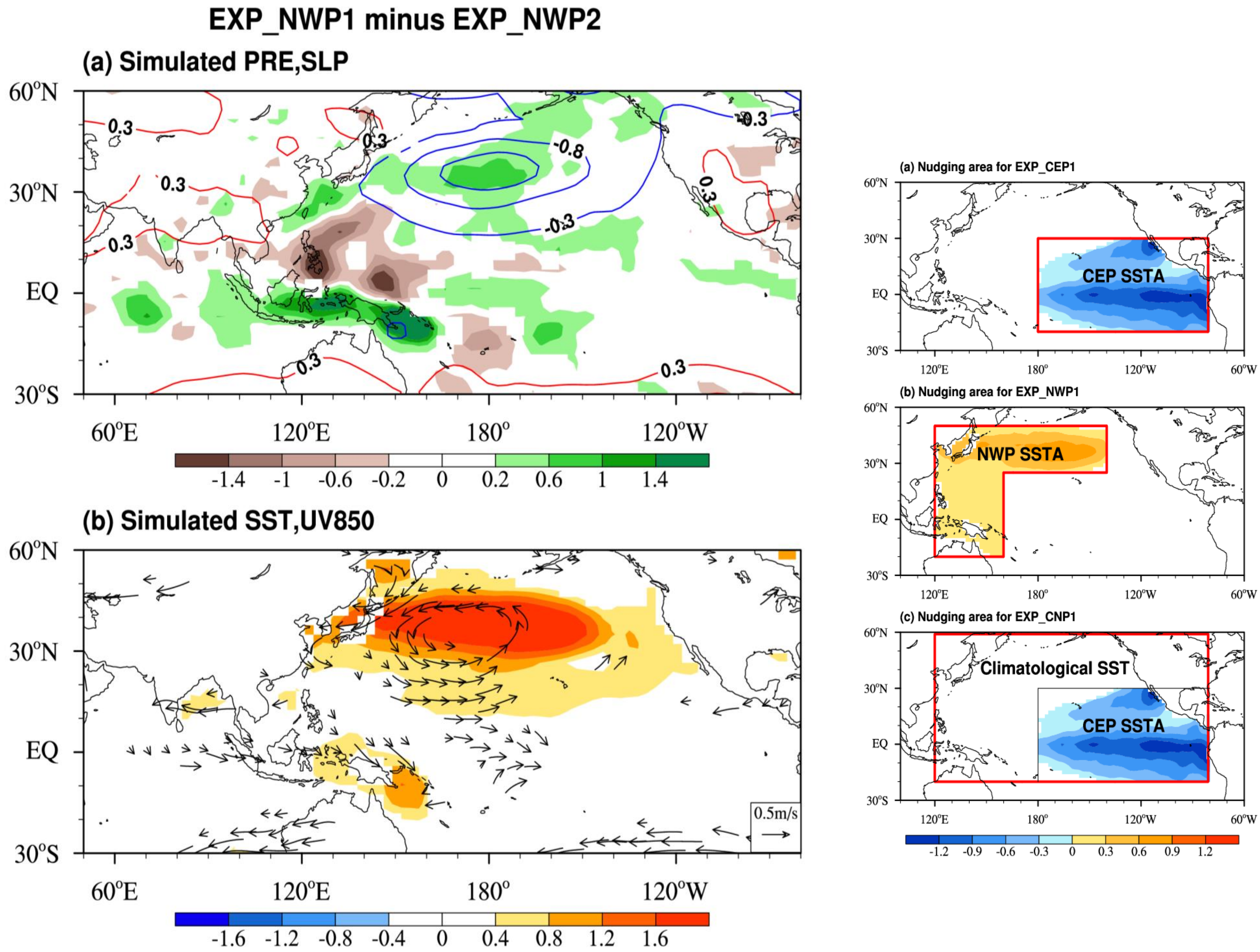
Experiments	Descriptions
EXP_CEP 1(2)	CTRL but nudging by predictor SSTA (-SSTA) in CEP[20°S-30°N, 180°-80°W] from May to Oct.
EXP_NWP1(2)	CTRL but nudging by predictor SSTA (-SSTA) in NWP [25°N-50°N, 120°E-140°W and 20°S-25°N, 120°E-160°E] from May to Oct.
EXP_CNP 1(2)	CTRL but nudging by climatological SST in NWP and predictor SSTA (-SSTA) in CEP from May to Oct.



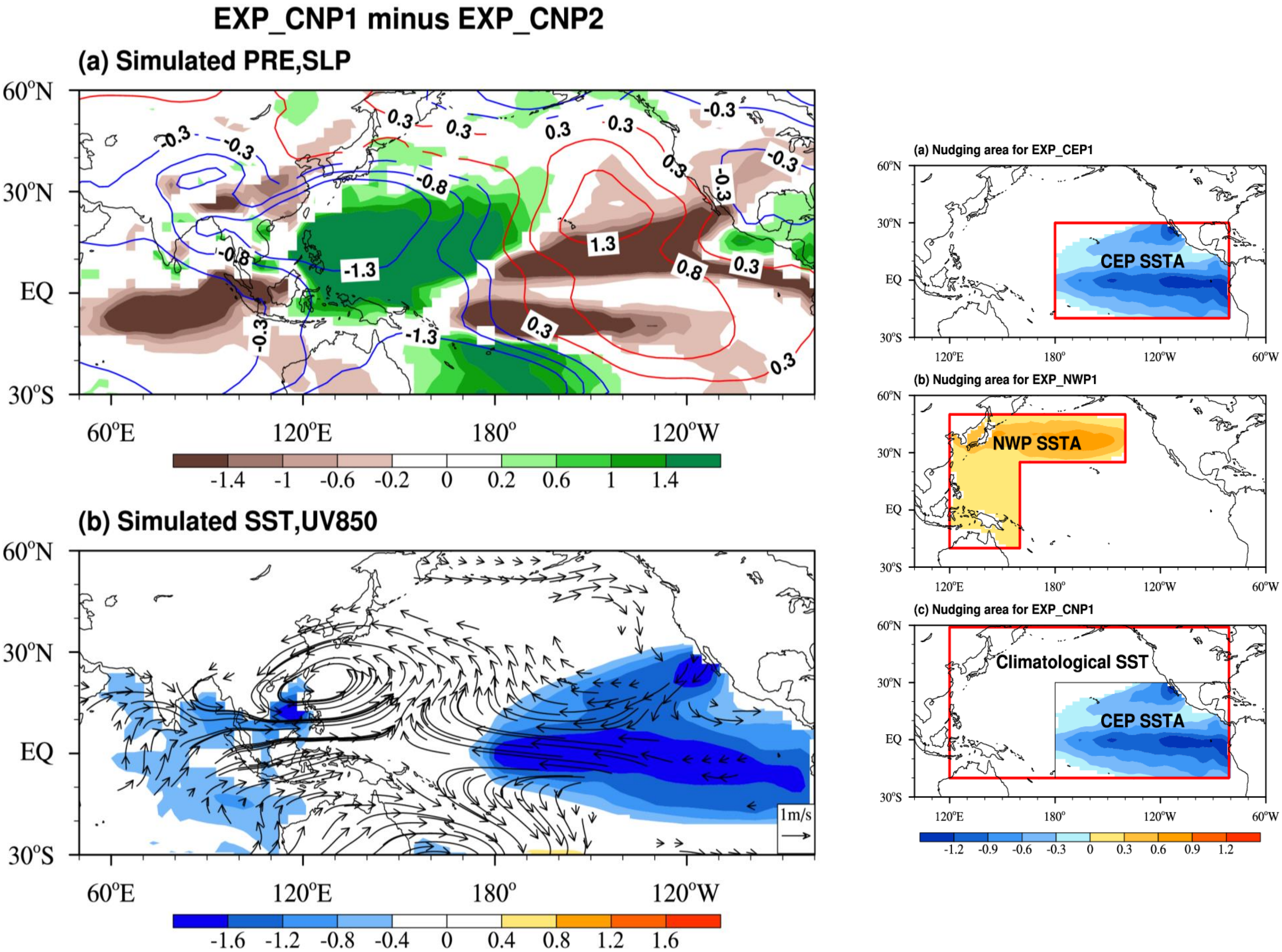
SSTA (ΔSST) in May



EXP_CEP1 minus EXP_CEP2
(a) Simulated PRE,SLP
(b) Simulated SST,UV850
Observation
(a) Correlation between TNPI and PRE,SLP
(b) Correlation between TNPI and SST,UV850
60°N
30°N
EQ
30°S
60°E
120°E
180°
120°W
0.8m/s
0.5
-1.4 -1 -0.6 -0.2 0 0.2 0.6 1 1.4
-1.6 -1.2 -0.8 -0.4 0 0.4 0.8 1.2 1.6
-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8



EXP_NWP1 minus EXP_NWP2
(a) Simulated PRE,SLP
(b) Simulated SST,UV850
0.5m/s
(a) Nudging area for EXP_CEP1
CEP SSTA
(b) Nudging area for EXP_NWP1
NWP SSTA
(c) Nudging area for EXP_CNP1
Climatological SST
CEP SSTA


EXP_CNP1 minus EXP_CNP2
(a) Simulated PRE,SLP
60°N
30°N
EQ
30°S
60°E
120°E
180°
120°W
-0.3
0.3
-0.8
-1.3
1.3
0.8
-1.4
-1
-0.6
-0.2
0
0.2
0.6
1
1.4
(b) Simulated SST,UV850
1m/s
-1.6
-1.2
-0.8
-0.4
0.4
0.8
1.2
1.6
(a) Nudging area for EXP_CEP1
CEP SSTA
60°W
(b) Nudging area for EXP_NWP1
NWP SSTA
(c) Nudging area for EXP_CNP1
Climatological SST
CEP SSTA
-1.2
-0.9
-0.6
-0.3
0
0.3
0.6
0.9
1.2

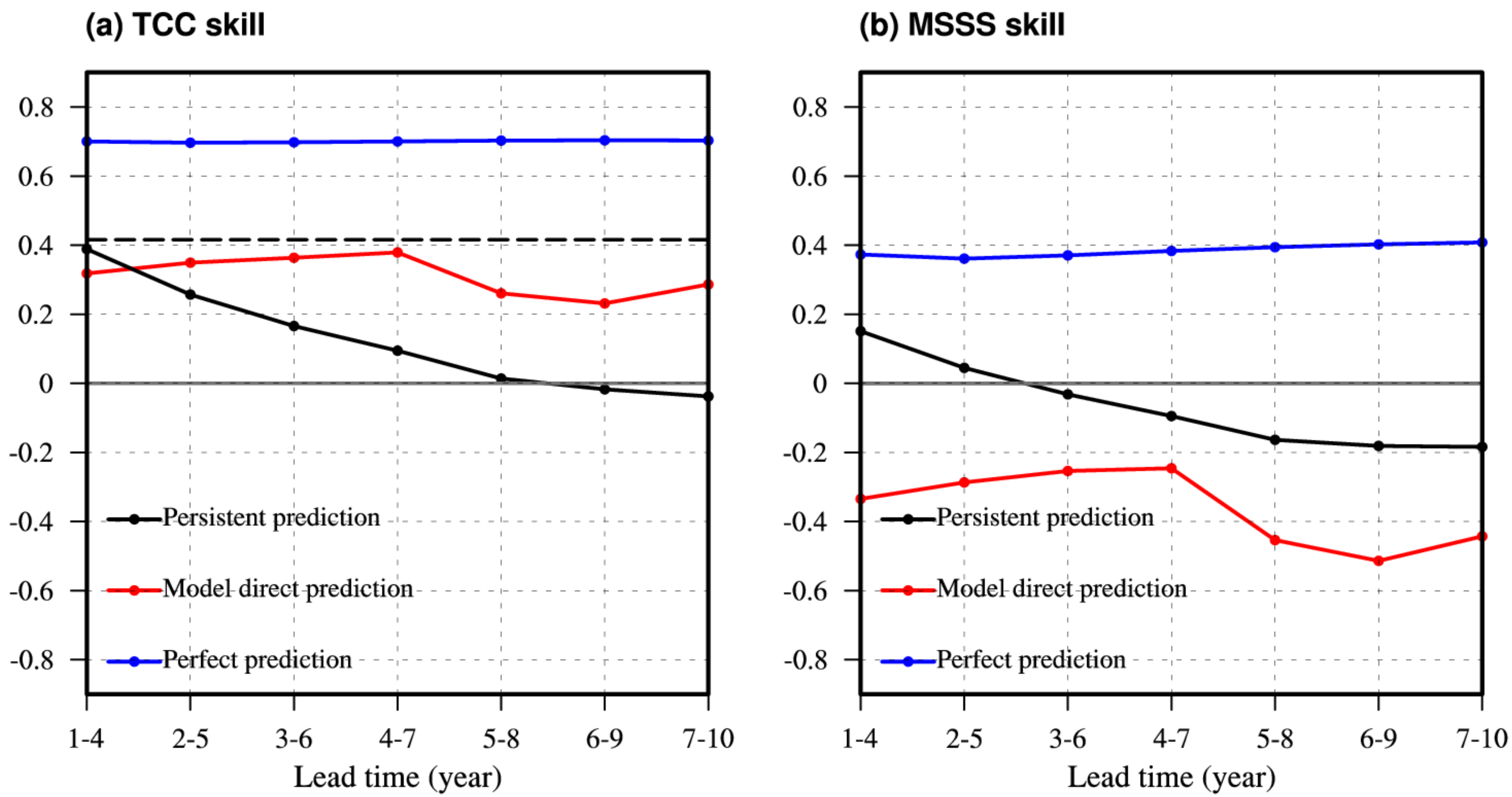


Figure 10. Decadal hindcast skills for EA-LI. (a). TCC skill derived by “perfect” prediction, model direct perdition and persistent prediction as functions of lead time (year) for the period of 1967-2011 (i.e. 4-y running mean from 1968 to 2009). The dashed horizontal line represents statistical significance of the correlation coefficients at 95% confidence level by Monte Carlo test. (b). Same as (a) but for MSSS skill.

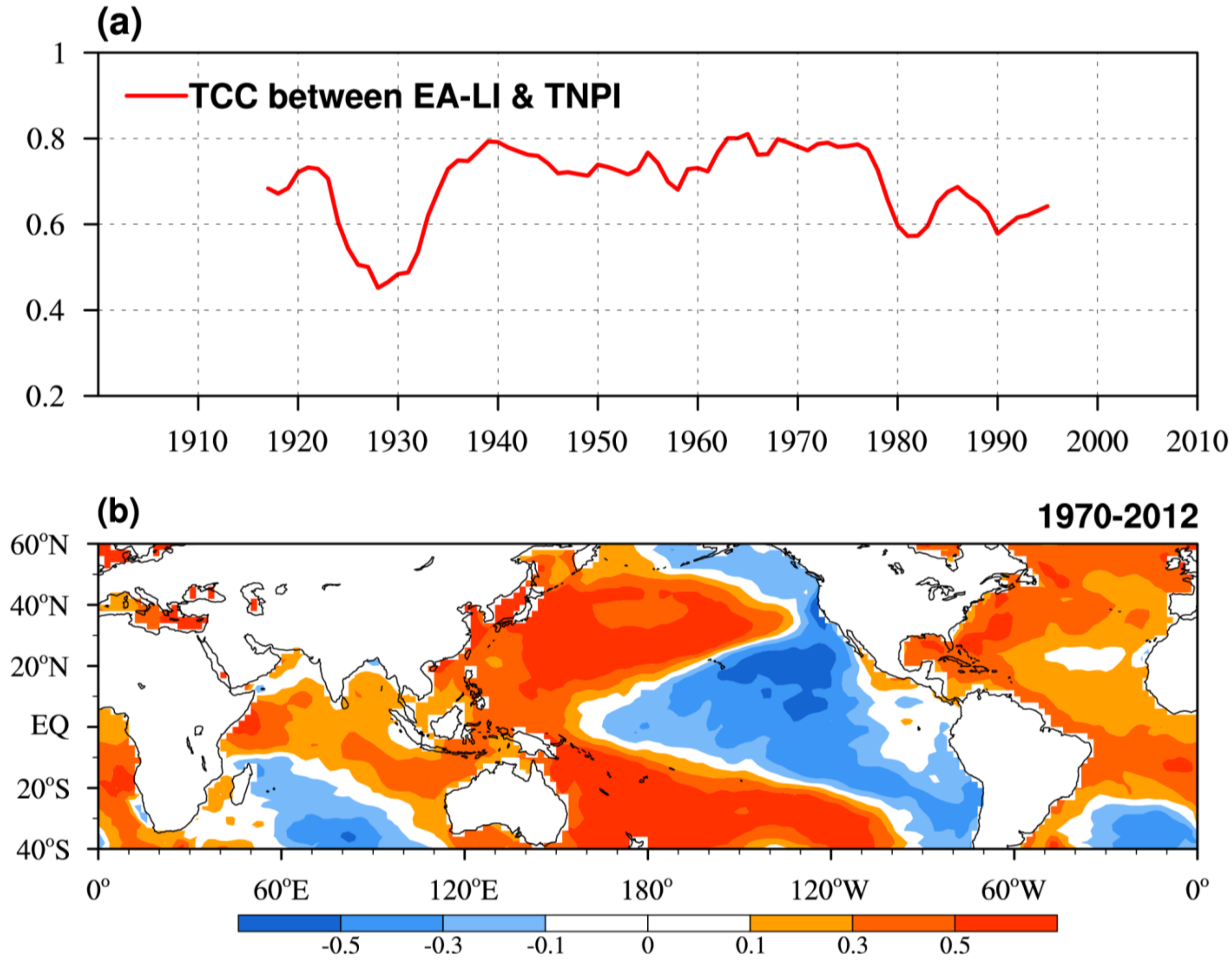
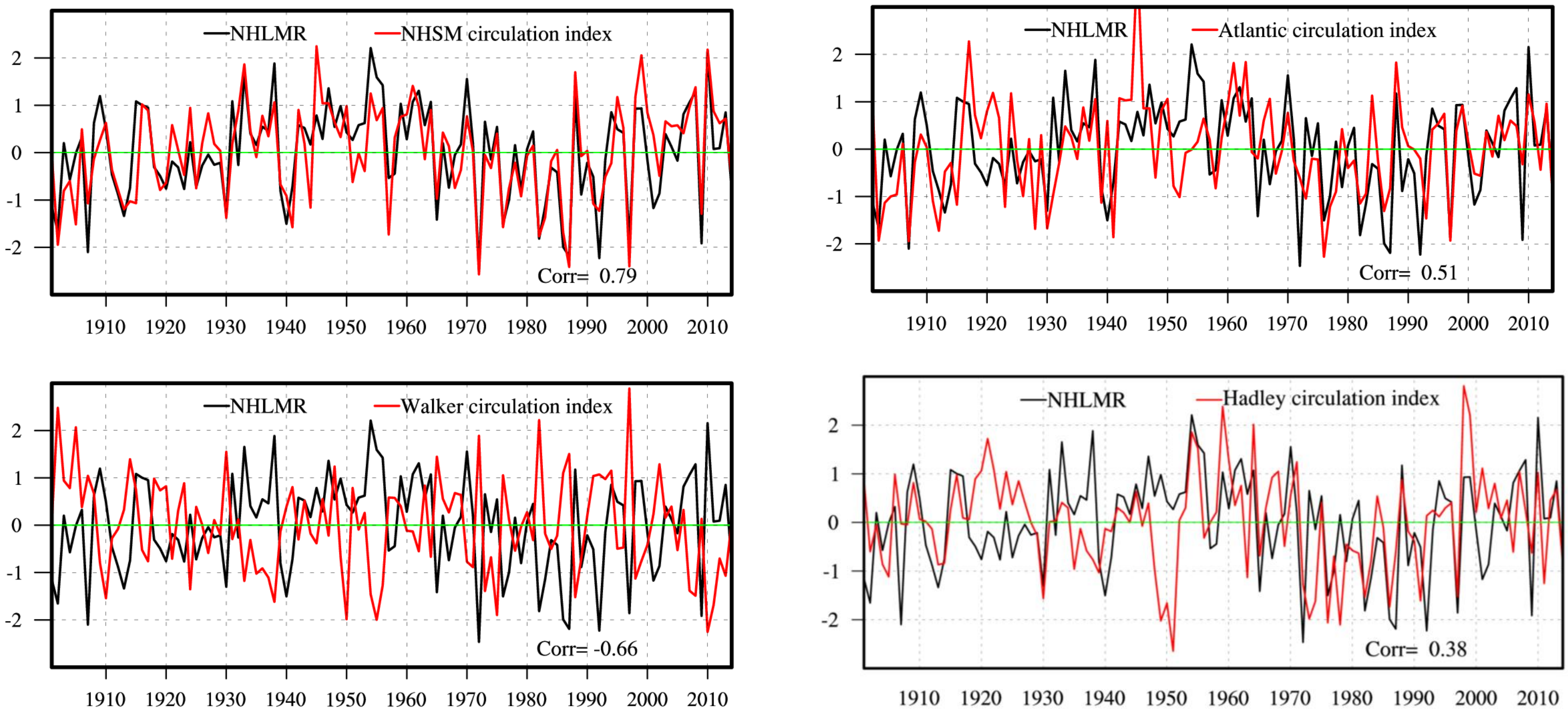


Figure 11. (a) Time series of the 31-year central sliding correlation coefficients between EA-LI and TNPI. (b) Simultaneous (MJJASO) correlation coefficient map of SST (shading over ocean) with reference to EA-LI using data from 1970 to 2012. Four-year running mean is applied.

Conclusion

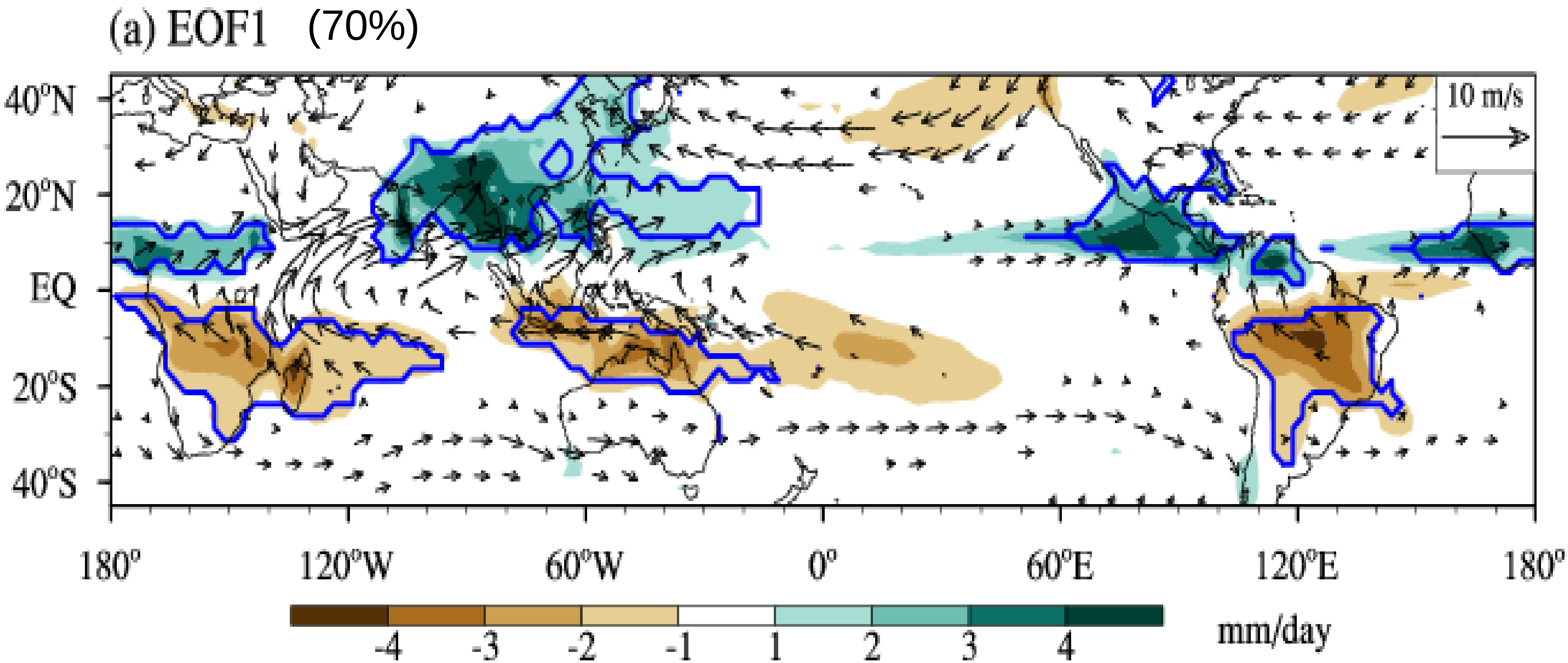
- The domain-averaged EA-LR index (EA-LI) during May-October represents the leading mode of decadal variability and its decadal variations is primarily linked to a cooling over CEP and a warming over the NWP.
- The CEP cooling may be a major driver to EA-LR, while the NWP warming is largely a response, which cannot be treated as a forcing to EA-LR. However, the atmosphere-ocean interaction in WNP is also critical for EA-LR variability.
- Assuming the tropical-North Pacific SSTA can be "perfectly" forecasted, the prediction of EA-LI using a PEM, yields a significant TCC skill of 0.70 at a 7-10-year lead time during a 40-year independent hindcast (1968-2009), providing an estimation of the lower bound of potential decadal predictability of EA-LI.

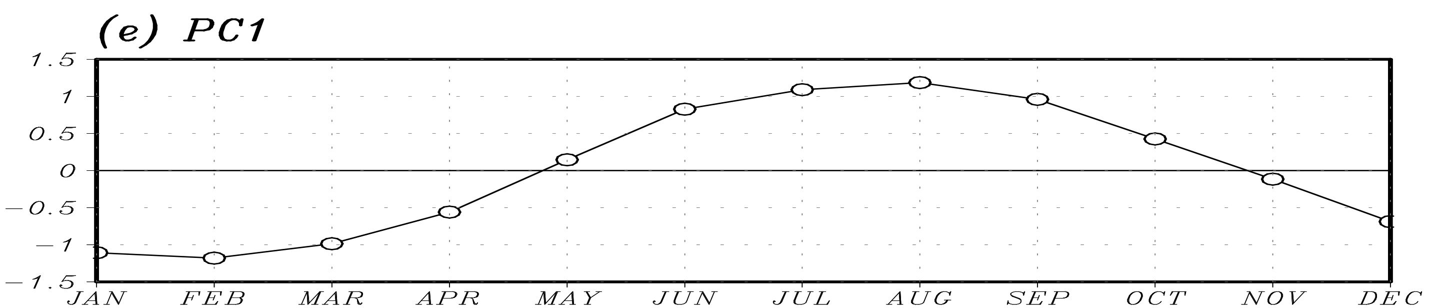

Thank you for
your comments



1901-1957 (20CR_V2) + 1958-2014(ERA40+ERA-interim)

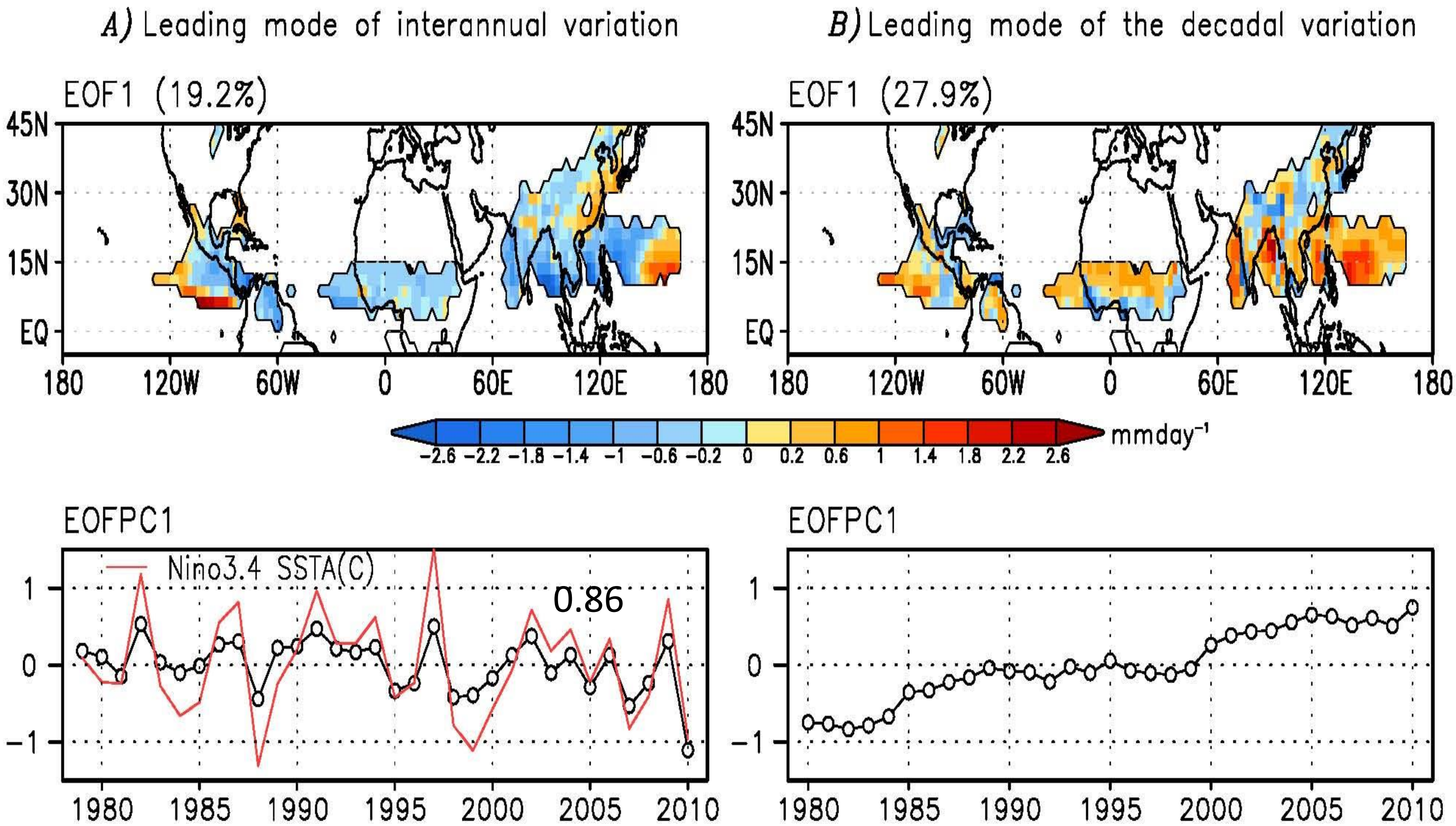
GM is a dominant mode of annual variation of Earth's climate





GM is an hemispheric antisymmetric mode

Leading EOF modes of the interannual and decadal variations of NH summer monsoon rainfall



NH Land monsoon rainfall and Nino 3.4 correlation (monsoon year) is 0.73 (1979-2012)

Background: studies of decadal LMR variation

- Decadal variations in Monsoon rainfall are mainly studied on regional monsoon scales (Webster et al. 1998; Sutton and Hodson 2005; Goswami et al. 2006; Lu et al. 2006; Meehl and Hu 2006; Zhang and Delworth 2006).
- Total global monsoon rainfall over both ocean and land during the short period of 1979-2012 studied (Wang et al. 2012; Wang et al. 2013). But LMR matters the most.
- Global-scale LMR studies could not differentiate between the anthropogenic trends and natural climate variability due to the relatively short record used (Wang and Ding 2006; Zhou et al. 2008).

Data

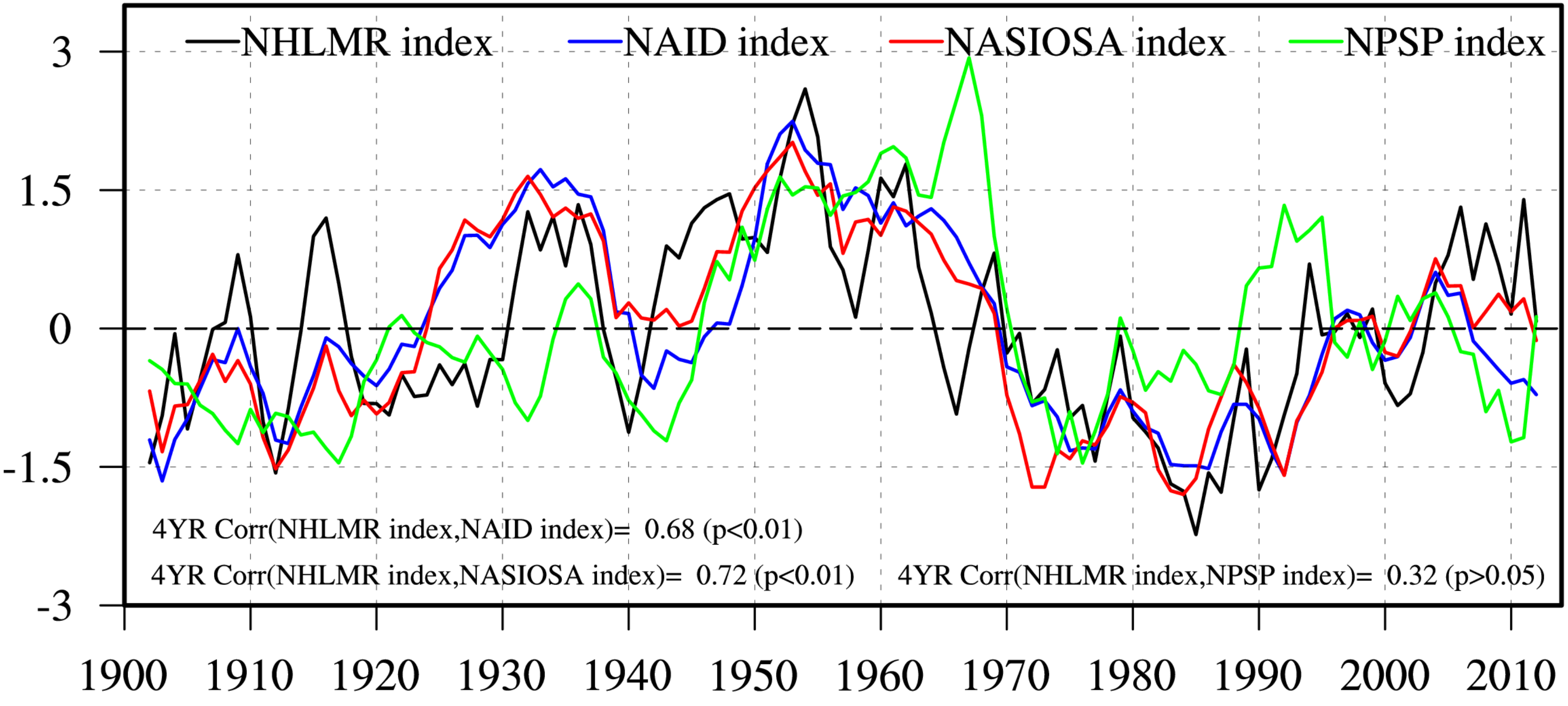
1. Monthly precipitation over global land
Climatic Research Unit (CRU) TS3.23 0.5x0.5,1901-2014 (Harris et al. 2014), 20C reconstructed precipitation 5x5,1901-2008 (Smith et al. 2010),

2. Monthly mean circulation data
20th Century Reanalysis (Compo et al. 2011) 2x2°, 1901-1960, Combined ERA40 (Uppala et al. 2005) and ERA interim (Dee et al. 2011) data for 1958-2014,

3. Blended monthly mean SST from
Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) (Rayner et al. 2003) 1x1°,1901-2014, and
NOAA extended reconstructed SST v4 (ERSST) (Huang et al. 2015) with a resolution of 2x2°,1901-2014.

4. To make these spatial resolutions comparable, we re-gridded all datasets using a uniform resolution of 2.5° x 2.5°.

NAID represents NH-SH thermal contrast in Atlantic-IO



Decadal variation of the index of Hemispheric SSTA contrast in Pacific (NPSP), which is measured by SST over NH (0-60^{o}N) minus that over SH (0-40^{o}S) Pacific oceans, and the **index of Hemispheric SSTA contrast in the Atlantic-Indian Ocean sector,** NASIOSA (2x NA SSTA - SIO SSTA - SA SSTA)

How NAID affects NHLMR

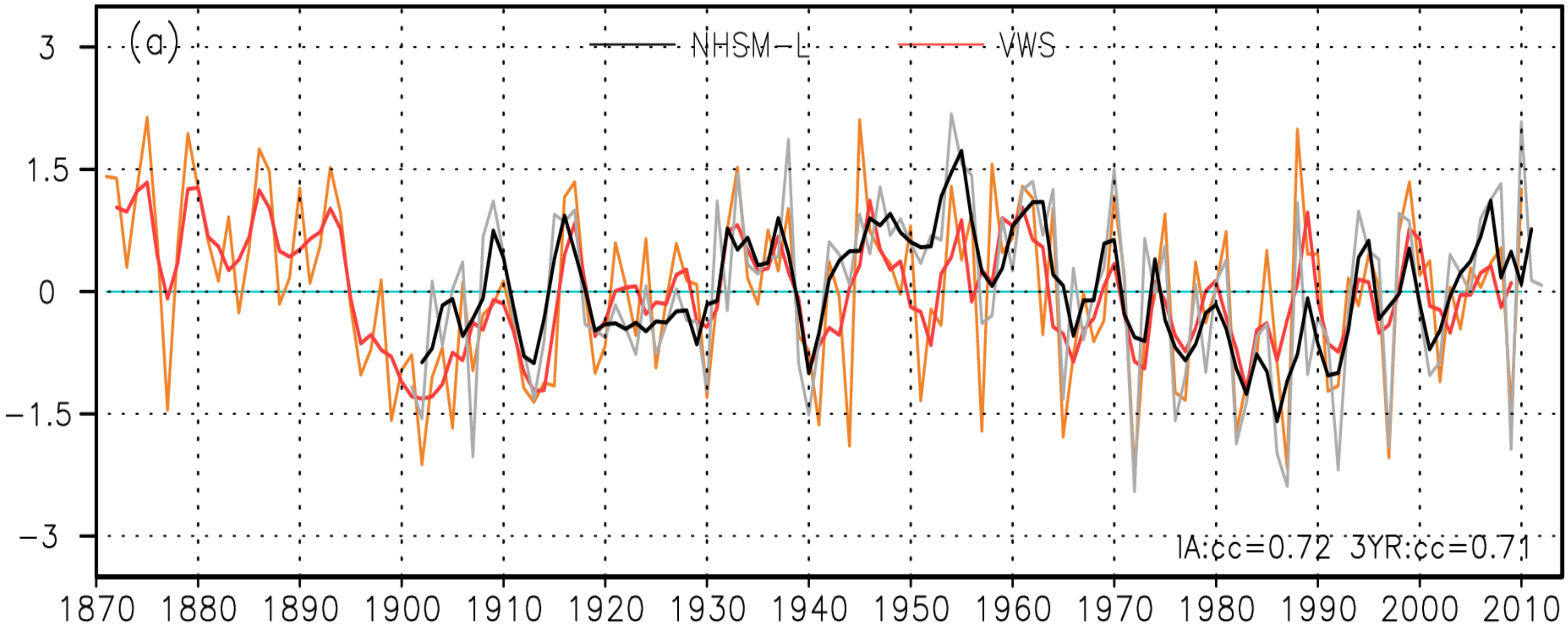
The NAID dominates the overall NH-SH SST contrast, and the NHLMR can be changed by the interhemispheric SST gradients-induced low-level, northward cross-equatorial flows (Liu et al. 2009; Liu et al. 2012; Wang et al. 2013).

A positive phase of NAID combines the effects of a warm NA and a cold SIO. A warm NA can shift the ITCZ northward (Schneider et al. 2014), enhancing NAM (Sutton and Hodson 2005; Meehl and Hu 2006), NAF monsoon, (Gaetani and Mohino 2013; Martin and Thorncroft 2014; Otero et al. 2015) and Asian rainfalls (Lu et al. 2006; Meehl and Hu 2006; Zhang and Delworth 2006); A cold SIO can enhance the northward temperature gradient between the Indian Ocean and Asian continent, strengthening the Asian monsoon rainfall (Webster et al. 1998).

How Mega-ENSO affects NHLMR

Physically, the eastern Pacific cooling and western Pacific warming are consistent with a strengthening of the two Pacific subtropical highs in the northern and southern hemispheres and their associated trade winds, causing moisture to converge into the Asian and African monsoon regions and thus contributing to the intensification of NHSM rainfall (Wang et al. 2013).

The other 70% of increasing trend is due to multidecadal variations



The NHSM land precipitation and circulation indices (1870-2012)

The NH VWS circulation index: VWS of normalized zonal winds (925hPa minus 200hPa) averaged over (0-20N, 100W-100E) (Wang et al. 2013).

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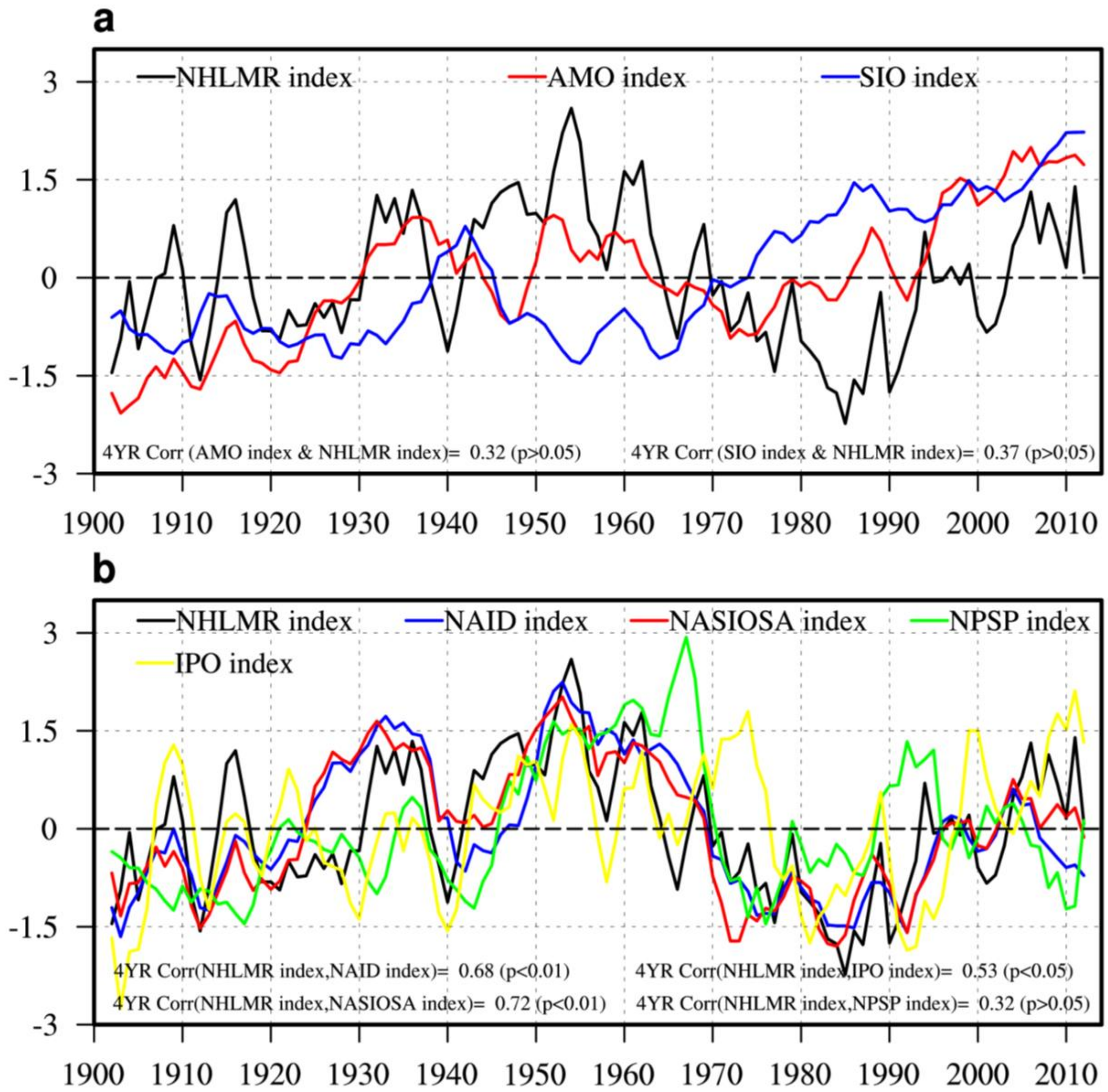
Correlations between NHLMR and four regional LMR indices

TCC	NAF-L index	EA-L index	NAM-L index	IND-L index
NHLMR index	0.73	0.56	0.51	0.67

The correlation coefficients between NHLMR index and northern Africa land monsoon rainfall (NAF-L) index, East Asian land monsoon rainfall (EA-L) index, North American land monsoon rainfall (NAM-L) index, and Indian land monsoon rainfall (IND-L) index. All correlation coefficients are significant at 0.01 significance level taking autocorrelations into account.

Why NAID? The N-S thermal contrast in Atlantic and IO sector



AMO index

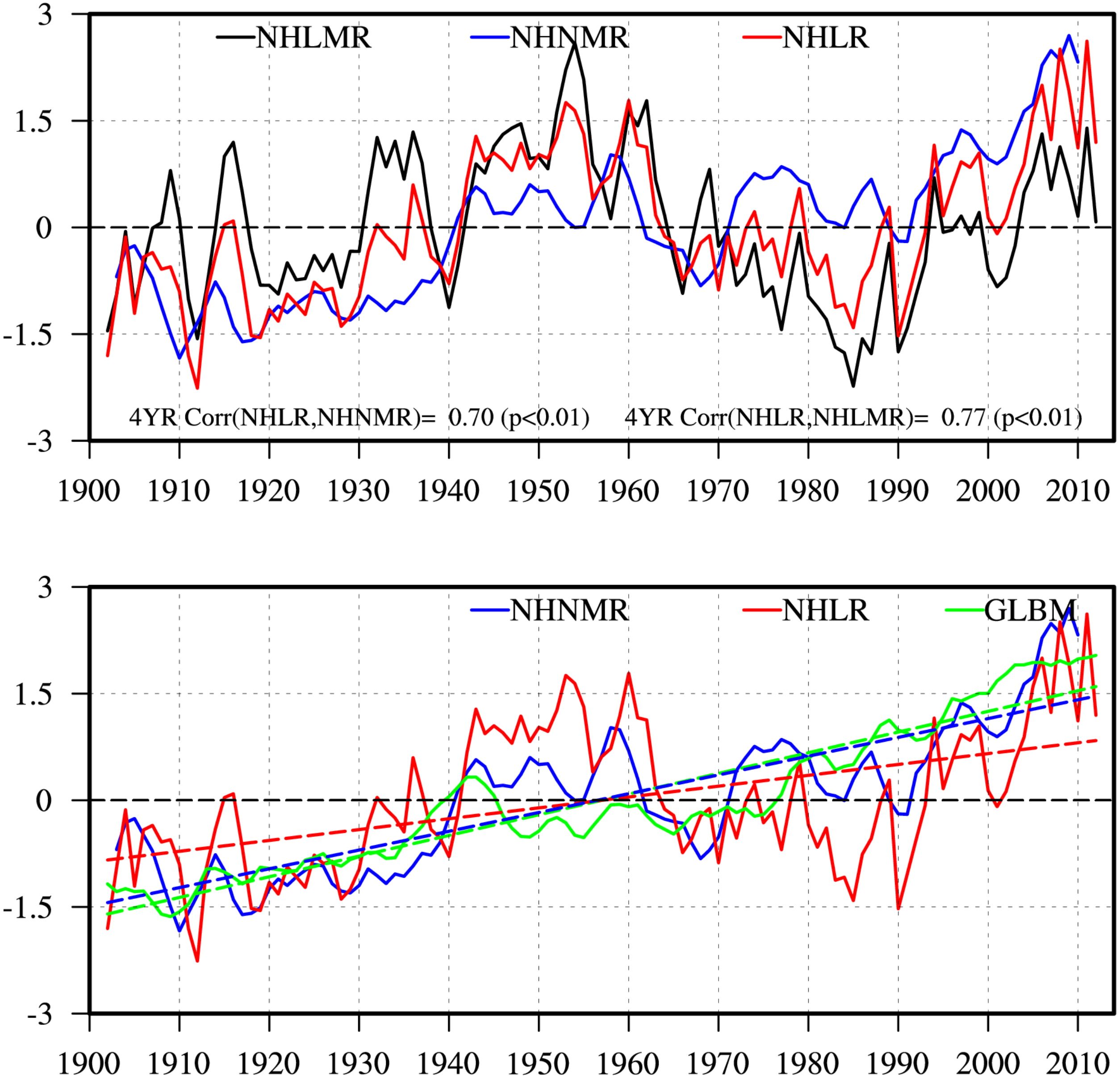
SIO index

NHLMR index

IPO index

NASIOSA (2x NA SSTA - SIO SSTA - SA SSTA) index,

NPSP index = SSTA over North Pacific (0-60^{o}N) minus that over South Pacific (0-40^{o}S),



Northern Hemisphere land rainfall (NHLR) : MJJAS mean precipitation averaged over the NH land area between 0° and 90° N.

Northern Hemisphere Non-monsoon land rainfall (NHNMR) : MJJAS mean precipitation averaged over the NH non-monsoon land area between 0° and 90° N.

GLBM: global averaged annual mean temperature

Dash line: linear trend

Use detrended NAM-L may have higher CC?

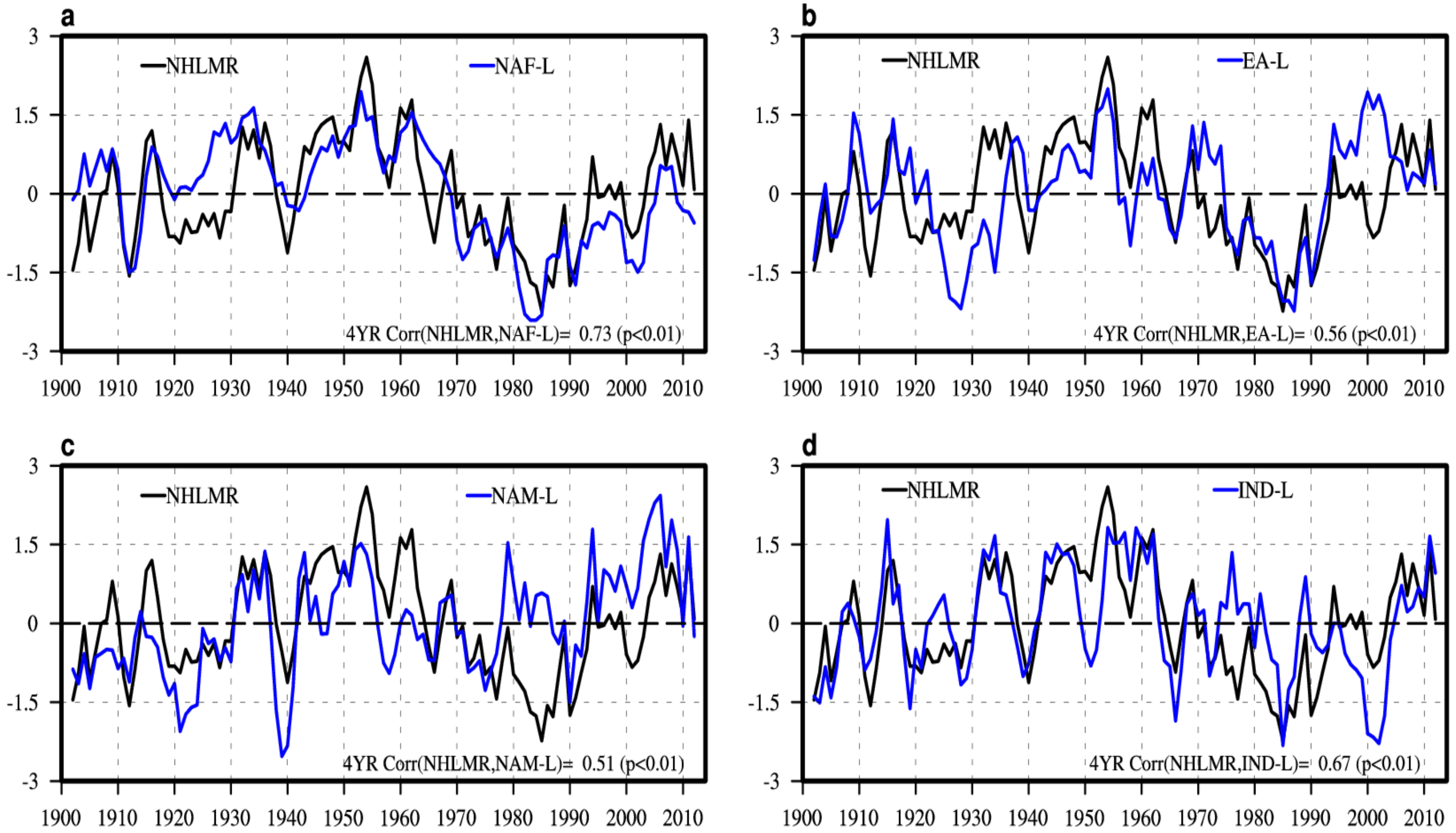
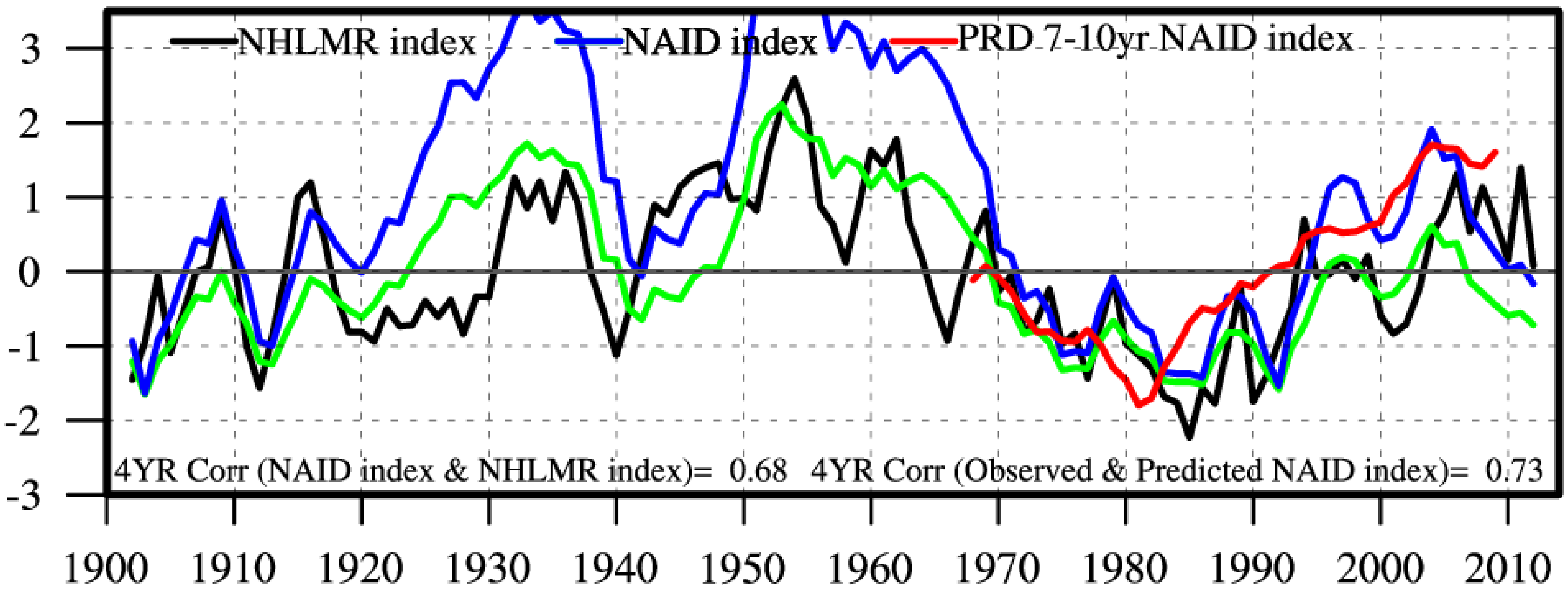


Fig. 4 Decadal variations of four regional LMR indices. a, northern Africa land monsoon rainfall (NAF-L). **b**, East Asian land monsoon rainfall (EA-L). **c**, northern American land monsoon rainfall (NAM-L). **d**, Indian land monsoon rainfall (IND-L). The regional monsoon domains are shown in Extended Data Fig. 4. The correlation coefficients and their corresponding statistical significance level are shown in the bottom of each panel.

Green line: NAID index normalized by using 1901-2014 data
Blue line: NAID index normalized by using 1968-2009 data



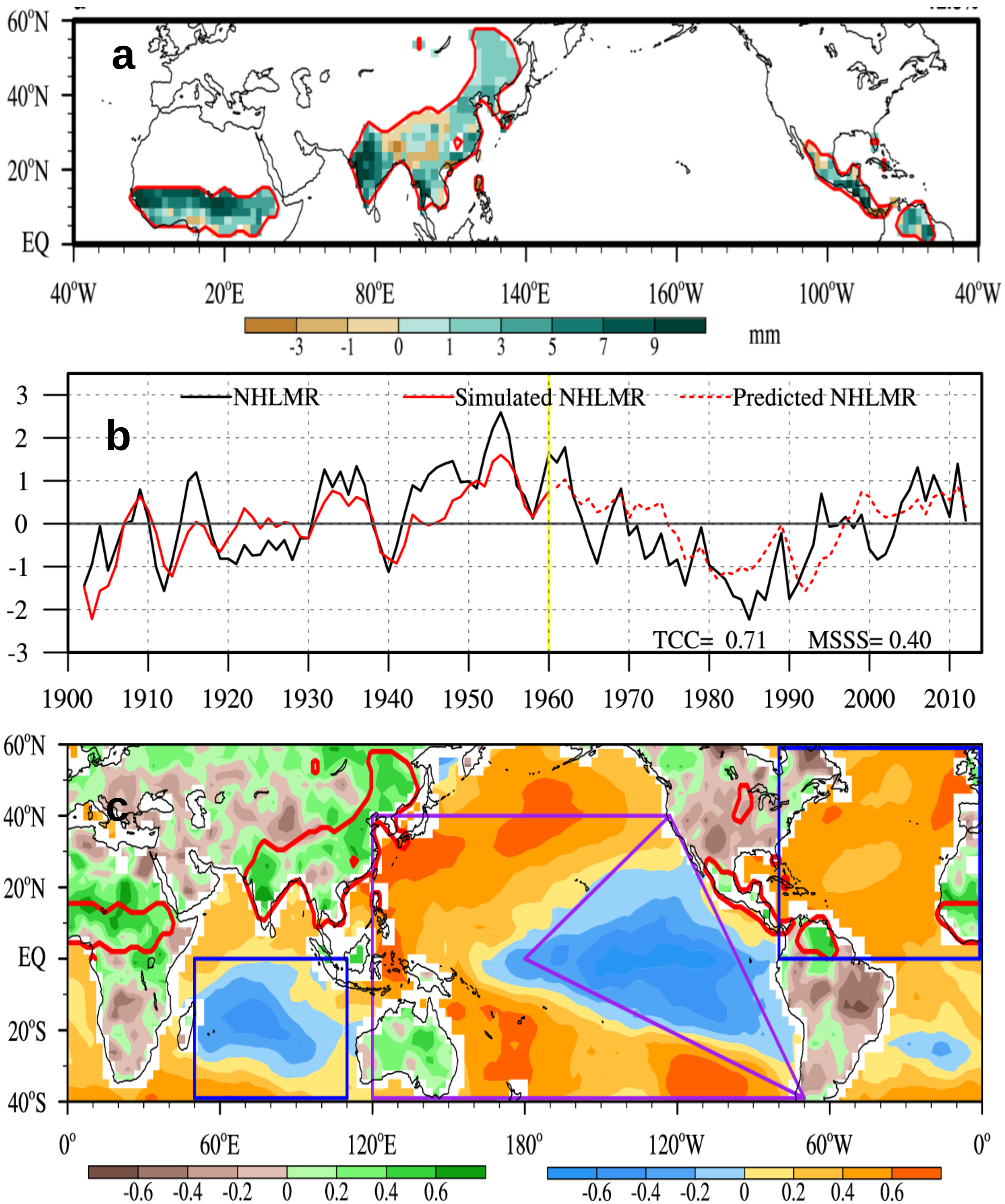
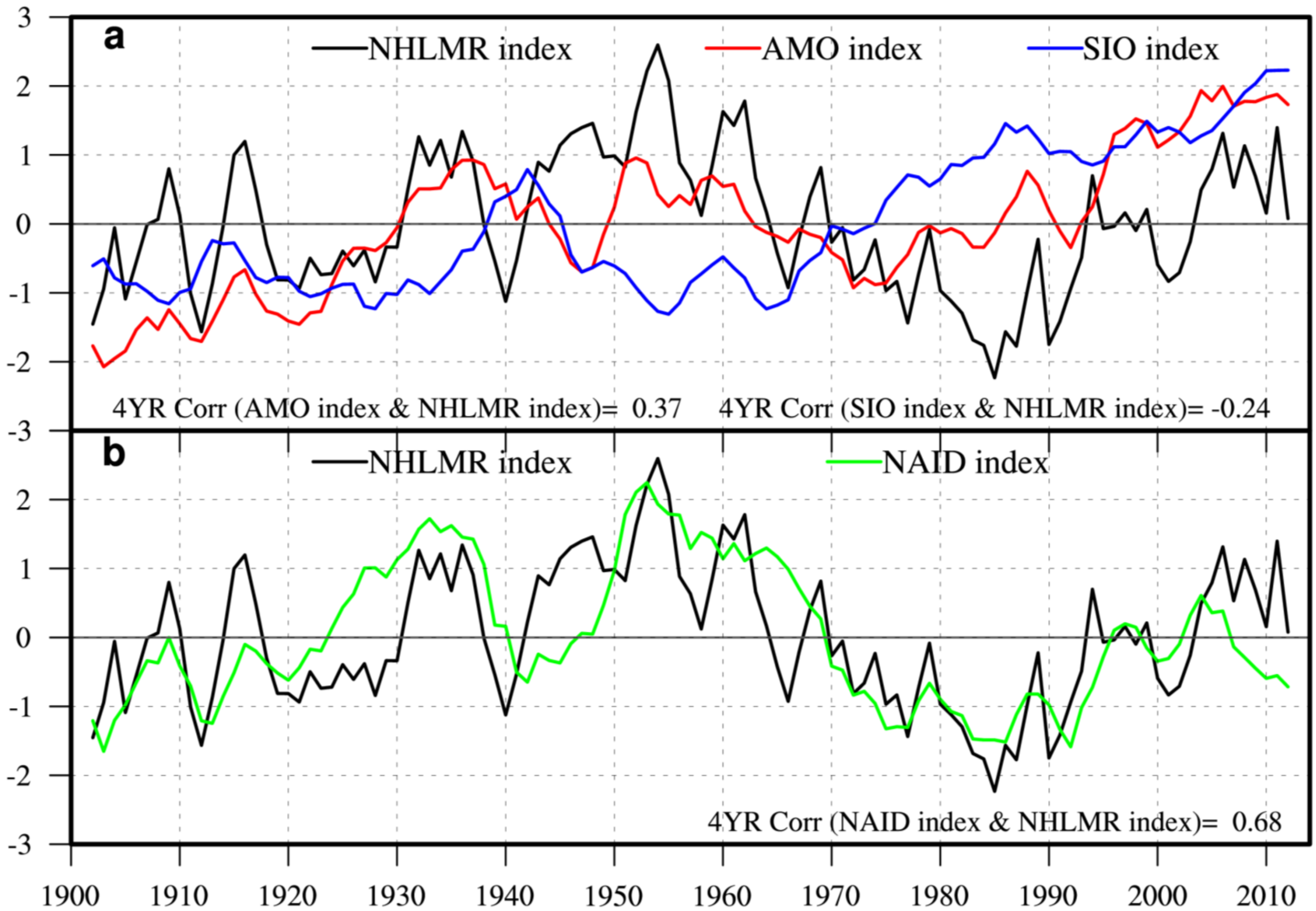
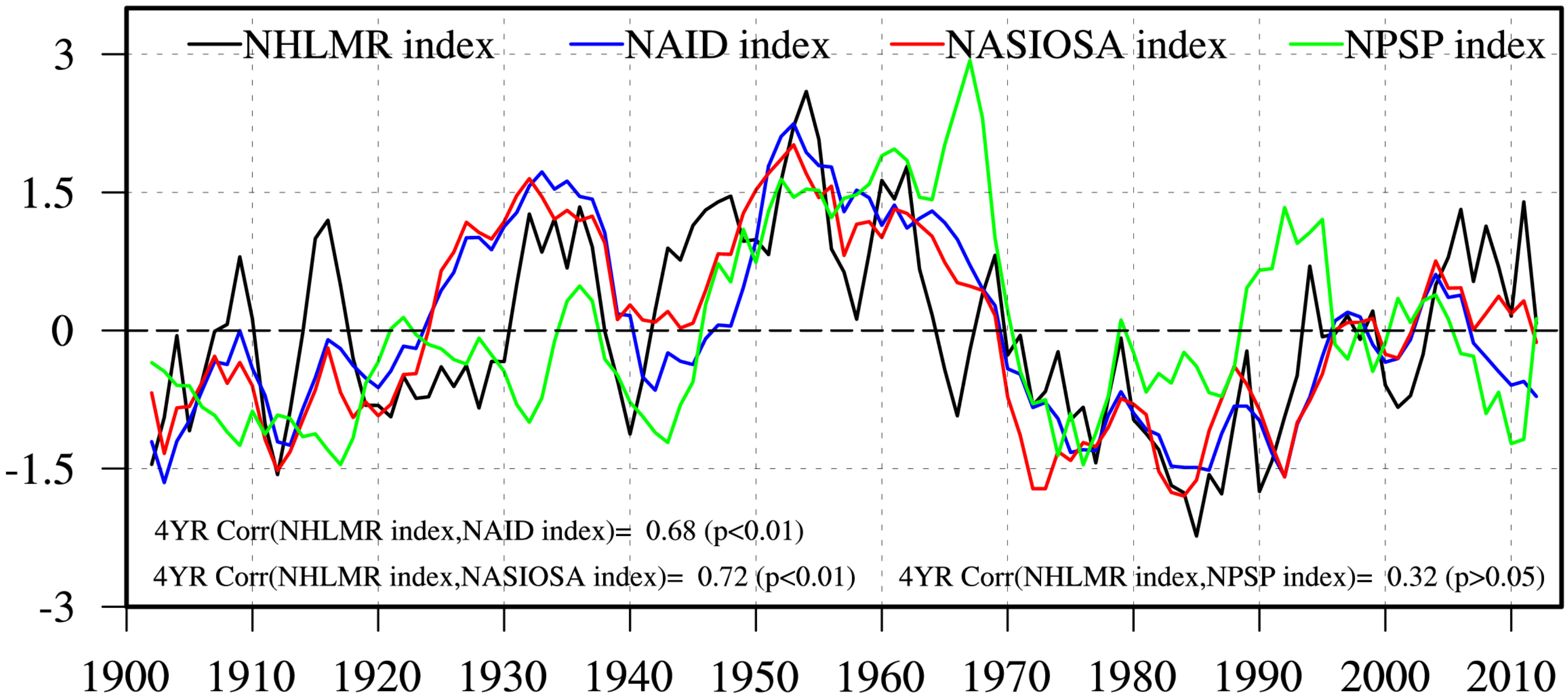


Fig. 1 Leading decadal mode of NH land summer monsoon rainfall (NHLMR) variability and the associated SST anomalies. **a,** Spatial pattern of the first EOF mode of the decadal (four-year running mean) NHLMR. The NHLMR domain (outlined by the red contours) is defined by the regions where the local summer-minus-winter precipitation exceeds 300 mm and the local summer precipitation exceeds 55% of the annual total. Here, summer denotes May-September, and winter, November-March. **b**, The observed decadal NHLMR index (black), the simulated decadal NHLMR index using the SST indices during the training period of 1901-1960 (solid red), and the predicted decadal NHLMR index for the period of 1961-2014 (dashed red). The NHLMR index is defined as the area-weighted mean summer precipitation within the NHLMR domain. The yearly mark represents the second year of the four-year running mean. **c**. The correlation map of boreal summer (May-September) SST (shading over the ocean) and land rainfall (shading over the land) with respect to the decadal NHLMR index during 1901-1960. The blue and purple lines outline the areas used for defining the NAID and IPO indices, respectively.



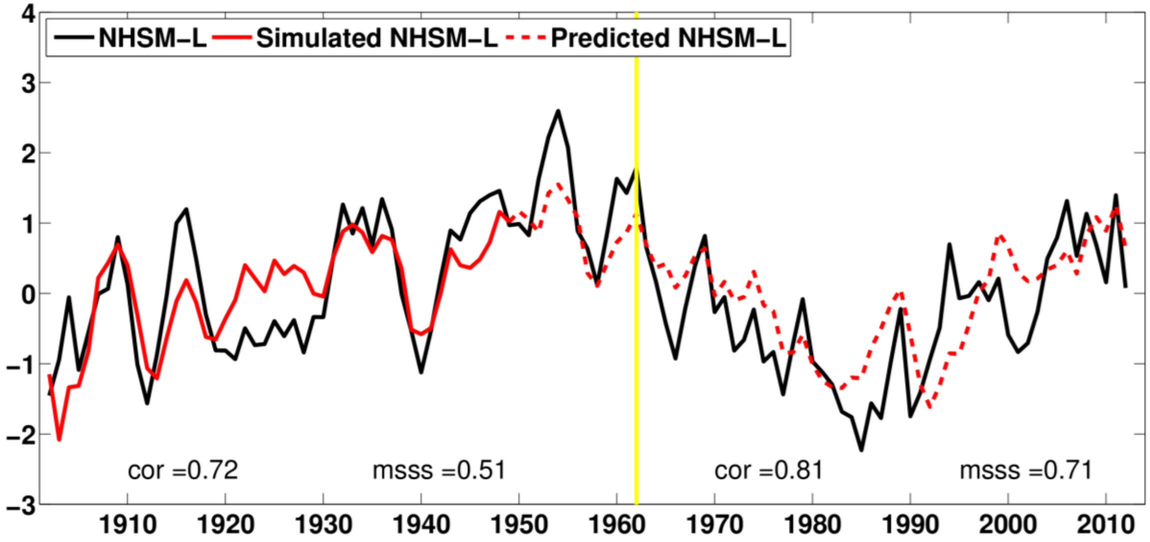
Extended Data Figure 4 | **Decadal variation (4-year running mean) of **a, AMO and southern Indian Ocean (SIO) SSTA, and **b**, NAID indices**.** For comparison, the decadal NHLMR index is also shown. The correlation coefficients and **their statistical significance levels** are shown in the bottom of each panel.



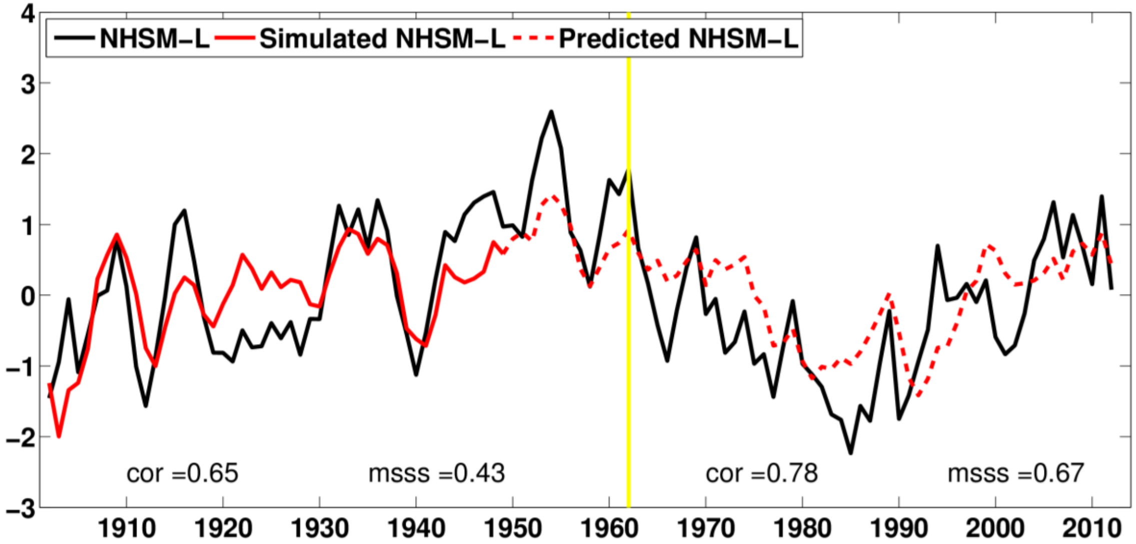
Extended Data Figure 5 | Decadal variation of the index of Hemispheric SST contrast in Pacific (NPSP). NPSP index is measured by SST over NH (0-60^{o}N) minus that over SH (0-40^{o}S) Pacific oceans. For comparison, the 4-year running mean time series of NAID and NASIOSA (2x NA SSTA - SIO SSTA - SA SSTA) indices are also shown. The correlation coefficients and the corresponding statistical significance levels are shown in the bottom of each panels.

Important sensitivity tests

NASIOSA+IPO



NAID+IPO



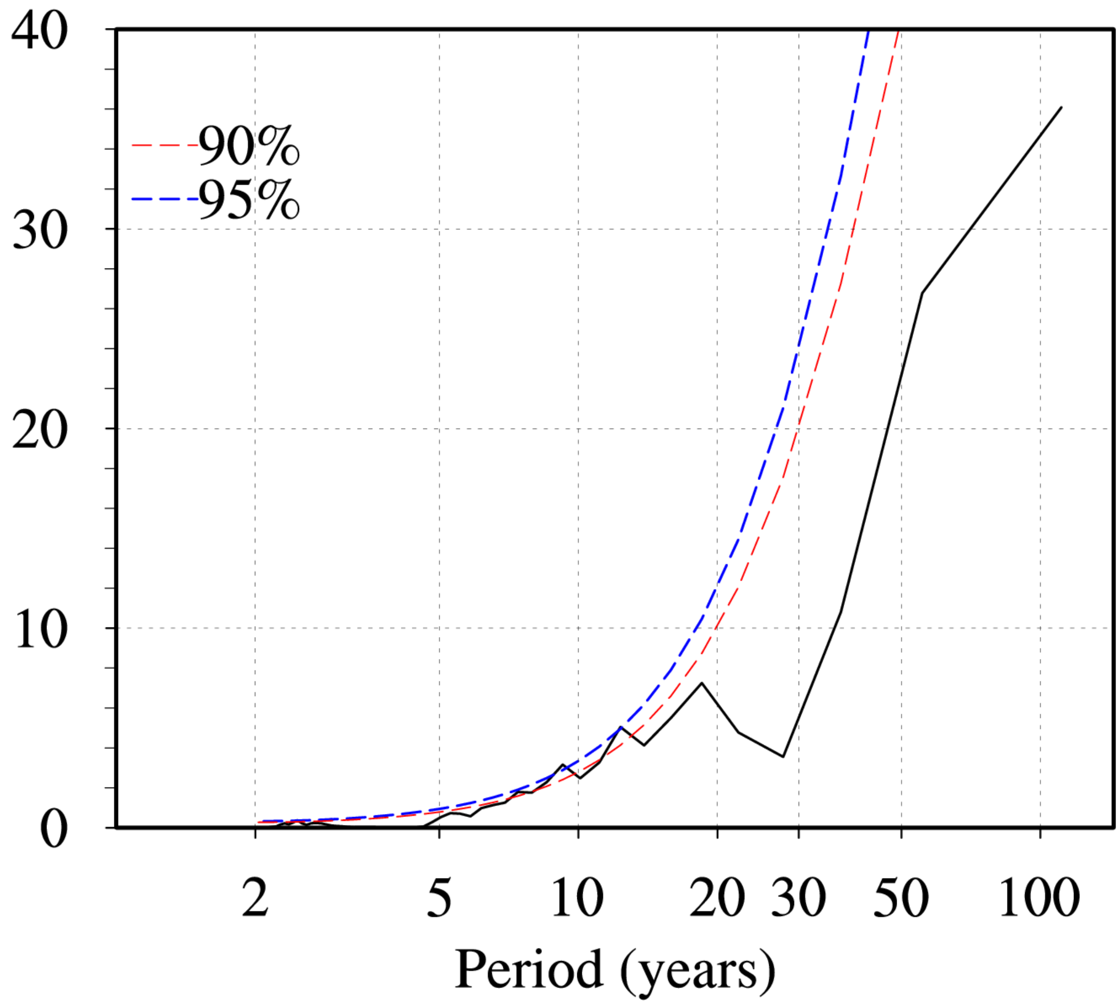


Fig. S1. Power spectrum of the first principal component of the 4yr running mean NH summer LMR.

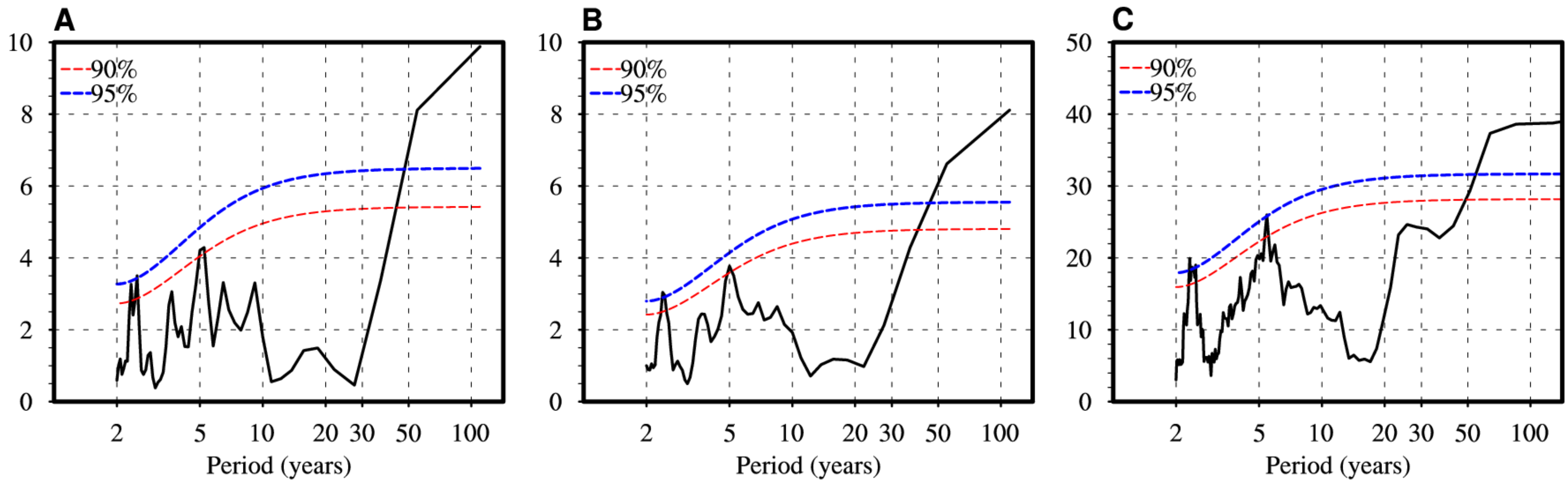


Fig. S2. Spectra of summer (MJJAS) mean NHLMR index obtained (*A*) with averaging three periodogram bins (bandwidth: 45), (*B*) with averaging five periodogram bins (bandwidth: 25) and (*C*) using Multi-Taper Spectral Analysis Method (four tapers). The confidence levels are given by theoretical estimate of the red noise spectrum.

1. Correlation between southern Indian Ocean (SIO)/northern Atlantic(NA) SST and NHLMR

Cor(SIO&NHLMR)= -0.24 (SIO:0-40S,50E-110E) for the period 1901-2014
Cor(NA&NHLMR)= 0.37 (NA:0-60N,80W-0) (non-detrended)

Cor(detrended SIO&NHLMR)= -0.36 for the period 1901-2014
Cor(detrended NA&NHLMR)= 0.59
Regression equation NHLMR=0.59*NA(detrended)-0.36*SIO(detrended) for the period 1901-2014
TCC=0.69, MSSS=0.48 for the simulation during 1901-2014

Regression equation NHLMR=0.42*NA(detrended)-0.2*SIO(detrended) for the period 1901-1950
TCC=0.81, MSSS=0.62 for the independent prediction as Fig2b during the period of 1951-2014

2. Correlation between northern Atlantic(NA) minus southern Atlantic-Indian Ocean (SAIO) SST and NHLMR

Cor((NA-SAIO)&NHLMR)= 0.45 (SAIO:0-40S,60W-110E) for the period 1901-2014

Regression equation NHLMR= 0.16*NASAIO for the period 1901-1950
TCC=0.68, MSSS=0.31 for the independent prediction as Fig2b during the period of 1951-2014

3. Correlations related to PC3

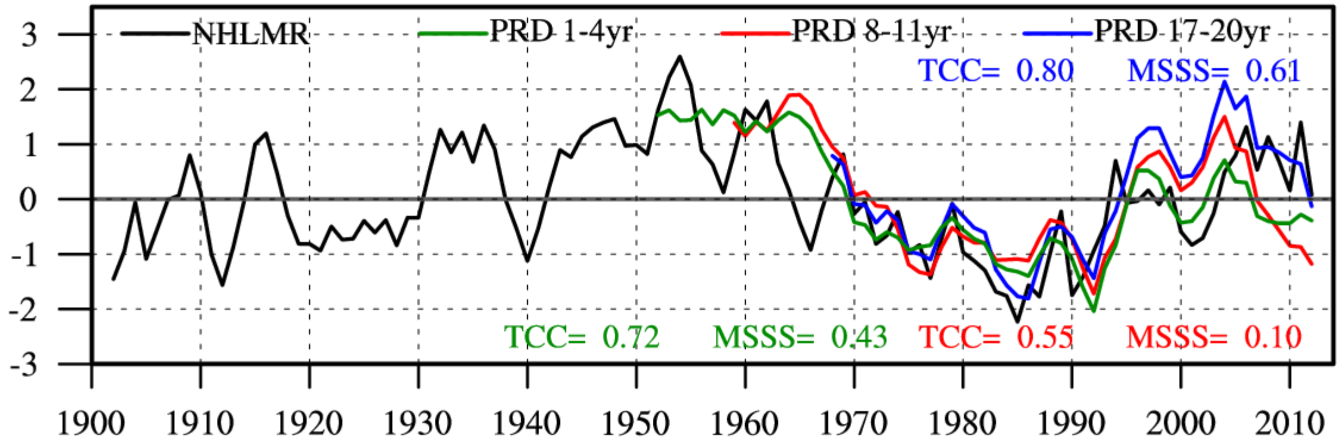
Cor(NP&PC3)= 0.44 (NP:0-60N,150E-110W) for the period 1901-2014
Cor(NP+NA-SIO&PC3)= 0.78

Cor(PC3&NHLMR)=0.41
Regression equation NHLMR=0.2*PC3 for the period 1901-1950
TCC=0.48, MSSS=0.31 for the independent prediction as Fig2b during the period of 1951-2014

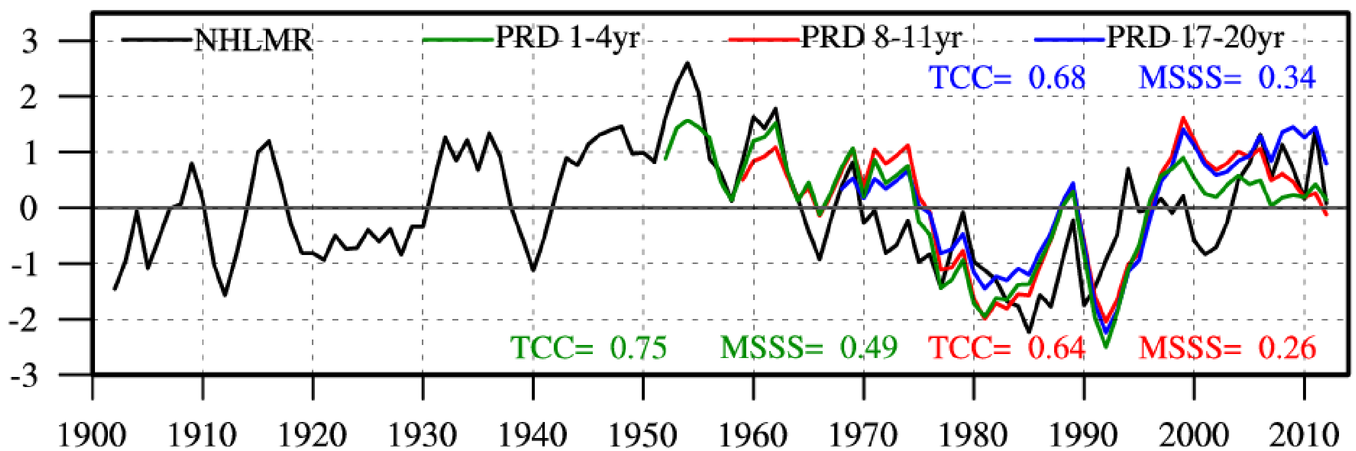
All correlations are based on 4yr running mean data

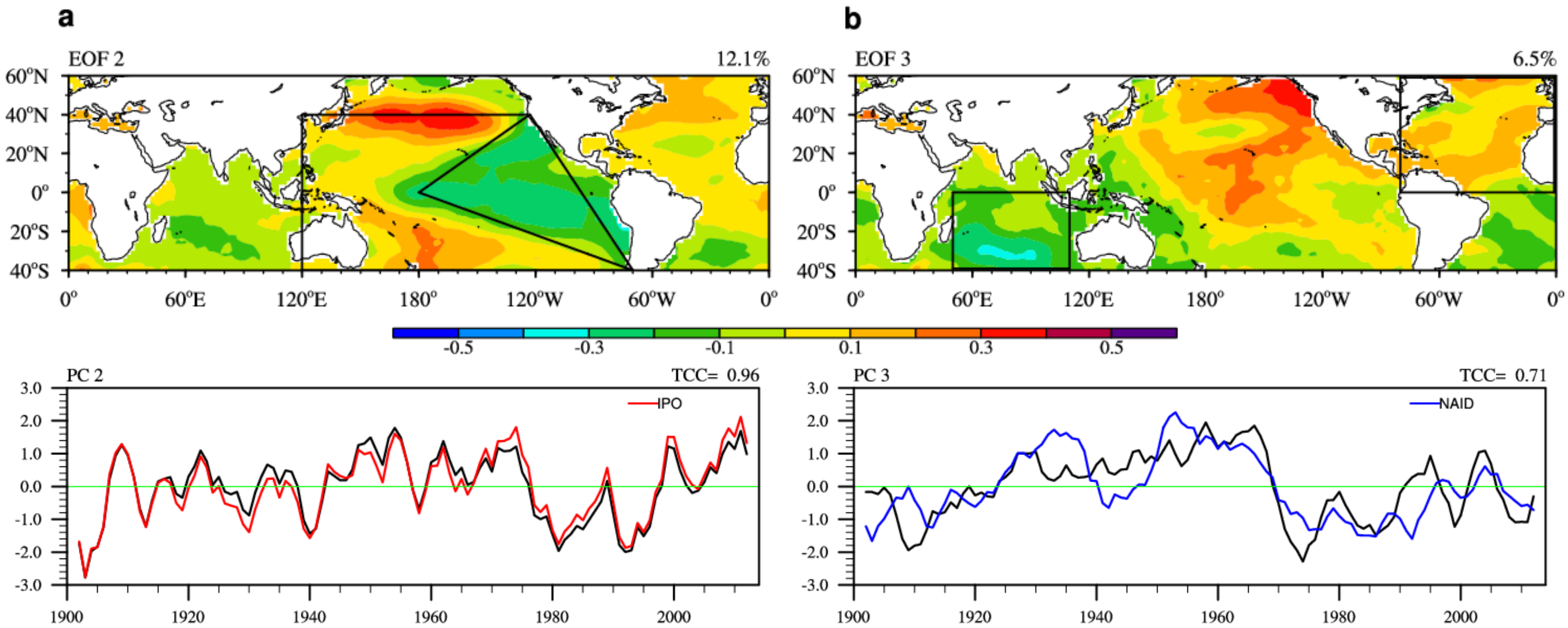
1. you showed me the results using detrended SIO and NAtlantic SST as separate predictors, the independent prediction is skillful. Can you further try to make a computation for the “50y-20y” rolling forecast as did in Fig. 2c?

Using detrended SIO + detrended NA



Using detrended SIO + detrended NA+ IPO



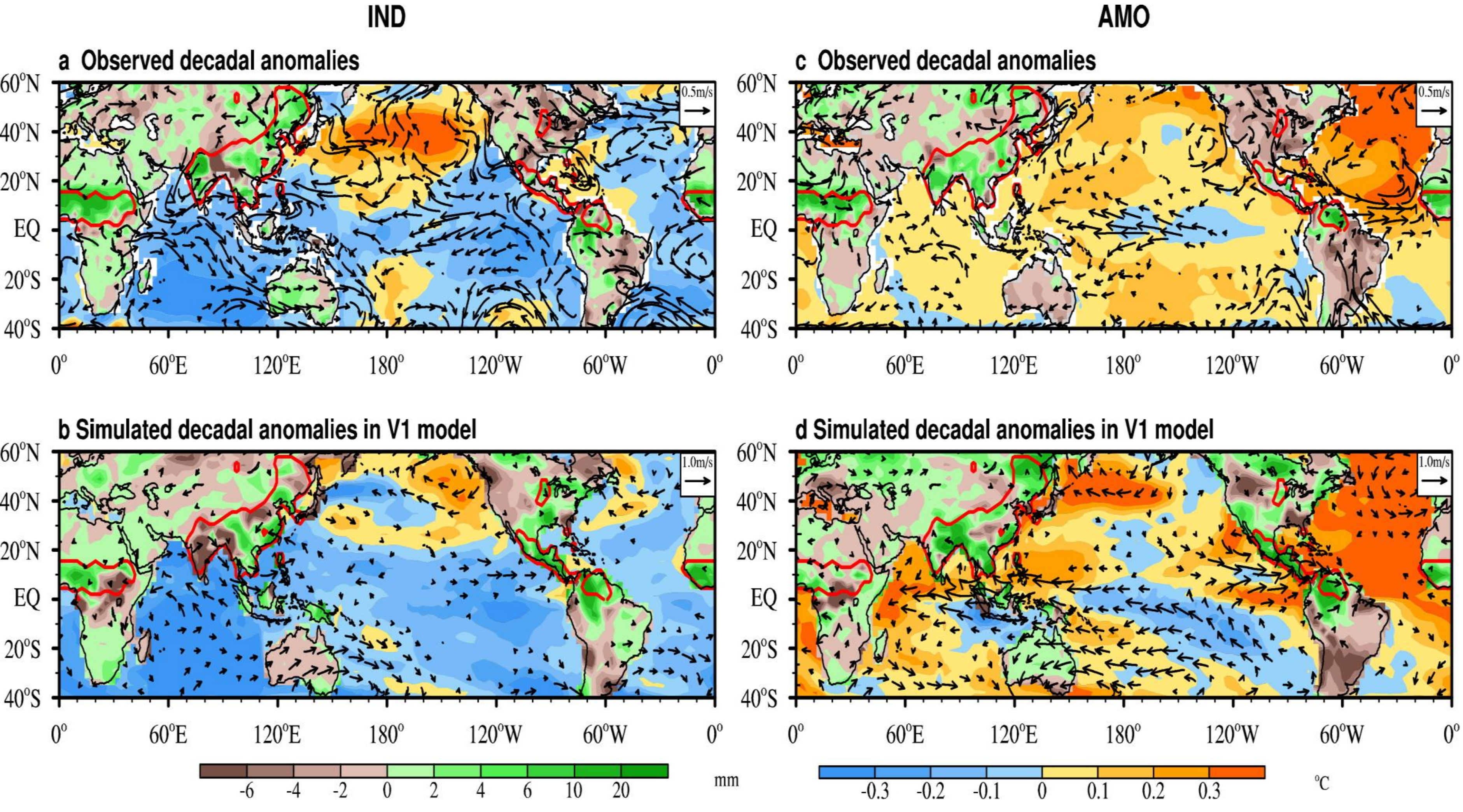


Extended Data Figure 4| Second and third EOF modes of the global SST in MJJAS for the period of 1901-2014. The upper panels are spatial patterns, and the lower panels are corresponding principal components. The 4-year running mean blended HadISST and ERSST data were used. For comparison, the 4-year running mean IPO index (red) is shown in **a** and the 4-year running mean NAID index (blue) is shown in **b** with the TCC indicated.

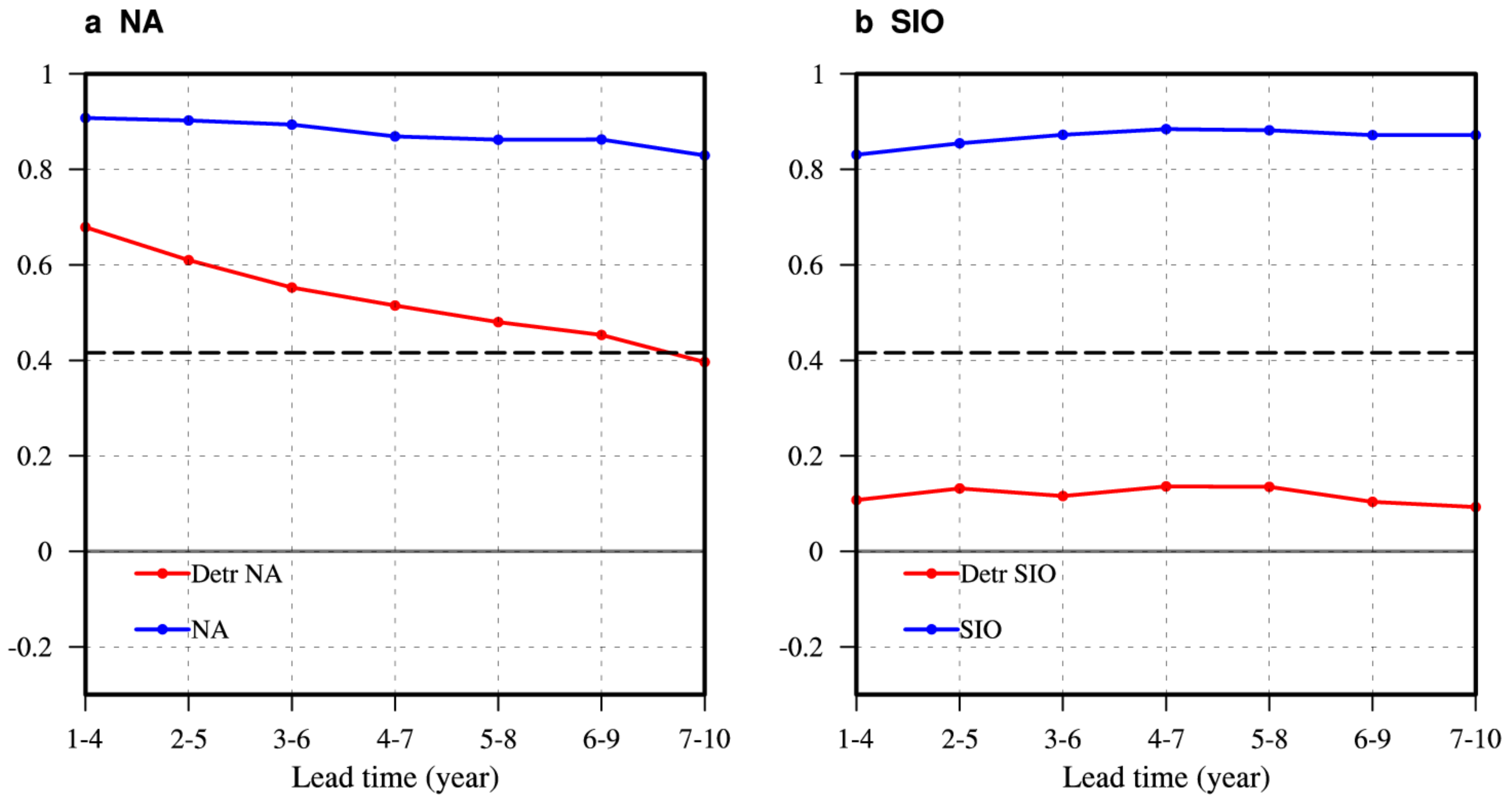
NAID also correlated with PC2, What is the CC?

Detrended SST forcing nudging experiment

Regressions with reference to detrended index during 1901-2012 are used as forcing



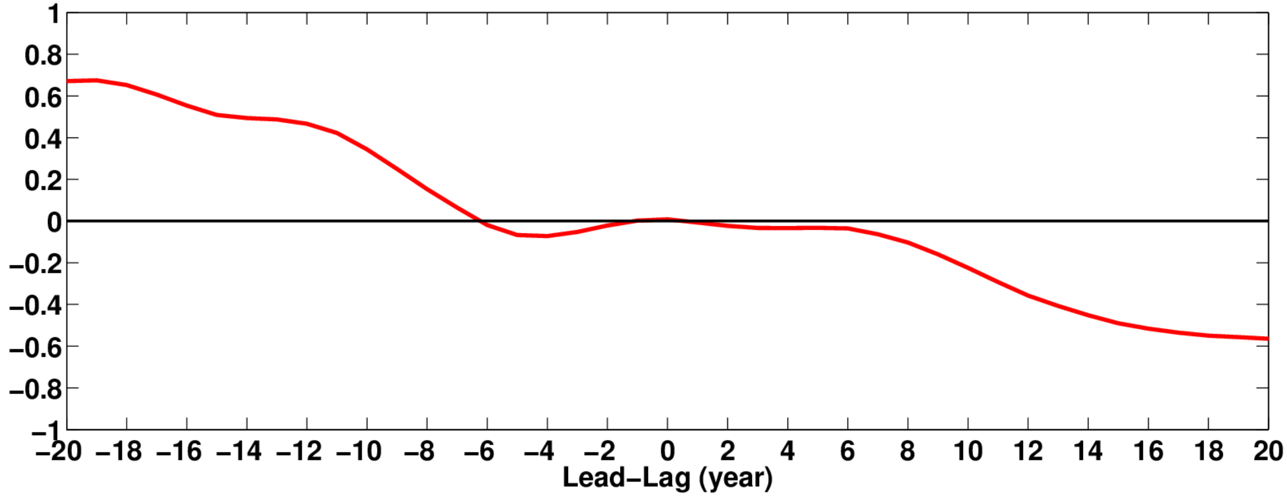
2. Further, if we use CMIP 5 models' predicted SIO and NA SST to make hybrid forecast, what the results would be? (You may try both detrended and non-detrended data)



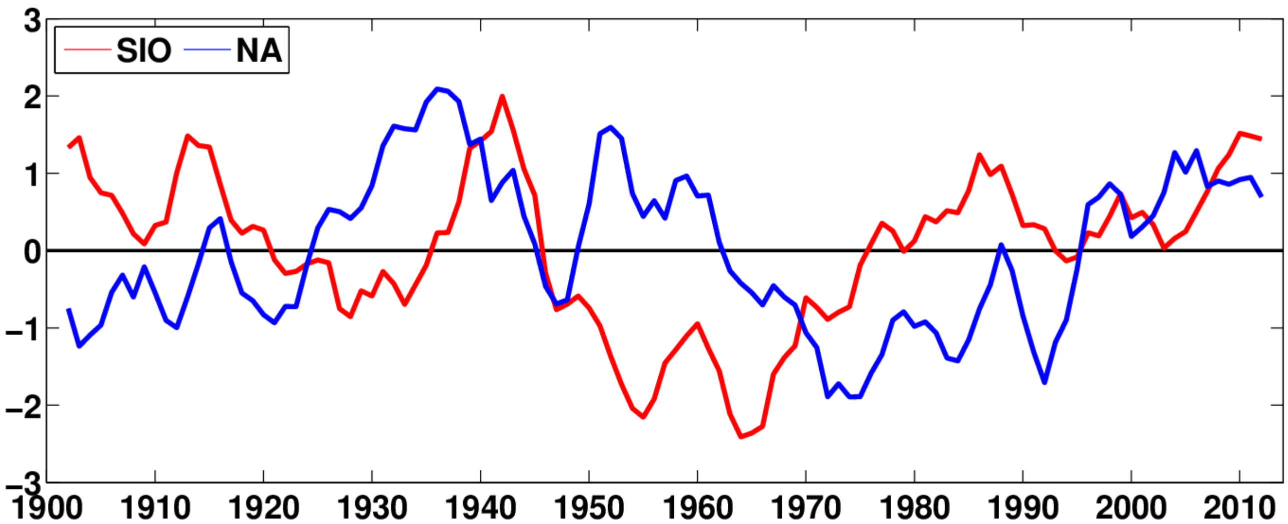
TCC skills derived from model predicted SIO and NA index before and after detrending

3. Also, can you compute the lead-lag correlation between detrended AMO and detrended SIO SST? They are negatively correlated at zero lag, but is the zero lag leads to best negative correlation?

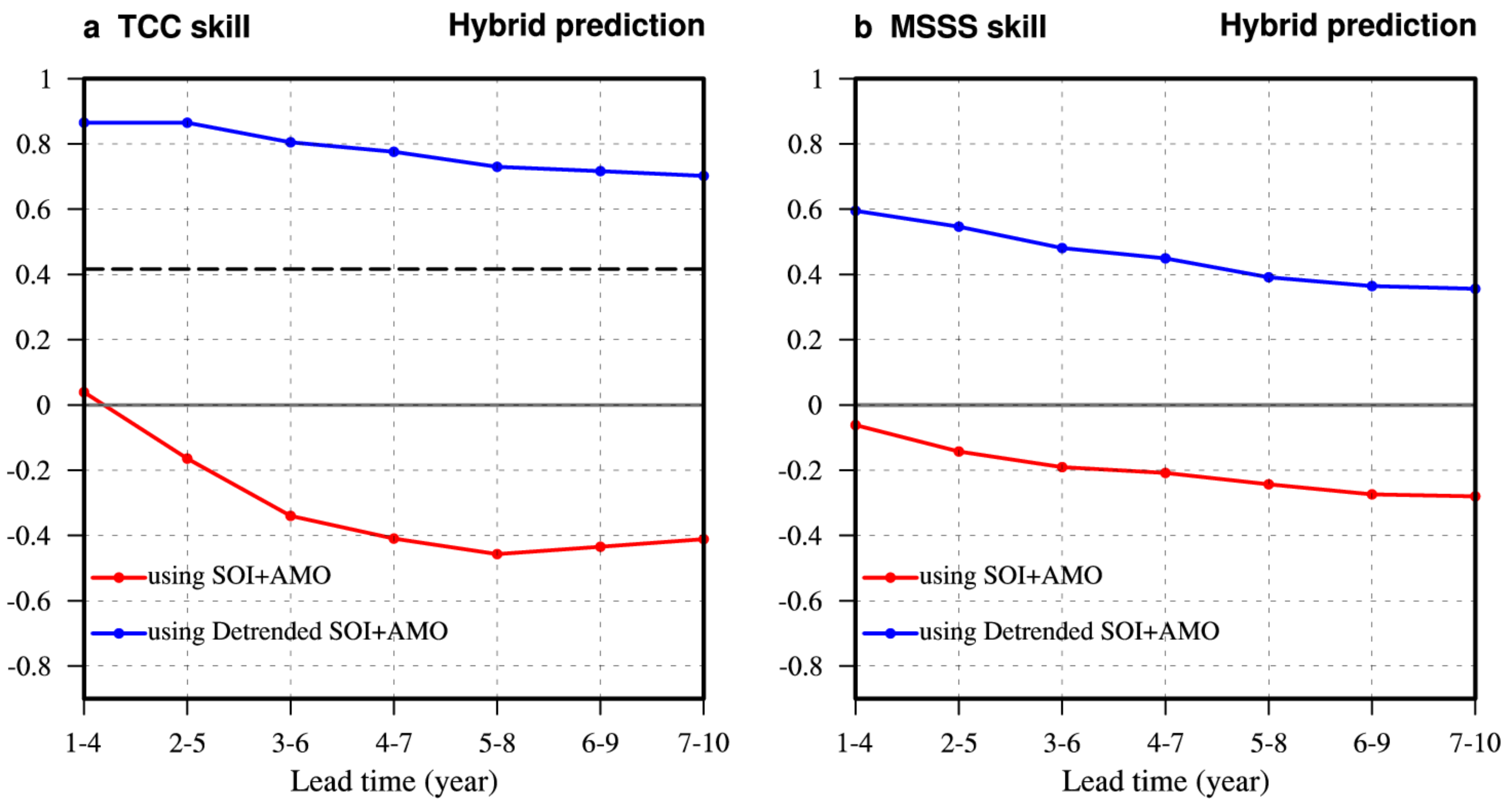
Lead-lag correlation between detrended SIO and detrended NA (-10 means SIO lead NA 10 years)



Time series of detrended SIO and NA indices



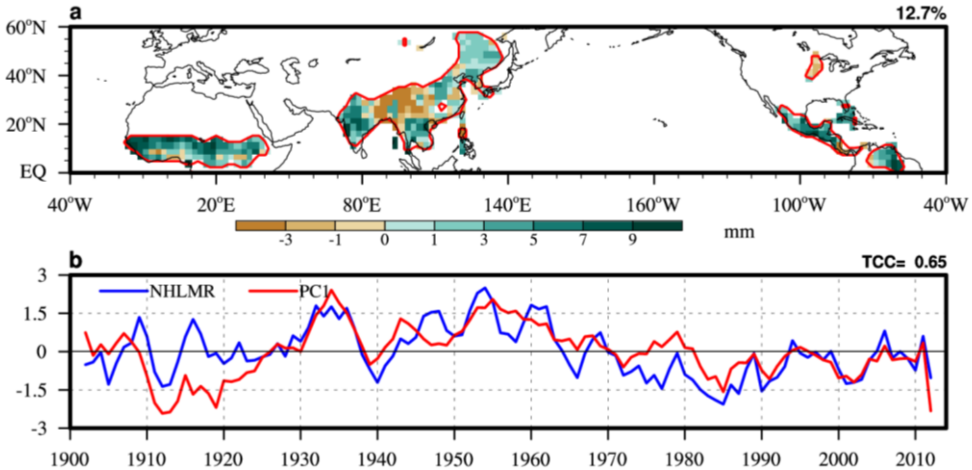
4. In the hybrid prediction, model predicted AMO and SIO have trends. What is the skill if AMO and SIO were used as separated predictor?



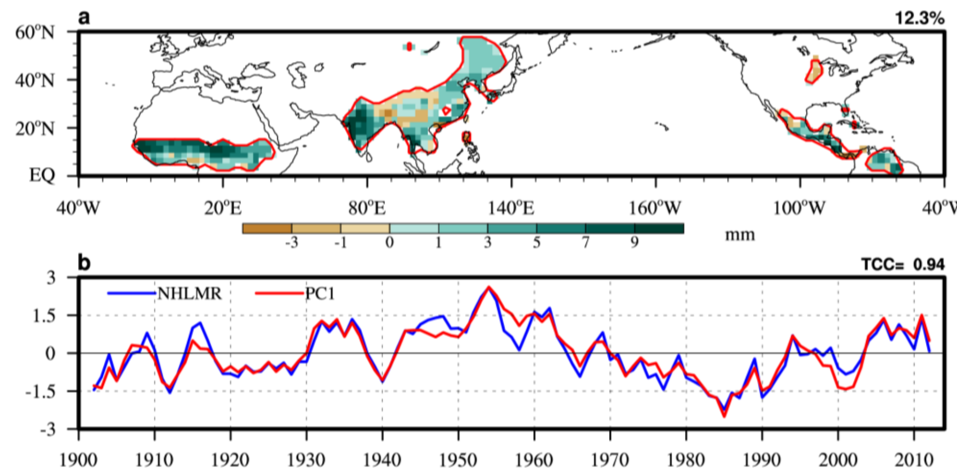
Comparison of long –term data sets

Relationship of NHLMR and circulation indices

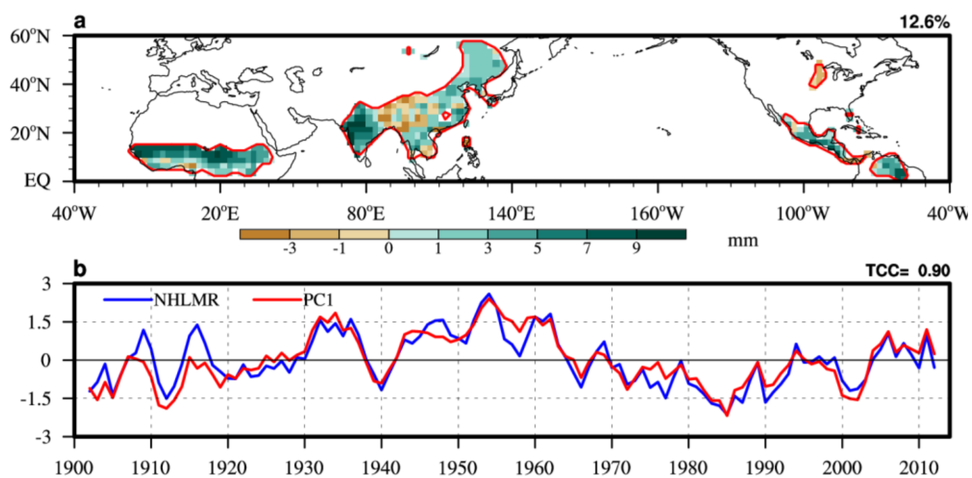
GPCC



CRU

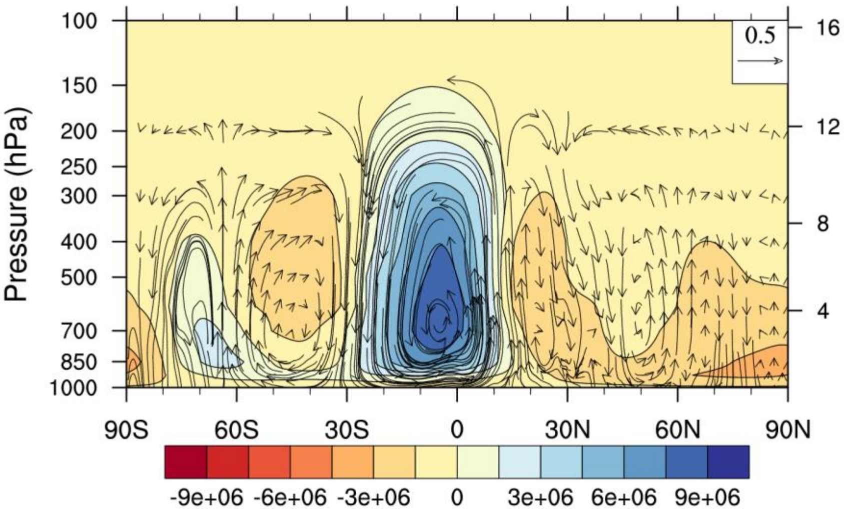


GPCC+CRU

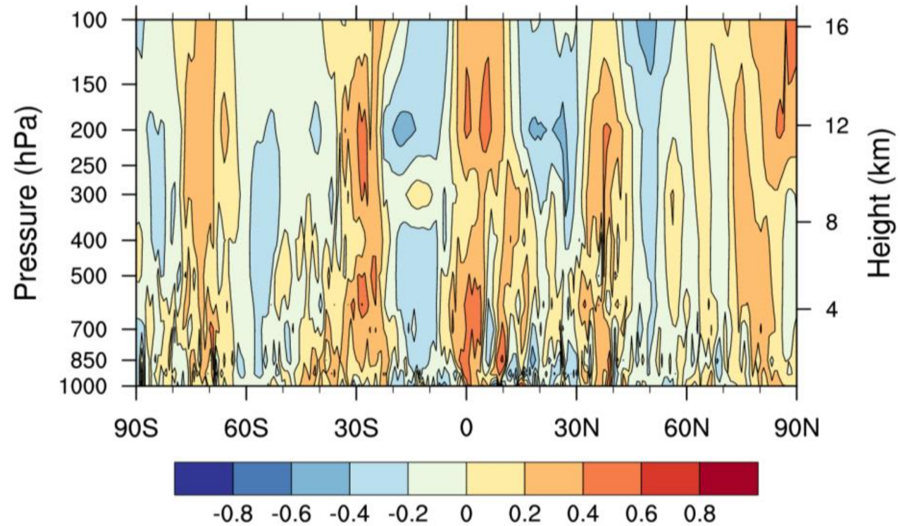


Hadley circulation index

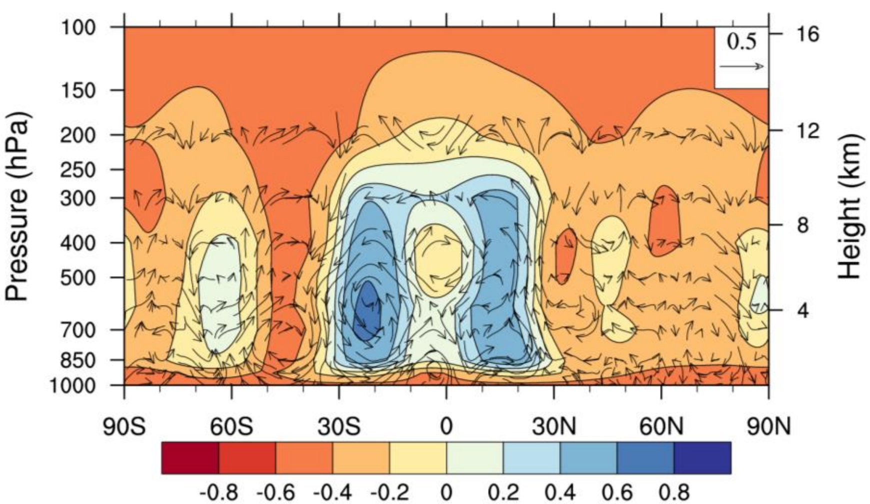
Climatology MJJAS mean stream function



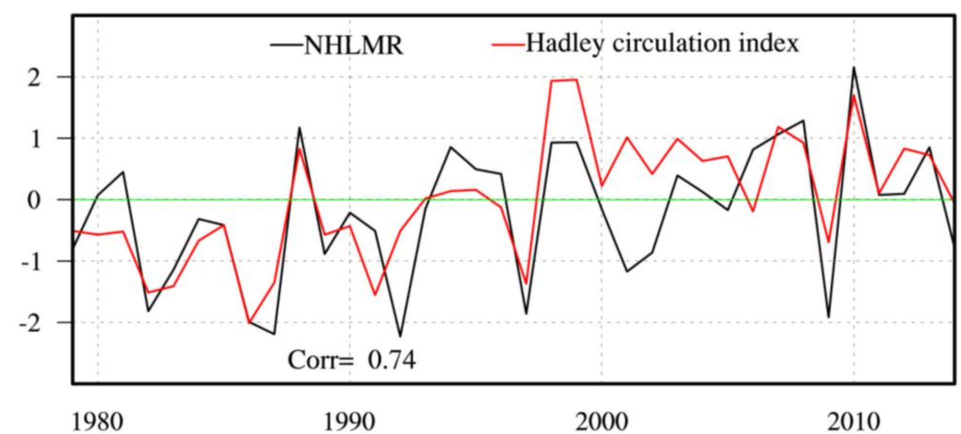
Correlations between NHSM-L & Omega

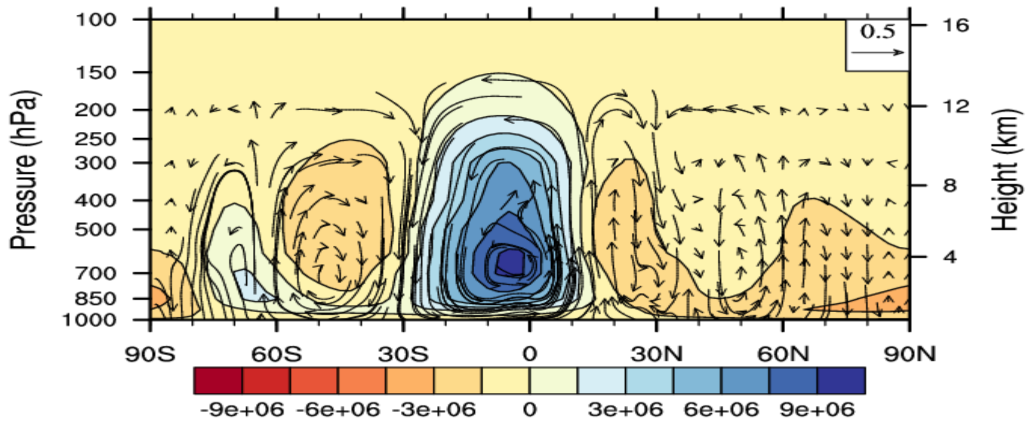


Correlations between NHSM-L & Stream function

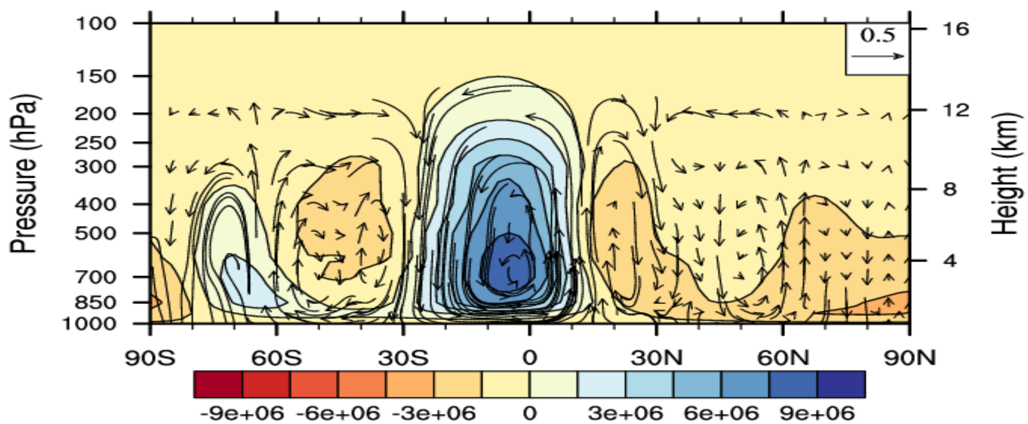


Stream function(10N-25N, 850hPa-300hPa)+
Stream function(15S-30S, 850hPa-300hPa)

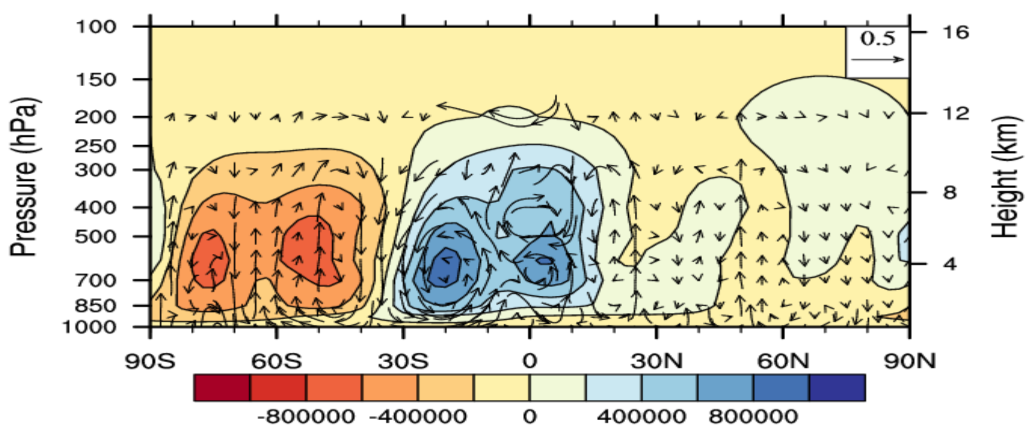




2010（strong）



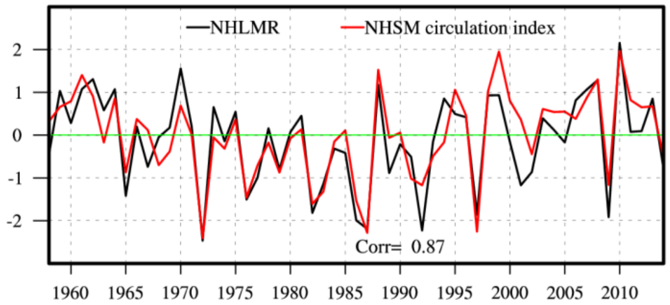
1986（weak）

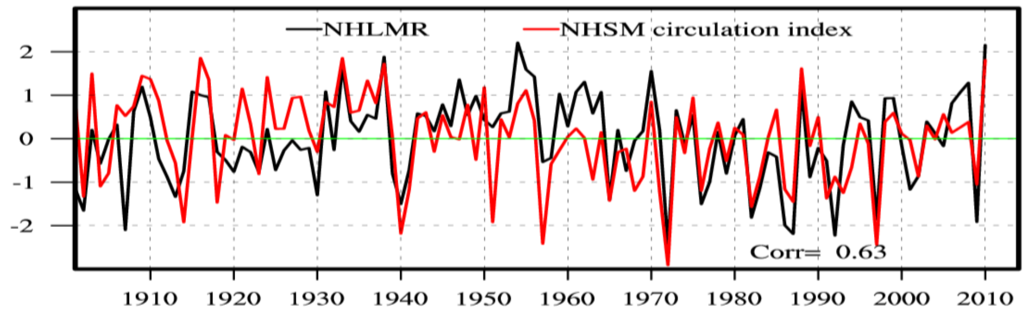


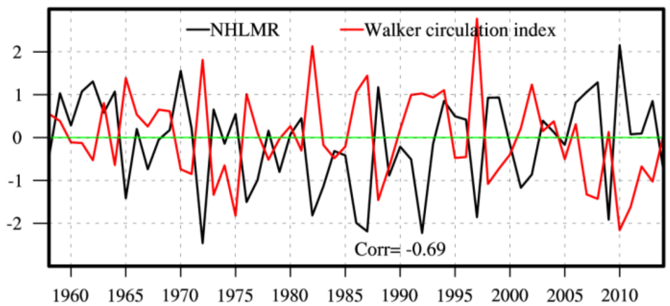
Differences (2010 minus 1986)

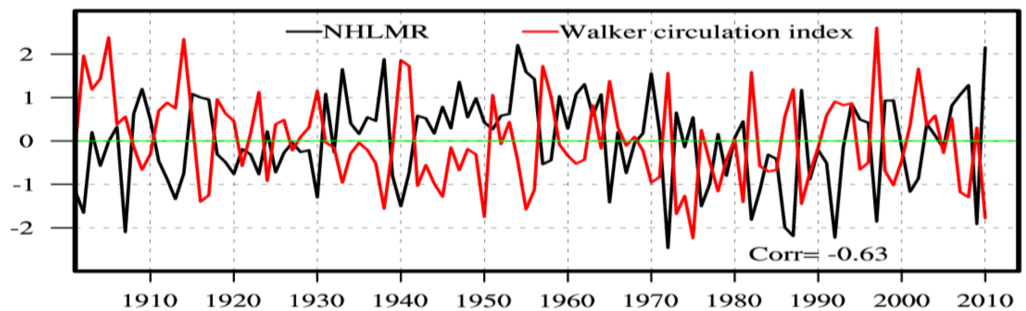
1958-2014 ERA40+ERA-interim

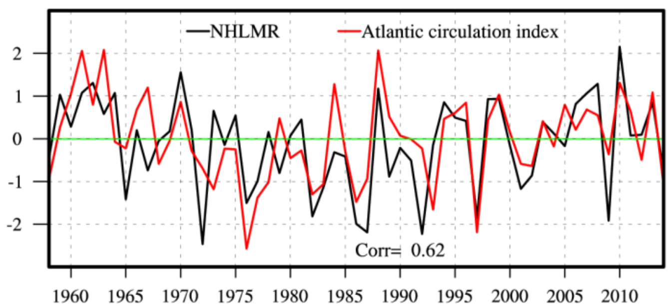
1901-2010 ERA-20C

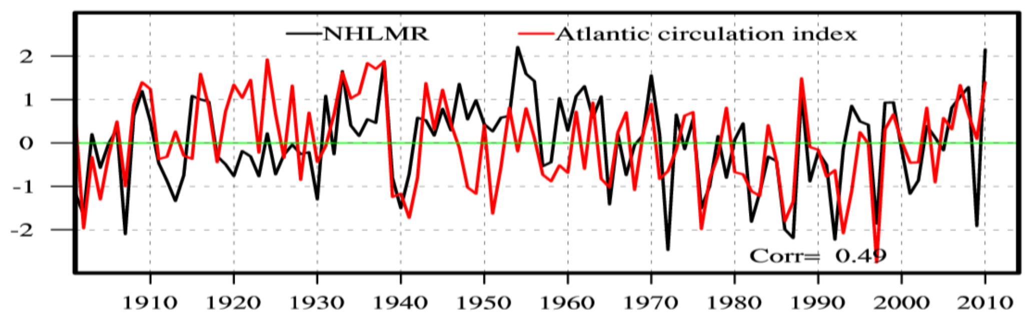


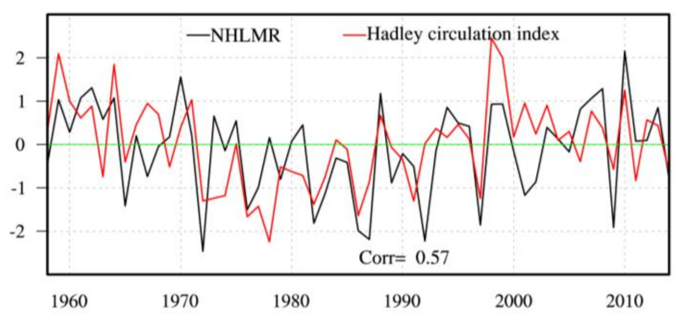






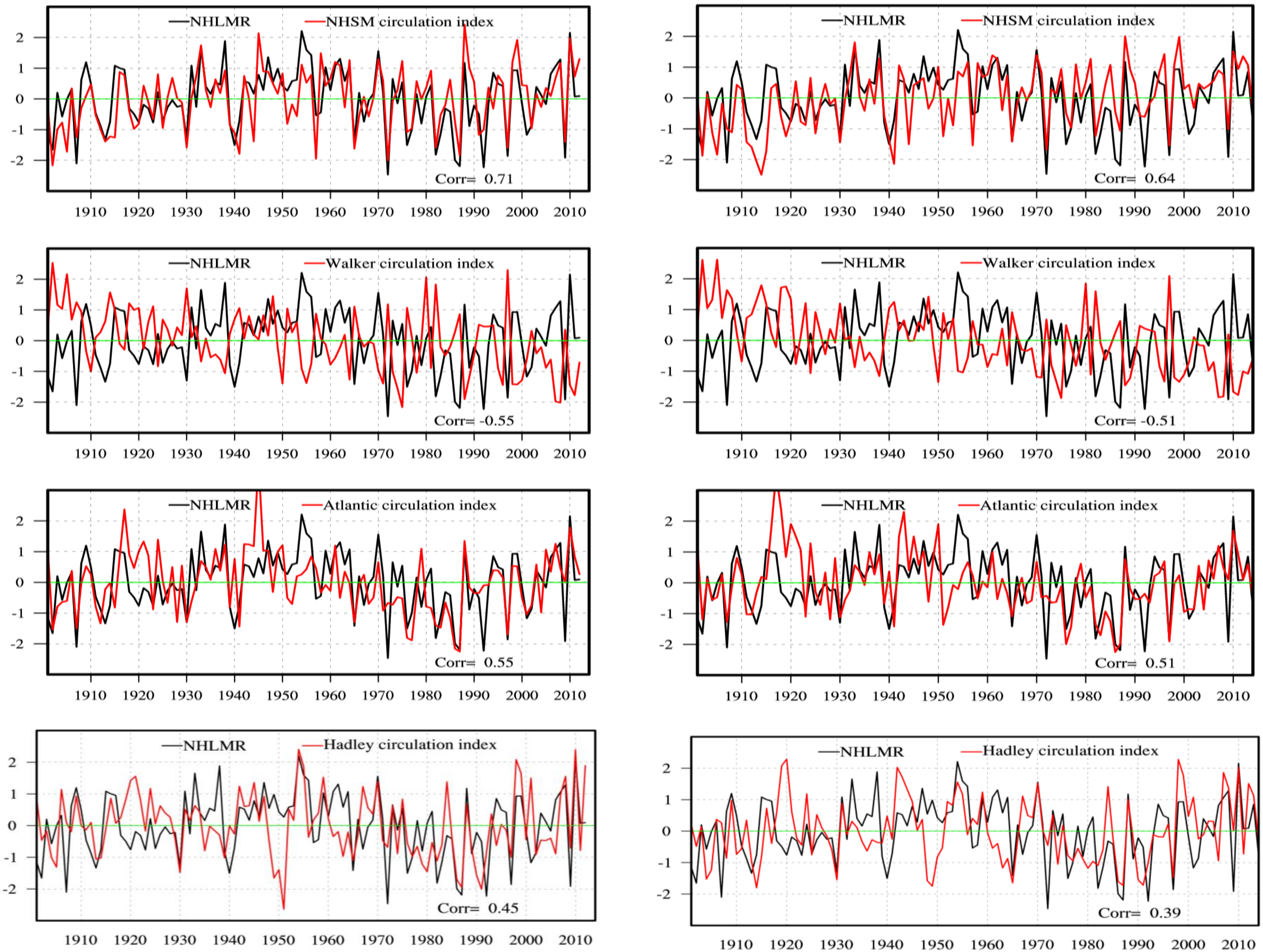




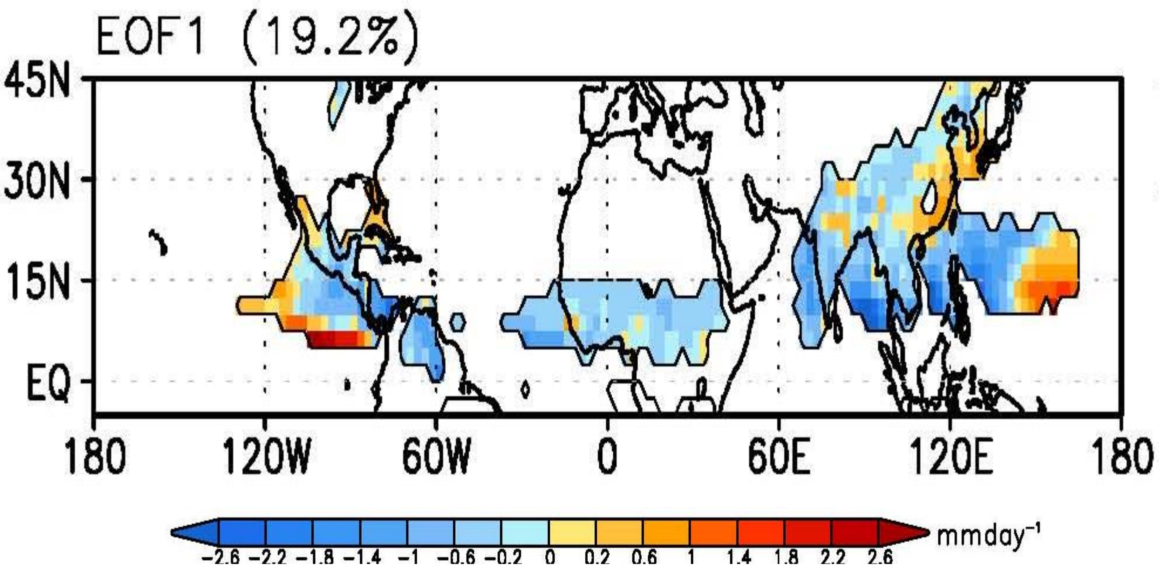


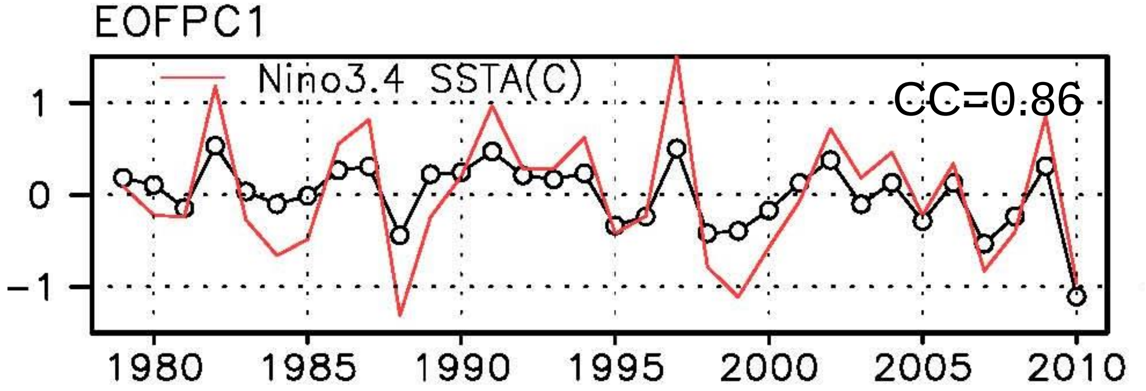
1901-2012 20CR_V2

1901-2014 20CR_V2C



Coherent interannual variation of total NHSM rainfall driven by ENSO





NH Land monsoon rainfall and Nino 3.4 correlation (monsoon year) is 0.73 (1979-2012)