A new perspective on studying ENSO teleconnections

Mátyás Herein[1], Tímea Haszpra[1,2], Tamás Bódai[3,4]

[1]MTA–ELTE Theoretical Physics Research Group, Eötvös Loránd University, Budapest, Hungary

[2]Institute for Theoretical Physics, Eötvös Loránd University, Budapest, Hungary

[3]Pusan National University, Busan, Republic of, Korea

[4]Center for Climate Physics, Institute for Basic Science, Busan, Republic of Korea

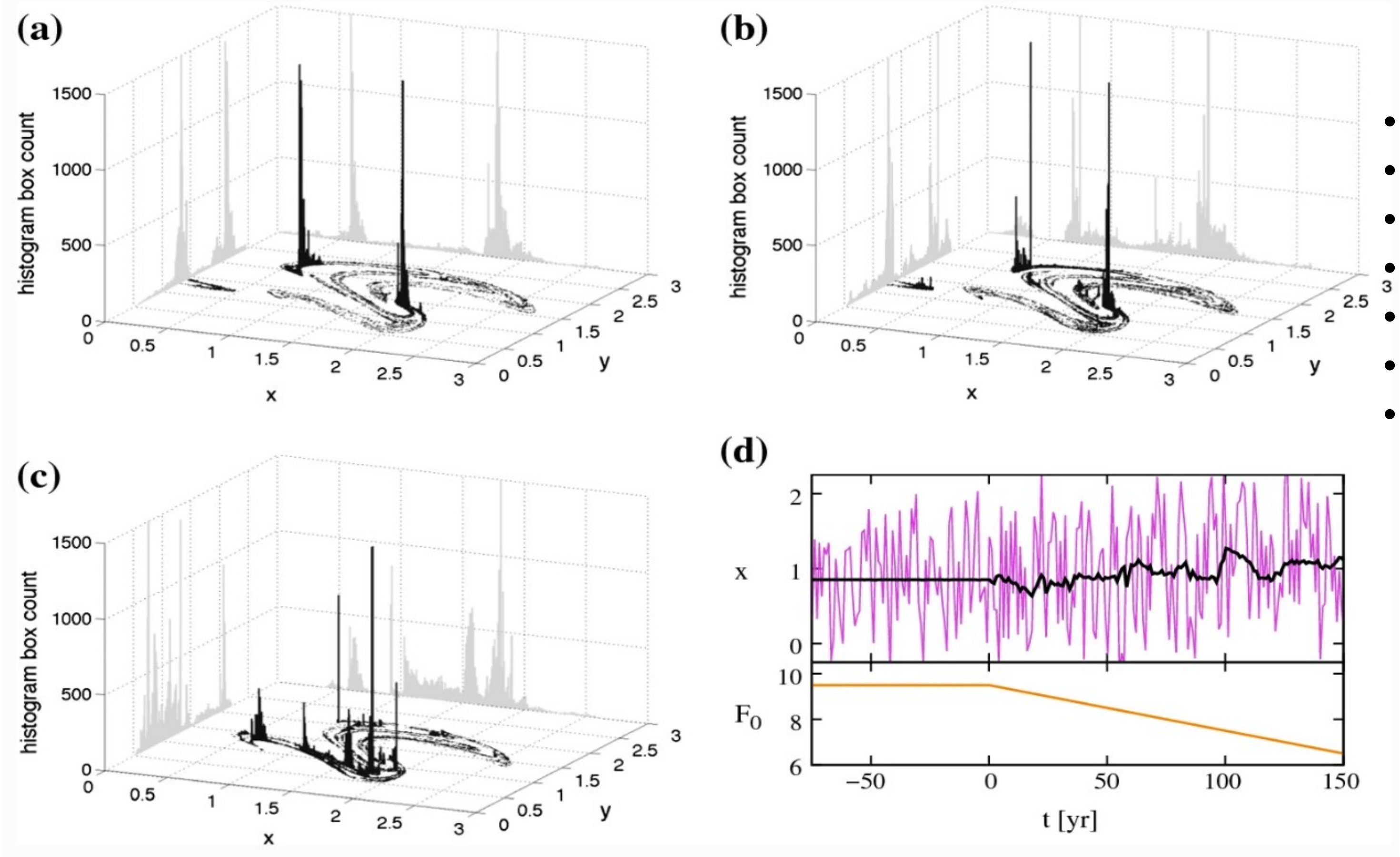
Motivation – The Snapshot attractor view

- What is climate (theoretically)?

  „The climate is what you expect, the weather is what you get" /Robert Heinlein, 1973/

  „Climate lasts all the time and weather only a few days" */Mark Twain, 1887/*

- Question: if climate is what we „expect", then what is the **expectation value**, what is the underlying **statistics (probability)**?
- Answer: climate is the natural probability distribution of the so-called snapshot attractor and its change is the climate change (Romeiras et al., 1990; Ghil et al., 2008; Bódai et al., 2011; Drótos et al., 2015)



- Lorenz 84 system with time-dependent forcing
- Trajectories evolving from the distant past
- A set to which the system evolves after a long enough time
- Climate change: if the shape of the attractor changes
- Variability: the characteristic size of the attractor
- Instantaneously permitted parallel climate realizations
- Instantaneous ensemble average changes only if climate also changes

<u>Probability distribution of the snapshot attractor</u>

(a) 25 years (b) 50 years (c) 85 years after climate change

(d) One member (magenta), ensemble average (black) and forcing (orange) after Tél et al., 2019.

Motivation – The Snapshot attractor view in GCMs

- Climate is based on ensemble statistics and could be defined by the snapshot method

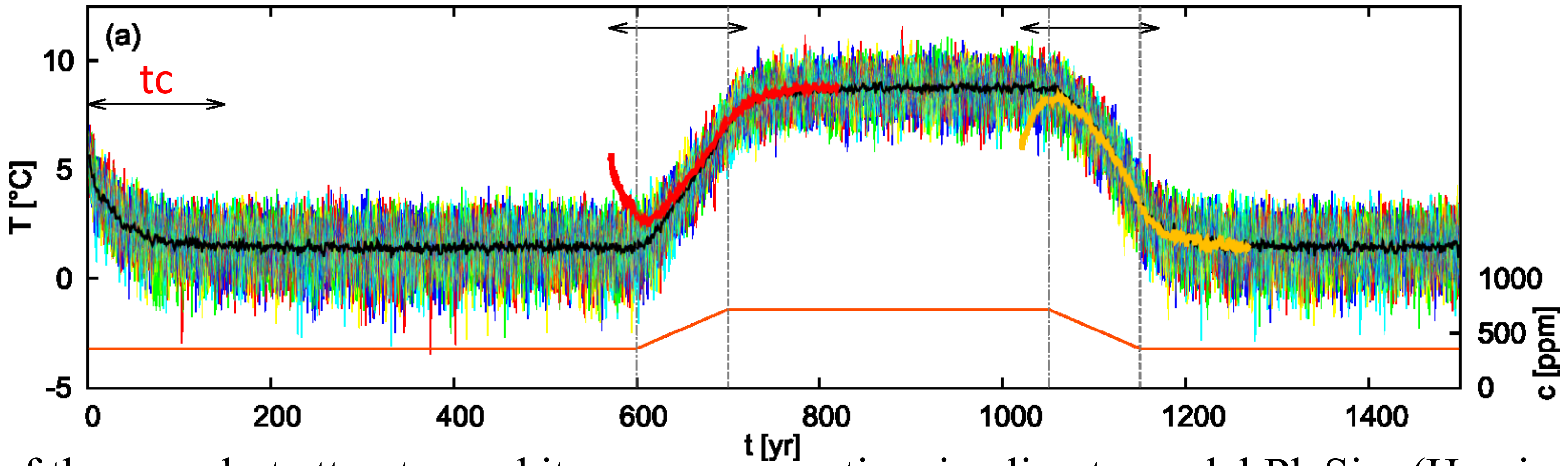


Illustration of the snapshot attractor and its convergence time in climate model PlaSim (Herein et al., 2016)

- Snapshot method defines climate instantaneously across the ensemble (numerically) in a GCM
- In theory we need infinite ensemble members → in practice we have large climate ensembles (e.g. CESM-LE)
- Climatic mean : instantaneous ensemble average
- Internal variability: higher order moments
- Ensemble statistics is only valid if we converged to the attractor, when initial conditions are forgotten (after tc) (few decades (for ocean could be more), but depends on the climate model)
- Variability is a property of the system, cannot be reduced with the increase of ensemble members
- We compute all the statistics across the ensemble,
- New application is snapshot empirical orthogonal function analysis (SEOF) (Haszpra et al., 2020a)

SEOF – a new way of teleconnection analysis

- **Teleconnections are important due to their regional/global impacts**
- **In a changing climate physical parameters shifting in time, the dynamics is time-dependent**
- **In a changing climate the strength of teleconnections might change**
- Time evolution of teleconnections in a changing climate?
- Examples: focus on Arctic Oscillation and ENSO

Question: How to characterize teleconnections in a changing climate?
Answer: parallel climate realizations (Herein et al., 2017, Tél et al., 2019) and SEOF (Haszpra et al., 2020a)

A recent review about snapshot method and parallel climate realizations (Tél et al., 2019)

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The Theory of Parallel Climate Realizations

A New Framework of Ensemble Methods in a Changing Climate: An Overview

T. Tél[1,2] · T. Bódai[3,4] · G. Drótos[2,5] · T. Haszpra[1,2] · M. Herein[1,2] · B. Kaszás[1] · M. Vincze[2]

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The theory of parallel climate realizations as a new framework for teleconnection analysis

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Mátyás Herein[1,2], Gábor Drótos[1,2], Tímea Haszpra[1,2], János Márfy[1,2] & Tamás Tél[1,2]

Teleconnections are striking features of the Earth climate system which appear as statistically correlated climate-related patterns between remote geographical regions of the globe. In a changing climate, however, the strength of teleconnections might change, and an appropriate characterization of these correlations and their change (more appropriate than detrending the time series) is lacking in the literature. Here we present a novel approach, based on the theory of snapshot attractors,

SEOF analysis

- Classical EOF method can also revisited, as it is based on temporal averages
- Ensemble based EOF method: **Snapshot EOF=SEOF; SPCs=snapshot principal components** (Haszpra et al., 2020a)

$(\mathbf{A}^{\mathrm{T}}\mathbf{A})$ **EOF** $= \mathbf{\Lambda}$ **EOF** & **PC** $=$ **A EOF**, where the eigenvalues are on the leading diagonal of $\mathbf{\Lambda}$

a) Traditional EOF for a single member *m* using **time-mean** centralization

$$\text{time}\downarrow \overset{\text{space}\rightarrow}{\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{t1} & \cdots & a_{tn} \end{pmatrix}} = \mathbf{A}(m)$$

EOF: eigenvectors

PC: principal components

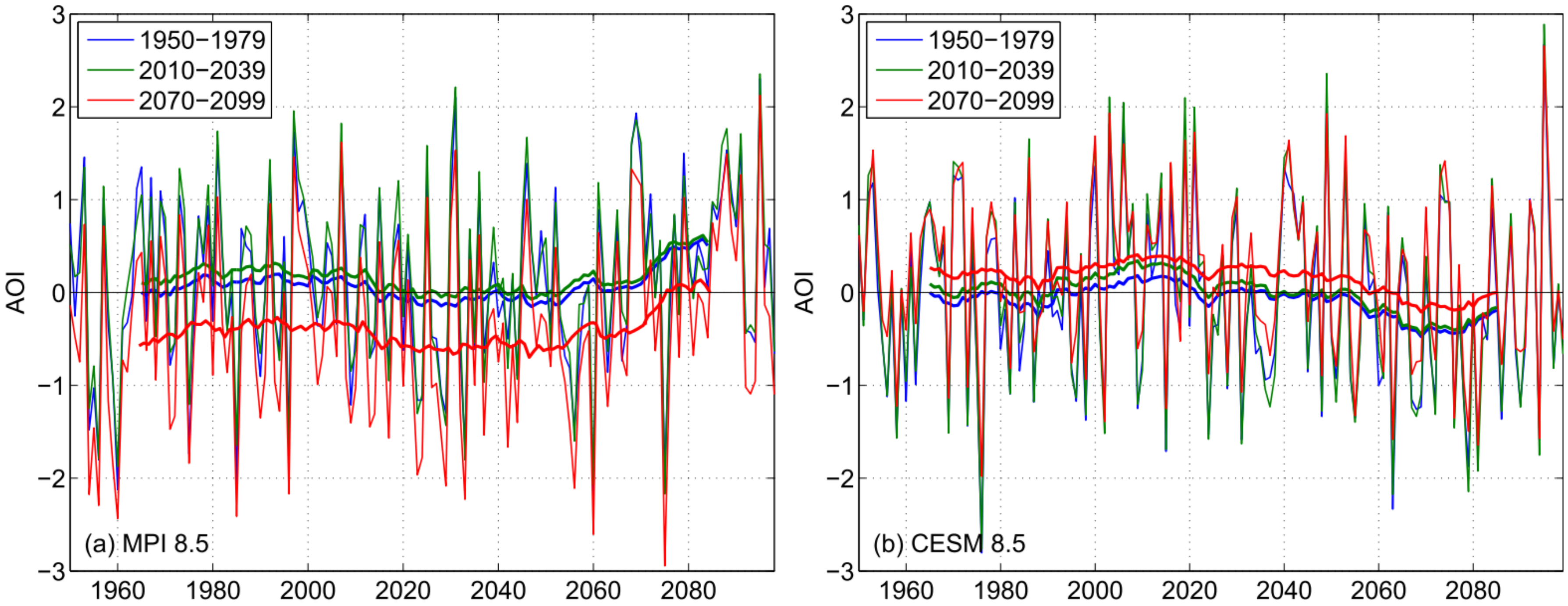
b) Snapshot EOF for a single time instant *t* using **ensemble-mean** centralization

$$\text{members}\downarrow \overset{\text{space}\rightarrow}{\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix}} = \mathbf{A}(t)$$

- A(m) and A(t) are anomaly matrices, where the anomalies are computed along time and along the ensemble, respectively
- Similar method (EOF-E) has been developed by (Maher et al., 2018).

Example 1: Arctic Oscillation (ambiguity of temporal statistics)

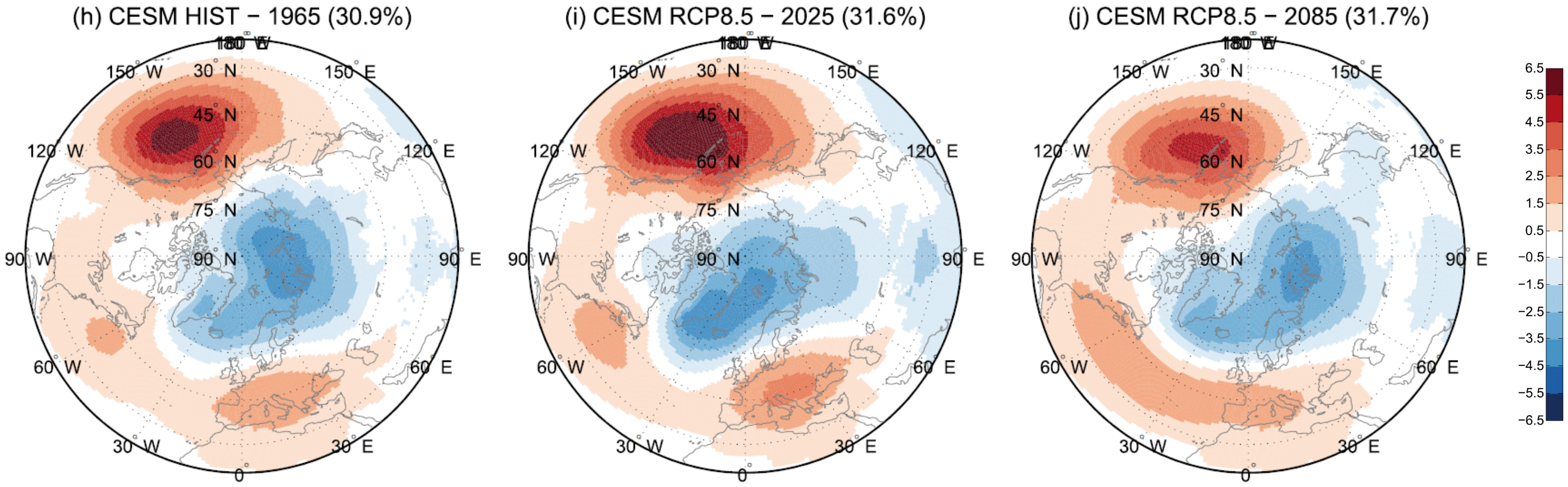
- Models: **MPI-ESM (100 members)** with RCP2.6, 4.5 and 8.5 and **CESM-LE (40 members)** with RCP8.5
- AO is the leading EOF pattern of sea-level pressure 20–90° N
- Traditional AOI is not representative (uses temporal averaging)



Traditional AOI time series (thin solid lines) for the $E = 1$ member of the MPI-GE for the RCP8.5 scenario and of the CESM-LE calculated by using different climatologies (indicated in the legend). The time series of the 30-year moving mean (thick solid lines) are also plotted. (Haszpra et al., 2020a)

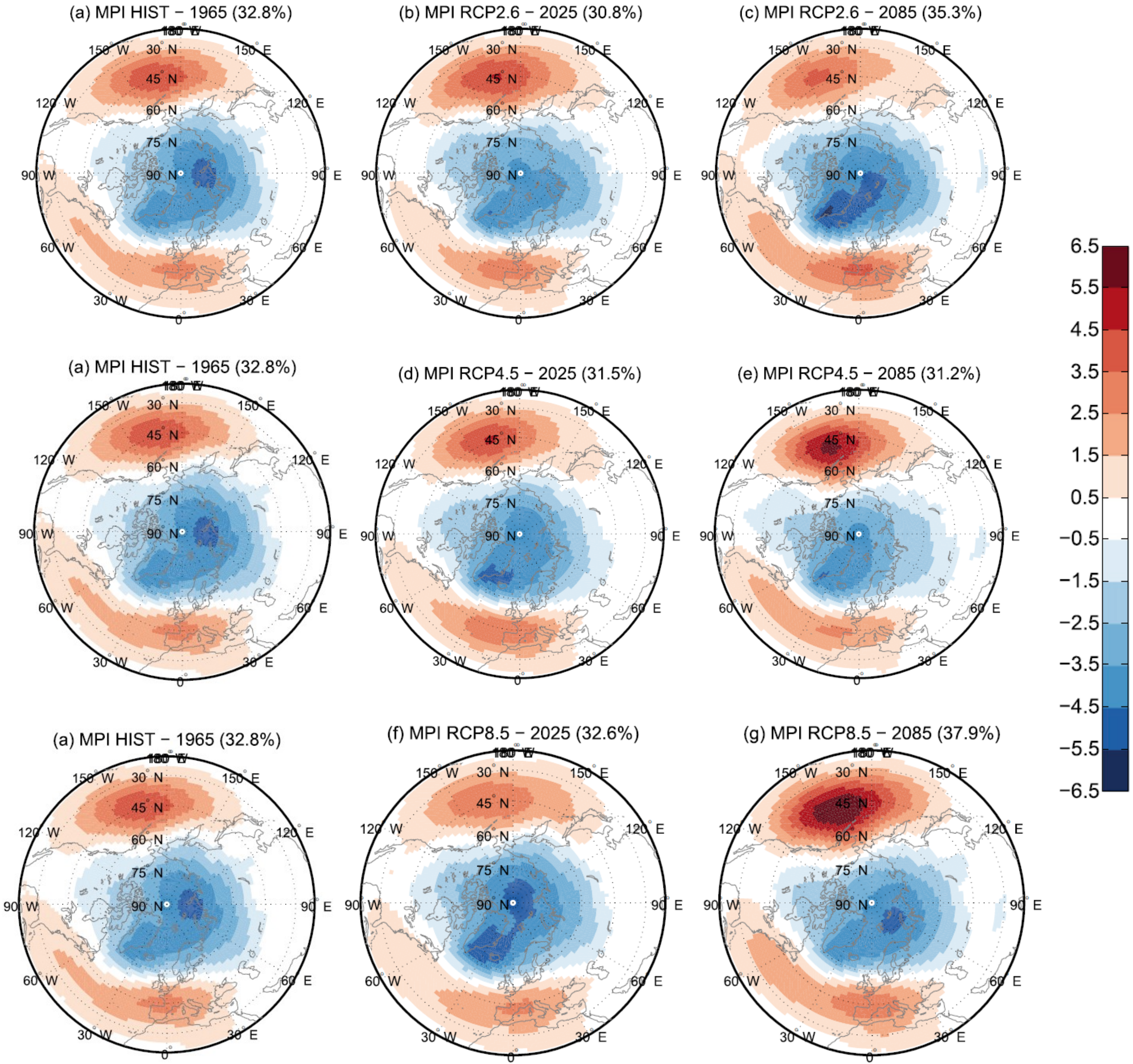
- AOI defined by the leading PCs in the ensembles – SEOF method
- We calculate the ensemble based correlation coefficient (r) between „AOI" and surface temperature (TS) for winters (DJF mean)

SEOF – CESM-LE

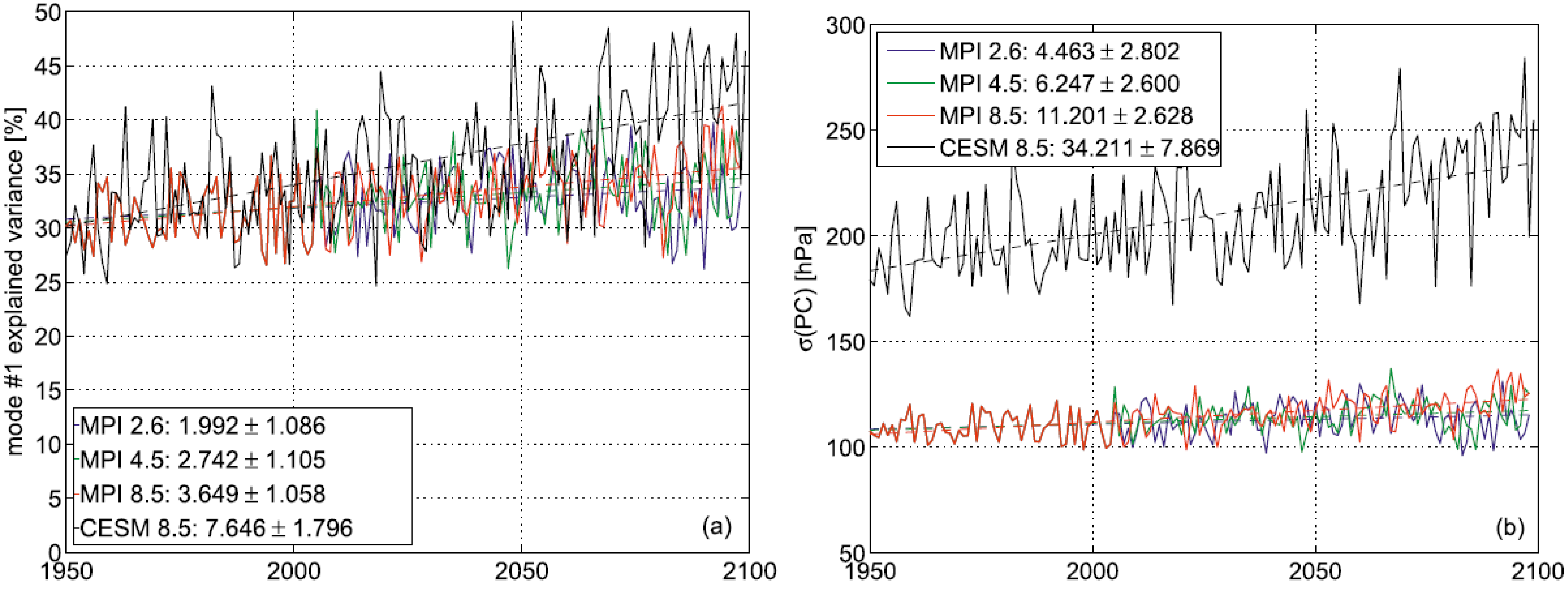


DJF mean SLP anomalies (hPa) regressed onto the first EOF mode (explained variance is indicated in parentheses) using SEOF analysis for the indicated years. (Haszpra et al., 2020a)

SEOF – MPI



DJF mean SLP anomalies (hPa) regressed onto the first EOF mode (explained variance is indicated in parentheses) using SEOF analysis for the indicated years. (Haszpra et al., 2020a)



(a) The explained variance of the first EOF mode (10^{-2} %yr^{-1}) and (b) the amplitude of the AO as the standard deviation of the PC data using SEOF analysis (10^{-2} %yr^{-1}). Curves are colored according to the ensemble (MPI-GE with different forcings, or CESM). Legend includes the slope of the linear regression with 95% confidence intervals. (Haszpra et al., 2020a)

New methodology for correlation computation

- Instead of traditional climate indices we redefine teleconnections as instantaneous ensemble based correlations (r),

$$r[A,B]=\frac{\langle AB\rangle-\langle A\rangle\langle B\rangle}{\sqrt{\left(\langle A^2\rangle-\langle A\rangle^2\right)\left(\langle B^2\rangle-\langle B\rangle^2\right)}}$$

,where A can be any ensemble based „index” and B any meteorological variable, < > denotes averaging over the ensemble

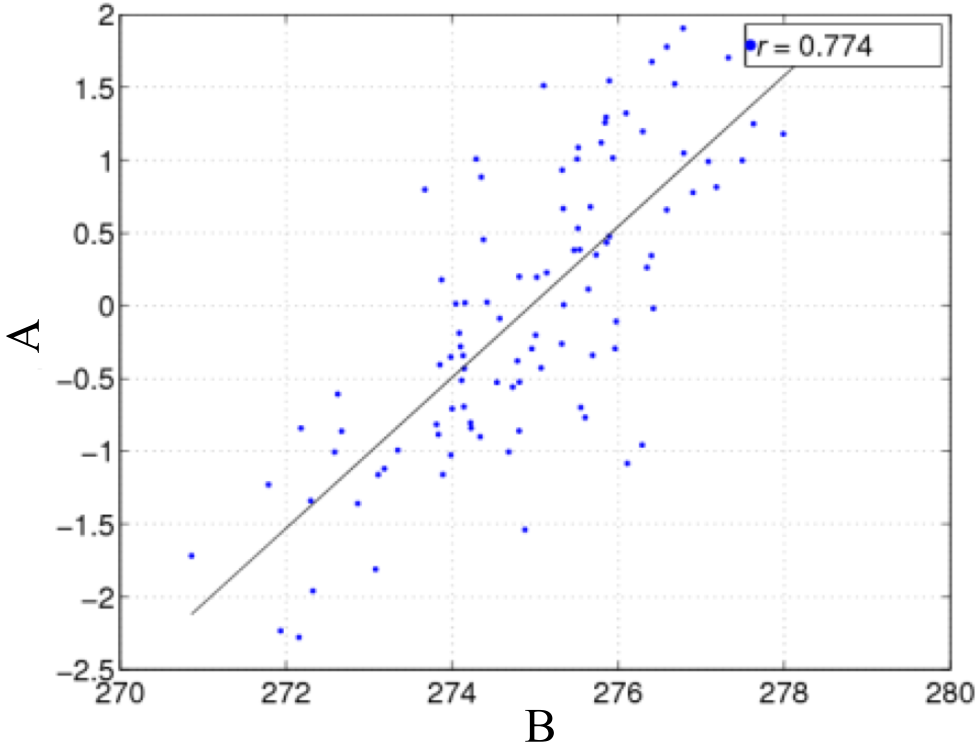
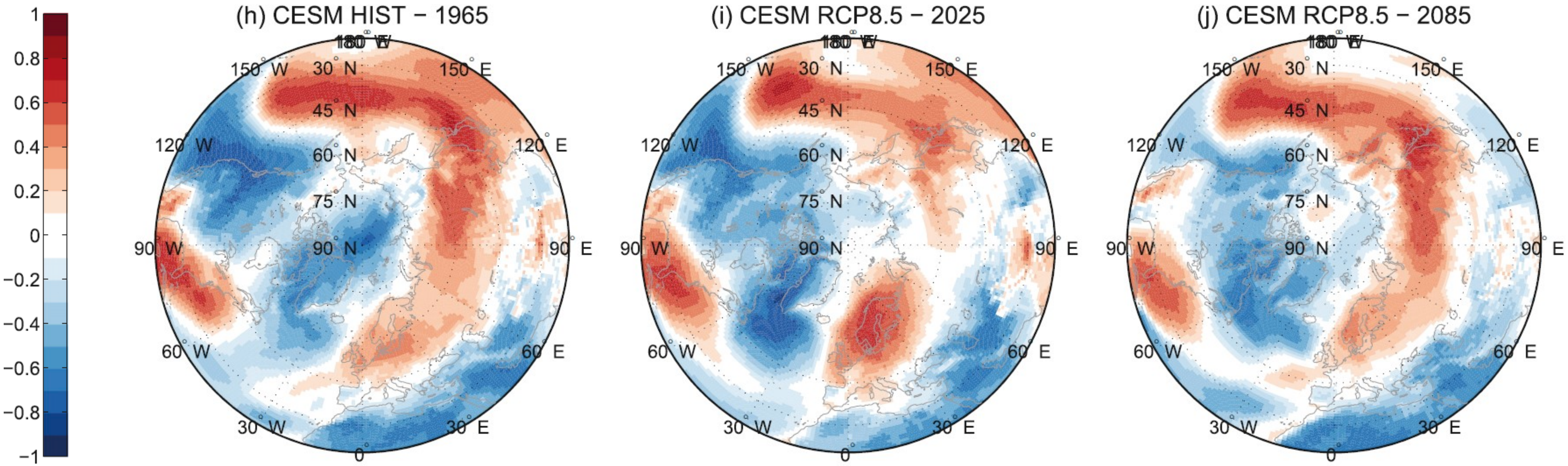


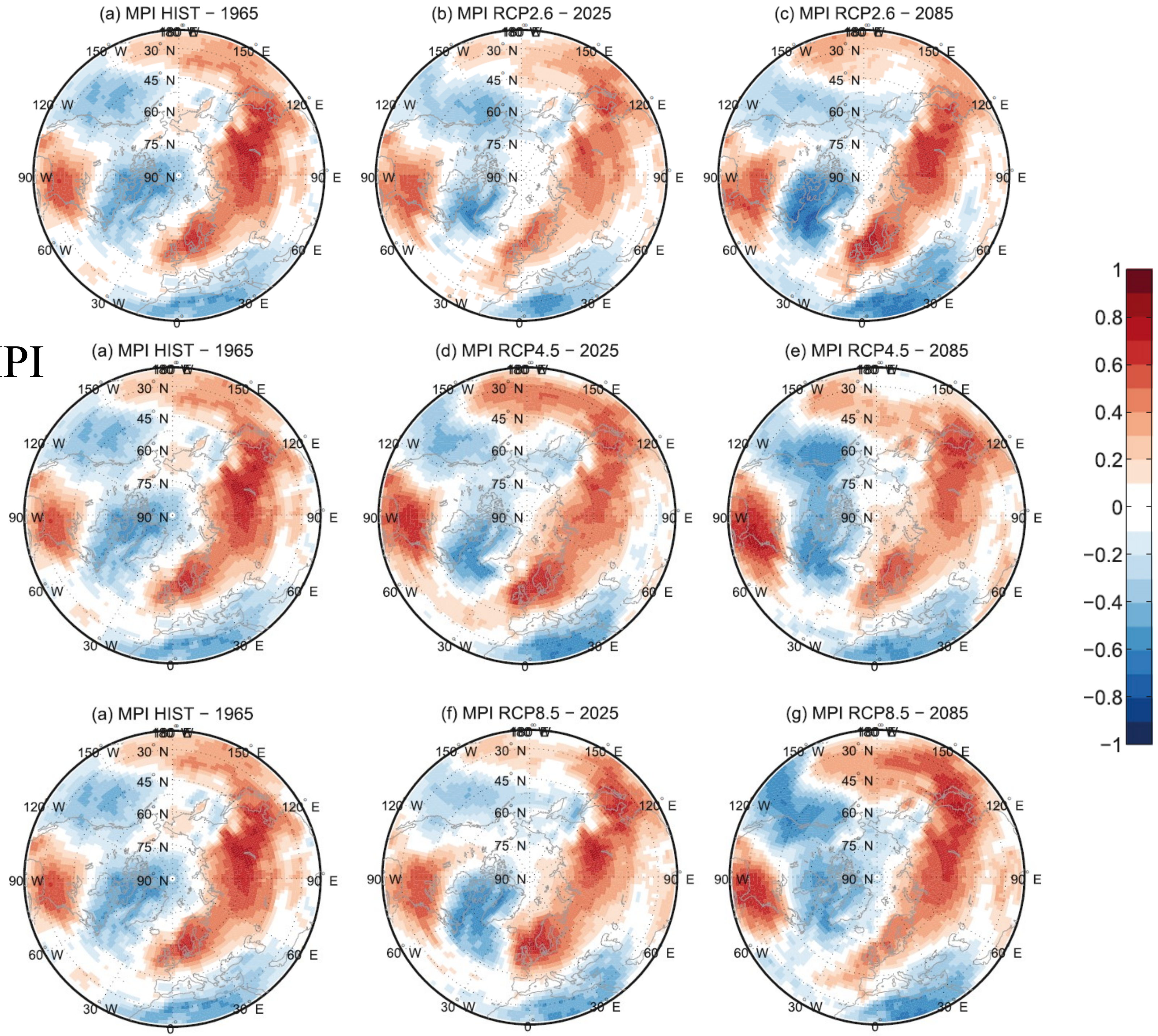
Illustration of the instantaneous ensemble based correlation (r)

Snapshot correlation in CESM-LE



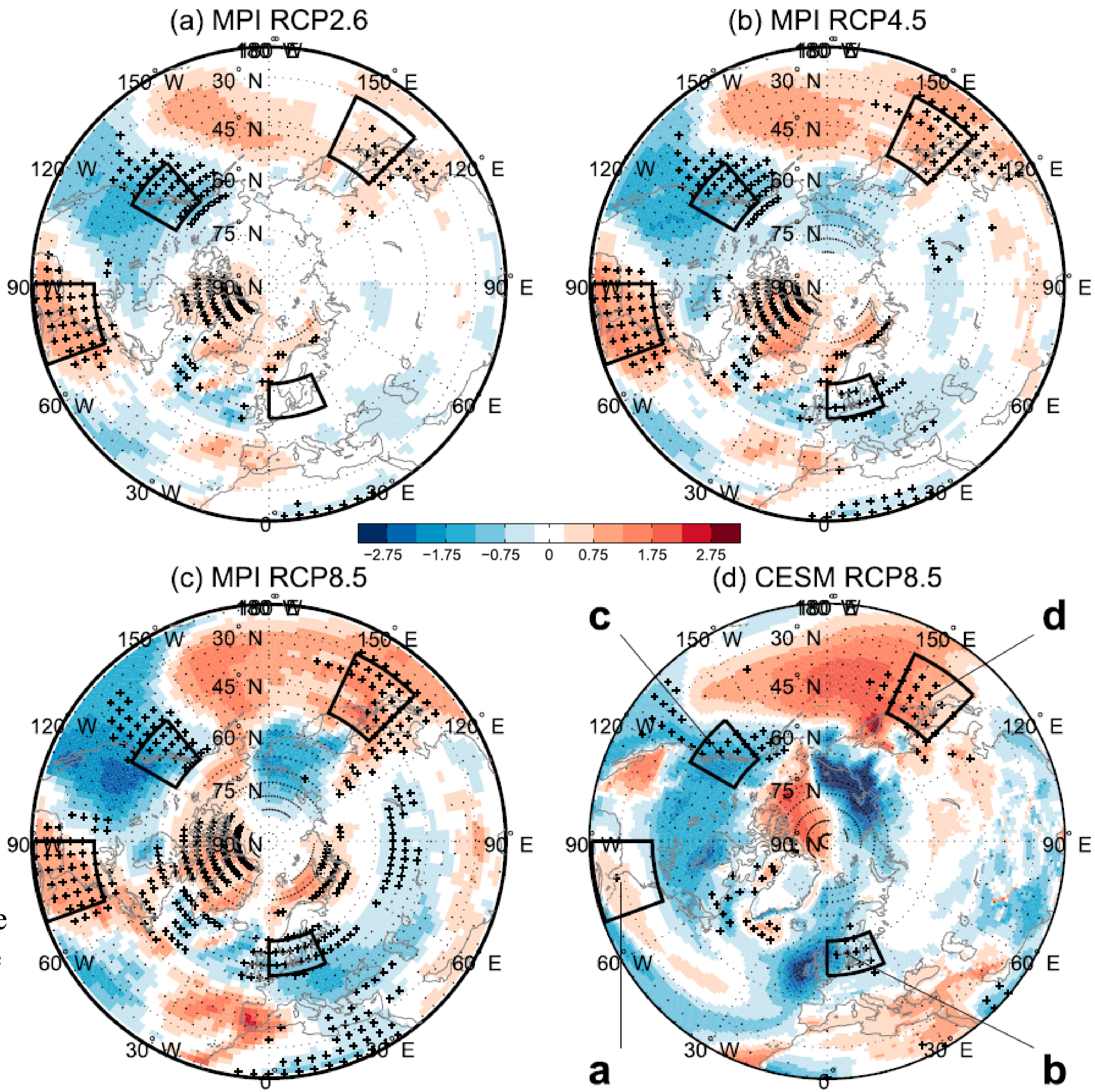
Ensemble-based snapshot correlation coefficient field between AOI and TS for the indicated years in CESM-LE for the scenarios indicated in the panel titles. (Haszpra et al., 2020a)

Snapshot correlation in MPI



Ensemble-based snapshot correlation coefficient field between AOI and TS for the indicated years in MPI-GE
for the scenarios indicated in the panel titles.
(Haszpra et al., 2020a)

Linear correlation trends in CESM-LE and MPI-GE



Linear trend (10^{-3} 1/yr) of *r* over time 1950–2099 for the MPI-GE scenarios RCP2.6, RCP4.5, RCP8.5 and for the CESM-LE. Black dots represent geographical locations where the trend is significant at the 95% level. (Haszpra et al., 2020a)

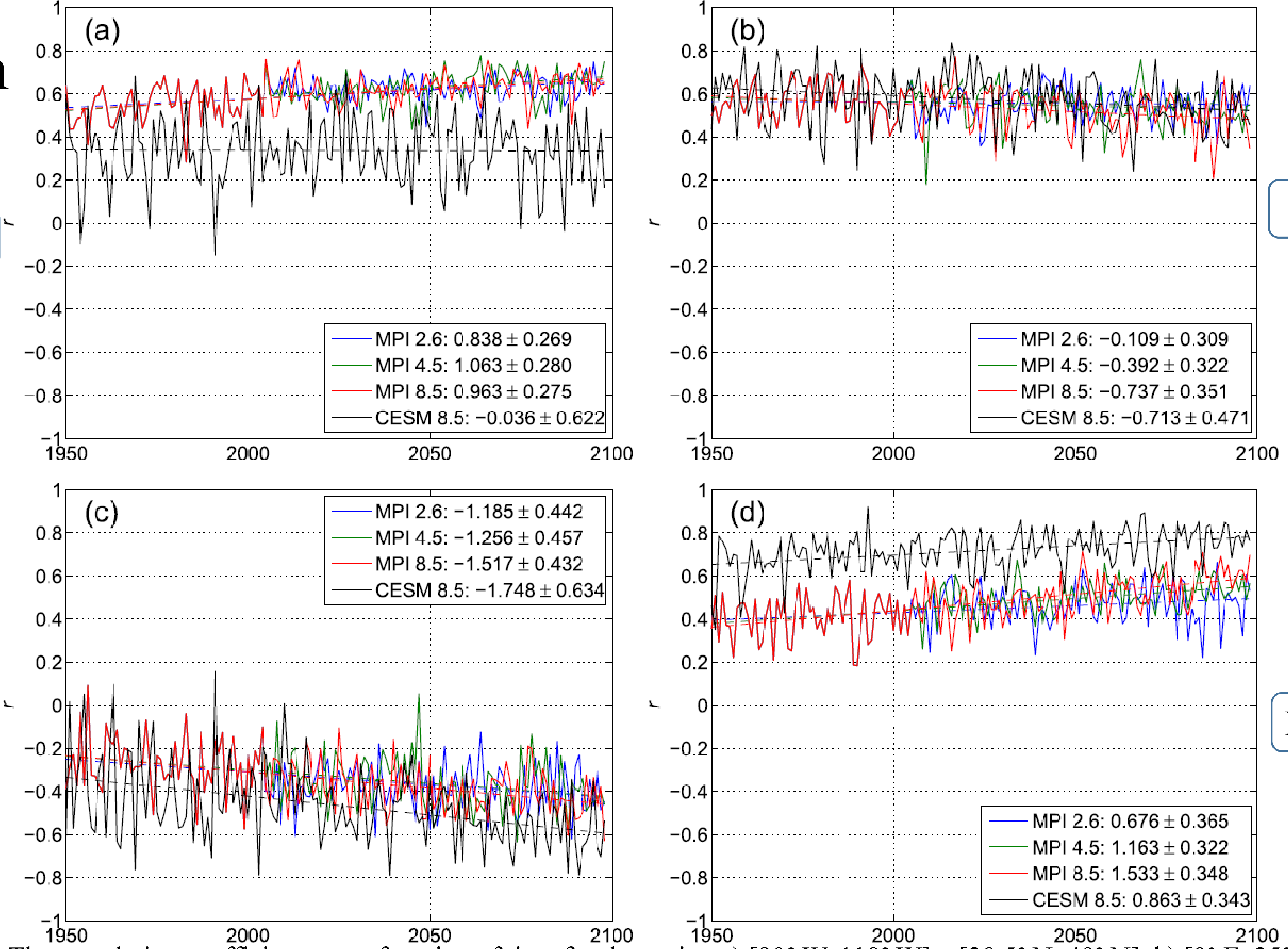
Time evolution of r

East coast US

Scandinavia

Alaska

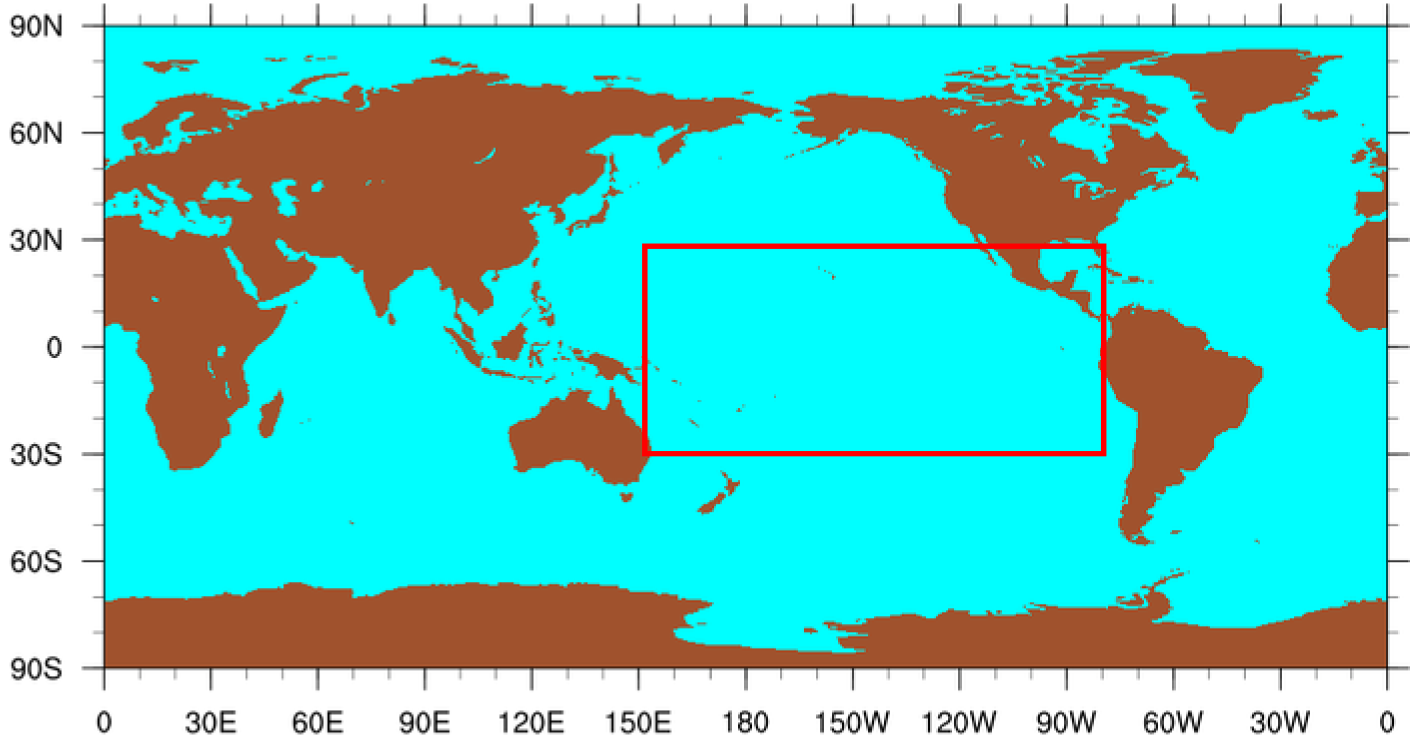
Eastern Asia

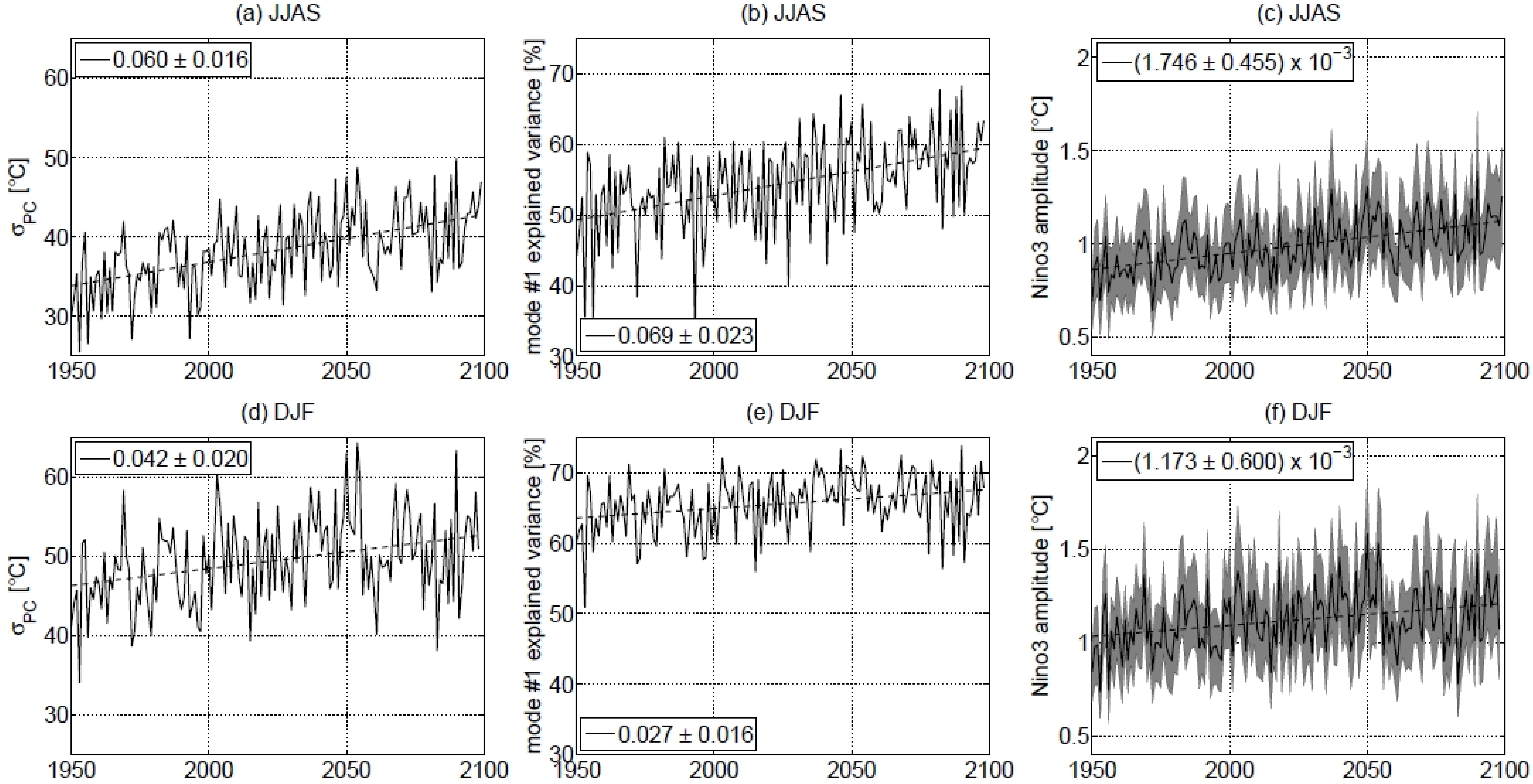


The correlation coefficient r as a function of time for the region a) [90° W, 110° W] × [20.5° N, 40° N], b) [0° E, 25° E] × [52° N, 62° N], c) [140° E, 120° E] × [45° N, 60° N], d) [135° E, 155° E] × [30° N, 50° N]. Curves are colored according to the ensemble (MPI-GE with different forcings, or CESM).Legend includes the slope of the linear regression with 95% confidence intervals [10^{-3} yr^{-1}]. (Haszpra et al., 2020a)

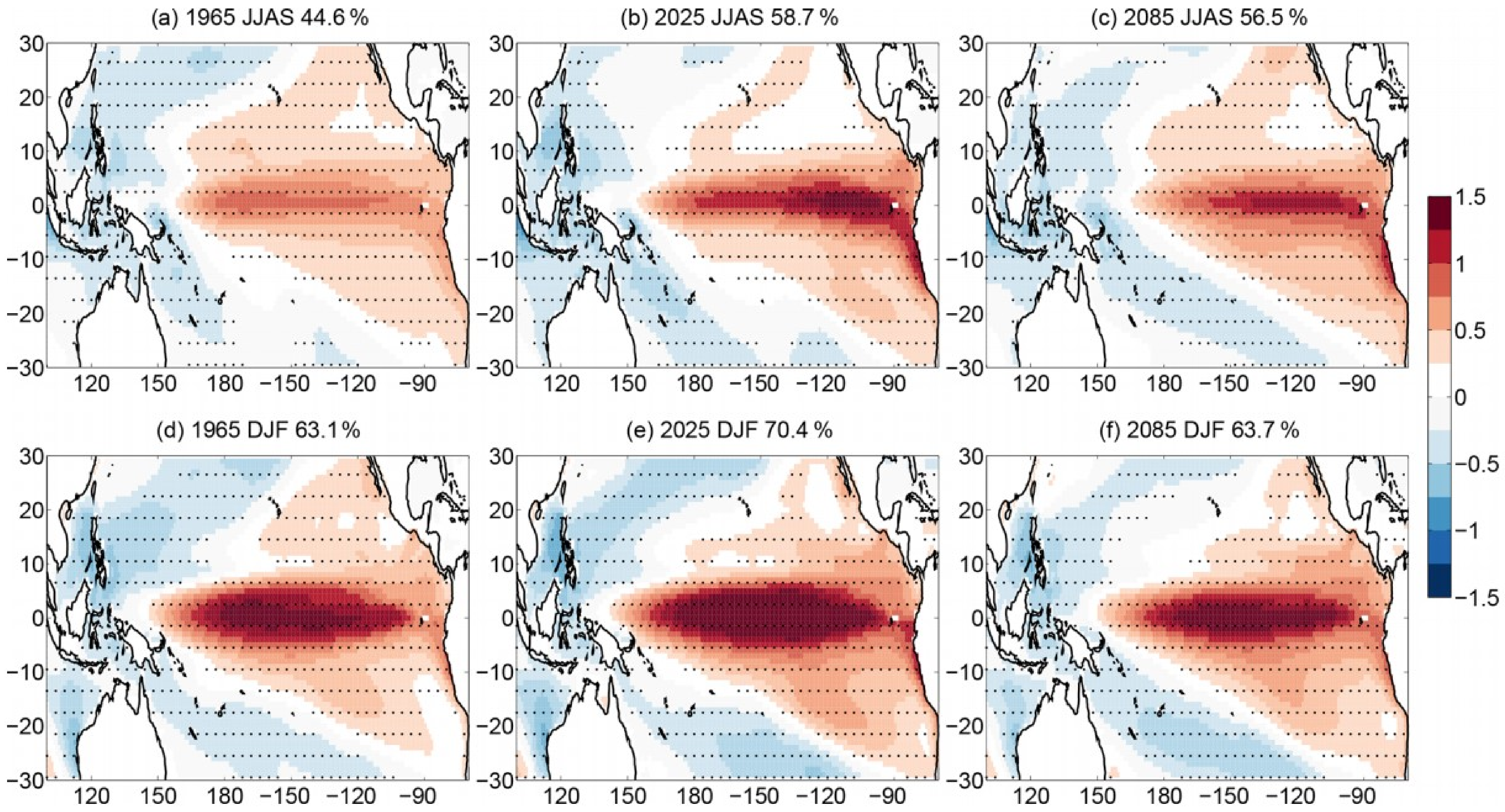
Example 2: ENSO – global precipitation correlations

- Model: **CESM-LE (40 members)** with RCP8.5
- NINO Box: -30S–30° N, 160-295° W
- SEOF method applied→SPCs
- We calculate the ensemble based correlation coefficient (*r*) between „SST SPCs" and Precipitation(P) → time evolution of *r*

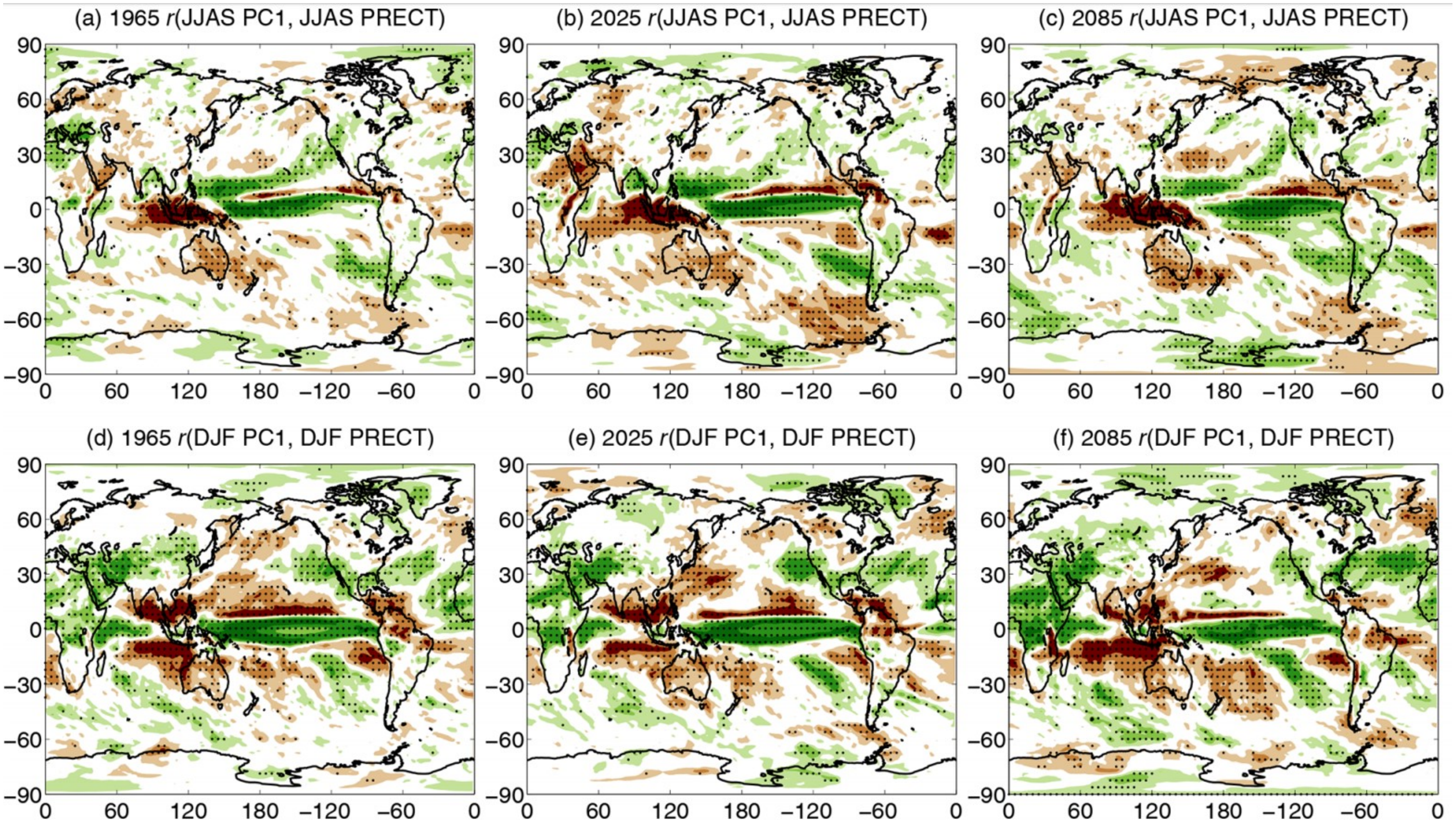




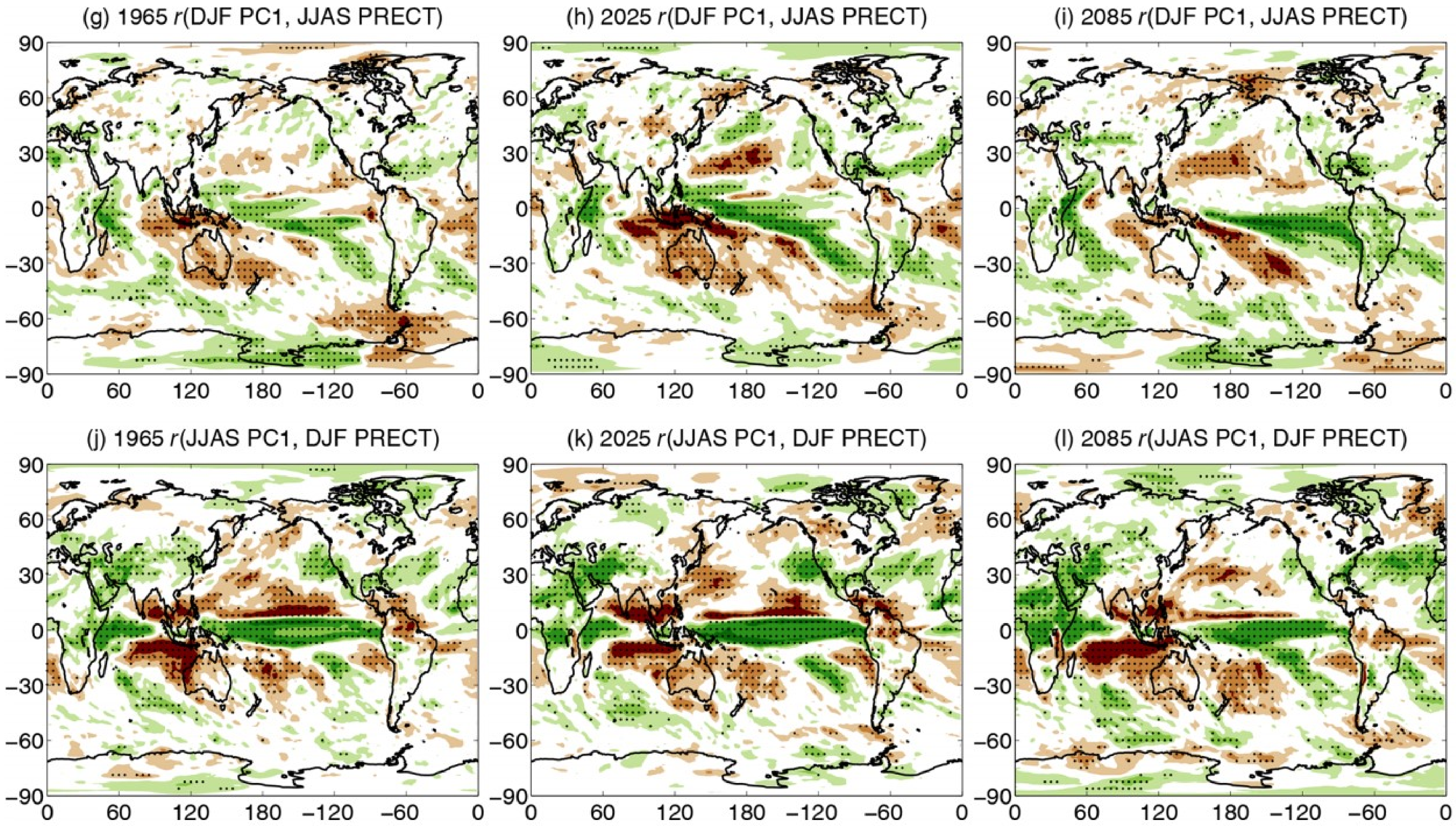
(a, d) Ensemble-based ENSO strength as the ensemble standard deviation of the PC1 (σPC), (b, e) the explained variance in the first SEOF mode, and (c, f) Niño3 amplitude as the area-mean (thick line) ensemble standard deviation of SST in the Niño3 region and its area standard deviation (grey band) in (a–c) JJAS and (d–f) DJF. Linear fits are indicated by dashed lines; legends indicate the slope of the linear fits with 95 % confidence intervals. (Haszpra et al., 2020b)



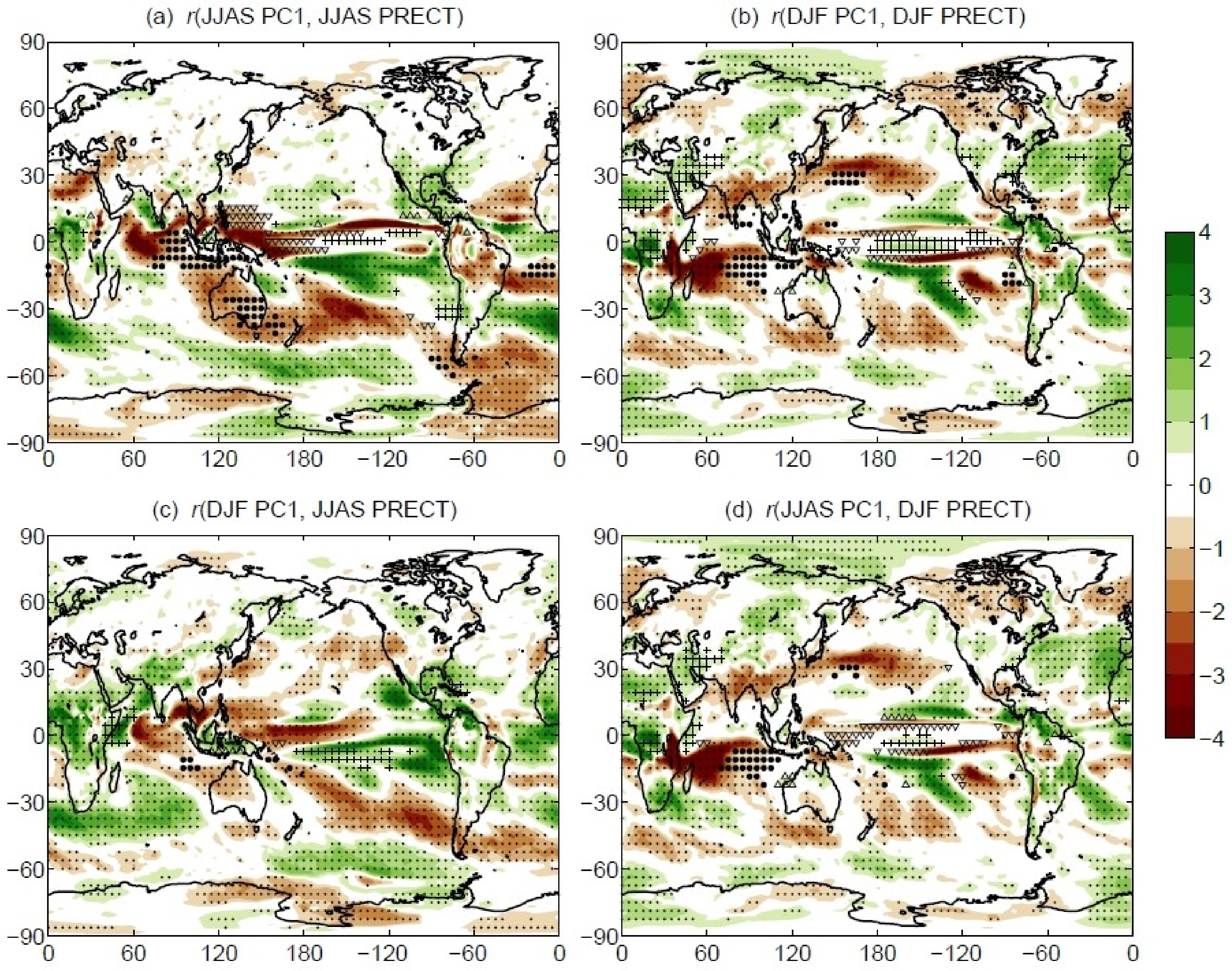
Ensemble-based SST regression maps [in degrees Celsius] for years given in the title of the panel for (a–c) JJAS and (d–f) DJF. The explained variance in the first SEOF mode is also displayed in the title of the panels. Dots represent geographical locations where the regression coefficient is significant at the 95 % level. For better visibility, only every fourth grid point is dotted. (Haszpra et al., 2020b)



Ensemble-based correlation coefficient r maps for the (a–c) JJAS PC1 and JJAS PRECT, (d–f) DJF PC1 and DJF PRECT. Specific years are indicated in the panels. Dots represent geographical locations where the correlation coefficient is significant at the 95 % level. For better visibility, only every fourth grid point is dotted. (Haszpra et al., 2020b)



Ensemble-based correlation coefficient *r* maps for the DJF PRECT, (g–i) DJF PC1 and JJAS PRECT, and (j–l) JJAS PC1 and DJF PRECT. Specific years are indicated in the panels. Dots represent geographical locations where the correlation coefficient is significant at the 95 % level. For better visibility, only every fourth grid point is dotted. (Haszpra et al., 2020b)



The slope of the linear fits (10^{-3} yr^{-1}) at each grid point for the correlation coefficient *r* for the (a) JJAS PC1 and JJAS PRECT, (b) DJF PC1 and DJF PRECT, (c) DJF PC1 and JJAS PRECT, and (d) JJAS PC1 and DJF PRECT. Dots represent geographical locations where the trend is significant at the 95 % level. (Haszpra et al., 2020b)

Conclusions

•Traditional (temporal average based) climate indices **might be misleading in a changing climate! → Traditional climate indices should be reconsidered in climate projections!**

•The strength of the **teleconnections should be characterized by correlation coefficients (or maps)** calculated over the ensemble

• An alternative, revised EOF method: **SEOF**

• **Due to the climate change the strength of teleconnections can be strongly time-dependent**

• **Artic Oscillation** can change due to climate change, changes can be relevant for US (**Alaska**) and Northern-Europe, also for Eastern Asia (based on CESM-LE and MPI-GE).

• **ENSO-global prec. relationship**: time-dependent, changes in South-Asian monsoon?

- We offer a **new view of teleconnection dynamics** with the benefits:
  - naturally separates externally induced trends from internal fluctuations (no detrending needed)
  - Time evolution of teleconnections

It should be incorporated into the analysis of climate projections obtained in any large-scale climate model, preferably with large amount of members.

- *Larger ensembles needed (x100-1000 members)??*

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Thank you for your attention!!
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