Modelling-robustness of the past and future forced changes of the ENSO-Indian summer monsoon teleconnection

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ENSO-Indian Summer Monsoon Teleconnection

- In India, the summer monsoon period begins in the late May or early June and lasts up to September, bringing nearly 75% of country's annual rainfall.
- The interannual variability of the Indian Summer Monsoon (ISM) is strongly associated with the El Niño Southern Oscillation (ENSO).
- In general, El Niño (La Niña) years are associated with above (below) normal ISM rainfall.
- Most of the severe droughts occur over the Indian region are during El Niño years while there have been drought years without El Niño.

- The inverse relationship between El Niño and **ISMA** Ninos SST ISM weakened in the recent decades, particularly after 1970s [*Kumar et al.*, 1999]. They argued that the weakening is mainly due to rise in the Eurasian surface temperature during winter and summer, and shifting of the Walker cell towards south-eastward direction.
- Recent studies linked the weakening of the teleconnection to global warming, AMO, PDO, co-occurrence of El Nino and IOD events, shift in the ENSO's center of action

Fig: displays the time-evolution of 21 year window moving correlation coefficients (r), between Nino3 SST and ISM rainfall.

etc

The teleconnection strength is typically increasing on the long term in view of appropriately revised ensemble-wise indices. Bodai et al., 2020, J. Cli

Fig: Moving temporal correlation coefficient (between Nino3 SST and ISM rainfall) for the Fig. Moving temporal correlation coefficient (between Ninos SST and ISM familian) for the
MPI-GE in the historical period and RCP8.5 forcing scenario. The thin gray lines show all the realizations while three realizations are shown in color, providing examples. Thick blue lines
show the ensemble average of the terms
and correlation, which are blown up in insets to better. show the ensemble average of the temporal correlation, which are blown up in insets to better indicate any trend. Bodai et al., 2020, J. Cli indicate any trend. The realizations while the realizations are shown in color, providing examples. This is a shown in color, providing examples. This is a shown in color, providing examples. This is a shown in color and t Sov blow the temporal correlation, which are blown up in insets to be the temporal correlation, which are blown up in indicate any trend.

Objective

Study the forced response of the teleconnection between the ENSO and the Indian Summer Monsoon (ISM) in a multi-model ensemble of initial conditional ensembles under historical forcing and future forcing scenarios.

The forced response of the teleconnection, or a characteristic of it, is defined as the time dependence of a correlation coefficient evaluated over the ensemble.

The Forced Evolution of Correlation Coefficients: Historical Period

- None of the models shows a significant weakening of teleconnection at the end of 20th century.
	- This shows that the role of external forcing is relatively weak in the observed weakening of ENSO-ISM teleconnection at the end of $20th$ century, and internal variability might have played a crucial role in it. This result is in agreement with Li and Ting 2015.

Fig: Top row displays the time-evolution of ensemble-wise correlation coefficients (r), between Nino3 SST and AISMR during 1901-2005 period. Magenta curve shows 21-year moving mean and cyan curve shows the yearly values. Bottom row is same as top, but for Nino 3.4 SST.

EOF Pattern and Variability of Pacific SST

- EOF1 pattern looks similar to the results in the literature. Furthermore, the forced change is very weak in model and other models shows significant variabilities.
- In the second half of 20th century and first half of 21st century ENSO variability increases in most of the models. While, under strong future forcing scenarios (late $21st$ century), typically ENSO variability starts to decline in a nonmonotonic, nonlinear fashion.

Fig2: Shows the ensemble-wise standard deviation of Nino3 SST during the JJA season. Magenta curve shows 21-year moving mean and cyan curve shows the yearly values.

The Forced Evolution of Correlation Coefficients:

- Under moderate, historical and early 21st century, forced change of ENSO-ISM teleconnection is strengthening or nondecreasing in all the models.
- \blacksquare In the second half of 21st century, the teconnection strengthening or nondecreasing in 5 models and a weakening is observed in GFDL ESM 2M and MIROC6 models.

Fig: Top row displays the time-evolution of ensemble-wise correlation coefficients (r), between Nino3 SST and AISMR during 1950-2100 period. Magenta curve shows 21-year moving mean and cyan curve shows the yearly values. Bottom row is same as top, but for Nino 3.4 SST.

- The strengthening of ENSO-ISM teleconnection observed in MPIESM, CanESM5, CanESM2 CSIRO-MK-360, in the second half end of 21st century are statistically significant. While, CESM2 doesn't show any significant change.
- The late 21^{st} century weakening of teleconnection observed in GFDL ESM 2M and MIROC6 models are significant.

FIG: Test statistics of the Mann-Kendall test for the stationarity of correlation coefficient. Red and blue shades correspond to $p < 0.05$, i.e., a detection of nonstationarity at that significance level.

variability in the given regions (which may be represented e.g., becompos $\frac{1}{2}$ consider the constant $\frac{1}{2}$ as a function of the constant of th Decomposition of the Forced Change of the Teleconnection Strength where Φ, Ψ and ξ represent the ENSO (or ENSO-related) signal, t Change of the Teleconnection strength red Change of the Teleconnection Strength Once the r(t) signal is established, we can ask about the origin of e telecolmection prieugin

most. The are not a regression $\frac{1}{\pi}$ drivers of the te spatial rearrangements of the relevant areas contribute to In a regression analysis framework we identify three by further analyses would be necessary. drivers of the teleconnection change:

model

(i) ENSO varia Similarly to ENSO, we have a EOF and EOF and EOF and EOF and EOF and EOF and The Contract on t (i) ENSO variability

of the variability in the two regions that are interrelated the

orthogonal, but not the CCA modes. By comparing these

our case, we might possibly obtain some hints about how much

belonging to teleconnection representations or characteristics

 \overrightarrow{v} (ii) ENSO-ISM (ii) ENSO-ISM coupling strength and

(iii) noise stren dominant modes of variability from a local point of view, for which which we have a local point of view, $f(x) = f(x)$ (iii) noise strength.

We attribute an $(i)-(ii)$, namely ENSO- ISM connection strength, but contains the teleconomic strength, and the teleconomic strength, $\sum_{i=1}^{n}$ gthening of the teleconnection to

• The ENSO variability σ_{ϕ} = std(Φ); (i)-(ii), namely, increasing ENSO variability and \bullet The ENSO-IM coupling a, being the regr we authorite any strengthening of (1) ^{- (1)}, mannery, mercasing E_1 ENSO- ISM coupling strength **differentiary dimension to** \bullet The ENSO variability $\sigma_{\Phi} = \text{std}[\Phi];$ We attribute any strengthening of the teleconnection to • The noise strength $\sigma_{\xi} = \text{std}[\xi]$.

we identify three $\Psi = a\Phi + \xi$, σ_{Ψ} and σ_{Ψ} and σ_{Ψ} and σ_{Ψ} and σ_{Ψ} are latent to σ_{Ψ} ing strength and $r = \frac{r}{\sqrt{1+(\left(\frac{r}{c}\right)/\tau)^2}}$ correlation coefficient $\mathcal{L}^{\mathbf{1}}$ fraction of the fraction of the variance of the varia of the predictand Ψ that the predictor Φ can deterministically $p_{\text{ref}}(t) = \frac{p_{\text{ref}}(t)}{p_{\text{ref}}(t)}$ $r =$ $a\sigma_\Phi$ σΨ . (3) $\mathbf{V} = \mathbf{V} \cdot \mathbf{V$ mechanisms, here we pursue only a statistical attribution. We consider the linear regression model (Eq. 2) which underpins the linear regression model (Eq. 2) which underpin
The linear regression model (Eq. 2) which underpins the linear regression model (Eq. 2) which under the linear in r to the factors, via considering the relationship to the relationship of $v_i = \frac{d\sigma_{\Phi}}{dt}$ $r = \frac{1}{\sqrt{1 - \left(\frac{1}{(1 - \left(\frac{1}{($ 1 $\frac{1}{1-(1+\lambda)^2}$ $\sqrt{1 + ((\sigma_{\xi}/a)/\sigma_{\Phi})^2}$ **Regression Equation** $\mathcal{O}(\mathcal{C})$ signal is established, we can ask about the origin of origin of \mathcal{C} \mathbf{M} observed time dependence. Instead of the trying terminal physical ph $m = u + v$, consider the linear regression model (Eq. 2) which under $\mathcal{U}\mathcal{U}\oplus\mathcal{U}$ correlation coefficient r. In this model, we can attribute changes $r =$ in r to three factors, via considering the relationship of $\mathbf{1}$ $\overline{\qquad \qquad }$ $\frac{1}{\left(\left(\sigma_{\xi}/a\right)/\sigma_{\Phi}\right)^2}$

we may do regard the with the weight of the with the with the with the with the with those EOFs. As a associated with the w

- The ENSO variability $\sigma_{\Phi} = \text{std}[\Phi]$;
- **Fariability** and The ENSO-IM coupling a, being the regression coefficient;
• The noise strength $\sigma_{\epsilon} = \text{std}[\xi]$.

σΨ

EOF1 or EOF2 on the Pacific side.

r !

 $\overline{}$, state strength $\overline{}$ state strength of $\overline{}$

. 2021 Bodai et al., 2021 $\frac{21}{2}$ • The ENSO-IM coupling a, being the regression coefficient; variability wrt. the ensemble, for every year separately. That is, like

The non-decreasing teleconnection strength in the early and middle part of 21st century is due to an increasing ENSO variability as well as coupling strength.

This non-increasing nature of coupling strength and decreasing ENSO variability, played a dominant role in the weakening of the ENSO-ISM teleconnection in GFDL ESM 2M and MIROC6 models under strong late 21st century forcing.

Spatial Pattern of Correlation Coefficient and its Forced Change

• The spatial pattern of the forced response of ENSO-ISM teleconnection shows an east-west dipole pattern over north-India, in most of the models. However, there is no inter-model robustness in the south India.

- § The forced response of the teleconnection between the ENSO and the Indian summer monsoon (ISM) evaluated using a multi-model ensemble of initial conditional ensembles under historical forcing and future (RCP8.5/SSP5-8.5/SSP3-7.0) forcing scenarios.
- \blacksquare The role of external forcing is relatively weak in the observed weakening of ENSO-ISM teleconnection at the end of $20th$ century, internal variability might have played a crucial role in it.
- In the early and middle part of the 21st century that the teleconnection is strengthening or nondecreasing. This considerable robustness is owing to an increasing ENSO variability as well as coupling strength.
- In the end of the 21^{st} century, there is no inter-model robustness in the projected teleconnection. This is mainly due to the ENSO variability change is not projected robustly across models: either the start of the ENSO variance decline is not captured robustly, or the rates of the decline of ENSO variance competing this time with an increase of the coupling strength.

EOF Pattern and Variability of ISM Rainfall

Fig1: Top row displays the EOF1 pattern (JJAS) of ISM rainfall during 1900-1950 or1950-2000. Bottom row shows the EOF1 pattern difference, 2050-2100 minus 1900-1950 or 1950-2000.

• The spatial pattern of the forced response of ISM rainfall shows an east-west dipole pattern over north-India, in most of the models (except CanESM2 and GFDL ESM 2M).

Under future forcing scenarios, the ensemblewise variance of ISM rainfall increases in MPIESM, CanESM5, Csiro MK 3.6 and CESM2 models. Hardly any forced change is observed in the other three models.

Fig2: Shows the ensemble-wise standard deviation of ISM rainfall during the JJAS season. Magenta curve shows 21-year moving mean and cyan curve shows the yearly values.