# Potential Increase in MJO Predictability Under Global Warming

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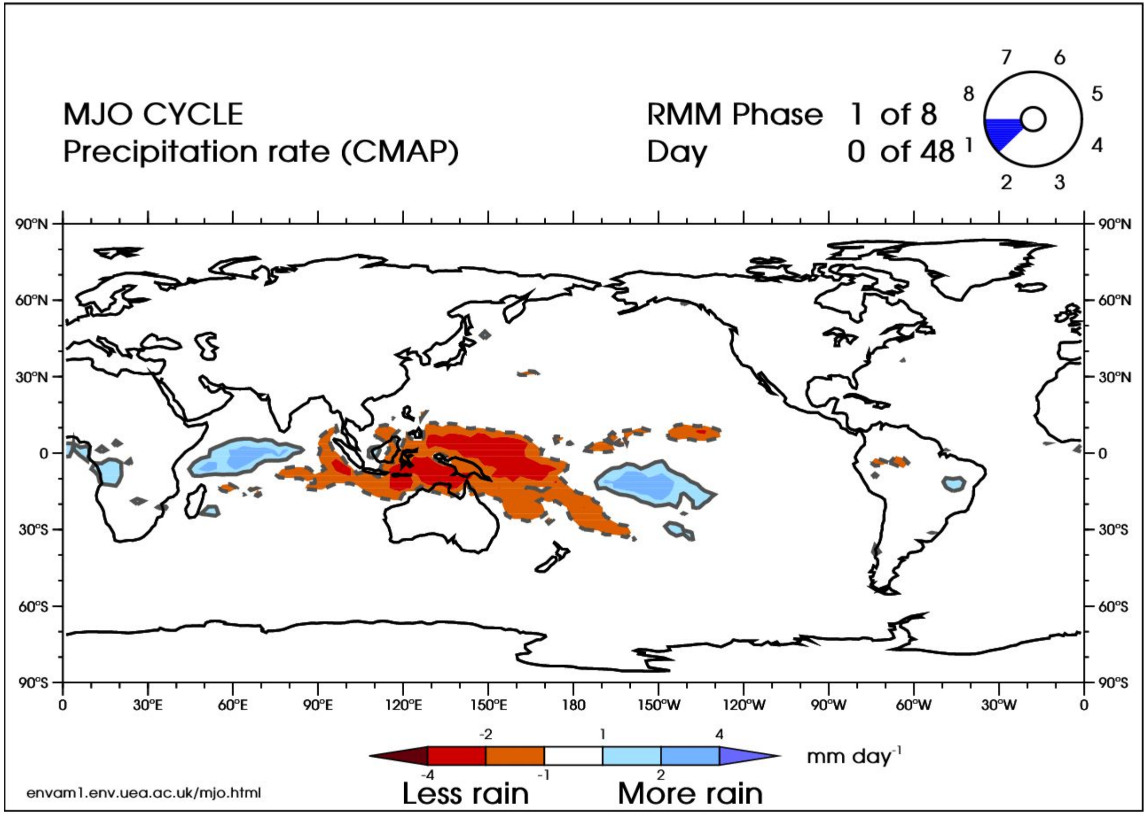


MJO CYCLE
Precipitation rate (CMAP)
RMM Phase 1 of 8
Day 0 of 48
7 6 8 5 1 4 2 3
90°N 60°N 30°N 0 30°S 60°S 90°S
0 30°E 60°E 90°E 120°E 150°E 180 150°W 120°W 90°W 60°W 30°W 0
-4 -2 -1 1 2 4
mm day⁻¹
Less rain
More rain
envam1.env.uea.ac.uk/mjo.html

## The Real-time Multivariate MJO Index (RMMI) is commonly used to monitor the MJO activity.

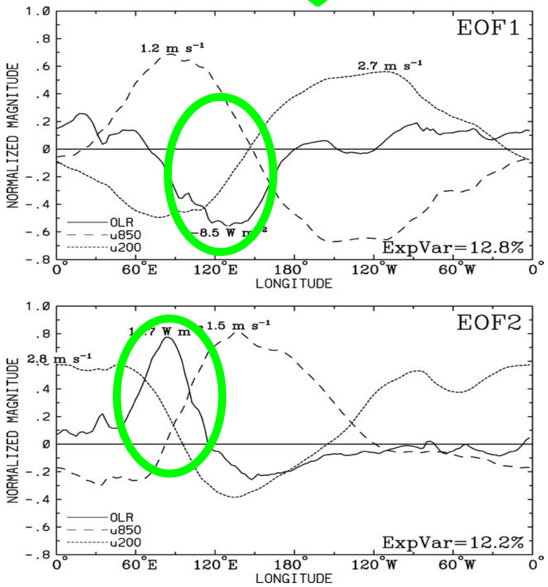
Empirical orthogonal function (EOF) analysis on the combined fields of near-equatorially averaged:

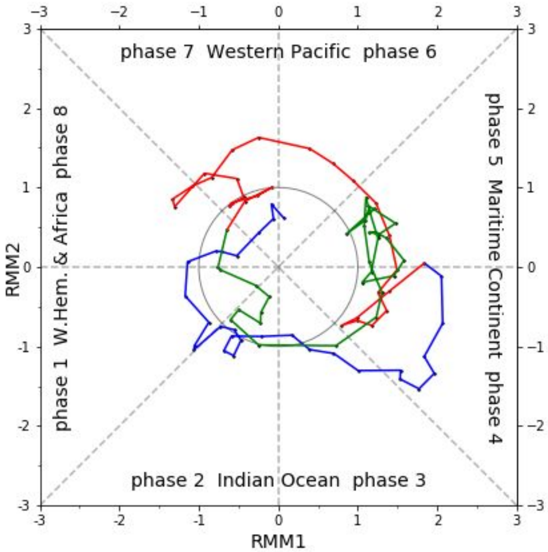
- Daily zonal wind at 850 hPa (U850)
- Daily zonal wind at 200 hPa (U200)
- Daily outgoing longwave radiation (OLR; a proxy of deep convection)

We obtain:

- 2 EOF modes
- 2 Principal Component (PC) time series
  - **RMM1**
  - **RMM2**

RMM1 and RMM2 determine the **amplitude** and the **location** of the MJO active convection.

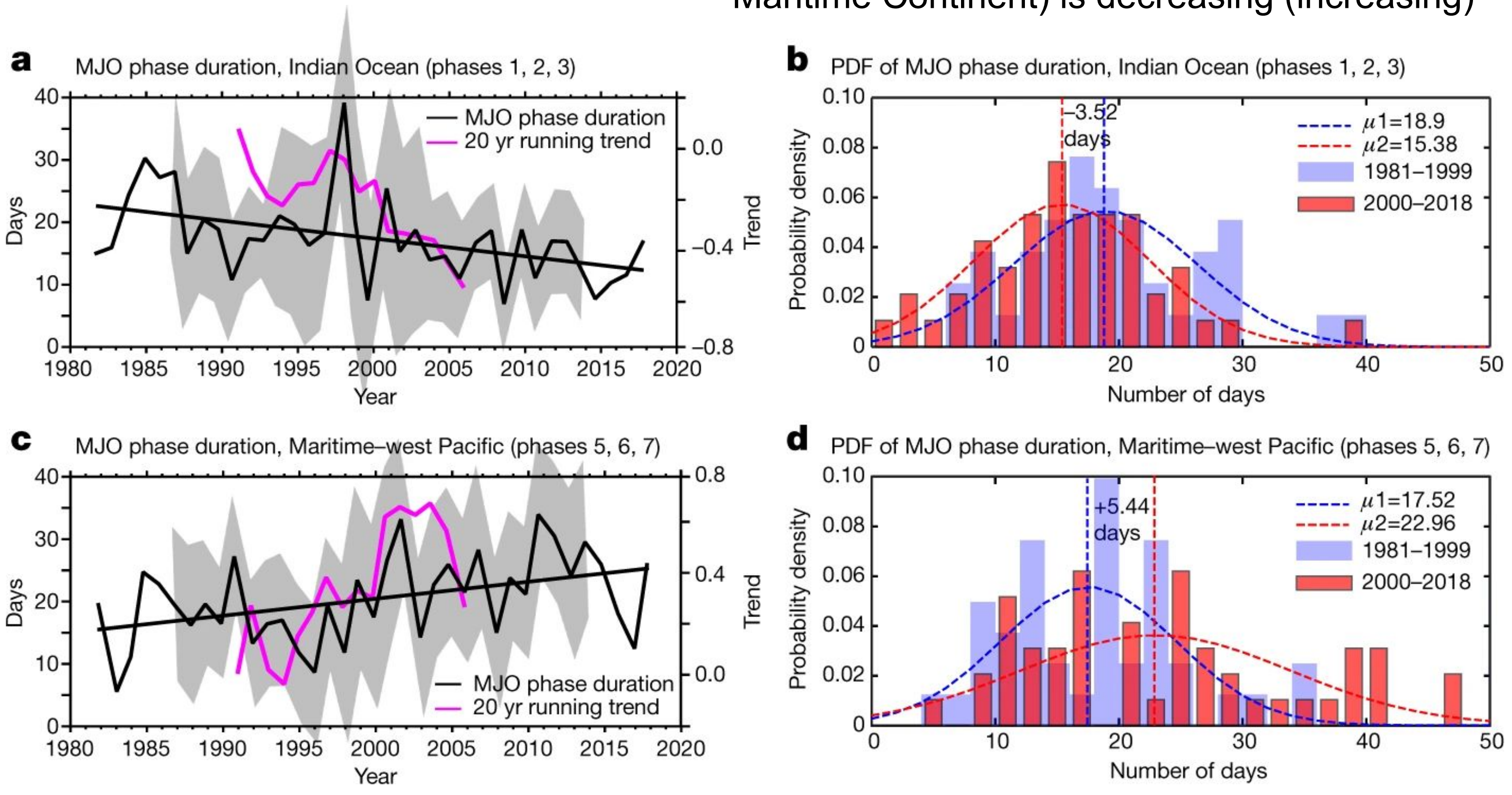



Wheeler and Hendon, 2004

**MJO is changing under global warming.**

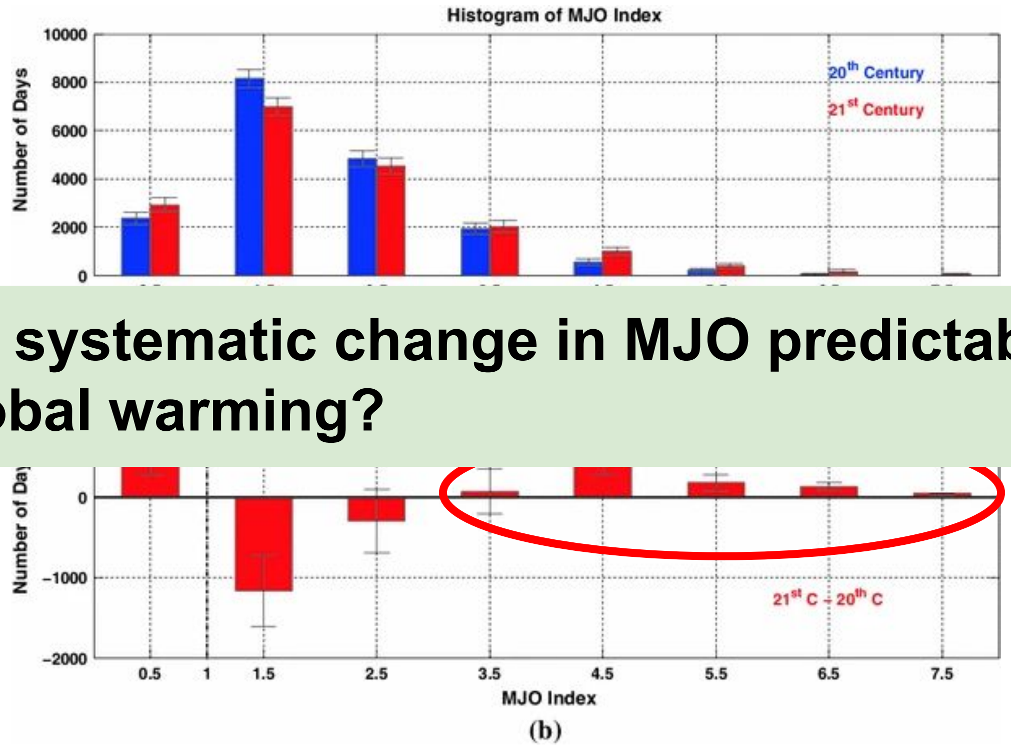
MJO duration over the Indian Ocean (Indo-Pacific Maritime Continent) is decreasing (increasing)




Roxy et al., 2019

MJO is changing under global warming.

Larger-amplitude MJO events would occur more often under a warming climate.




**Is there a systematic change in MJO predictability under global warming?**

Subramanian et al., 2014

## The common practice in estimating MJO predictability is to use the model ensemble forecasts.

Bivariate Anomaly Correlation Coefficient (ACC)

$$ACC(\tau) = \frac{\sum_{t=1}^{N}[a_1(t,\tau)b_1(t,\tau) + a_2(t,\tau)b_2(t,\tau)]}{\sqrt{\sum_{t=1}^{N}[a_1^2(t,\tau) + a_2^2(t,\tau)]}\sqrt{\sum_{t=1}^{N}[b_1^2(t,\tau) + b_2^2(t,\tau)]}}$$

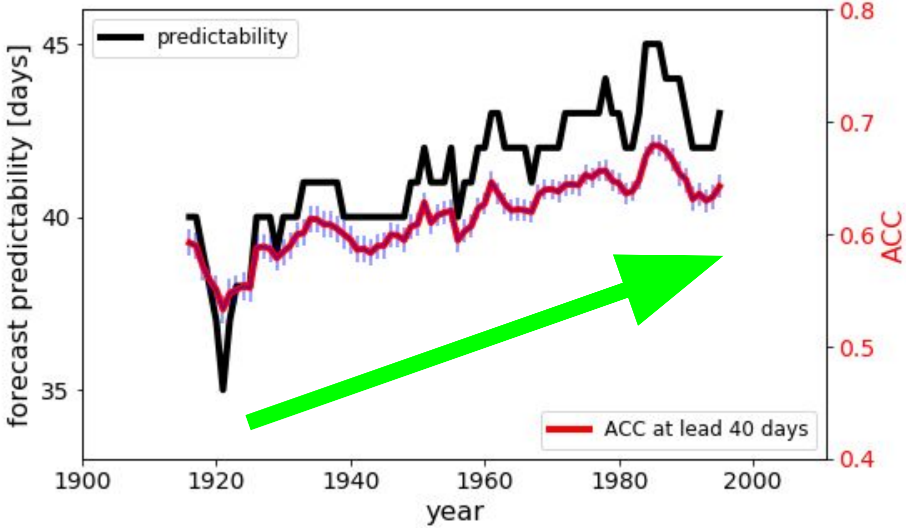
τ: forecast lead time
t: initialization time
n: total number of initializations
a: one forecast member
b: the mean of the rest of the ensemble forecasts
1: RMM1
2: RMM2

- This method is computationally expensive.
- Given the existing forecasts, we cannot determine whether the increased MJO predictability is caused by global warming

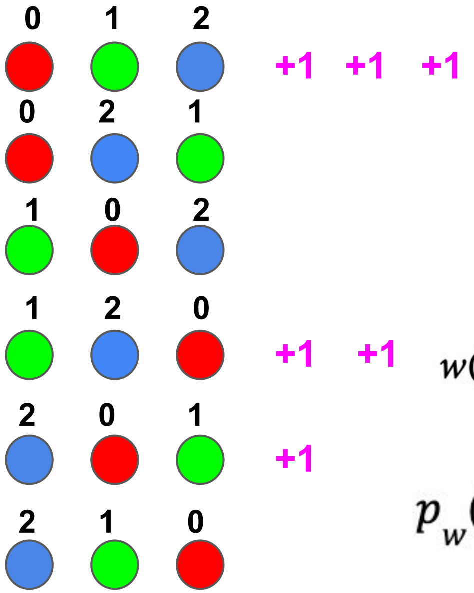
Initial condition → small perturbations → M1 M2 M3 … Mn

30-year window
1 initialization per year
51 ensemble members
acc threshold of 0.6

ECMWF CSF-20C



## The weighted permutation entropy (WPE): a new approach to analyze predictability
## The lower the WPE, the higher the predictability




M = 3, Tau = 1, [x(t), x(t+1), x(t+2)]

$$[x_i, x_{i+\tau}, \ldots, x_{i+(m-1)\tau}] \equiv X_i^{m,\tau}$$

[1,2,3,4,2,3,4,2]

- Step 1: choose the length and the time delay of the embedding vector
- Step 2: categorize the embedding vector into each permutation by the order of each element in the vector
- Step 3: weight the probability distribution function of permutations by the variance of each embedding vector
- Step 4: follow the entropy formula to calculate the WPE

$$w(X_i^{m,\tau}) = \frac{1}{m}\sum^{m}\left(x_{i+(j-1)\tau} - \overline{X_i^{m,\tau}}\right)^2$$

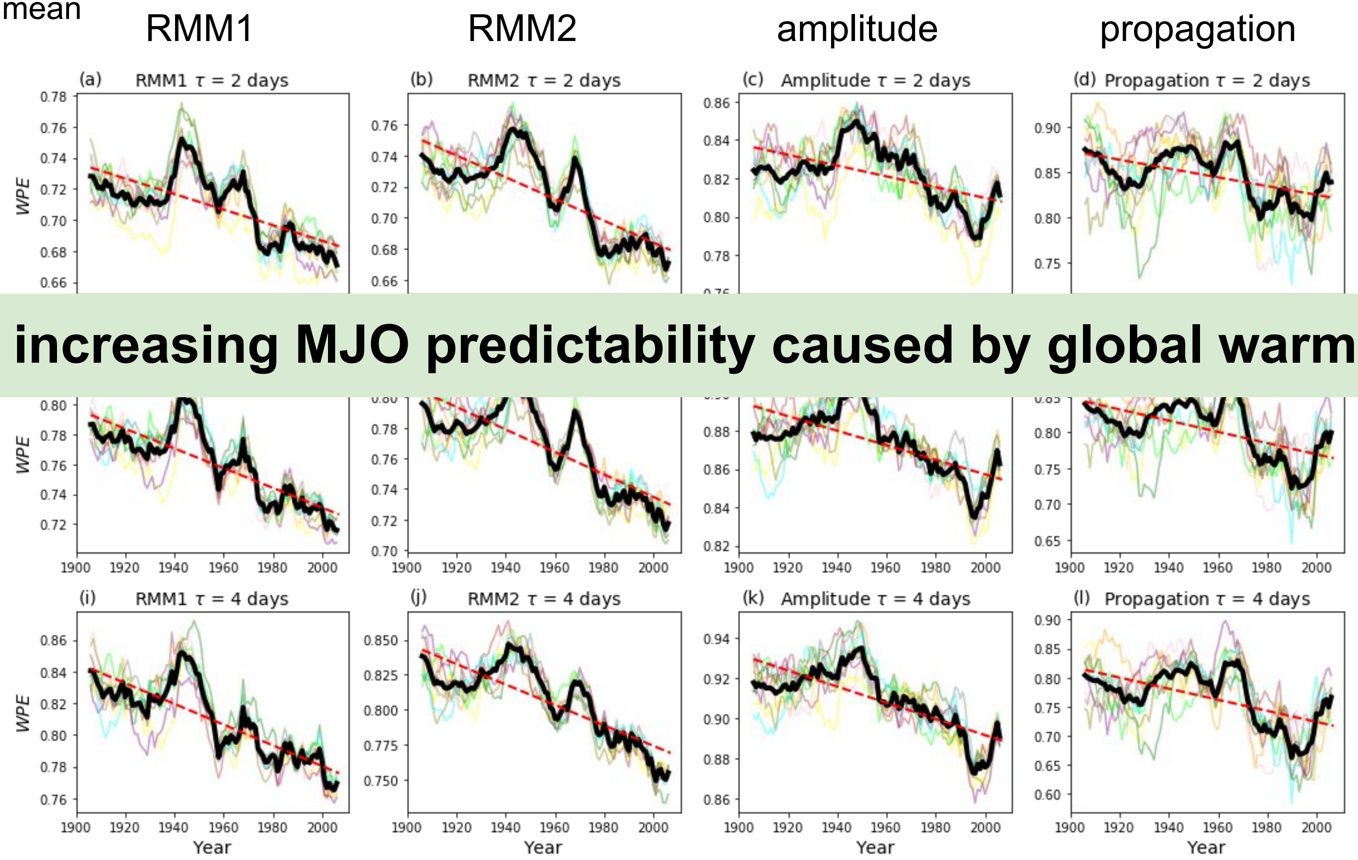
$$p_w(\pi) = \frac{\sum_t w(x_i^{m,\tau}) \cdot \delta(\phi(x_i^{m,\tau}), \pi)}{\sum w(x_i^{m,\tau})}$$

$\delta(a, b)$ is 0 when the $a \neq b$ and is 1 otherwise.

$$WPE = -\frac{1}{log_2(m!)}\sum_{i=1}^{m!} P_{wi} log_2 P_{wi}$$

## Decreasing WPE over the past century indicates the increasing MJO predictability

CERA-20C reanalysis
m = 3 (6 permutations)
10-year running mean



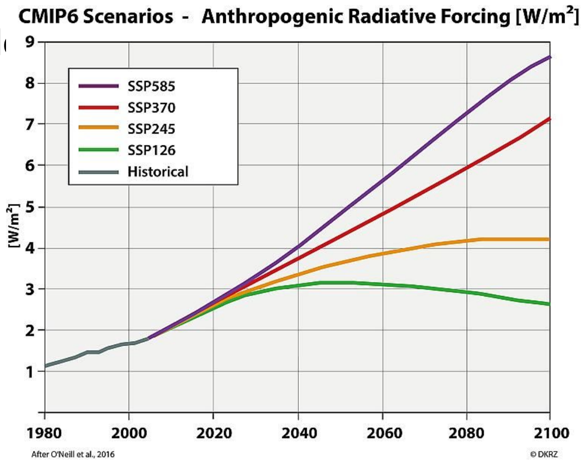

## Is the increasing MJO predictability caused by global warming?

## We use Community Earth System Model version 2 (CESM2) to test our assumption

**Control run (1 ensemble member from CESM2)**
1200 years
pre-industry forcing -> internal variability

**Historical run (10 ensemble members from CESM2 and 3 from CESM2-WACCM)**
from 1850 to 2014 -> under global warming

**Ssp585 future projection (3 ensemble members from CESM2 and 5 from CESM2-WACCM)**
With an additional radiative forcing of 8.5 W/m² by the year 2100
this scenario represents the upper boundary of the range of scenarios d
from 2015 to 2100 -> under more severe global warming




**Step 1: compute WPE time series in each run**

**Step 2: estimate the spread of WPE slope from the control run**
Internal variability

**Step 3: compare the historial run / ssp585 run with the control run**

# Historical run v.s. Control run

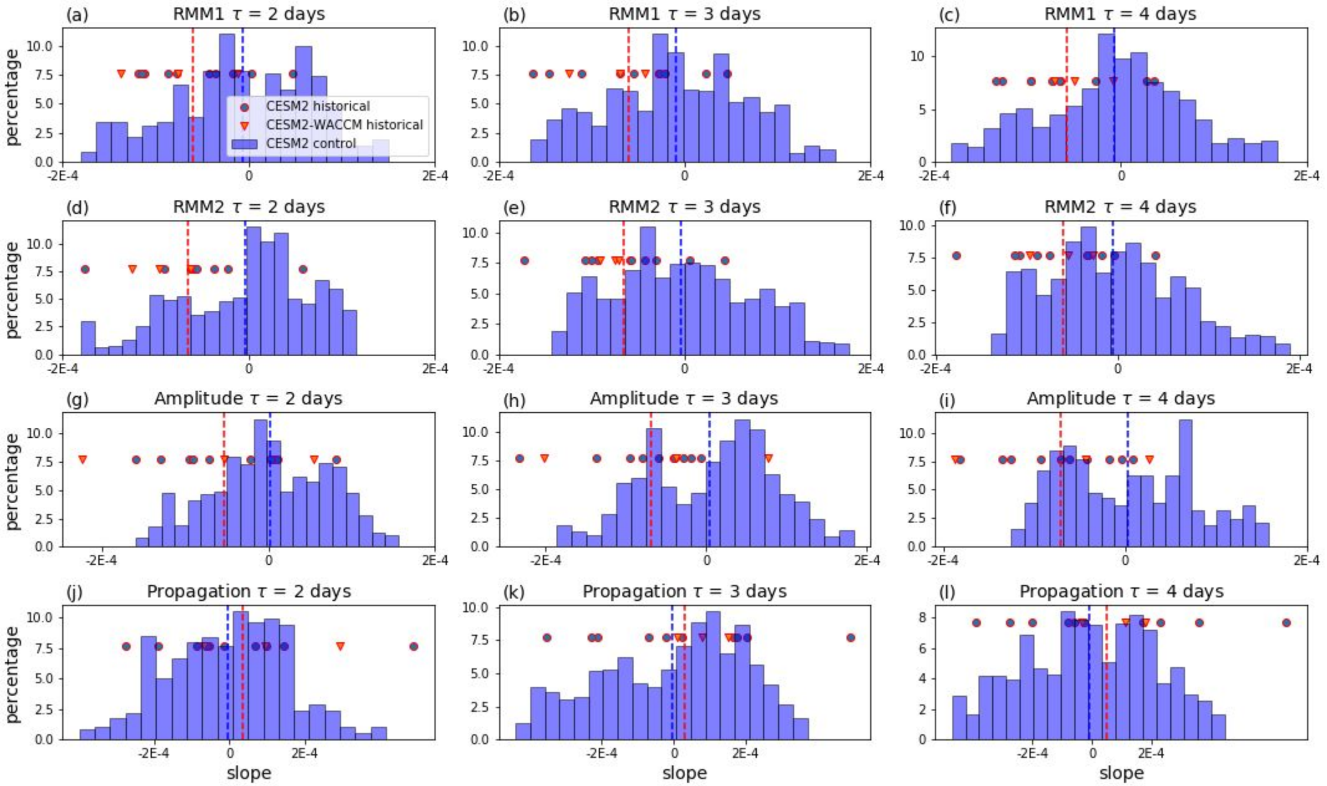
**Blue bars**: WPE slope spread estimated from the control run
**Dots and triangles**: WPE slope fitted from each historical run ensemble member

RMM1

RMM2

amplitude

propagation




Within the spread; yet biased to the negative side

Within the spread; Not biased

## ssp585 run v.s. Control run

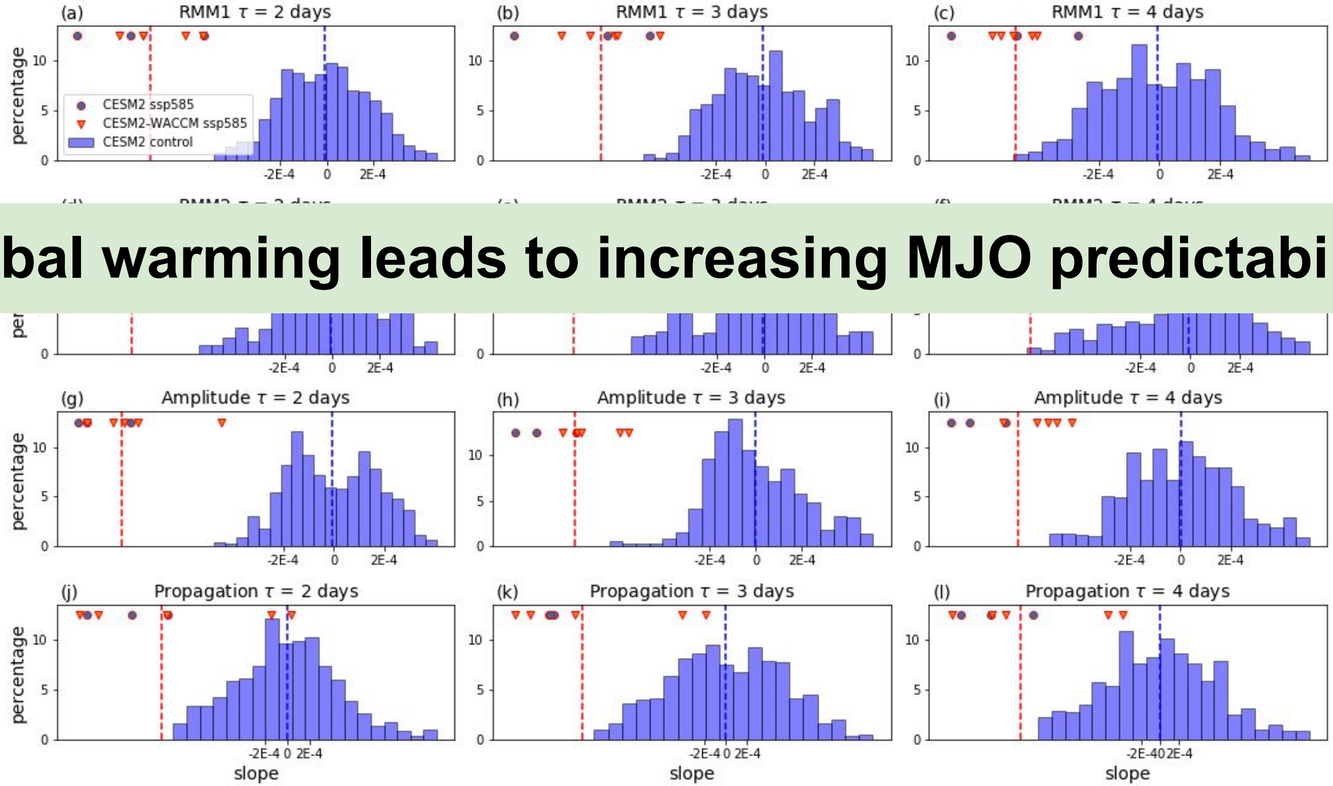
**Blue bars**: WPE slope spread estimated from the control run
**Dots and triangles**: WPE slope fitted from each ssp 585 ensemble member

RMM1

RMM

amplitude

propagation




# Global warming leads to increasing MJO predictability

significantly biased to the ...ve side;

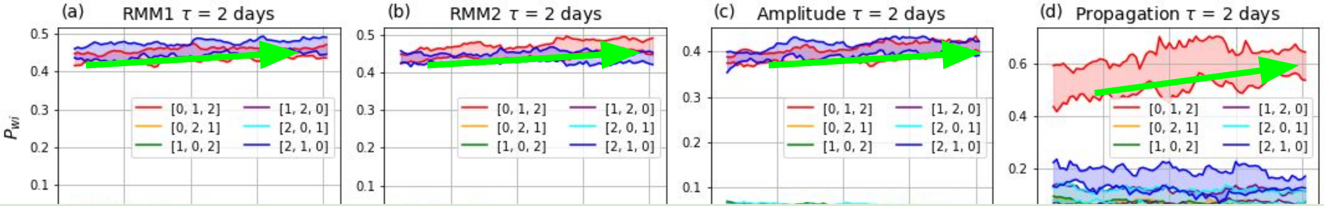
...Negative WPE slope indicates the increasing MJO predictability

## ssp585: Pw change for different permutations (patterns)

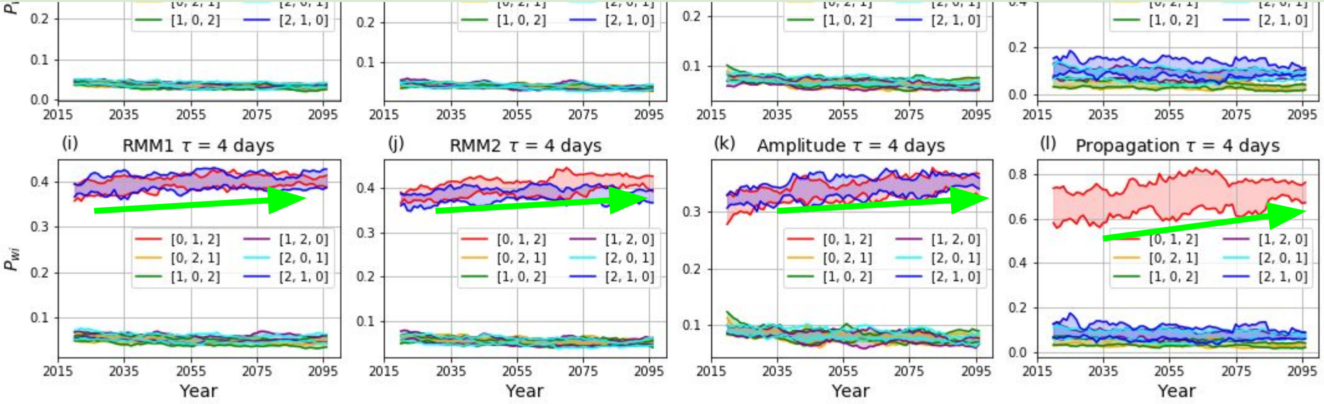
RMM1, RMM2, MJO amplitude:
The increasing/decreasing pattern

MJO propagation:
The eastward propagation pattern

$$p_w(\pi) = \frac{\sum_t w(x_i^{m,\tau}) \cdot \delta(\phi(x_i^{m,\tau}), \pi)}{\sum_t w(x_i^{m,\tau})}$$



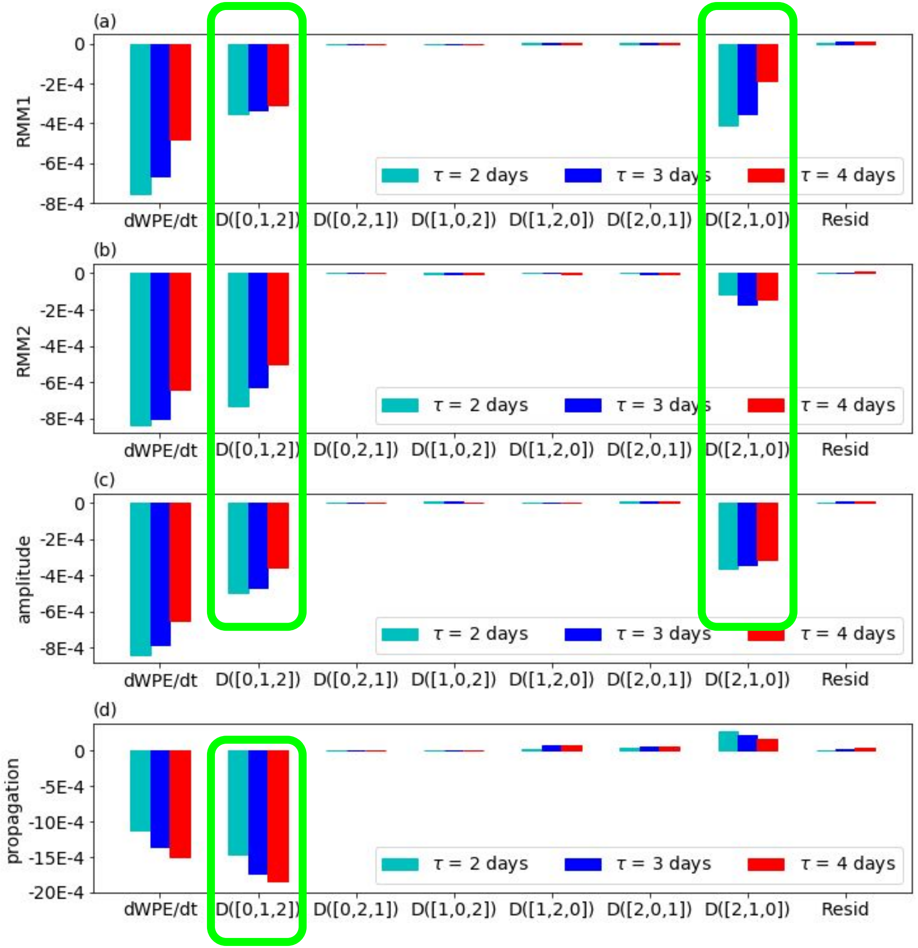

**Under global warming, the MJO tends to show more organized patterns, which increases its predictability**



WPE is calculated from the weighted occurrence frequency $P_{wi}$ of $m!$ possible permutations. Therefore, WPE can be written as $WPE(P_{w1}, P_{w2}, ...P_{wN})$, where $N = m!$. Since $\sum_{i=1}^{N} P_{wi} = 1$, WPE only consists of $N-1$ independent variables. Hence, according to the chain rule, the time derivatie of WPE can be expressed as

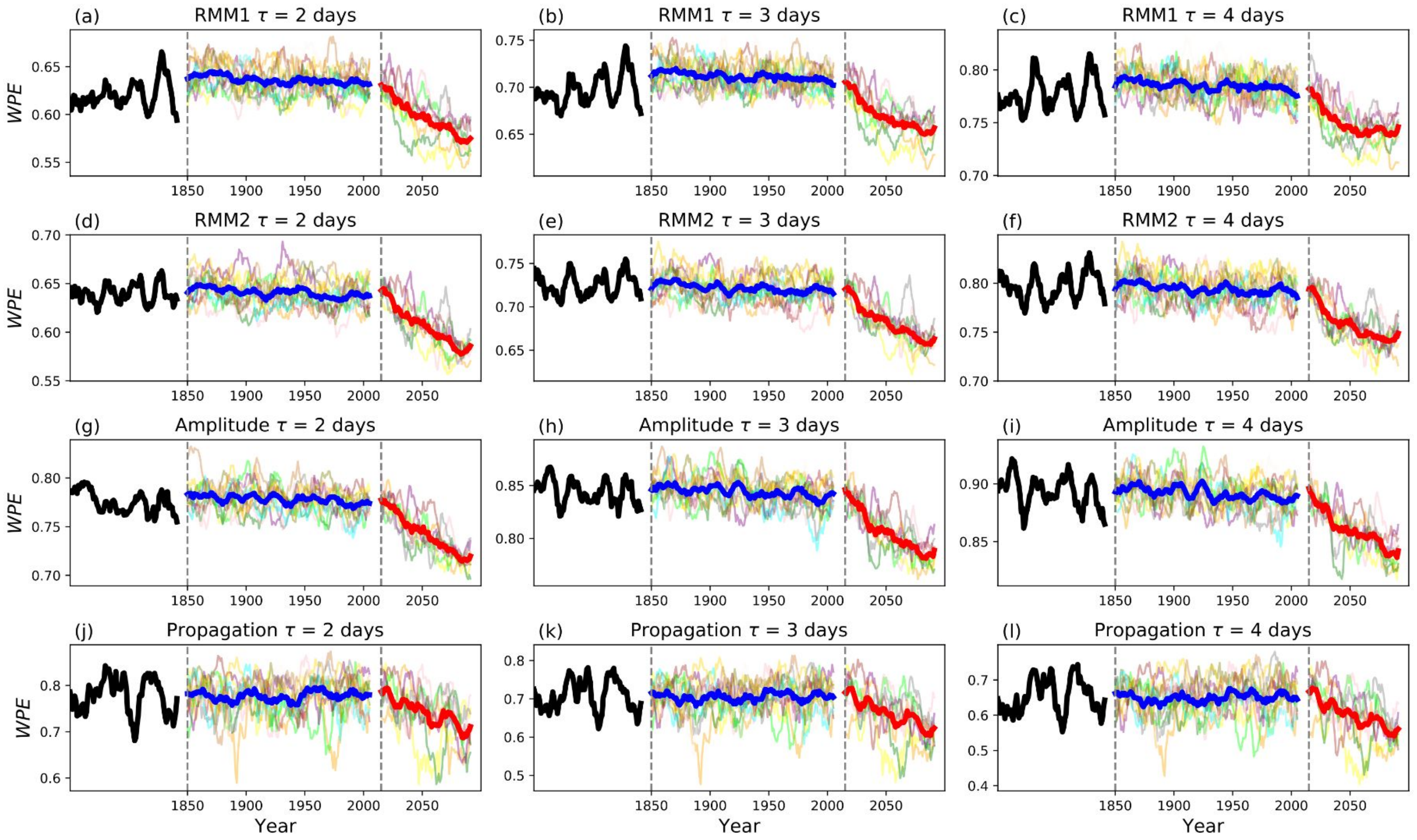
$$
\begin{aligned}
\frac{dWPE}{dt} &= \sum_{i=1}^{N-1} \frac{\partial WPE}{\partial P_{wi}} \frac{dP_{wi}}{dt} \\
&= \frac{1}{log_2 N} \sum_{i=1}^{N-1} \frac{\partial \left( -\sum_{j=1}^{N} P_{wj} log_2 P_{wj} \right)}{\partial P_{wi}} \frac{dP_{wi}}{dt} \\
&= \frac{1}{log_2 N} \sum_{i=1}^{N-1} \frac{\partial \left( -P_{wi} log_2 P_{wi} - P_{wN} log_2 P_{wN} \right)}{\partial P_{wi}} \frac{dP_{wi}}{dt} \\
&= \frac{1}{log_2 N} \sum_{i=1}^{N-1} \left( -log_2 P_{wi} - \frac{1}{ln2} + log_2 P_{wN} + \frac{1}{ln2} \right) \frac{dP_{wi}}{dt} \\
&= -\frac{1}{log_2 N} \sum_{i=1}^{N-1} \left( log_2 \frac{P_{wi}}{P_{wN}} \right) \frac{dP_{wi}}{dt}.
\end{aligned}
$$

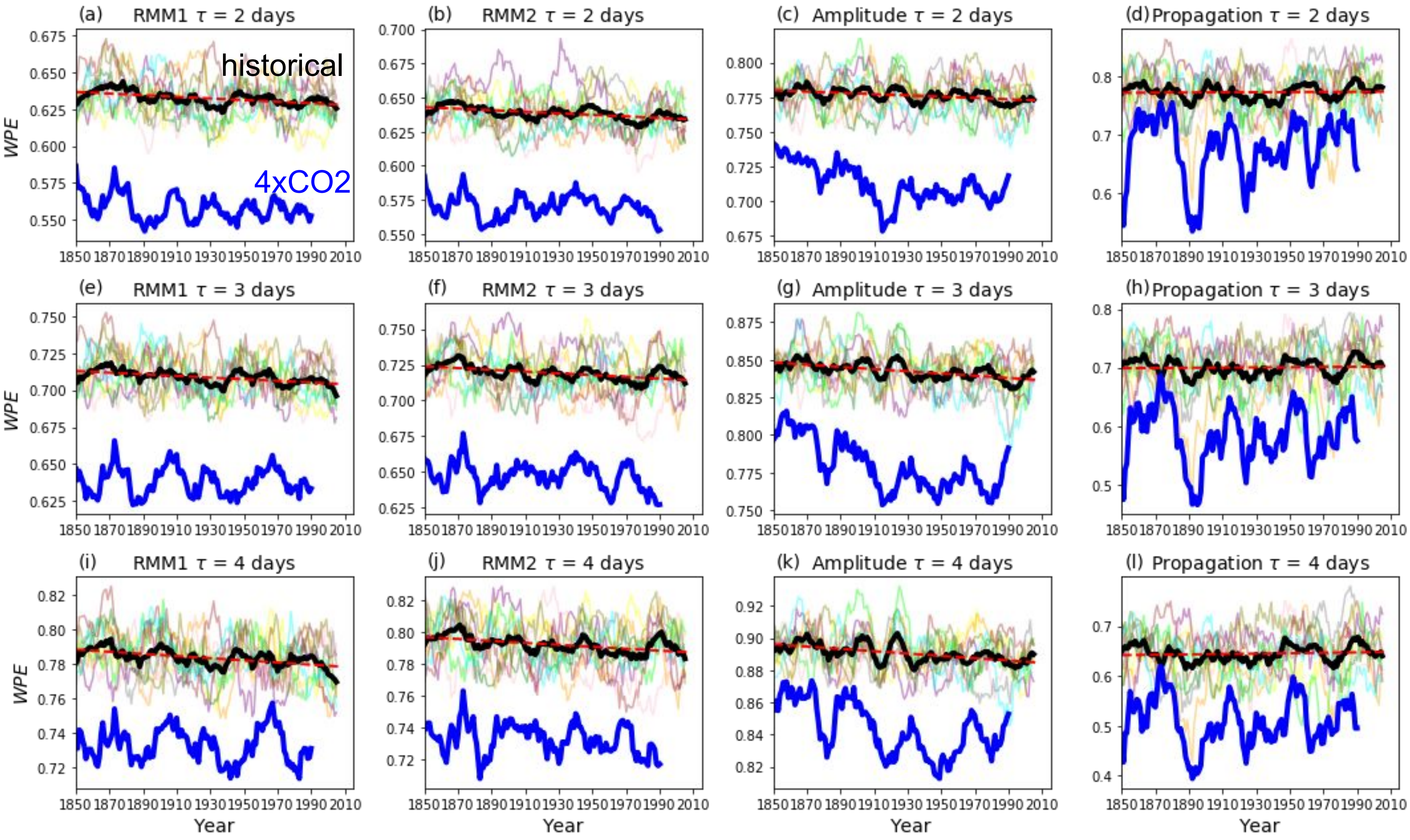
## ssp585: how each permutation contributes to the WPE

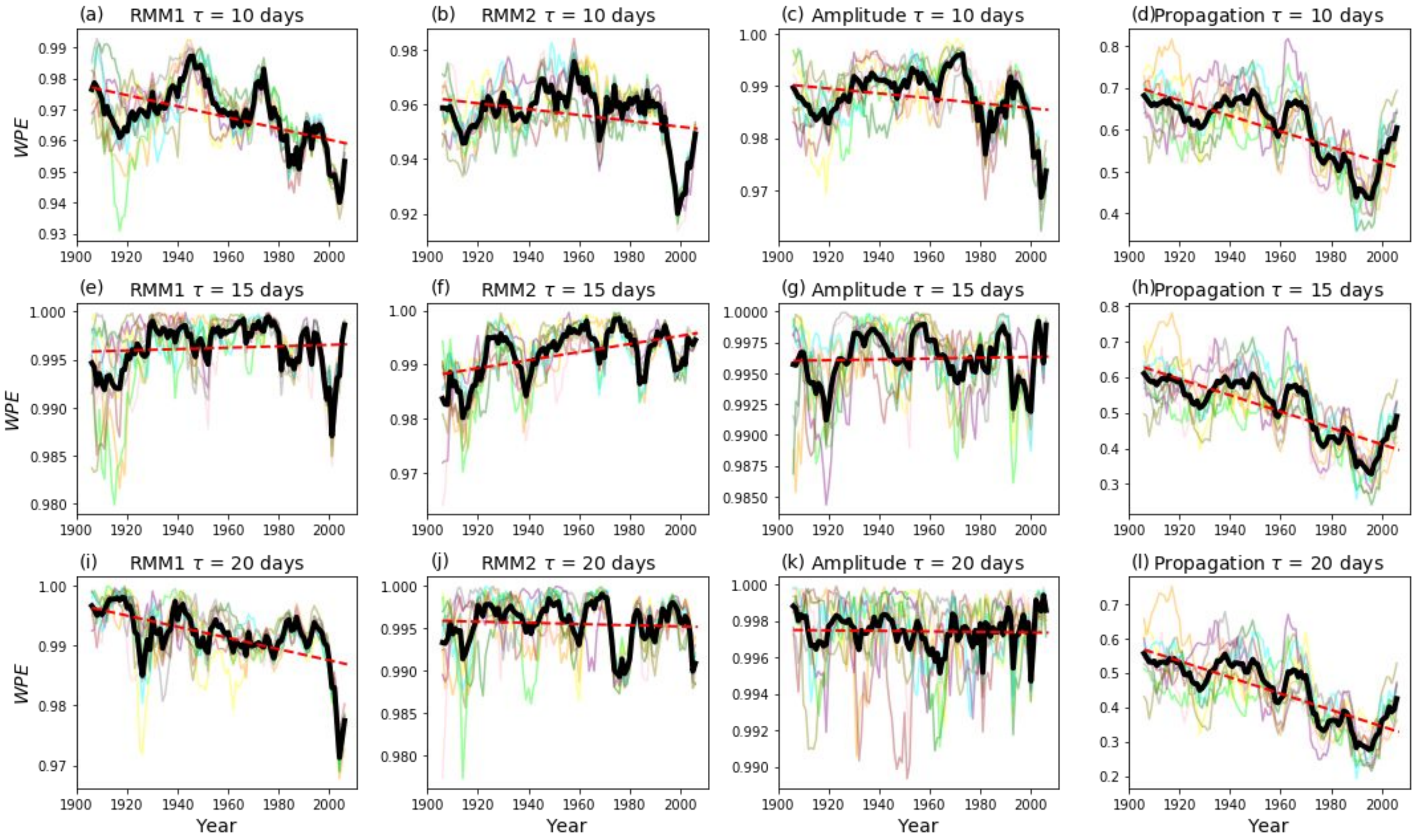


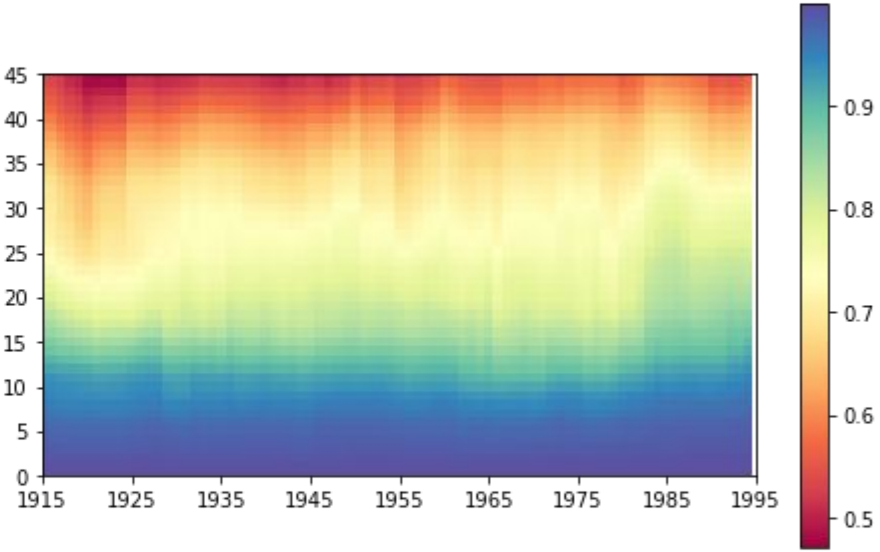
## Summary

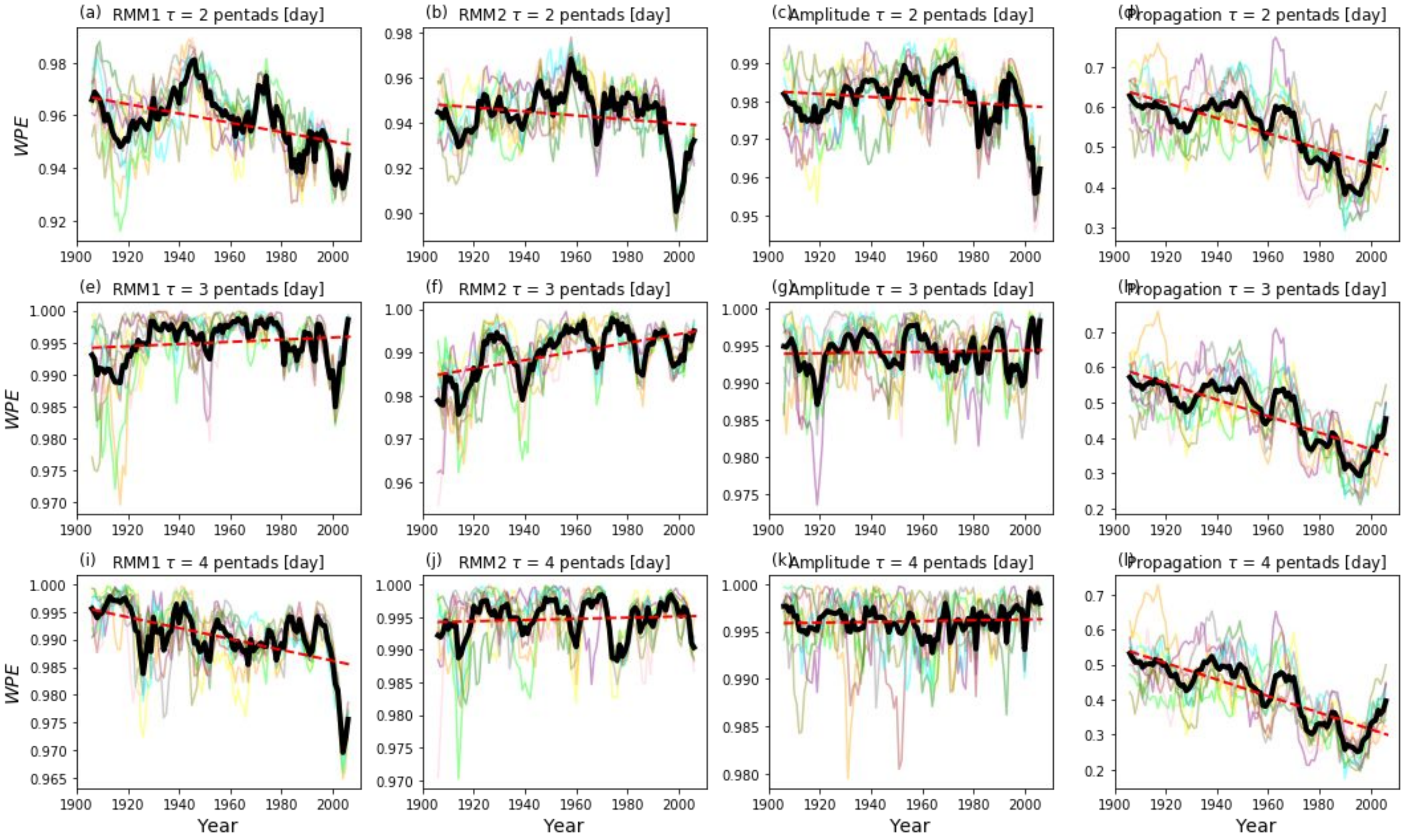
- During the past century, both the ensemble subseasonal forecasts and the reanalysis data indicate an increase in MJO predictability.
- Examining with CESM2 model ensemble, we find such an increase in MJO predictability is likely caused by global warming. Under more severe global warming, the MJO tends to be more predictable.
- MJO gains more predictability by showing more organized patterns: the oscillation pattern (amplifying/weakening of RMM1, RMM2 and MJO amplitude) and the organized eastward propagation occur more and more frequently.


(a) RMM1 τ = 2 days
(b) RMM1 τ = 3 days
(c) RMM1 τ = 4 days
(d) RMM2 τ = 2 days
(e) RMM2 τ = 3 days
(f) RMM2 τ = 4 days
(g) Amplitude τ = 2 days
(h) Amplitude τ = 3 days
(i) Amplitude τ = 4 days
(j) Propagation τ = 2 days
(k) Propagation τ = 3 days
(l) Propagation τ = 4 days
WPE
1850 1900 1950 2000 2050
Year


(a) RMM1 τ = 2 days
(b) RMM2 τ = 2 days
(c) Amplitude τ = 2 days
(d) Propagation τ = 2 days
(e) RMM1 τ = 3 days
(f) RMM2 τ = 3 days
(g) Amplitude τ = 3 days
(h) Propagation τ = 3 days
(i) RMM1 τ = 4 days
(j) RMM2 τ = 4 days
(k) Amplitude τ = 4 days
(l) Propagation τ = 4 days
historical
4xCO2
WPE
Year


(a) RMM1 τ = 10 days
(b) RMM2 τ = 10 days
(c) Amplitude τ = 10 days
(d)Propagation τ = 10 days
(e) RMM1 τ = 15 days
(f) RMM2 τ = 15 days
(g) Amplitude τ = 15 days
(h)Propagation τ = 15 days
(i) RMM1 τ = 20 days
(j) RMM2 τ = 20 days
(k) Amplitude τ = 20 days
(l) Propagation τ = 20 days
WPE
Year


45
40
35
30
25
20
15
10
5
0
1915
1925
1935
1945
1955
1965
1975
1985
1995
0.9
0.8
0.7
0.6
0.5



(a) RMM1 τ = 2 pentads [day]
(b) RMM2 τ = 2 pentads [day]
(c) Amplitude τ = 2 pentads [day]
(d) Propagation τ = 2 pentads [day]
(e) RMM1 τ = 3 pentads [day]
(f) RMM2 τ = 3 pentads [day]
(g) Amplitude τ = 3 pentads [day]
(h) Propagation τ = 3 pentads [day]
(i) RMM1 τ = 4 pentads [day]
(j) RMM2 τ = 4 pentads [day]
(k) Amplitude τ = 4 pentads [day]
(l) Propagation τ = 4 pentads [day]
WPE
Year