Potential Increase in MJO Predictability Under Global Warming

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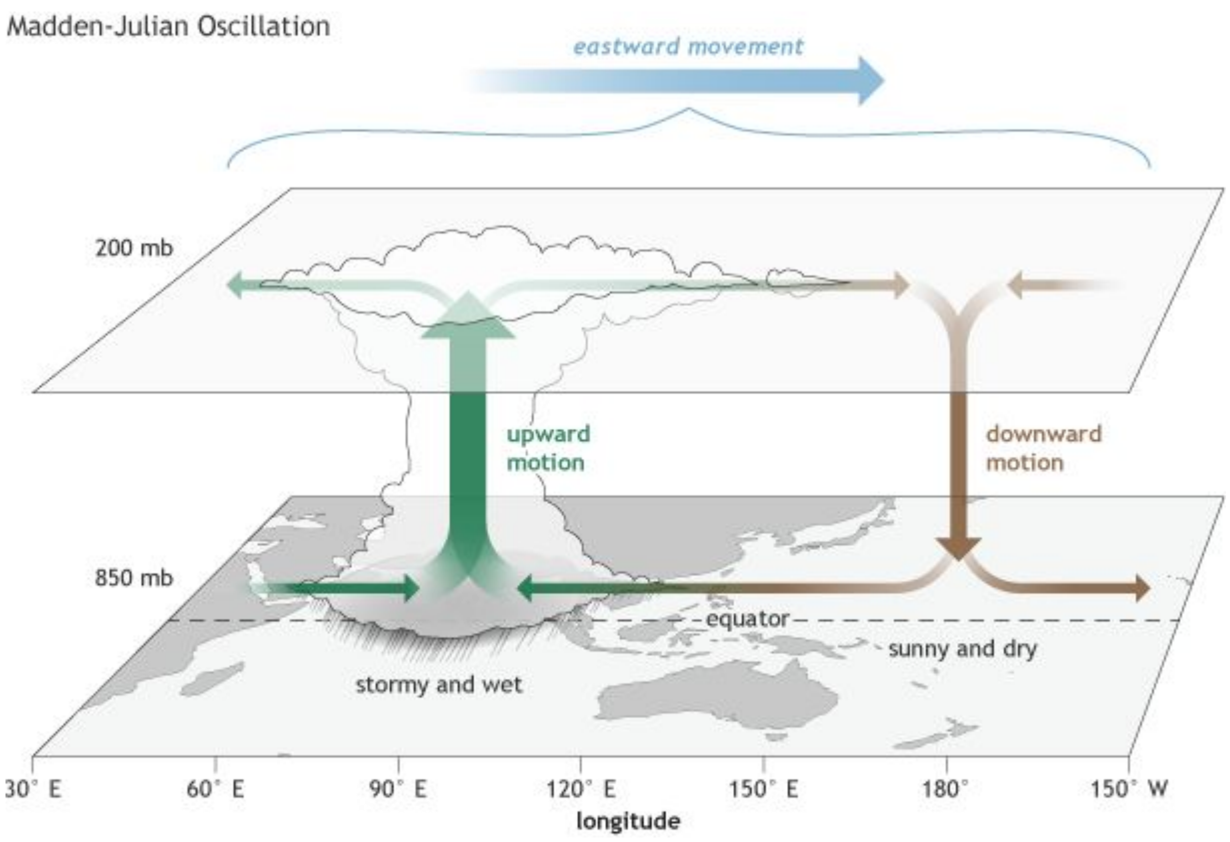

Madden-Julian Oscillation
eastward movement
200 mb
upward motion
downward motion
850 mb
equator
sunny and dry
stormy and wet
30° E
60° E
90° E
120° E
150° E
180°
150° W
longitude

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

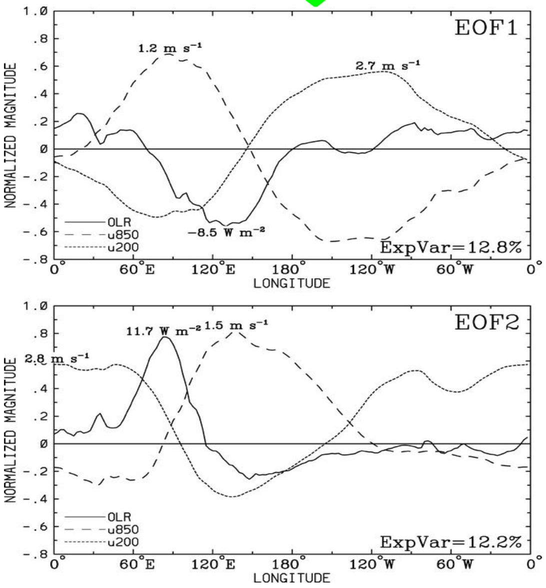
Empirical orthogonal function (EOF) analysis on the combined fields of near-equatorially averaged:

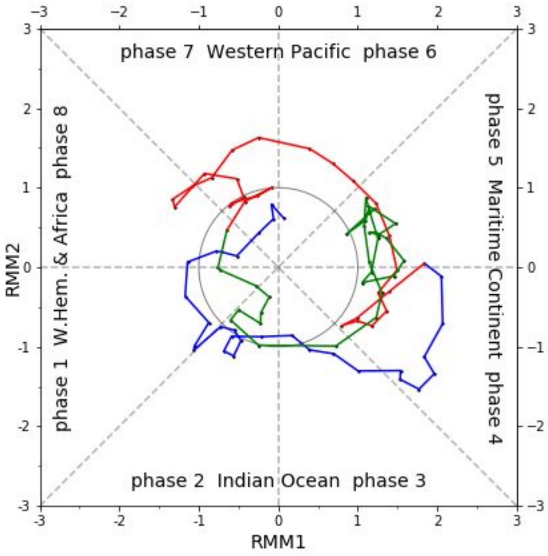
- Daily zonal wind at 850 hPa (U850)
- Daily zonal wind at 200 hPa (U200)
- Daily outgoing longwave radiation (OLR; a proxy of deep convection)

We obtain:

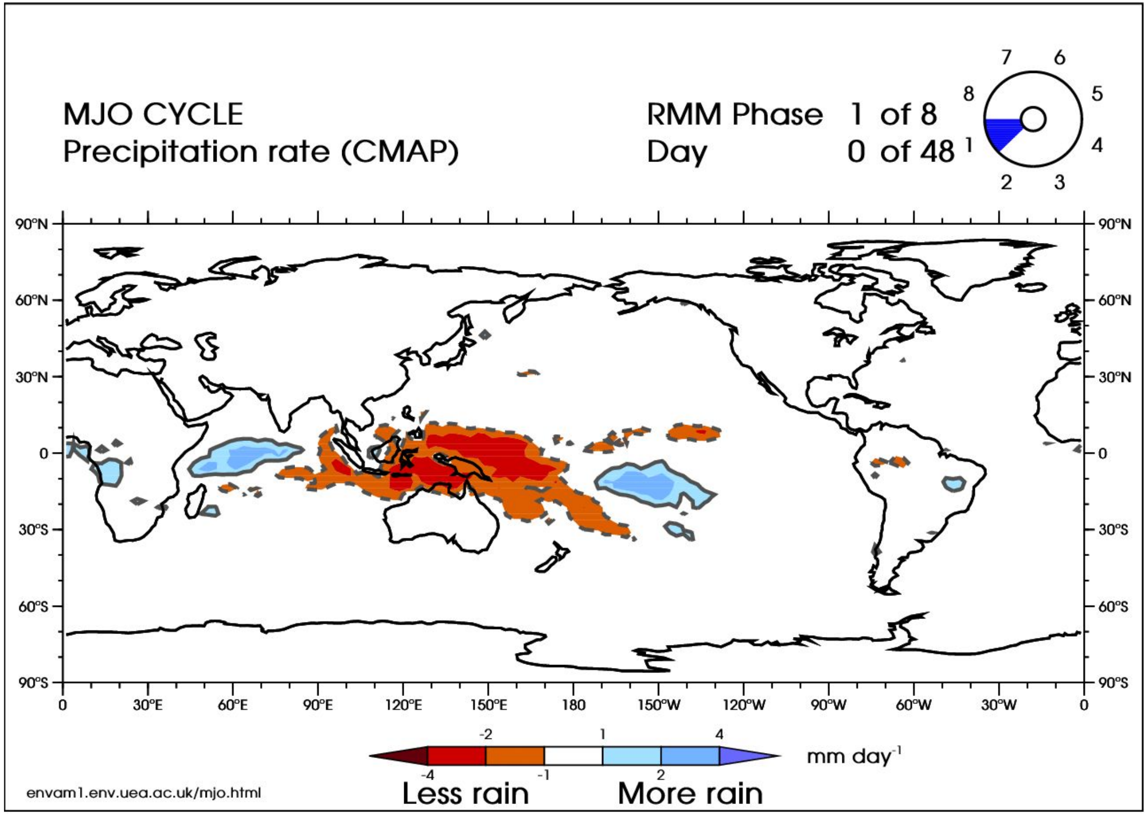
- 2 EOF modes
- 2 Principal Component (PC) time series
  - **RMM1**
  - **RMM2**

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



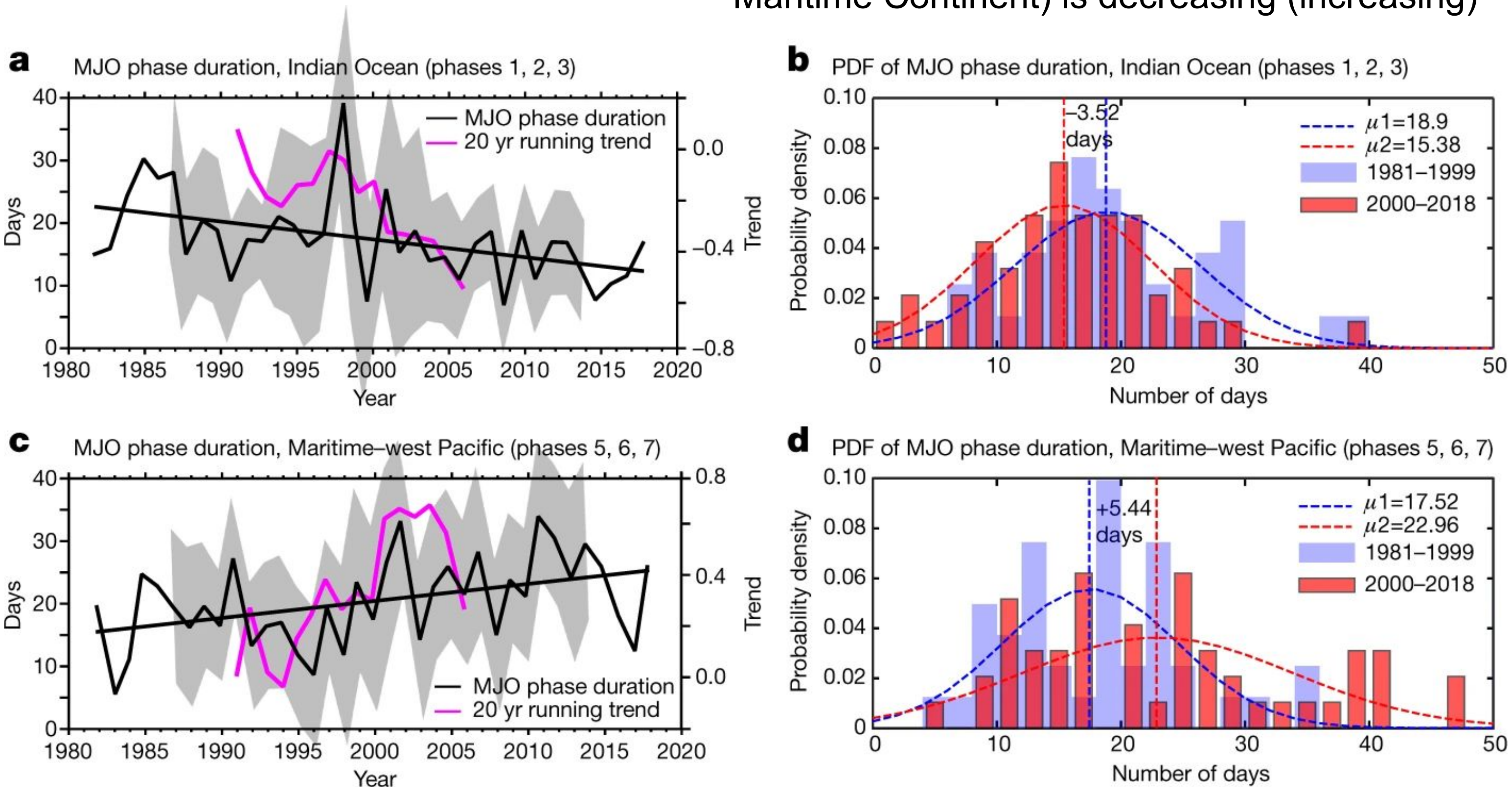


Wheeler and Hendon, 2004


MJO 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

MJO is changing under global warming.

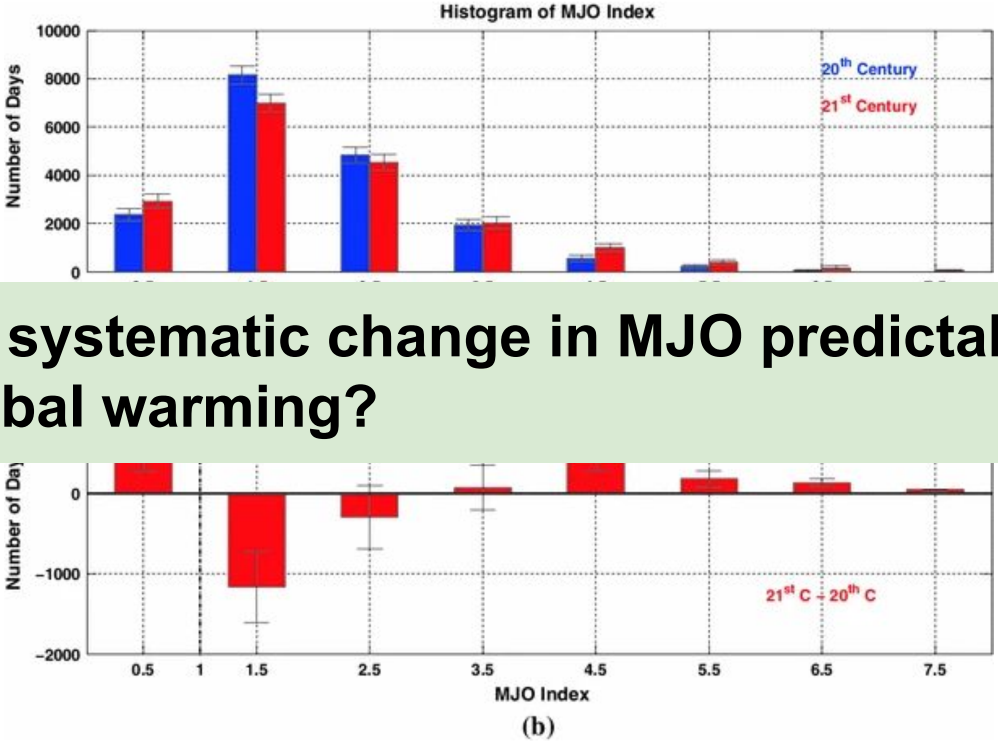
MJO duration over the Indian Ocean (Indo-Pacific Maritime Continent) is decreasing (increasing)



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)

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

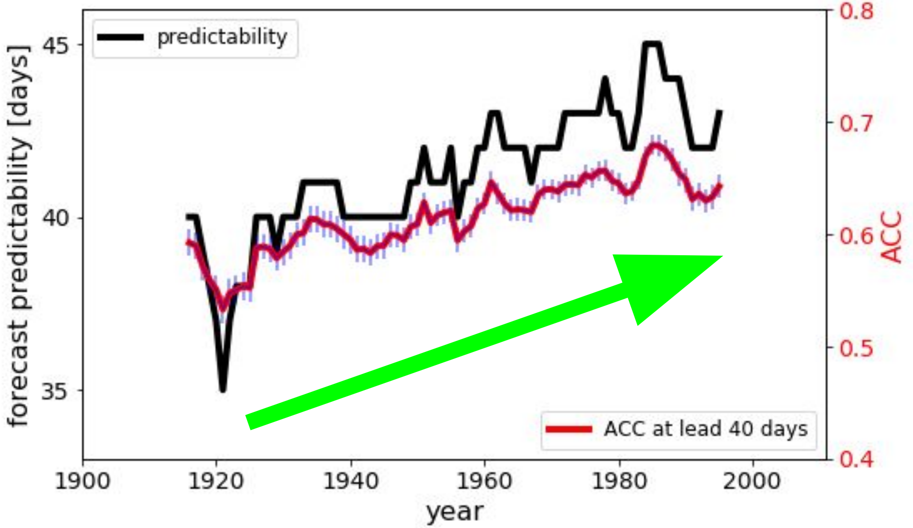
τ: forecast lead time
t: initialization time
n: total number of initializations
a: one forecast member
b: the mean of the rest of the ensemble forecasts
1: RMM1
2: RMM2

Initial condition → small perturbations → M1, M2, M3, …, Mn

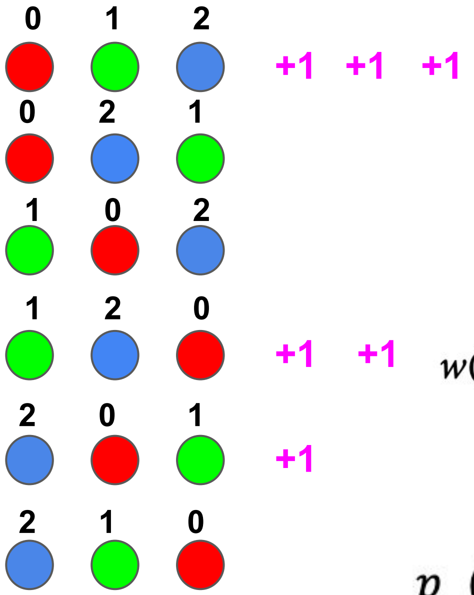
30-year window
1 initialization per year
51 ensemble members

This method requires:

- The existence of such forecasts
- A large ensemble size
- Enough initializations



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



M = 3, Tau = 1

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

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

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

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

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

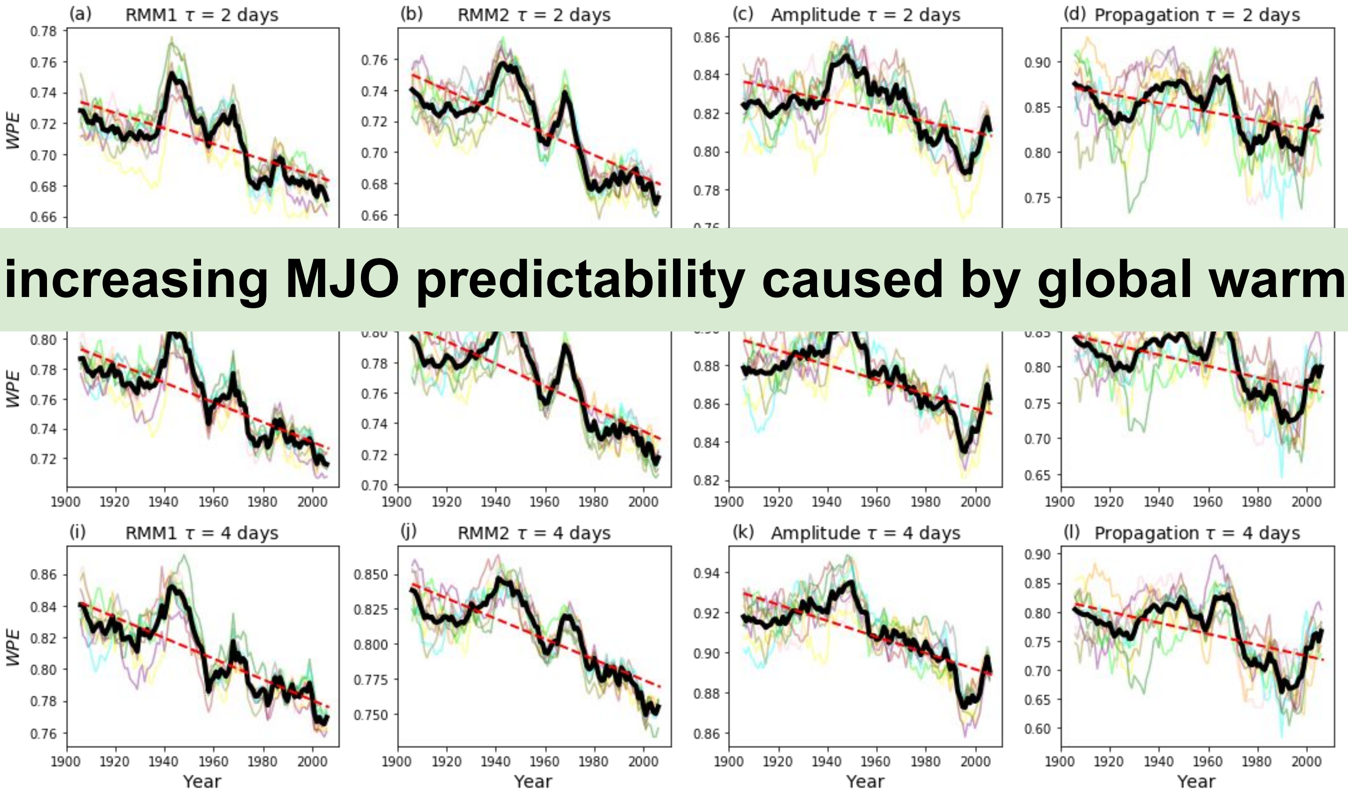
$\delta(a, b)$ is 0 when the $a \neq b$ and is 1 otherwise.

$$\mathrm{PE}(m, \tau) = -\sum_{\pi \in S_m} p(\pi) \log_2 p(\pi).$$

Decreasing WPE over the past century indicates the increasing MJO predictability

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

RMM1 | RMM2 | amplitude | propagation



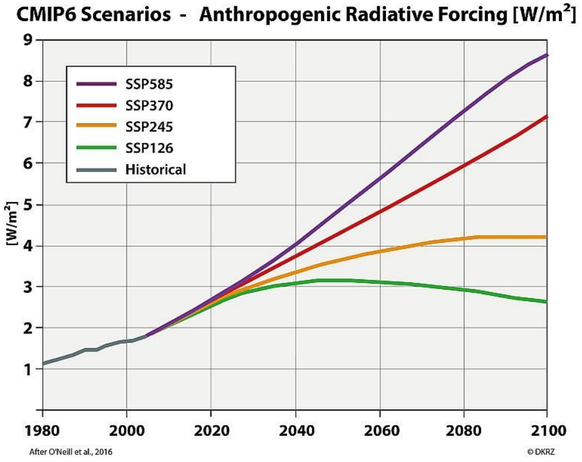
Is the increasing MJO predictability caused by global warming?

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/m^2 by the year 2100
this scenario represents the upper boundary of the range of scenarios described in the literature
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

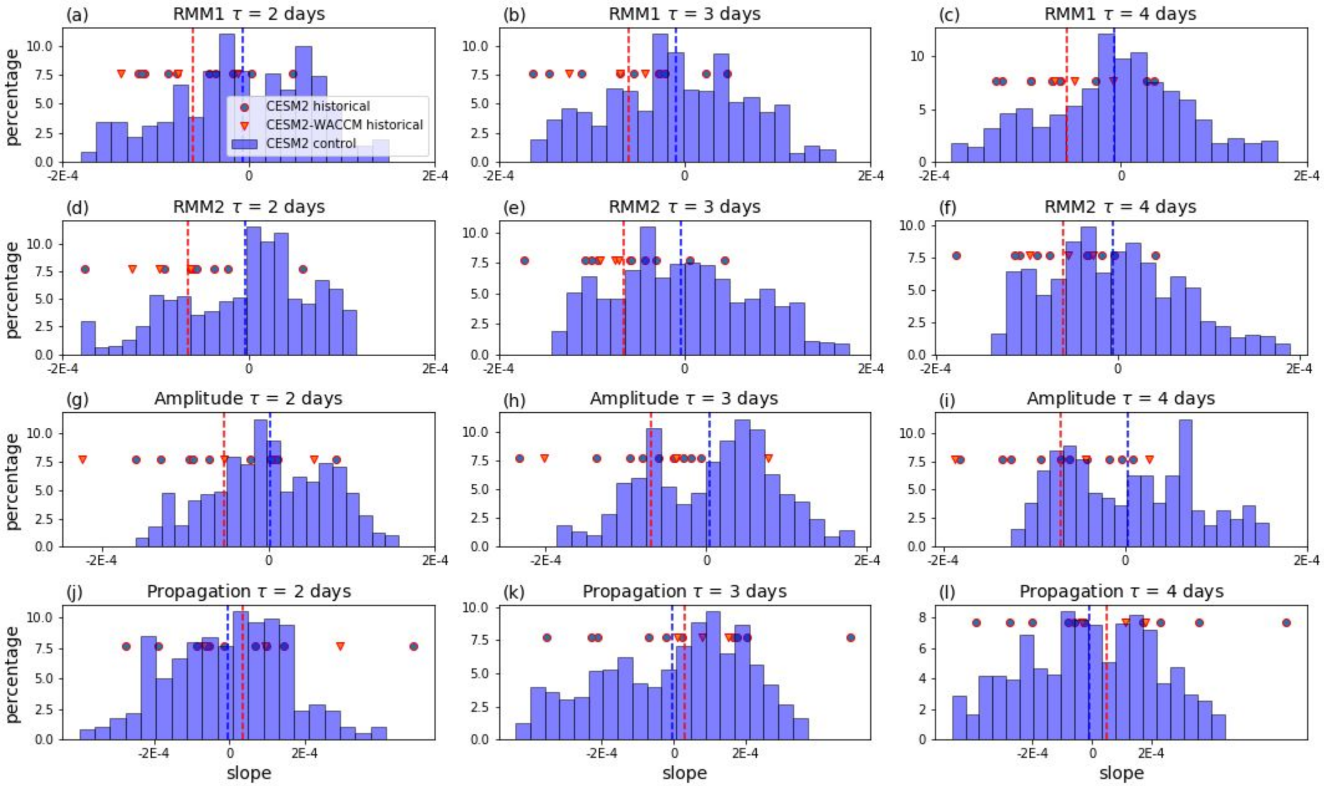
The increasing MJO predictability during the past century might be a result of both the internal variability and the global warming forcing

RMM1

RMM2

amplitude

propagation



Within the spread; yet biased to the negative side

Within the spread; Not biased

ssp585 run v.s. Control run

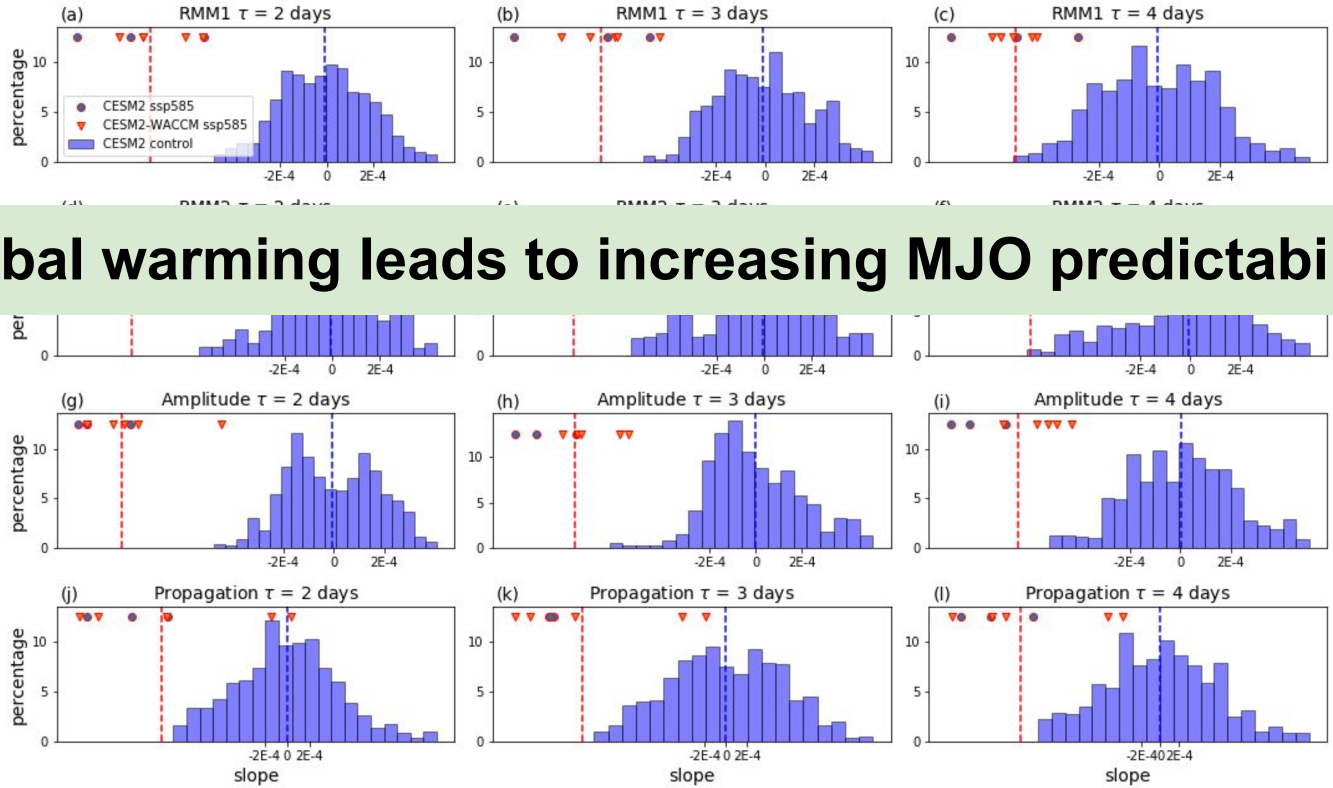
Blue bars: WPE slope spread estimated from the control run
Dots and triangles: WPE slope fitted from each ssp 585 ensemble member

RMM1

RMM

amplitude

propagation



Global warming leads to increasing MJO predictability

significantly biased to the ...ve side;

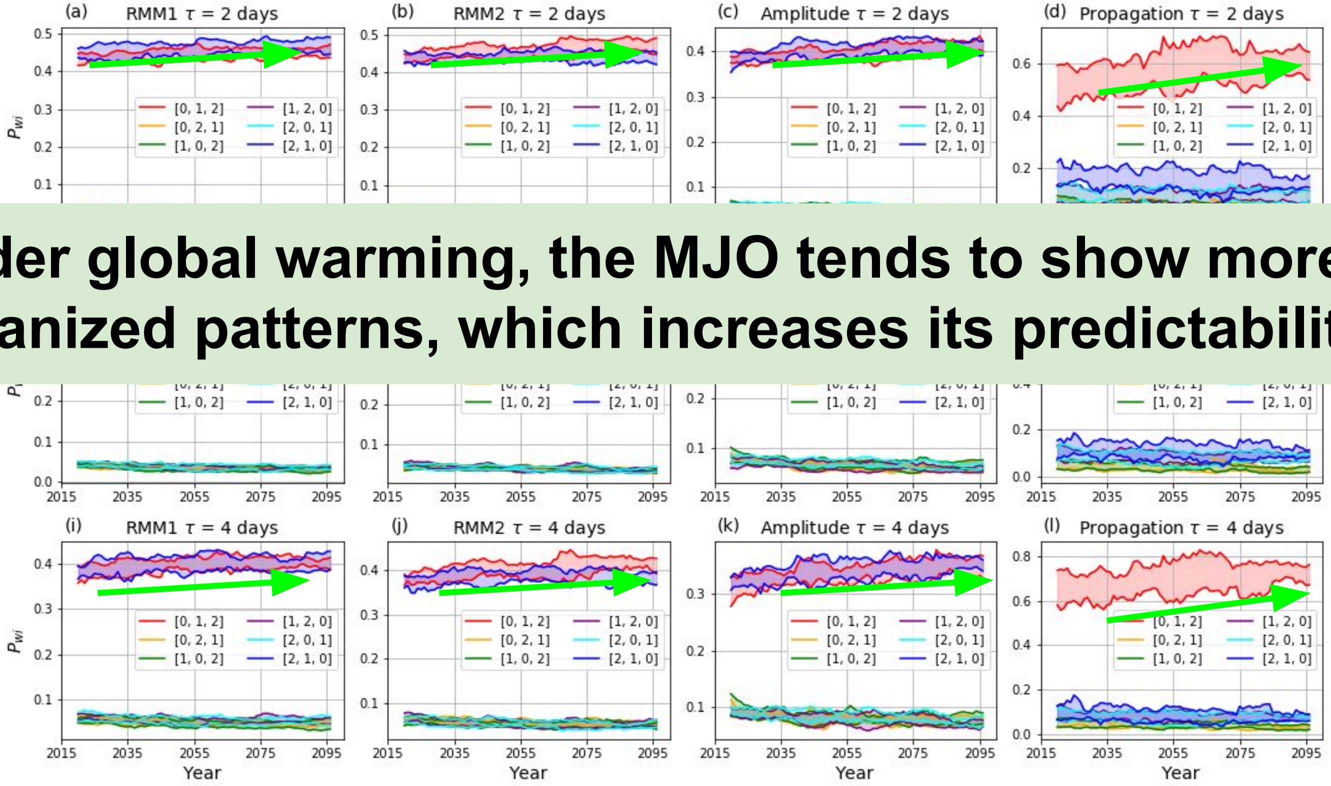
Negative WPE slope indicates the increasing MJO predictability

ssp585: Pw change for different permutations (patterns)

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

MJO propagation:
The eastward propagation pattern

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

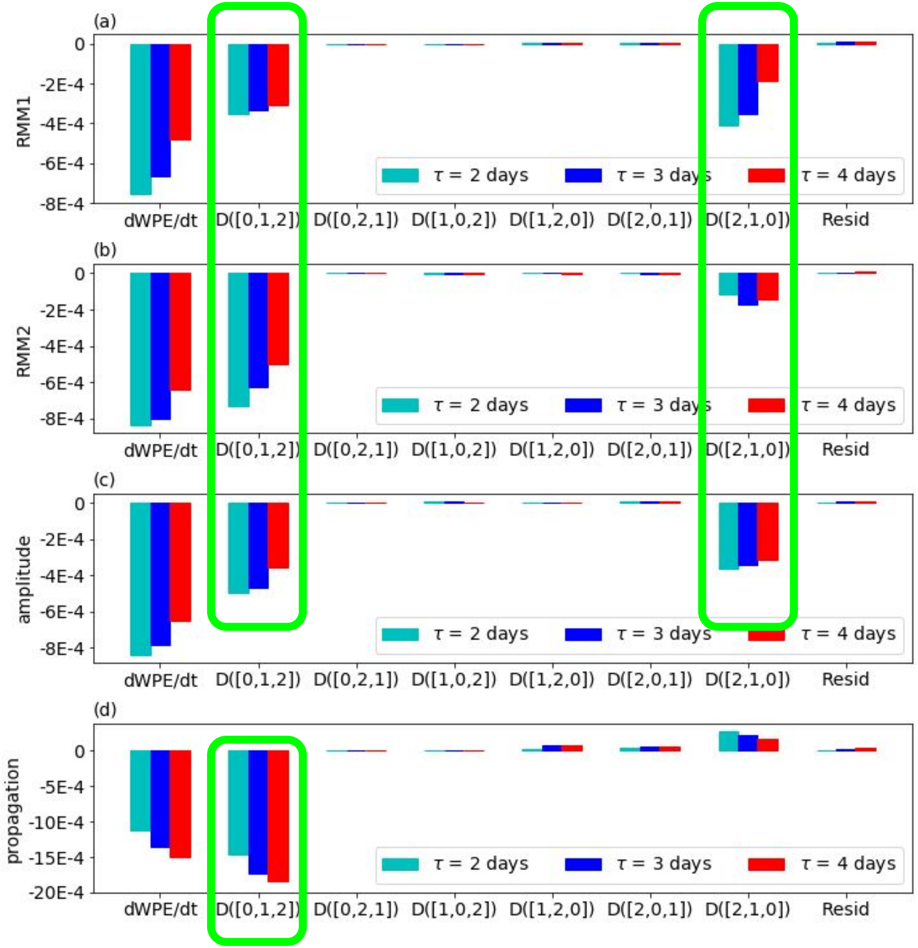


Under global warming, the MJO tends to show more organized patterns, which increases its predictability

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



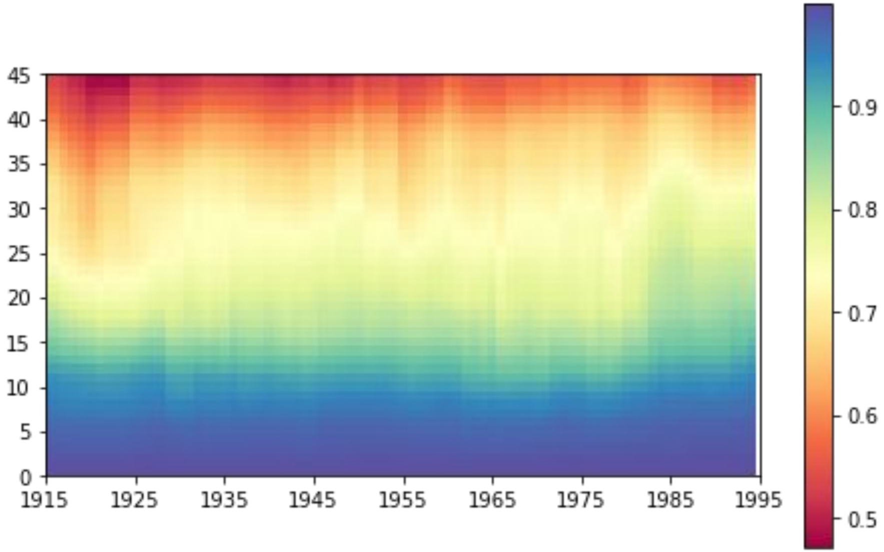
Summary

- During the past century, both the ensemble subseasonal forecasts and the reanalysis data indicate an increase in MJO predictability.

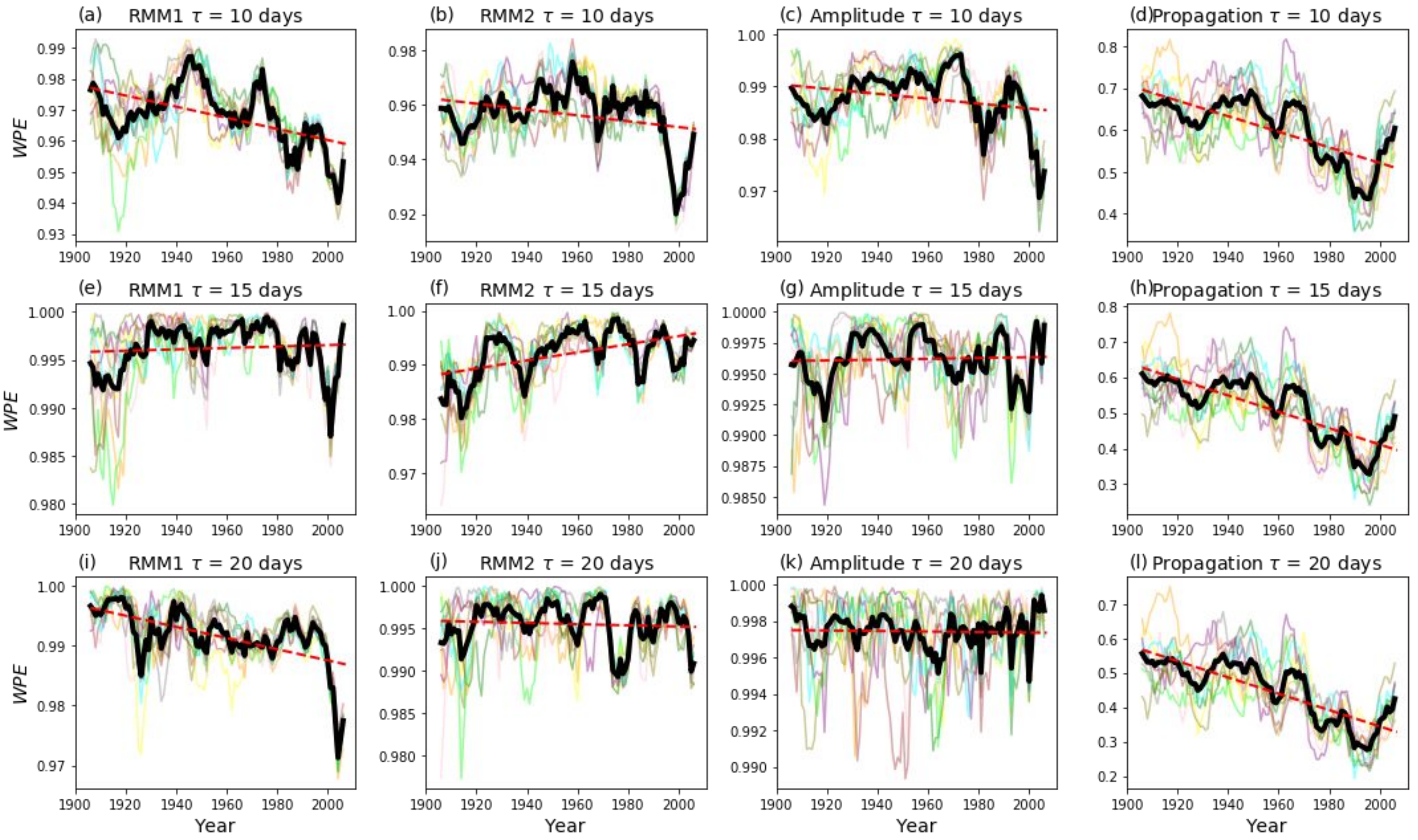
- Examining with CESM2 model ensemble, we find such an increase in MJO predictability is caused by internal variability and the external forcing - global warming. Under more severe global warming, the MJO tends to be more predictable.

- MJO gains more predictability through showing more organized patterns. Within a range of 10 days, the sequential amplifying/weakening of RMM1, RMM2 and MJO amplitude, and the organized eastward propagation occur more and more frequently.

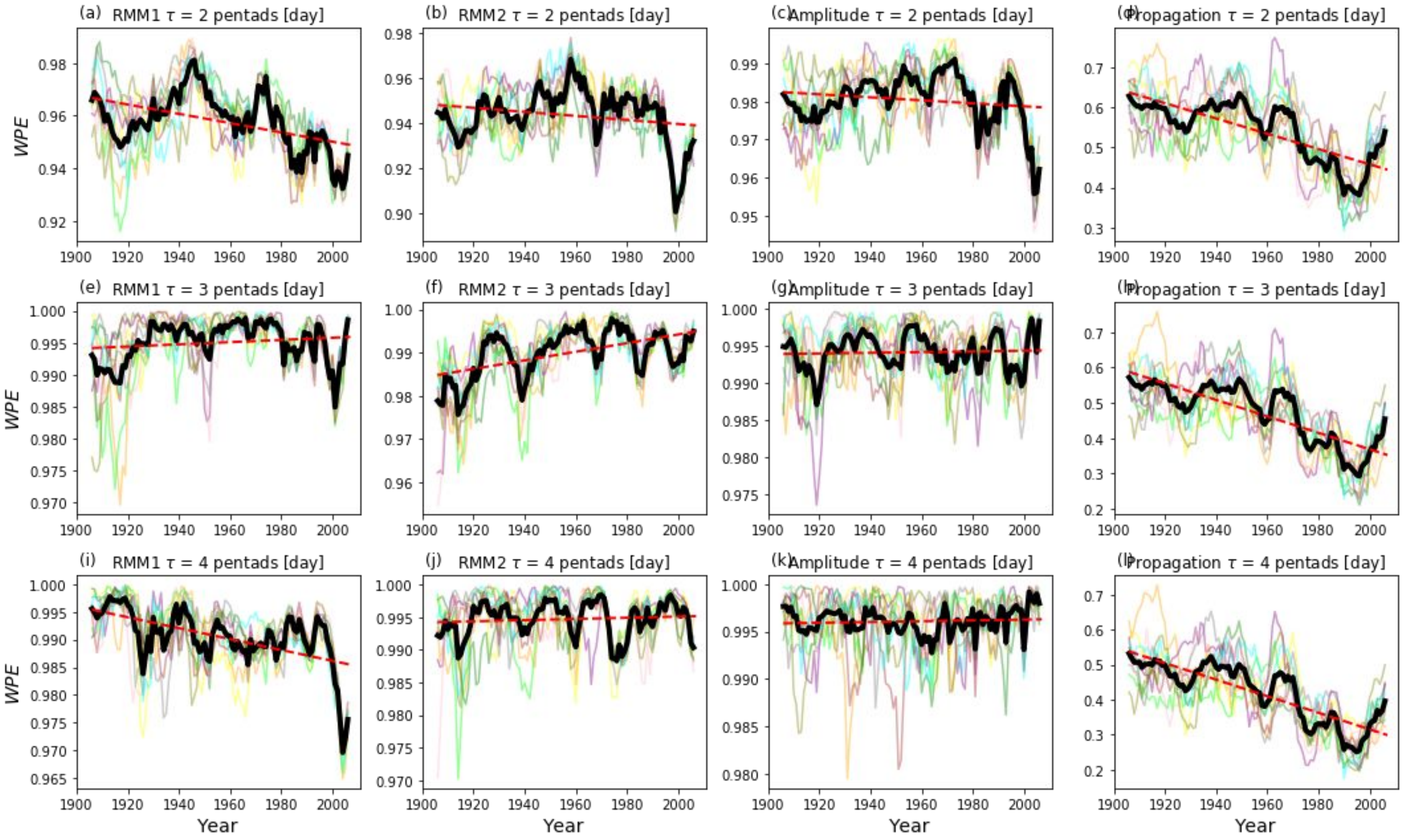
THANKS



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 = 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



(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