Critical role of biomass burning aerosols in enhanced historical Indian Ocean warming

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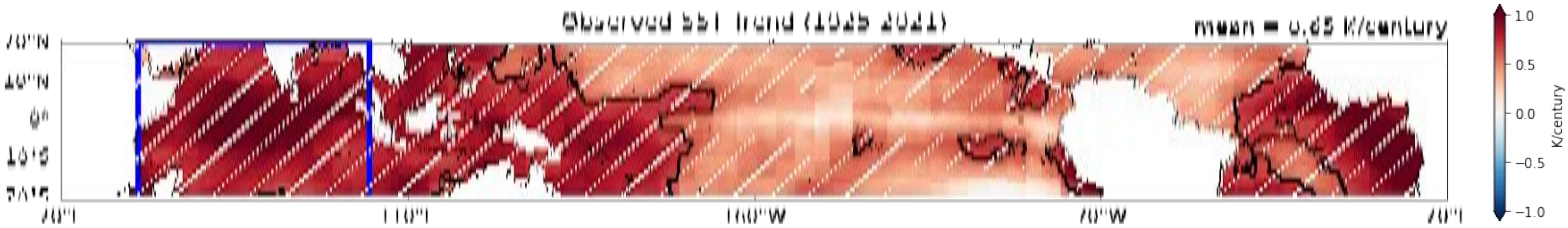
Enhanced Indian Ocean Warming



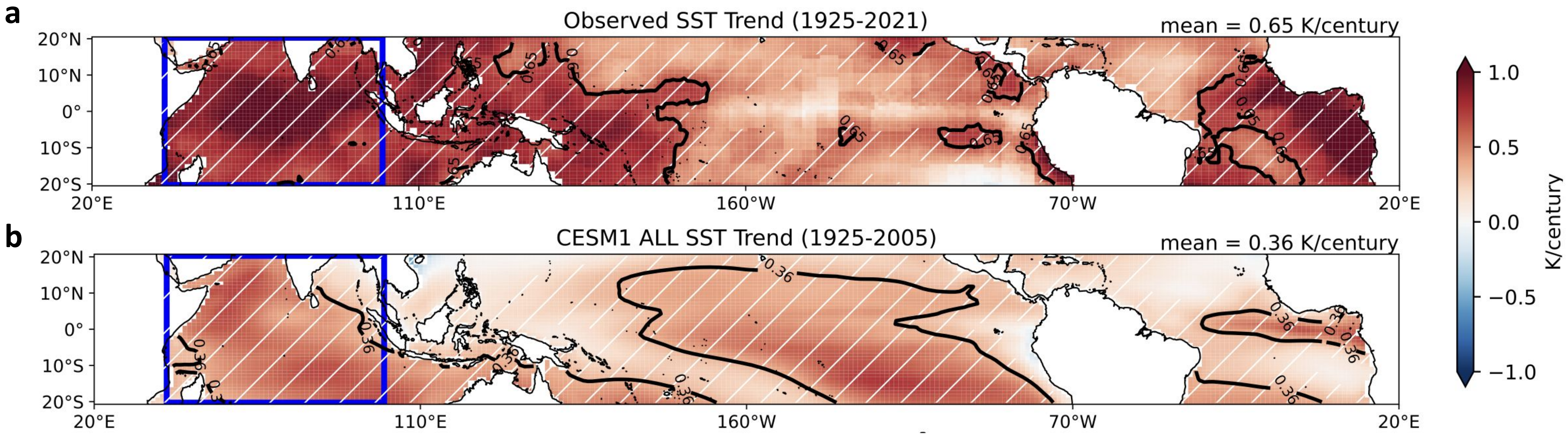
The tropical Indian Ocean (TIO) has experienced **enhanced** surface warming.

Climate impacts of TIO warming:

- Strengthened positive phase of NAO (Hoerling et al. 2001)
- Reduced Sahel rainfall (Lu et al. 2005)
- Enhanced Pacific Walker Circulation (Luo et al. 2012)
- The occurrence of a NAWH (Hu et al. 2020)
- Intensified AMOC (Hu et al. 2019)

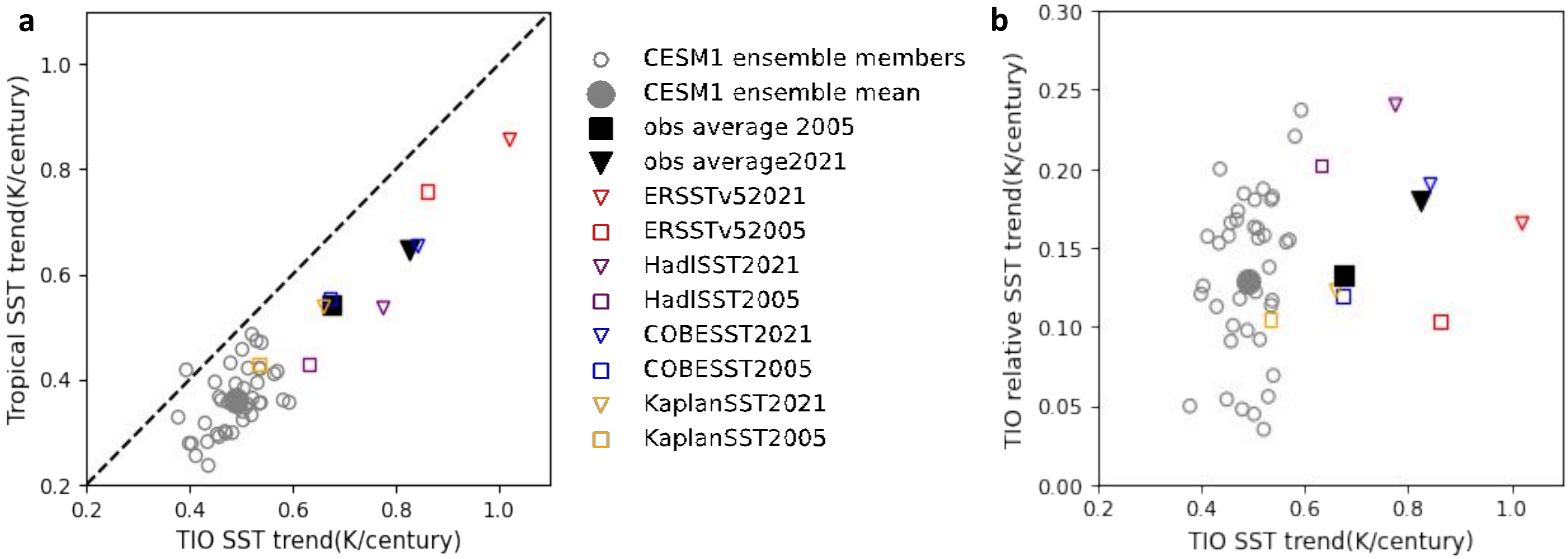
NAO: North Atlantic Oscillation; **NAWH**: North Atlantic Warming Hole; **AMOC**: Atlantic Meridional Overturning Circulation

CESM1 can capture TIO relative warming



- CESM1 all forcing (ALL) underestimates the observed tropical-mean SST trend.
- The enhanced TIO warming relative to the tropical mean is a robust feature.

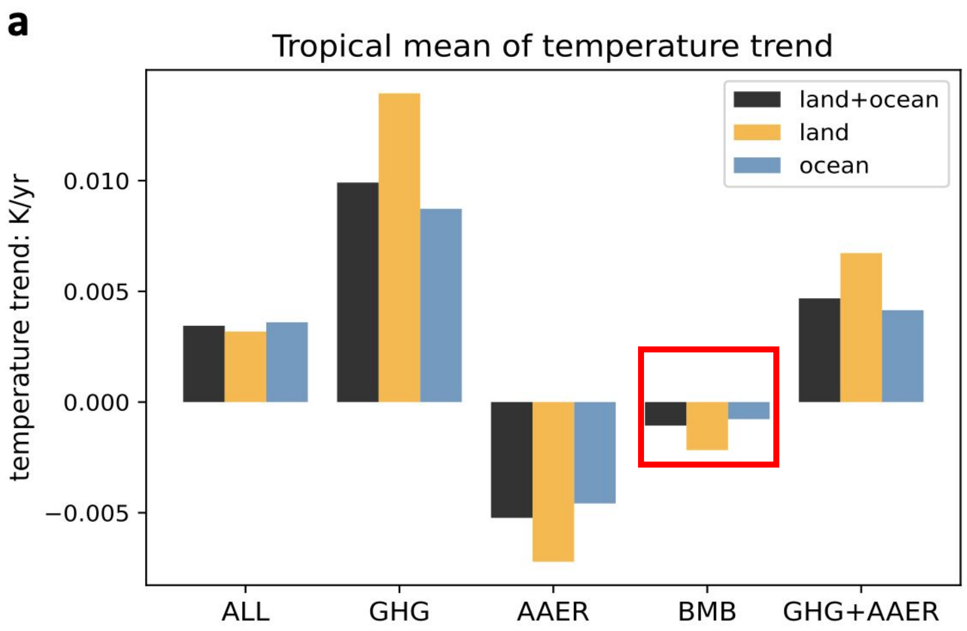
CESM1 can capture Tropical Indian Ocean(TIO) relative warming

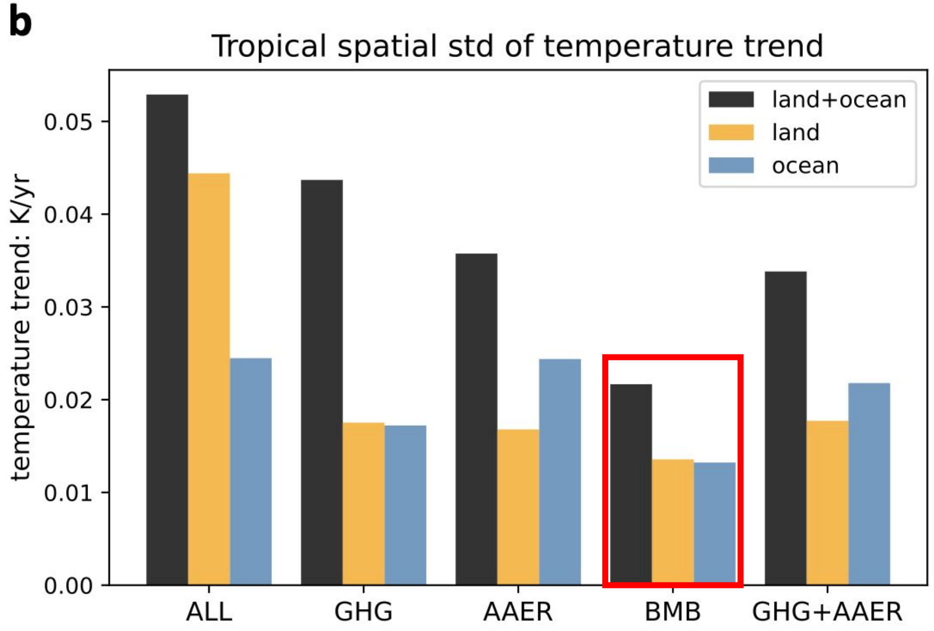


- CESM1 underestimates TIO absolute warming
- CESM1 has TIO enhanced warming as observations
- CESM1 performs well in TIO relative warming

Relative SST = absolute SST - tropical-mean SST

Tropical SST response to historical BMB changes



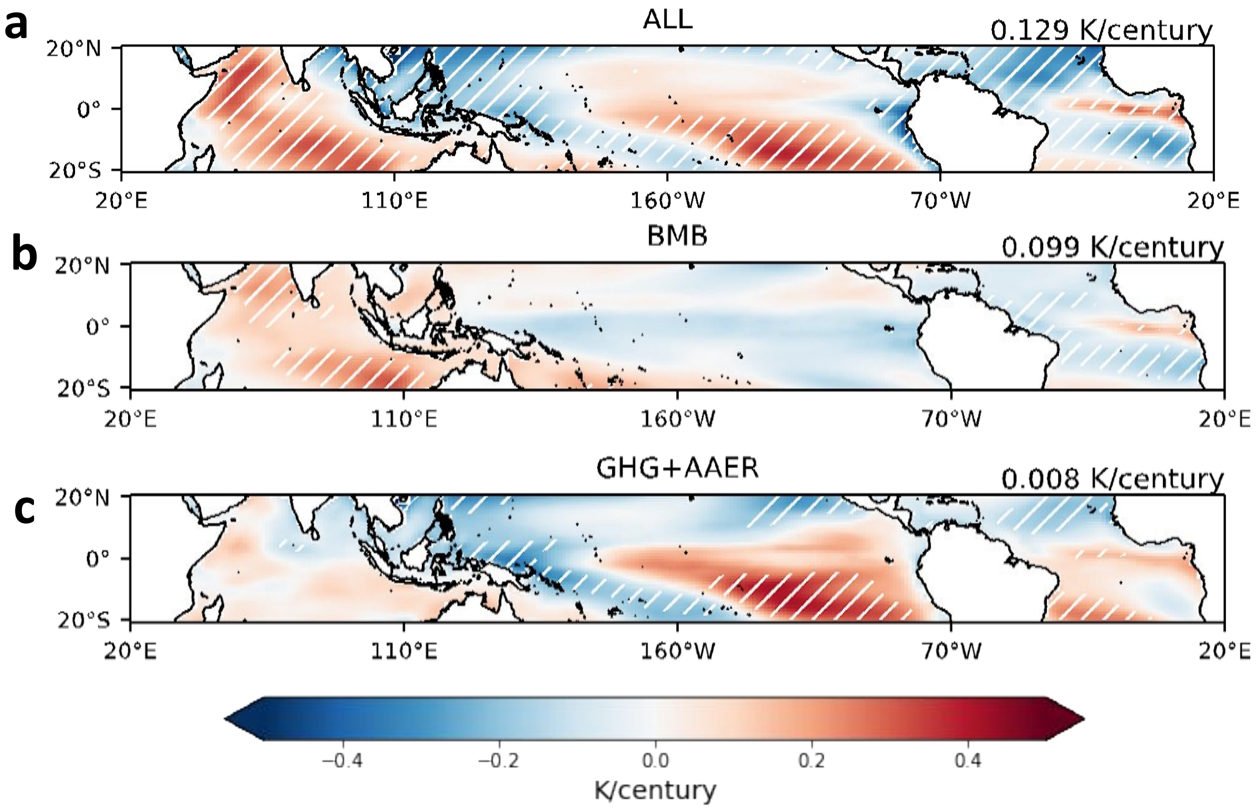


ALL: all forcing
GHG: greenhouse gases
AAER: anthropogenic aerosols
BMB: biomass burning aerosols

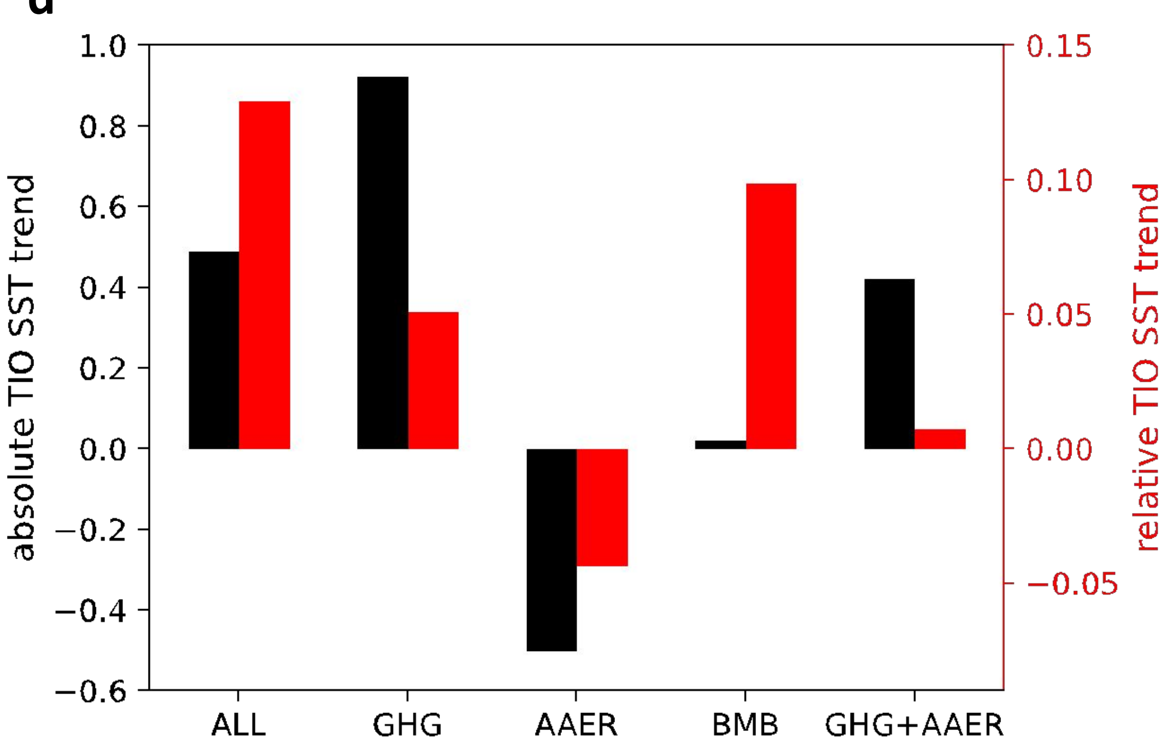
- BMB is as important as GHG and AER for tropical warming pattern formation.
- BMB is the main driver of the TIO relative warming in the historical period.

Tropical SST response to historical BMB changes

1925-2005 tropical relative SST trends



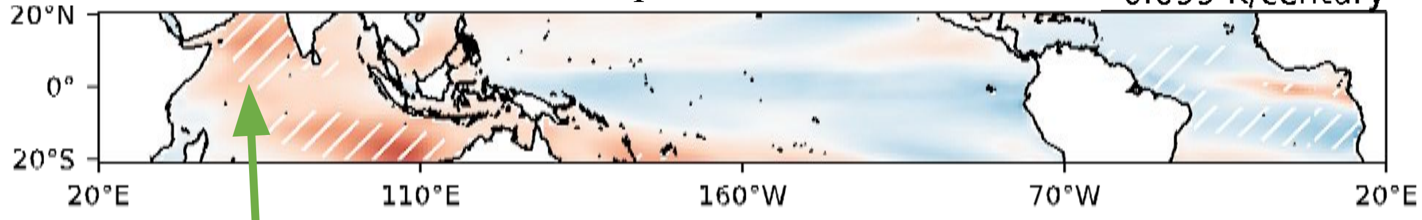
TIO forcing decomposition analysis



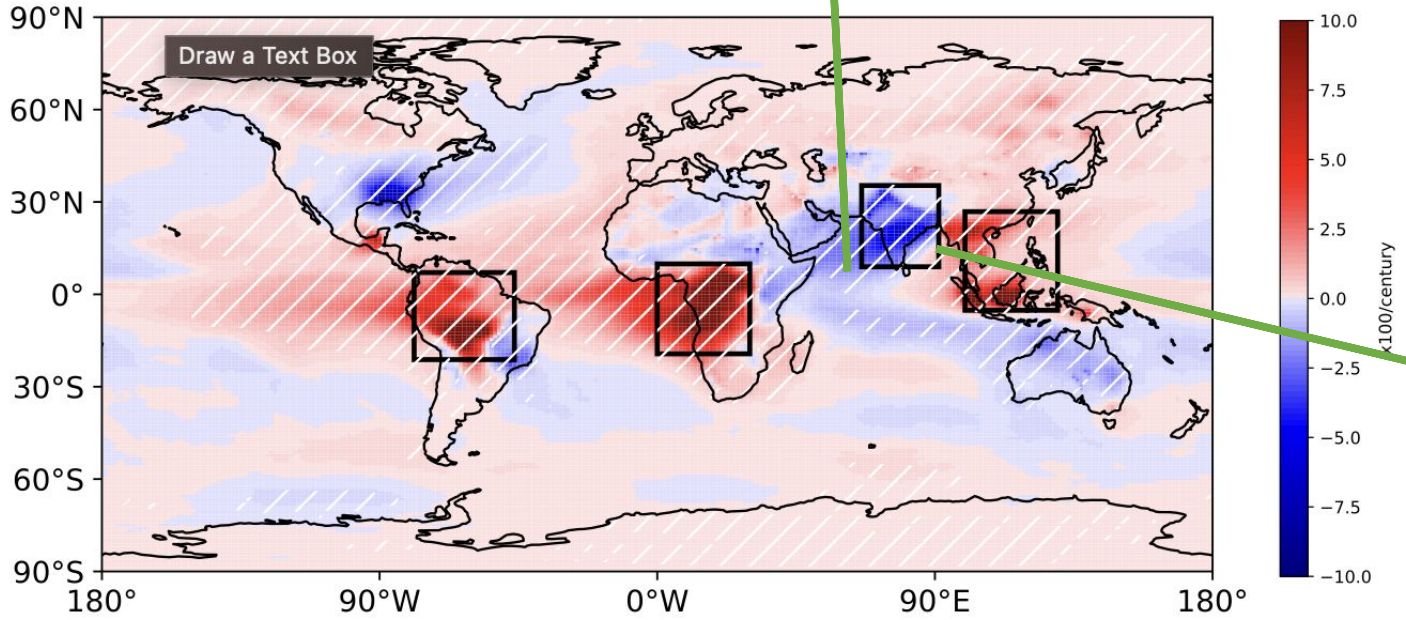
- Relative SST = absolute SST - tropical-mean SST
- BMB contributes little to the absolute TIO SST trend but acts as the most important radiative forcing for the TIO relative warming.
- GHG and AAER are two leading factors for TIO absolute SST changes, but not for TIO relative SST.

BMB changes in the historical period

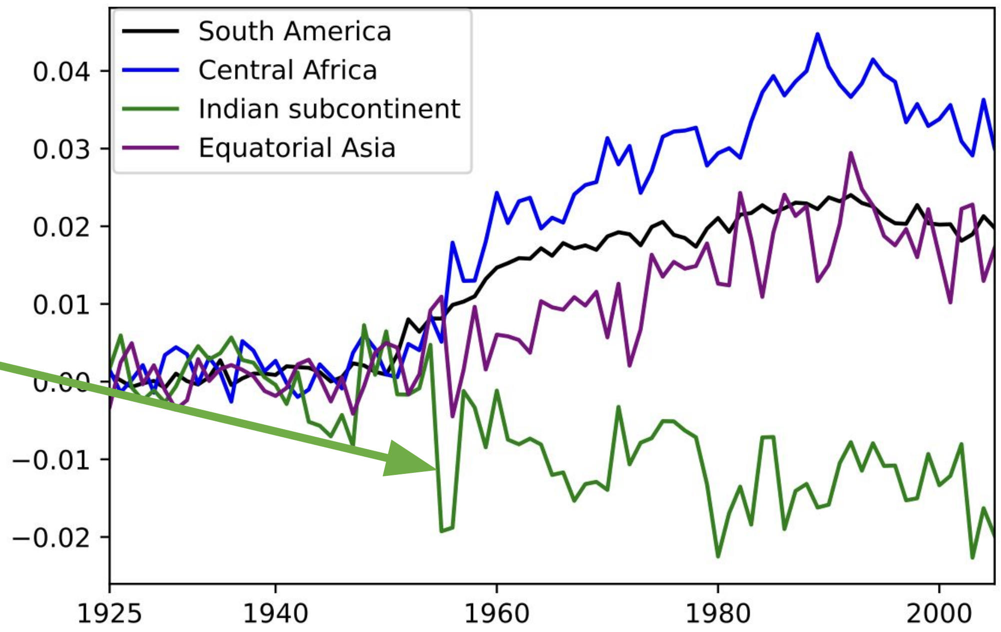
1925-2005 BMB-induced tropical relative SST trends



a 1925-2005 BMB-induced AOD trends



b BMB-induced AOD variations in specific regions

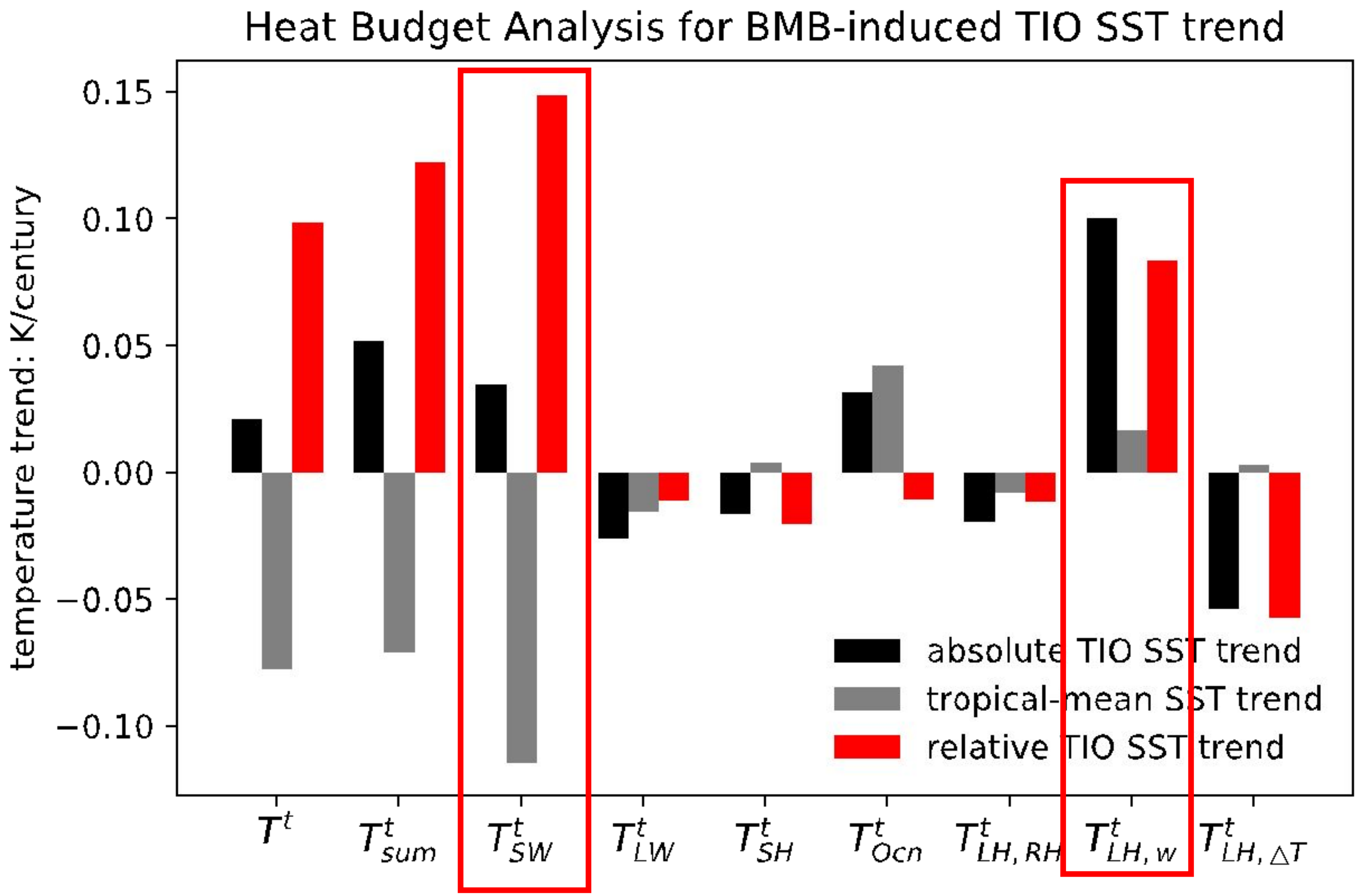


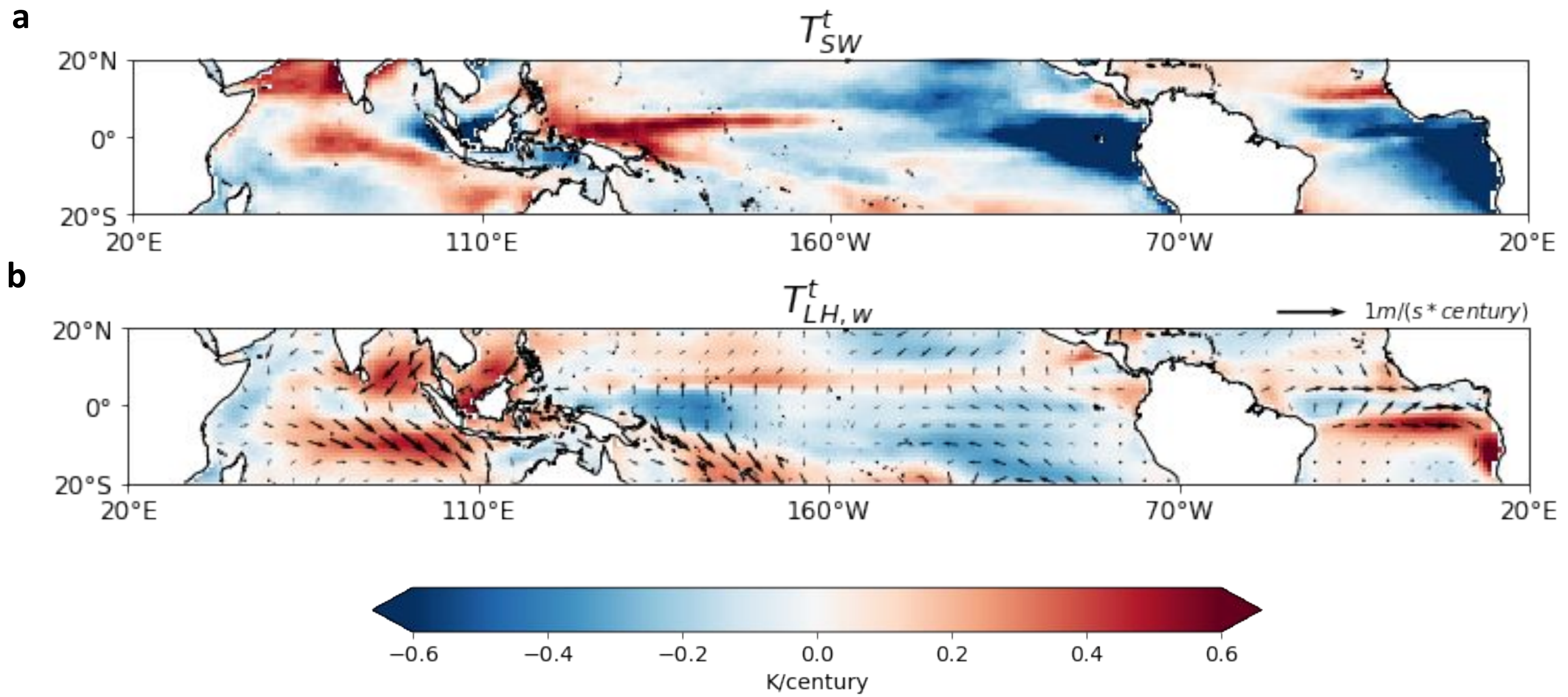
AOD: Aerosol optical depth

Mechanisms of BMB-induced TIO relative warming

Heat budget analysis:
(Follow Zhang et al. 2020)

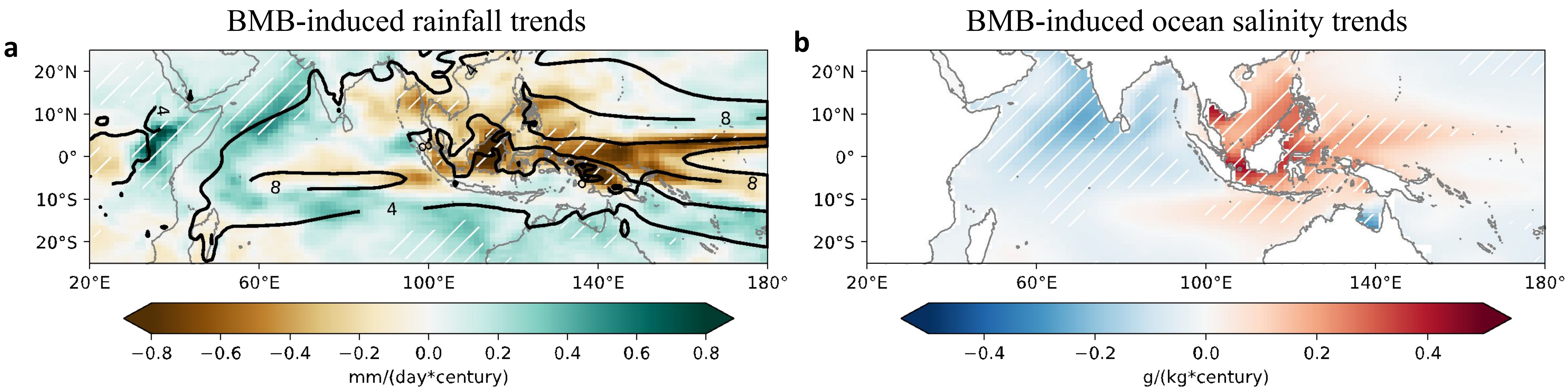
$$T^t \approx T^t_{SW} + T^t_{LW} + T^t_{SH} + T^t_{Ocn} + T^t_{LH,w} + T^t_{LH,RH} + T^t_{LH,\Delta T}$$





- ***T^t_{SW}*** (shortwave): BMB reduction over the TIO increases the clear-sky shortwave radiation reaching the surface, while cloud changes contribute to the warming primarily near the equator.
- ***$T^t_{LH,w}$*** (surface wind speed *by* latent heat flux): The anomalous easterly and northwesterly winds in the TIO oppose the background wind and cause decreases in surface wind speed.

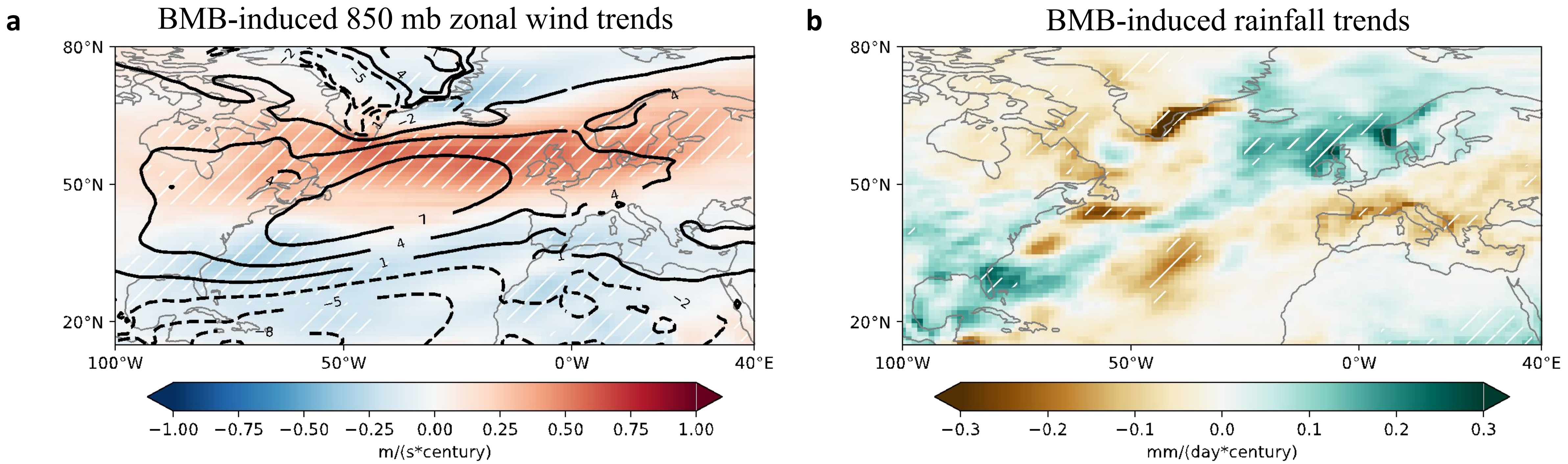
Regional impacts of BMB-induced TIO relative warming



climatological rainfall (contours; mm/d)

- The TIO relative warming leads to a significant increase of rainfall over most of the TIO.
- The TIO becomes fresher while the western Pacific becomes saltier.

Global impacts of BMB-induced TIO relative warming



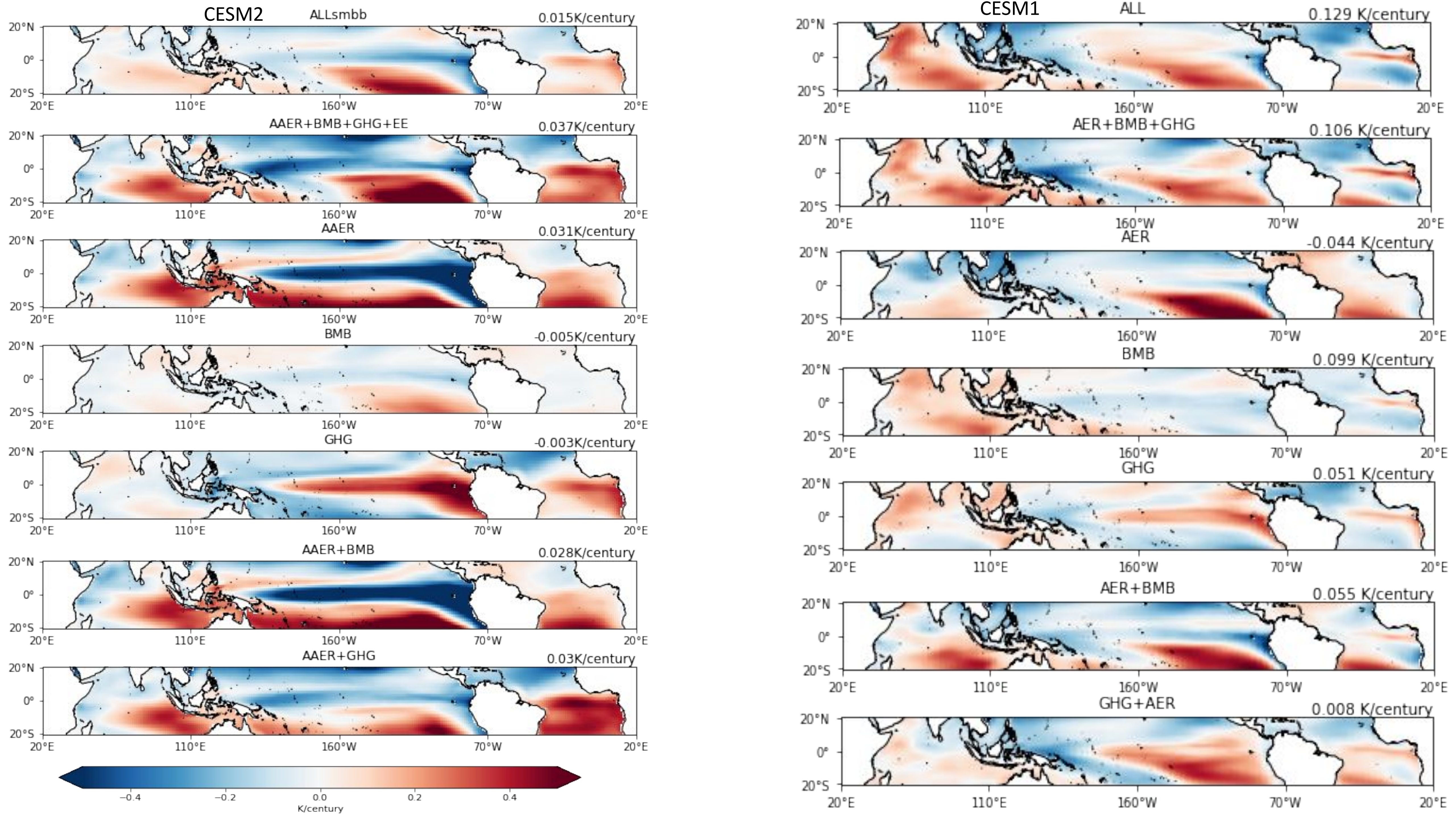
climatological 850 mb zonal wind (contours; m/s)

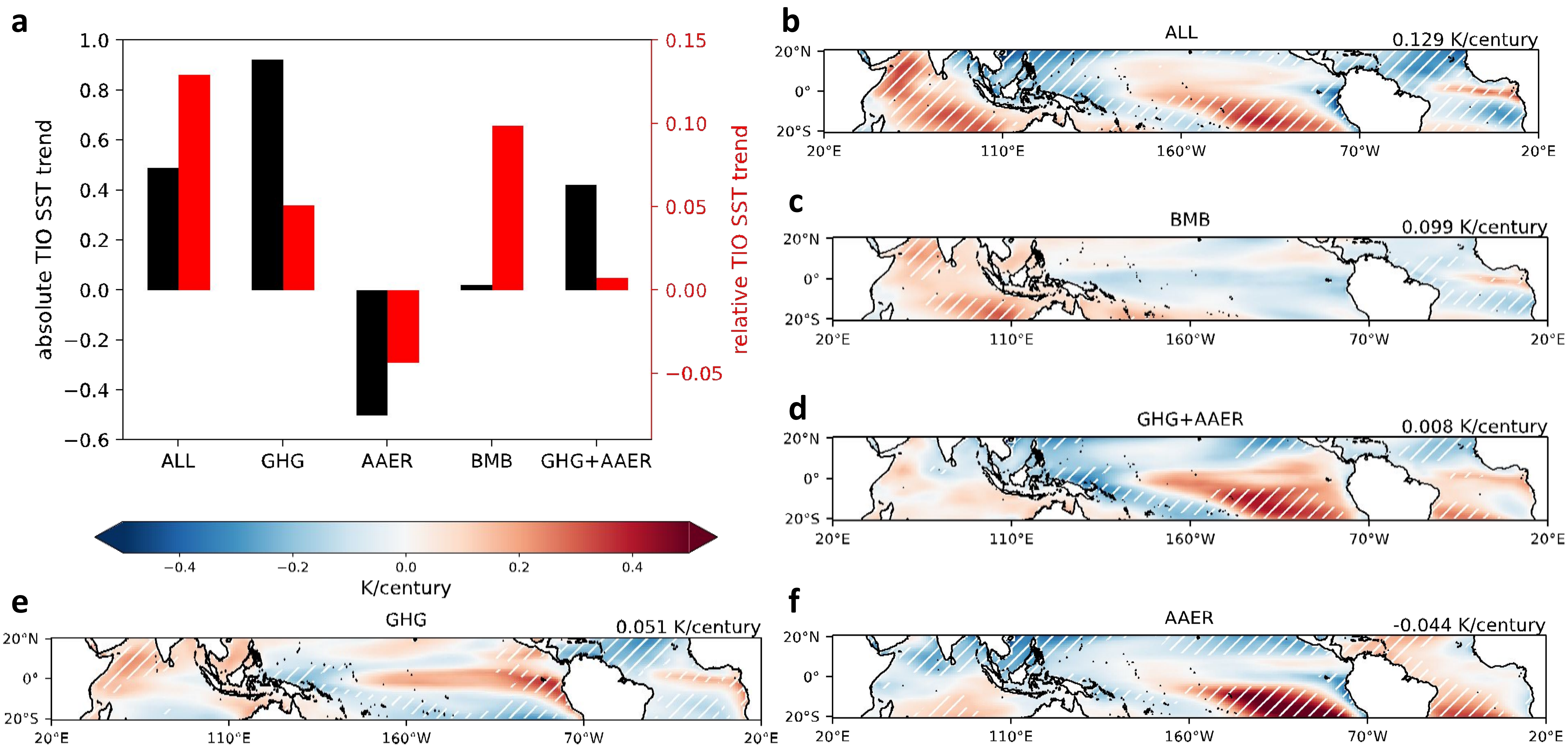
The BMB-induced changes in the North Atlantic jet and the associated European rainfall pattern suggest a shift toward the positive NAO phase.

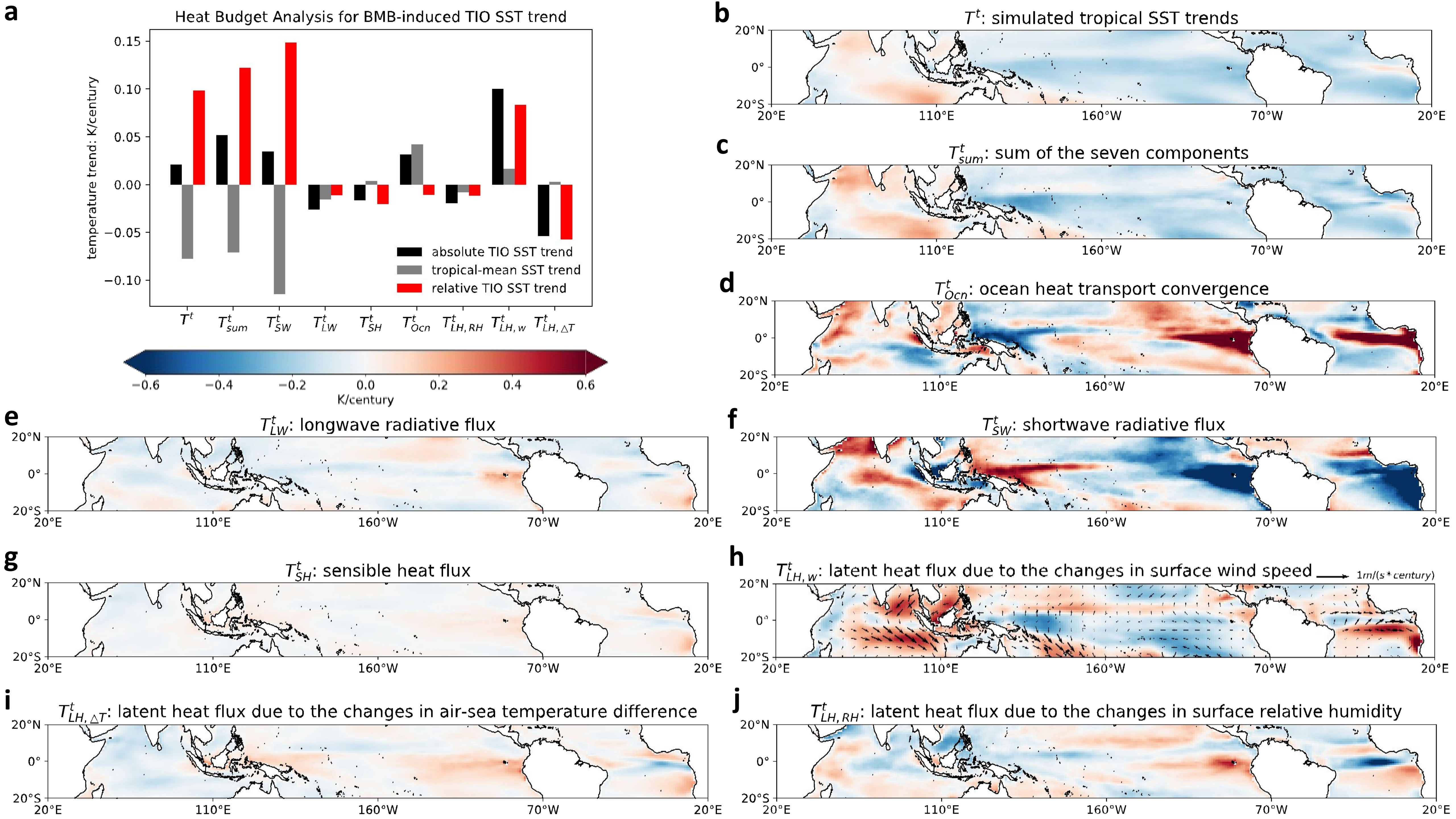
Summary

- BMB is the dominant contributor to the forced component of TIO relative warming in CESM1, at least compared to GHG and AER.
- The BMB-induced tropical rainfall changes may in turn cause a positive NAO phase via atmospheric teleconnections.
- There exists an urgent need to accurately represent the chemical, microphysical, and radiative properties of BMB aerosols in GCMs.

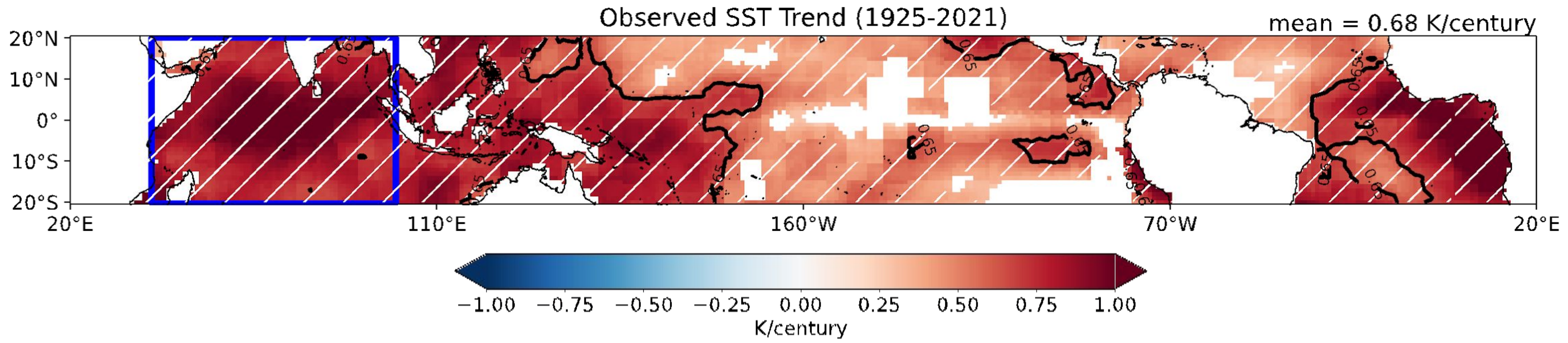
Supplementary plots


CESM2
ALLsmbb
0.015K/century
AAER+BMB+GHG+EE
0.037K/century
AAER
0.031K/century
BMB
-0.005K/century
GHG
-0.003K/century
AAER+BMB
0.028K/century
AAER+GHG
0.03K/century
K/century
CESM1
ALL
0.129 K/century
AER+BMB+GHG
0.106 K/century
AER
-0.044 K/century
BMB
0.099 K/century
GHG
0.051 K/century
AER+BMB
0.055 K/century
GHG+AER
0.008 K/century

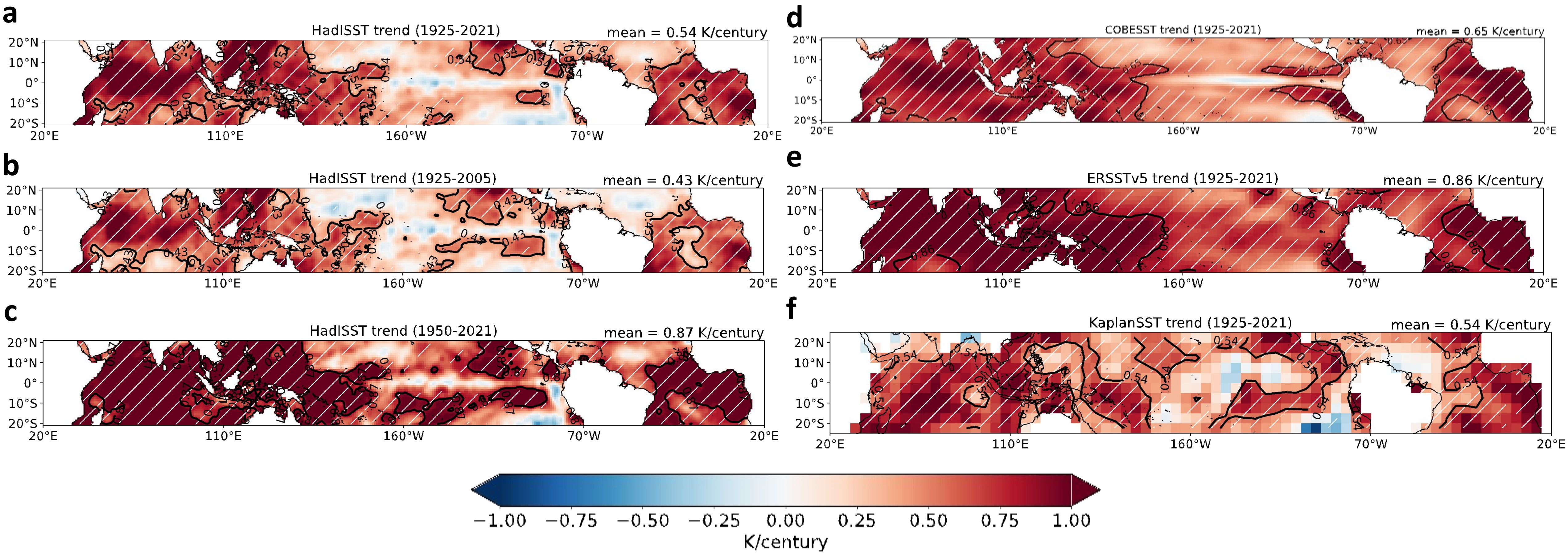

a
absolute TIO SST trend
relative TIO SST trend
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0.15
0.10
0.05
0.00
−0.05
ALL
GHG
AAER
BMB
GHG+AAER
b
ALL
0.129 K/century
c
BMB
0.099 K/century
d
GHG+AAER
0.008 K/century
e
GHG
0.051 K/century
f
AAER
-0.044 K/century
20°N
0°
20°S
20°E
110°E
160°W
70°W
20°E
−0.4
−0.2
0.0
0.2
0.4
K/century



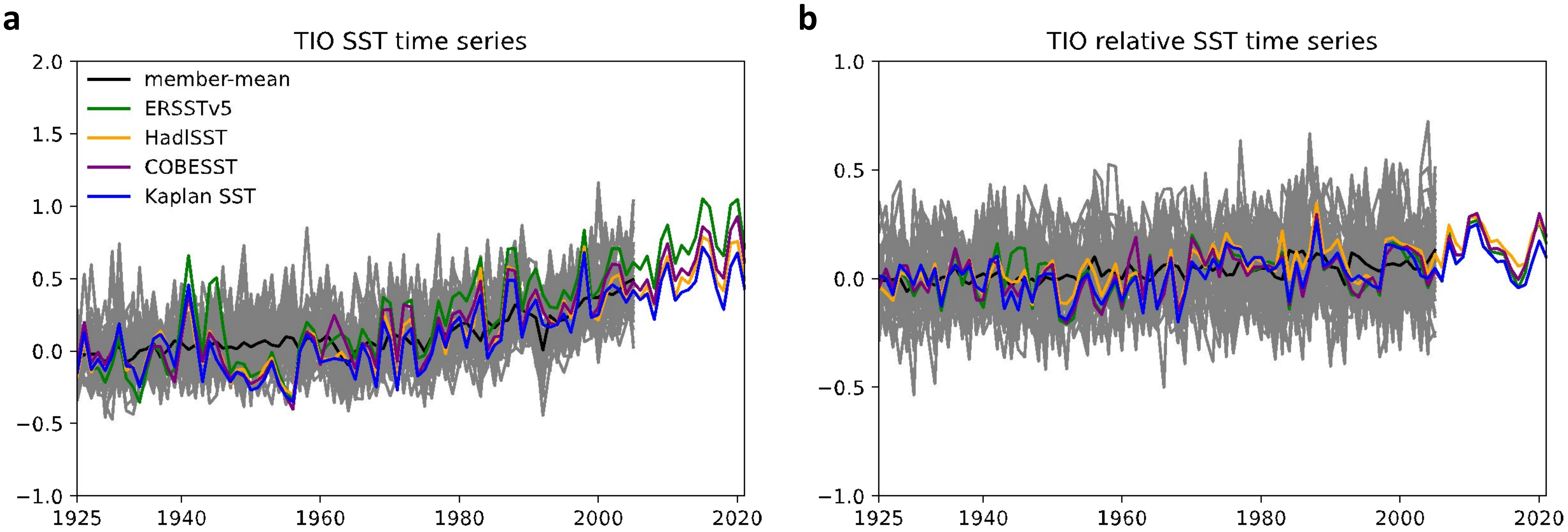
a
Heat Budget Analysis for BMB-induced TIO SST trend
temperature trend: K/century
absolute TIO SST trend
tropical-mean SST trend
relative TIO SST trend
T^t
T^t_{sum}
T^t_{SW}
T^t_{LW}
T^t_{SH}
T^t_{Ocn}
$T^t_{LH,RH}$
$T^t_{LH,w}$
$T^t_{LH,\triangle T}$
K/century
b
T^t: simulated tropical SST trends
c
T^t_{sum}: sum of the seven components
d
T^t_{Ocn}: ocean heat transport convergence
e
T^t_{LW}: longwave radiative flux
f
T^t_{SW}: shortwave radiative flux
g
T^t_{SH}: sensible heat flux
h
$T^t_{LH,w}$: latent heat flux due to the changes in surface wind speed
1m/(s*century)
i
$T^t_{LH,\triangle T}$: latent heat flux due to the changes in air-sea temperature difference
j
$T^t_{LH,RH}$: latent heat flux due to the changes in surface relative humidity
20°N
0°
20°S
20°E
110°E
160°W
70°W

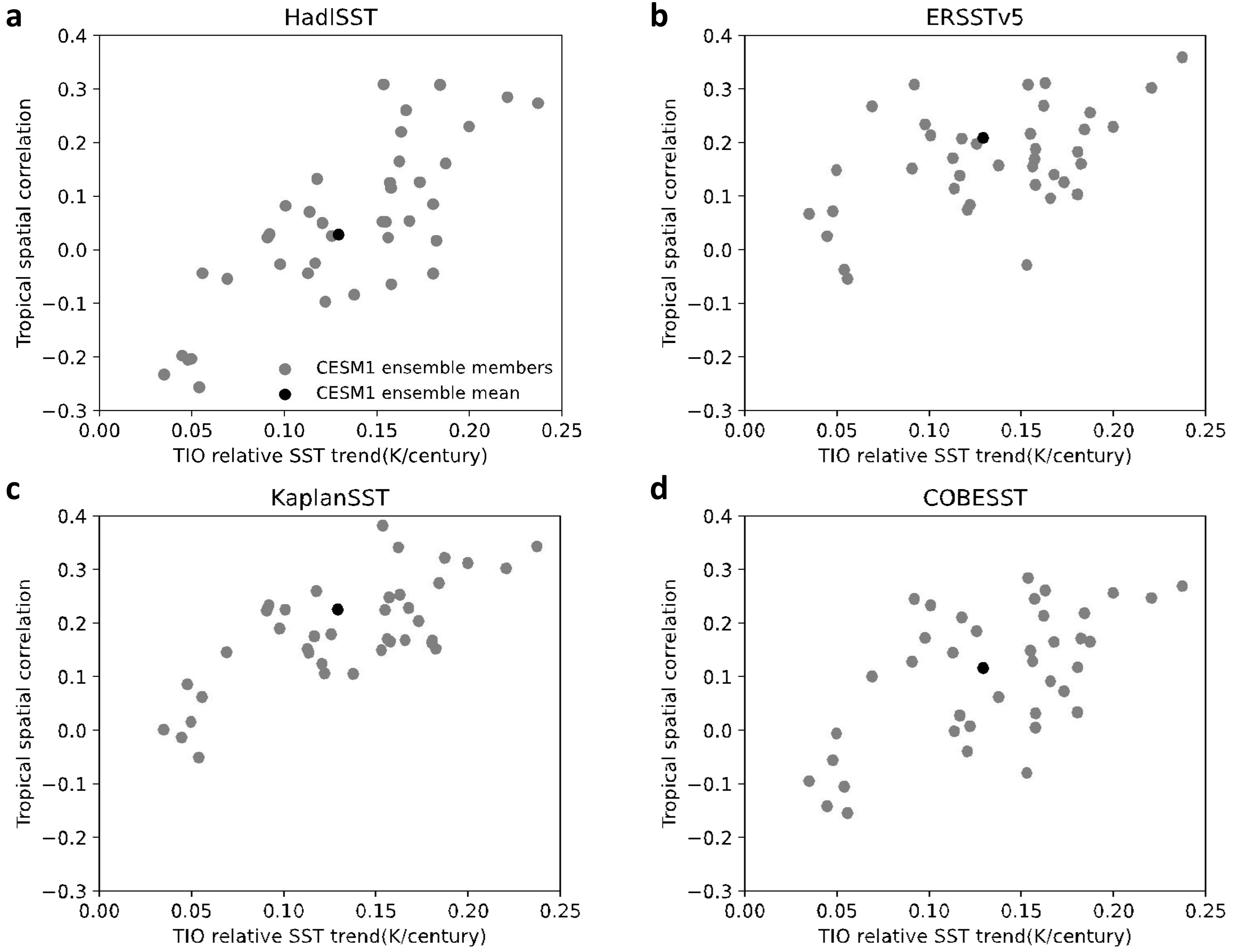


Observed SST Trend (1925-2021)
mean = 0.68 K/century
20°N
10°N
0°
10°S
20°S
20°E
110°E
160°W
70°W
20°E
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
K/century

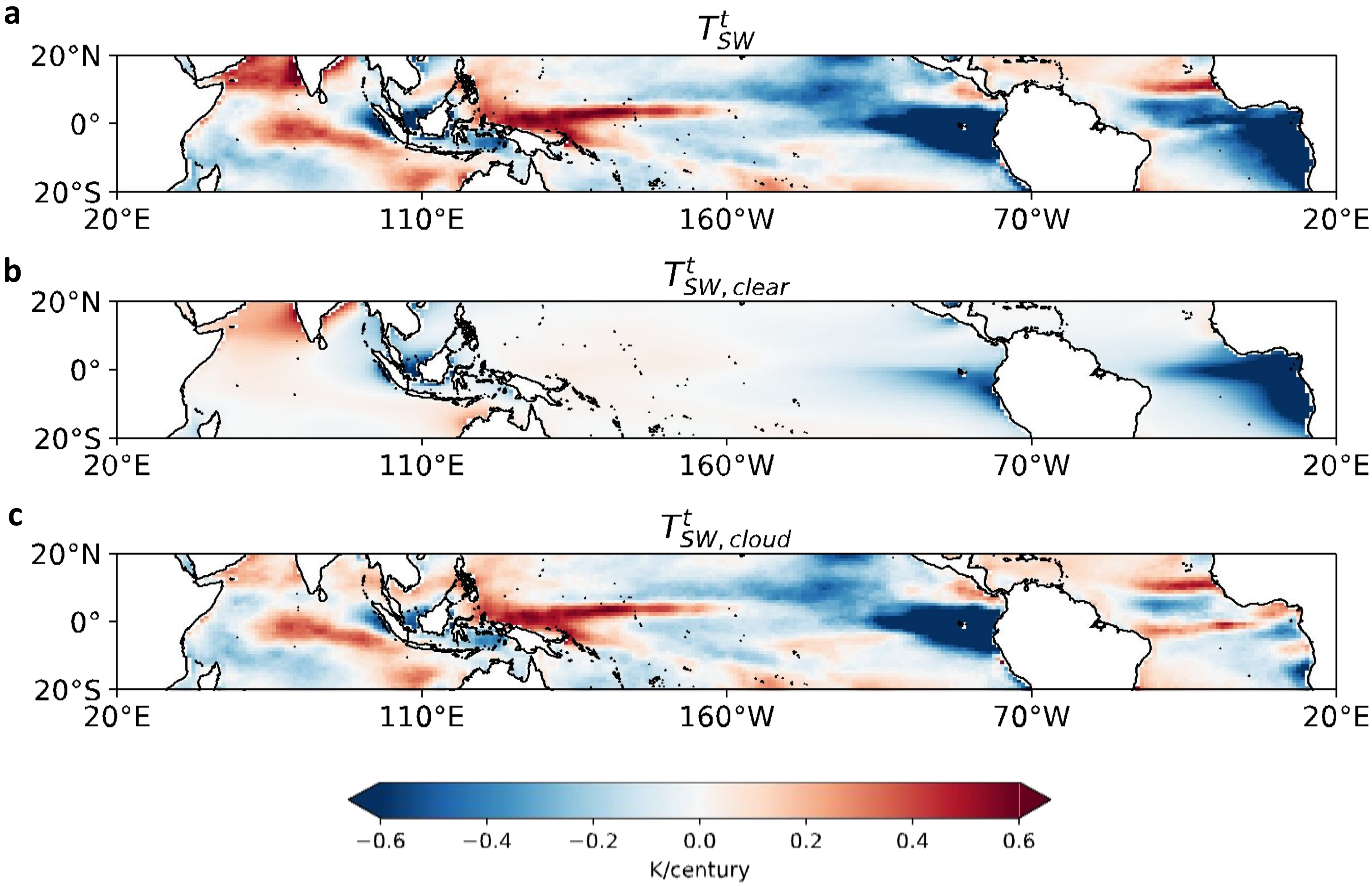


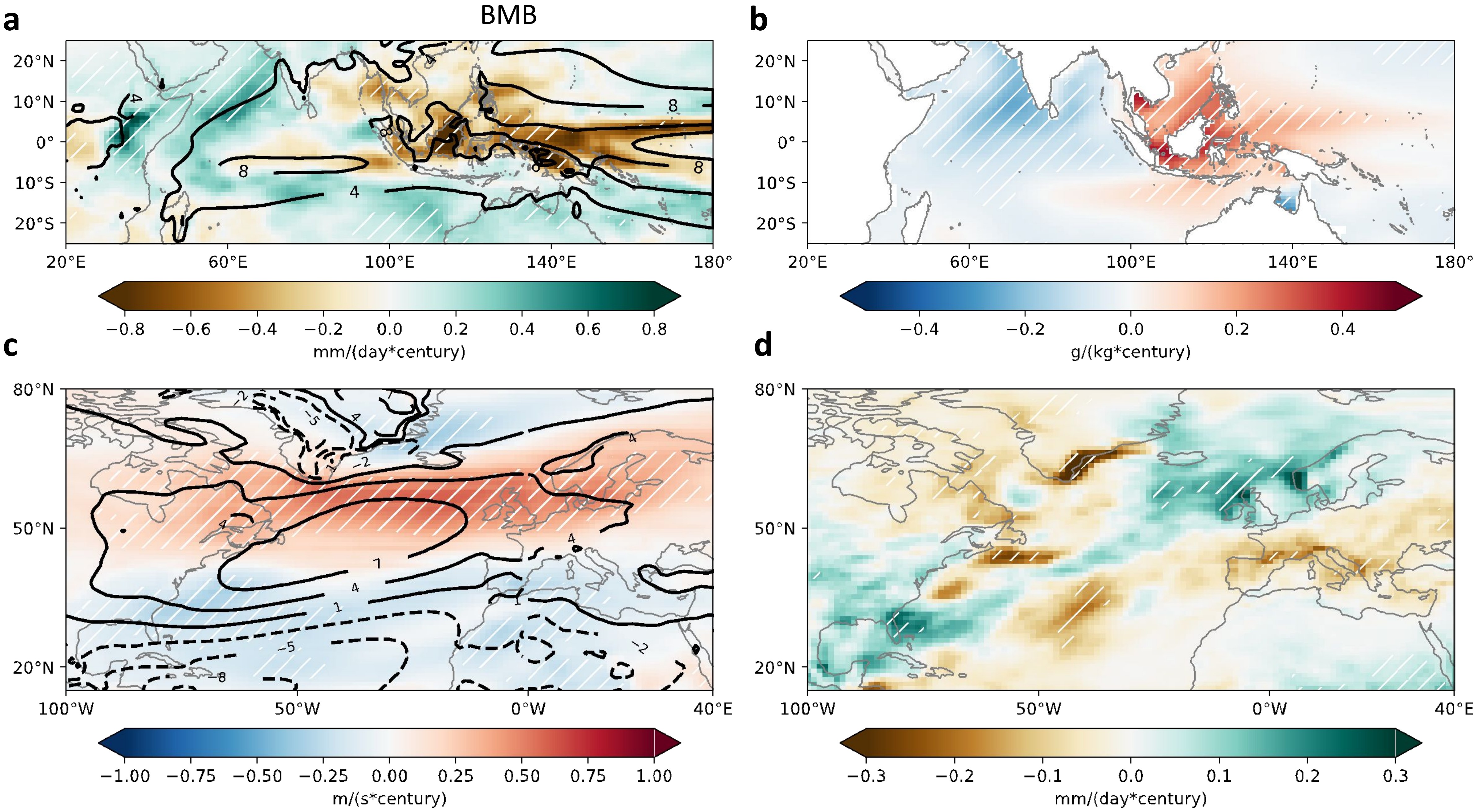
a
HadISST trend (1925-2021)
mean = 0.54 K/century
b
HadISST trend (1925-2005)
mean = 0.43 K/century
c
HadISST trend (1950-2021)
mean = 0.87 K/century
d
COBESST trend (1925-2021)
mean = 0.65 K/century
e
ERSSTv5 trend (1925-2021)
mean = 0.86 K/century
f
KaplanSST trend (1925-2021)
mean = 0.54 K/century
20°N
10°N
0°
10°S
20°S
20°E
110°E
160°W
70°W
20°E
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
K/century


a
TIO SST time series
member-mean
ERSSTv5
HadISST
COBESST
Kaplan SST
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
1925
1940
1960
1980
2000
2020
b
TIO relative SST time series
1.0
0.5
0.0
−0.5
−1.0
1925
1940
1960
1980
2000
2020

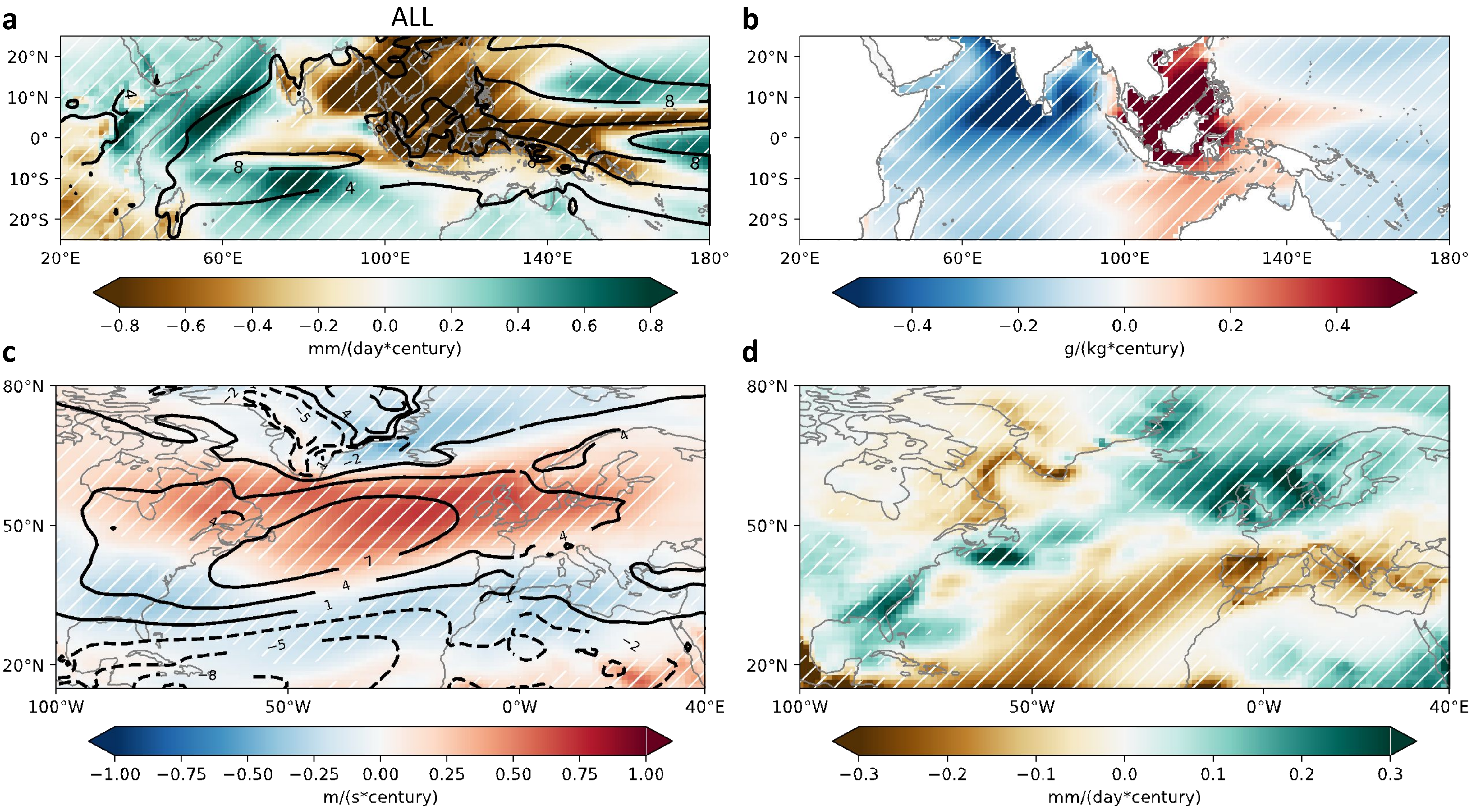


a
HadISST
b
ERSSTv5
c
KaplanSST
d
COBESST
Tropical spatial correlation
TIO relative SST trend(K/century)
CESM1 ensemble members
CESM1 ensemble mean
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.00
0.05
0.10
0.15
0.20
0.25

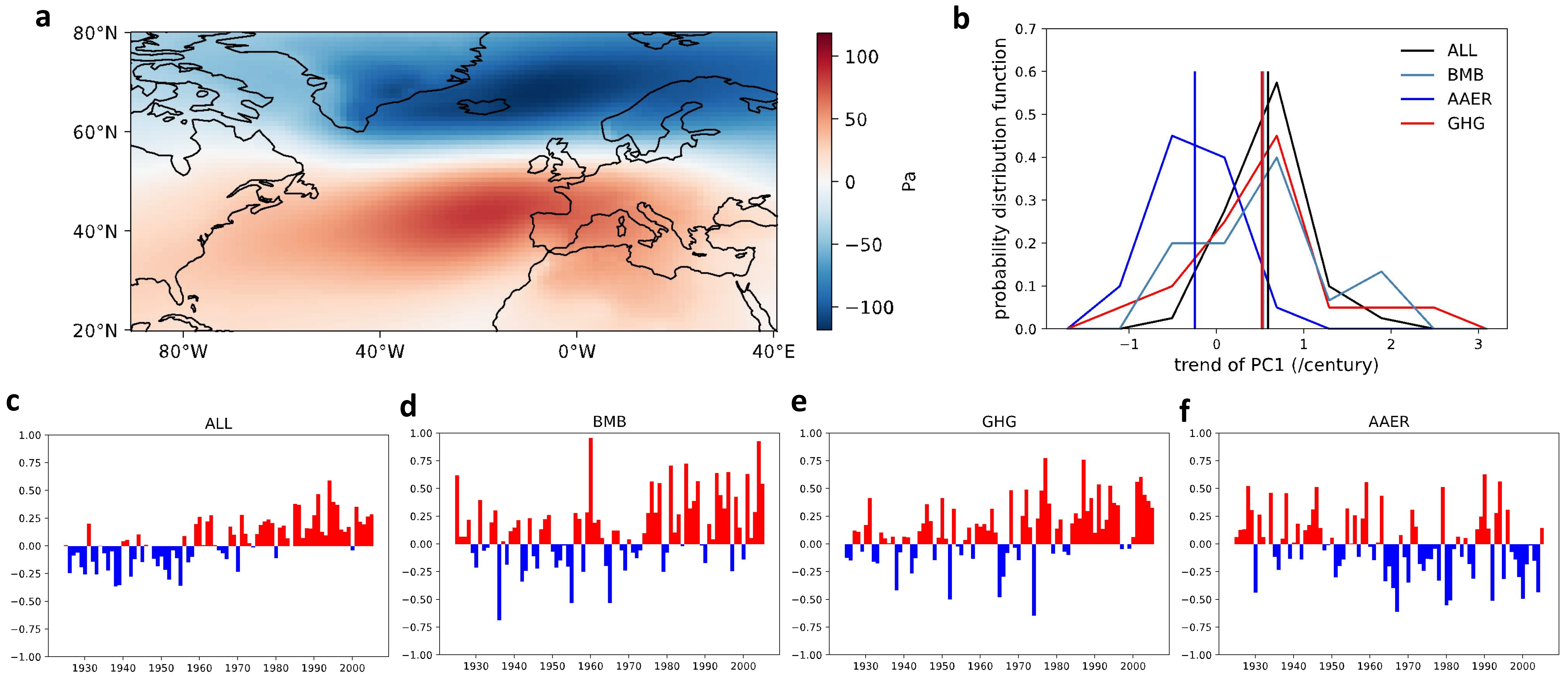

a
T^t_{SW}
b
$T^t_{SW,clear}$
c
$T^t_{SW,cloud}$
20°N
0°
20°S
20°E
110°E
160°W
70°W
20°E
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
K/century

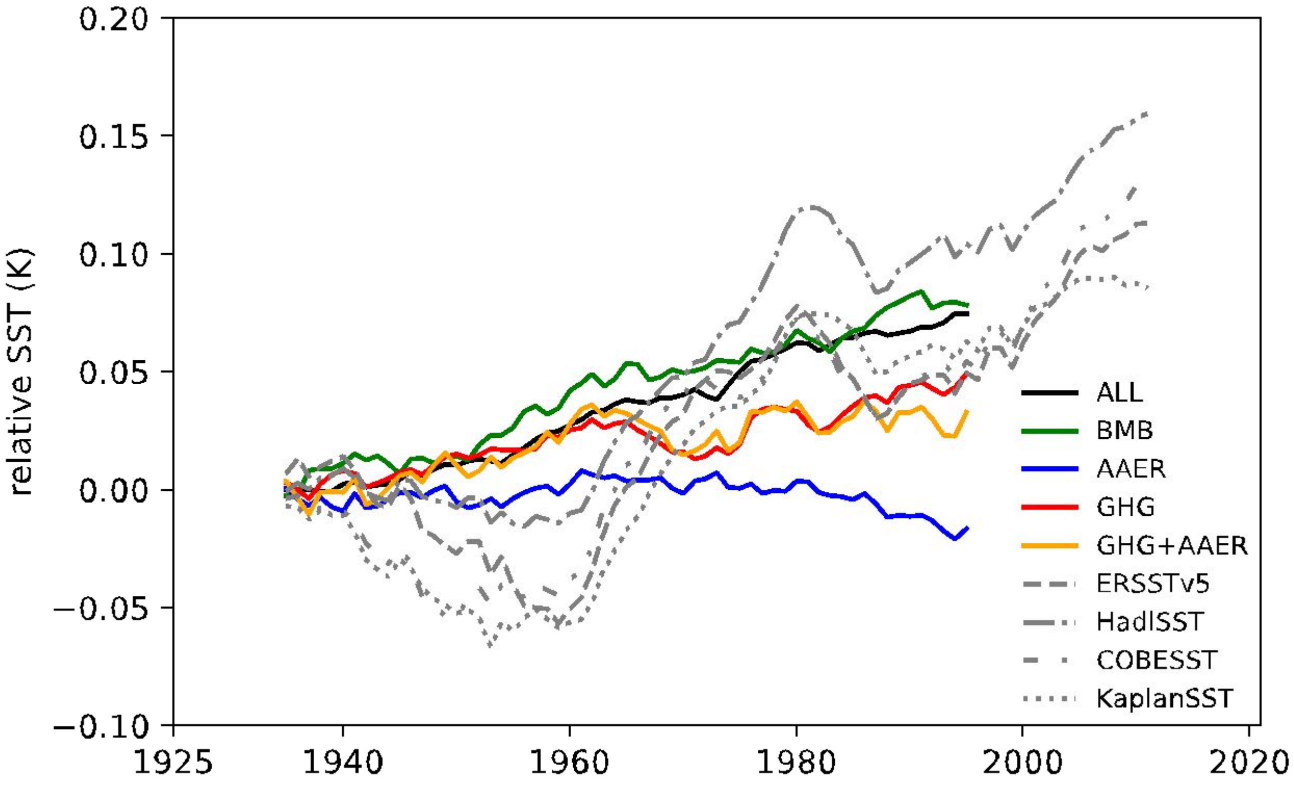


a
BMB
b
c
d
20°N
10°N
0°
10°S
20°S
20°E
60°E
100°E
140°E
180°
−0.8 −0.6 −0.4 −0.2 0.0 0.2 0.4 0.6 0.8
mm/(day*century)
−0.4 −0.2 0.0 0.2 0.4
g/(kg*century)
80°N
50°N
20°N
100°W
50°W
0°W
40°E
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00
m/(s*century)
−0.3 −0.2 −0.1 0.0 0.1 0.2 0.3
mm/(day*century)



a
ALL
b
c
d
20°N
10°N
0°
10°S
20°S
20°E
60°E
100°E
140°E
180°
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
mm/(day*century)
−0.4
−0.2
0.0
0.2
0.4
g/(kg*century)
80°N
50°N
20°N
100°W
50°W
0°W
40°E
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
m/(s*century)
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
mm/(day*century)


a
80°N
60°N
40°N
20°N
80°W
40°W
0°W
40°E
100
50
0
−50
−100
Pa
b
probability distribution function
trend of PC1 (/century)
ALL
BMB
AAER
GHG
c
ALL
d
BMB
e
GHG
f
AAER



relative SST (K)
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
1925
1940
1960
1980
2000
2020
ALL
BMB
AAER
GHG
GHG+AAER
ERSSTv5
HadISST
COBESST
KaplanSST