The role of water vapor and cloud feedback on the evolution of the Indian summer monsoon over the last 22,000 years

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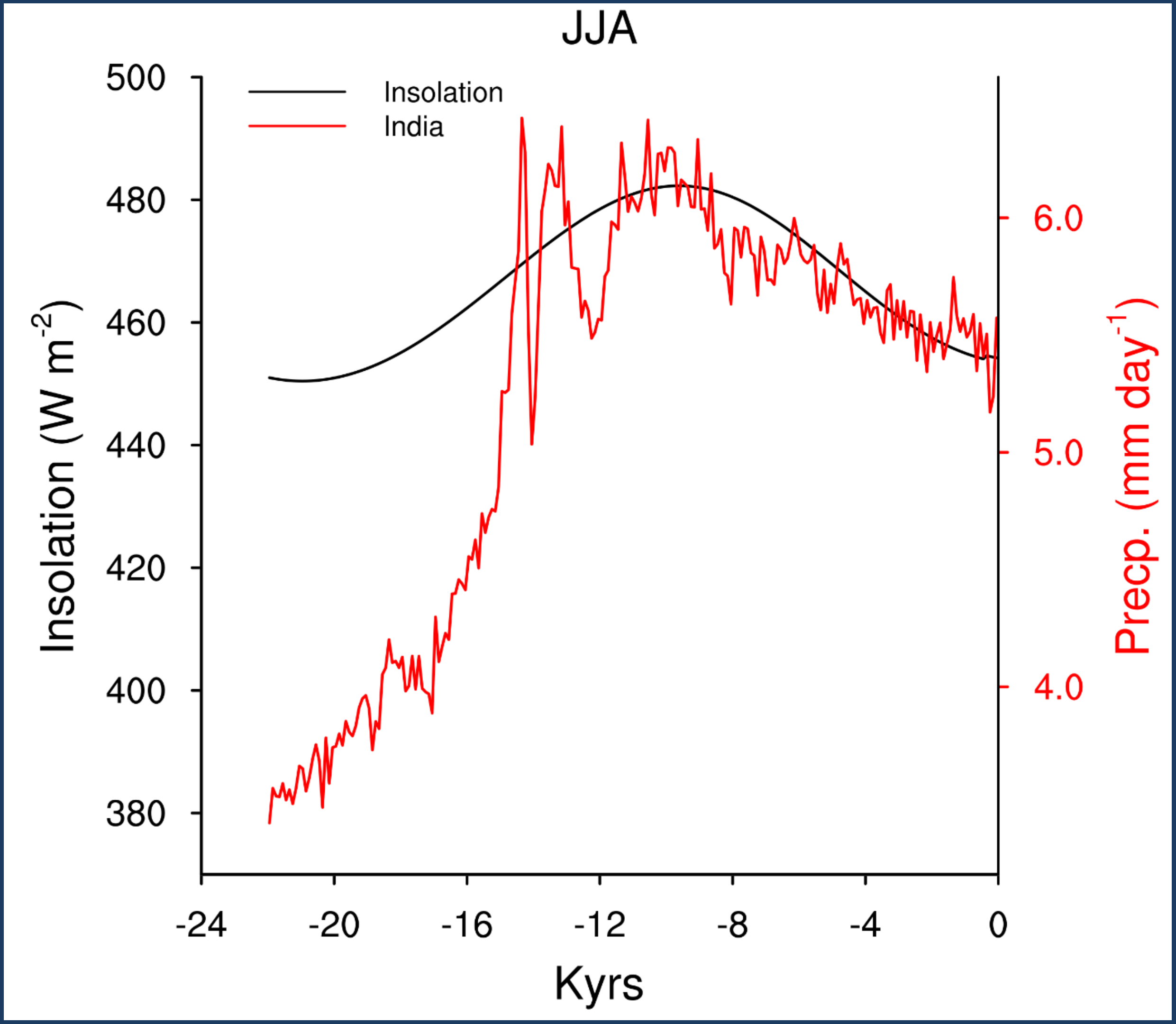
Short version

DIFFERENT SENSITIVITY OF MONSOON TO INSOLATION



TraCE21K simulation

Model: CCSM3, fully coupled ESM, with transient boundary conditions, 3.75º x 3.75º

Duration: 22 Kyrs

OBJECTIVE

Identify the feedbacks.

Quantify the role of forcings and feedbacks.

ENERGETICS FRAMEWORK

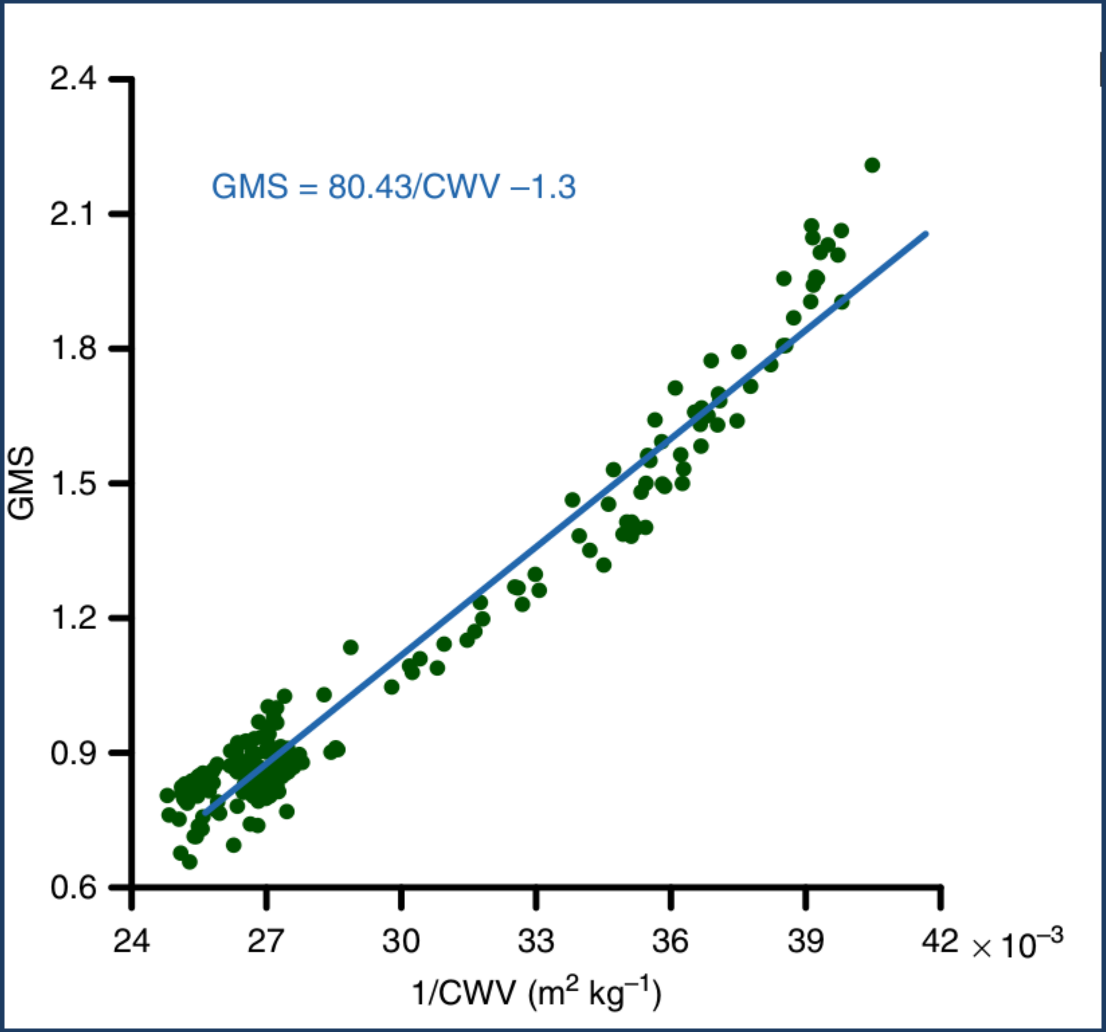
(*Neelin & Held 1987; Raymond 2009*)

$$P - E = \frac{Q_{div}}{GMS}$$

- Q_{div} → **Net energy flux into atmosphere**
- GMS → **Gross Moist Stability**

$$GMS = -\frac{\int_{P_B}^{P_T} \vec{U}.\nabla m + \omega \frac{\partial m}{\partial p}\, dp}{L_v \int_{P_B}^{P_T} \vec{U}.\nabla q + \omega \frac{\partial q}{\partial p}\, dp}$$

GMS IS A UNIQUE FUNCTION OF WATER VAPOR

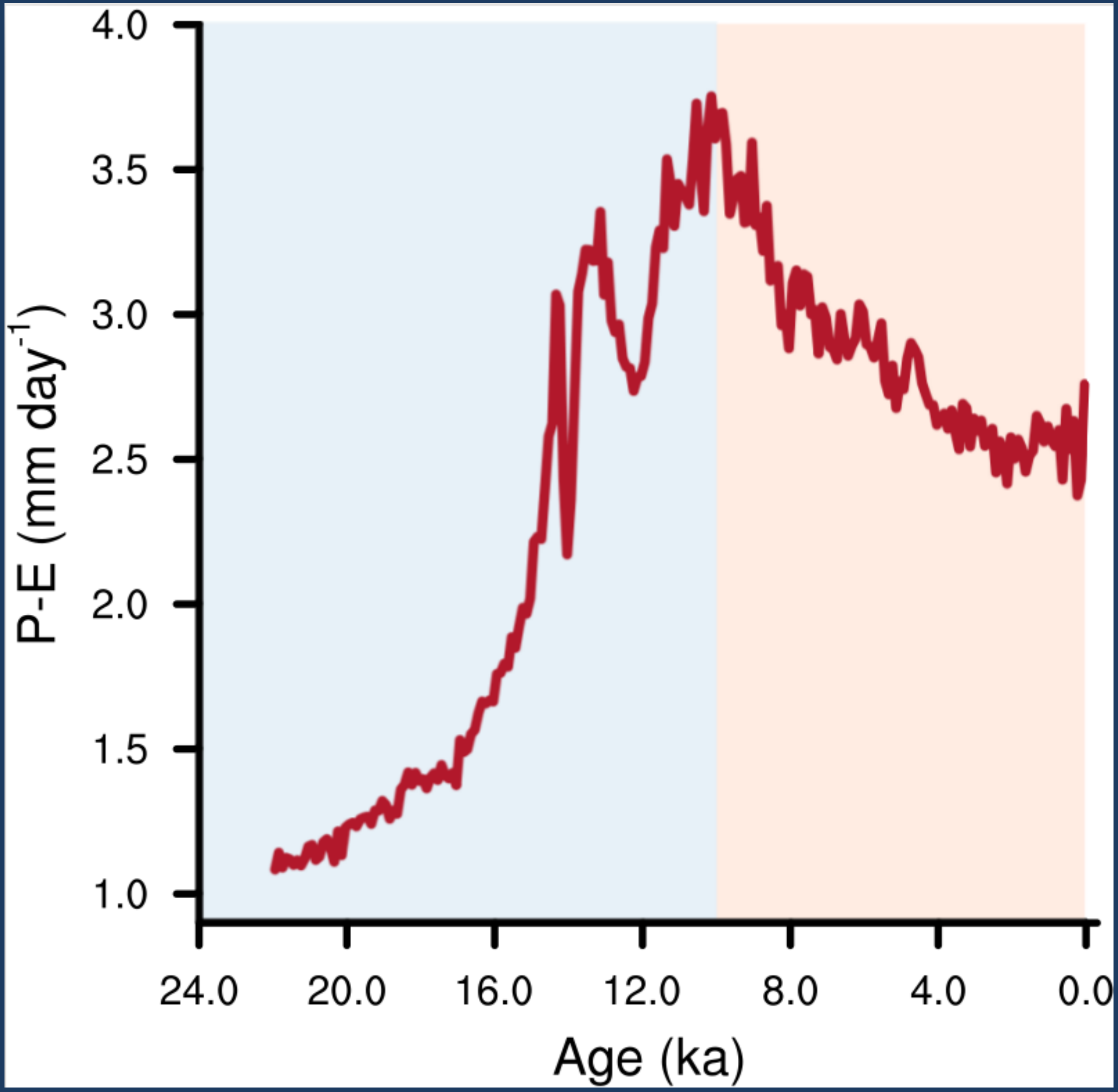


$$P - E = \frac{Q_{div}}{GMS}$$

$$P - E = \frac{Q_{div}}{80.4/_{CWV} - 1.3}$$

Jalihal et al. (2019) Nat. Comm.

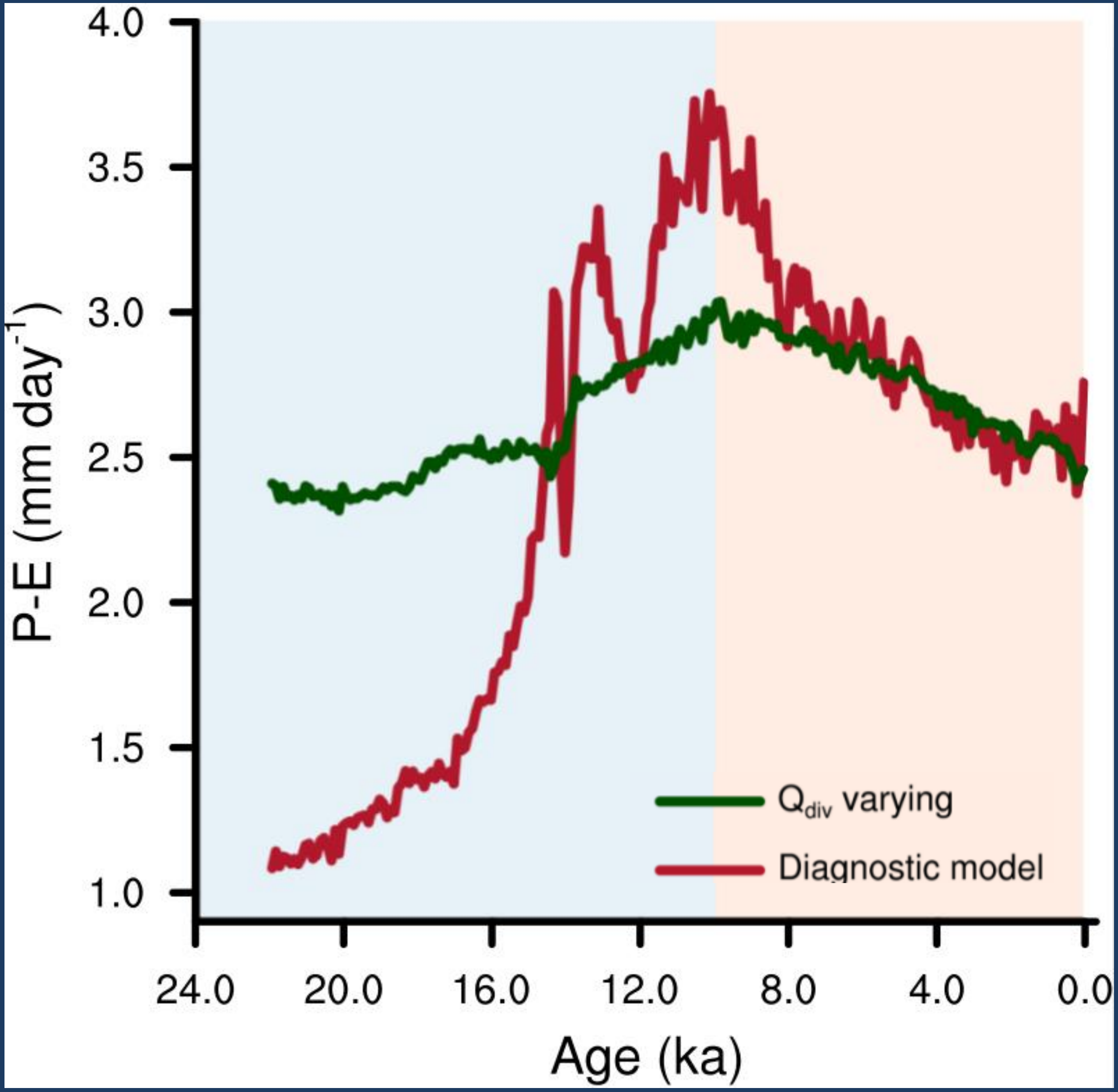
(P-E) OVER THE LAST 22,000 YRS



$$P - E = \frac{Q_{div}}{80.4/_{CWV} - 1.3}$$

Jalihal et al. (2019) Nat. Comm.

Q_{DIV} DRIVES (P-E) DURING HOLOCENE

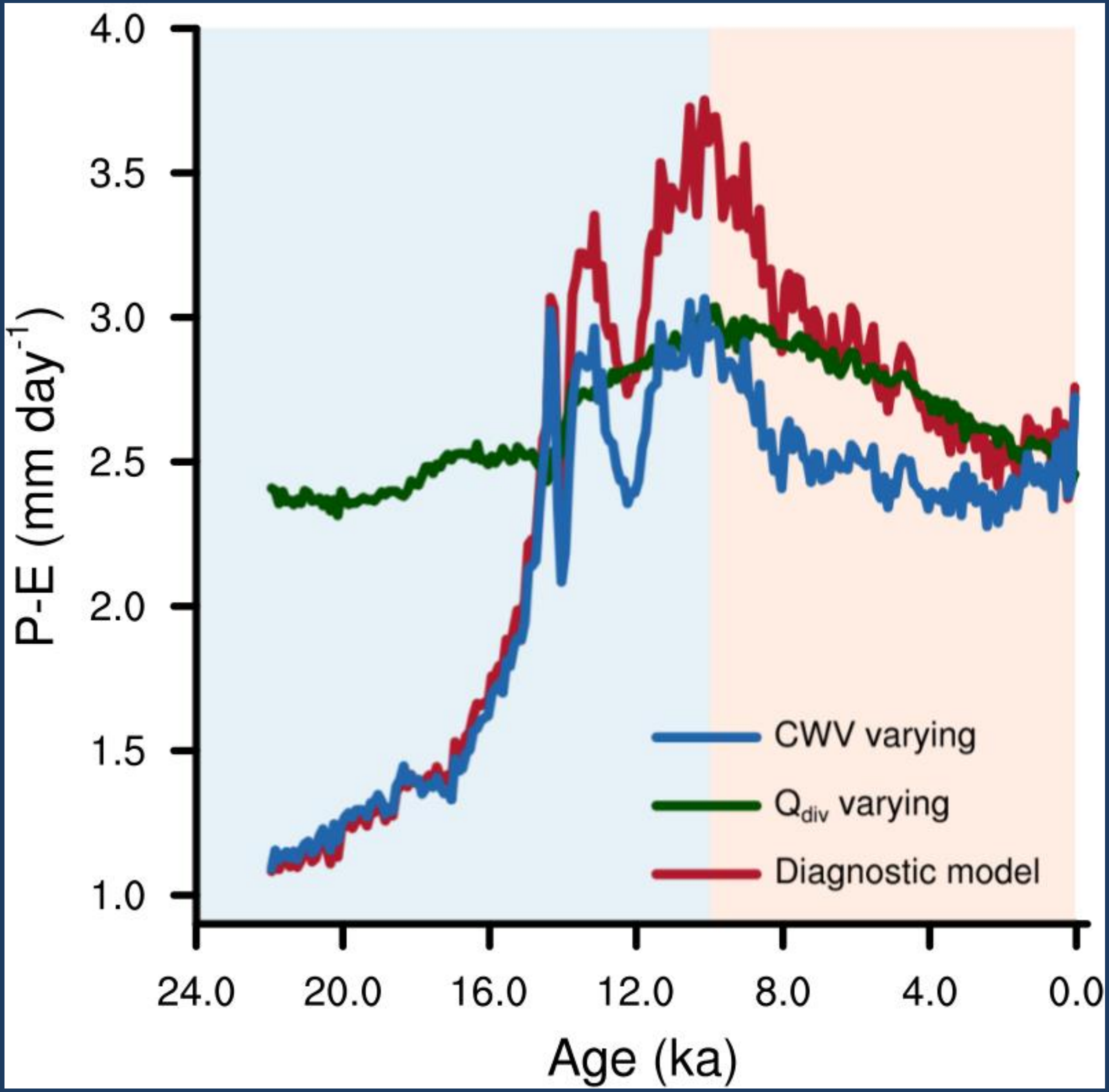


$$P - E = \frac{Q_{div}}{80.4/_{CWV} - 1.3}$$

CWV fixed at pre-industrial values.

Jalihal et al. (2019) Nat. Comm.

WATER VAPOR PLAYS CRUCIAL ROLE DURING DEGLACIAL

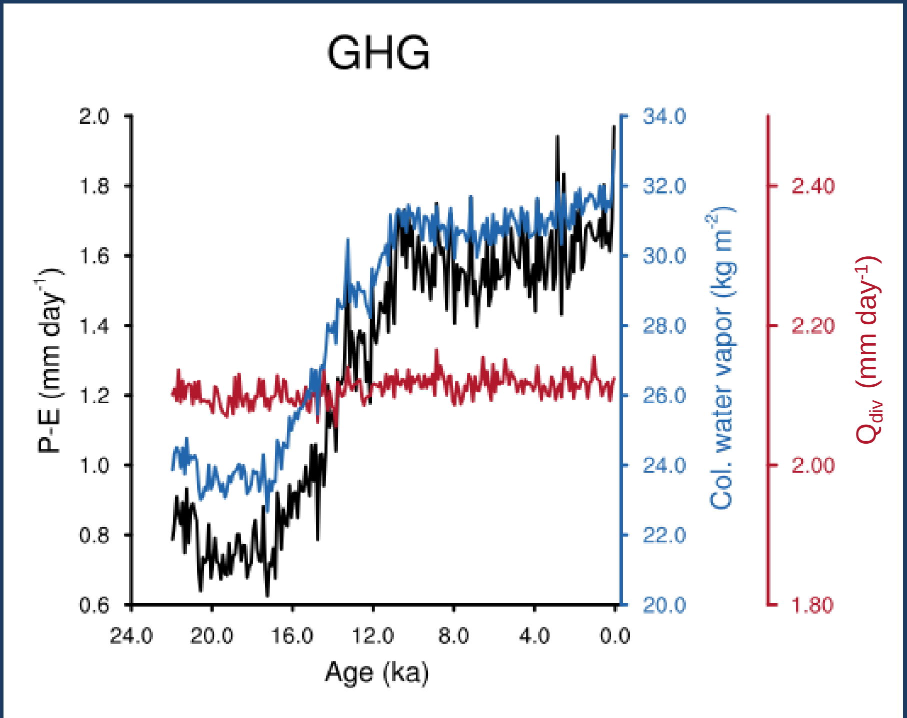


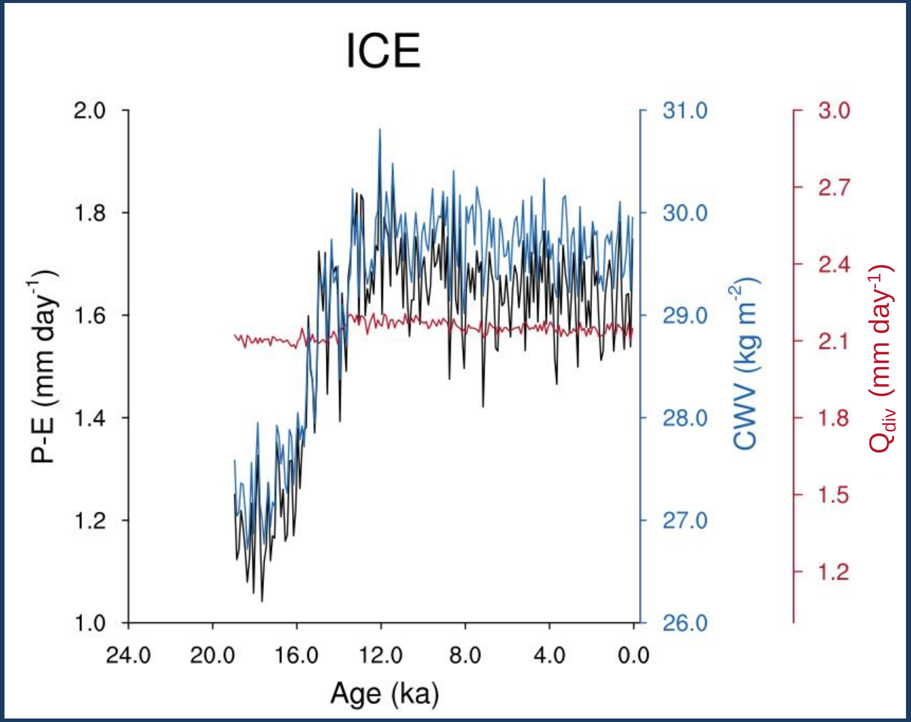
$$P - E = \frac{Q_{div}}{80.4/CWV - 1.3}$$

Q_{div} fixed at pre-industrial values.

Jalihal et al. (2019) Nat. Comm.

GREENHOUSE GASES AND ICE SHEETS AFFECT GMS ALONE



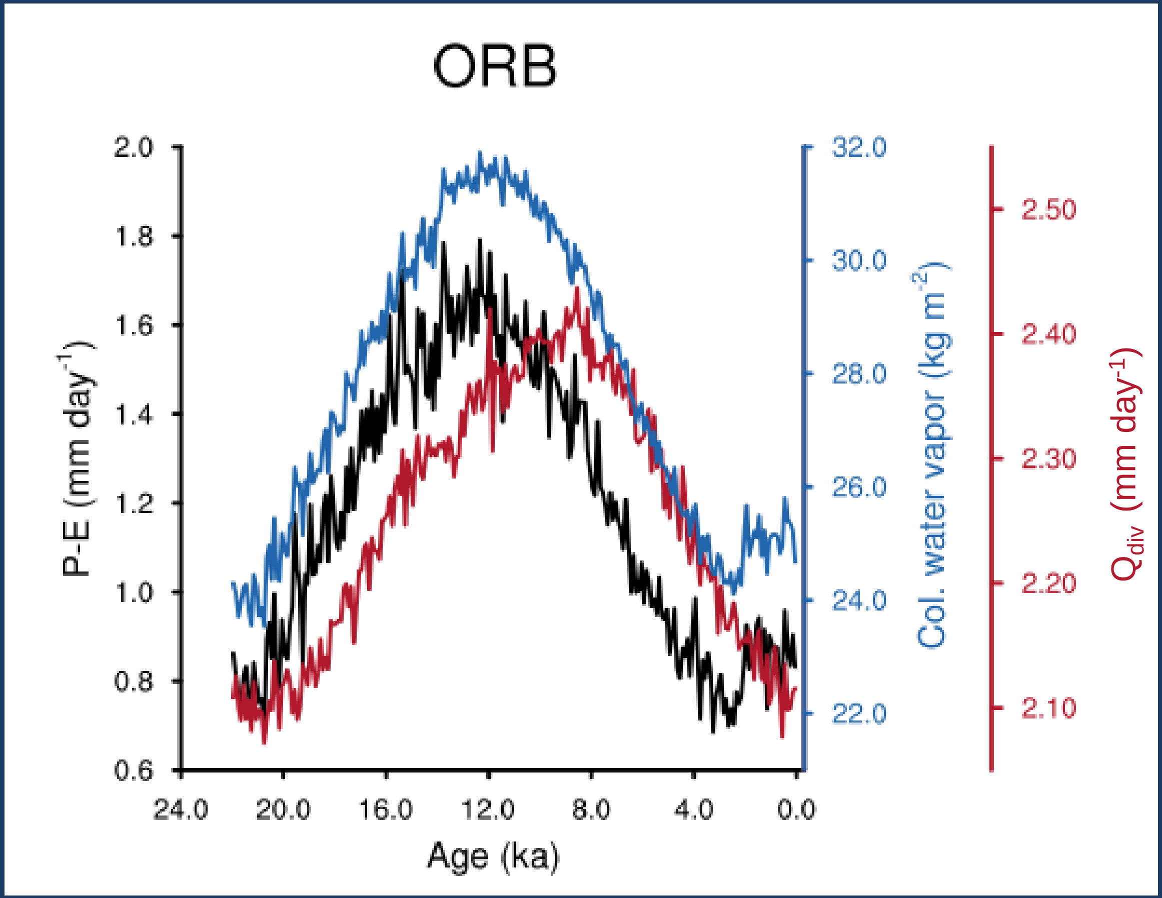


$$P - E = \frac{Q_{div}}{80.4/_{CWV} - 1.3}$$

GHG and ice sheets do not influence Q_{div}

Jalihal et al. (2019) Nat. Comm.

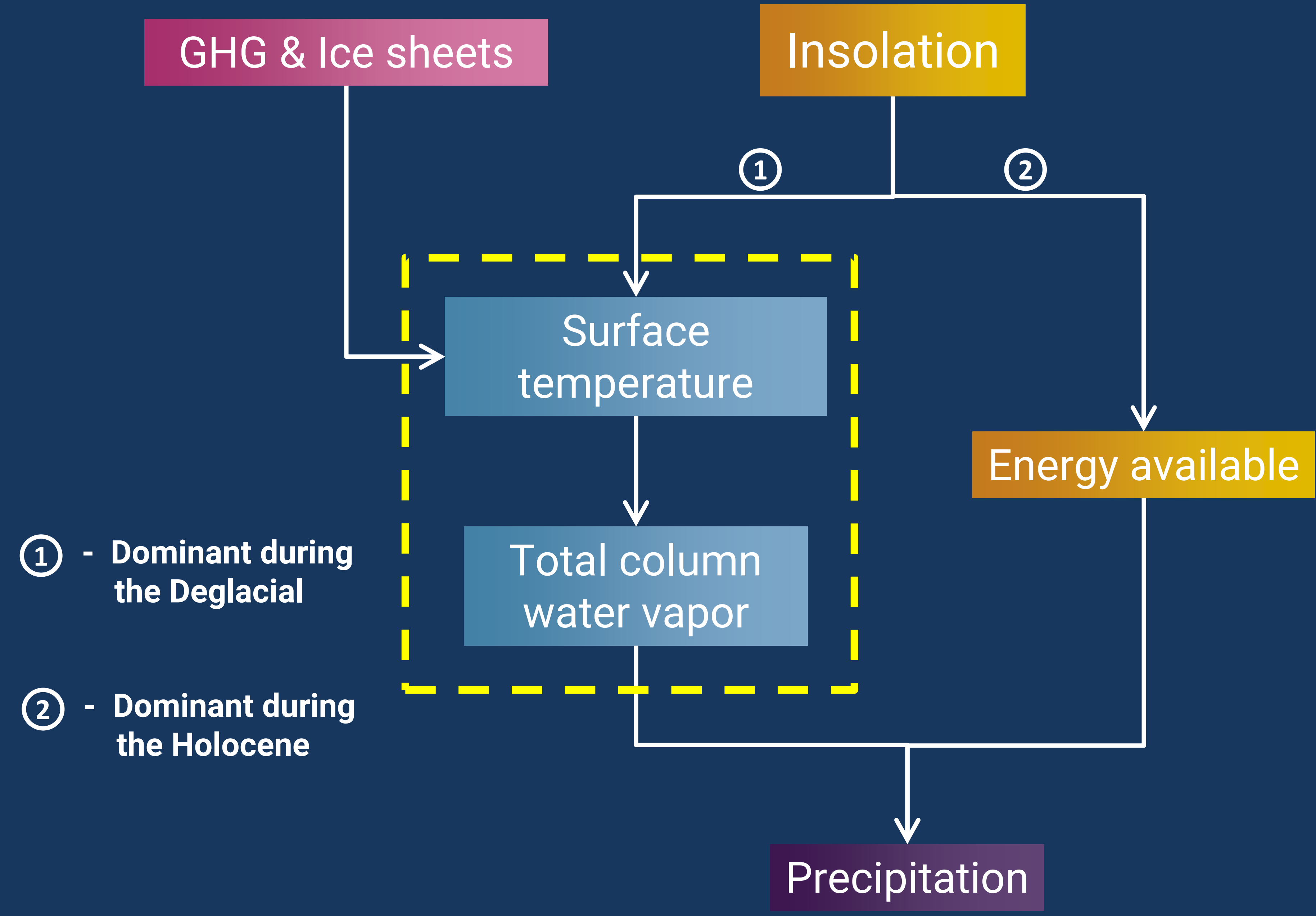
ORBITAL FORCING AFFECTS BOTH GMS AND Q_{DIV}



$$P - E = \frac{Q_{div}}{{80.4}/{CWV} - 1.3}$$

Even though both Qdiv and GMS are influenced,
GMS is dominant, when boundary conditions are that of LGM.

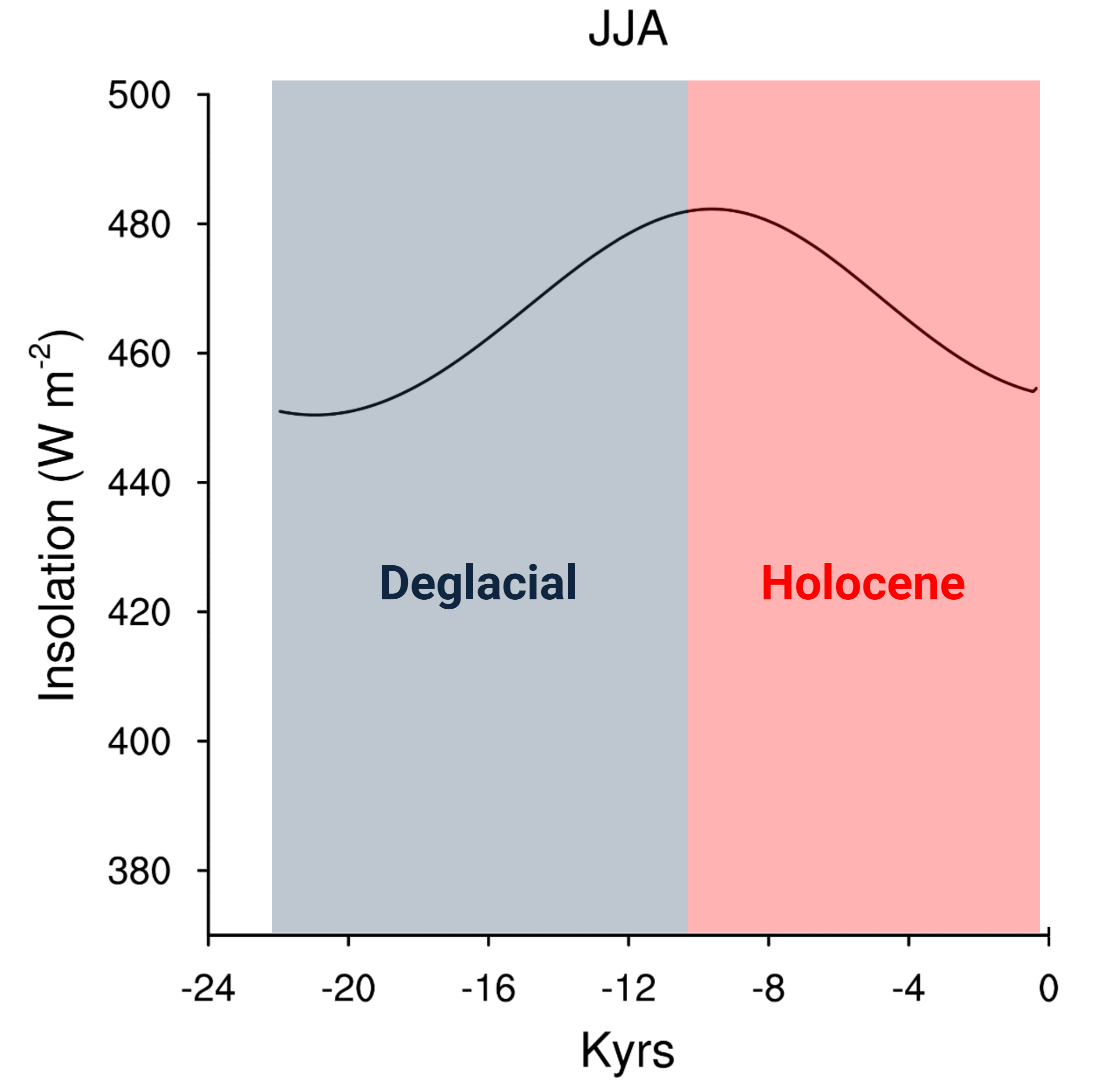
Jalihal et al. (2019) Nat. Comm.



Jalihal et al. (2019) Nat. Comm.

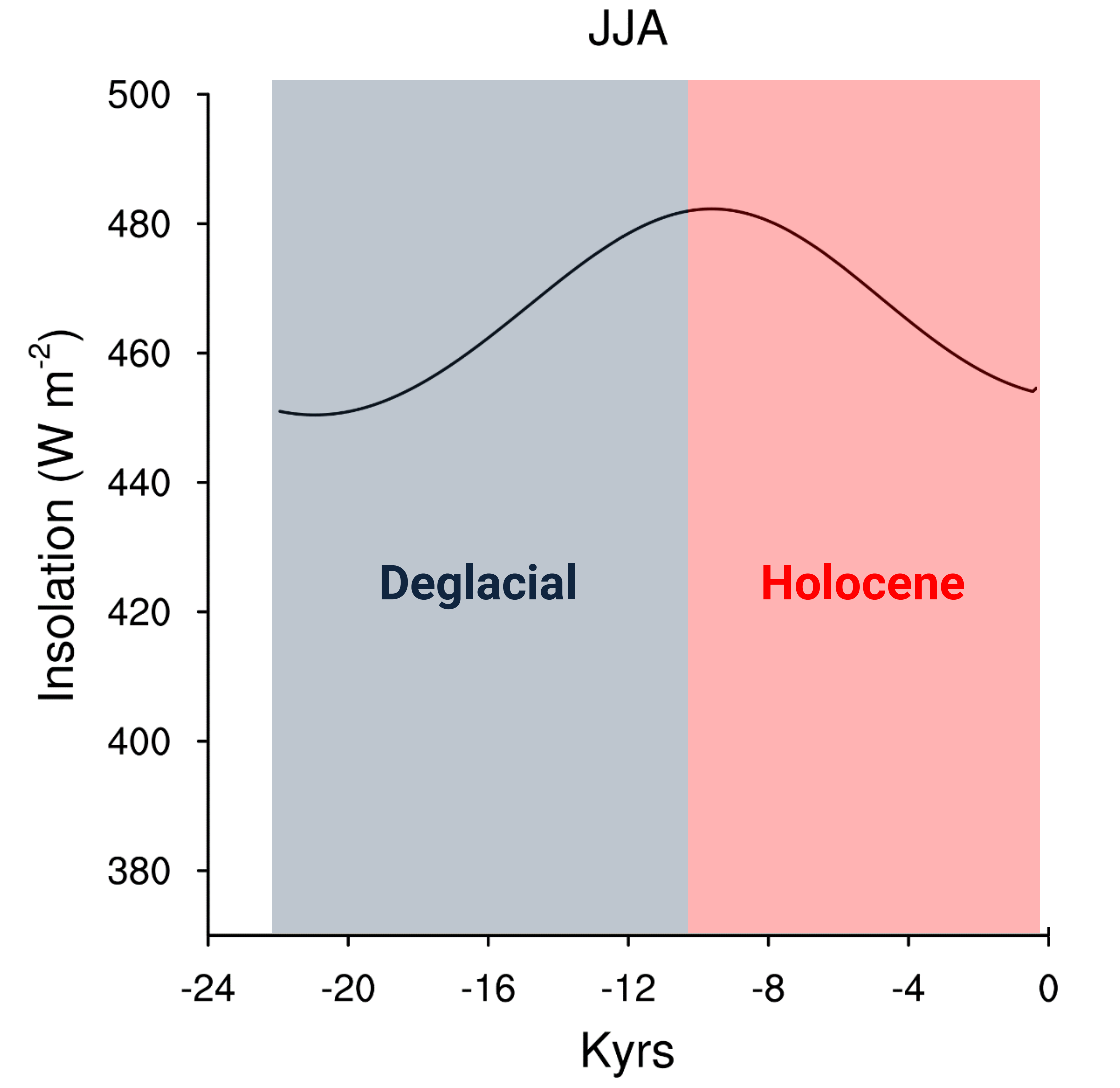
Long version

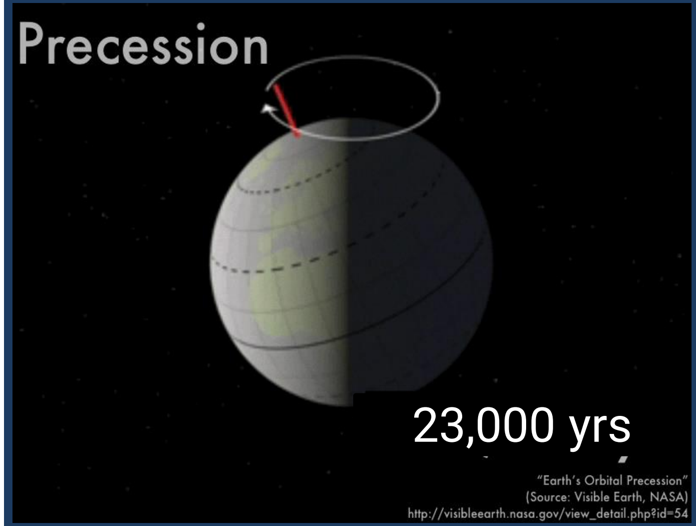
INSOLATION OVER LAST 22,000 YRS



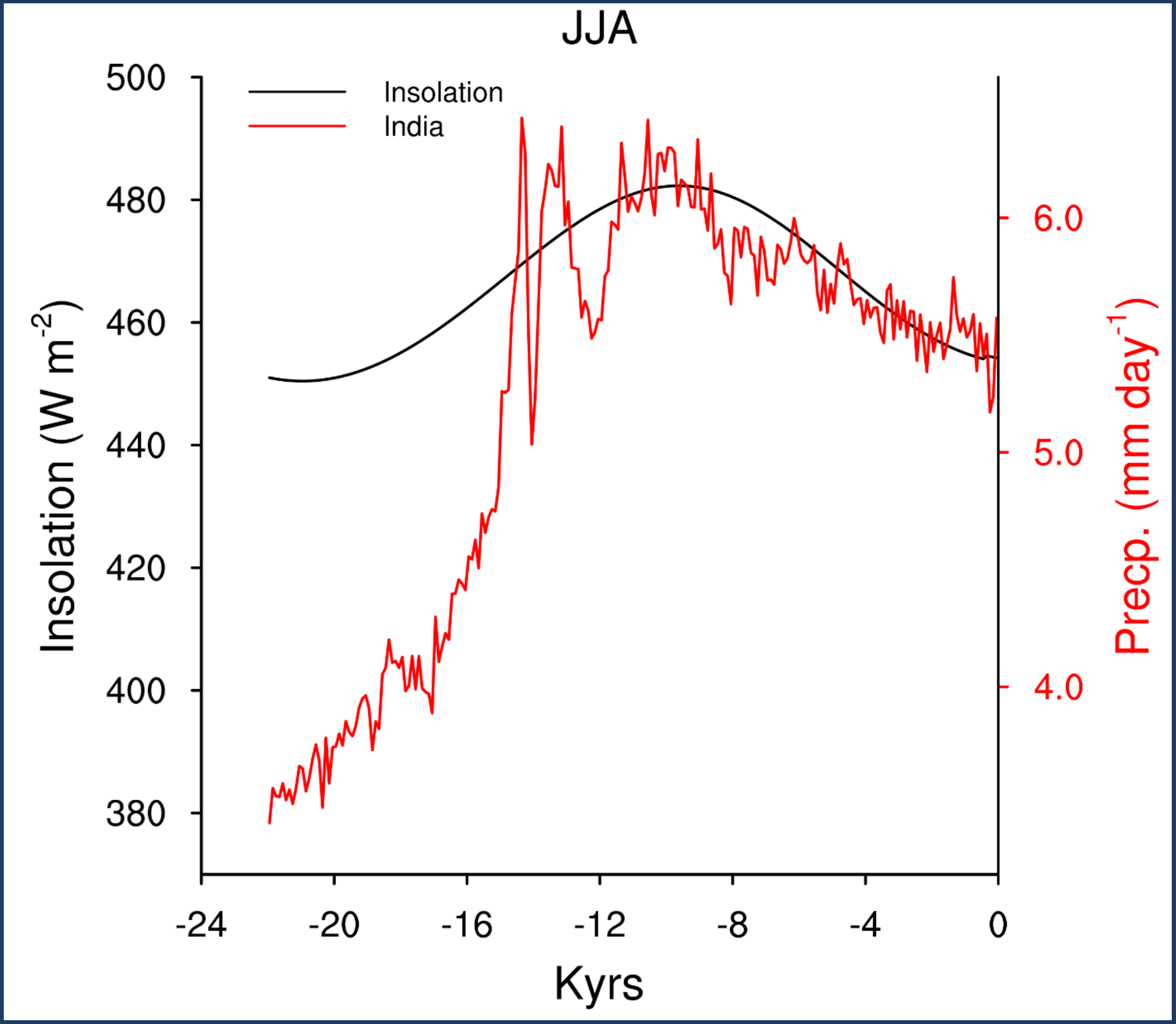
Summer insolation over India

THIS VARIATION IS DUE TO PRECESSION OF EARTH





DIFFERENT SENSITIVITY OF MONSOON TO INSOLATION



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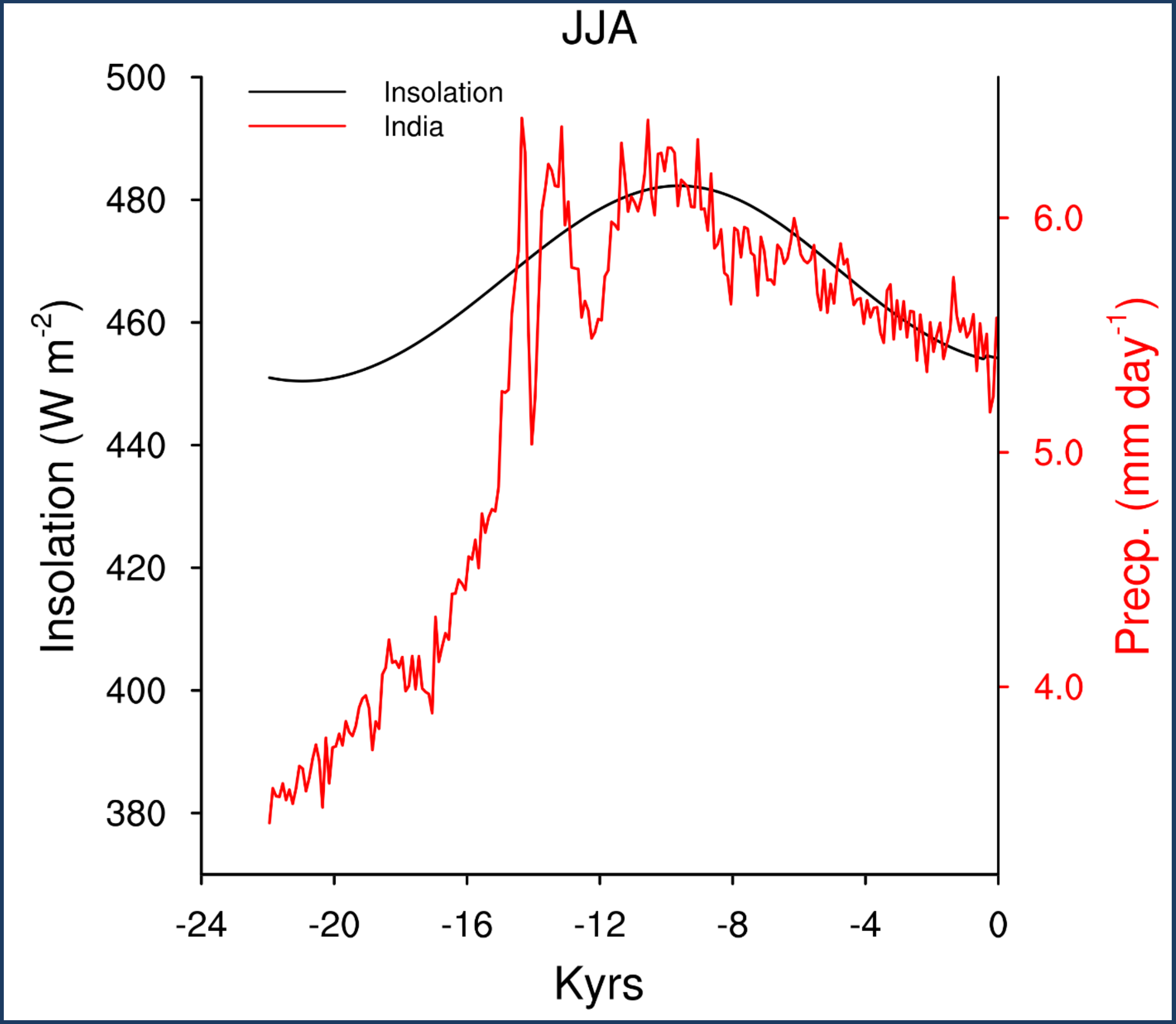

Deglacial forcings:
Insolation
greenhouse gases
ice sheets

Holocene forcings:
Mainly insolation

OBJECTIVE

Identify the feedbacks.

Quantify the role of forcings and feedbacks.

Method

ENERGETICS FRAMEWORK

Based on the equations for **conservation of moisture & Moist Static Energy.**

$$\int_{Pt}^{Pb} \left(\vec{U}.\nabla m + \omega \frac{\partial m}{\partial p}\right) dp = g[Fb - Ft]$$

$$\int_{Pt}^{Pb} \left(\vec{U}.\nabla q + \omega \frac{\partial q}{\partial p}\right) dp = g[E - P]$$

m - Moist Static Energy;

($m = C_p*T + g*Z + Lv*q$)

Fb - Bottom Fluxes

Ft - Fluxes at Top of Atm.

u - x component of velocity

q - Specific Humidity (kg/Kg)

ω - Vertical velocity (Pa/s)

Pb - Surface Pressure

Pt - Top Pressure

v - y component of velocity

ENERGETICS FRAMEWORK

(*Neelin & Held 1987; Raymond 2009*)

$$\boldsymbol{P - E = \frac{Q_{div}}{GMS}}$$

$$\boldsymbol{GMS} = -\frac{\int_{P_B}^{P_T} \vec{\boldsymbol{U}}.\boldsymbol{\nabla m} + \boldsymbol{\omega}\frac{\partial \boldsymbol{m}}{\partial p}\, dp}{L_v \int_{P_B}^{P_T} \vec{\boldsymbol{U}}.\boldsymbol{\nabla q} + \boldsymbol{\omega}\frac{\partial \boldsymbol{q}}{\partial p}\, dp}$$

ENERGETICS FRAMEWORK

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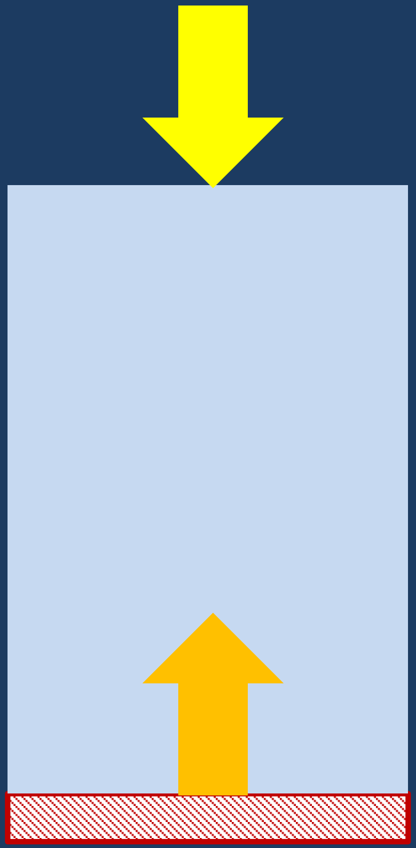


Net energy flux into atmosphere (top + bottom)

Over land net surface energy fluxes are small.

$$GMS = -\frac{\int_{P_B}^{P_T} \vec{U}.\nabla m + \omega \frac{\partial m}{\partial p}\, dp}{L_v \int_{P_B}^{P_T} \vec{U}.\nabla q + \omega \frac{\partial q}{\partial p}\, dp}$$

ENERGETICS FRAMEWORK

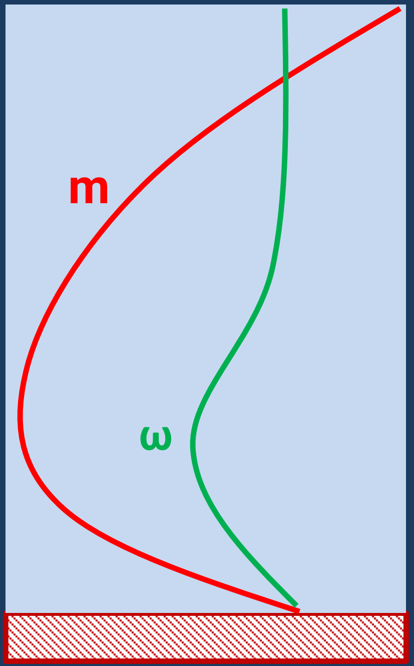
(*Neelin & Held 1987; Raymond 2009*)

$$P - E = \frac{Q_{div}}{GMS}$$

Gross Moist Stability.

Primarily depends on vertical profile of m and ω

$$GMS = -\frac{\int_{P_B}^{P_T} \vec{U}.\nabla m + \omega \frac{\partial m}{\partial p}\, dp}{L_v \int_{P_B}^{P_T} \vec{U}.\nabla q + \omega \frac{\partial q}{\partial p}\, dp}$$



ENERGETICS FRAMEWORK

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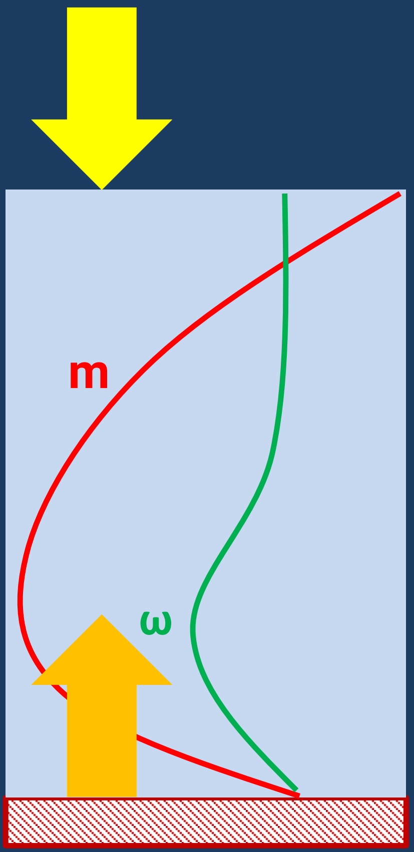

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A CLOSER LOOK AT Q_{DIV}

$$Q_{div} = \underbrace{TOA\_Net\_SW - TOA\_OLR}_{Q_{net}} + SFC\_RAD + SHF + LHF$$

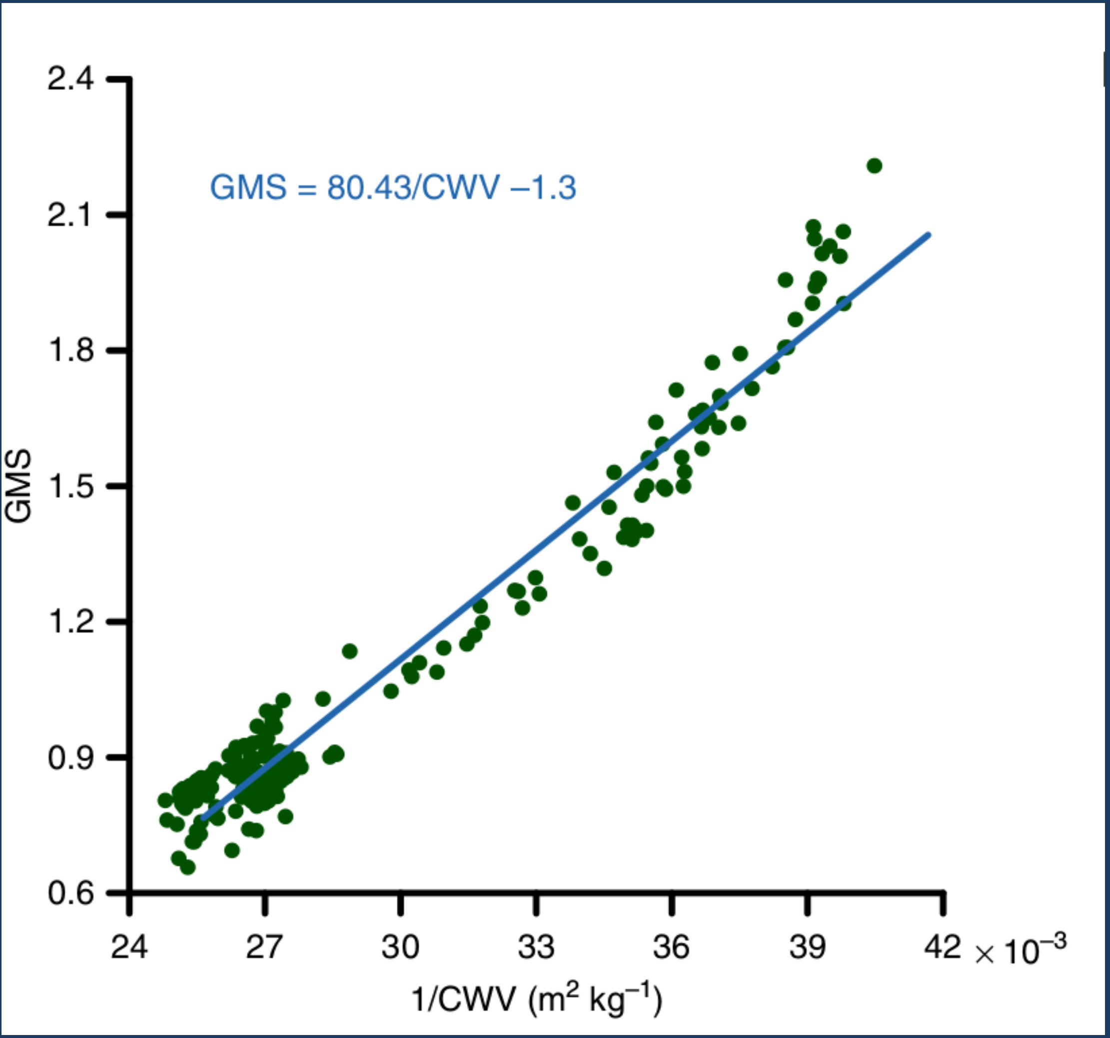
TOA_Net_SW- Net Short Wave at Top of Atm

TOA_OLR - Net Outgoing Longwave Radiation

Q_{div} over land is influenced by insolation and cloud radiative feedback.

Results

GMS IS A UNIQUE FUNCTION OF WATER VAPOR



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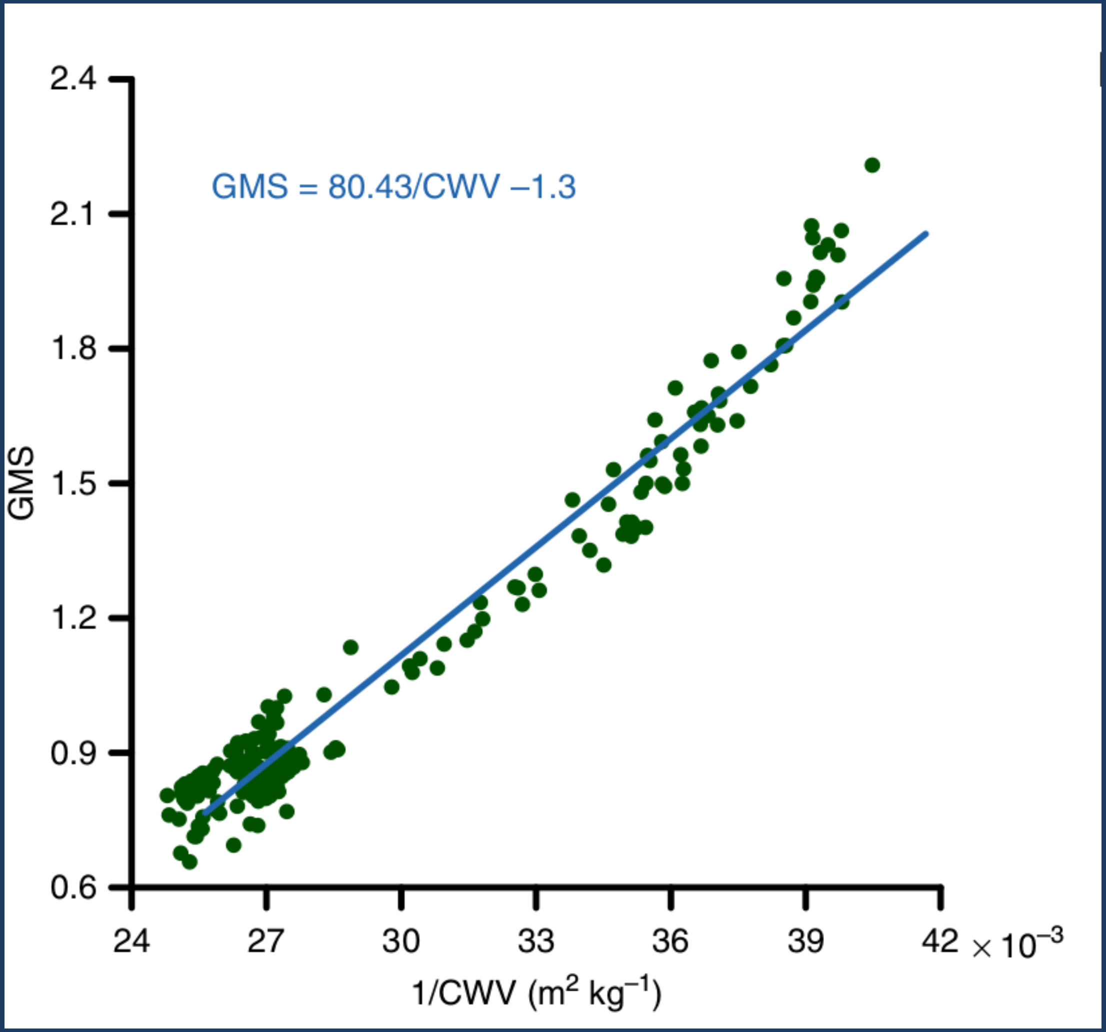
GMS IS A UNIQUE FUNCTION OF WATER VAPOR



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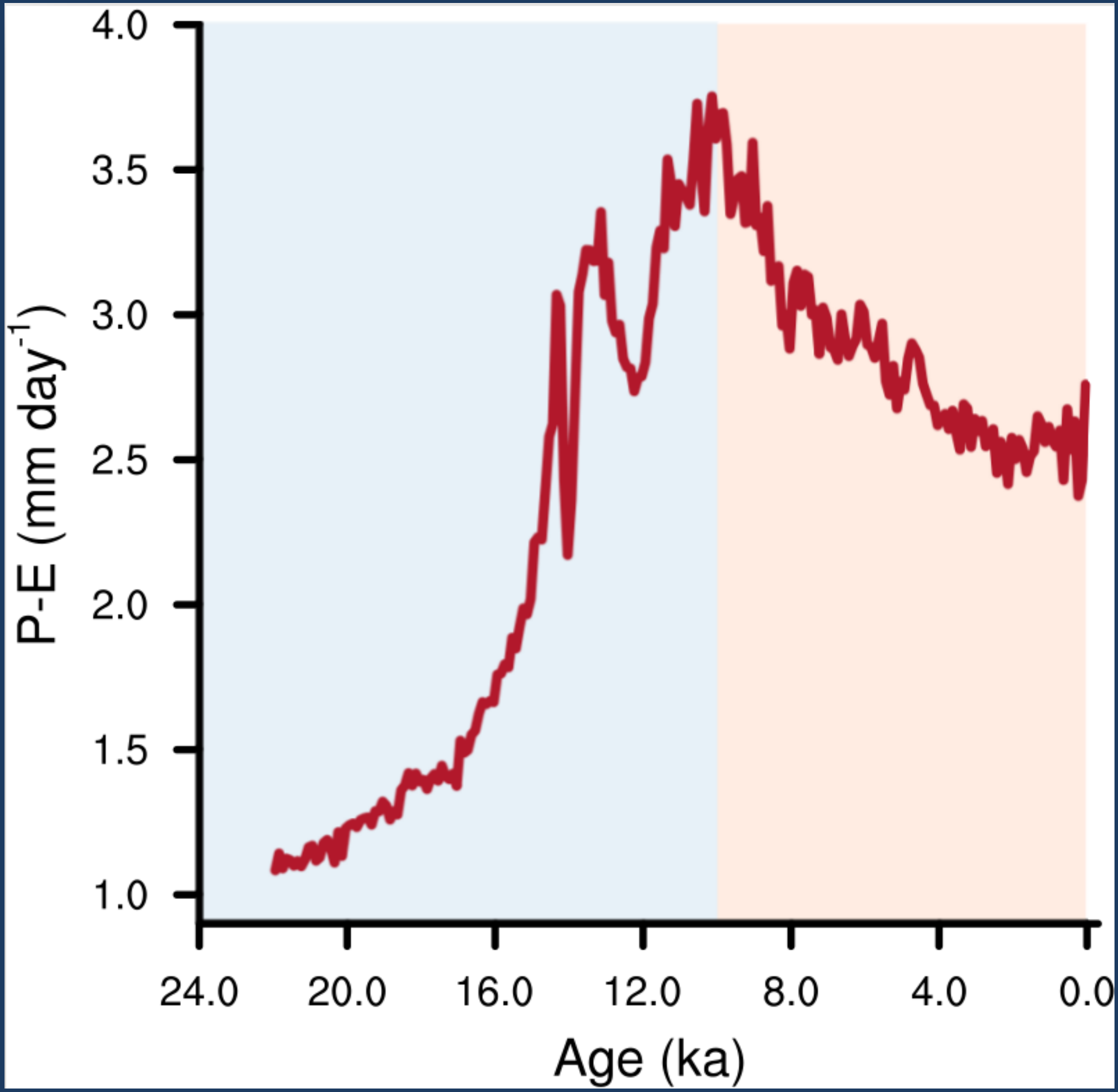
(P-E) OVER THE LAST 22,000 YRS



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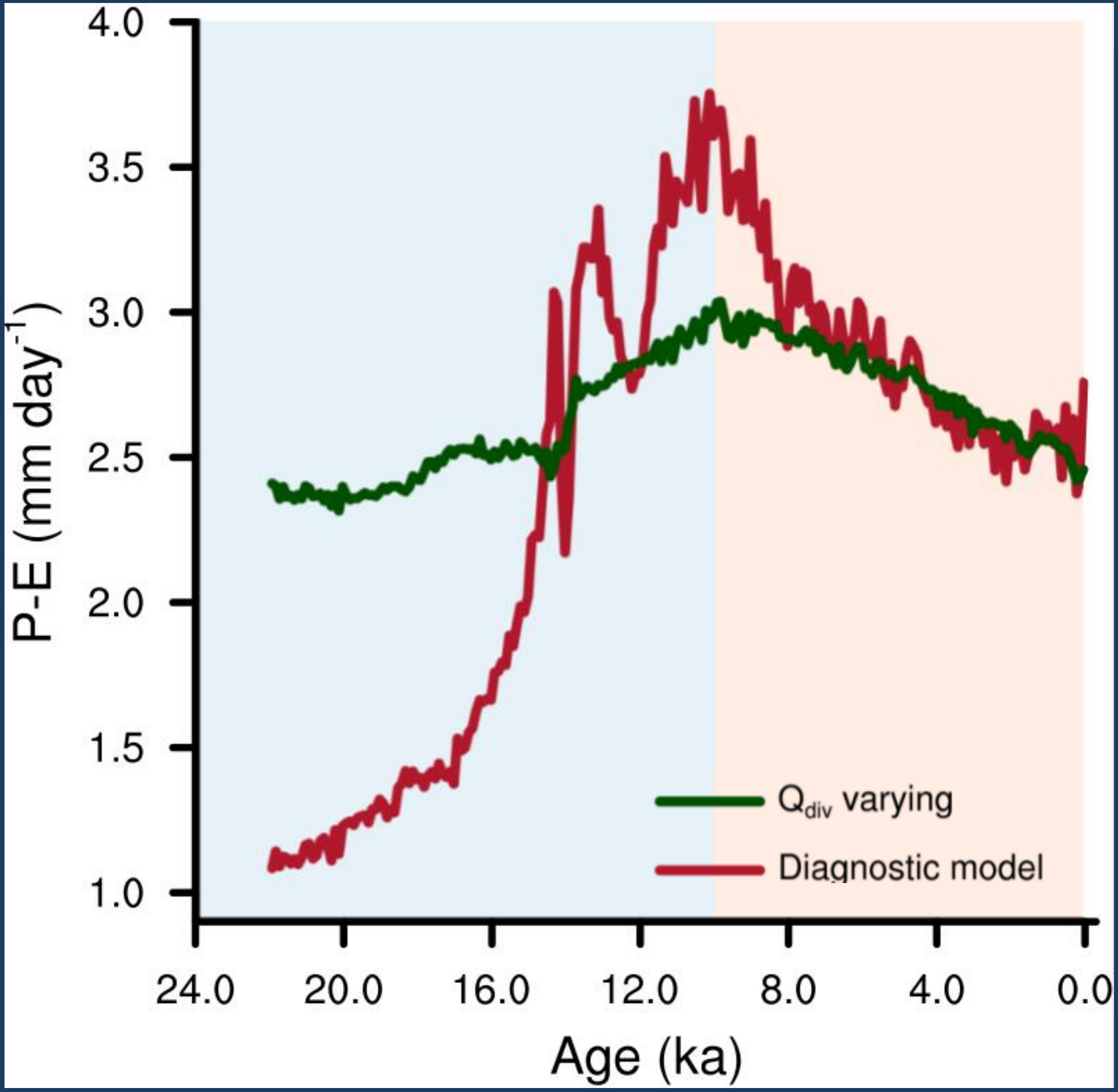
Q_{DIV} DRIVES (P-E) DURING HOLOCENE



$$P - E = \frac{Q_{div}}{80.4/_{CWV} - 1.3}$$

CWV fixed at pre-industrial values.

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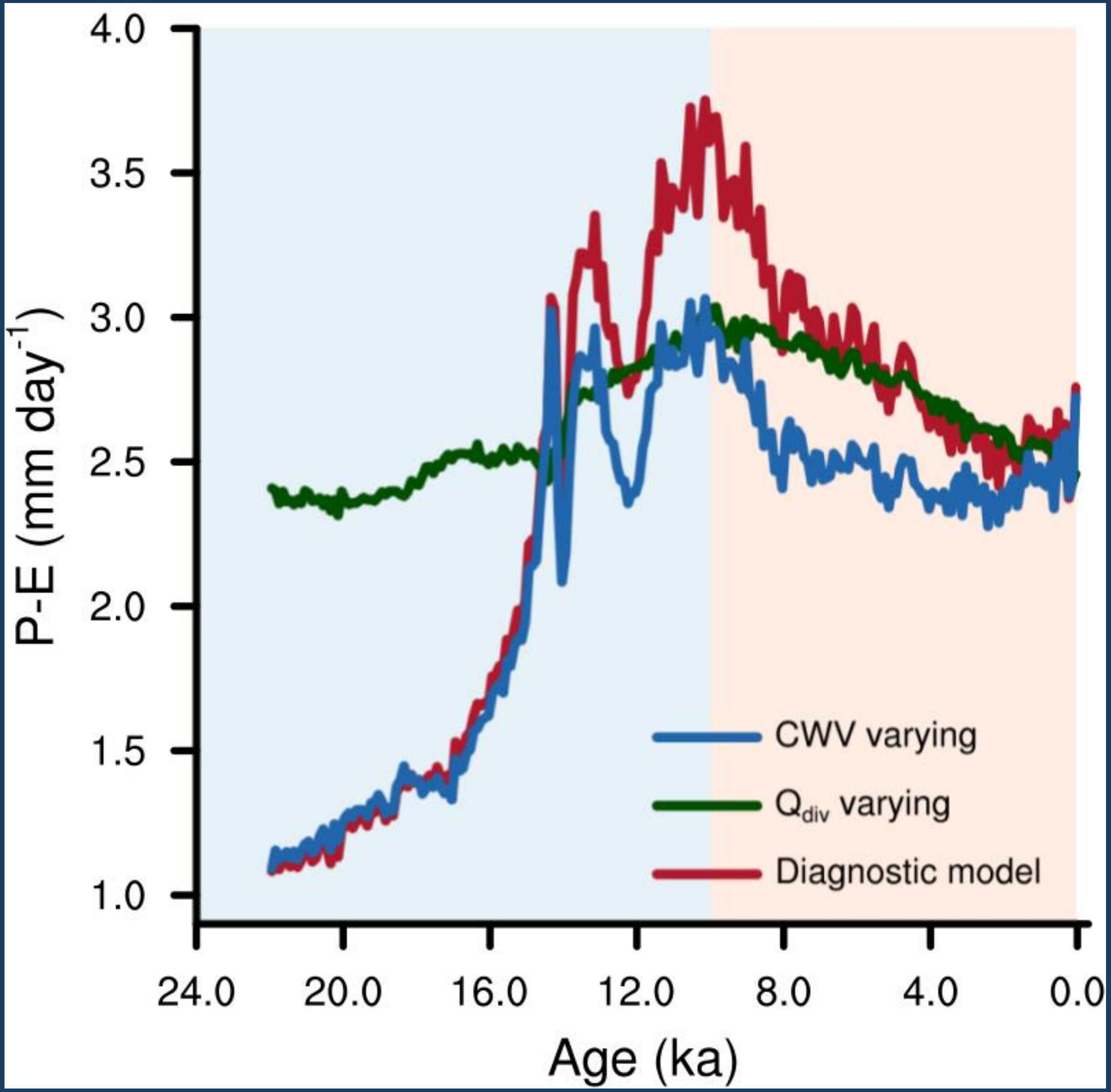
WATER VAPOR PLAYS CRUCIAL ROLE DURING DEGLACIAL



$$P - E = \frac{Q_{div}}{80.4/CWV - 1.3}$$

Q_{div} fixed at pre-industrial values.

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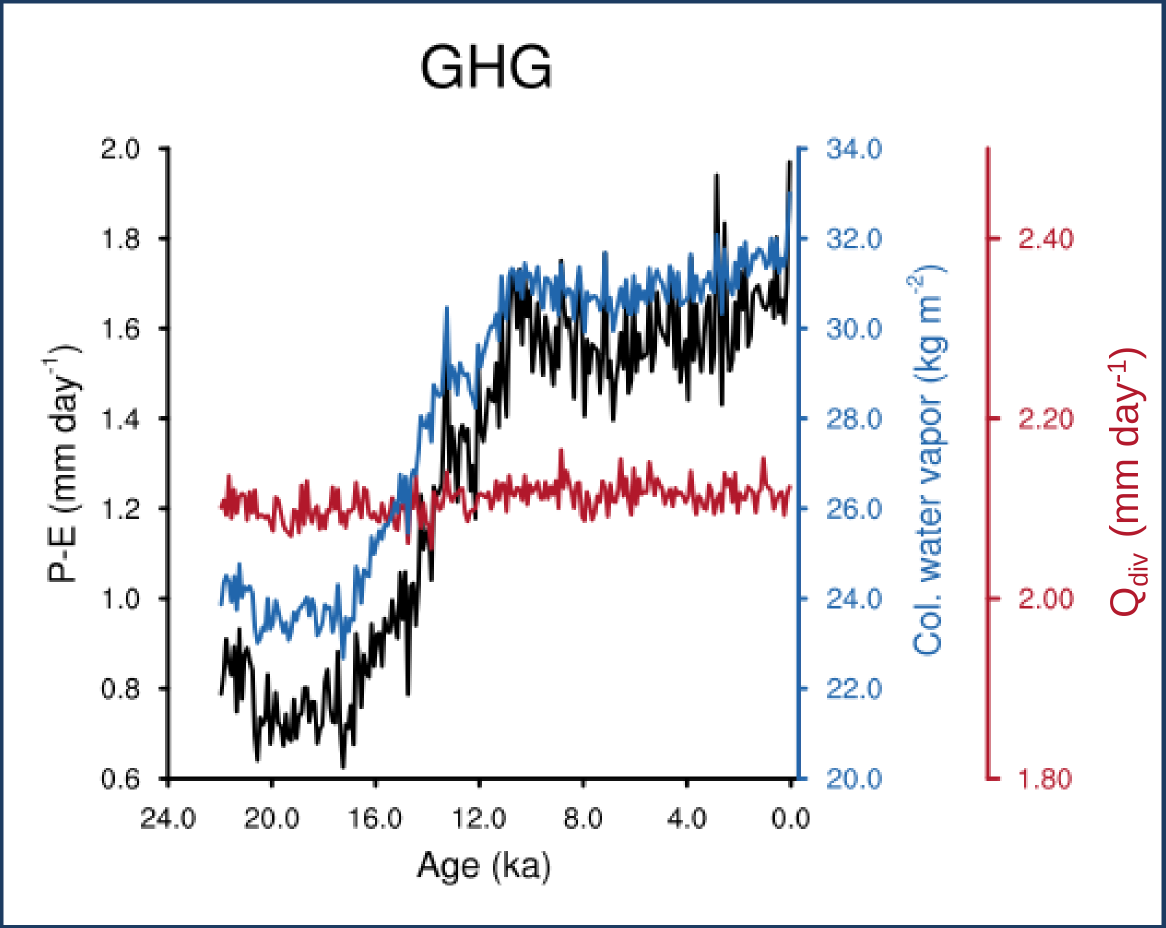
Role of different forcings

GREENHOUSE GASES AFFECT GMS ALONE



$$P - E = \frac{Q_{div}}{80.4/_{CWV} - 1.3}$$

GHG does not influence Q_{div}

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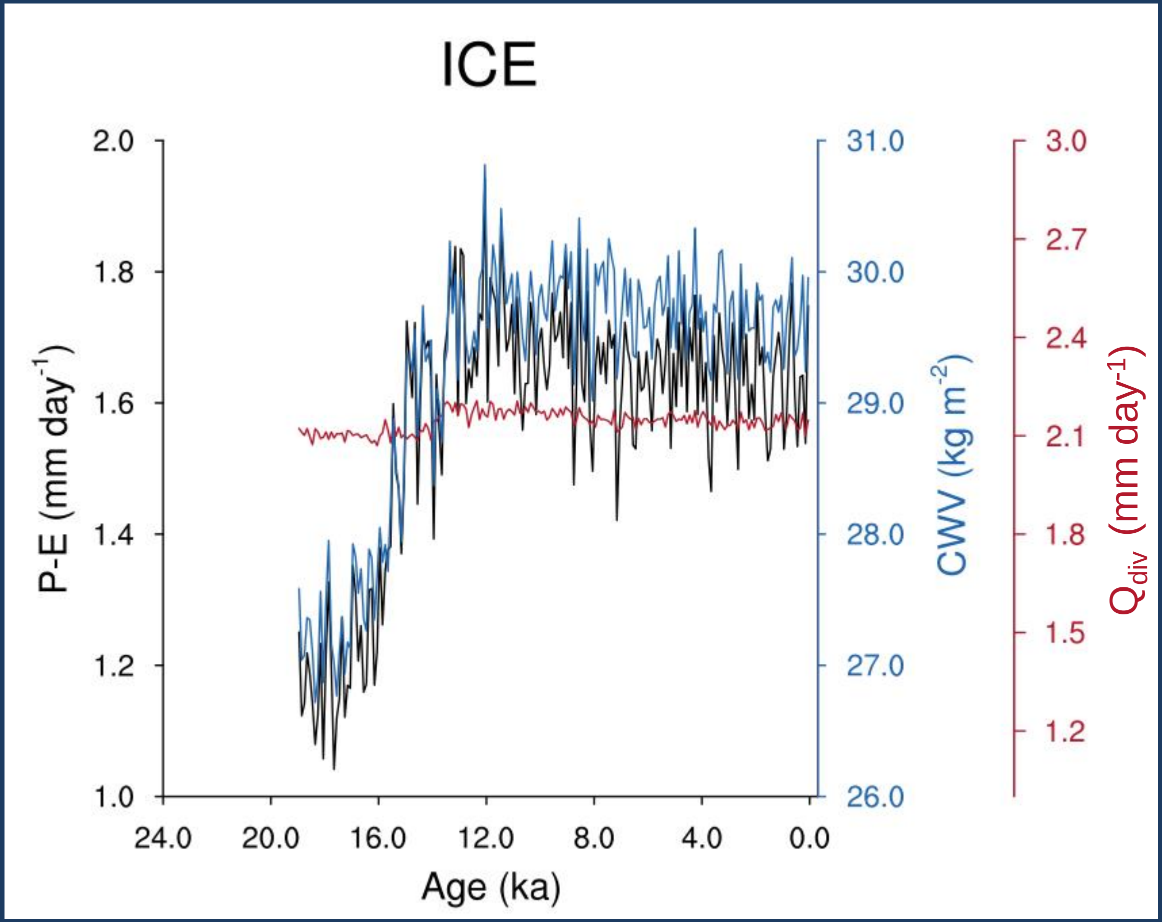
ICE SHEETS AFFECT GMS ALONE



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Ice sheets do not influence Q_{div}

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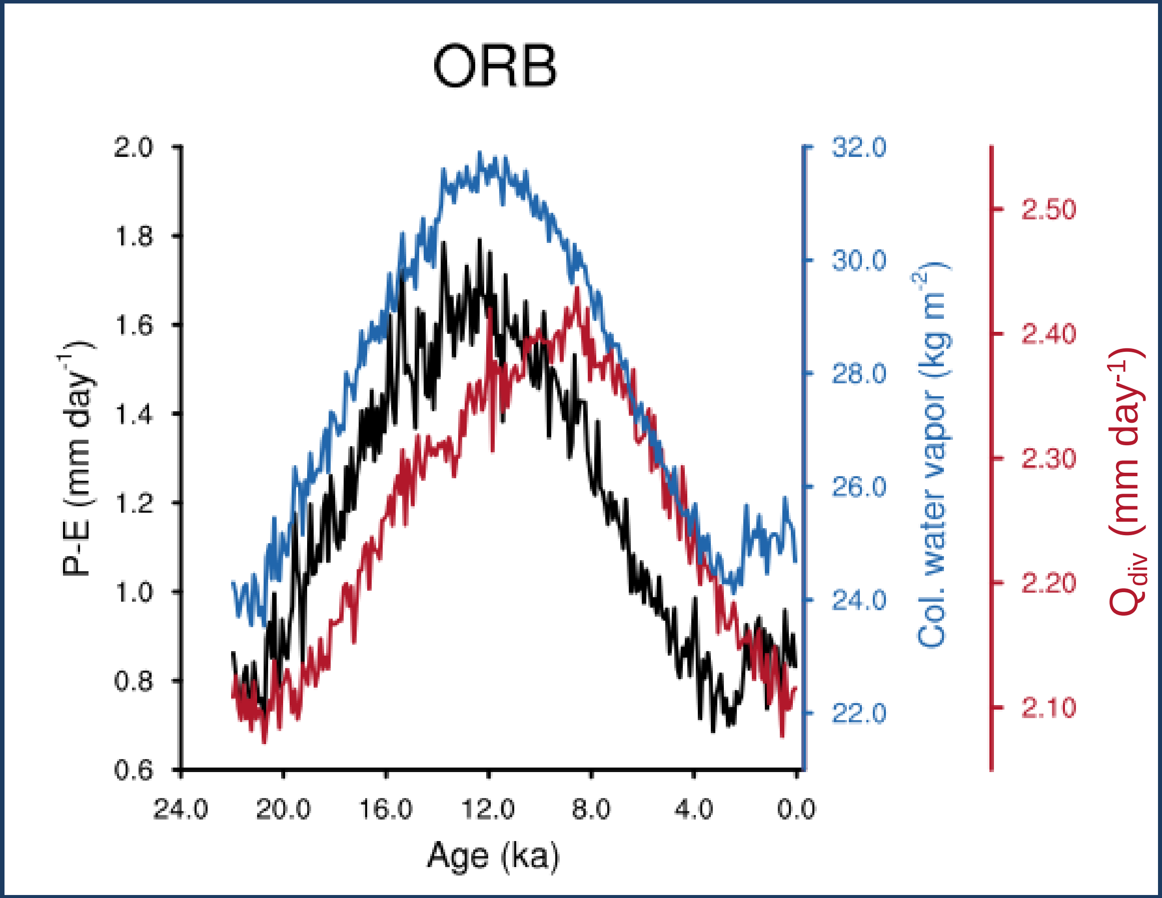
ORBITAL FORCING AFFECTS BOTH GMS AND Q_{DIV}

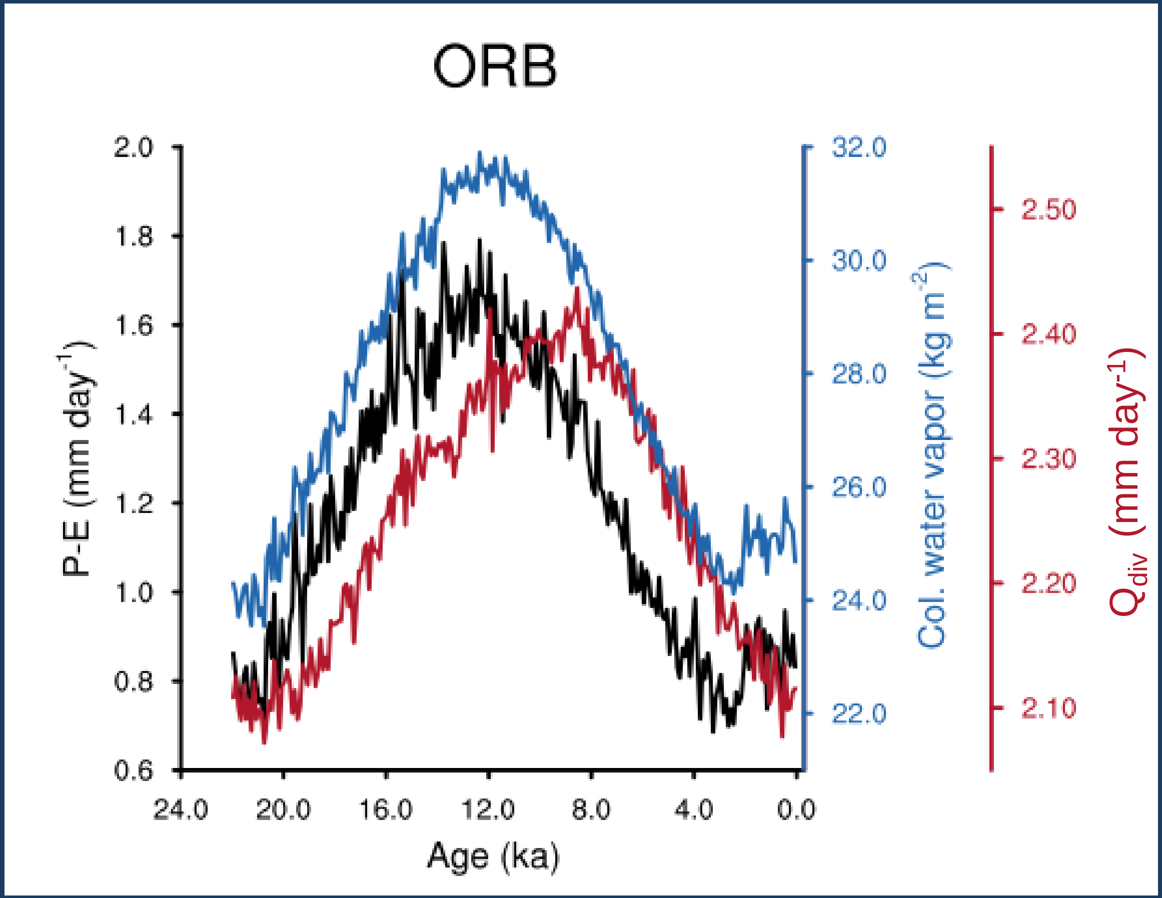


$$P - E = \frac{Q_{div}}{80.4/_{CWV} - 1.3}$$

Even though both Qdiv and GMS are influenced, GMS is dominant.

Jalihal et al. (2019) Nat. Comm.

ORBITAL FORCING WITH GLACIAL BOUNDARY CONDITIONS

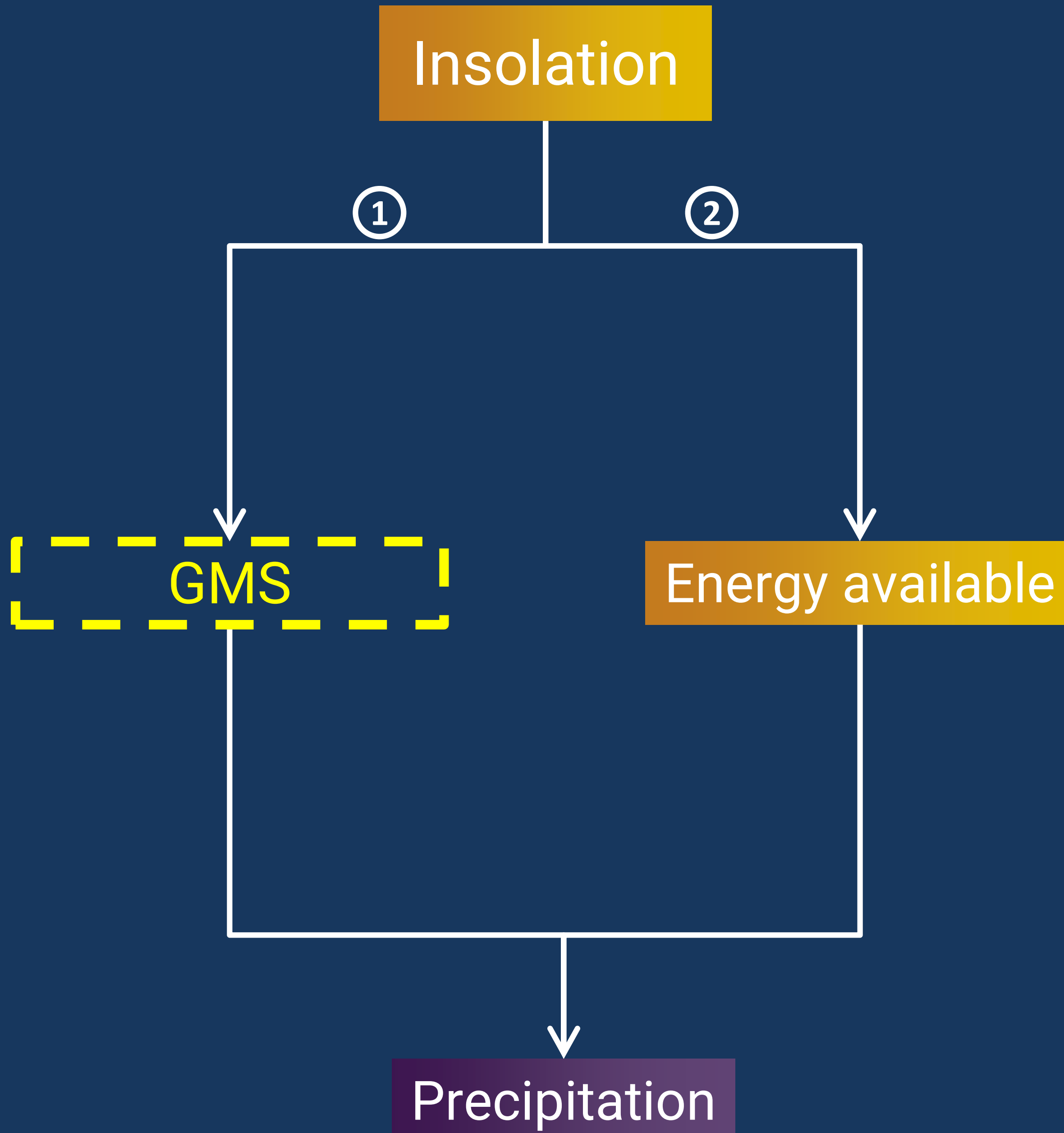


$$P - E = \frac{Q_{div}}{80.4/_{CWV} - 1.3}$$

ORB:
orbital parameters only. Constant LGM values for all other boundary conditions.

During cold periods, orbital forcing drives monsoon through GMS.

Jalihal et al. (2019) Nat. Comm.



① - **Dominant during the Deglacial**

② - **Dominant during the Holocene**

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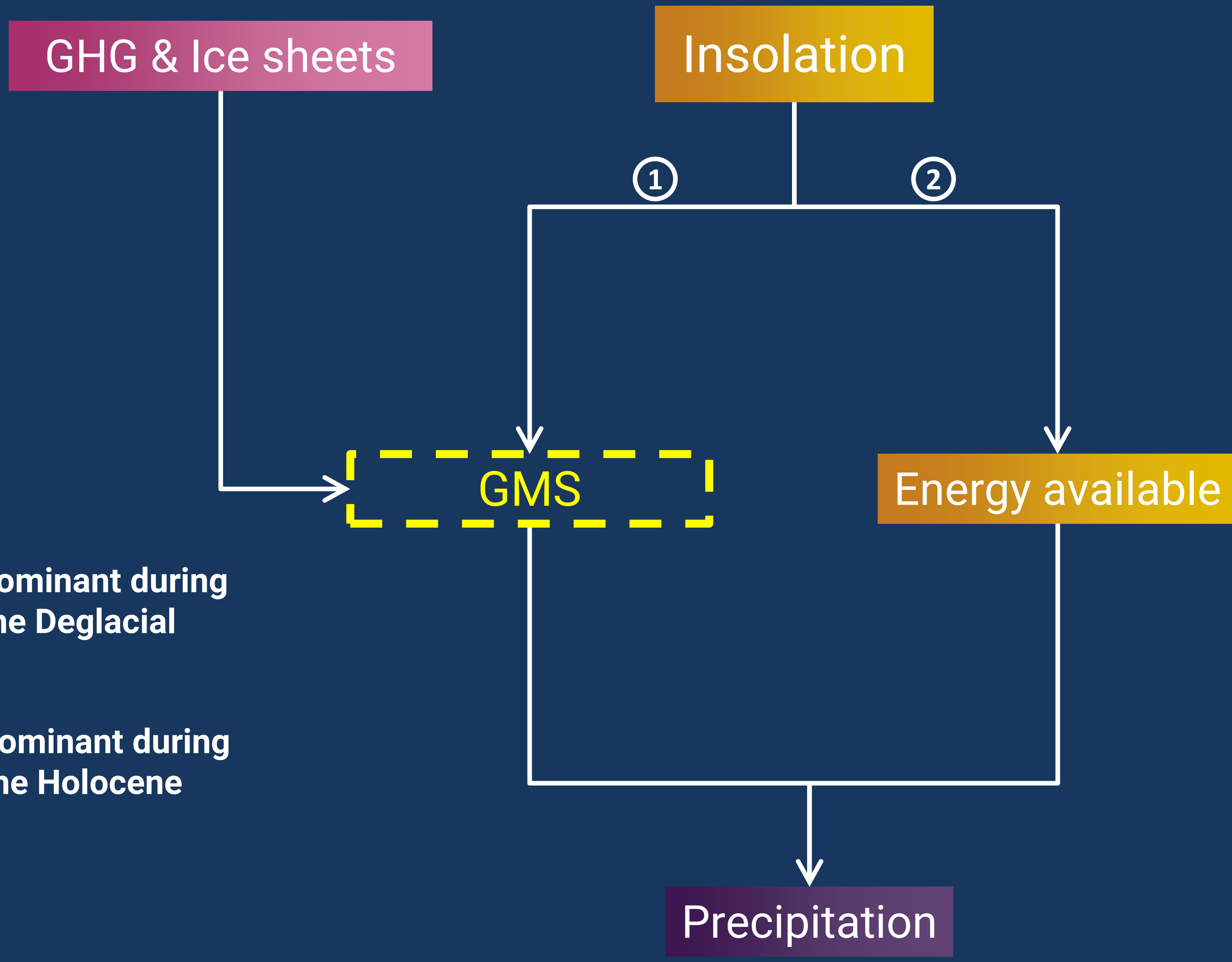

1 - **Dominant during the Deglacial**

2 - **Dominant during the Holocene**

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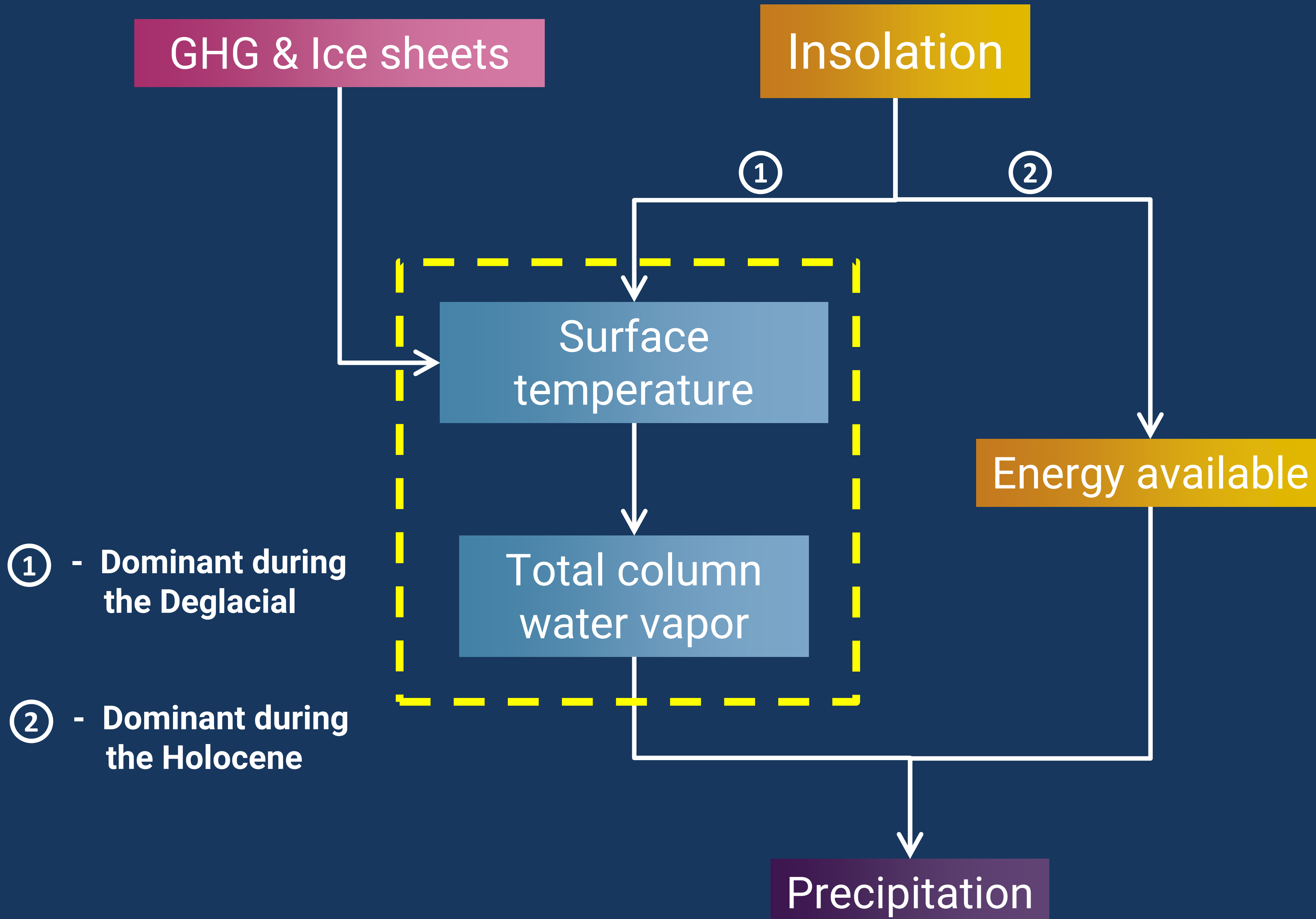


Jalihal et al. (2019) Nat. Comm.

Conclusions

CONCLUSIONS

- Changes in insolation is an initial trigger, final response involves feedbacks as well.

- Water vapor feedback amplifies solar forcing during deglacial.

- Cloud radiative feedback influences monsoon during Holocene.

CONCLUSIONS

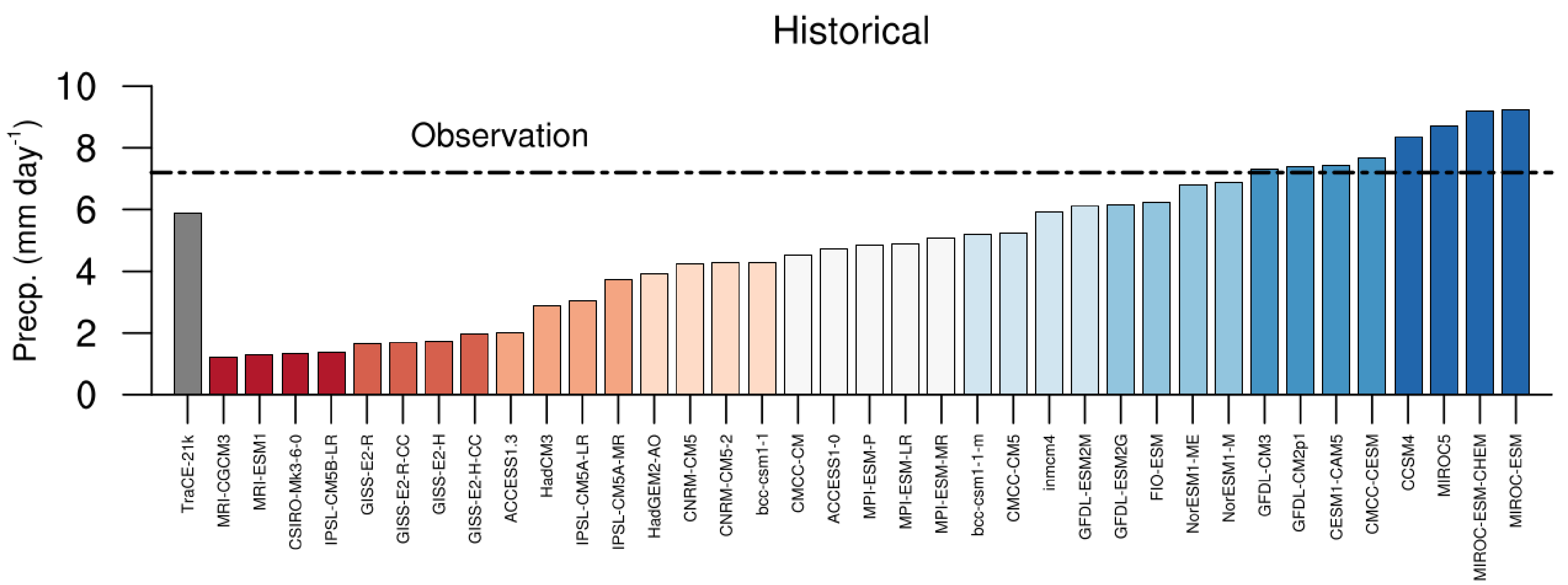
- Insolation can drive monsoon through two different pathways.

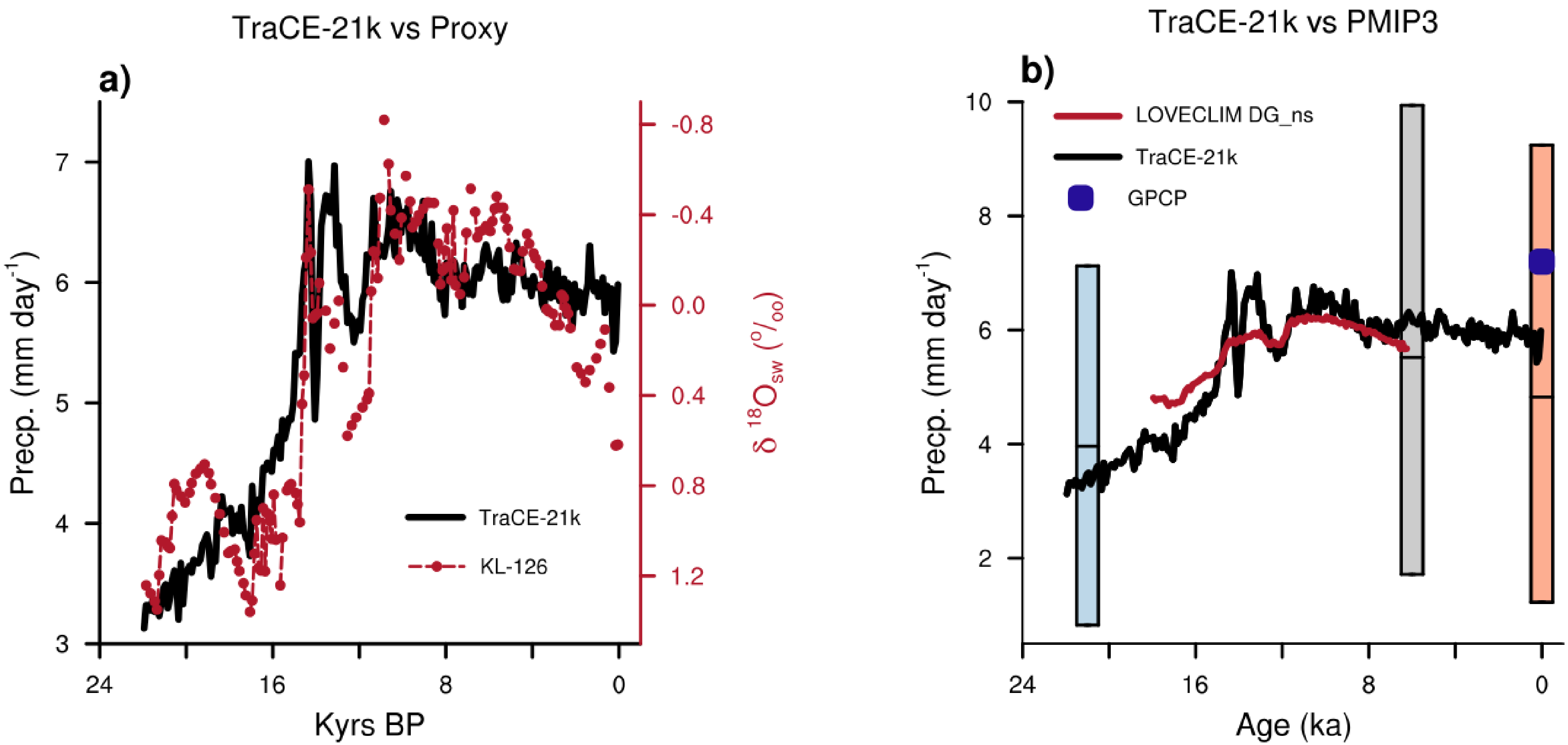
- Through energy available during warm periods, and through GMS during cold periods

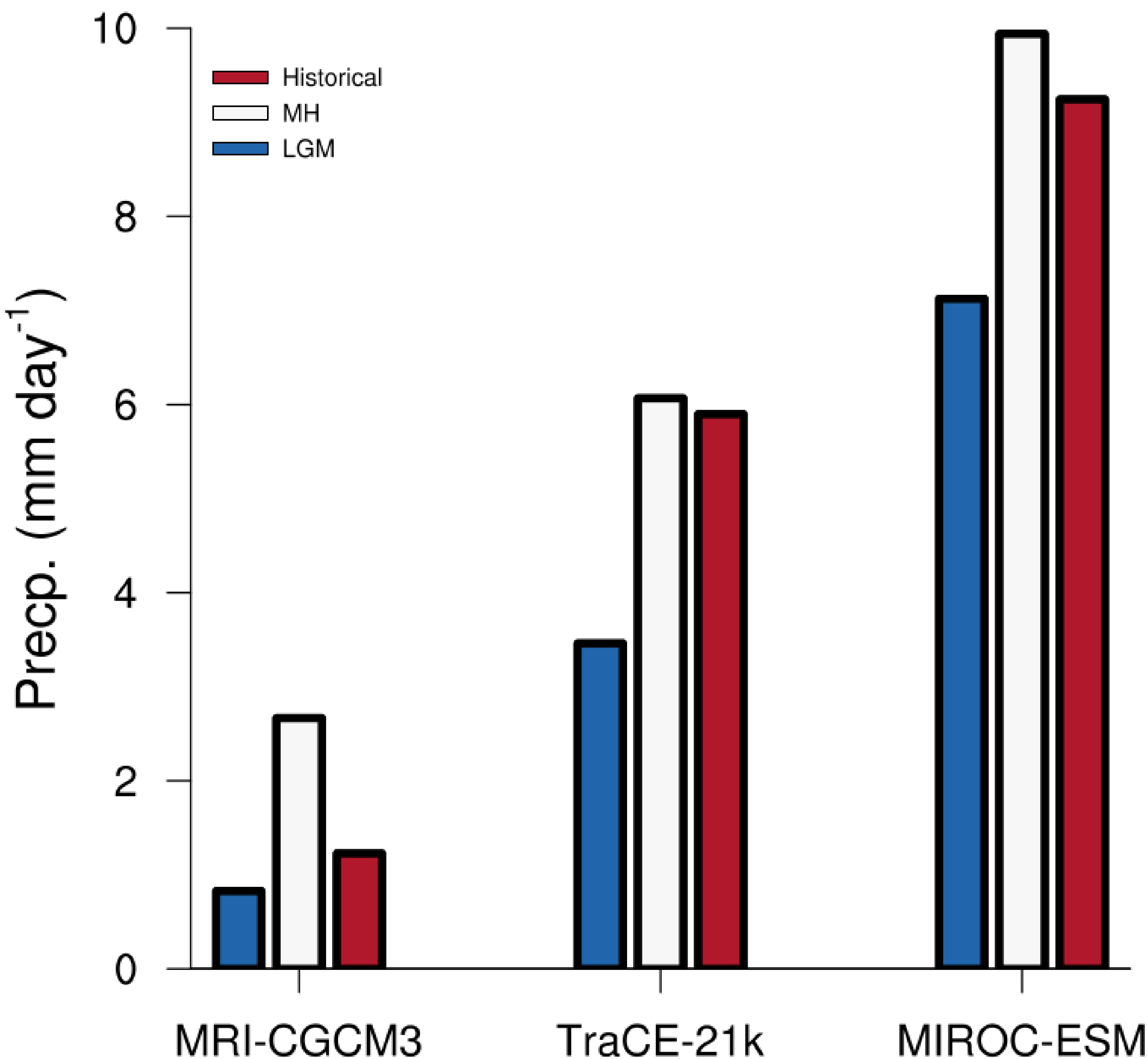
- Greenhouse gases and ice sheets only affect GMS.

Thank you

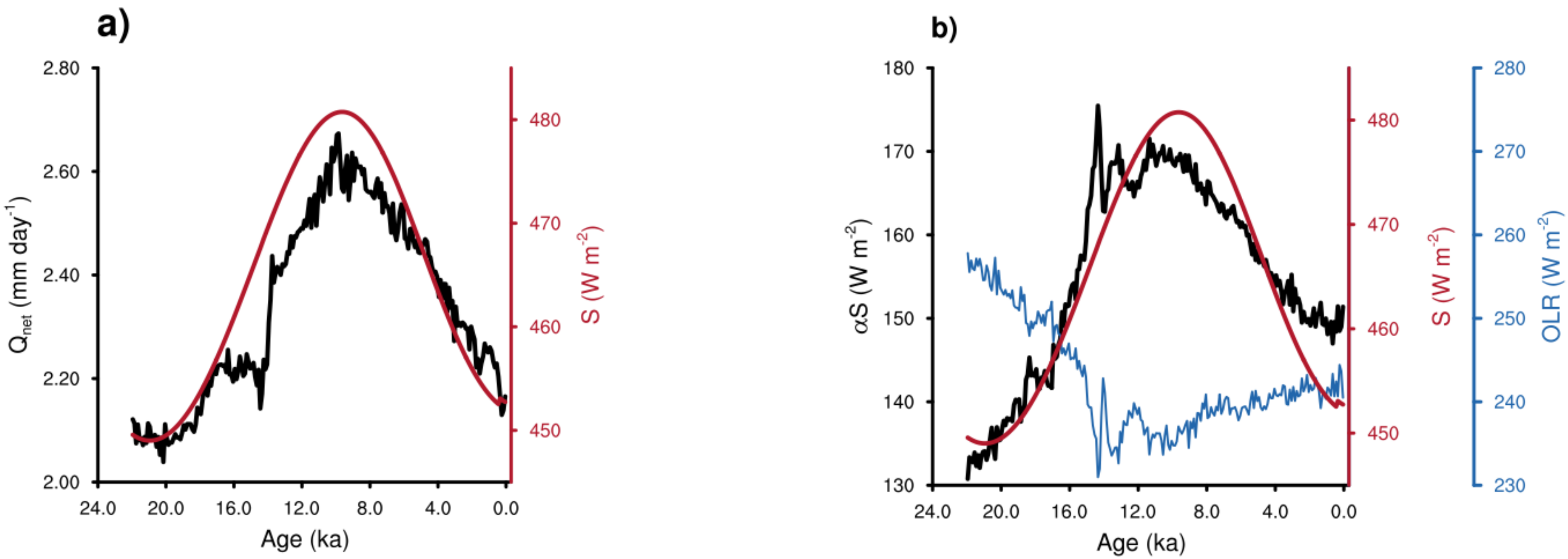
Extra Slides

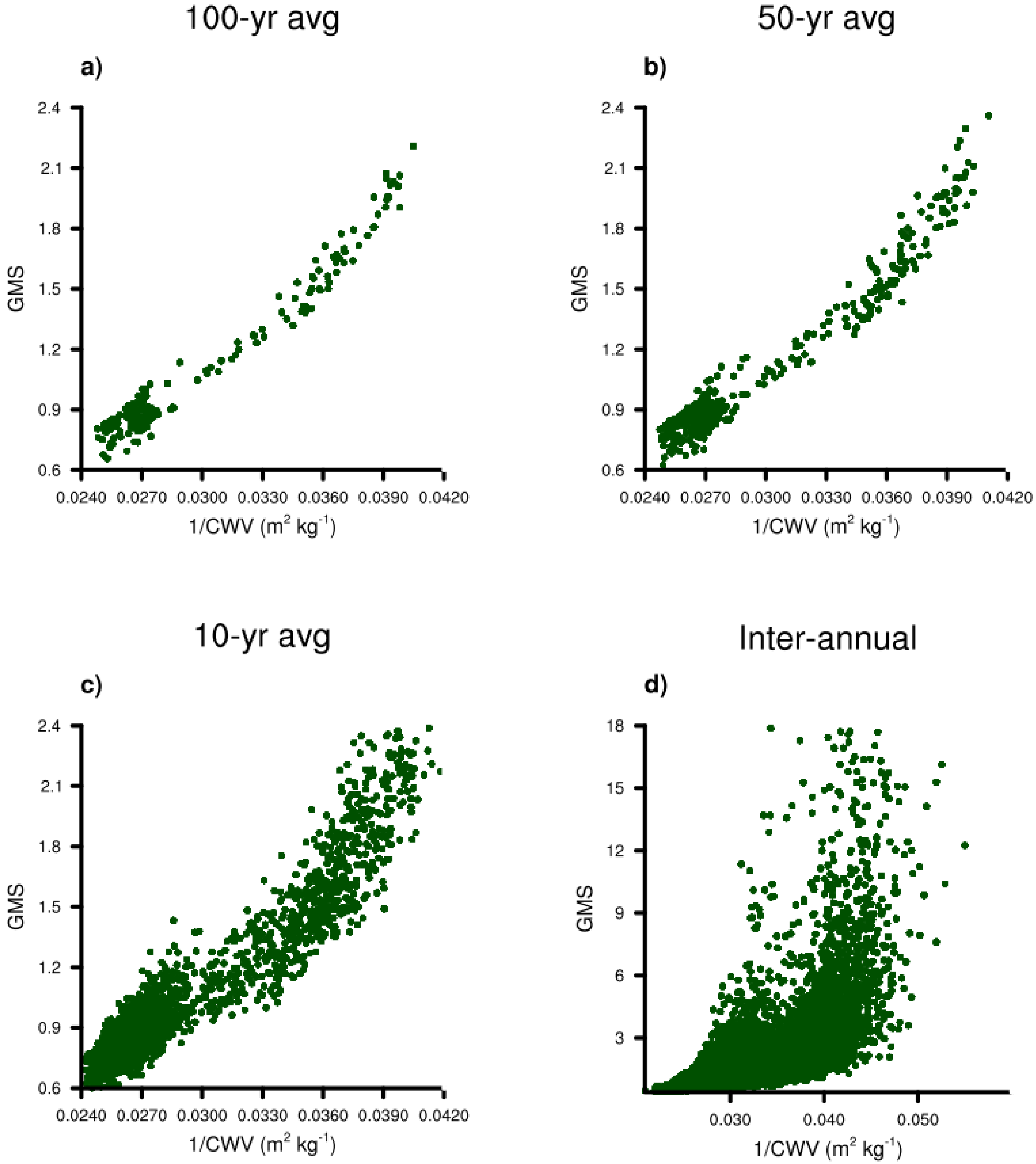

Historical
Precp. (mm day-1)
Observation
10
8
6
4
2
0
TraCE-21k
MRI-CGCM3
MRI-ESM1
CSIRO-Mk3-6-0
IPSL-CM5B-LR
GISS-E2-R
GISS-E2-R-CC
GISS-E2-H
GISS-E2-H-CC
ACCESS1.3
HadCM3
IPSL-CM5A-LR
IPSL-CM5A-MR
HadGEM2-AO
CNRM-CM5
CNRM-CM5-2
bcc-csm1-1
CMCC-CM
ACCESS1-0
MPI-ESM-P
MPI-ESM-LR
MPI-ESM-MR
bcc-csm1-1-m
CMCC-CM5
inmcm4
GFDL-ESM2M
GFDL-ESM2G
FIO-ESM
NorESM1-ME
NorESM1-M
GFDL-CM3
GFDL-CM2p1
CESM1-CAM5
CMCC-CESM
CCSM4
MIROC5
MIROC-ESM-CHEM
MIROC-ESM

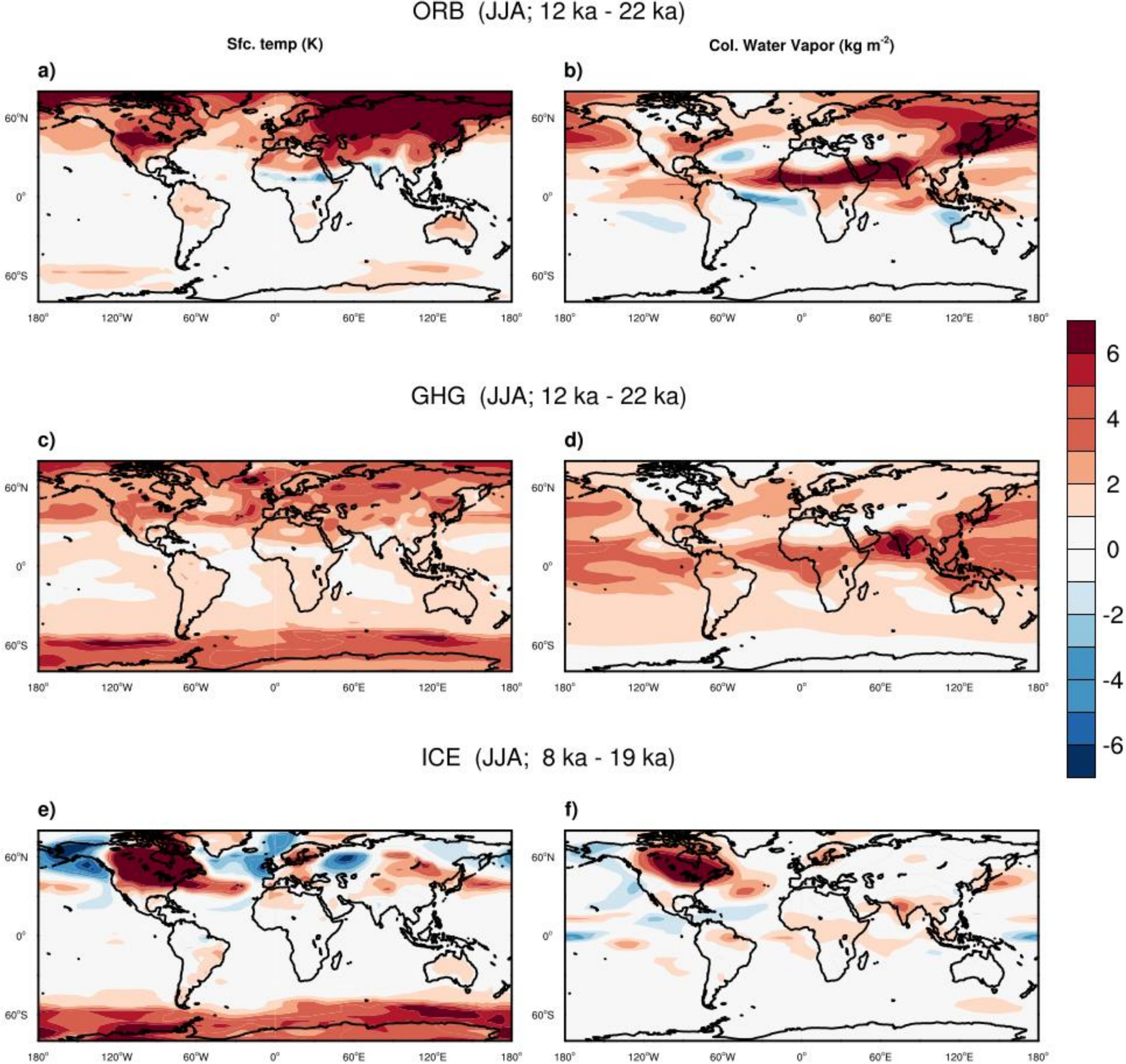

TraCE-21k vs Proxy
a)
Precp. (mm day^{-1})
$\delta^{18}O_{sw}$ (‰)
TraCE-21k
KL-126
Kyrs BP
TraCE-21k vs PMIP3
b)
LOVECLIM DG_ns
TraCE-21k
GPCP
Precp. (mm day^{-1})
Age (ka)

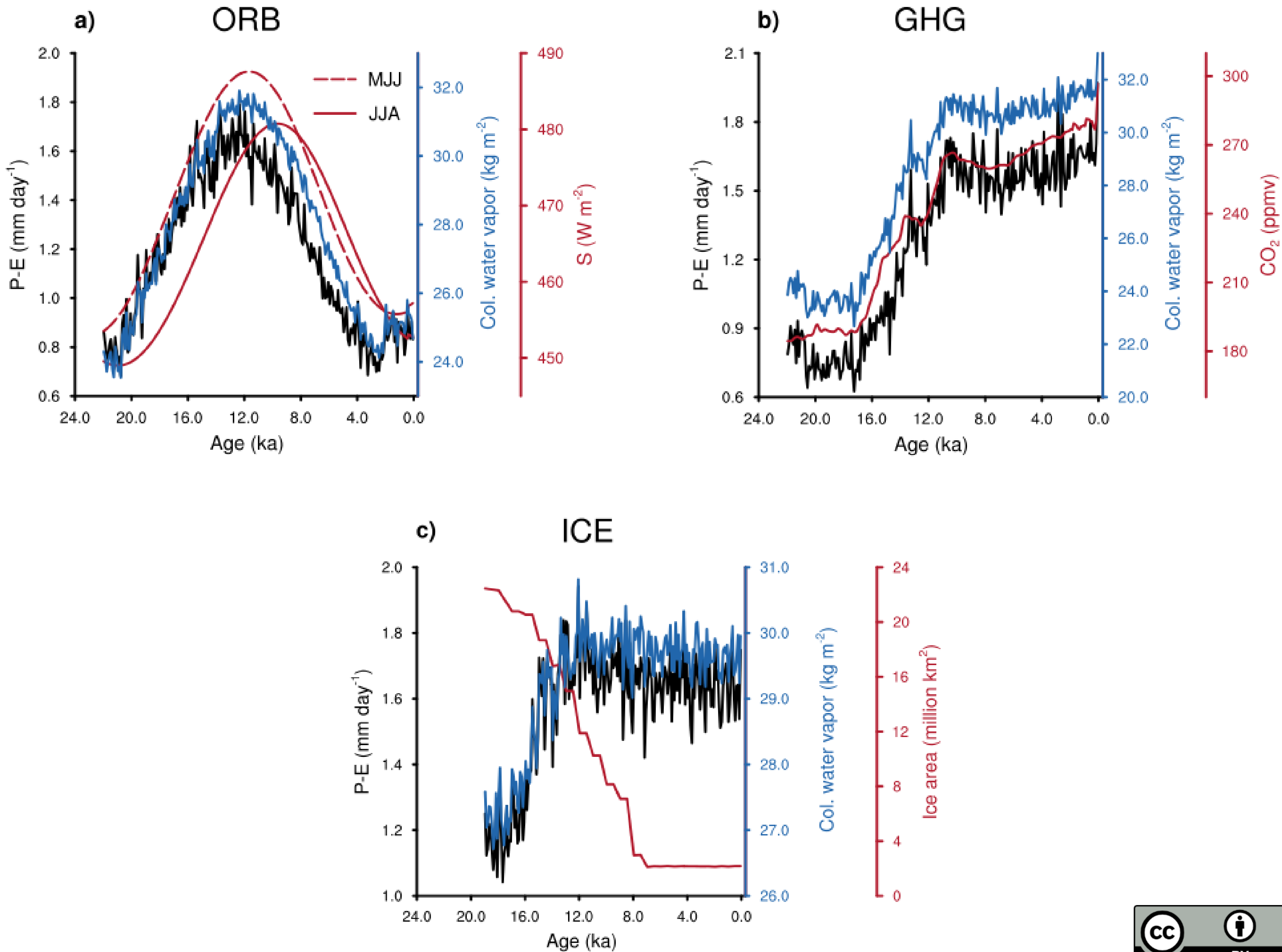

10
8
6
4
2
0
Precp. (mm day-1)
Historical
MH
LGM
MRI-CGCM3
TraCE-21k
MIROC-ESM

TraCE-21k (JJA)

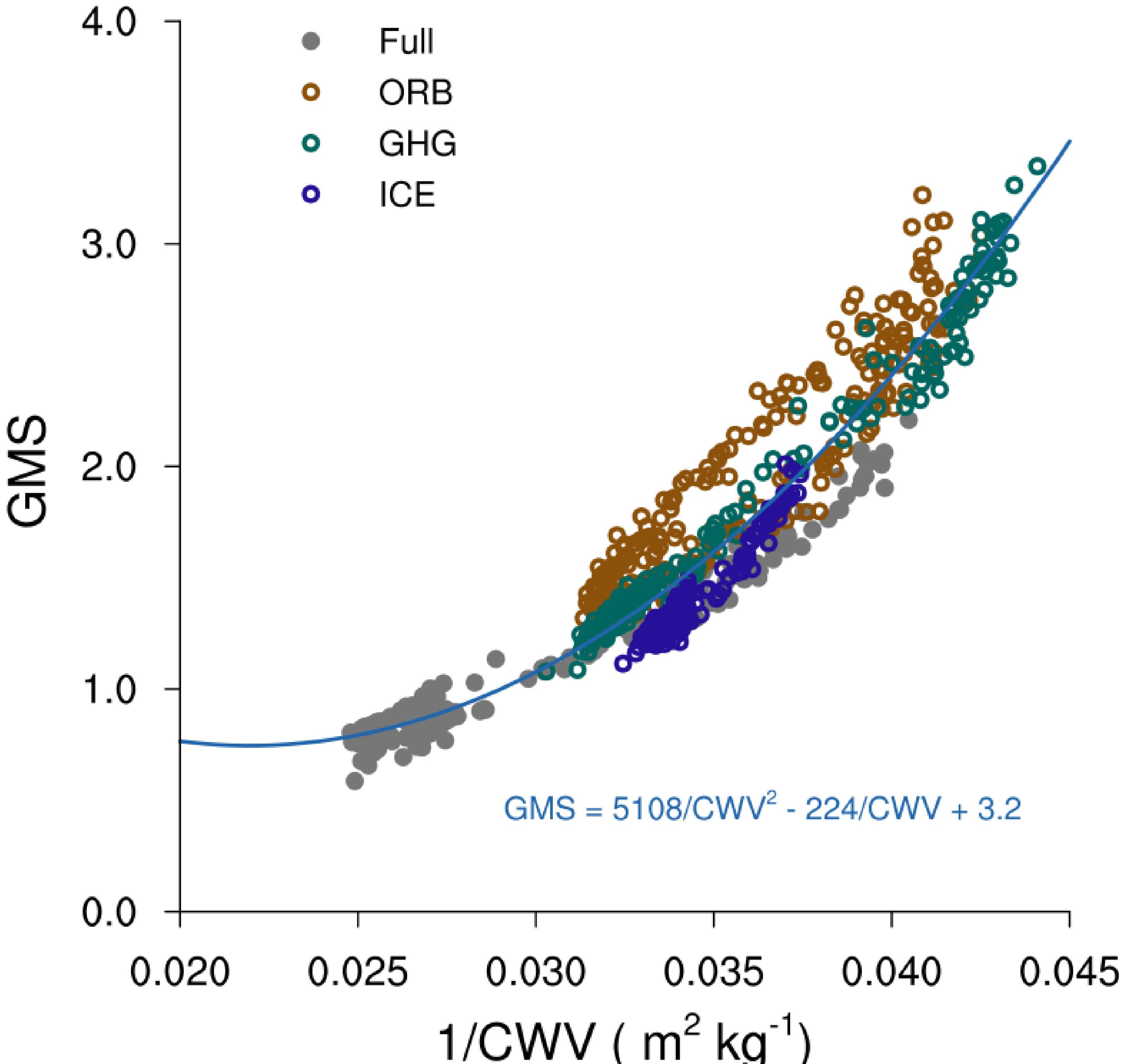



100-yr avg
a)
50-yr avg
b)
10-yr avg
c)
Inter-annual
d)
GMS
1/CWV (m^2 kg^{-1})
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.0240 0.0270 0.0300 0.0330 0.0360 0.0390 0.0420
18
15
12
9
6
3
0.030 0.040 0.050

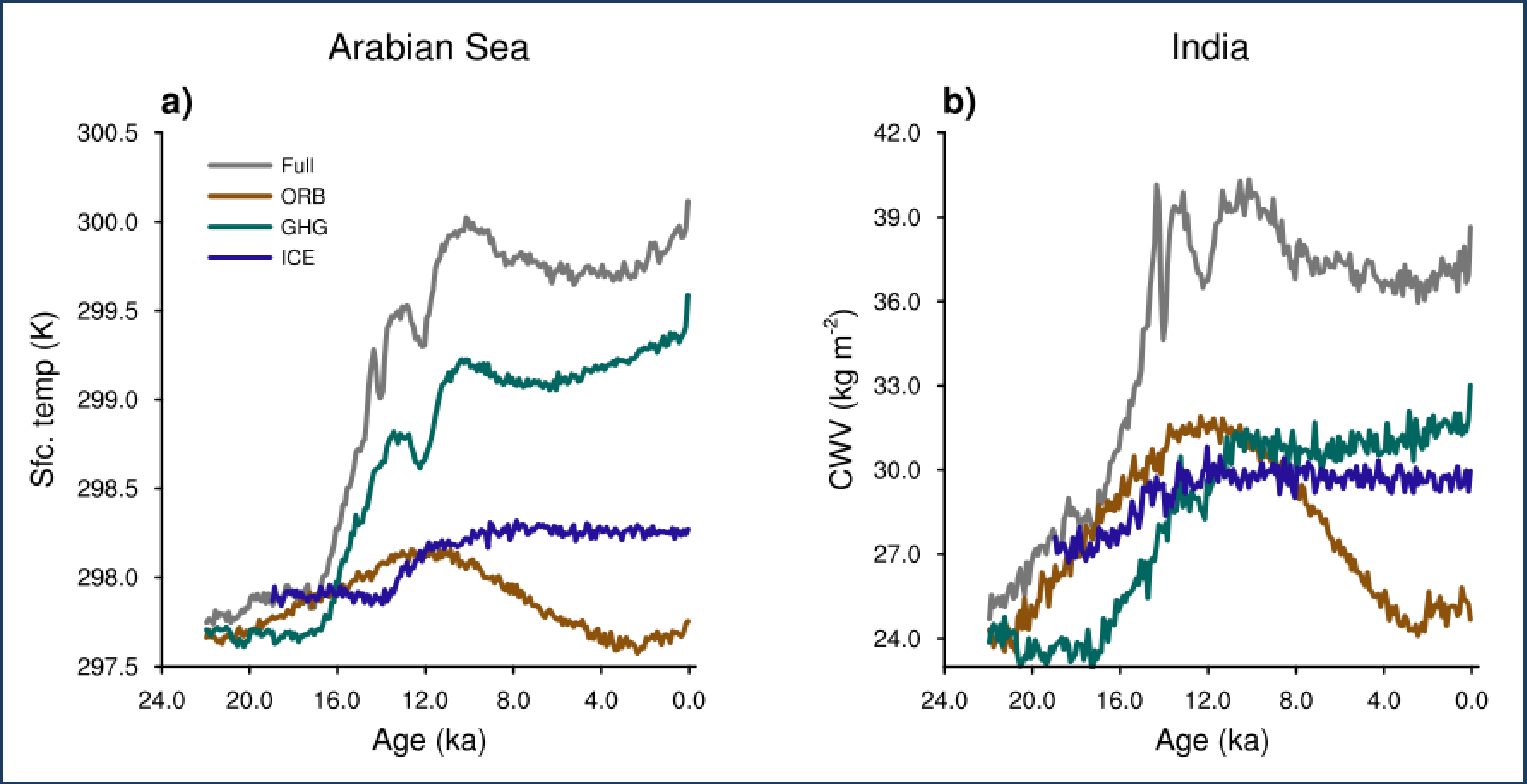

ORB (JJA; 12 ka - 22 ka)
Sfc. temp (K)
Col. Water Vapor (kg m^{-2})
a)
b)
GHG (JJA; 12 ka - 22 ka)
c)
d)
ICE (JJA; 8 ka - 19 ka)
e)
f)
60°N
0°
60°S
180°
120°W
60°W
0°
60°E
120°E
180°
6
4
2
0
-2
-4
-6



a)
ORB
MJJ
JJA
P-E (mm day-1)
Col. water vapor (kg m-2)
S (W m-2)
Age (ka)
b)
GHG
P-E (mm day-1)
Col. water vapor (kg m-2)
CO2 (ppmv)
Age (ka)
c)
ICE
P-E (mm day-1)
Col. water vapor (kg m-2)
Ice area (million km2)
Age (ka)

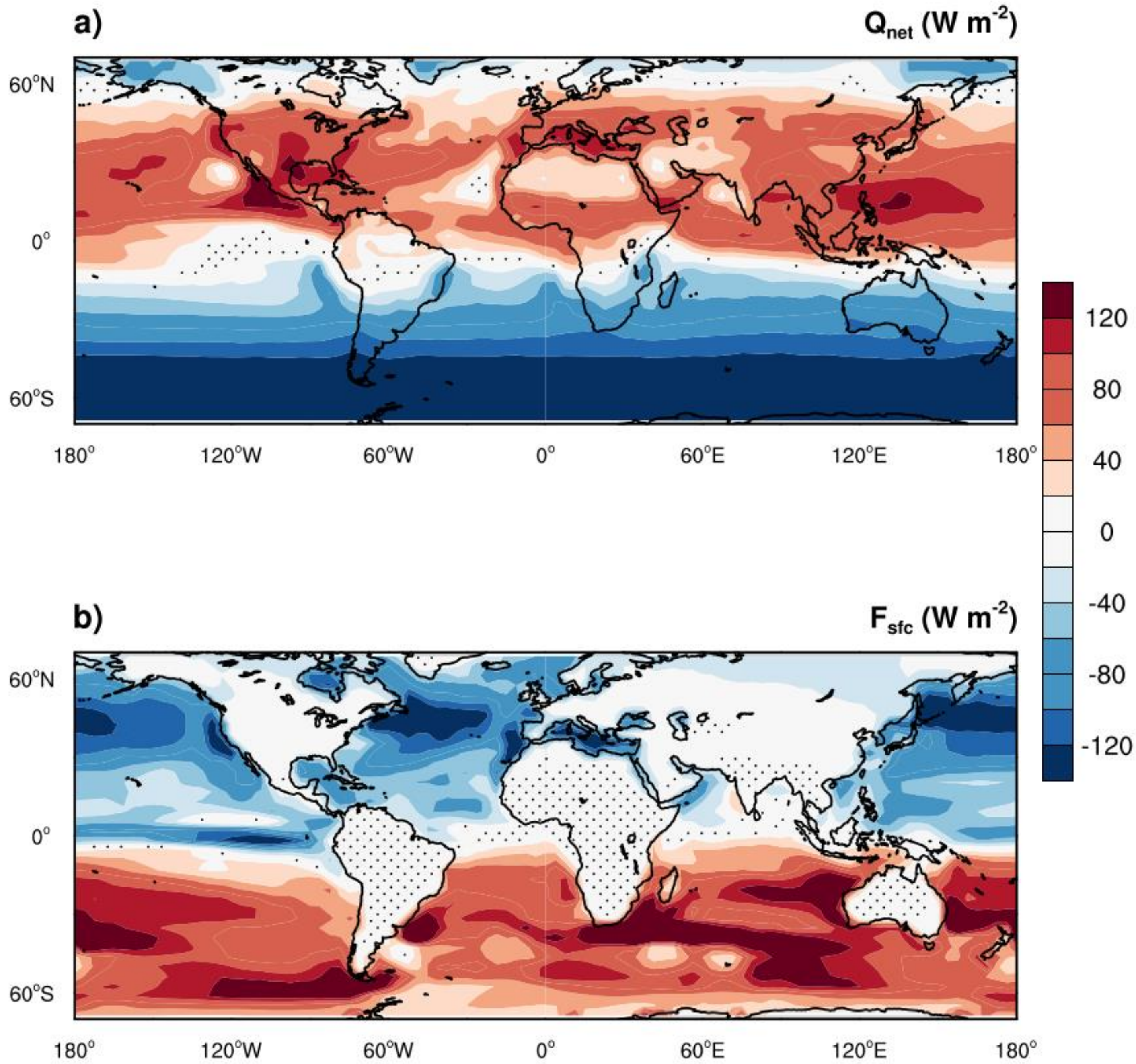


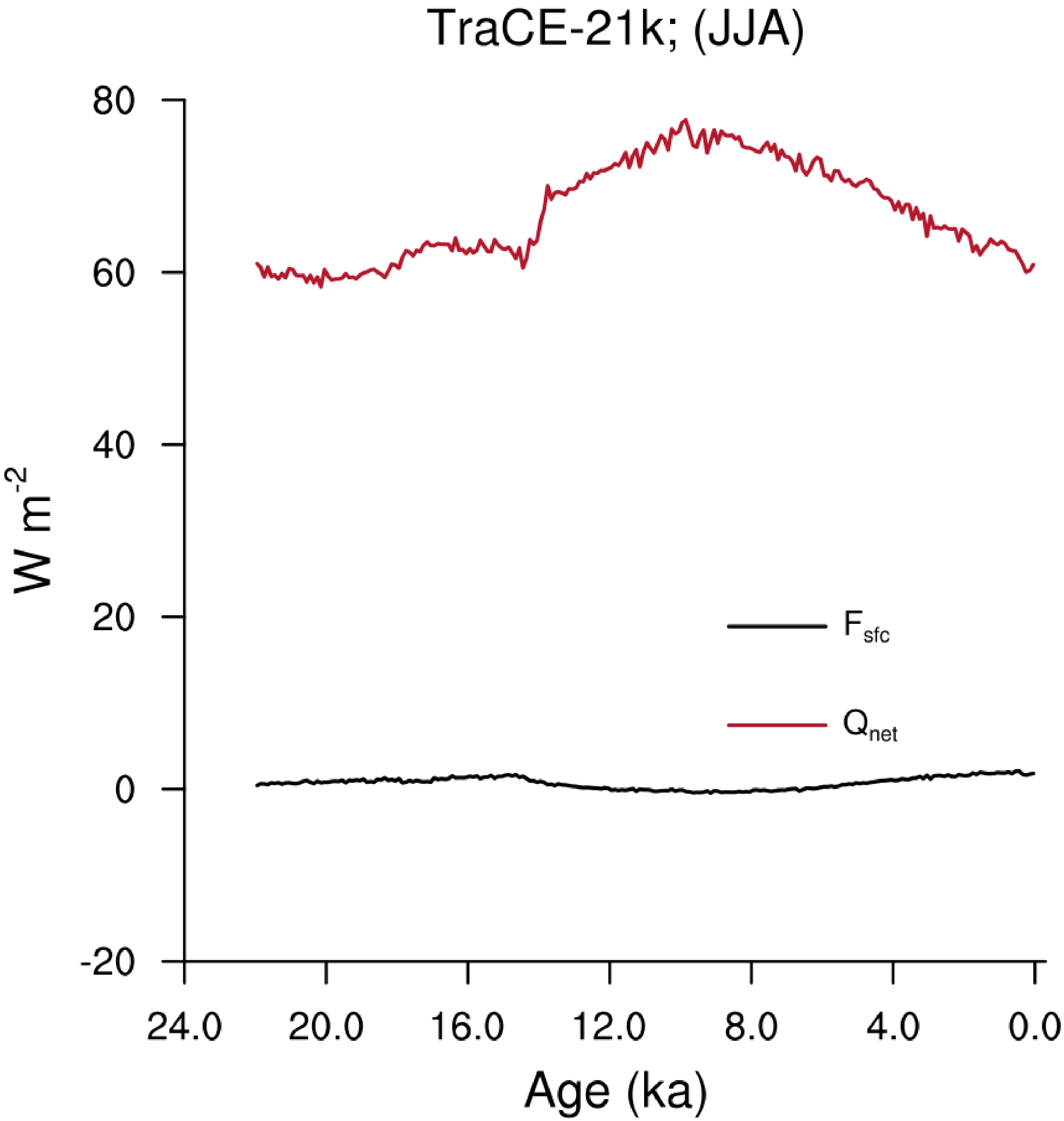
Full
ORB
GHG
ICE
GMS
4.0
3.0
2.0
1.0
0.0
0.020
0.025
0.030
0.035
0.040
0.045
1/CWV (m² kg⁻¹)
GMS = 5108/CWV² - 224/CWV + 3.2



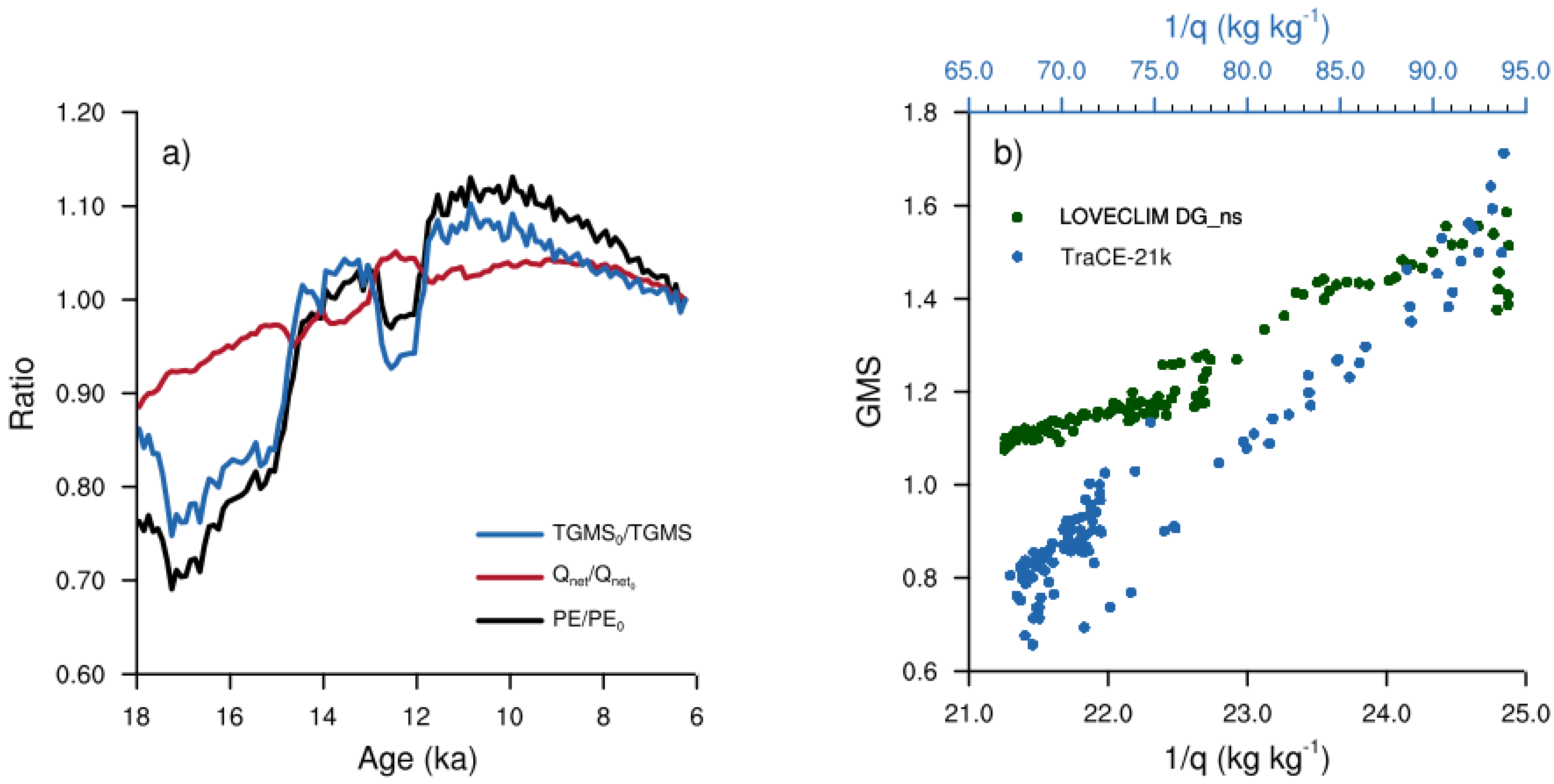
Arabian Sea
India
a)
b)
Full
ORB
GHG
ICE
Sfc. temp (K)
300.5
300.0
299.5
299.0
298.5
298.0
297.5
24.0
20.0
16.0
12.0
8.0
4.0
0.0
Age (ka)
CWV (kg m-2)
42.0
39.0
36.0
33.0
30.0
27.0
24.0

TraCE-21k (JJA; 1850 - 1950 AD)





TraCE-21k; (JJA)
80
60
40
20
0
-20
W m^{-2}
F_{sfc}
Q_{net}
24.0
20.0
16.0
12.0
8.0
4.0
0.0
Age (ka)



a)
Ratio
1.20
1.10
1.00
0.90
0.80
0.70
0.60
18
16
14
12
10
8
6
Age (ka)
TGMS$_0$/TGMS
Q_{net}/Q_{net_0}
PE/PE$_0$
b)
GMS
1/q (kg kg^{-1})
65.0
70.0
75.0
80.0
85.0
90.0
95.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
21.0
22.0
23.0
24.0
25.0
1/q (kg kg^{-1})
LOVECLIM DG_ns
TraCE-21k