Warming and Cooling Effect of Dust on Climate of the Past

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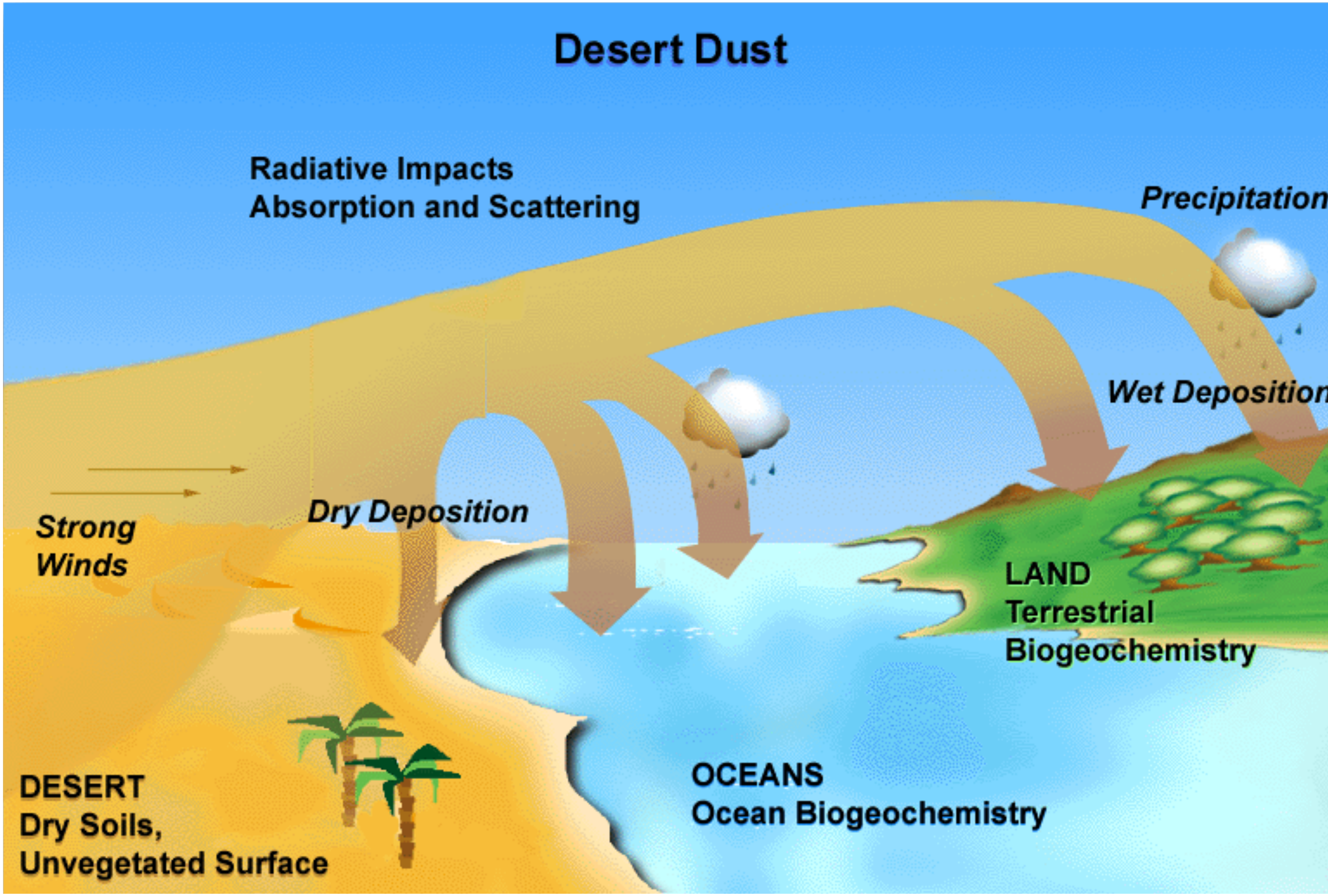
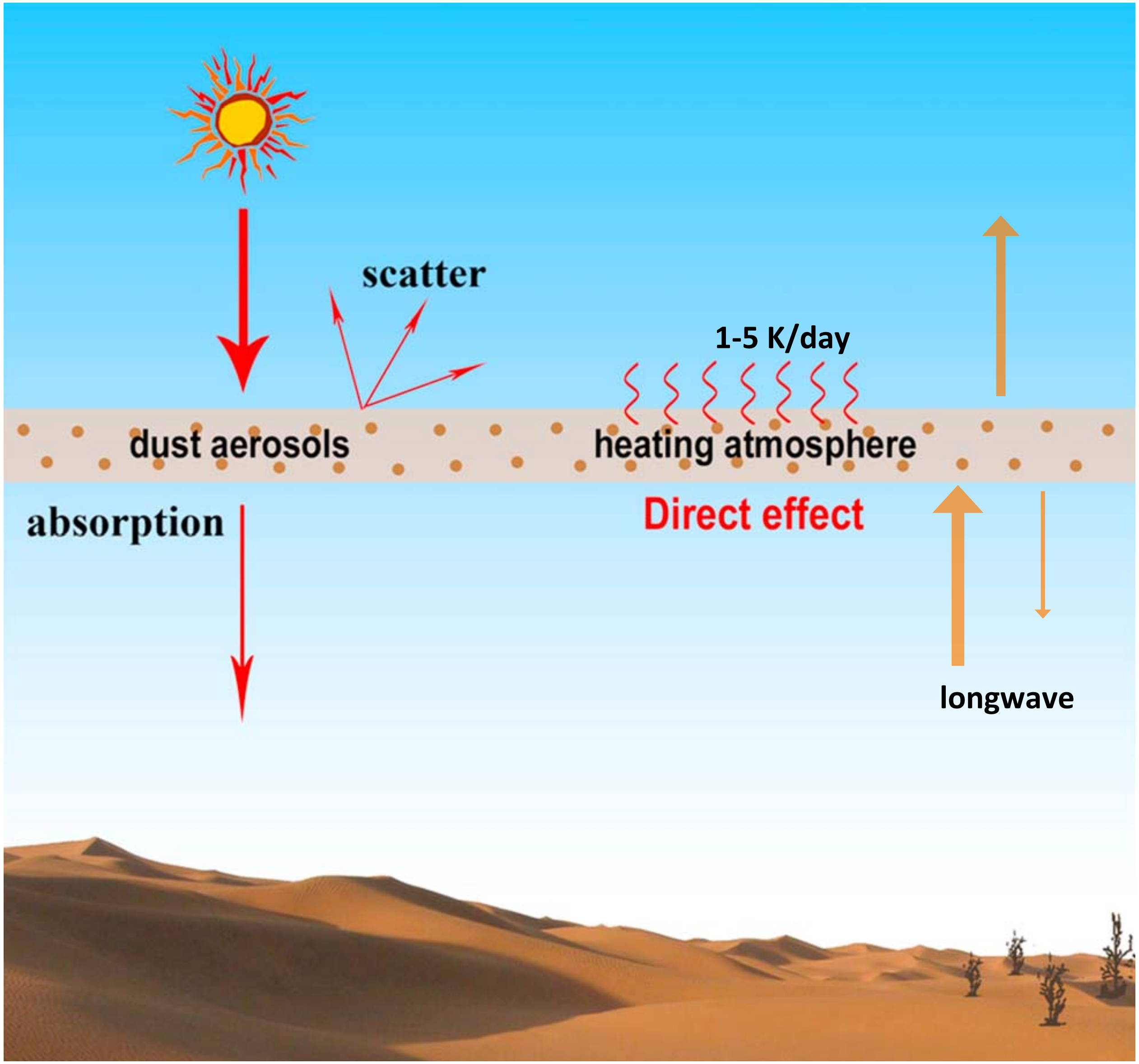


Natalie Mahowald webpage

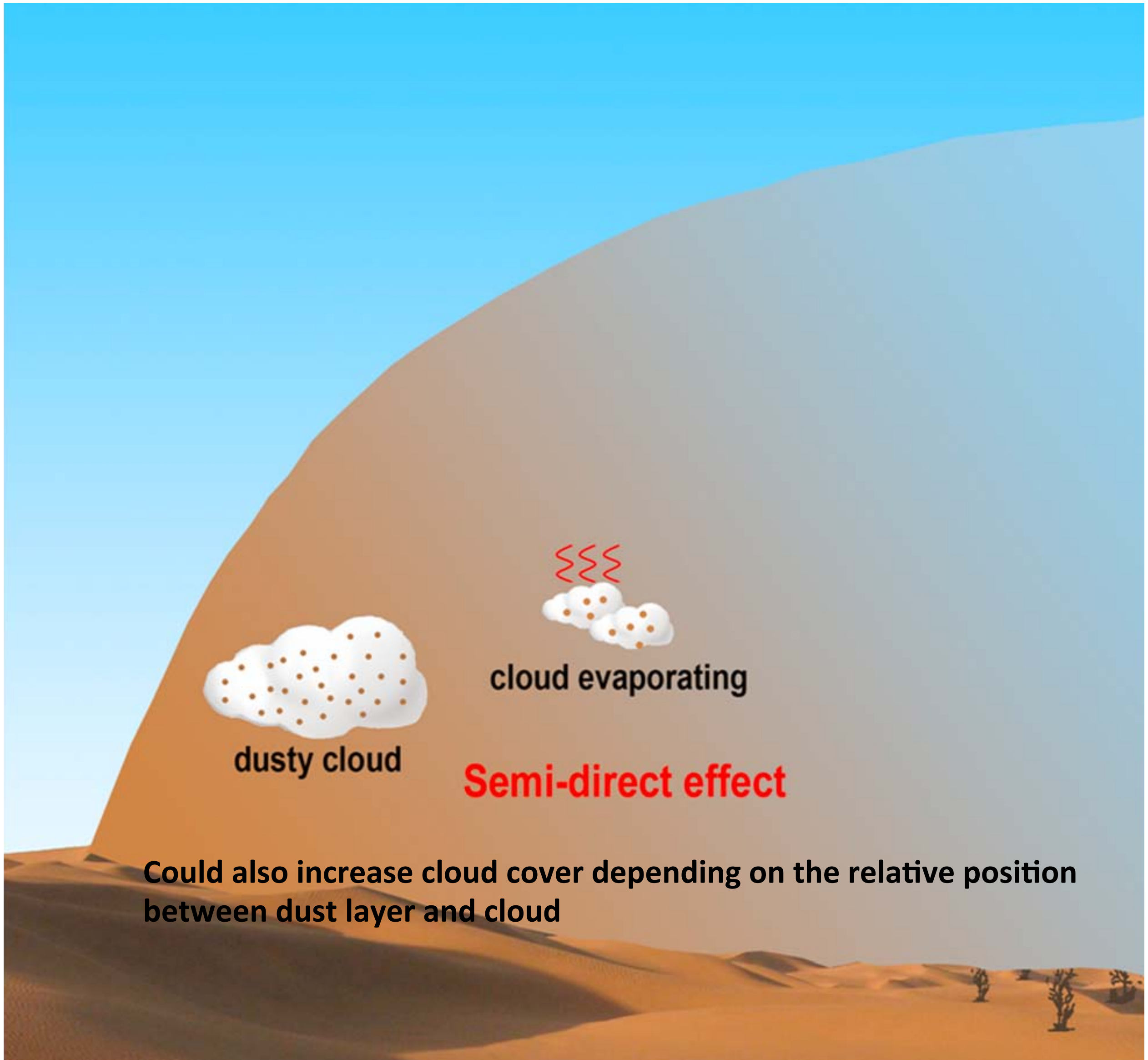
Direct Radiative Effect of Dust

-- Generally a Cooling Effect for the Surface



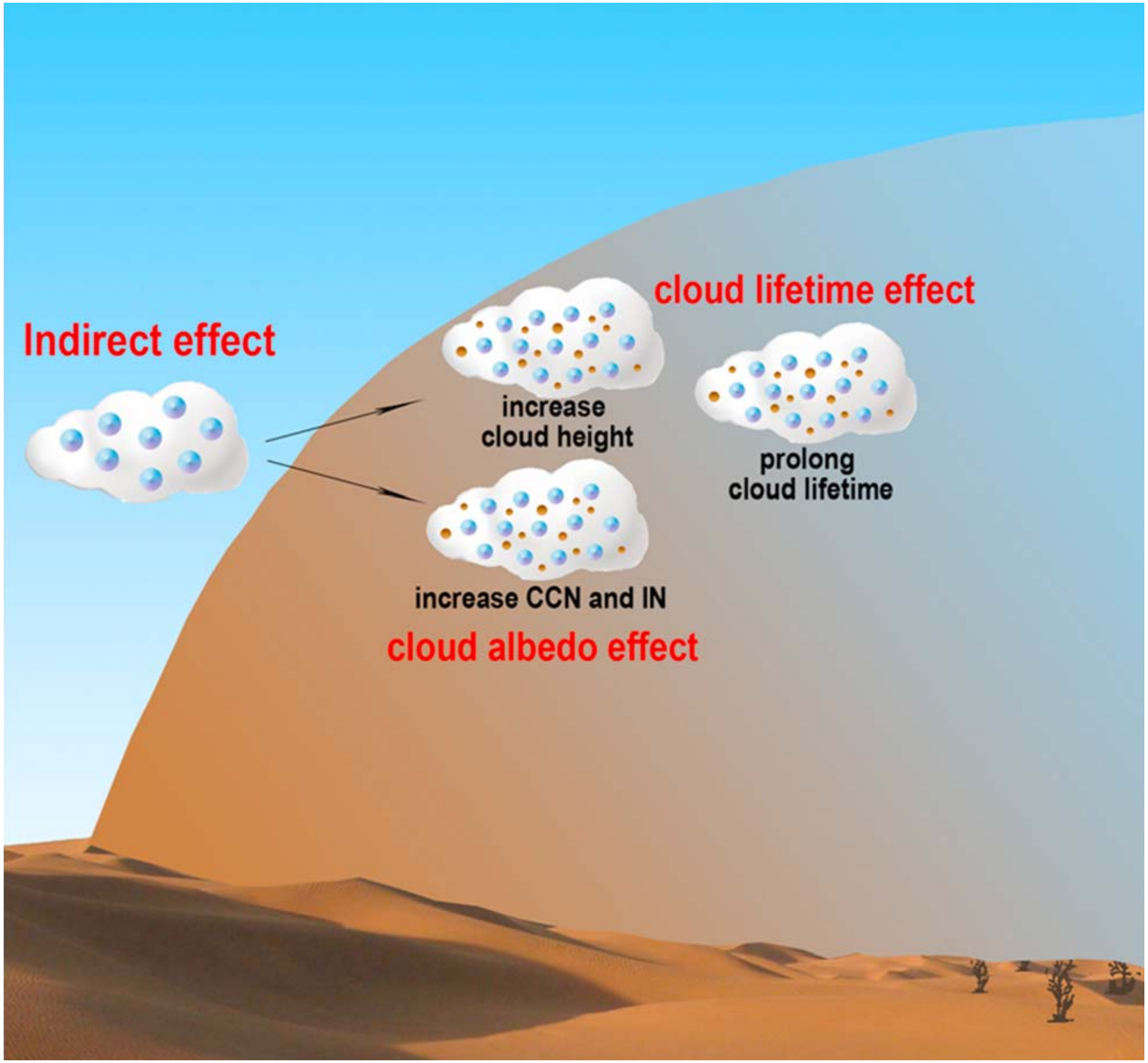
Huang et al. (2014, JGR)

Seimi-direct Effect
-- Generally Warming



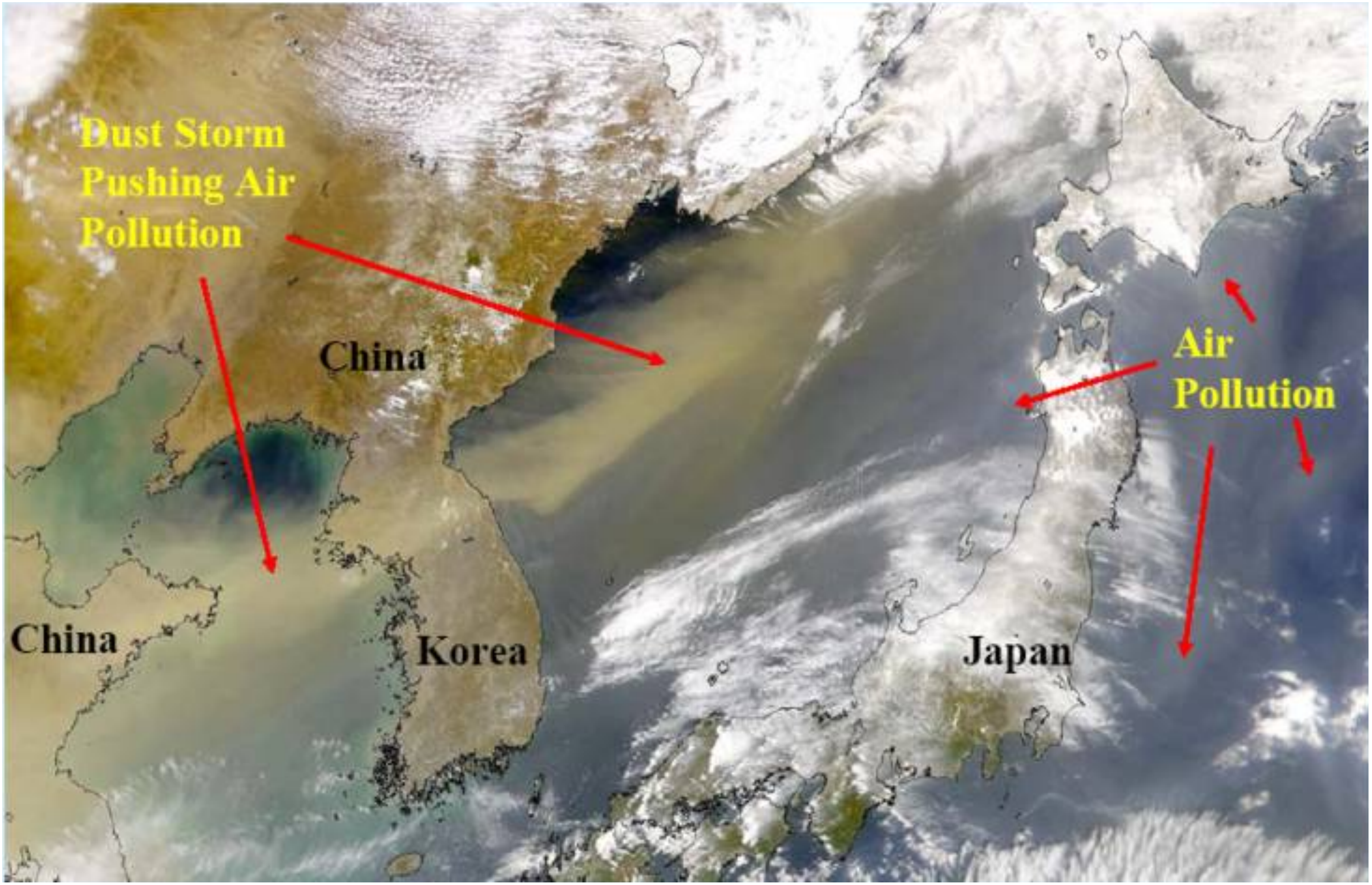
Huang et al. (2014, JGR)

Indirect Effect and Invigoration Effect
-- Generally a Cooling Effect



Huang et al. (2014, JGR)

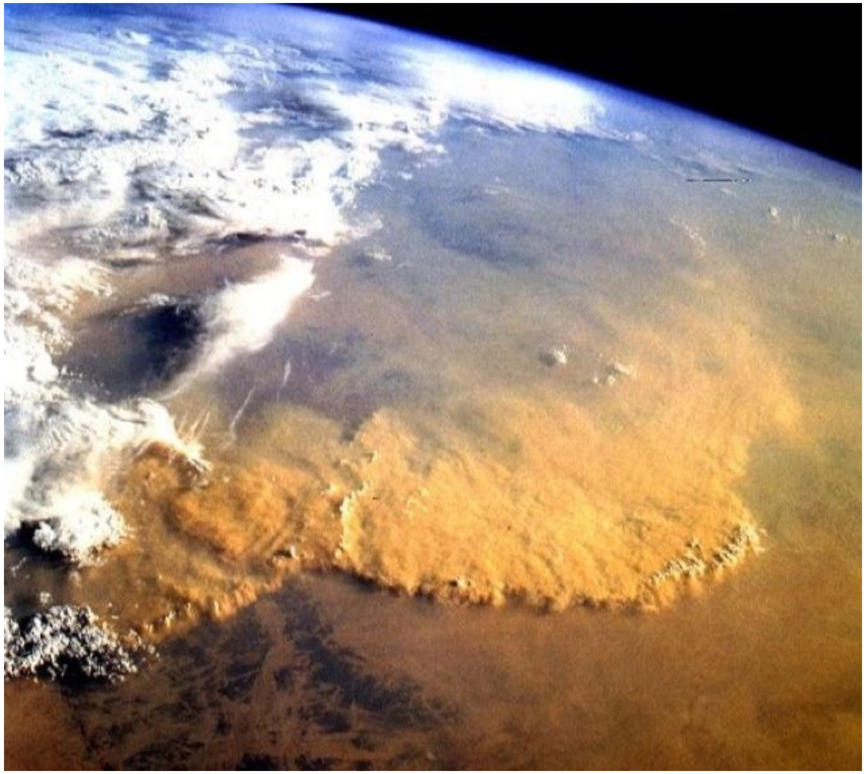
However, dust itself is only a good ice nuclei, it has to be polluted (e.g. by sea salt, anthropogenic pollutants) to become good liquid cloud nuclei (Choobari and Sturman, 2014)



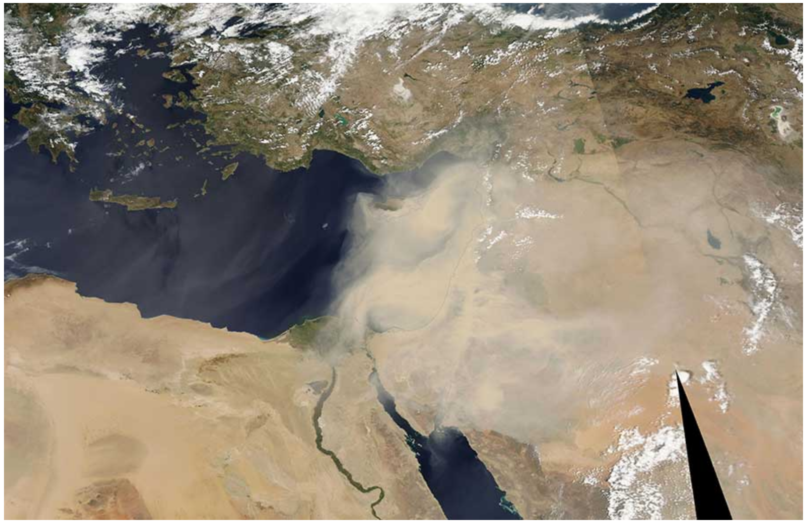
www.esrl.noaa.gov

Present-day Dry Area

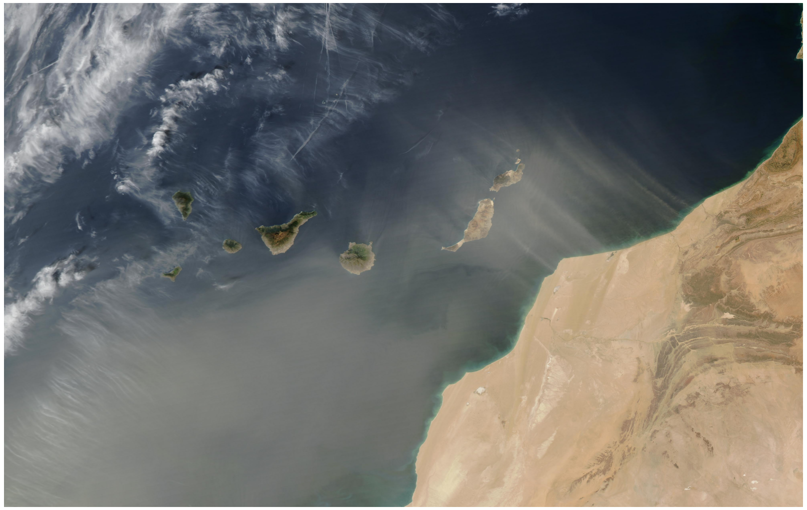
Mineral Dust



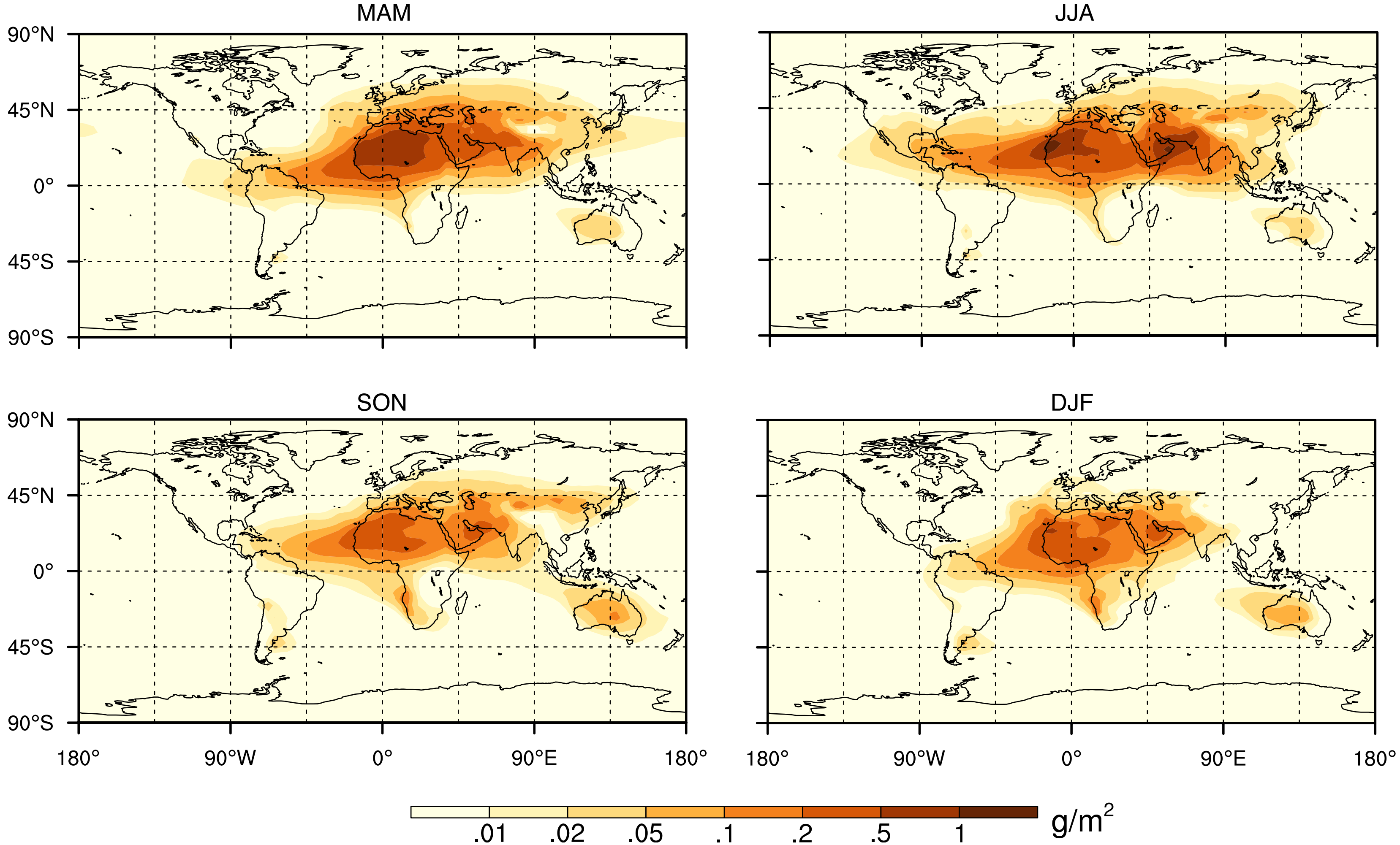
NASA



NOAA



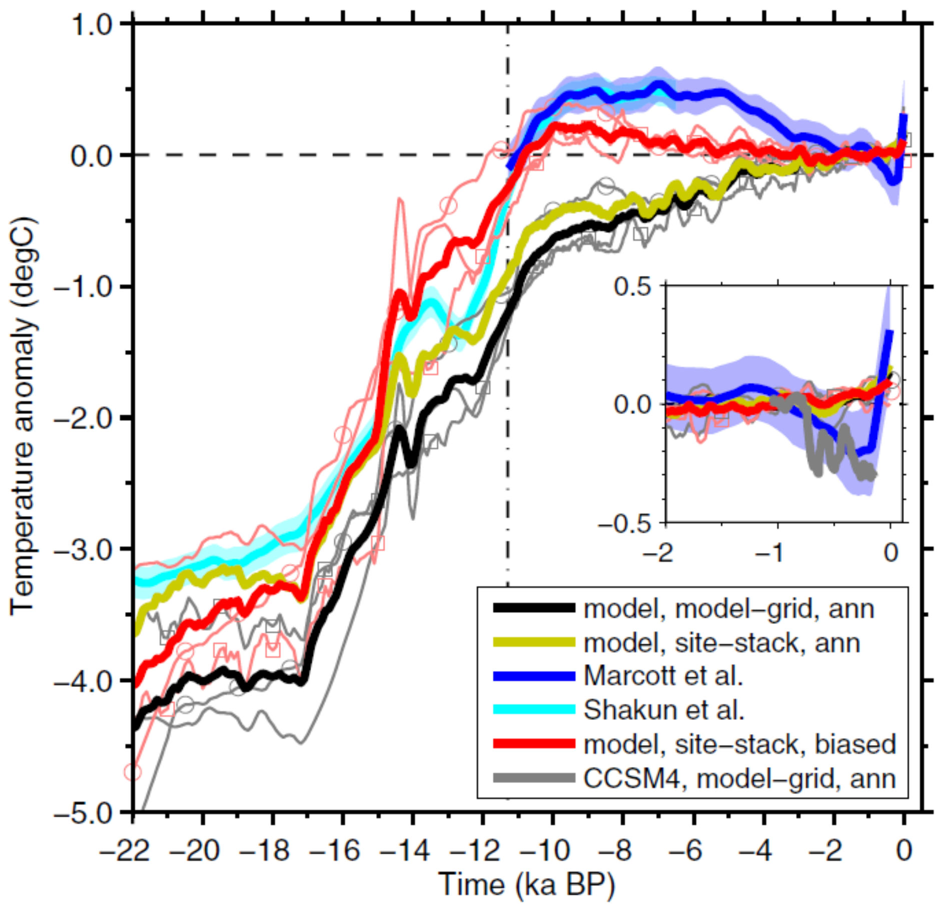
Seasonal Variation of Present-day Dust Loading



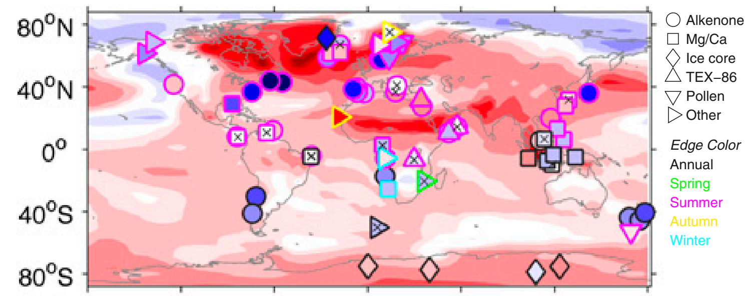
Effect of Dust on Climate for Three Periods

- Mid-Holocene (6 ka)
- Pre-industrial (1870 AD)
- Late Neoproterozoic (~700 Ma)

Holocene Temperature Conundrum

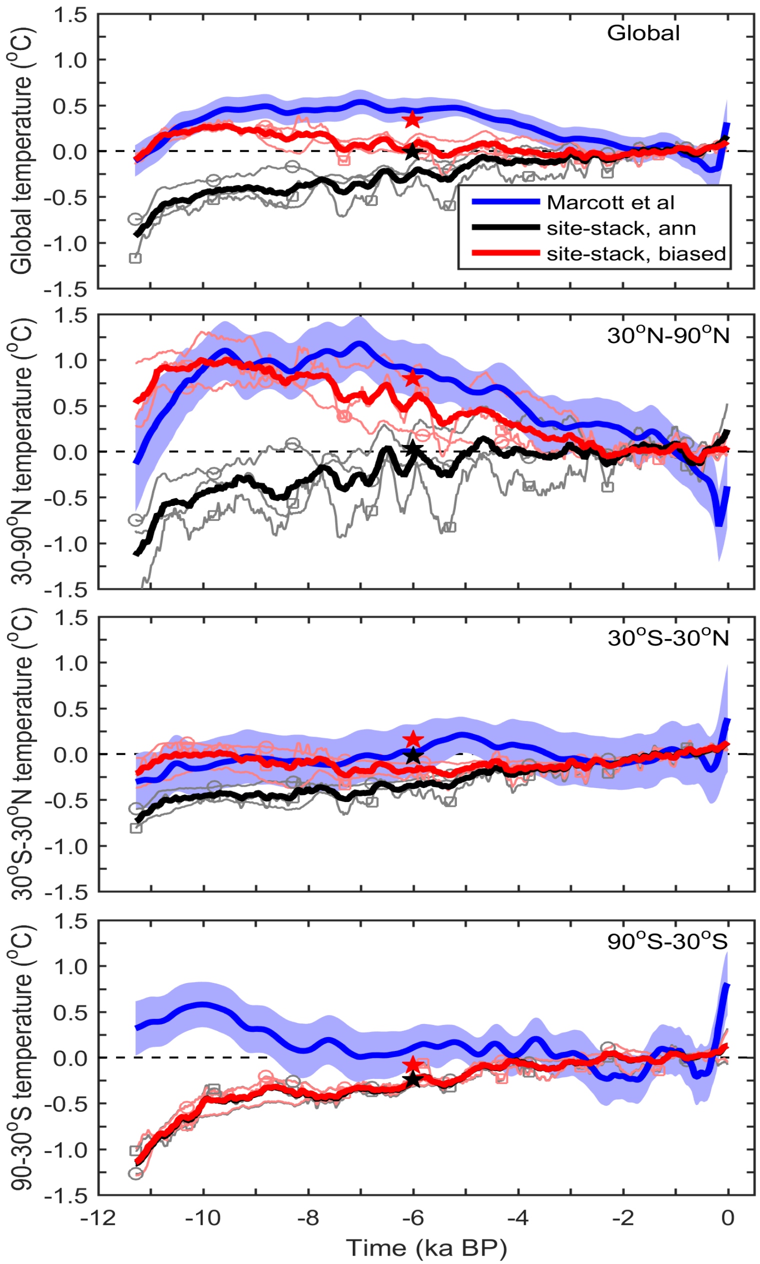


Z. Liu et al. (2014, PNAS)



Marcott et al. (2013, Science)

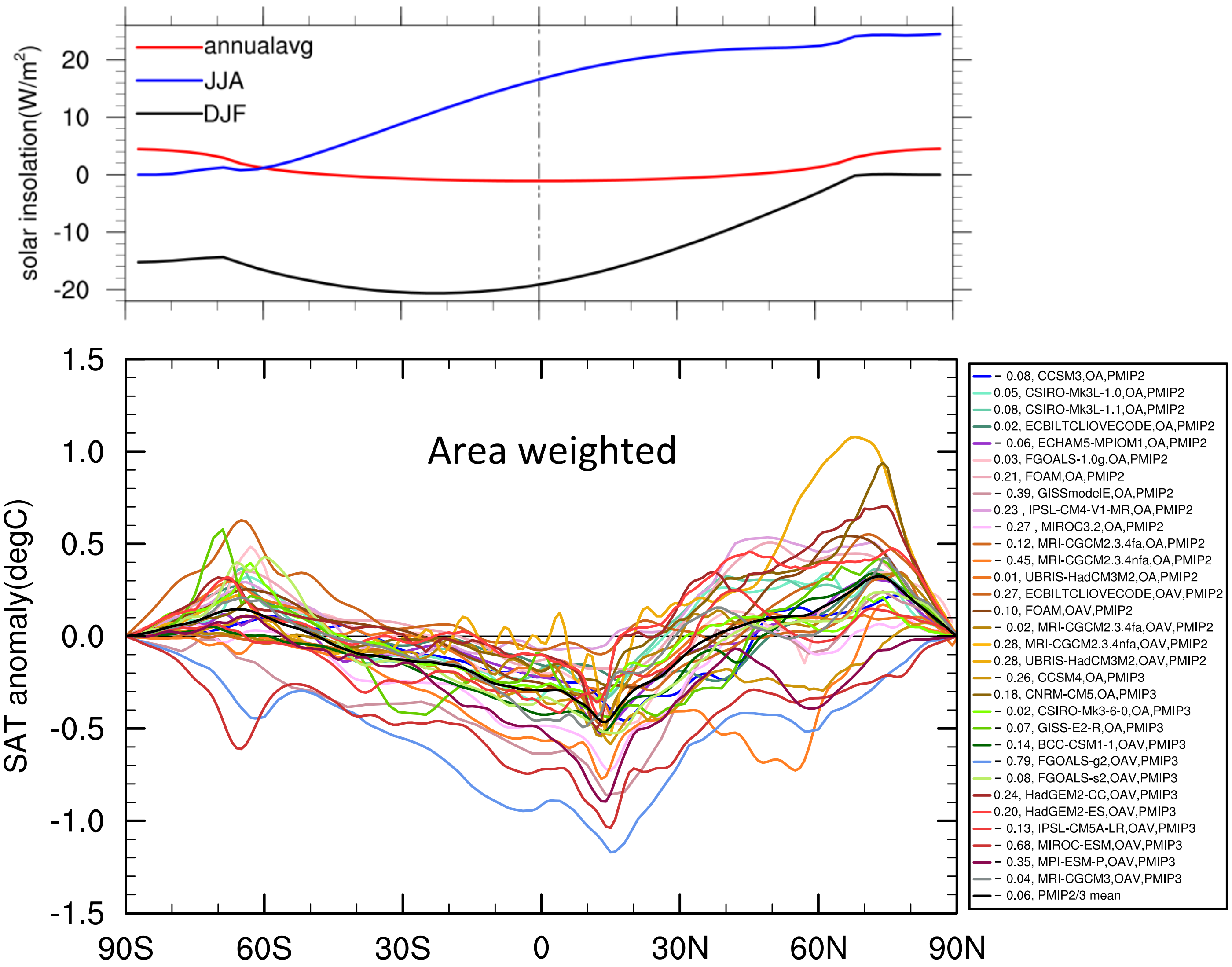
Model-Data Discrepancy

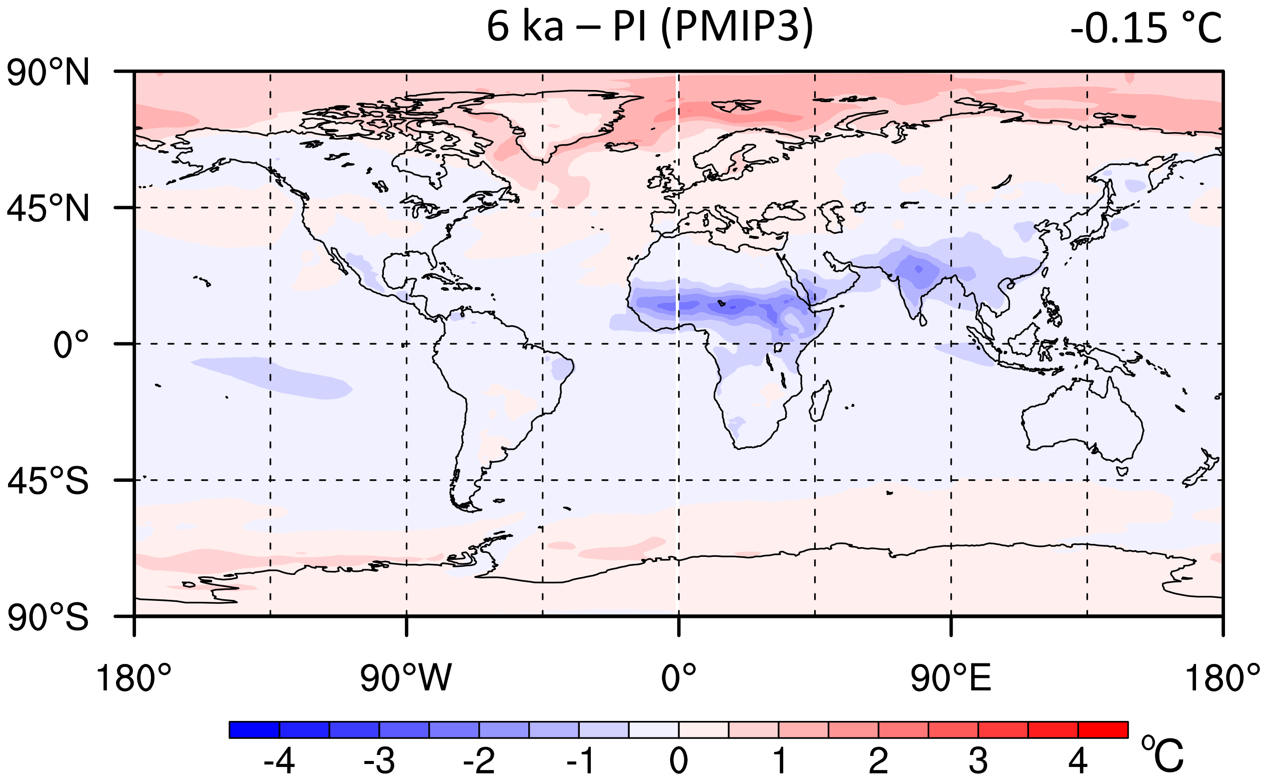


Discrepancy: difference between red and blue curves is ~0.5 °C at 6 ka

Southern hemisphere: black and red curves overlap with each other, meaning that proxy bias could not explain any of the discrepancy like at other latitudes.

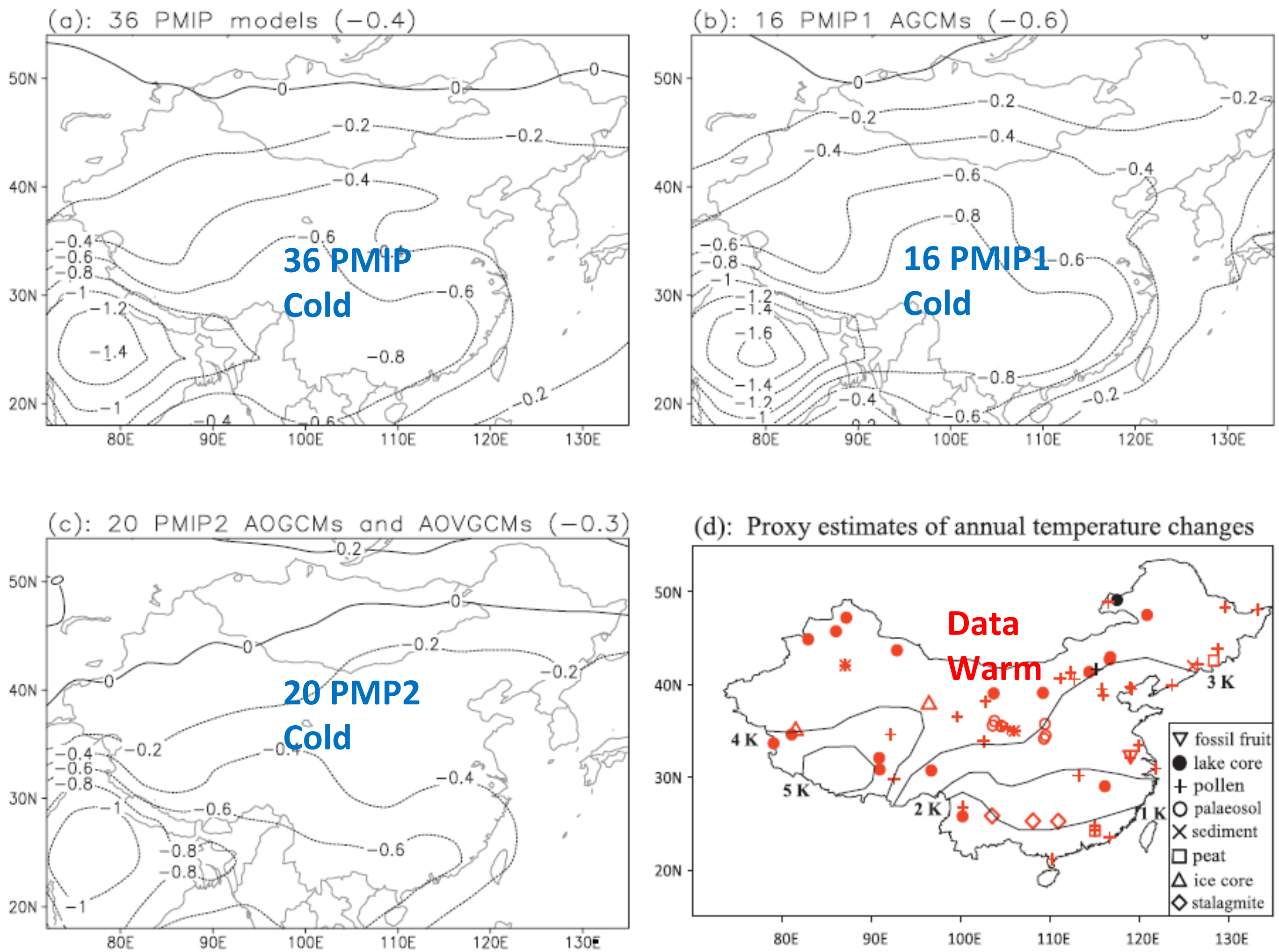
Mid-Holocene Surface Temperature (Relative to Pre-industrial) Obtained by PMIP2&3 Models





6 ka – PI (PMIP3)
-0.15 °C
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°
-4
-3
-2
-1
0
1
2
3
4
°C

Model-Data Mismatch in Annual-mean Temperature over China during the Mid-Holocene



Jiang et al. (2010, JC)

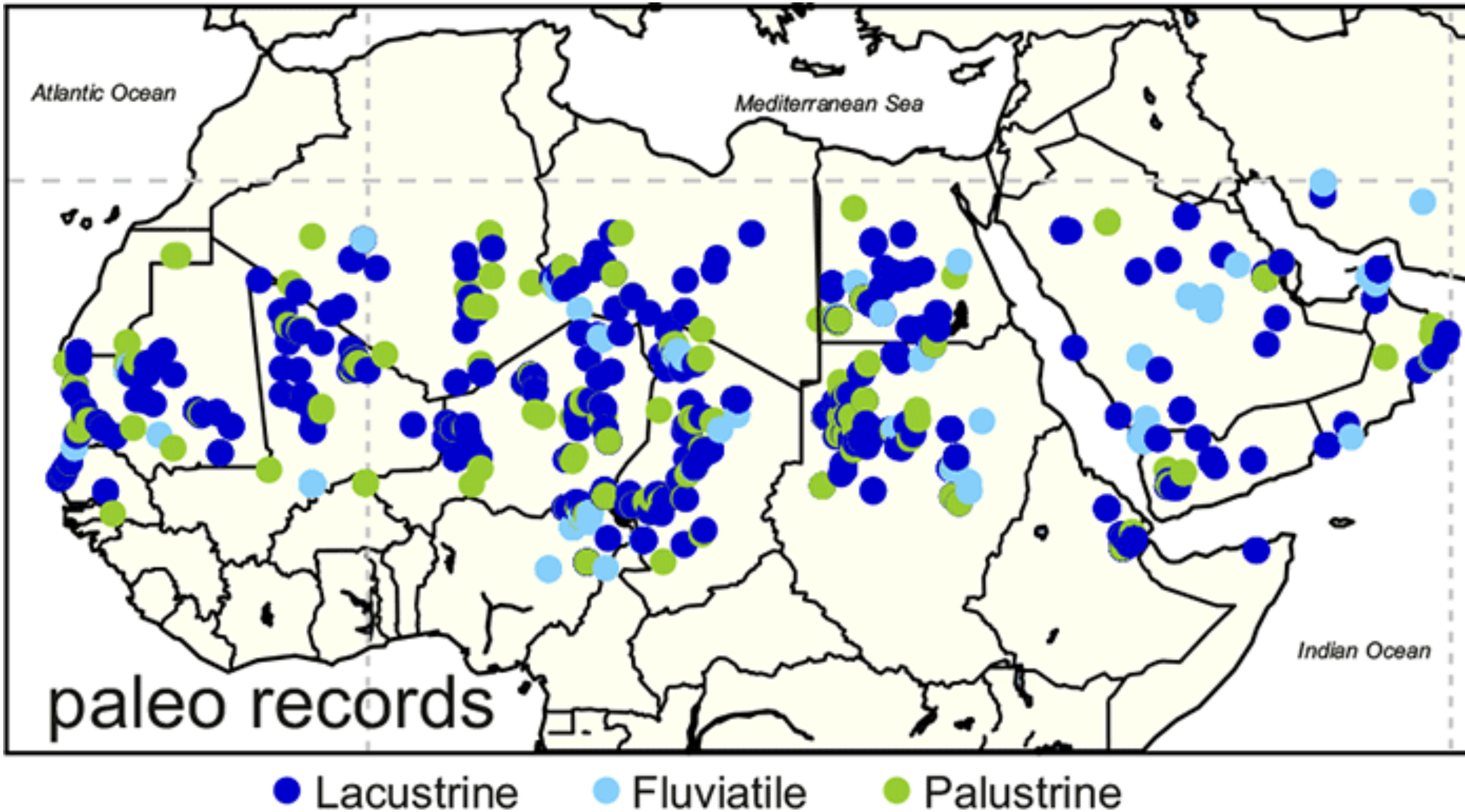
How to Solve the Holocene Temperature Conundrum?

Assuming there is no more bias in the observations, then there are only a few options left:

- **Exceptionally enhanced volcanic activity since the mid-Holocene**
- **Weakening solar insolation since the mid-Holocene**
- **Increasing dust emission since the mid-Holocene**

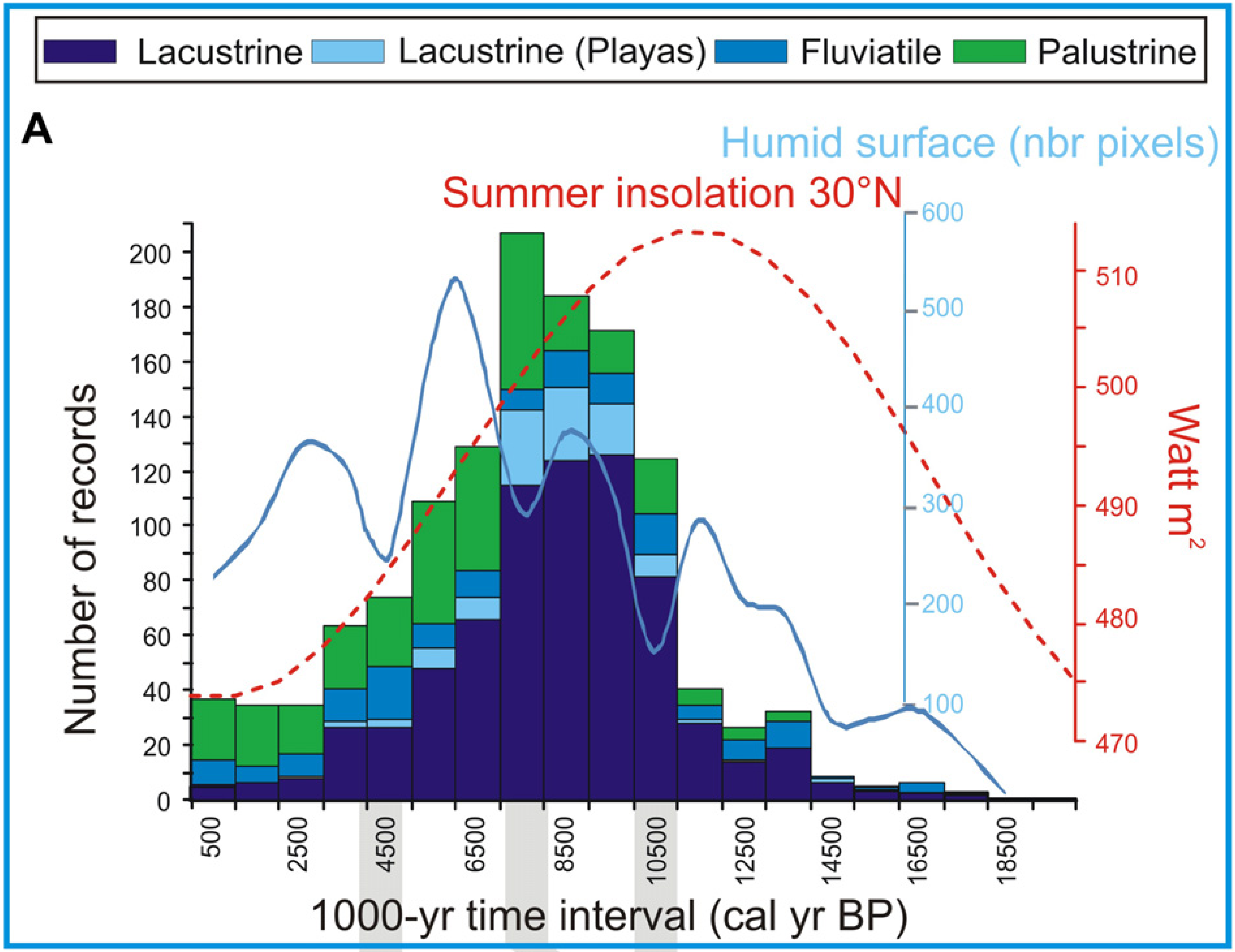
African Humid Period (14.8 – 5.5 ka)

Dated Records of Lakes, Swamps and Fluvial Activity During the Holocene



Lézine et al. (2014)

African Humid Period (14.8 – 5.5 ka)



Lézine et al. (2011)

Green Sahara

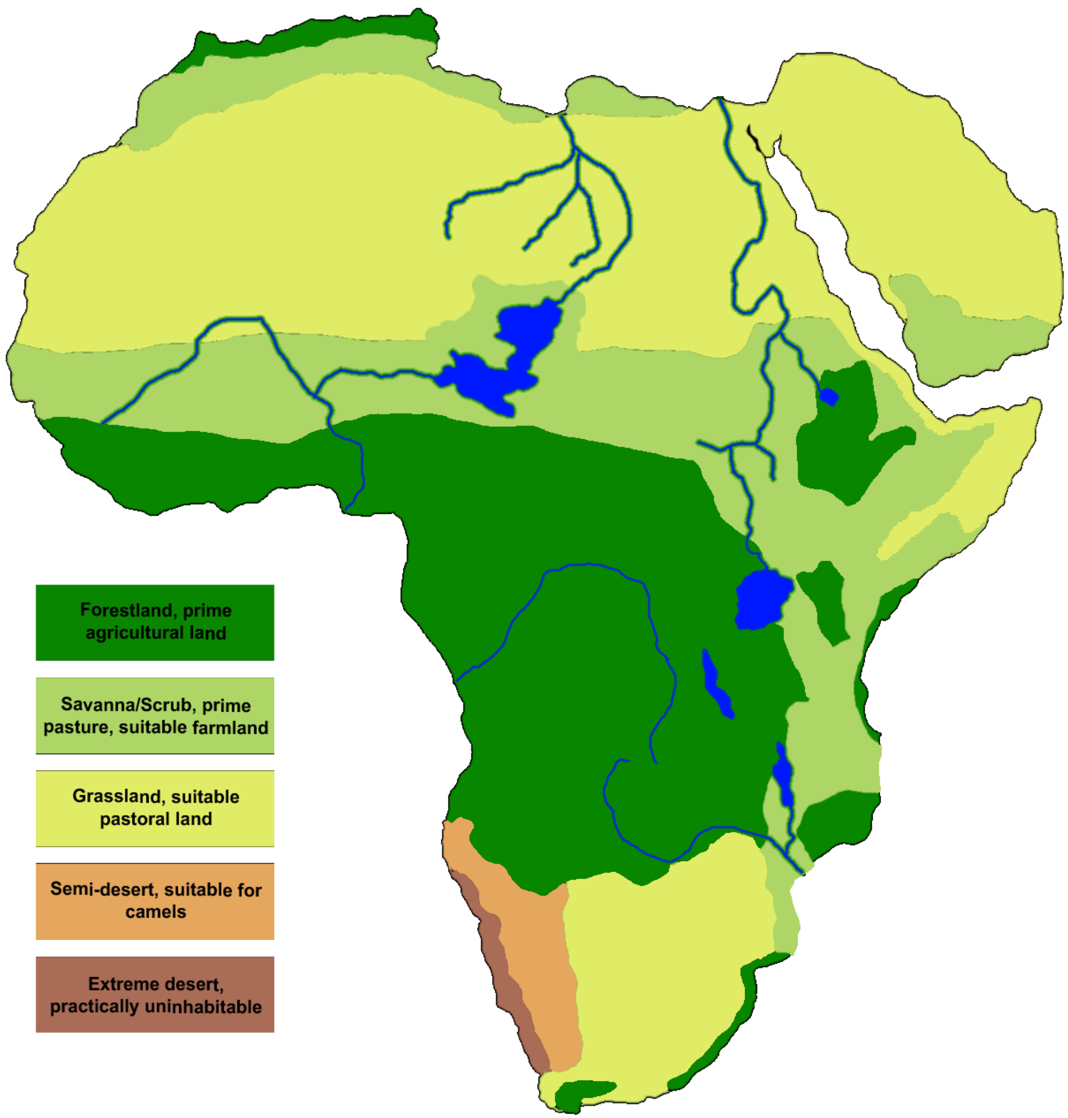
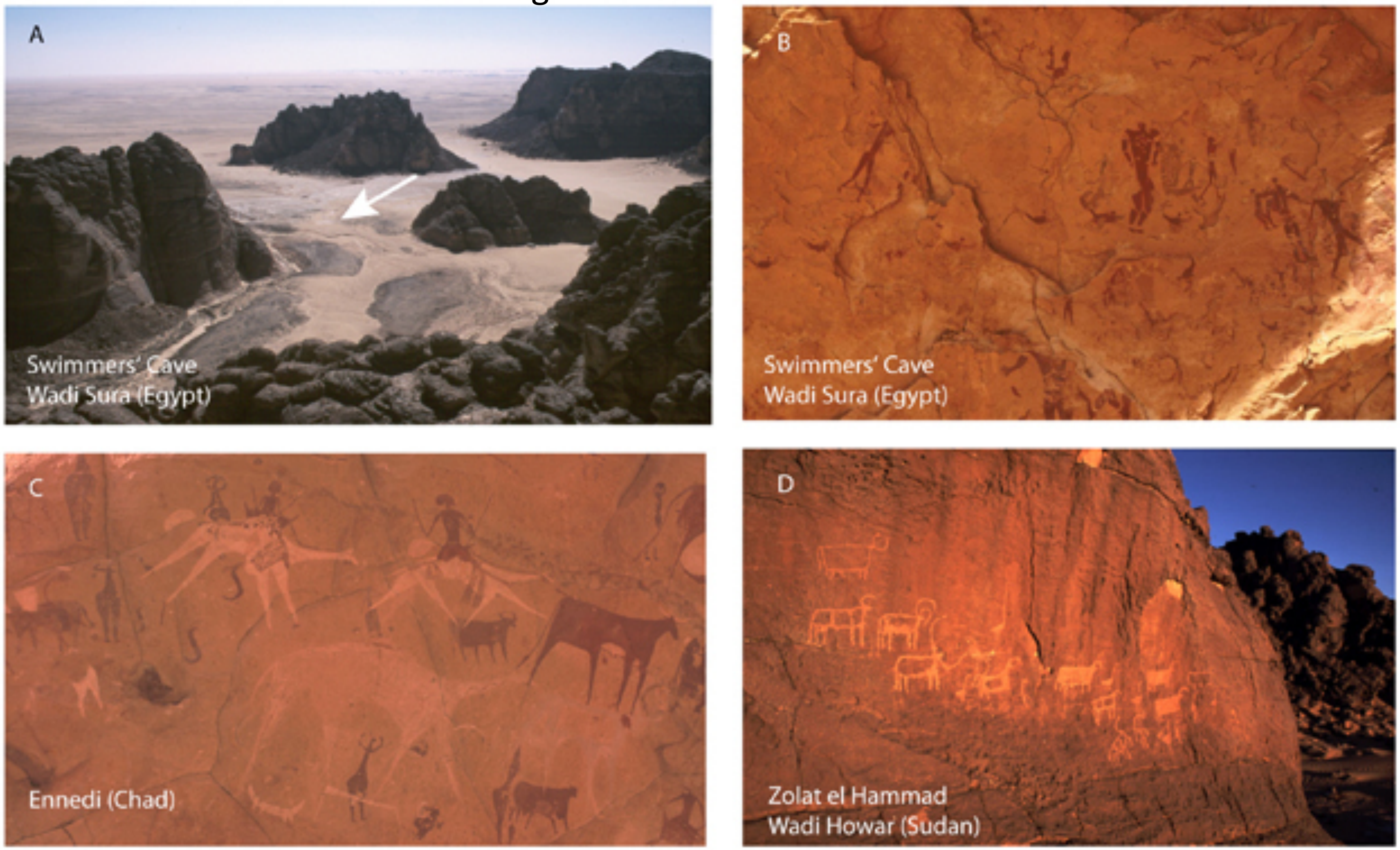


Figure from internet

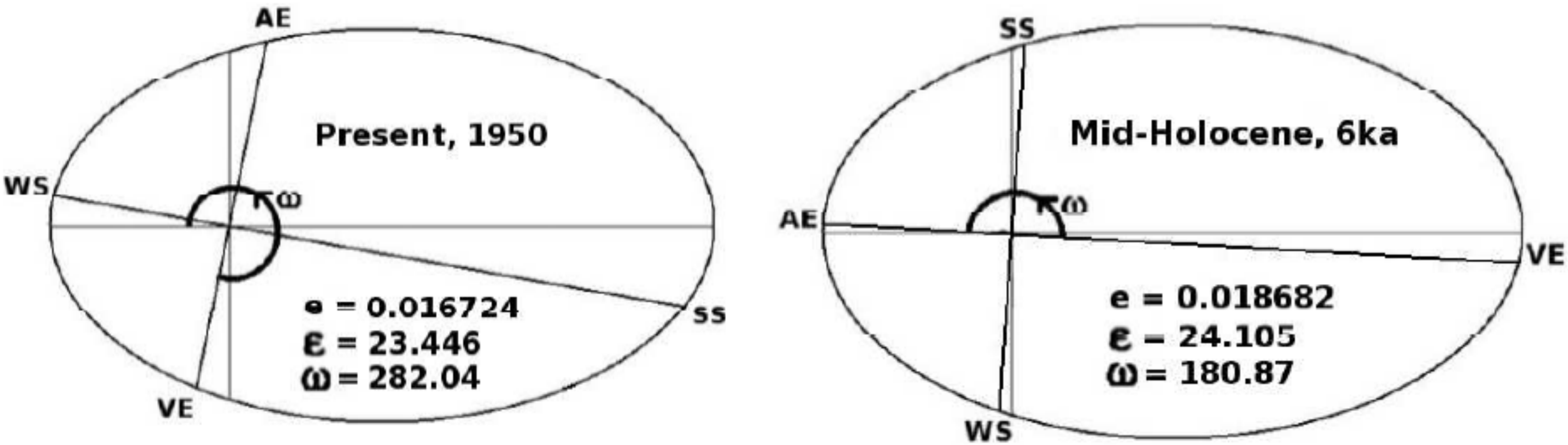
African Humid Period (14.8 – 5.5 ka)

Prehistoric Rock and Cave Paintings



deMenocal and Tierney (2012)

Orbital Configuration



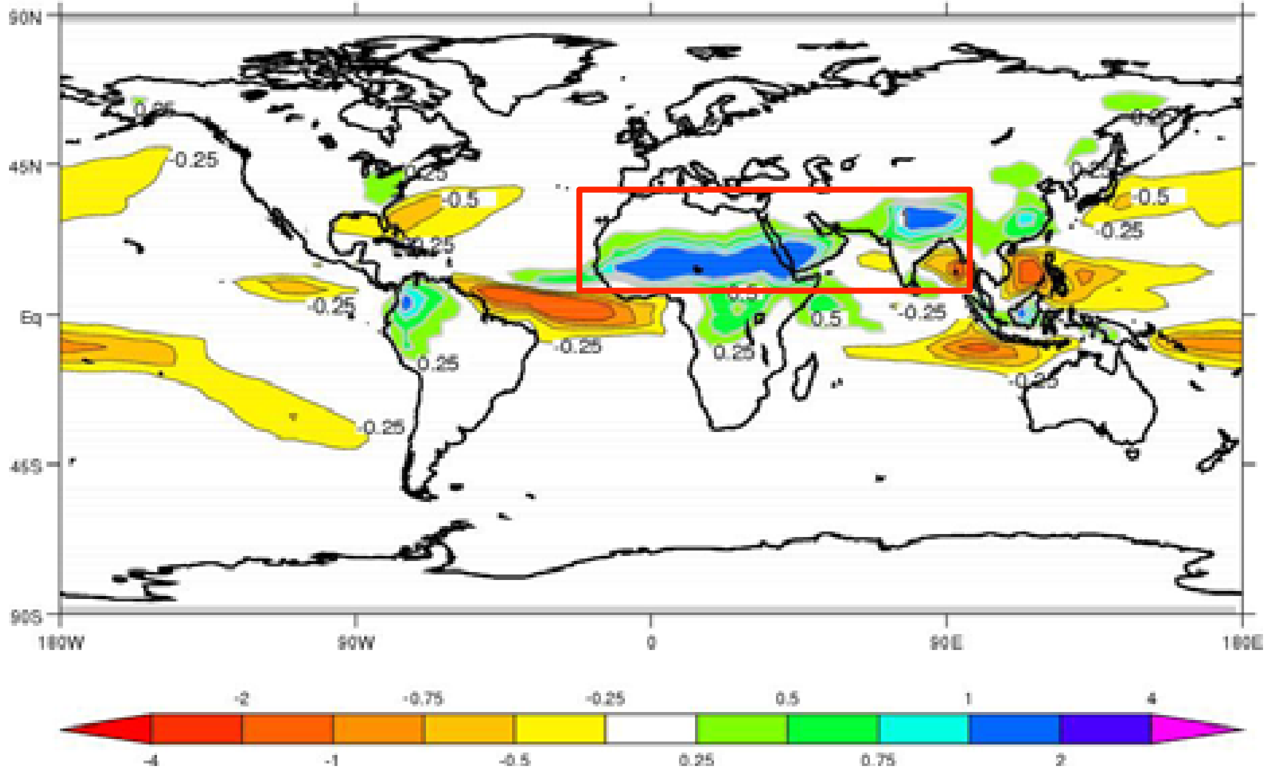
(J.H.C.Bosmns et al.,2012)

WW	Winter Solstice
SS	Summer Solstice
VE	Vernal Equinox
AE	Autumnal Equinox

e	Eccentricity
ε	Obliquity
ω	Precession: angle between the vernal equinox and perihelion

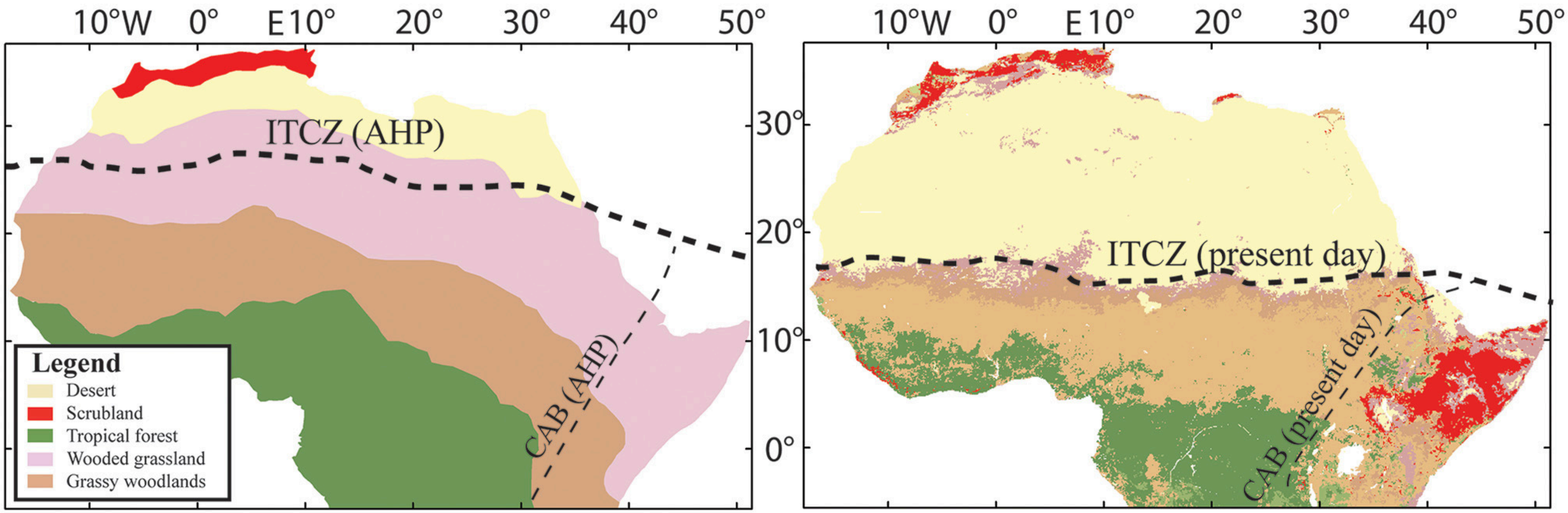
Enhanced Summer Monsoon During Early to Mid-Holocene

JJAS precipitation (6ka – PI), PMIP2



(Braconnot et al.,2007)

Orbital Influence on Vegetation



Wright (2017, Front. Earth Sci.)

Junginger et al. (2014)

Larrasoaña et al., 2013)

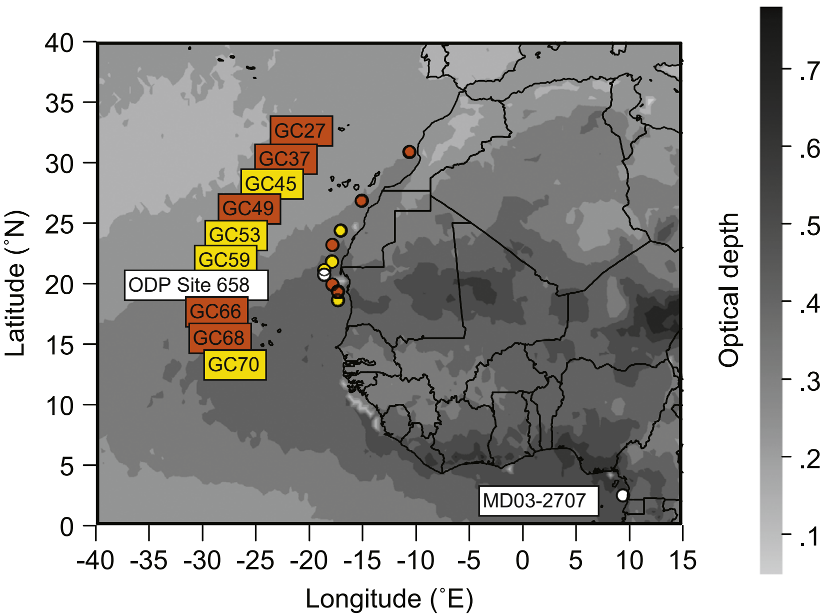
Humans Ended It?

Figure from internet

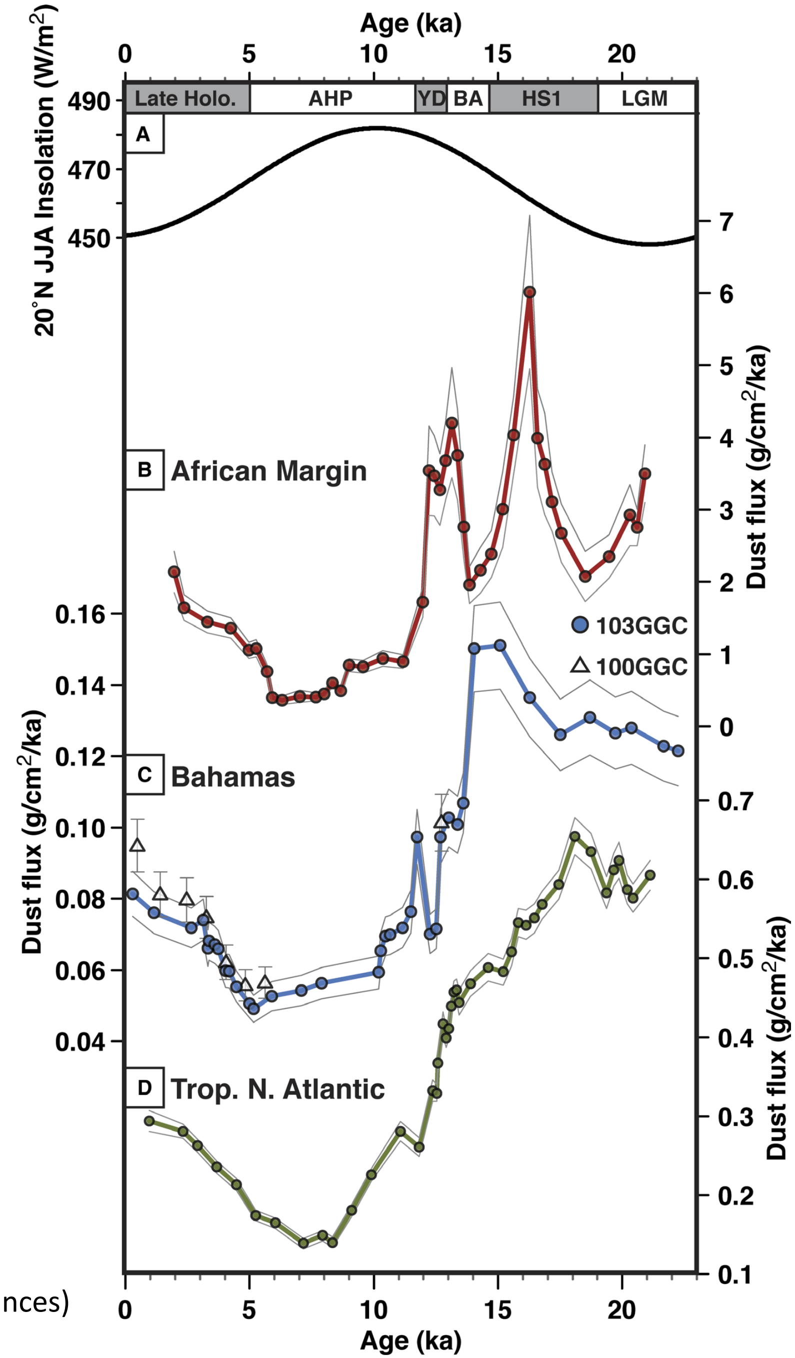
Wright (2017, Front. Earth Sci.)

Quantitative Evidence

Marine Sedimentary Cores



McGee et al. (2013, EPSL)



Williams et al. (2016, Science Advances)

The Effect of Dust Reduction on Mid-Holocene Climate

Model: CCSM3, same as that used in Liu et al. (2014)

Resolution: T31 (atm and lnd), gx3v5 (ocn and sea ice)

Orbital para: Same as PMIP 6ka experiment

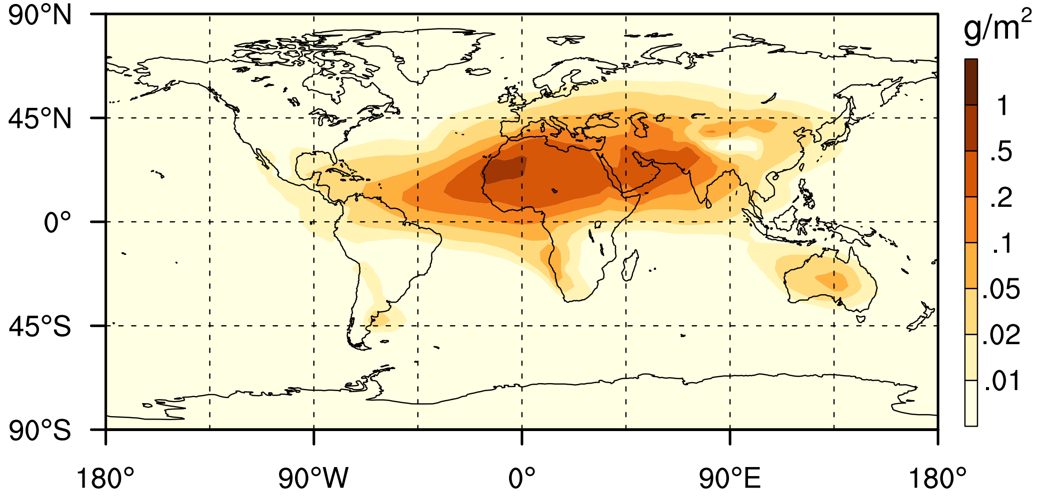
Dust is prescribed in this model

Dust is categorized into 4 bins: 0.1 – 1.0μm, 1.0–2.5 μm, 2.5–5.0 μm, and 5.0– 10.0 μm

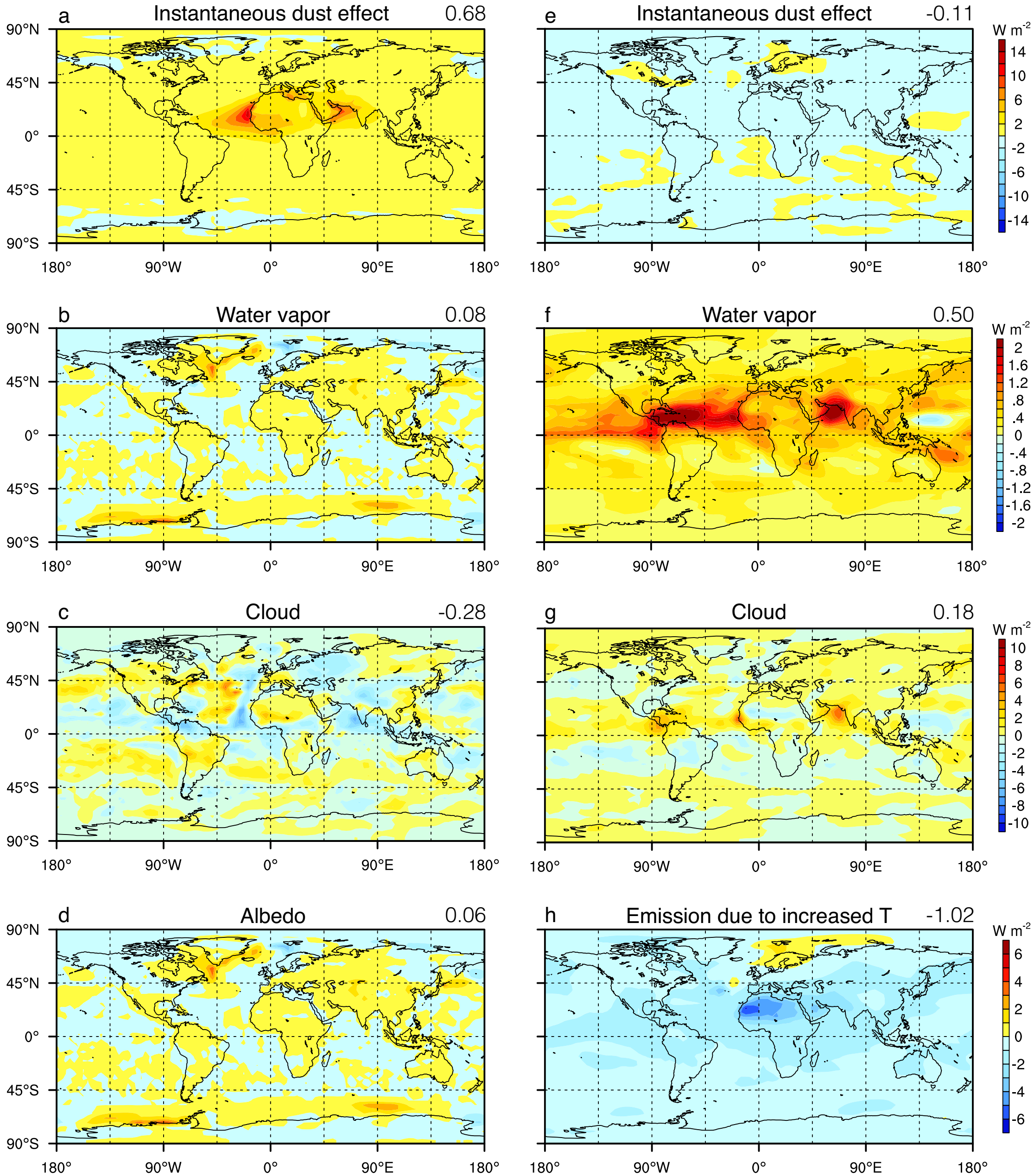
Indirect effect is not captured

Control expt: use the present-day dust loading

Perturb expt: reduce dust loading uniformly by a fraction (e.g. 100%)

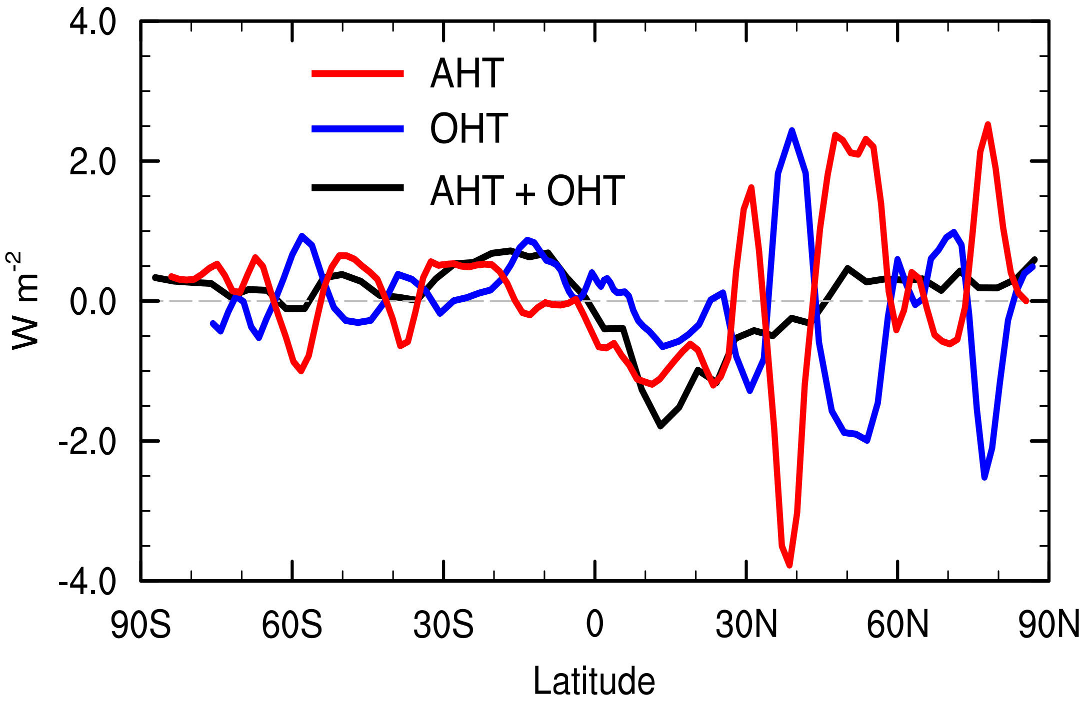


Radiative Effect



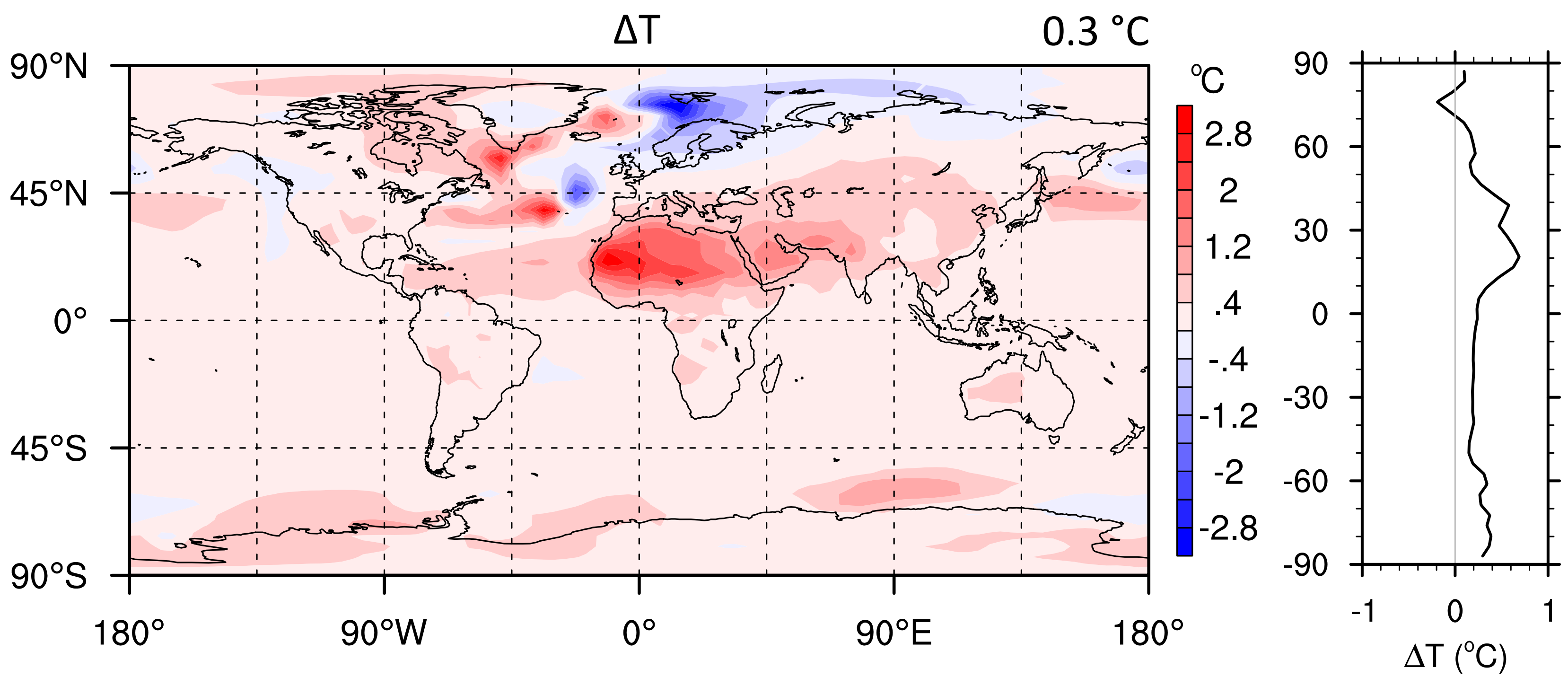
Atmospheric and Oceanic Heat Transport

Heat is transported away from the (previously) dusty region to other latitude (see the black curve)

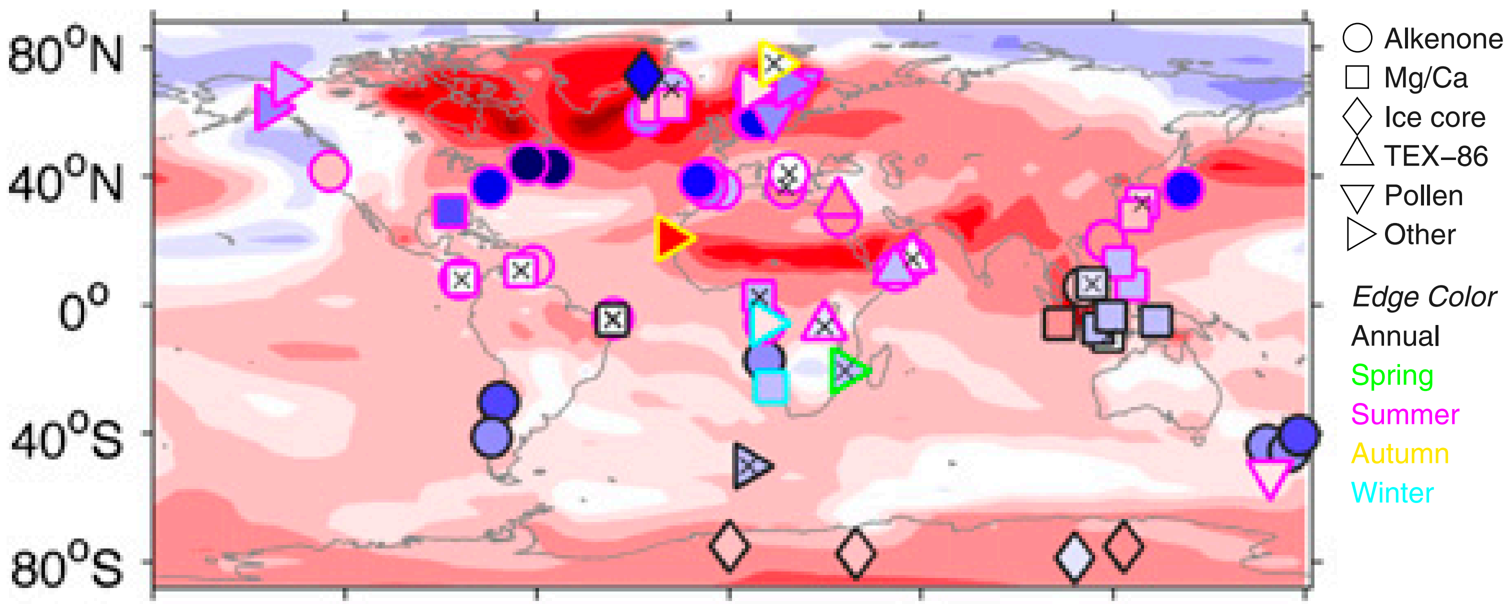


It does not increase the global mean energy input itself, but may trigger other positive feedbacks such as sea-ice albedo and water vapor effect

Results When Dust is Completely Removed



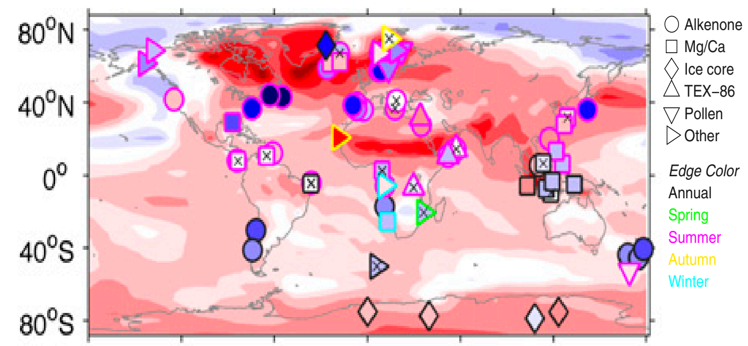
Location and Seasonal Bias of Proxy Data



Liu et al. (2014, PNAS), Marcott et al. (2013, Science)

Ignore the color shading

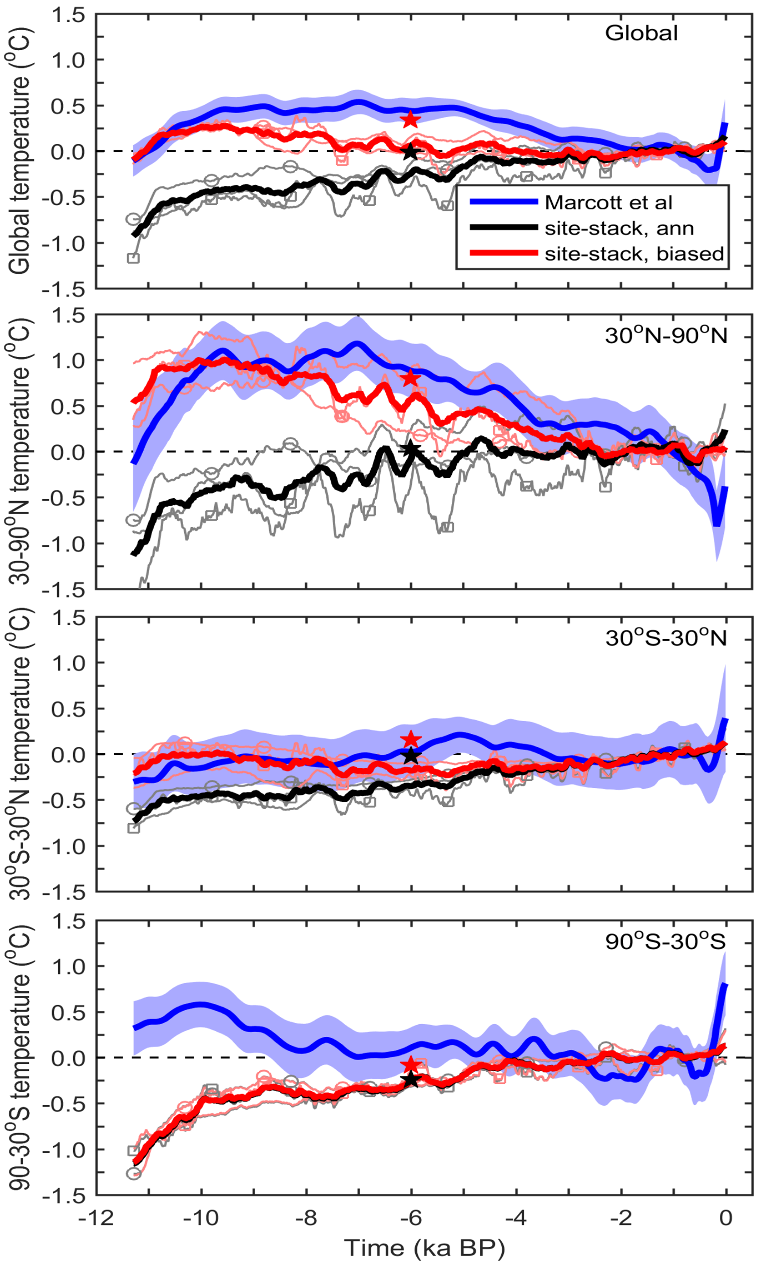
If global mean surface temperature is constructed from the model data only at proxy locations



Global ΔT = 0.28 °C

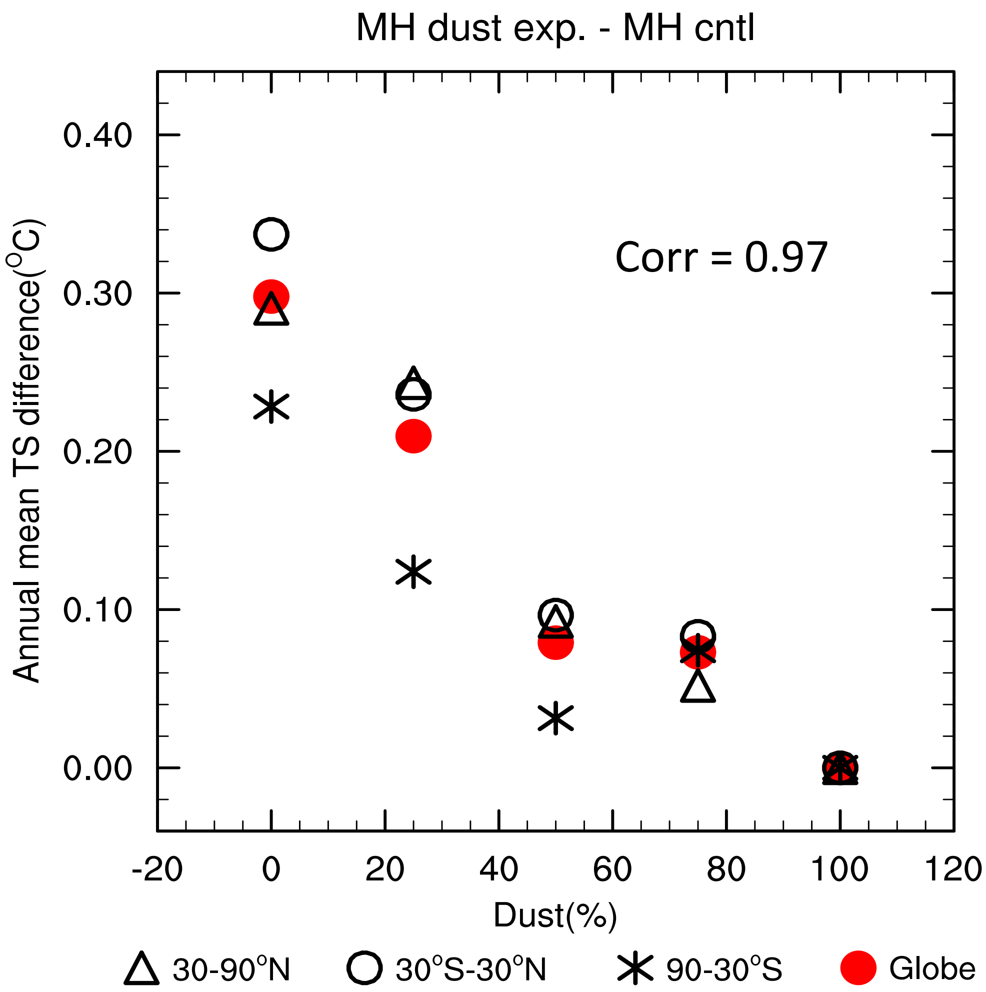
Northern hemisphere (30-90°N)	0.23 °C
Tropics (30°S-30°N)	0.33 °C
Southern hemisphere (90-30°S)	0.16 °C

Fraction of Model-Data Discrepancy Explained

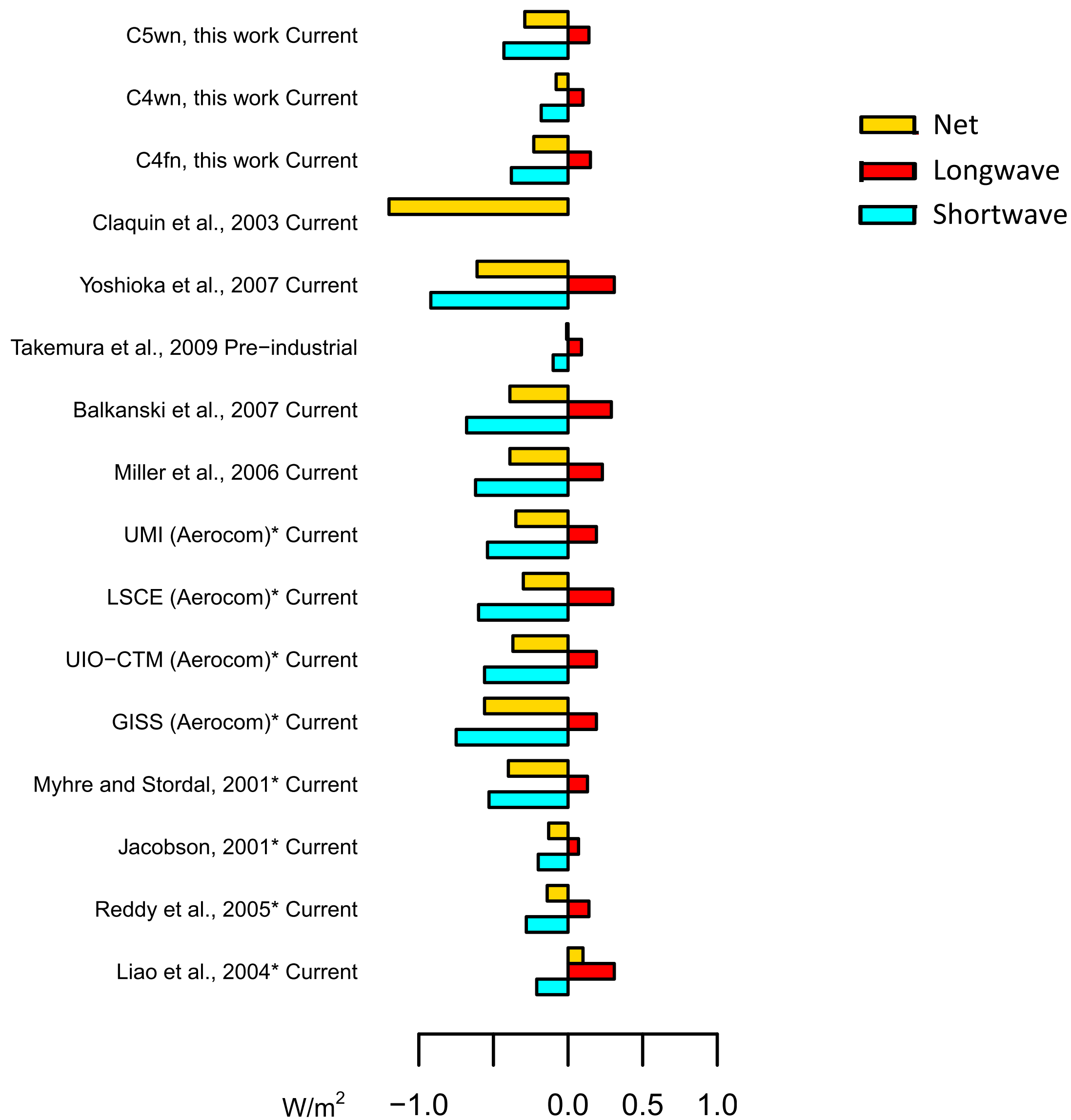


Stars show how much the red/ black curves would be shifted if dust were completely removed

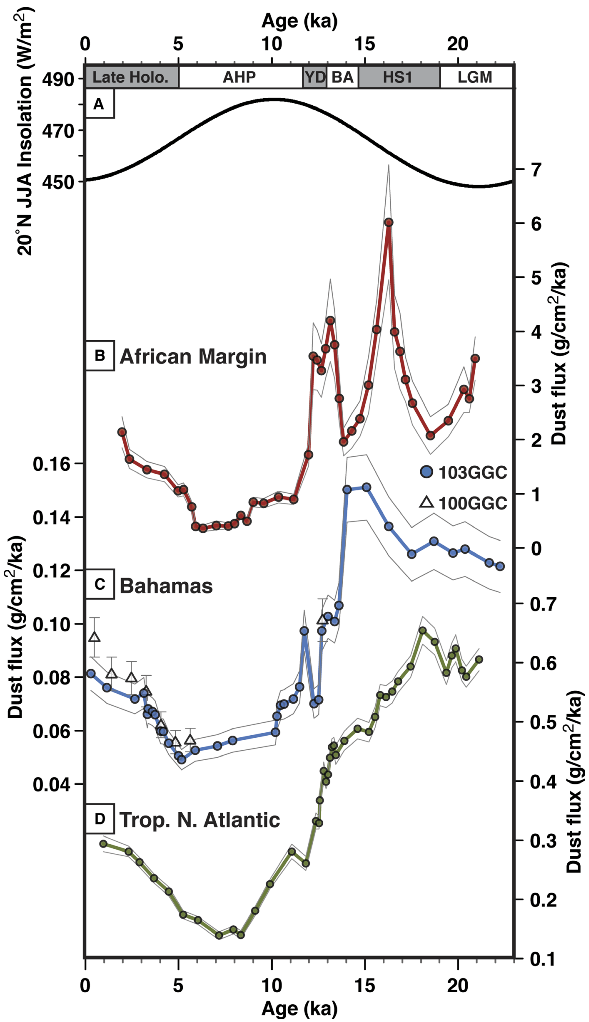
When only A Fraction of Dust is Removed



Direct Radiative Forcing of Dust in Other Models



Albani et al. (2014, J Adv. Modeling Earth Sys.)



Williams et al. (2016, Science Advances)

Dust modeling study that fits the observations well indicates that dust emission during mid-Holocene was 73% lower than pre-industrial (Egerer et al., 2016)

This corresponds to a 0.22 °C increase in global (annual) mean surface temperature

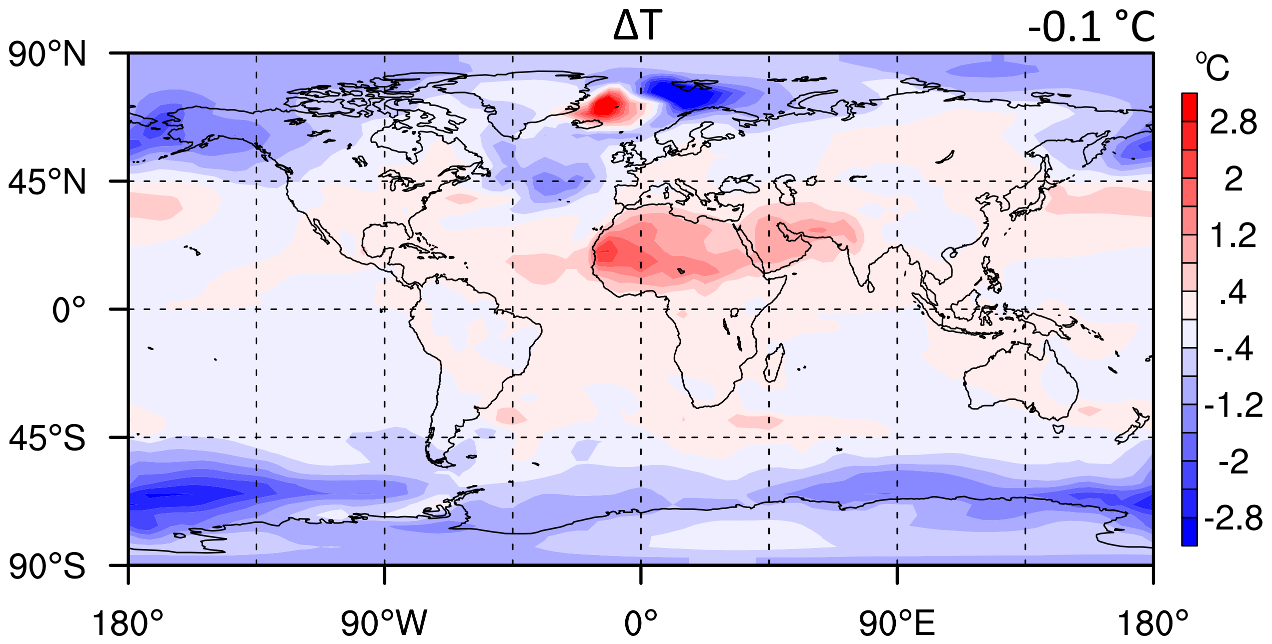
Therefore, considering the influence of dust in models could at least partially resolve the Holocene temperature conundrum.

Removing global dust = global warming?

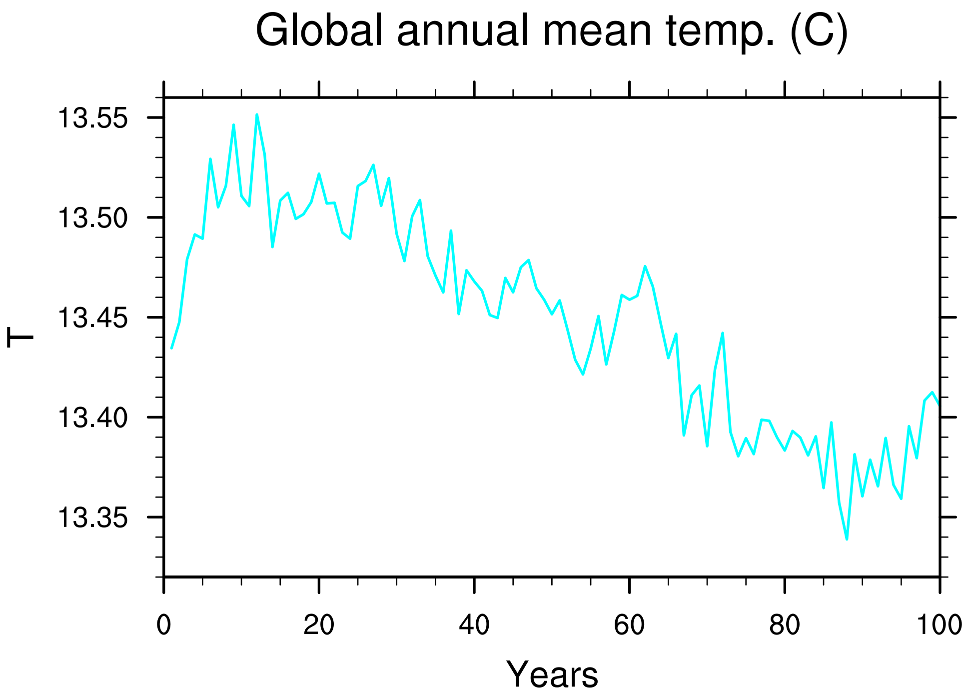
No! We will give two examples

Example 1: Pre-industrial

Same model, remove all the dust



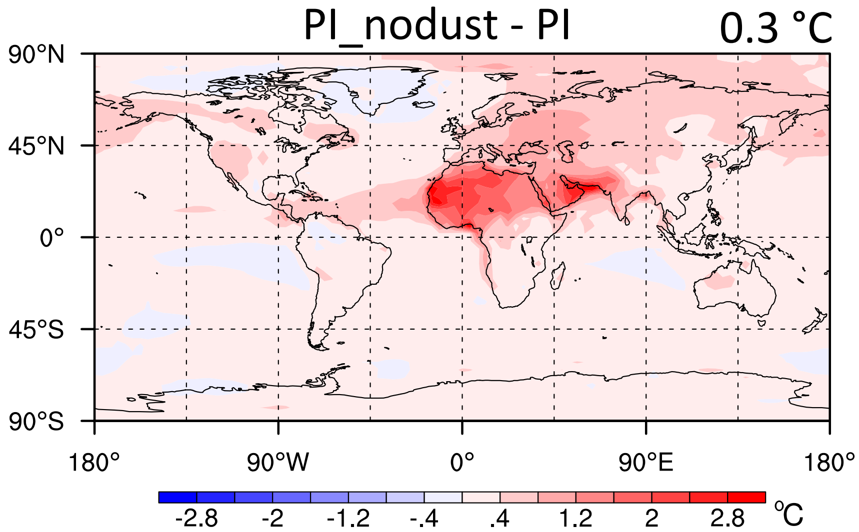
Example 1: Pre-industrial

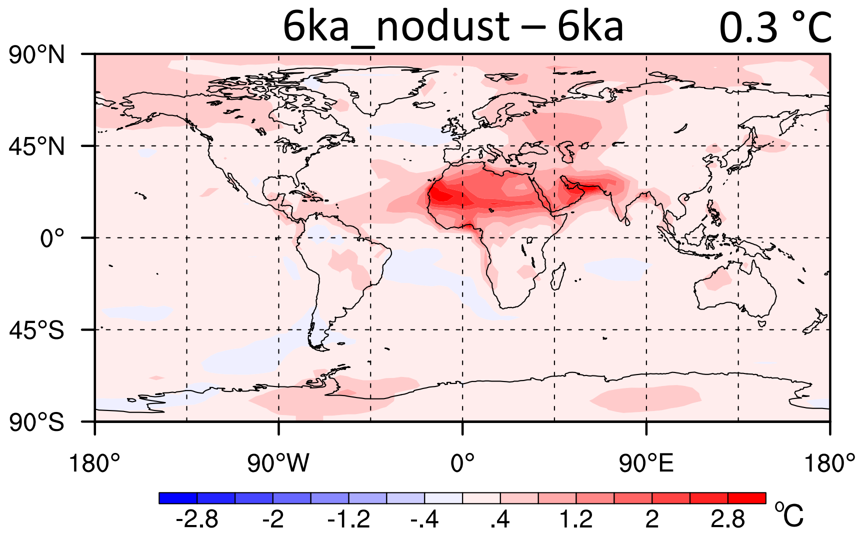


Twenty – member ensemble were performed with CCSM3

When the Effect of Dynamic Ocean is Removed

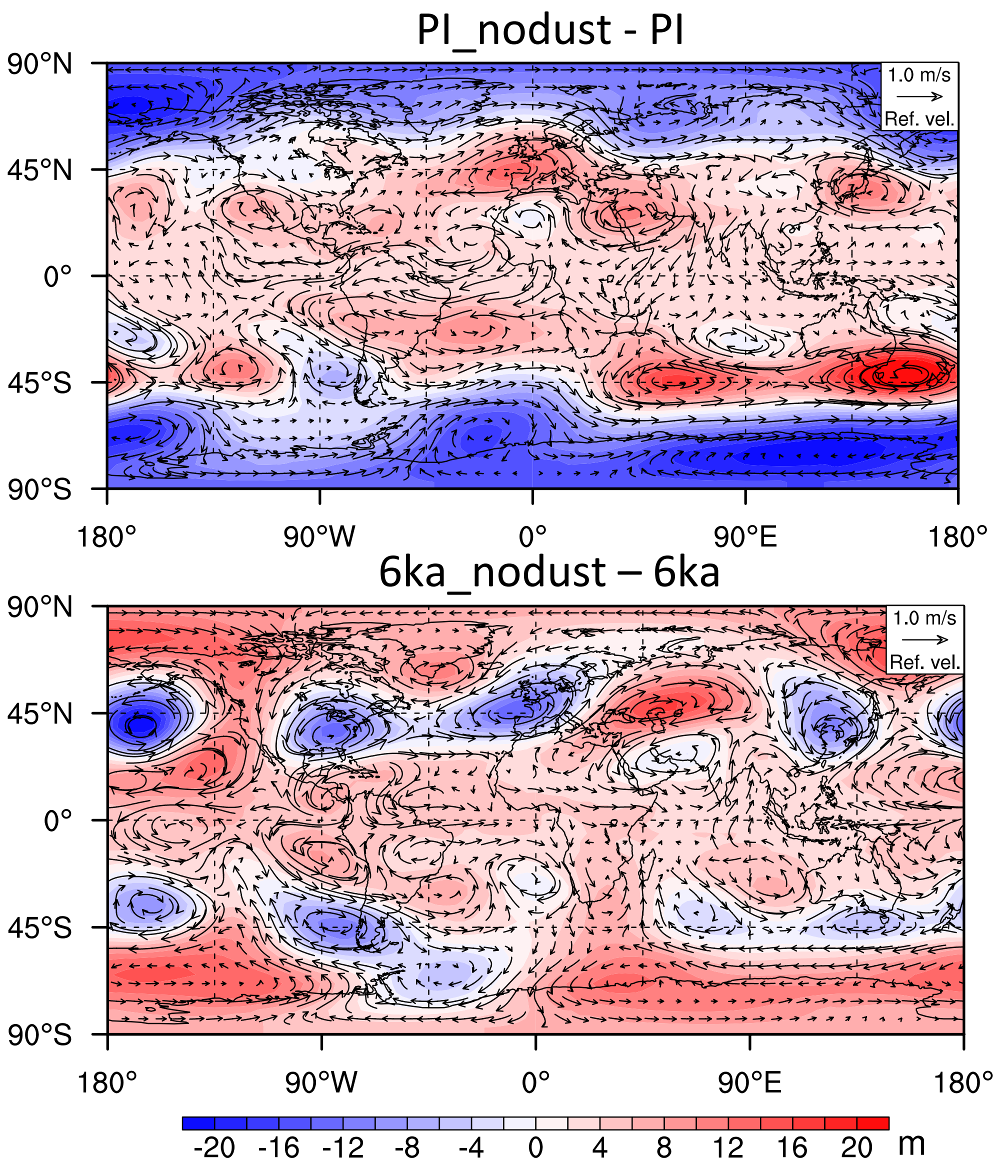
--- Slab Ocean Results





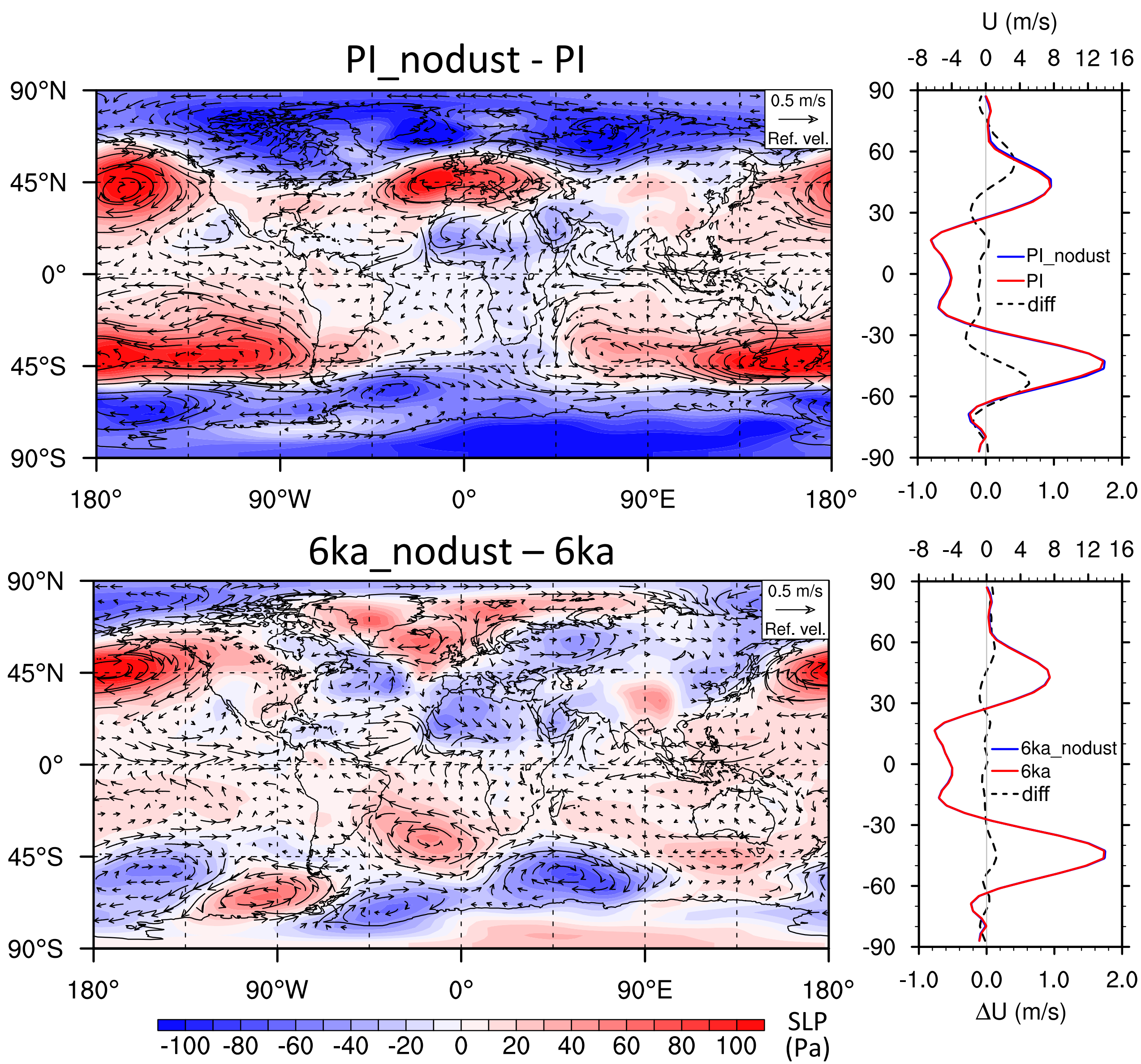
The negative feedback of the ocean and sea-ice dynamics can overwhelm the positive forcing of dust removal, depending on the background climate state

The Trigger is in the Atmosphere

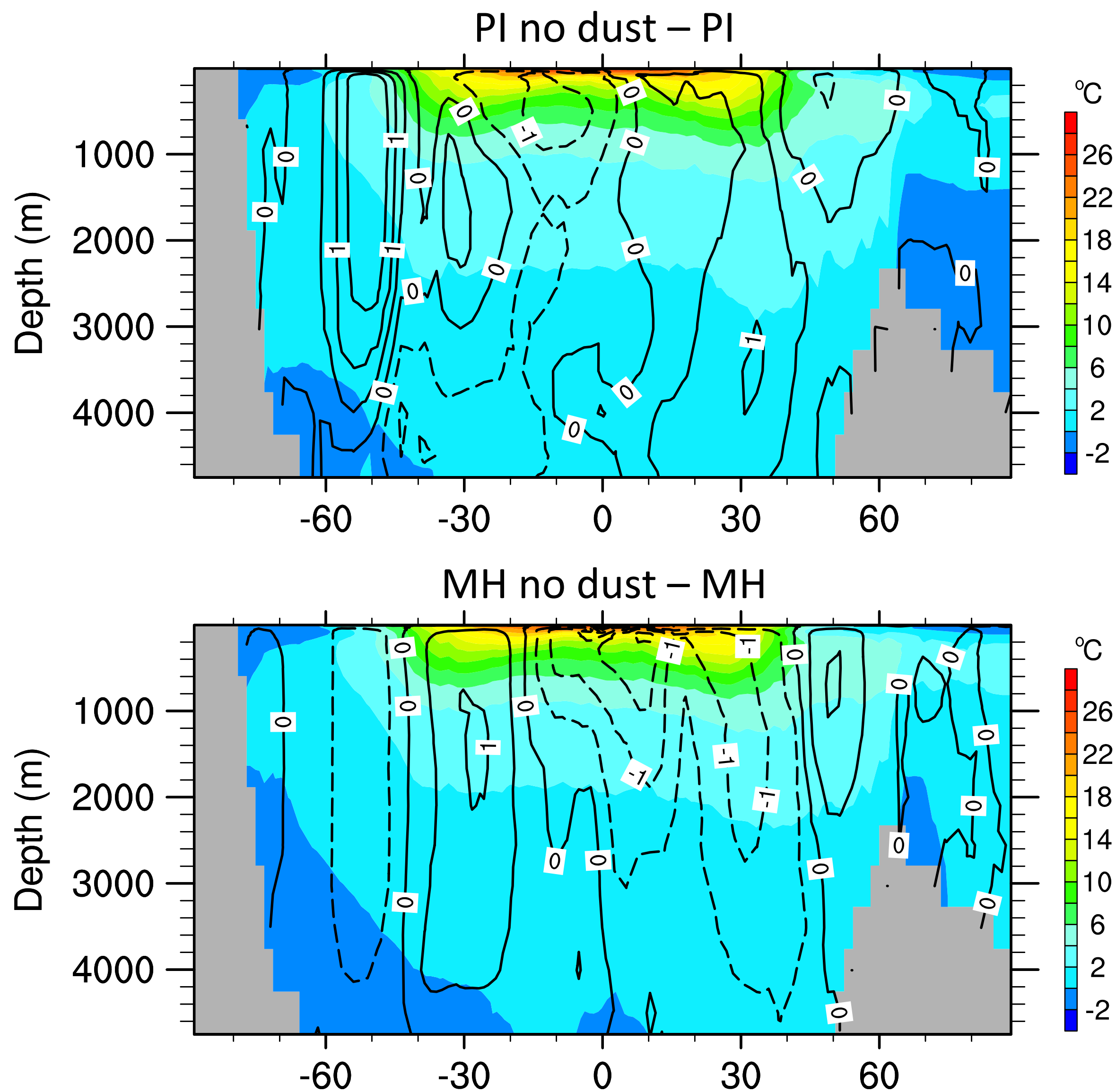


Anomalies of 200 mbar geopotential height (color shading) and wind (arrows) for **year 1**

Anomaly of sea-level pressure and zonal mean zonal wind at equilibrium

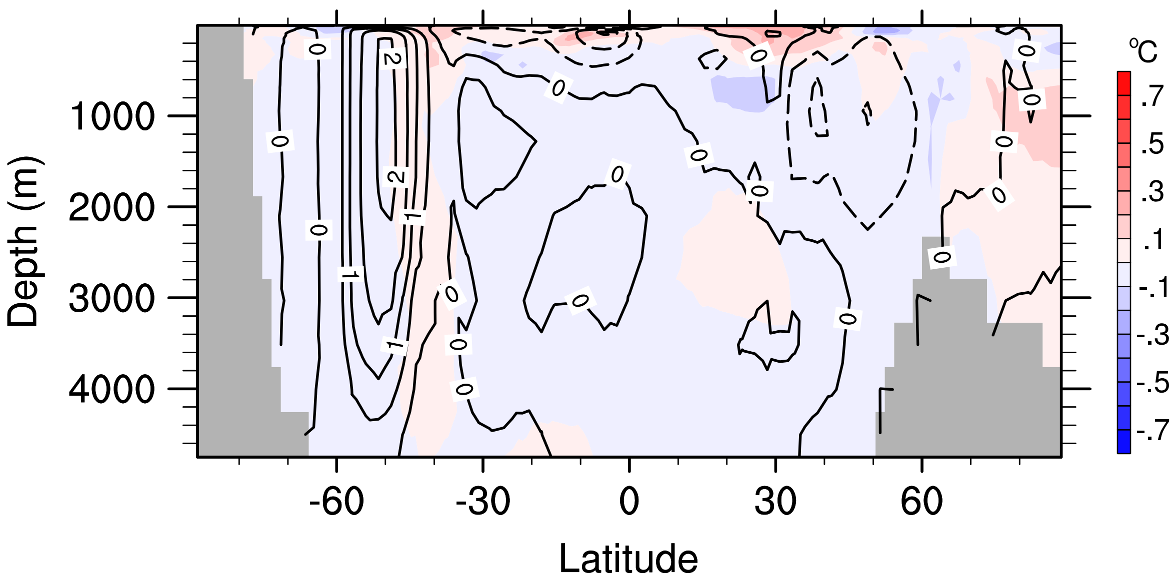


Ocean Response



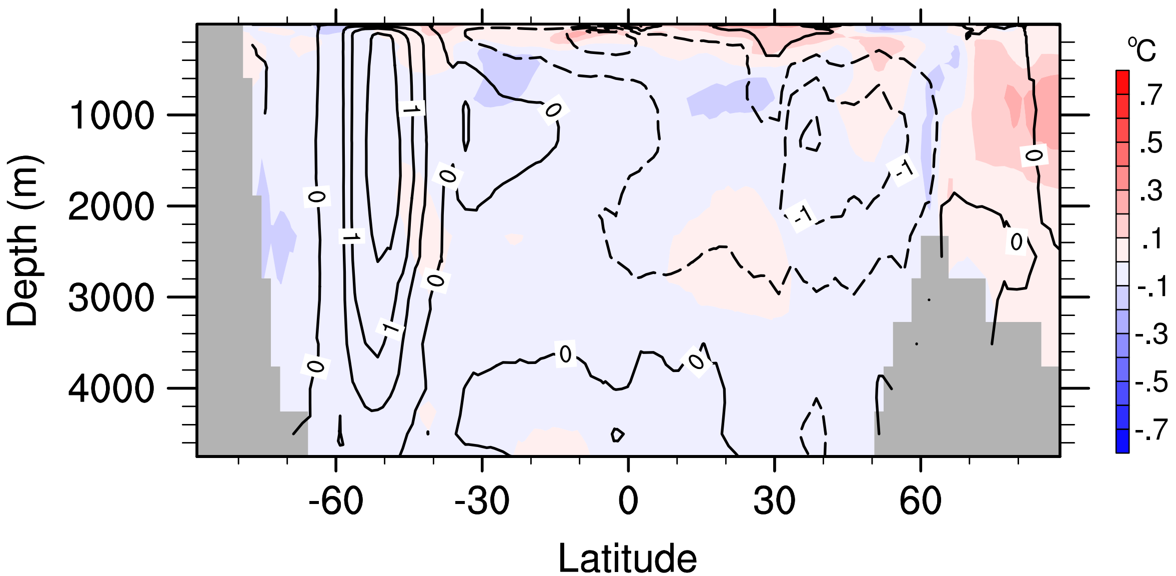
Contour lines are the changes in meridional ocean circulation (year 1).
Color shadings are the zonal mean ocean temperature

PI no dust – PI (year 6-10)

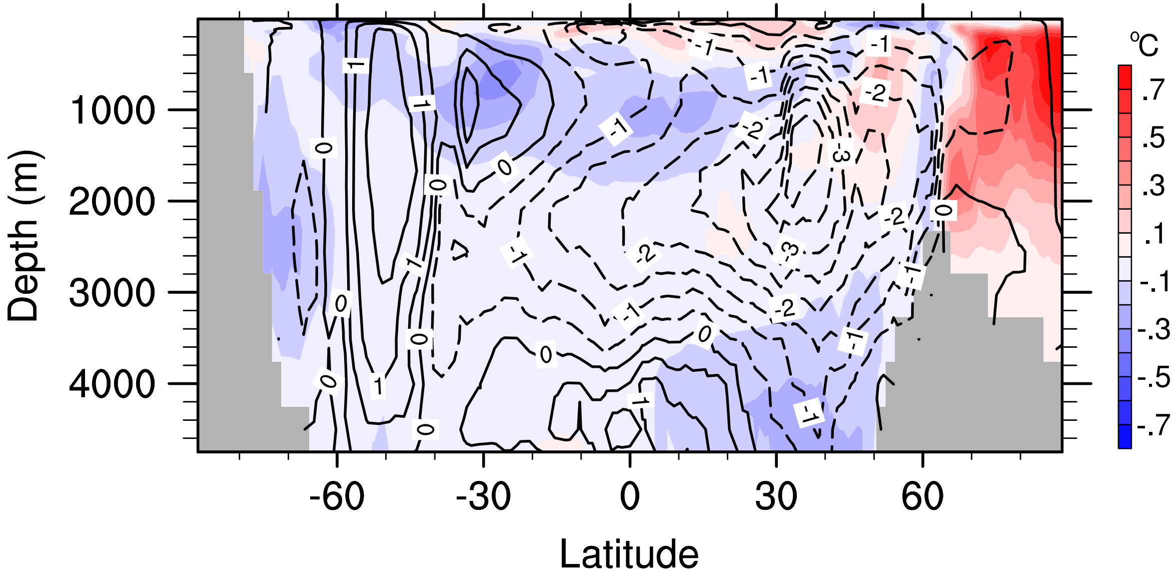


Enhanced southern westerlies induces a northward Ekman transport which cools the surface of the Southern Ocean.

PI no dust – PI (year 26-30)

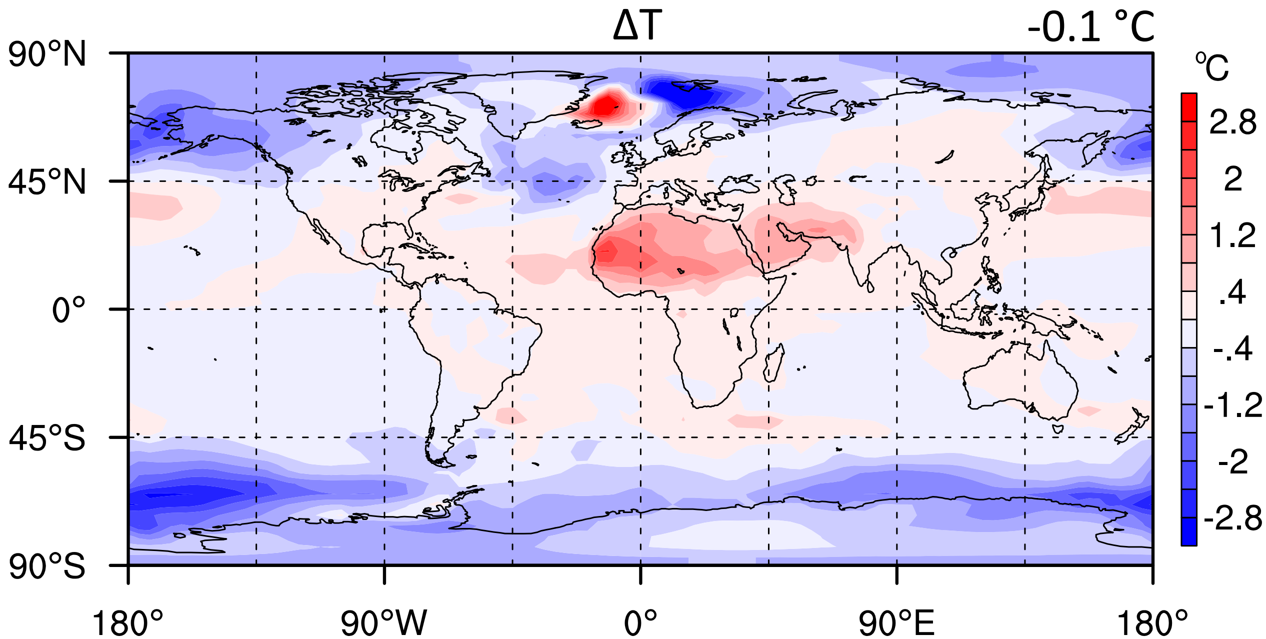


PI no dust – PI (year 91-100)



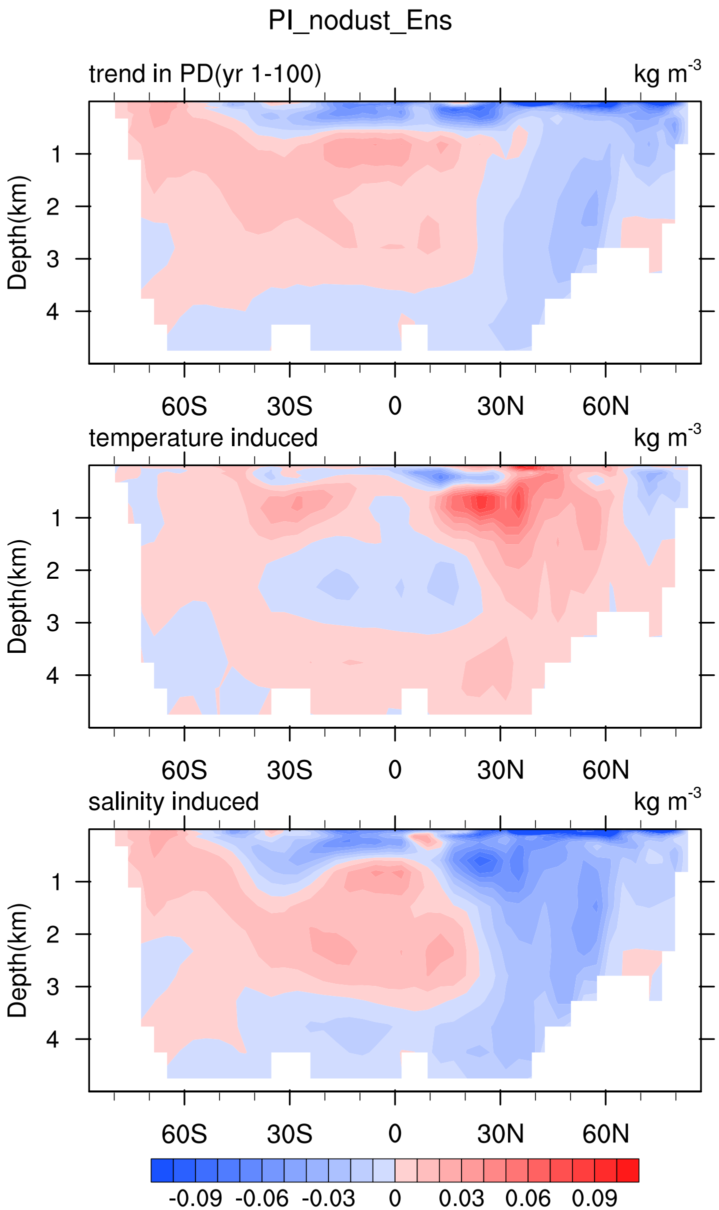
Example 1: Pre-industrial

Same model, remove all the dust

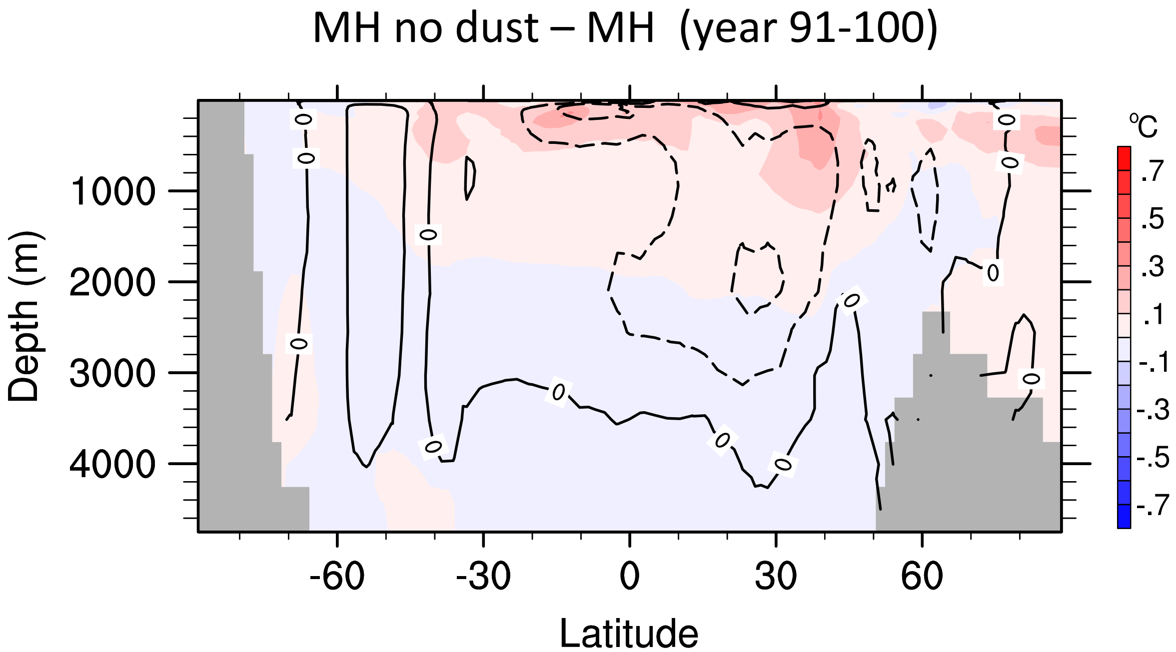


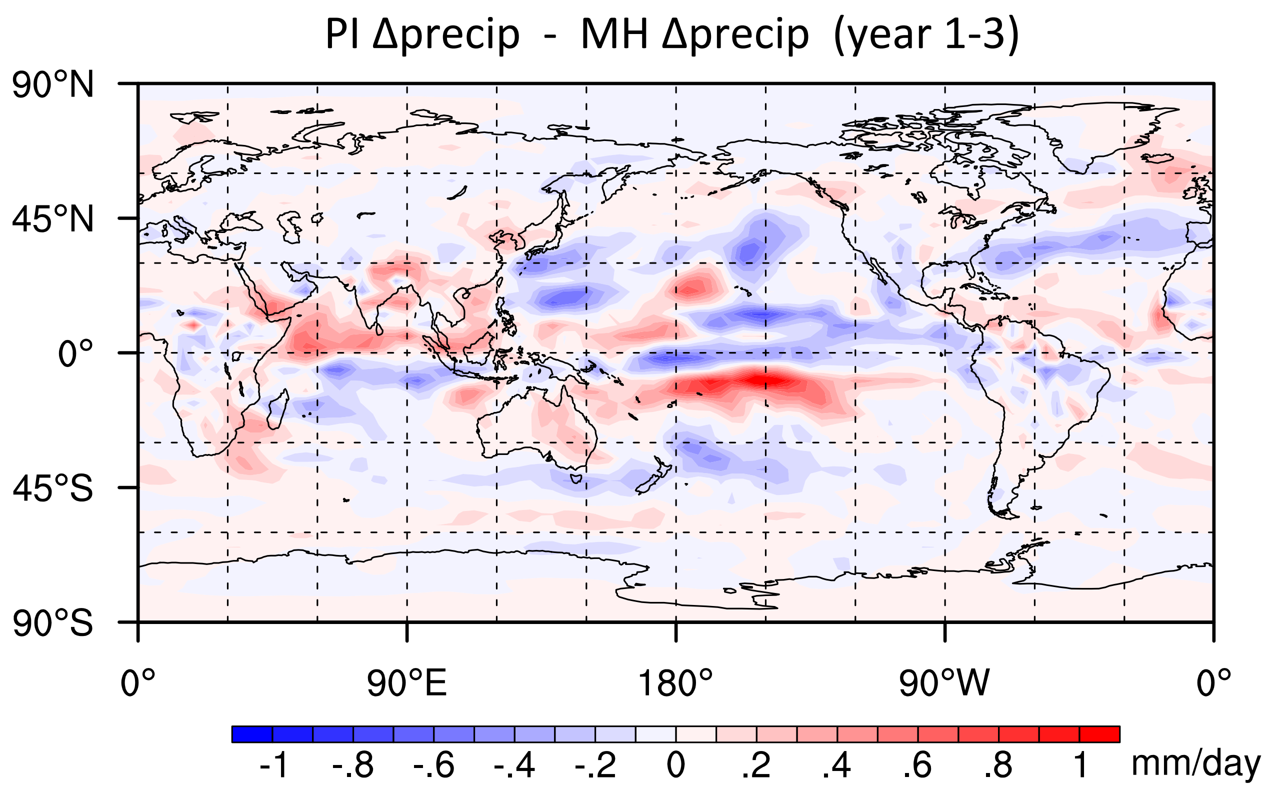
This is equivalent to saying that the dust has a warming effect for the pre-industrial climate

Why Does AMOC Weaken



In contrast, the mid-Holocene ocean shows a general warming

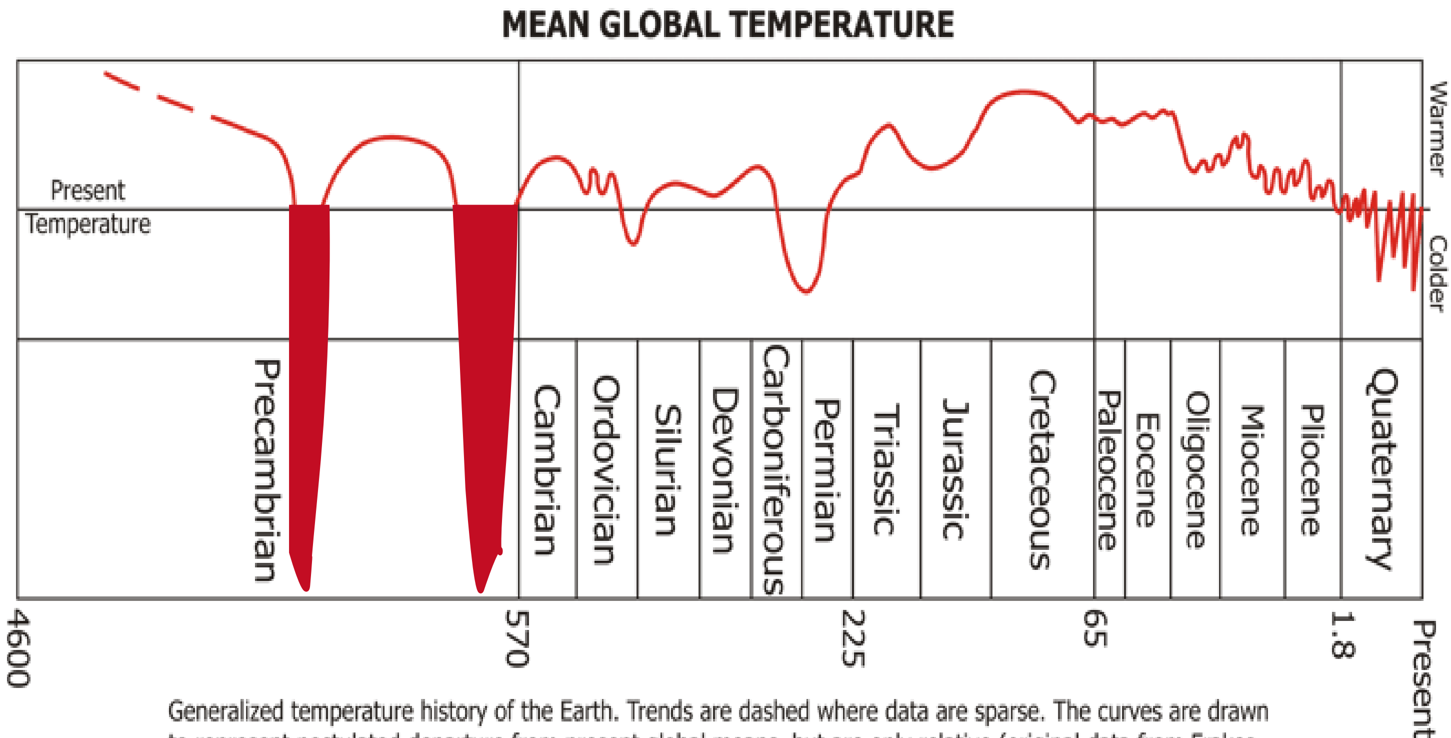



PI Δprecip - MH Δprecip (year 1-3)
90°N
45°N
0°
45°S
90°S
0°
90°E
180°
90°W
0°
-1
-.8
-.6
-.4
-.2
0
.2
.4
.6
.8
1
mm/day

Note that the model is not perfect, other models may obtain a warming of the pre-industrial climate when dust is removed

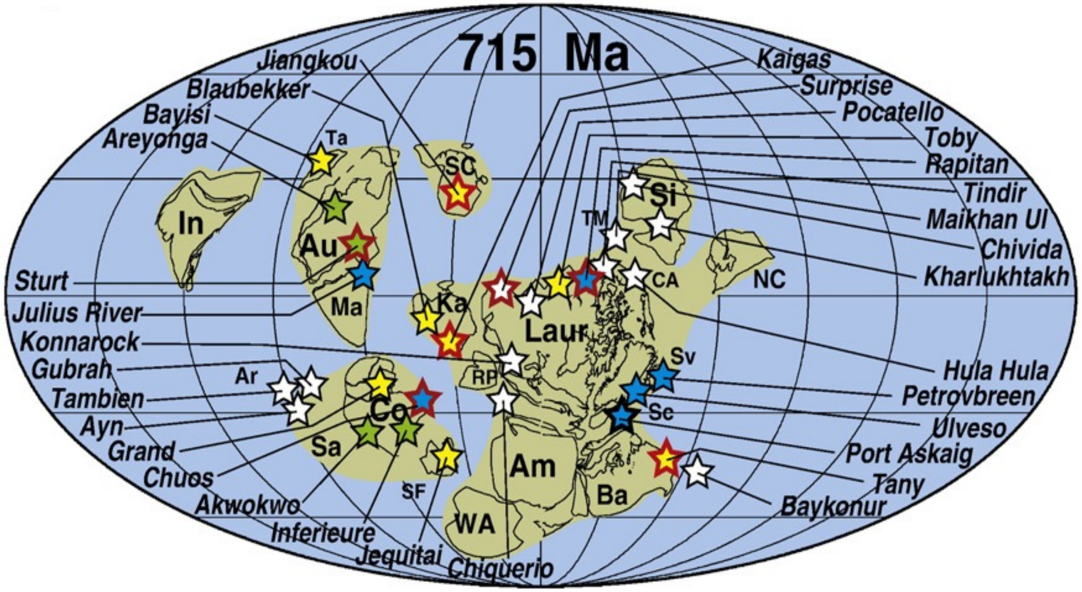
But the results indicate that there is possible dependence of climate response on the background climate

Example 2: Snowball Earth



Generalized temperature history of the Earth. Trends are dashed where data are sparse. The curves are drawn to represent postulated departure from present global means, but are only relative (original data from Frakes, 1979; diagram modified from Bradley, 1985). Ages are given in millions of years.

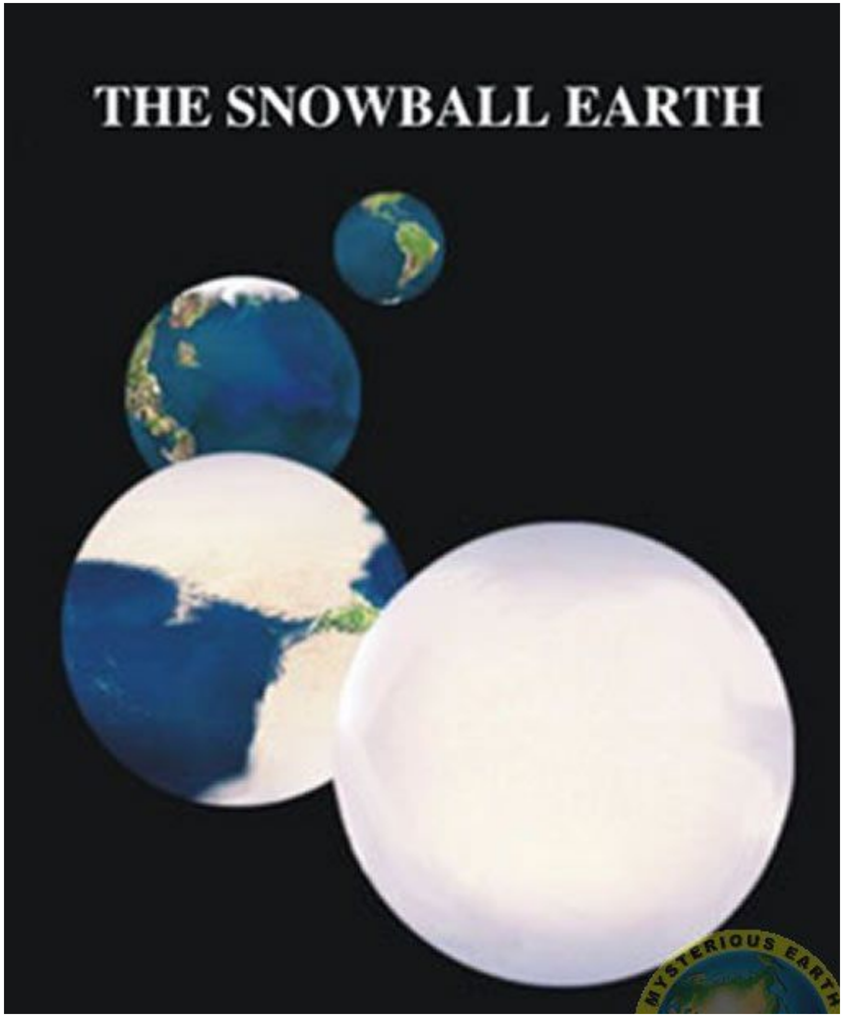
Neoproterozoic (1000 Ma – 541 Ma) Snowball Earth Events



Hoffman and Li (2009)

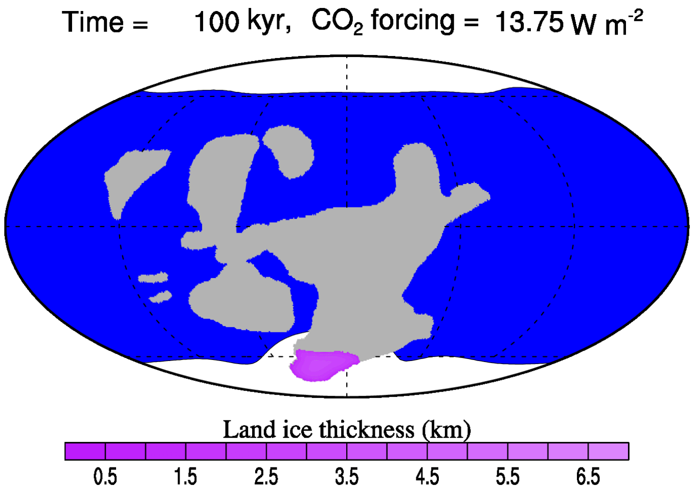
Namibia, Africa
Hoffman & Schrag (2002)

Snowball Earth



Hyde et al. (2000, Nature)

Weak sun + little CO_2



Liu et al. (2010, JGR)

Effect of Dust on Snowball Earth Formation

Model: CESM1.2.2

Resolution: T31 (atm and lnd), gx3v5 (ocn and sea ice)

Orbital para: Same as 1850 AD

Sun: 6% weaker than present day

Continents: 720 Ma

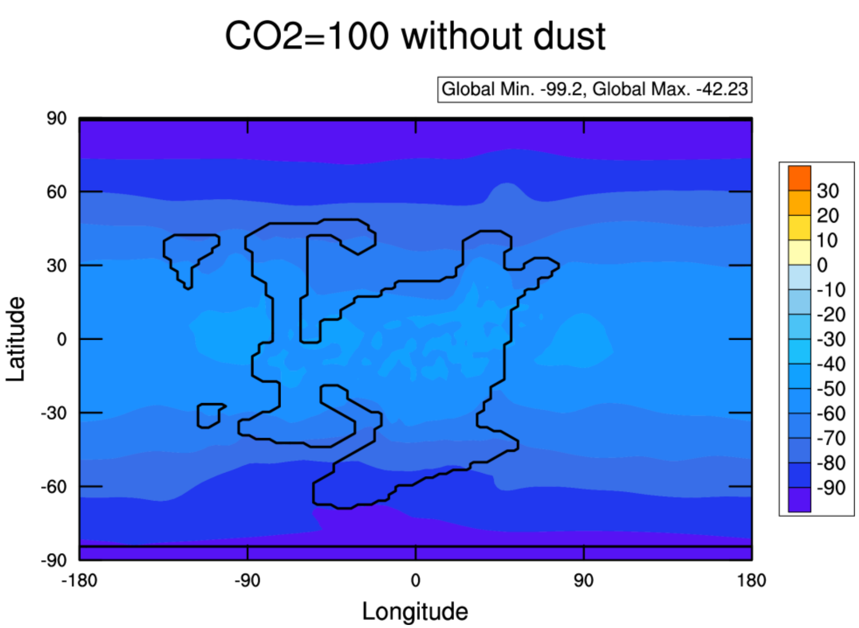
Vegetation: None

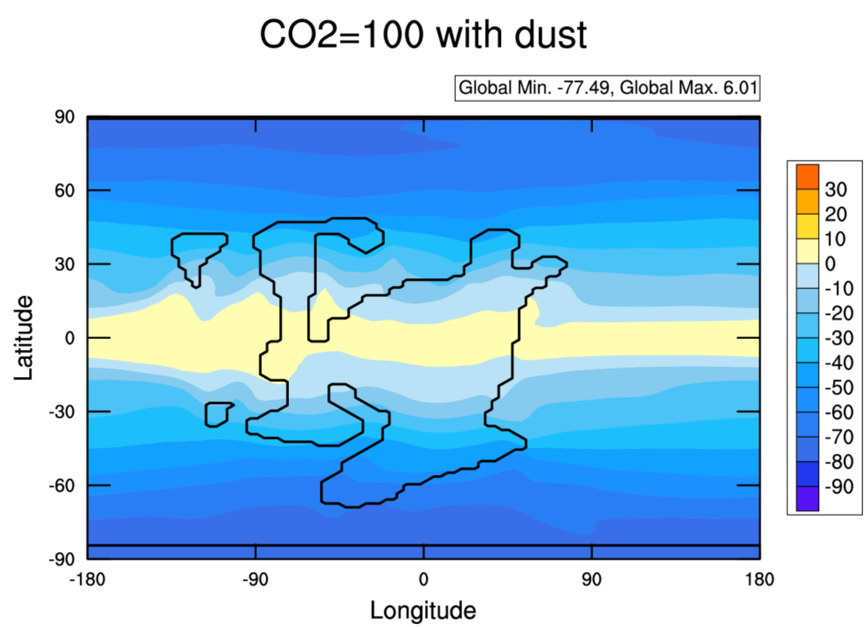
Dust emission, transportation and deposition are calculated by the model

Two cases: 1) dust emission is prohibited; 2) allowed

Effect of Dust on Snowball Earth Formation

The Earth enters a (hard) snowball Earth when pCO_2 = { 350 ppmv, no dust emission; 100 ppmv, with dust emission }



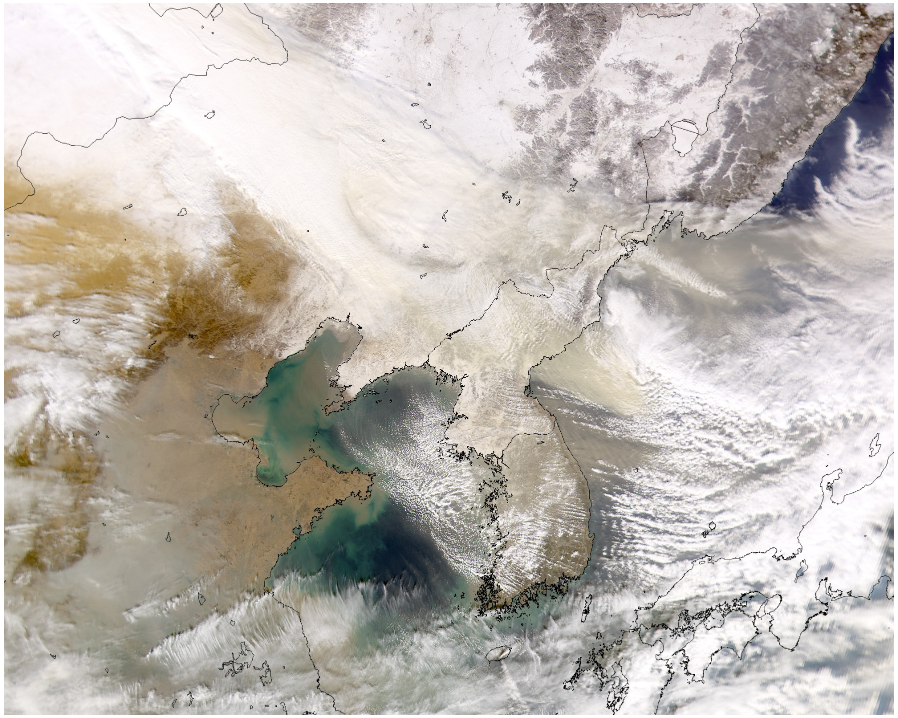


Effect of Dust on Snowball Earth Formation

Clearly dust has a warming effect rather than cooling for the snowball Earth climate

Reason： dust reduces surface albedo (as well as planetary albedo)

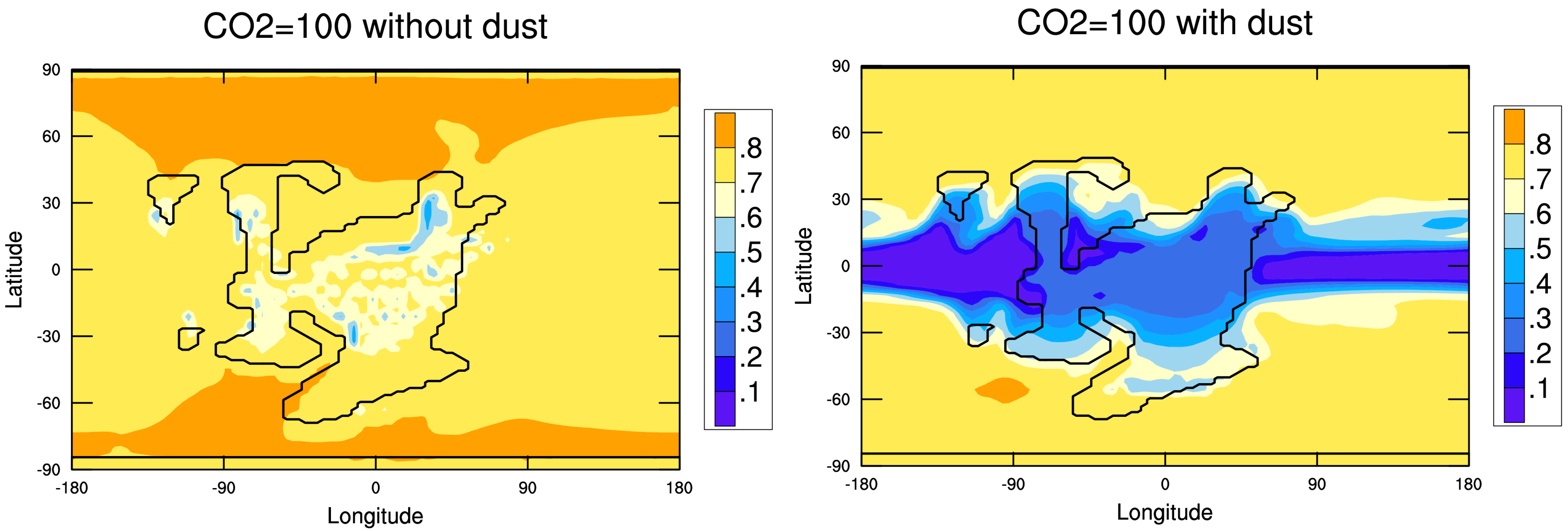
nsidc.org



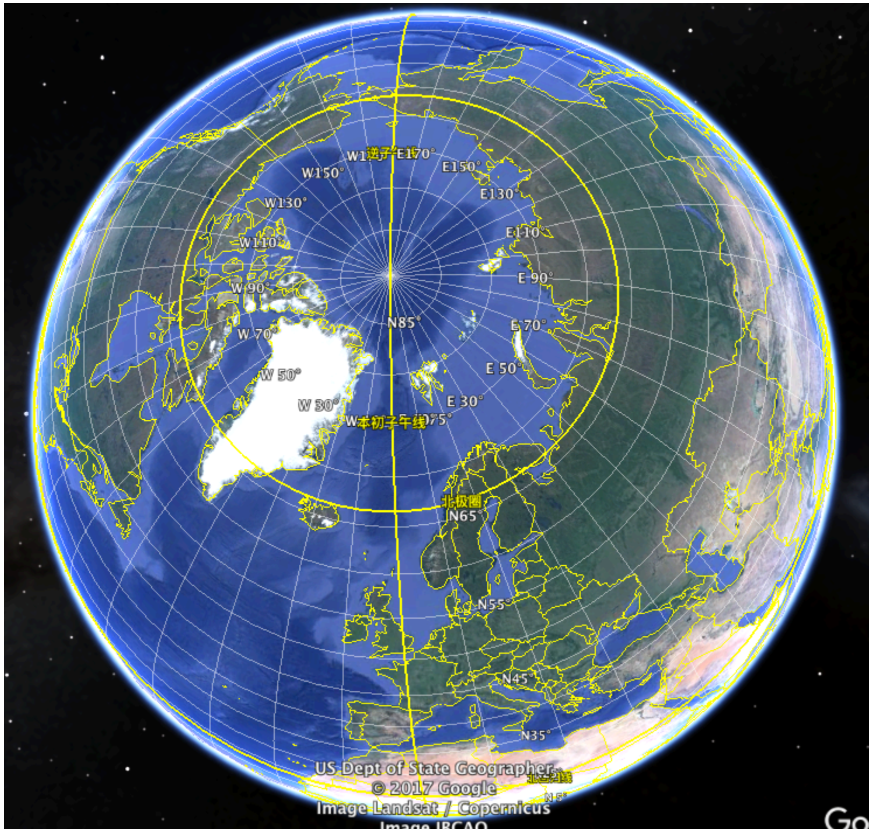
earthobservatory.nasa.gov

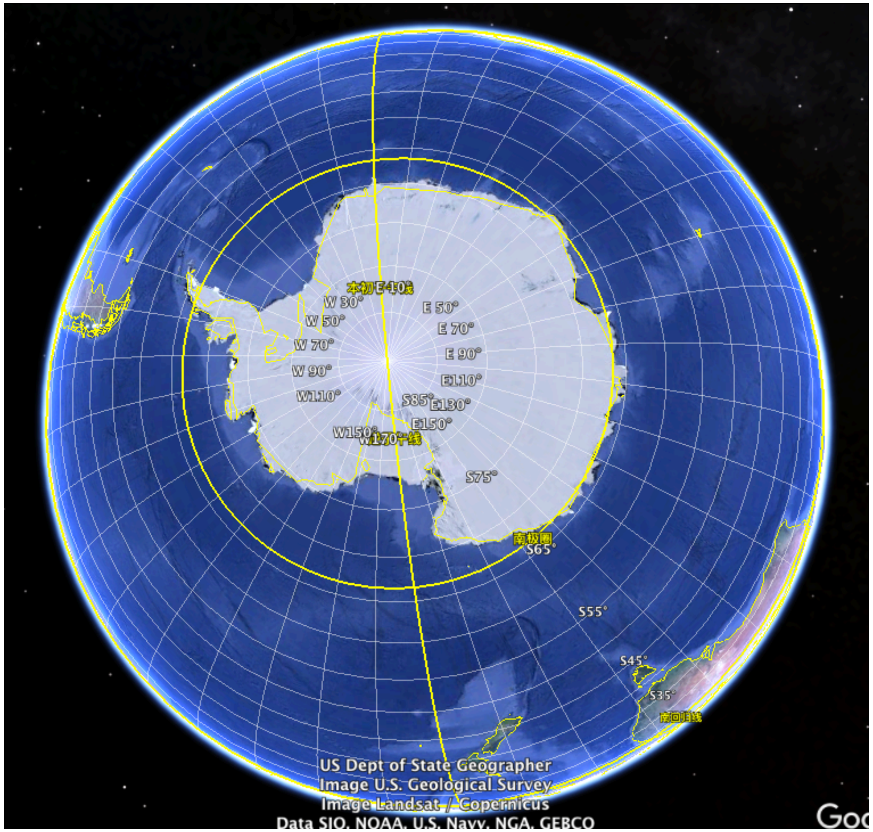
Effect of Dust on Snowball Earth Formation

Surface albedo



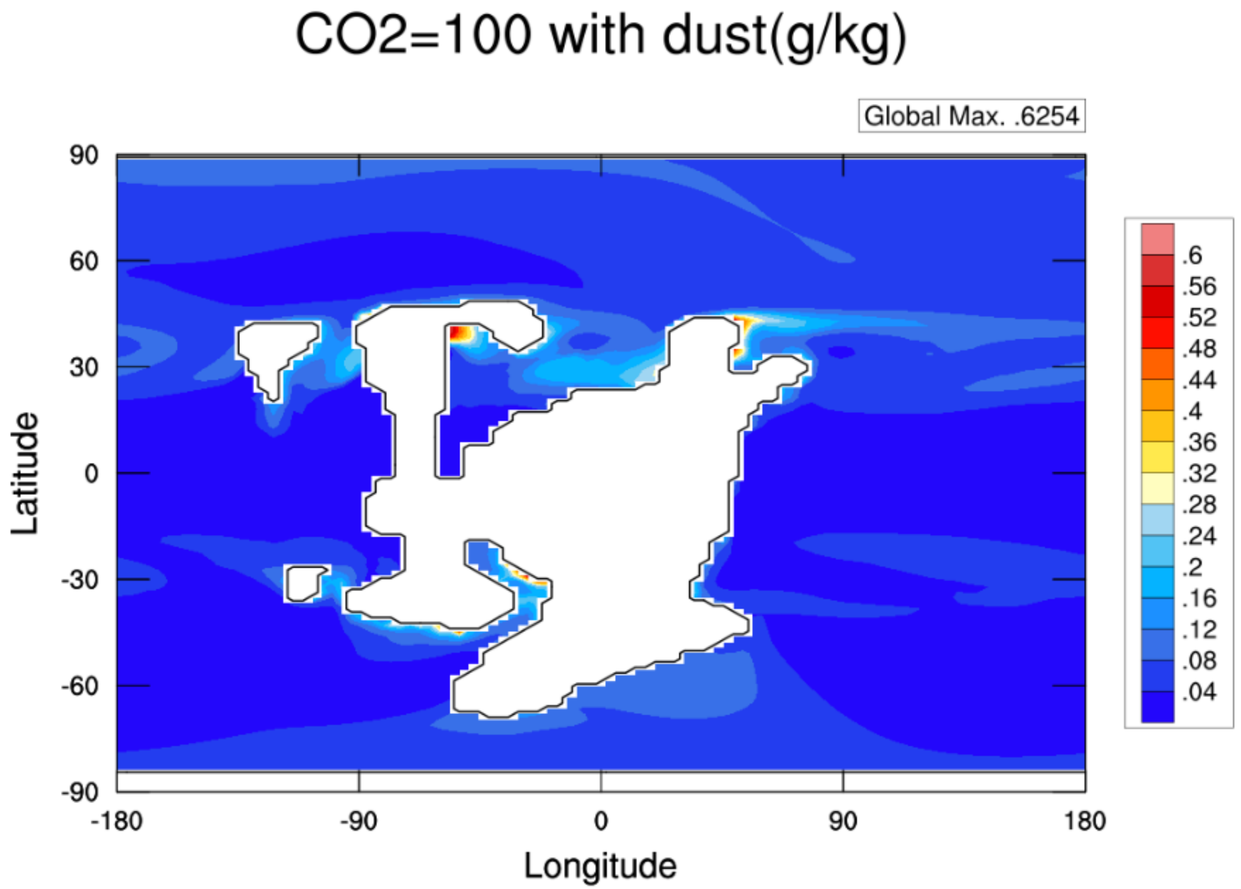
This Effect is not Significant for the Present-day Earth



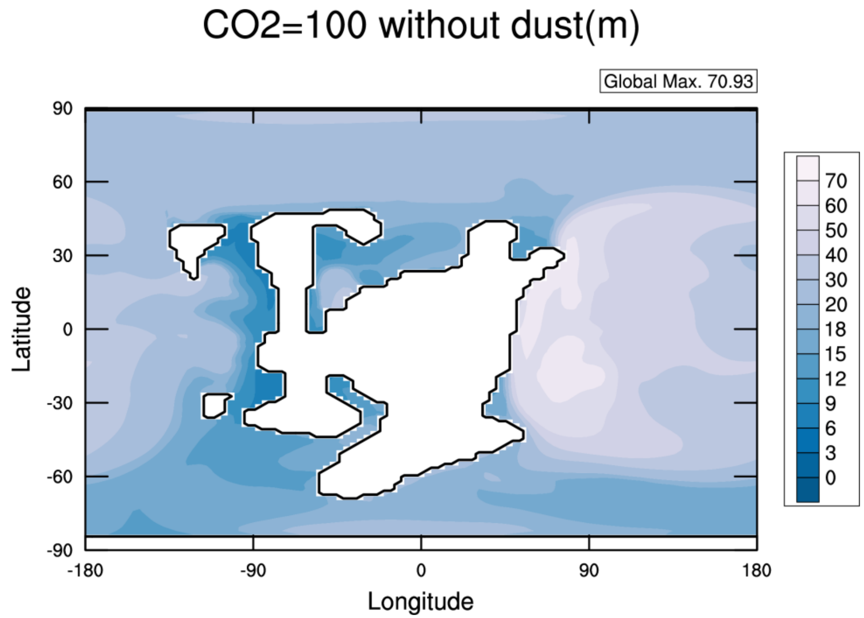


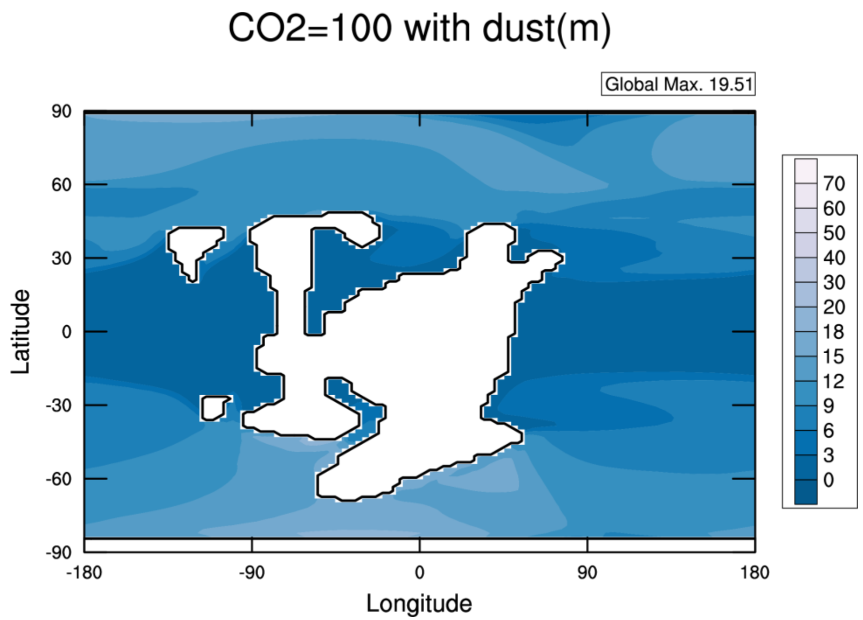
- Too much vegetation
- Not so extensive continental ice sheet or sea ice

Dust Deposition on Sea Ice (Snow)



Sea-ice Thickness





Conclusions

- **Dust can either cool or warm the climate**

• Mid-Holocene (6 ka)	Cooling due to scattering effect of dust
• Pre-industrial (1870 AD)	Warming due to ocean and sea ice feedback
• Late Neoproterozoic (~700 Ma)	Warming due to its effect on snow and ice albedo

- **Inclusion of dust effect in climate modeling may solve the Holocene temperature conundrum**

Note that the model is not perfect; the snowball Earth results are probably the most robust

Radiative Forcing Components

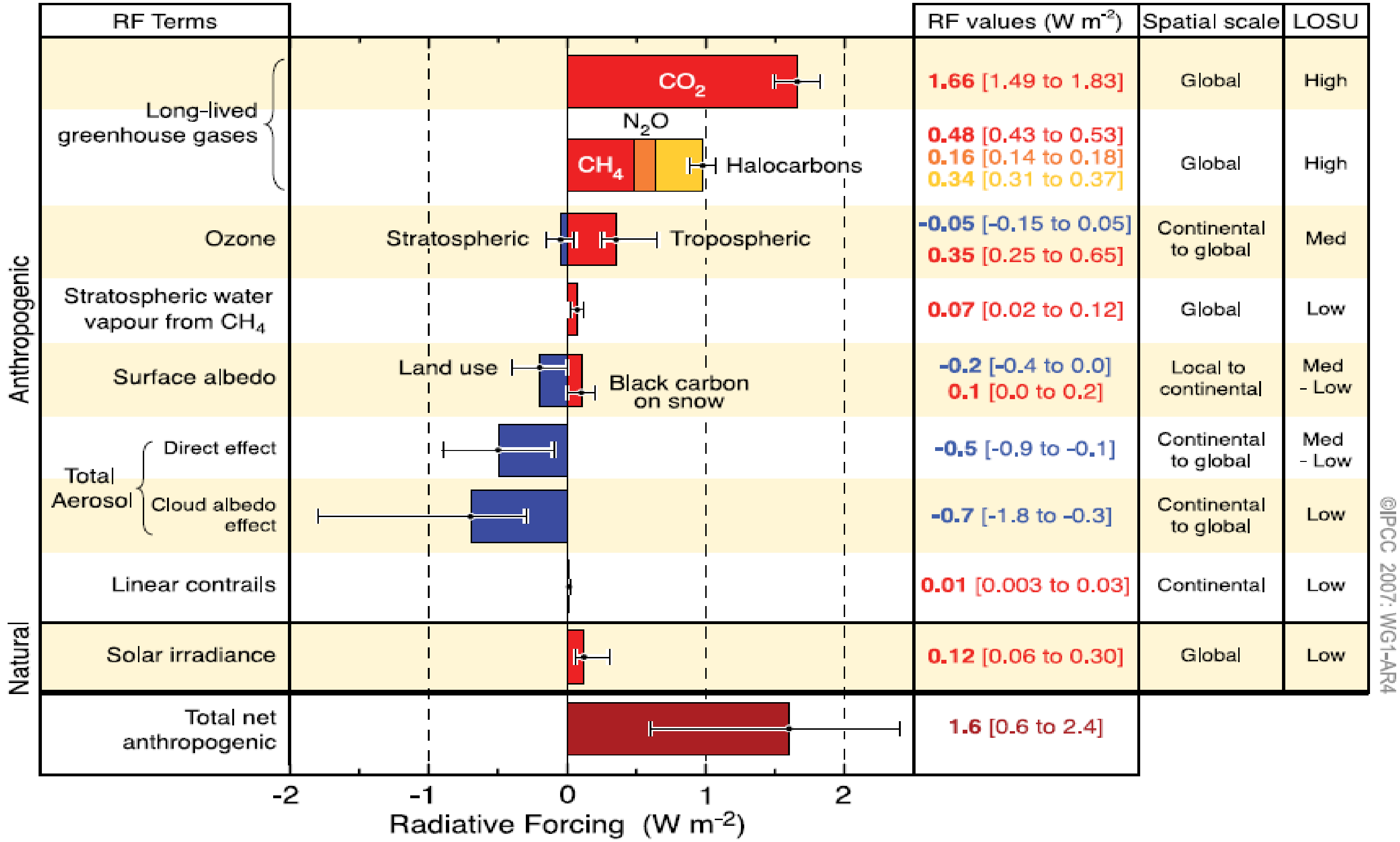


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

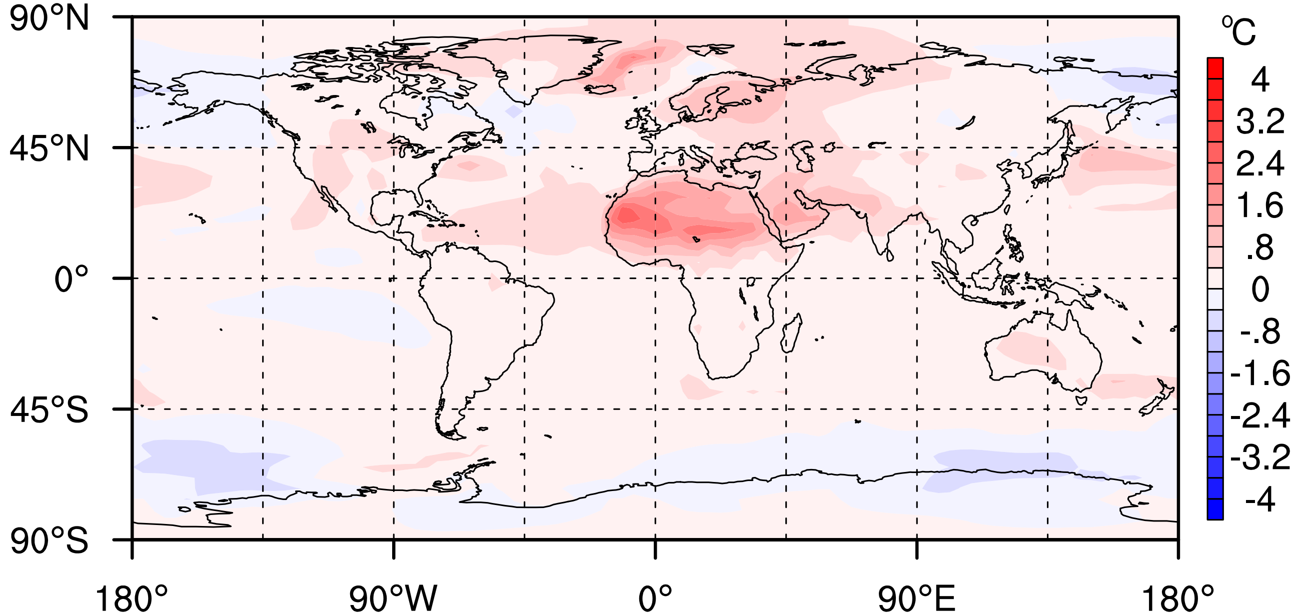
0.1 – 1.0 µm 3.8%; 1.0–2.5 µm 11%; 2.5–5.0 µm 17% and 5.0– 10.0 µm 67%

Table 2. Budgets for Dust Size Bins (SOM Case)

Diameter, µm	Dust Source, Tg/year	Wet Deposition, Tg/year	Dry Deposition, Tg/year	Wet Deposition Lifetime, days	Dry Deposition Lifetime, days	Column Burden, Tg	Total Lifetime, days
0.1 – 1	172	5	169	7.8	278.4	3.6	7.6
1 – 2.5	499	46	455	7.8	76.0	9.7	7.1
2.5 – 5	771	417	356	8.1	6.9	7.9	3.7
5 – 10	3040	2522	524	8.0	1.7	11.5	1.4
All bins	4483	2990	1503	8.0	4.0	32.6	2.7

Mahowald et al. (2006, JGR)

The temperature change when dust is completely removed and Saharan desert is changed to grassland



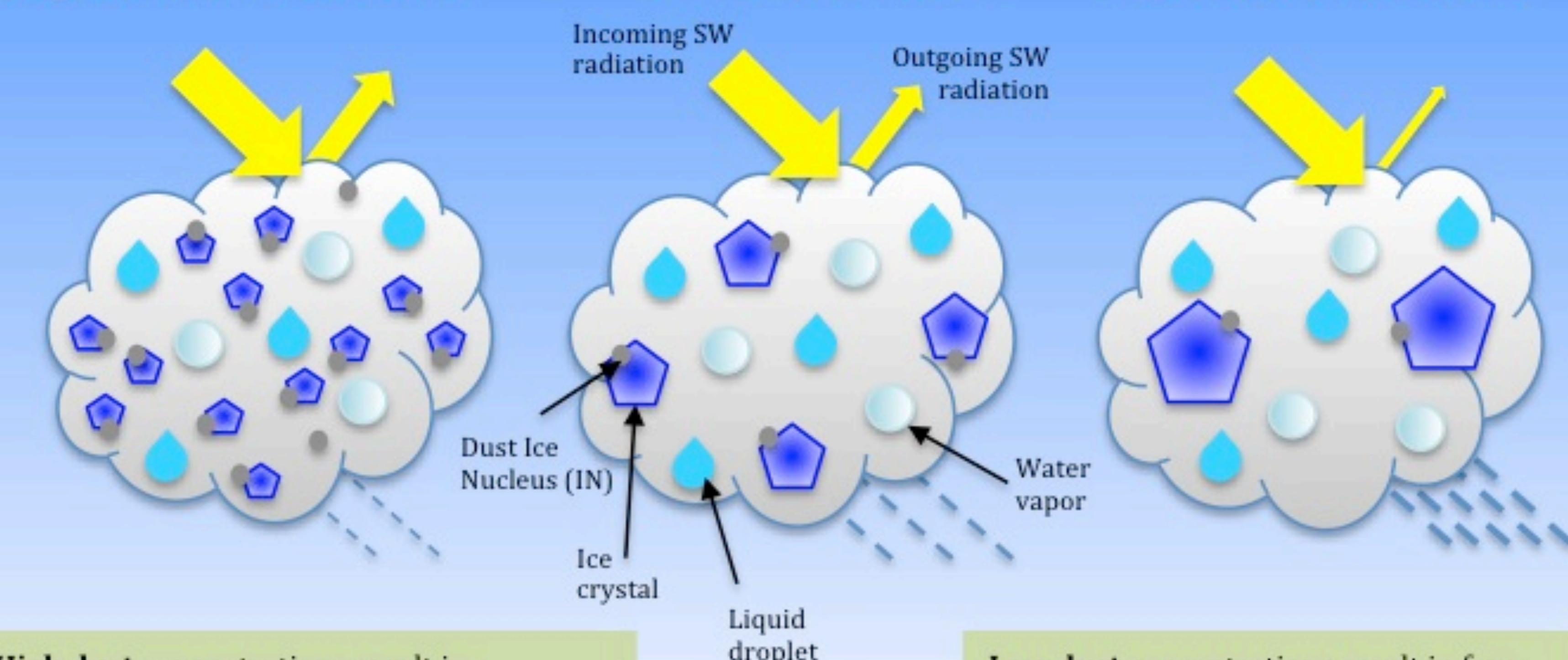
AMOC response is different from that when only dust is removed.

Arctic region warms more and tropical region warms less

Aerosol Indirect Effects of Mineral Dust on Mixed Phase Clouds*

Mineral dust aerosol is an important ice nuclei (IN) and changes in concentration can impact the physical and radiative properties of a cloud. This is referred to as the **Aerosol Indirect Effect**.

High Dust Concentration | **'Normal' Conditions** | **Low Dust Concentration**



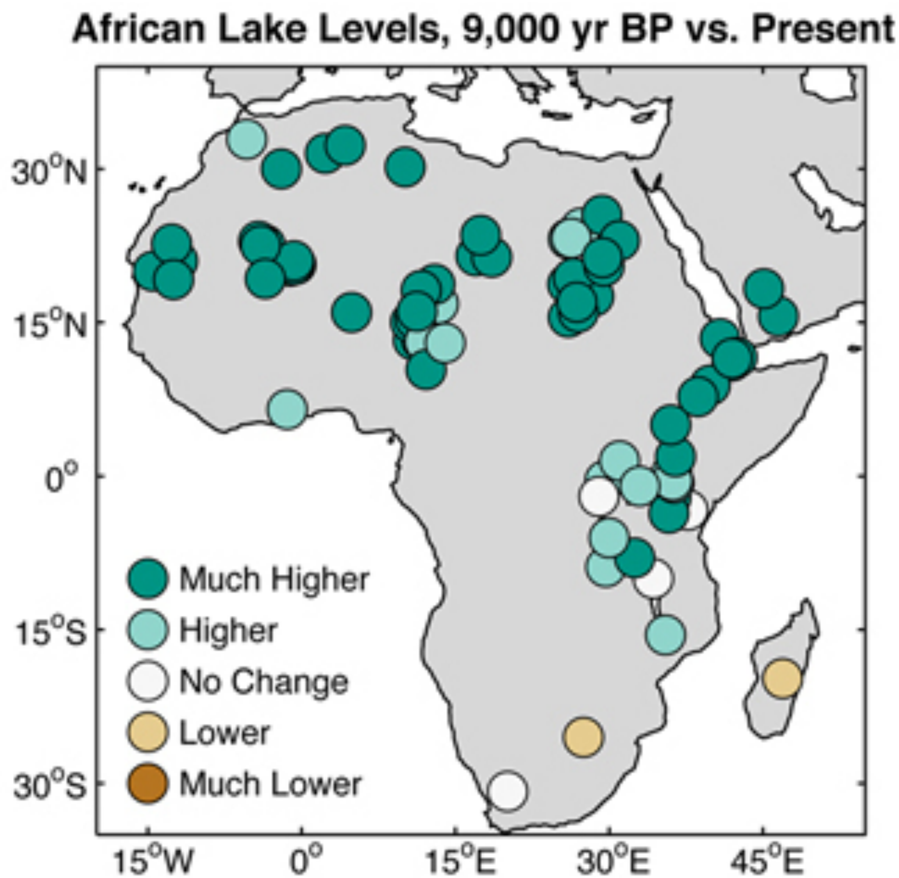
High dust concentrations result in numerous, smaller ice-crystals forming. This leads optically thicker clouds with longer lifetimes and suppressed precipitation.

Low dust concentrations result in few, larger ice-crystals forming. This leads to optically thinner clouds with shorter lifetimes and enhanced precipitation.

* Mixed Phase Clouds contain both liquid and ice and are present at temperatures from below freezing to ~ -39°C. Figure is not to scale.

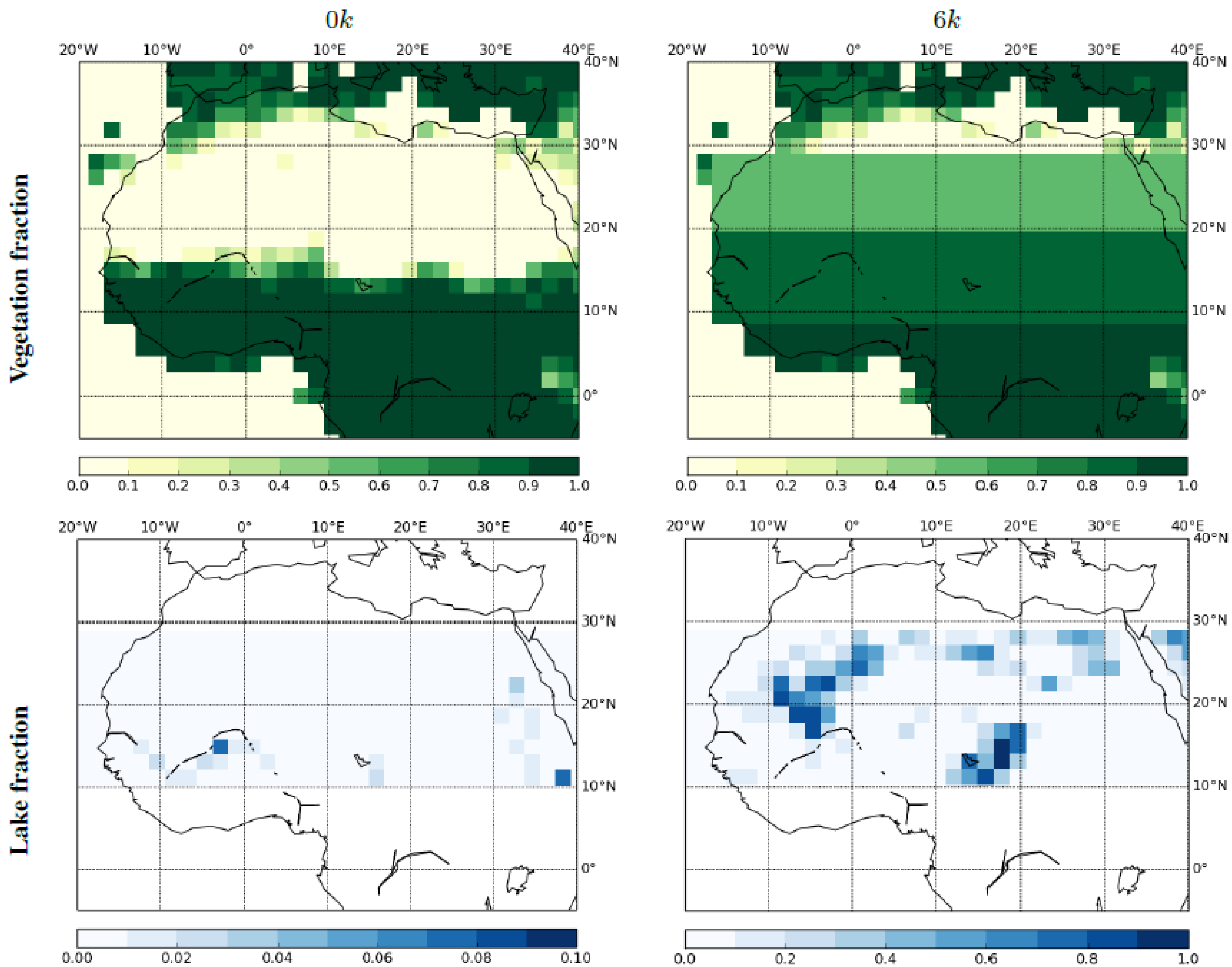
Navjit Sagoo webpage

African Humid Period



de Menocal and Tierney (2012)

Previous studies showed that Mid-Holocene dust emission was 70-80% lower than present day (e.g. Arbuszewski et al., 2013; deMenocal et al., 2000; McGee et al., 2013; Egerer et al., 2015)



Egerer et al. (2015)