SIMULATIONS OF PLIOCENE ARCTIC CLIMATE WITH PROGNOSTIC AEROSOL-CLOUD INTERACTIONS

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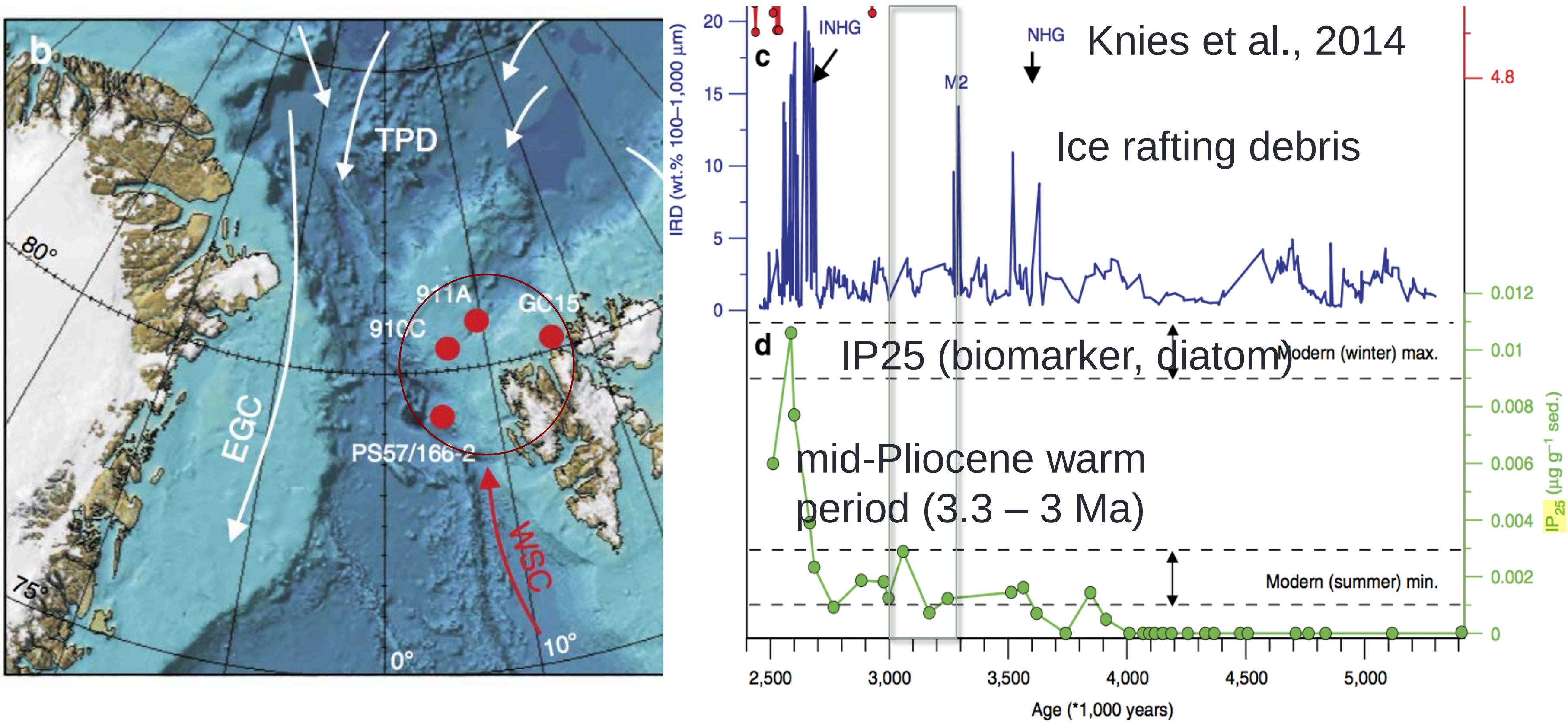
Low Arctic sea ice and warm high latitude climate

Pliocene: 2.6 – 5.3 Ma. High latitude temperatures: up to 18 °C warmer

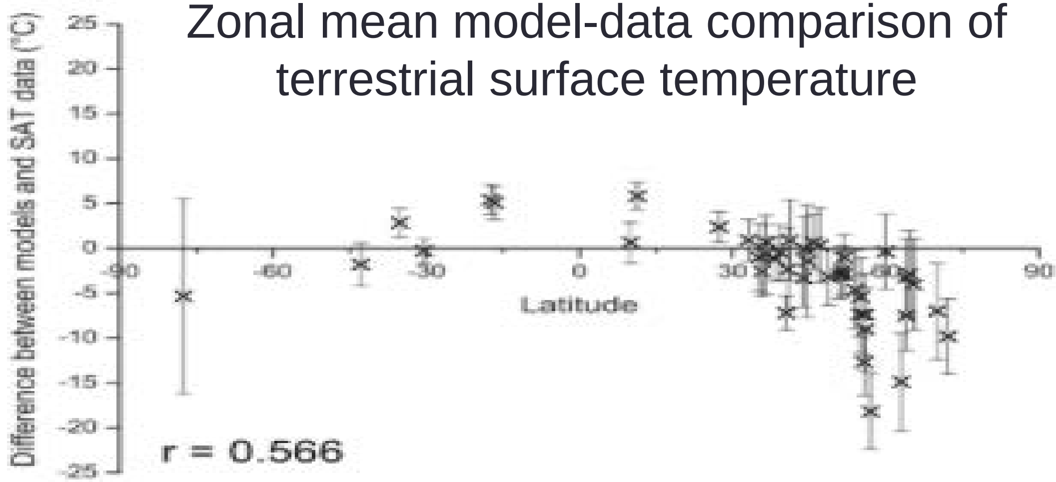


Significant Arctic sea ice reduction → seasonal sea ice free, annual sea ice approaching present-day summer minimum sea ice extent

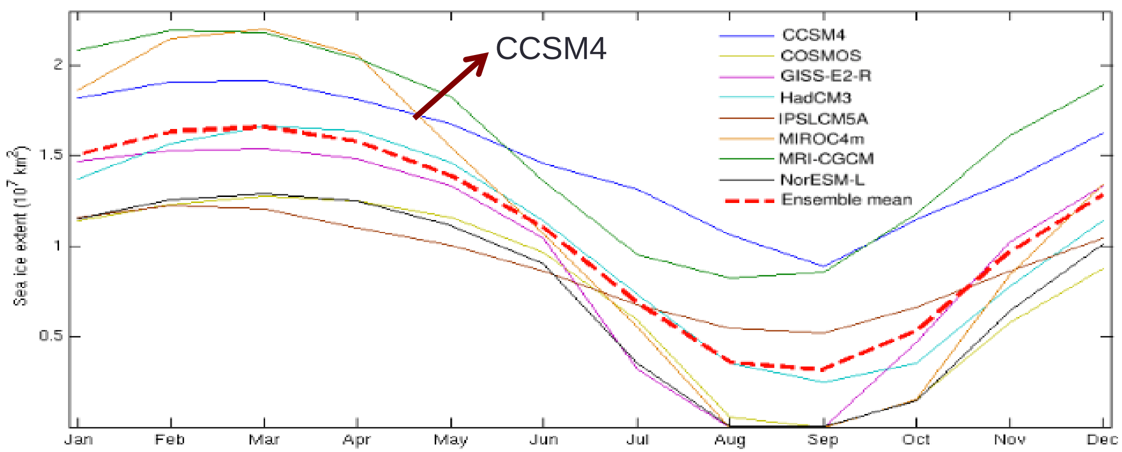
Challenges for model simulations

- Too cold high latitudes and too much Arctic sea ice

Zonal mean model-data comparison of terrestrial surface temperature



Arctic sea ice extent of PlioMIP I



Hypotheses to resolve the underestimate of Pliocene high latitude warming

- 1. Variability of **CO_2 and orbital forcing** (Prescott et al., 2014; Haywood et al., 2016; Feng et al., 2016, *in prep*)
- 2. **Arctic gateway changes** (Otto-Bliesner et al., 2016, *in Prep*) and **regional geographic changes** (Hill et al., 2015)
- 3**. Other climate forcings and feedbacks**
  - **Sea ice albedo** (HadCM3, Howell et al., 2016)
  - **Changing atmosphere chemistry in the past**
    - **Direct radiative effect (Unger and Xu, 2014)**
    - **Indirect effect – changes in cloud albedo and lifetime**
      - PETM (55 Ma), changing cloud condensation nuclei (Kiehl and Shields, 2013)

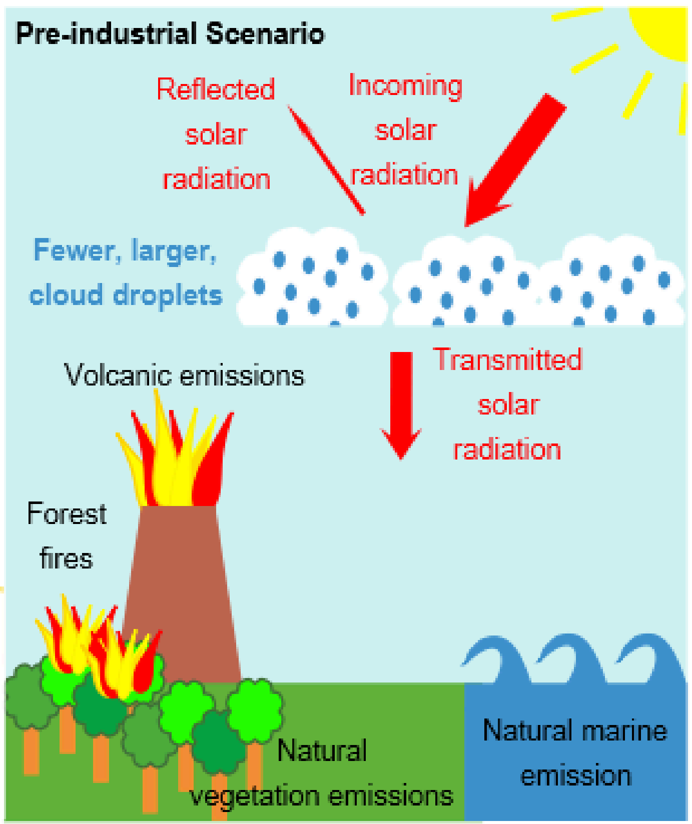
Outline

- Aerosol indirect effect
- Model simulations:
    - **Pliocene Arctic: an equilibrium state of clean atmosphere?**
- Changes in energy budget, sea ice and clouds

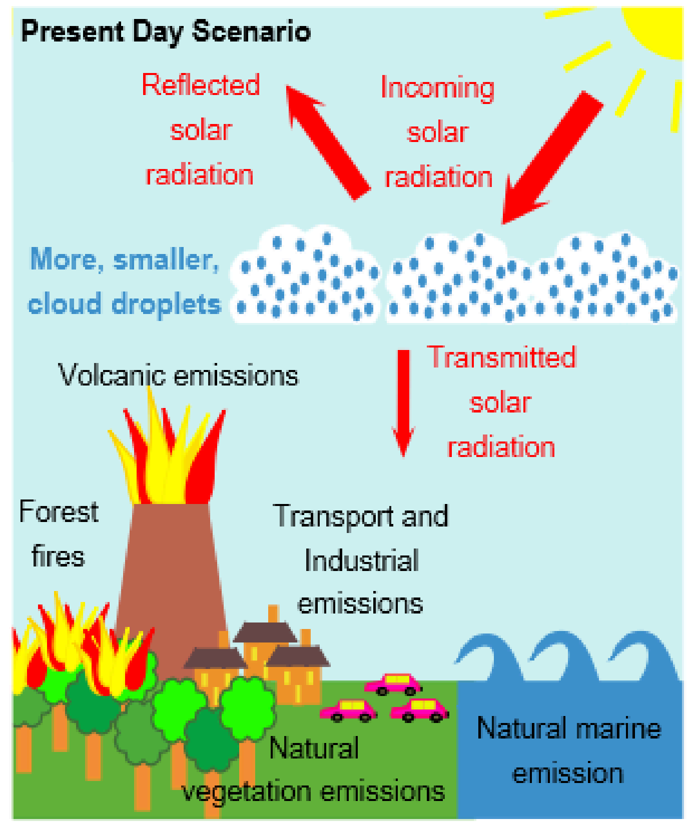
Indirect effect

- Cloud albedo
- Cloud lifetime

Clean air



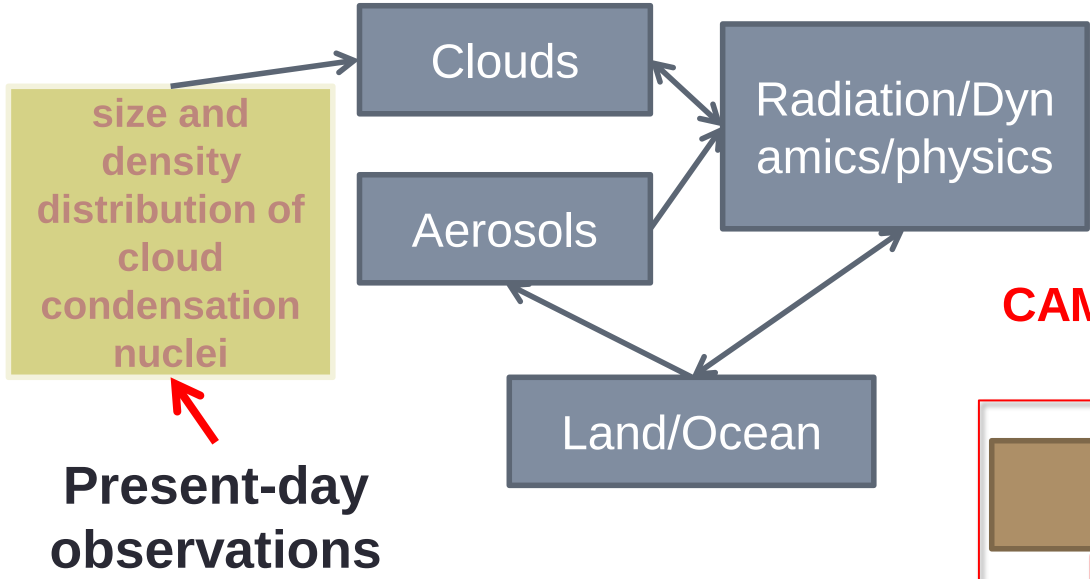
Polluted



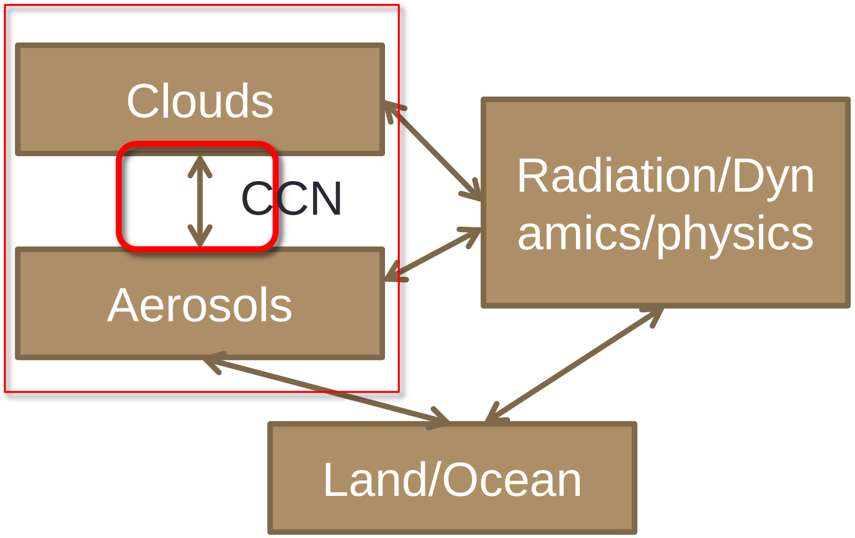
IPCC AR5: total radiative forcing due to changes in aerosols since 1750 is 0.7 W/m^2 (compare to 1.68 W/m^2 CO_2 forcing)

A clean Pliocene atmosphere

CAM4: only direct radiative effect of aerosol



CAM5 and later: aerosol-cloud interaction



Experiment Design

CCSM4 (CAM4) PlioMIP I (Rosenbloom et al., 2013)

Slab ocean (CAM5.3-MAM3) with fixed ocean heat flux

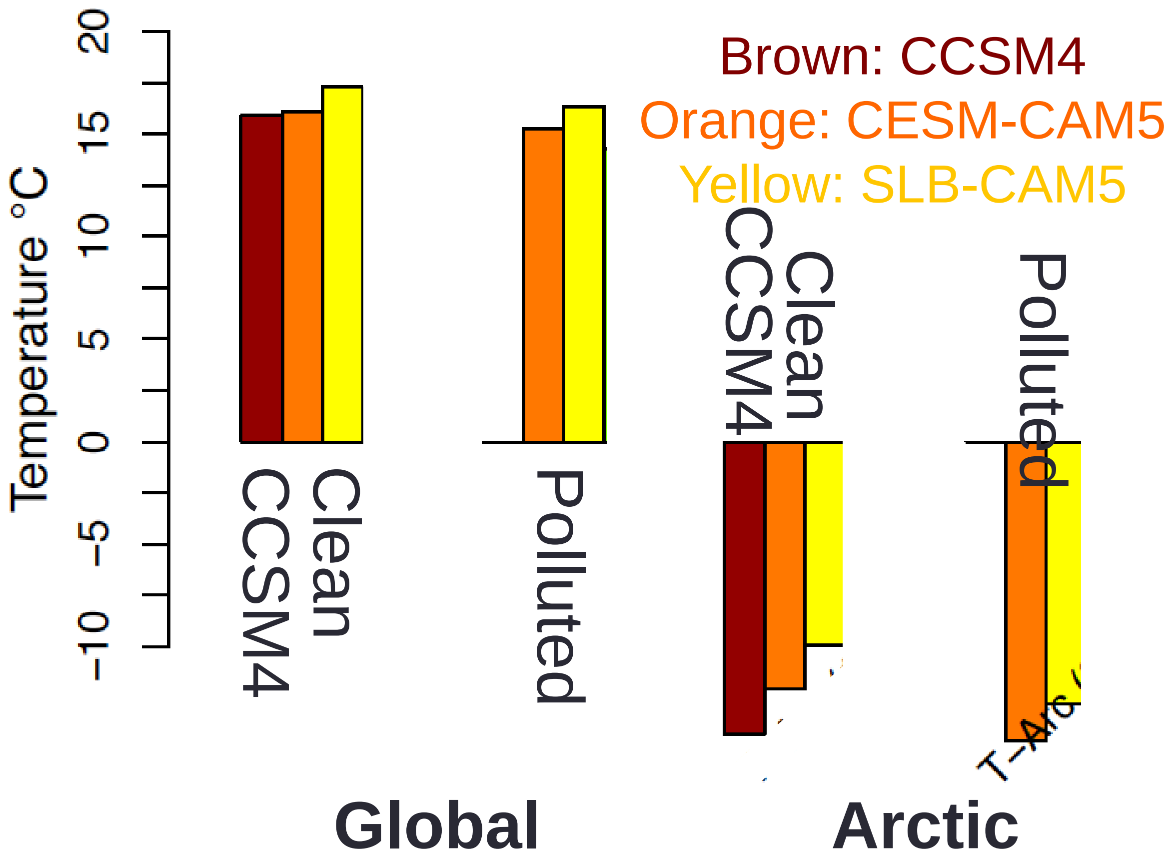
	Slb-clean	Slb-polluted	HCO_2-clean	LCO_2-clean	HCO_2-polluted	LCO_2-polluted
CO_2	405 ppm	405 ppm	560 ppm	280 ppm	560 ppm	280 ppm
Emission	Clean:1850 emission	Polluted: 1850: natural emission, 2000: industrial emission	clean	clean	polluted	polluted

0.9 x 1.25 ° atmosphere, 320x384 grid cells ocean

CESM1.2 (CAM5.3-MAM3)

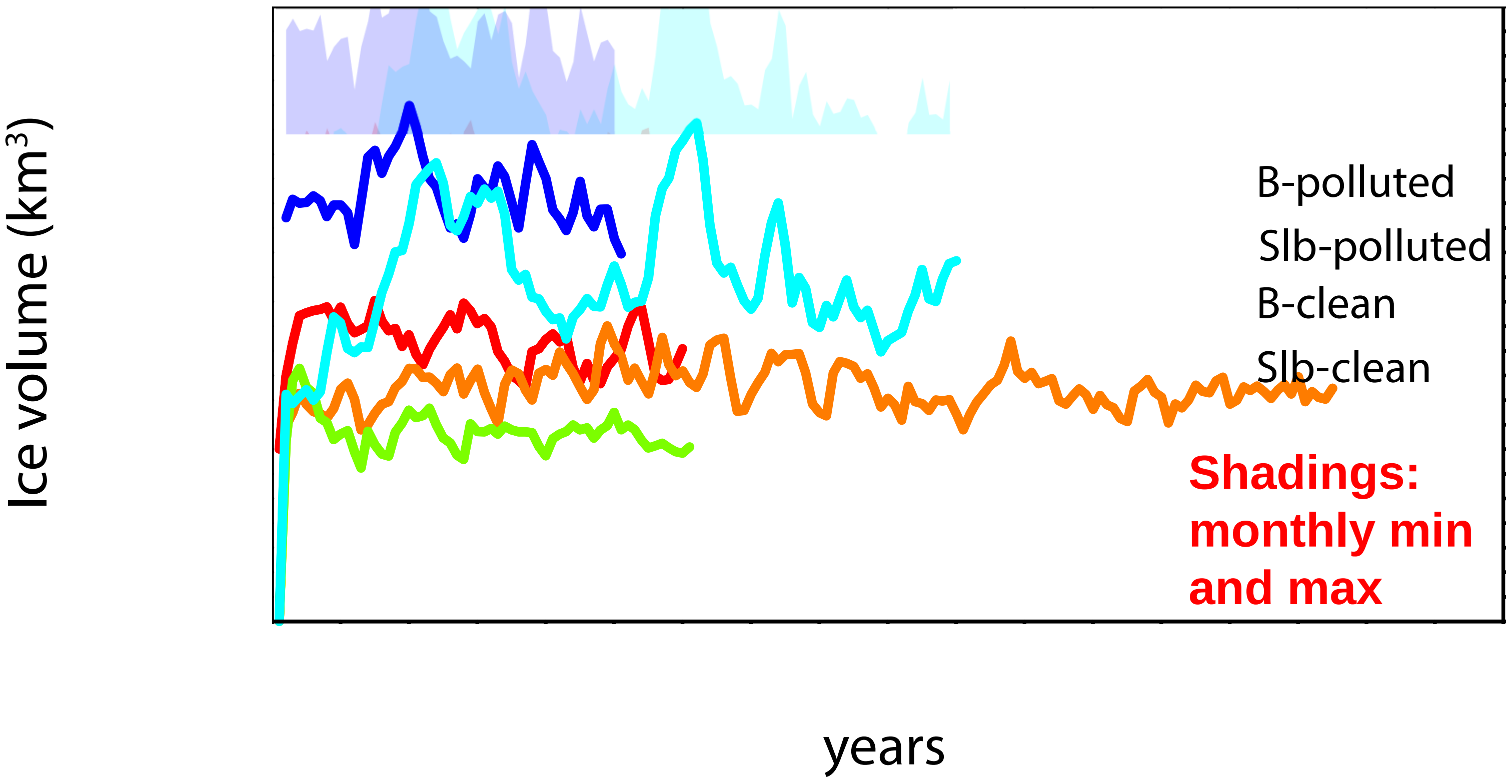
	B-clean	B-polluted
Emission	clean	polluted
CO_2	405 ppm	405 ppm

Global & Arctic temperature responses



1. T_s CCSM4 is comparable to B-polluted.
2. ~0.8°C warming of T_s-global, and 2.6 °C warming of T_s-Arctic (70° - 90 °N average).

Arctic sea ice volume



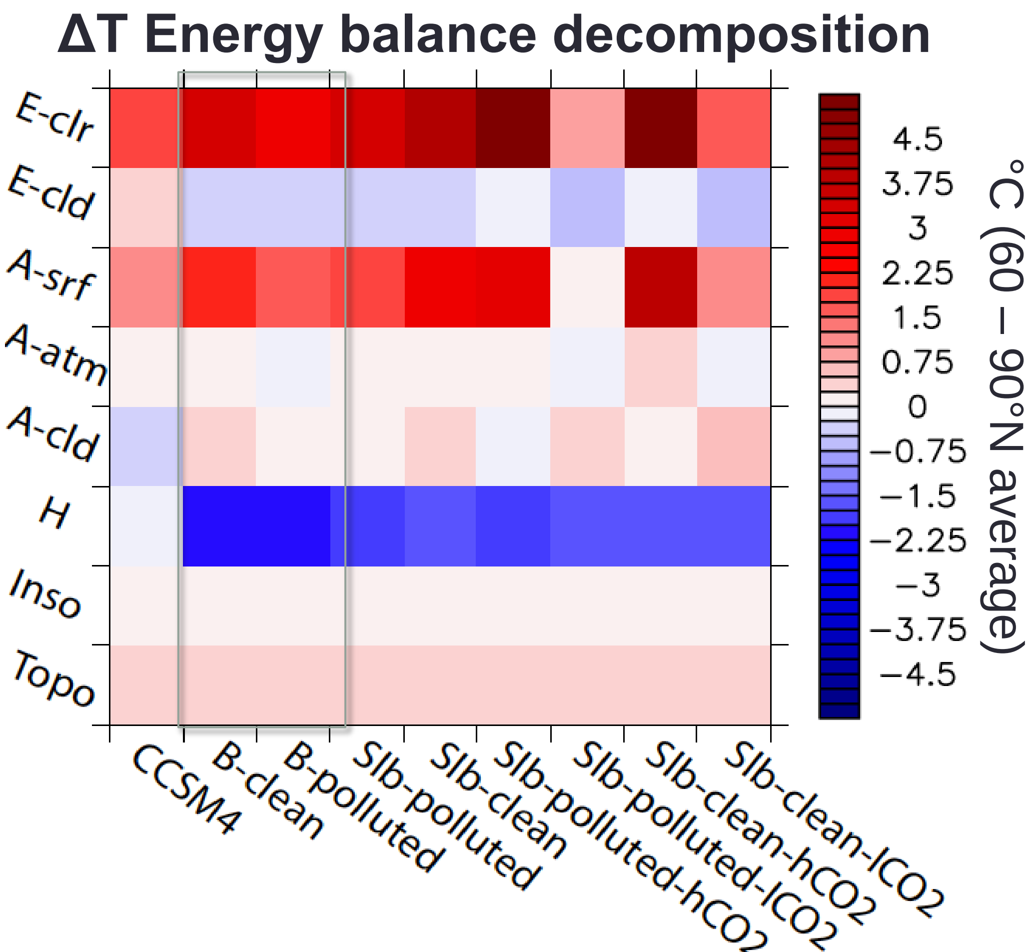
- 46% annual sea ice reduction in B-1850, 23% reduction in B-2000. 86% reduction in monthly minimum in B-1850, 53% in B-2000.
- Large improvement in simulating Pliocene low ice state

Energy balance (refer to CCSM4 pre-industrial)

$\Delta T = \Delta T(\Delta\alpha, \Delta\varepsilon, \Delta H, \xi)$ (Lunt et al., 2013; Hill et al., 2014)

$\Delta\alpha = \Delta\alpha_{cld} + \Delta\alpha_{srf} + \Delta\alpha_{atm}$ (APRP, Taylor, 2007) (α: planetary albedo)

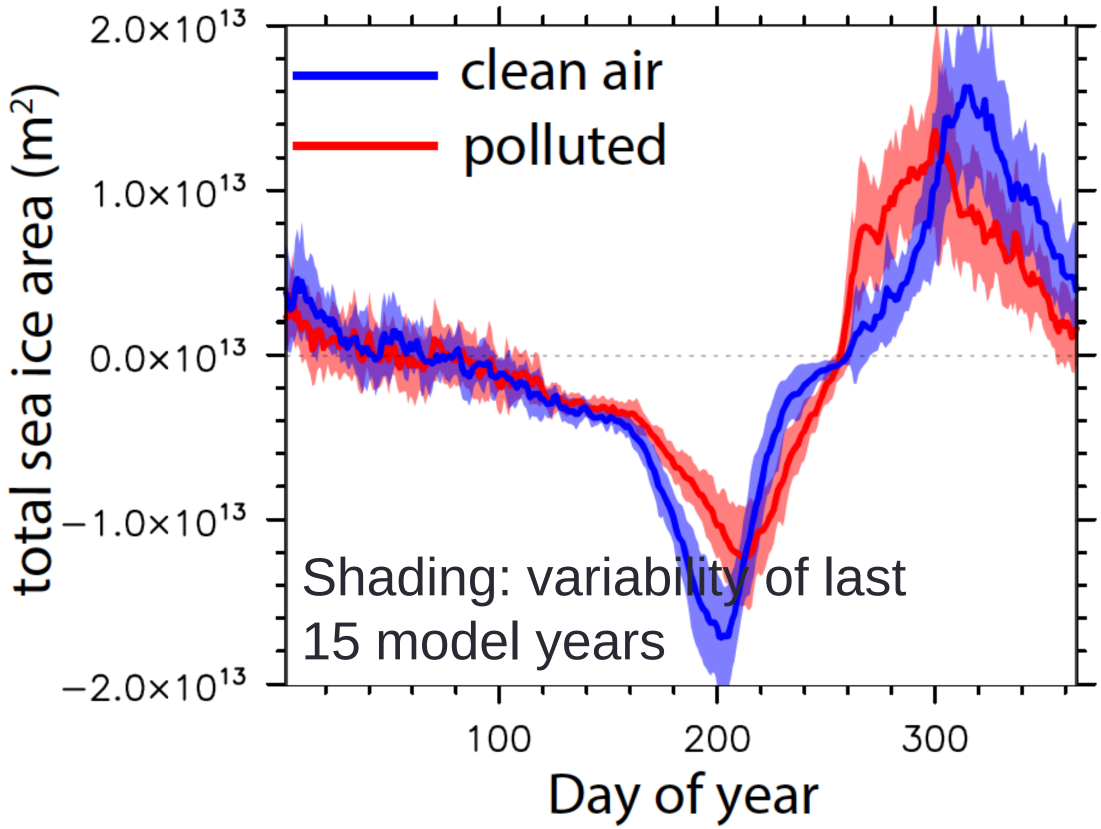
$\Delta T\text{-}\varepsilon = \Delta T\text{-}\varepsilon_{cldy} + \Delta T\text{-}\varepsilon_{clr}$ (ε: Emissivity)



- Warming: $\Delta\alpha_{srf}$ and $\Delta T\text{-}\varepsilon_{clr}$
- Cooling: total heat transport
- Mild warming effect from $\Delta\alpha_{cld}$ (clean conditions) and cooling from $\Delta T\text{-}\varepsilon_{cldy}$.

Sea ice melting behavior

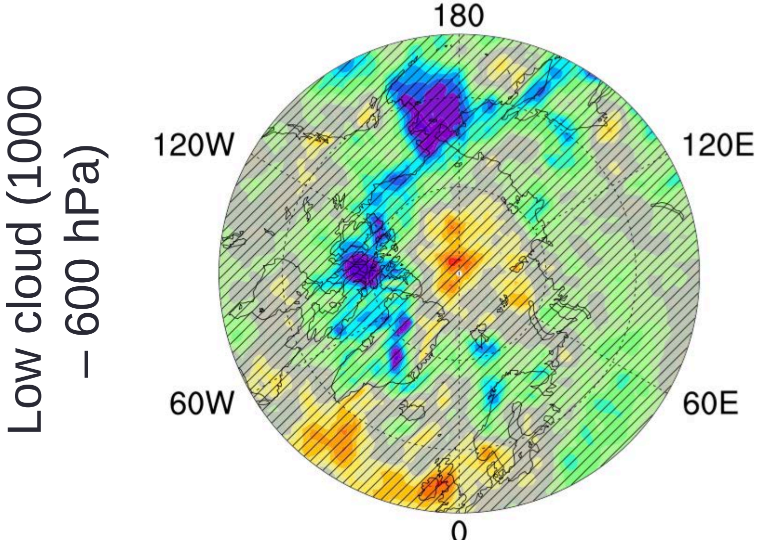
Daily rate of change of Arctic sea ice

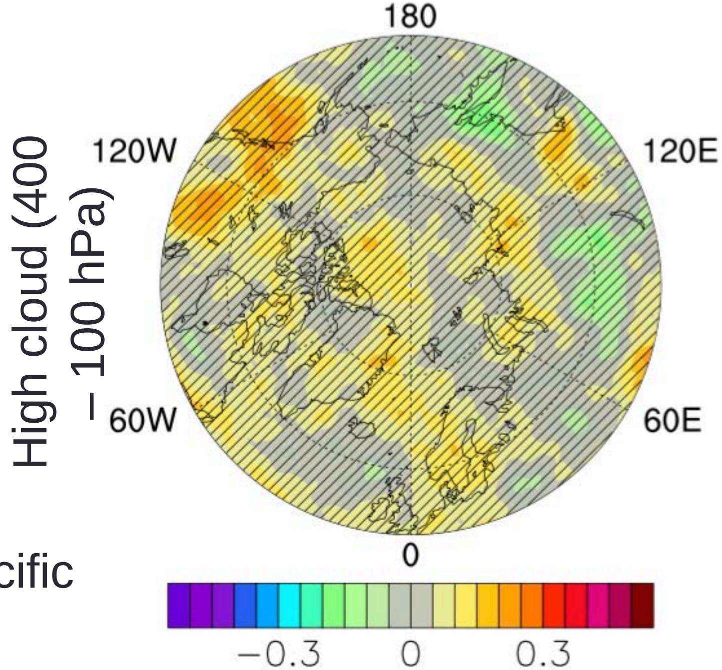


Clean air: earlier and stronger melting, slower accumulation

Cloud contributions

July changes in cloud fraction (clean minus polluted)





Zonal mean T (contour) and specific humidity (shaded) changes

fading of shortwave cloud forcing (cooling effect) and increasing longwave cloud forcing (warming effect)

Height (hPa)

kg/kg

Synthesis

Polluted regime:
More CCN →
more summer low clouds surrounding the Arctic →
slower summer ice retreat → high surface albedo and less water vapor

clean air regime:
Less CCN →
less summer low clouds and more high clouds surrounding the Arctic →
rapid retreat → low surface albedo, more water vapor

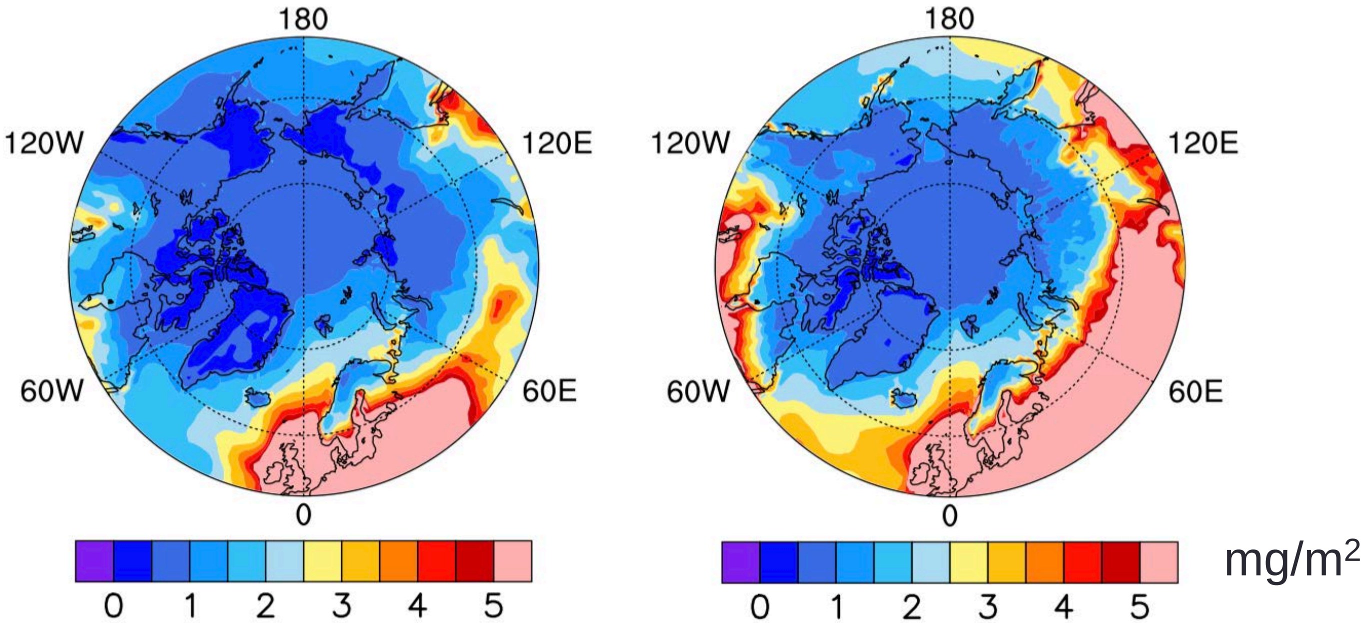
What happens next?

More realistic representation of Pliocene aerosol emissions

Fire & biogenic emission (really preliminary)

Fixed SST, CAM5.4-MAM4-CLM4.5-fire

Annual wet + dry black carbon deposition on the surface

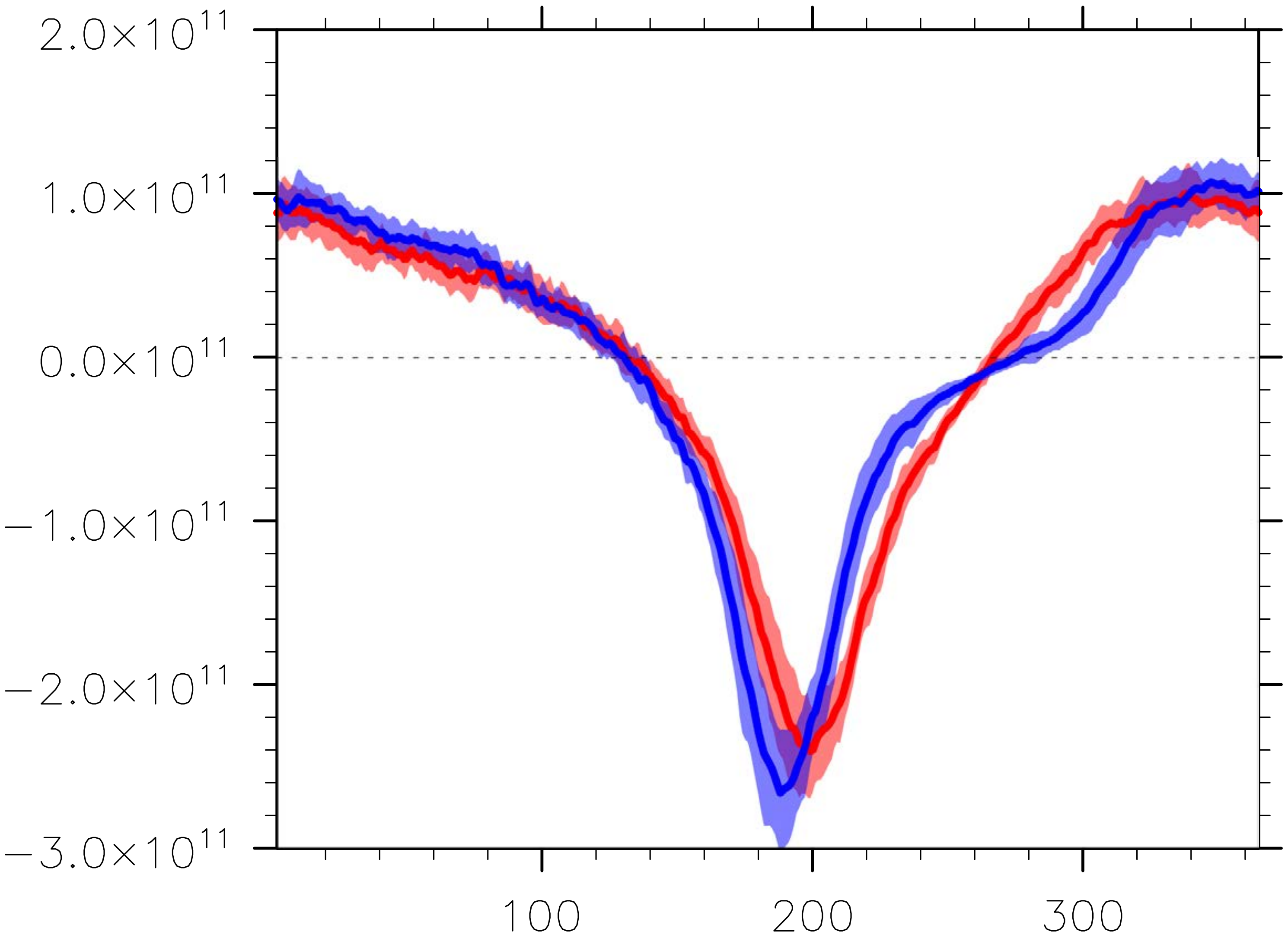


Present-day

Pliocene fixed SST (PRISM 3)&Sea ice (Knies et al., 2014)

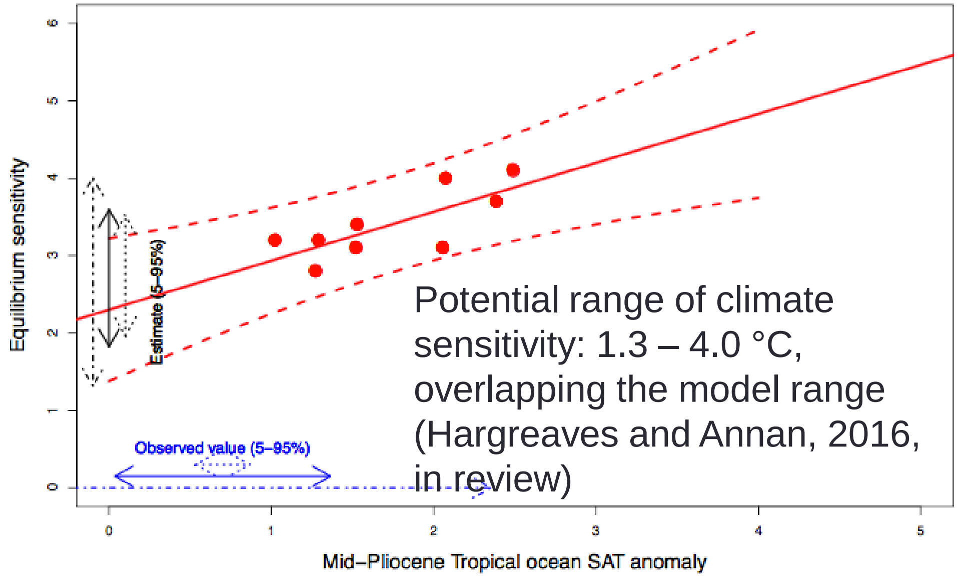
Thanks. Questions?

Daily rate of change of ice volume



Pliocene Earth System Sensitivity vs Climate sensitivity

Moderate CS: comparable to proxy estimates



Potential range of climate sensitivity: 1.3 – 4.0 °C, overlapping the model range (Hargreaves and Annan, 2016, in review)

Underestimates ESS (7.1 – 9.6 °C/doubling of CO_2): unlikely a CO_2 issue, changes in other components

(a) Experiment 2 Climate Models/Mean	(b) Pliocene ΔT (°C)	(c) CS (°C)	(d) ESS (° C) = mPWP $\Delta T \cdot 1.88$
CCSM4	1.86	3.2	3.51
COSMOS	3.60	4.1	6.77
GISS-E2-R	2.12	2.7	3.98
HADCM3	3.27	3.1	6.16
IPSLCM5A	2.18	3.4	4.10
MIROC4m	3.46	4.05	6.51
MRI-CGCM 2.3	1.84	3.2	3.45
NorESM-L	3.27	3.1	6.14
Ensemble Mean	2.66	3.36	5.01

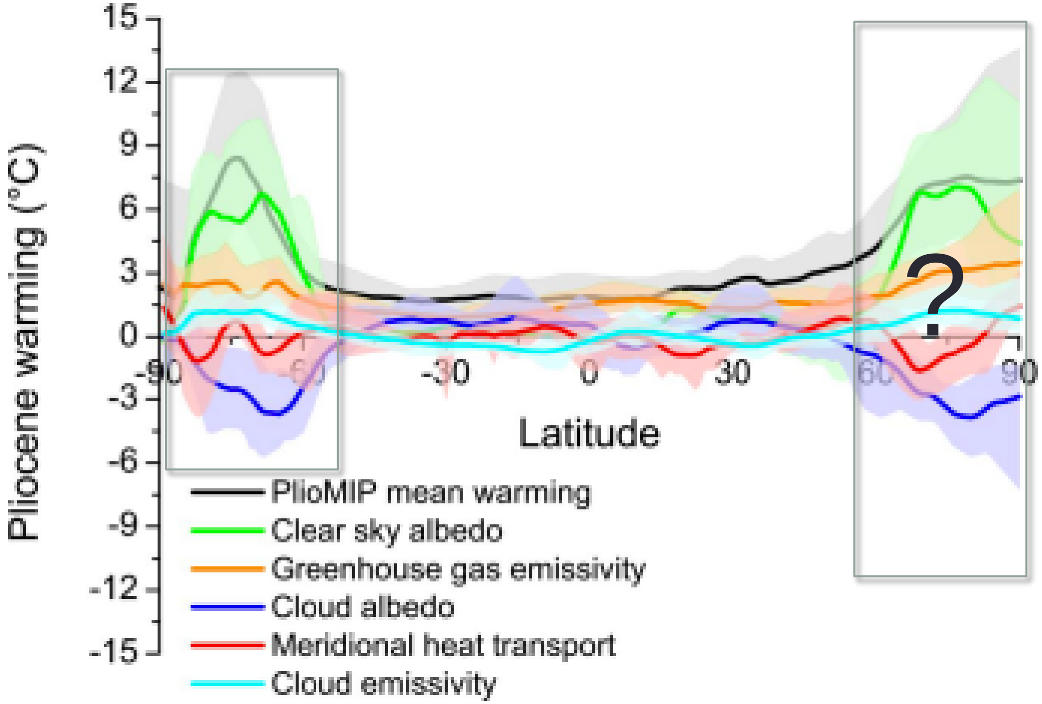
Energy balance

ΔT =Δ T(Δα, Δε, ΔH)+ΔT(syn), Δα = Δα(srf, cld, atm), Δε = Δε(clr, cldy) (Lunt et al., 2013; Hill et al., 2014).

α-cld: **Rad (total) – Rad (clear)**

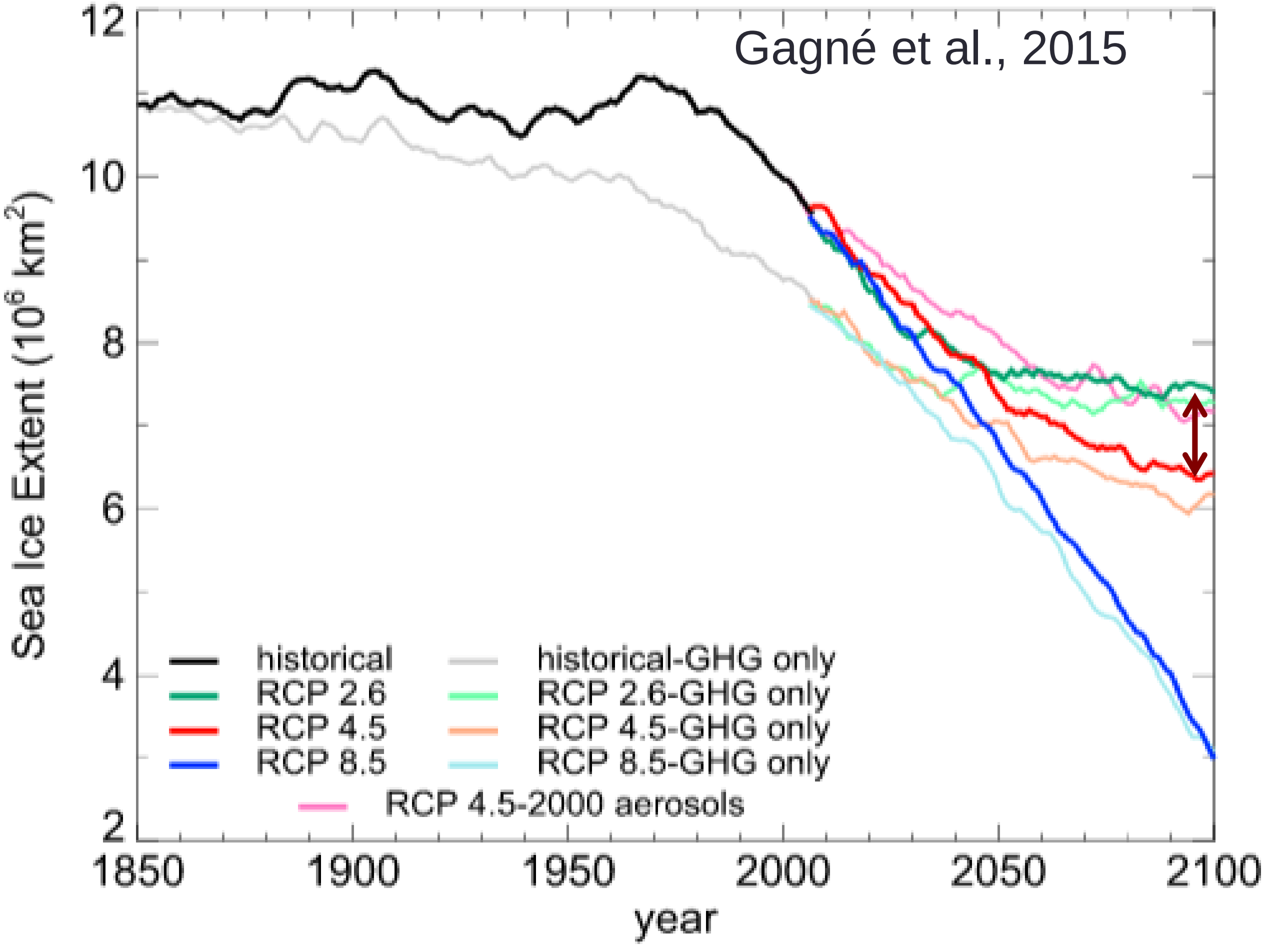
Δα-cld = Rad-A (total) – *Rad-A (clear)* – (Rad-B (total) – *Rad-B (clear)*) *Rad-B (clear) – Rad-A (clear) - due to surface albedo changes instead of clouds*

Energy balance for ensemble members of PlioMIP I



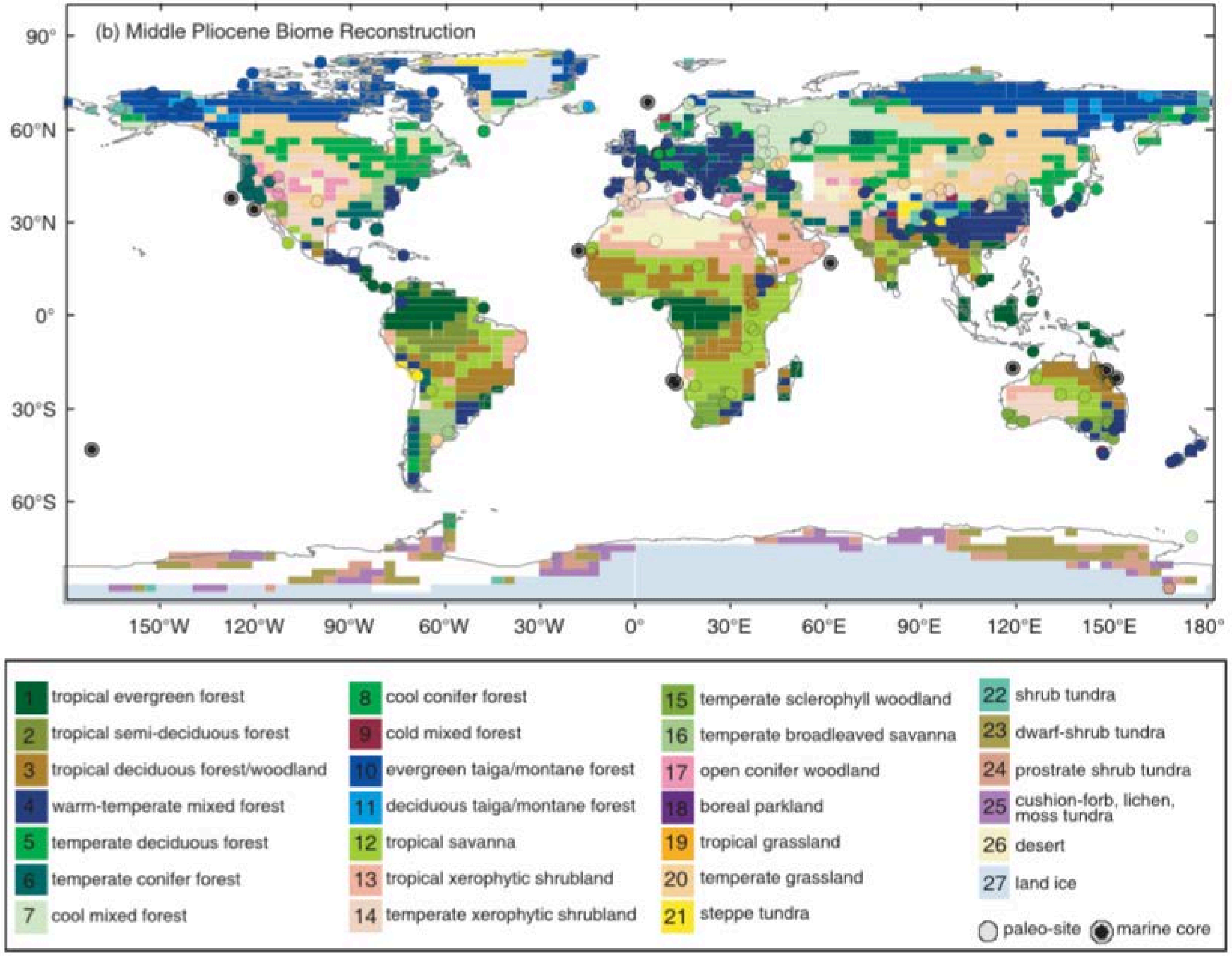
When surface albedo lowers, *Rad-B (clear) – Rad-A (clear) < 0,* ΔRad < 0, which could mislead the previous analysis.

Clean world in future



Arctic climate during the Pliocene

Pliocene: 5.3 – 2.6 Ma

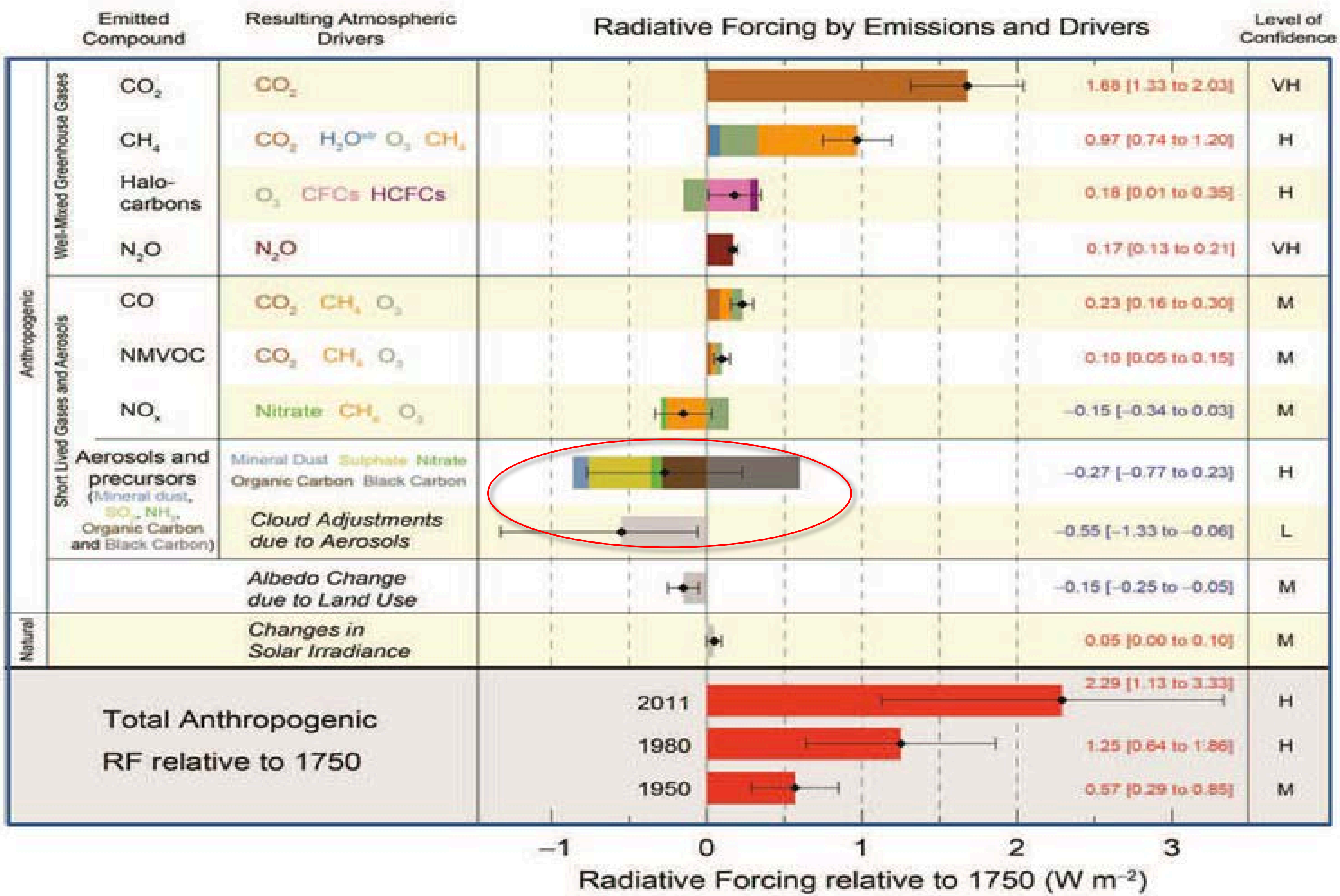


Ts-Arctic: up to ~18°C warmer than present-day at individual sites

CO_2: close to present

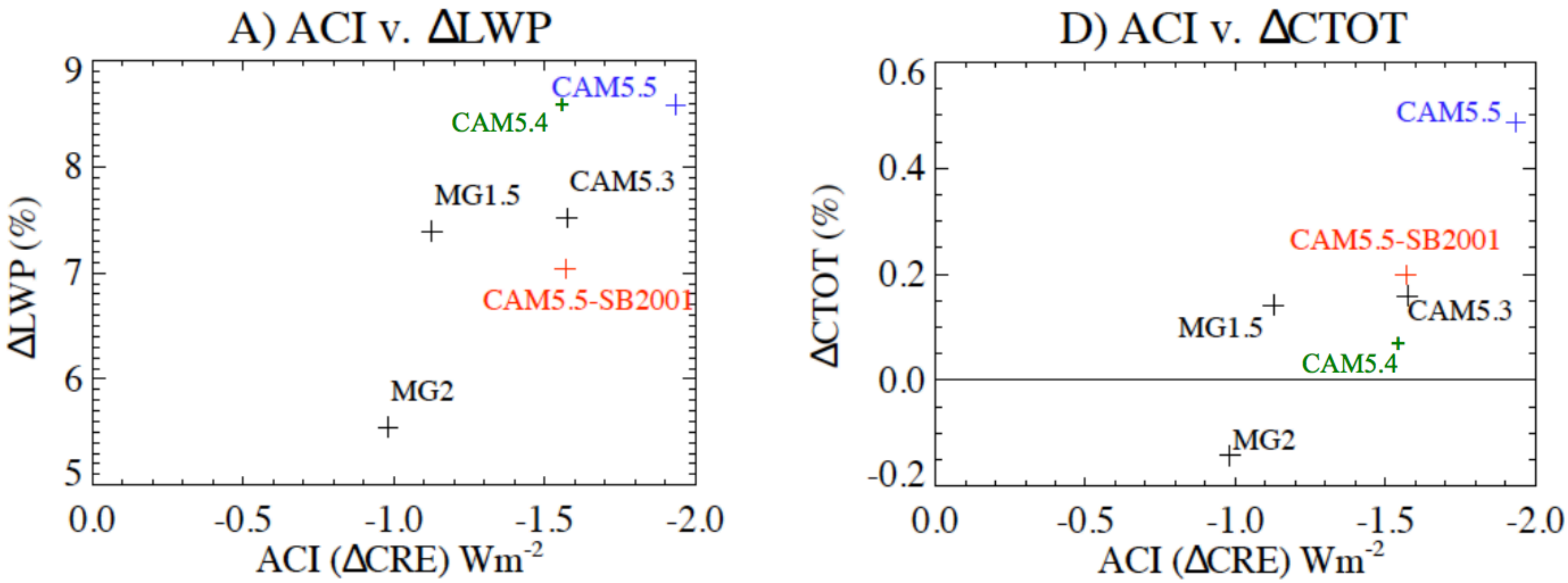
Salzmann et al, 2008; 2013

- IPCC AR5: total radiative forcing due to changes in aerosols is 0.7 W/m^2 (compare to 1.68 W/m^2 CO_2 forcing)



ACI

ACI Definition following Ghan 2013



- Started (CAM5.3) with ACI about -1.5 Wm^{-2}
- Decrease with MG1.5 and MG2
- Increase with CAM5.4 (mixed phase ice nucleation+ MAM4)
- Increase with CAM5.5 (shallow convective regime)
- Can Decrease with new Autoconversion (SB2001)

Gettleman et al., 2016, mini-breck

Table 2. Global (land/ocean) annual mean relationship slopes, computed as linear regression between the logarithm of cloud droplet number concentration (N_d), liquid water path (L), total cloud cover (f_{cld}), cloud-top temperature (T_{top}), planetary albedo (α), and outgoing long-wave radiation (OLR) with the logarithm of aerosol optical depth (τ_a). The land/ocean mean annual mean numbers are given as weighted mean of slopes for all seasons and land/ocean regions. Bold numbers show agreement with the Terra data to within ±25%, gray, underestimation by up to a factor of two, blue, stronger underestimation, green, overestimation by up to a factor of two, red, stronger overestimation compared to the Terra data. The data are plotted in Fig. 2. Gaps indicate that a particular satellite or model did not report all quantities.

Relationship		Terra	Aqua	ORAC	CAM-NCAR	CAM-Oslo	CAM-PNNL	CAM-Umich	ECHAM5	GFDL	GISS	HADLEY	LMDZ-INCA	SPRIN-TARS
N_d–τ_a	land	**0.083**	**0.078**		0.180	0.640	0.531	0.340	0.266	0.375	0.168	0.260	0.175	0.154
	ocean	**0.256**	**0.251**		0.408	0.787	0.471	0.348	0.111	0.155	0.162	0.483	0.198	0.213
L–τ_a	land	**0.074**	0.100	0.148	3.064	0.389	0.218	0.313	0.363	1.557	0.192	0.333	0.896	0.690
	ocean	**0.134**	0.093	**0.136**	3.615	0.309	0.466	0.315	0.572	1.422	0.000	1.340	0.339	0.308
f_{cld}–τ_a	land	**0.51**	**0.48**	0.27		0.34	−0.05	0.20	0.11	**0.52**	−0.04	0.11	0.09	0.13
	ocean	**0.31**	**0.29**	0.09		0.59	−0.00	**0.26**	0.00	1.09	0.15	**0.23**	0.14	0.21
T_{top}–τ_a	land	**−0.0064**	**−0.0083**	**−0.0064**	−0.0013	−0.0154	0.0161	−0.0103	**−0.0054**	−0.0116	0.0083	0.0009	−0.0044	0.0003
	ocean	**−0.0150**	**−0.0141**	−0.0082	0.0046	0.0007	0.0195	0.0082	−0.0013	−0.0284	−0.0072	0.0097	−0.0049	0.0200
α–τ_a	land	**0.17**	**0.16**			**0.14**	−0.01	**0.13**	0.02			0.00	−0.04	0.02
	ocean	**0.26**	**0.25**			0.41	0.05	**0.27**	0.12			0.19	0.00	0.08
OLR–τ_a	land	**−0.028**	−0.040		−0.070	−0.052	0.053	**−0.034**	−0.010	−0.060		0.014		0.006
	ocean	**−0.050**	**−0.054**		−0.109	−0.084	0.027	**−0.042**	0.025	−0.140		−0.017		0.034

Quaas et al., 2009