Simulating the Climate Response to Atmospheric Oxygen Variability in the Phanerozoic

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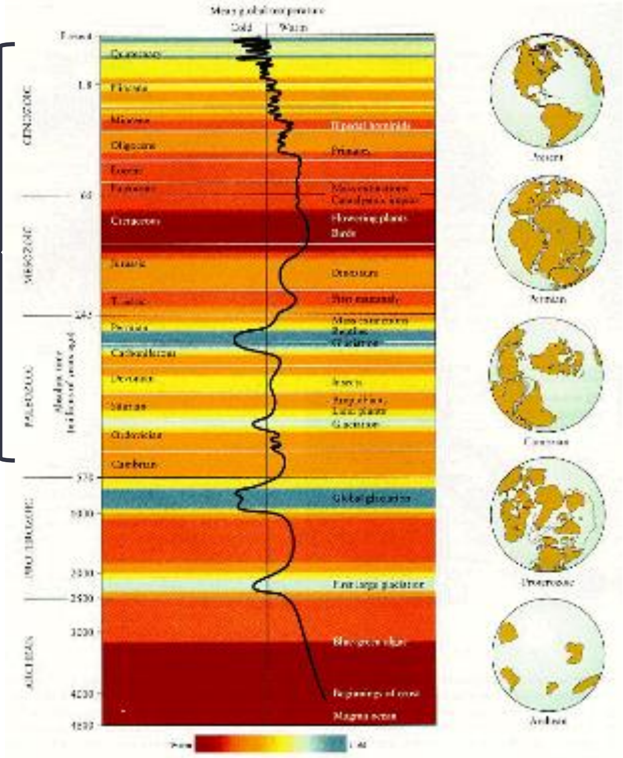
Both climate and the composition of the atmosphere have changed considerably over the history of Earth

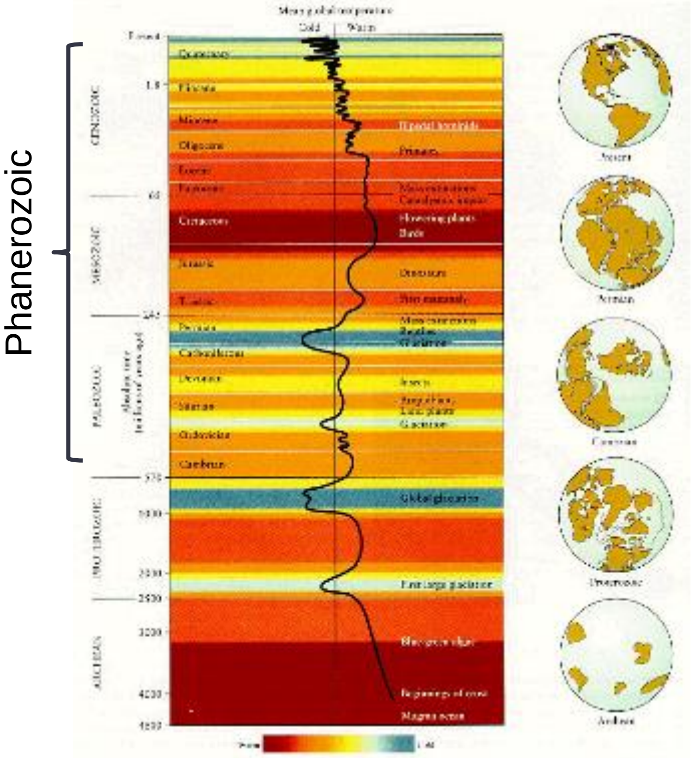
Phanerozoic



- We know from the geological records that our planet has undergone huge changes

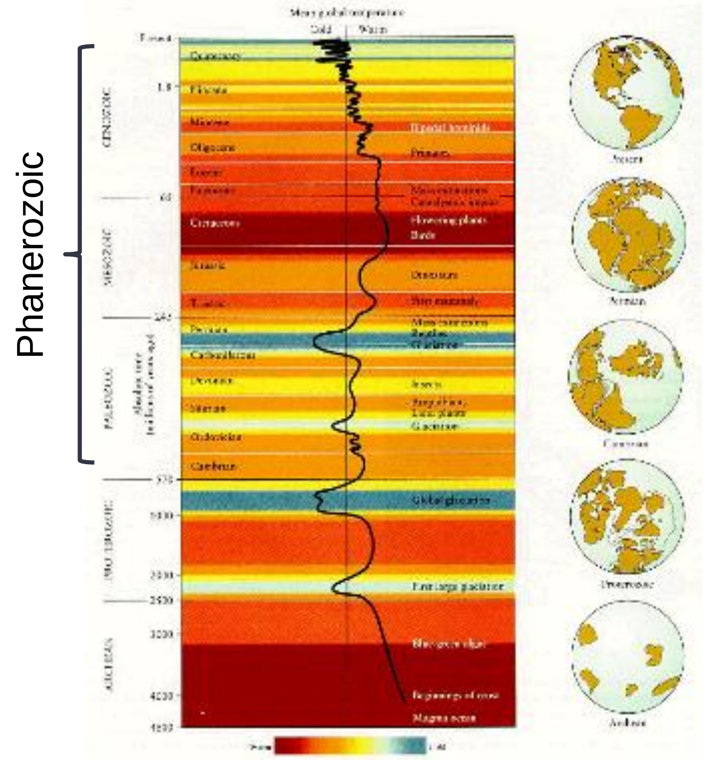
My “holiday” (aka rock nerd) snap

Both climate and the composition of the atmosphere have changed considerably over the history of Earth

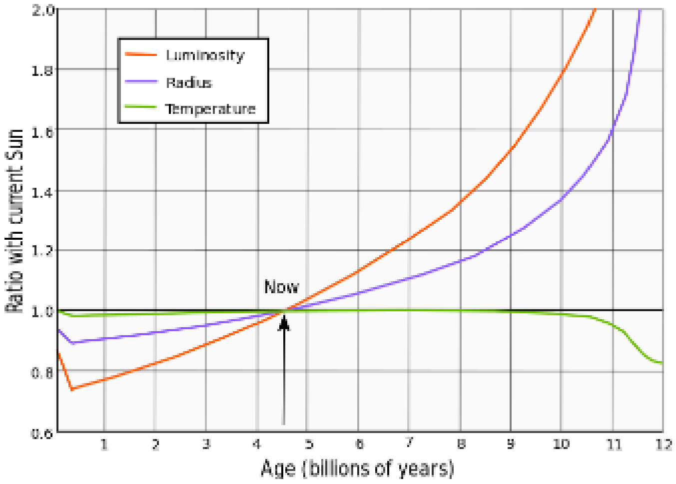


- We know from the geological records that our planet has undergone huge changes
- The main drivers for these changes are changes in incident solar radiation and changes in the composition of the atmosphere

Both climate and the composition of the atmosphere have changed considerably over the history of Earth

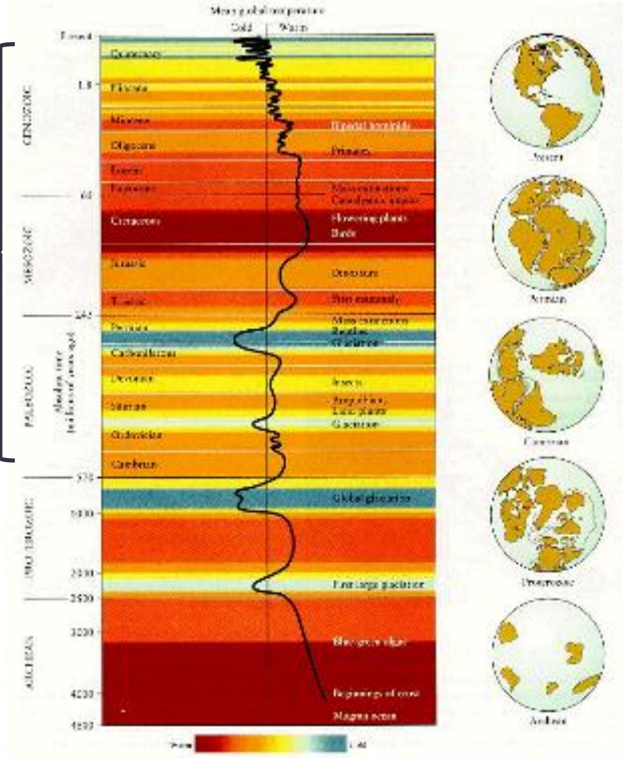


- The sun started out much fainter than it is today – although in the UV spectrum (important for photochemistry) we think it was more active



Both climate and the composition of the atmosphere have changed considerably over the history of Earth

Phanerozoic



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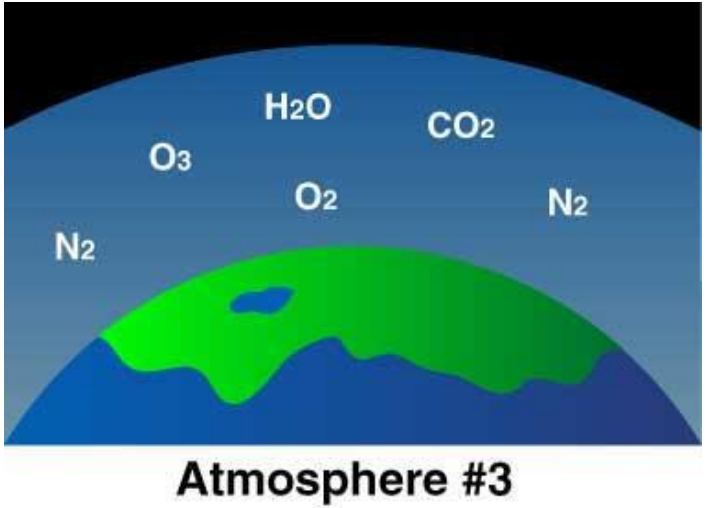
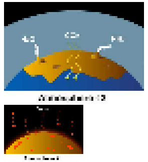
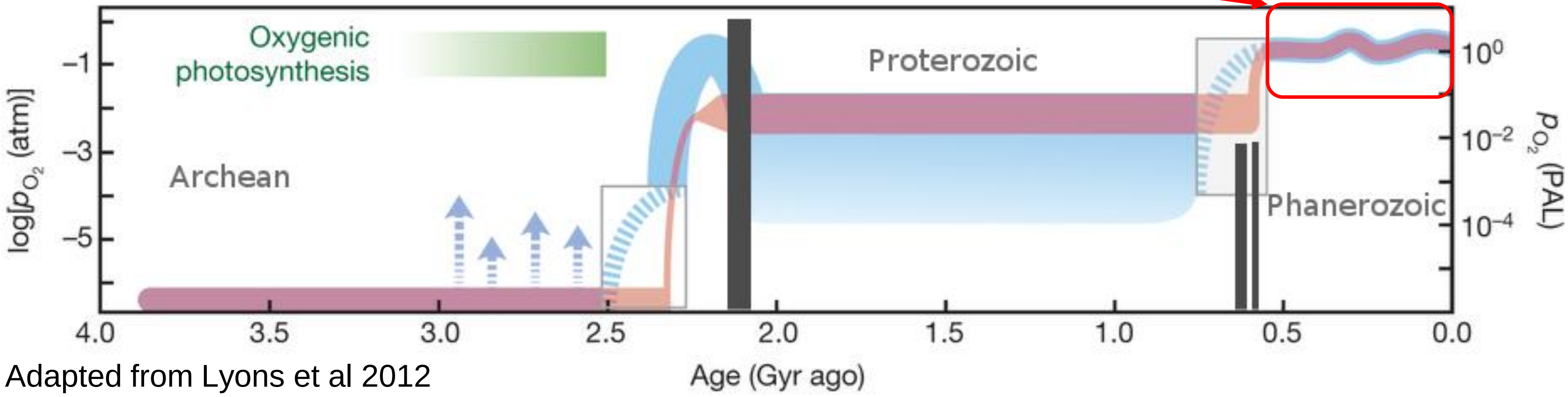




- The bulk composition has changed dramatically – from reducing to oxidising

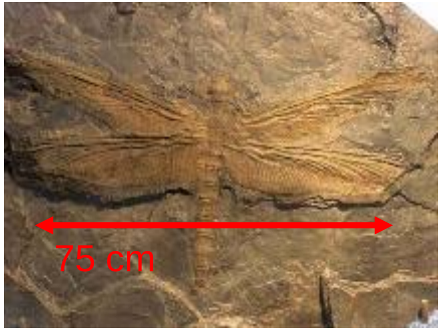
Brief History of Earth's oxidising capacity

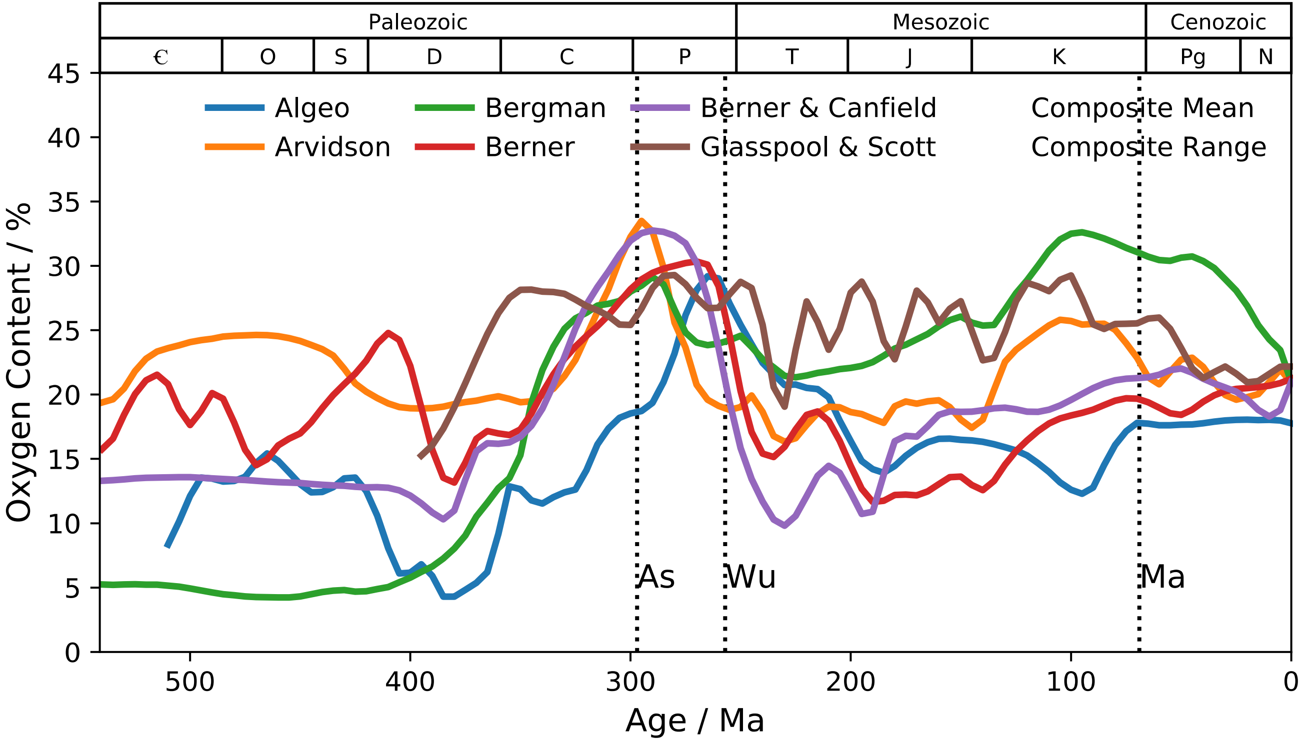
- Rise of oxygen:
  - "Two facts are known with certainty: Earth's earliest atmosphere was essentially devoid of oxygen; and today's atmosphere is composed of 21% oxygen. Most of the events that took place between these two time points are highly uncertain." Lee Kump
- But.. We think that it has changed a lot



Adapted from Lyons et al 2012

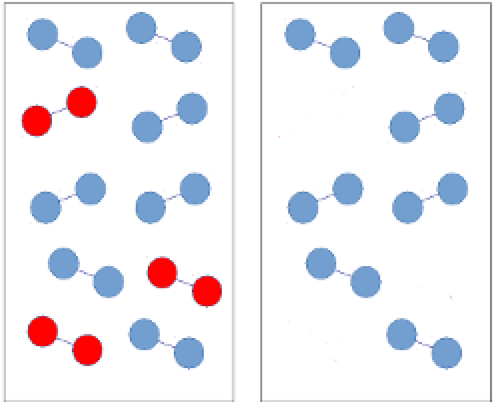
The evolution of oxygen (O_2) during the Phanerozoic



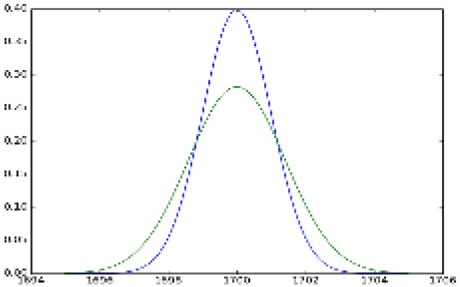


As = Asselian (early Permian 298 Ma)
Wu = Wuchapingian (end Permian 255 Ma)
Ma = Maastrictian (late cretaceous 70 Ma)

What has oxygen got to do with climate?



- Oxygen is a major gas in the present atmosphere:
  - Atmospheric Mass
- Radiation:
  - Rayleigh Scattering
  - Pressure Broadening



- Dynamics:
  - Atmospheric and oceanic heat transports
  - NB without wind stress $\langle T_s \rangle$ would be -8.7 K

Previous work

- Suggested that these changes in pO_2 (the partial pressure or amount of O_2 in the atmosphere) were important for climate.
- As pO_2 ↑ global mean surface temperature (GMST) ↓
- But.. We weren't convinced.. and the paper came out just as we had started!

RESEARCH | REPORTS

CLIMATE CHANGE

Long-term climate forcing by atmospheric oxygen concentrations

Christopher J. Poulsen,[1*] Clay Tabor,[1] Joseph D. White[2]

The percentage of oxygen in Earth's atmosphere varied between 10% and 35% throughout the Phanerozoic. These changes have been linked to the evolution, radiation, and size of animals but have not been considered to affect climate. We conducted simulations showing that modulation of the partial pressure of oxygen (pO_2), as a result of its contribution to atmospheric mass and density, influences the optical depth of the atmosphere. Under low pO_2 and a reduced-density atmosphere, shortwave scattering by air molecules and clouds is less frequent, leading to a substantial increase in surface shortwave forcing. Through feedbacks involving latent heat fluxes to the atmosphere and marine stratus clouds, surface shortwave forcing drives increases in atmospheric water vapor and global precipitation, enhances greenhouse forcing, and raises global surface temperature. Our results implicate pO_2 as an important factor in climate forcing throughout geologic time.

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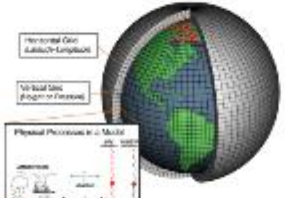
Model simulations



- Modifications made to the HadGEM3 and HadCM3 GCM codes, changing the models to be able to use variable amounts of O_2 – non trivial!

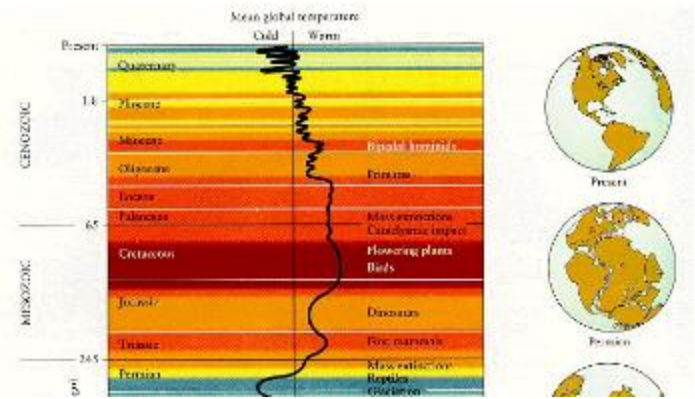
O_2 / %	21	10	35
O_2 / $kg\,kg^{-1}$	0.231	0.112	0.380
M_{air} / $g\,mol^{-1}$	28.97	28.55	29.51
P_{surf} / hPa	1000	879	1216
R_{air} / $J\,kg^{-1}\,°C^{-1}$	287	293	282
$C_{p,air}$ / $J\,kg^{-1}\,°C^{-1}$	1005	1024	988

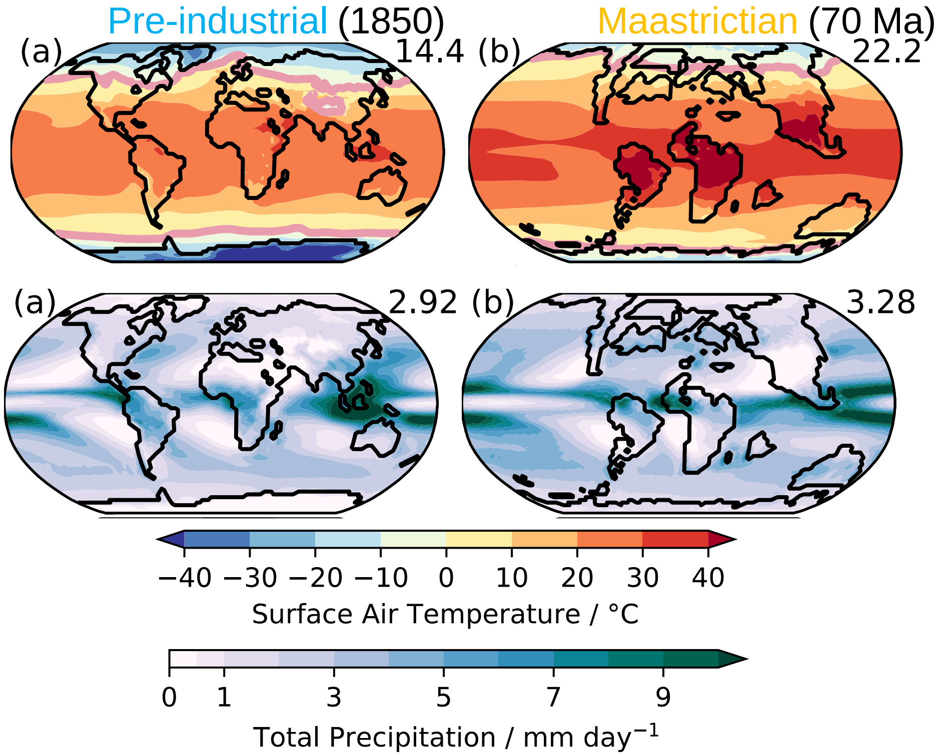
Experiment	Continents	Model	CO_2 / Pa	O_2 / %
PI-GEM	PIH	HadGEM3-AO	28	10,21,35
4xPI-GEM	PIH	HadGEM3-AO	112	10,35
PI-CM	PIH	HadCM3-BL	28	10,21,35
Ma-CM	Maastrichtian	HadCM3-BL	56	10,21,35
As-CM	Asselian	HadCM3-BL	28	10,21,35
Wu-CM	Wuchiapingian	HadCM3-BL	112	10,21,35
2xPI-CM*	PIH	HadCM3-BL	56	10,21,35
2xMa-CM*	Maastrichtian	HadCM3-BL	112	10,21,35
2xAs-CM*	Asselian	HadCM3-BL	56	10,21,35

- *denote 2xCO_2 sensitivity simulations

Base-state (pO_2 = 21%) results from HadCM3

- Model simulations match our understanding of the climates of the deep past – warmer phases in Ma and Wu and cooler in As





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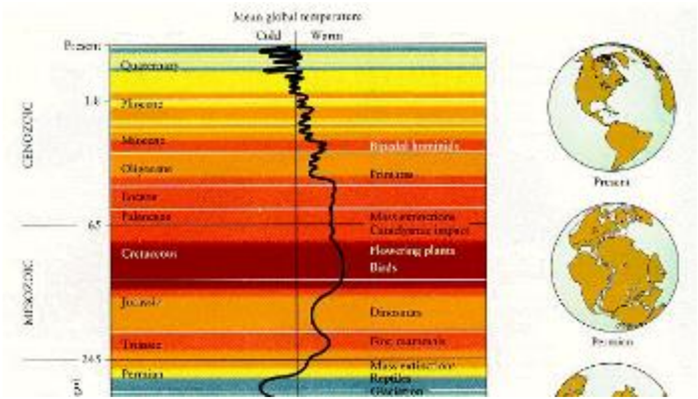
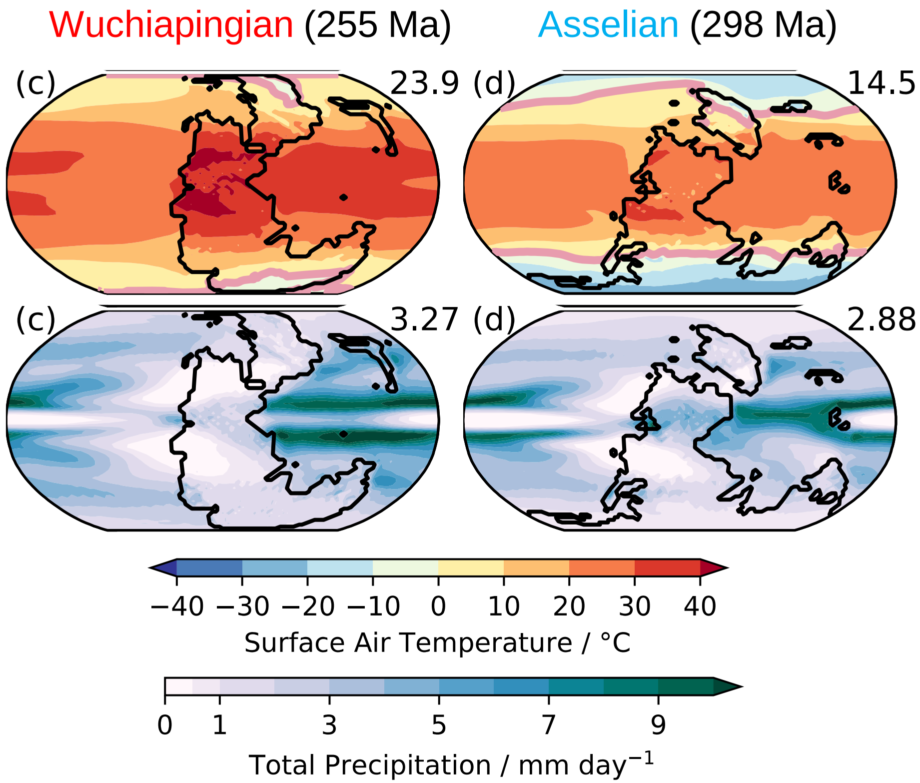
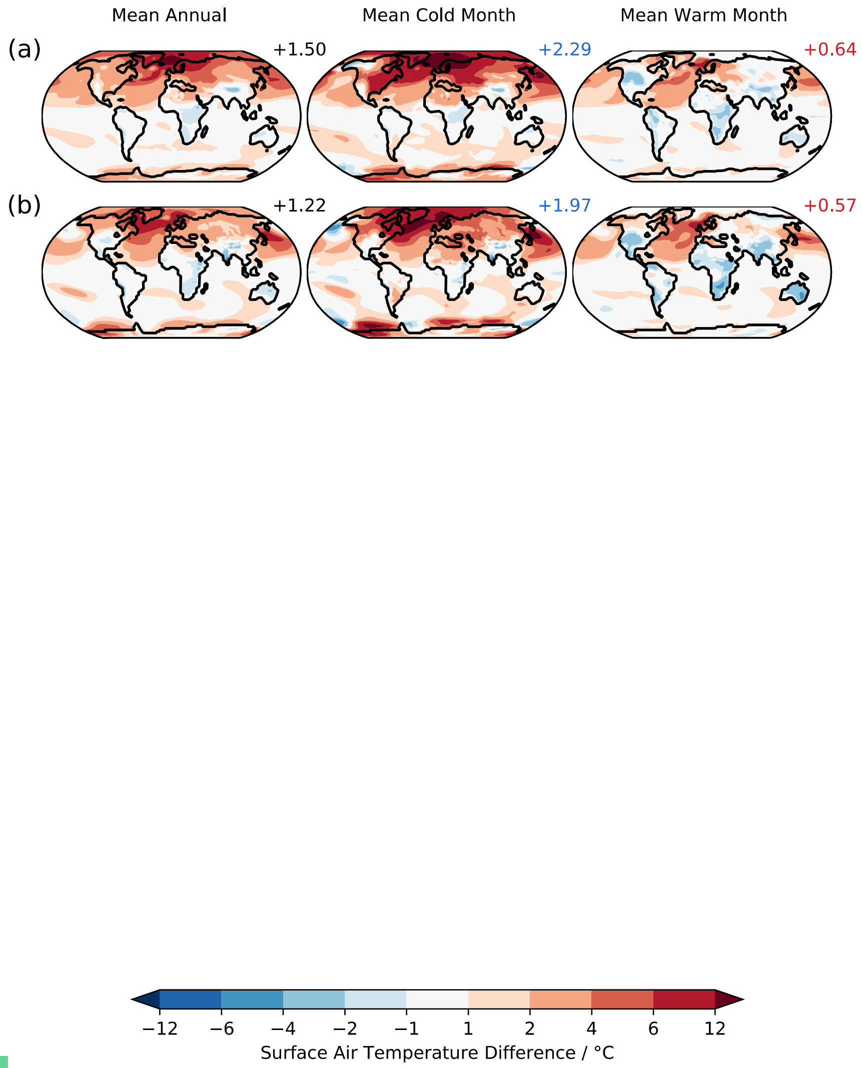
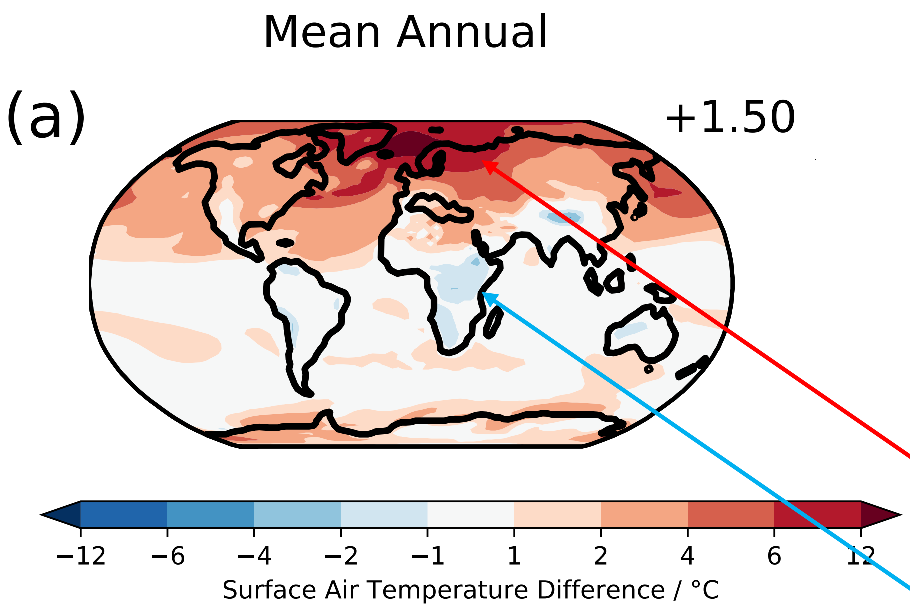






Impacts of changes in pO_2 on GMST

- (a)-(b) shows difference between response in HadGEM3 (a) and HadCM3 (b)
- Difference is pO_2 = 35 % - pO_2 = 10 %



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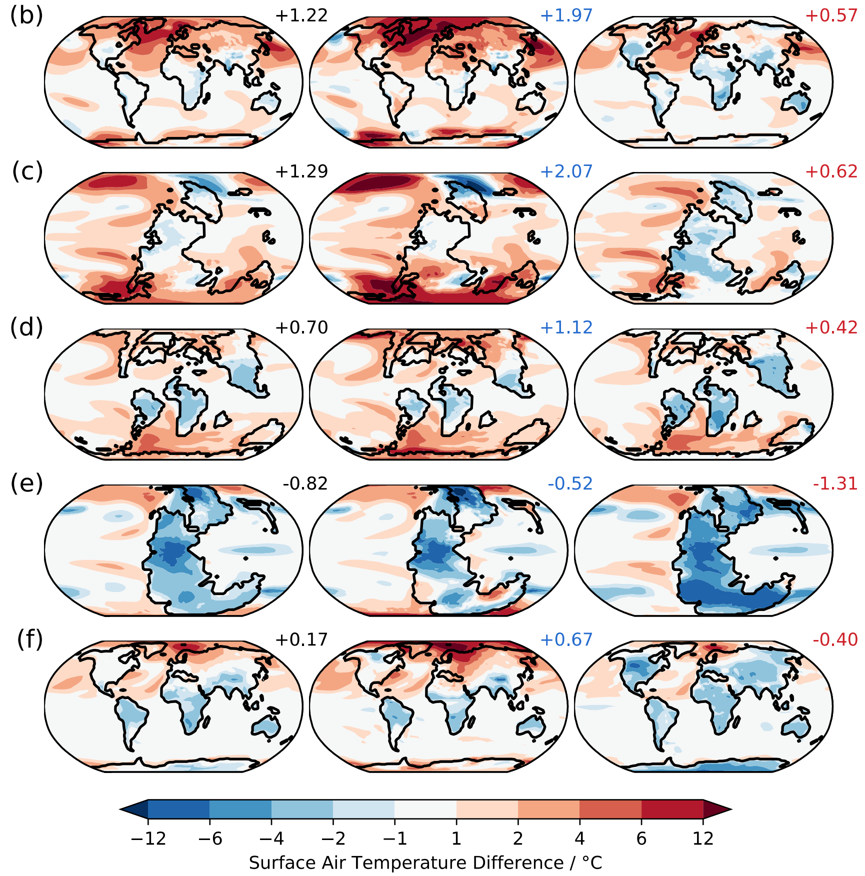
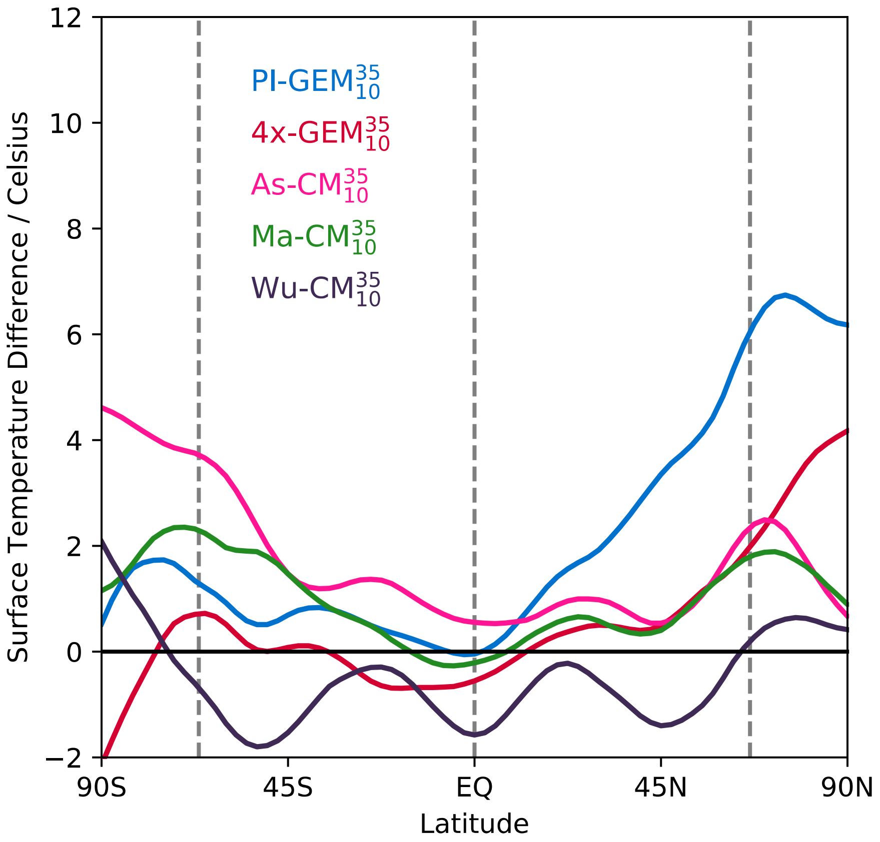
- (a)-(b) shows difference between response in HadGEM3 (a) and HadCM3 (b)
- Difference is $pO_2 = 35$ % - $pO_2 = 10$ %
- High latitude warming
- Continental/tropical cooling

Small changes in GMST in spite of HUGE changes in atmospheric composition!



Impacts of changes in pO_2 on GMST

- (a)-(b) shows difference between response in HadGEM3 (a) and HadCM3 (b)
- Difference is pO_2 = 35 % - pO_2 = 10 %
- (b)-(f) highlight the impacts of these changes in pO_2 on different periods of time (c = As; d = Ma; e = Wu; f = 4xPI CO_2)
- Our model simulations suggest that changes in pO_2 have a small impact on climate state



- Shading shows difference from annual mean and cold month mean

Impacts of changes in pO_2 on GMST

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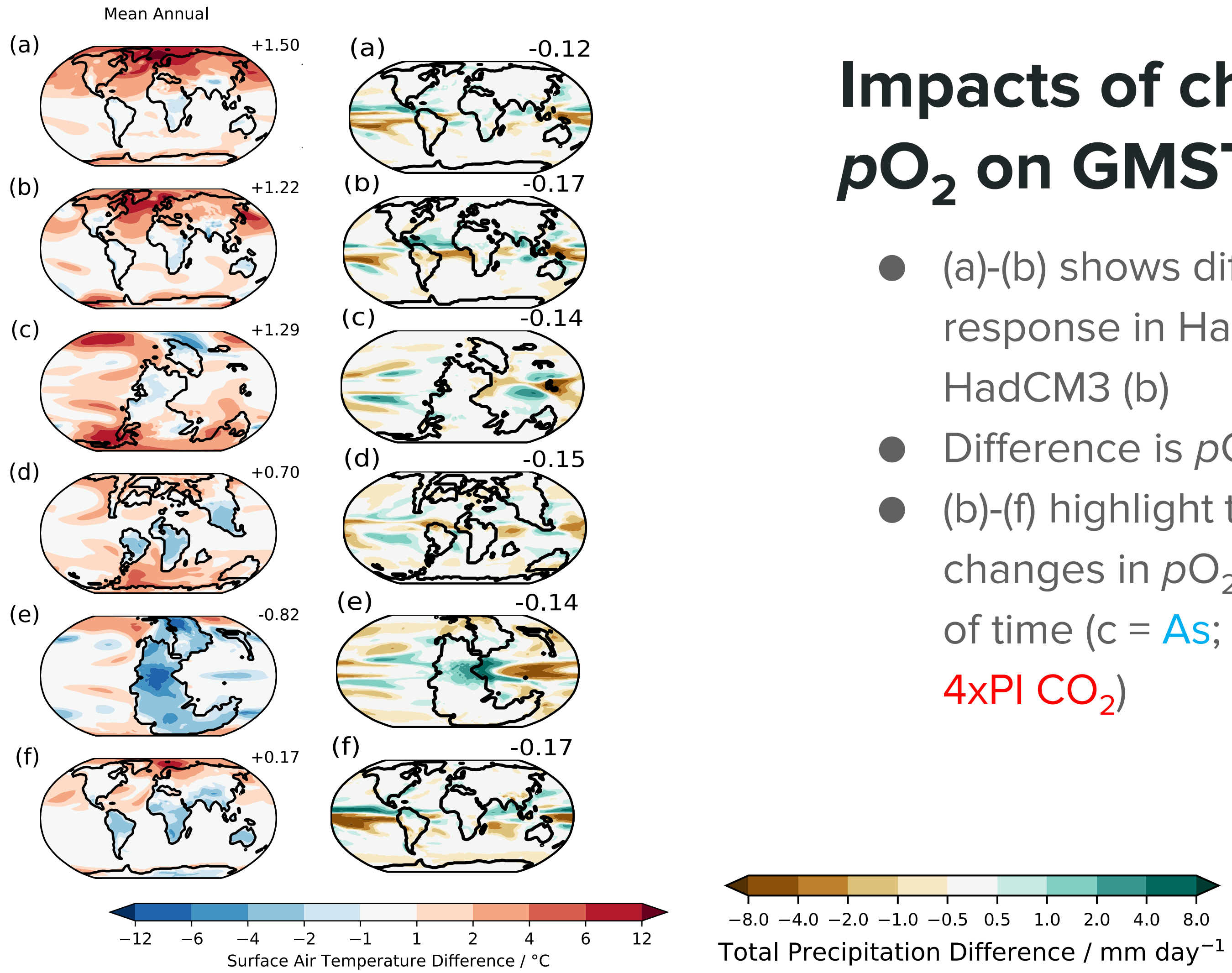

Impacts of changes in pO_2 on GMST and precip.

- (a)-(b) shows difference between response in HadGEM3 (a) and HadCM3 (b)
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- (b)-(f) highlight the impacts of these changes in pO_2 on different periods of time (c = As; d = Ma; e = Wu; f = 4xPI CO_2)

1D energy balance model

- Following Heinmann et al (2009) approach for deconvolving contributions from different parts of the climate system:

$$\mathrm{SW}_t^{\downarrow}(\phi)[1-\alpha(\phi)] - \frac{1}{2\pi R^2 \cos(\phi)}\frac{\partial F(\phi)}{\partial \phi} = \epsilon(\phi)\sigma T^4_{s,\mathrm{ebm}}(\phi)$$

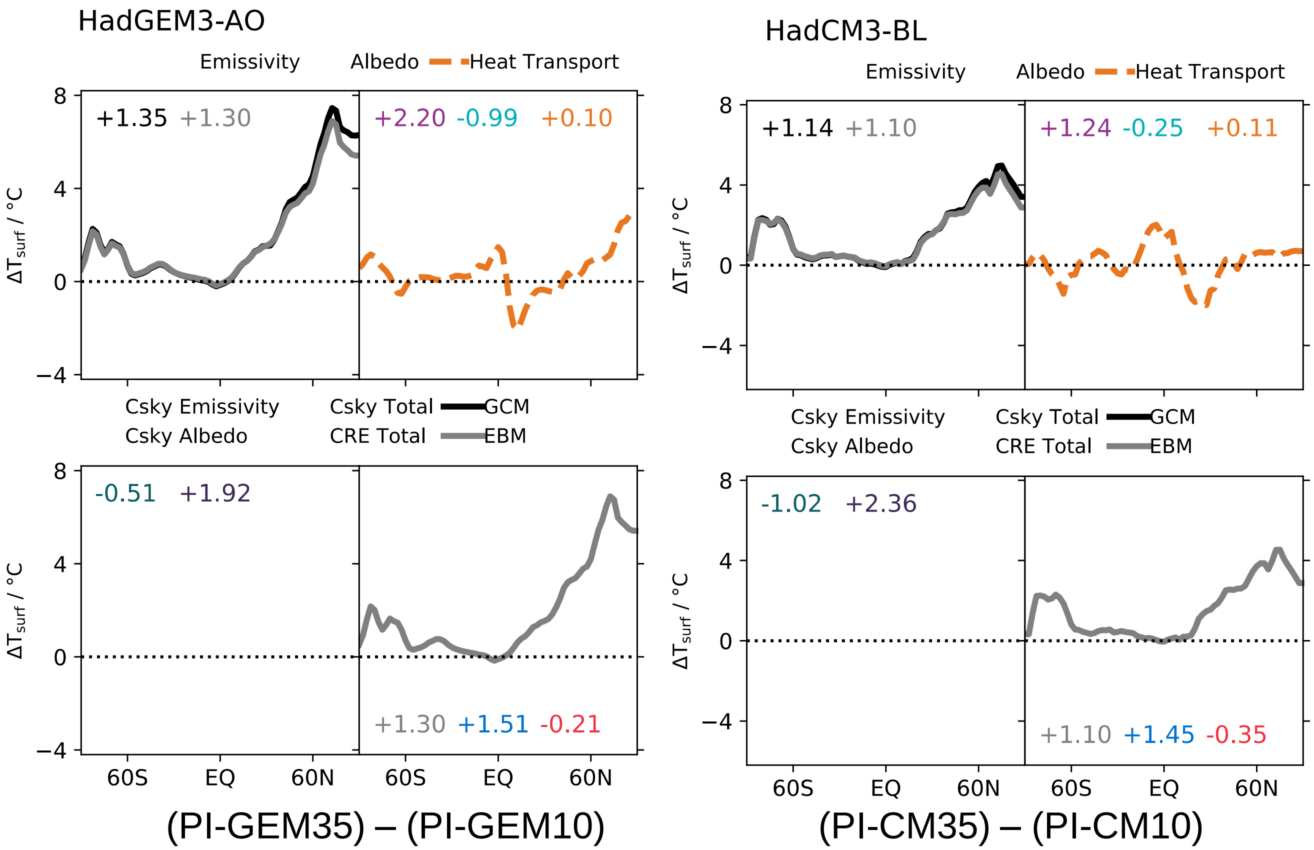
- Where the divergence of the total meridional heat transport is given by:

$$\frac{\partial F(\phi)}{\partial \phi} = -2\pi R^2 \cos(\phi)(\mathrm{SW}_t^{\mathrm{net}}(\phi) + \mathrm{LW}_t^{\mathrm{net}}(\phi))$$

- Solve for $T_{s,ebm}$ by using zonal and annual mean radiative fluxes from model simulations and calculate the cloud radiative effects by comparing clear-sky($_c$) and all-sky fluxes:

$$\alpha_c = \frac{\mathrm{SW}^{\uparrow}_{t,c}}{\mathrm{SW}^{\downarrow}_t}, \epsilon_c = \frac{\mathrm{LW}^{\uparrow}_{t,c}}{\mathrm{LW}^{\uparrow}_s}$$

Understanding the drivers for change in climate in PI

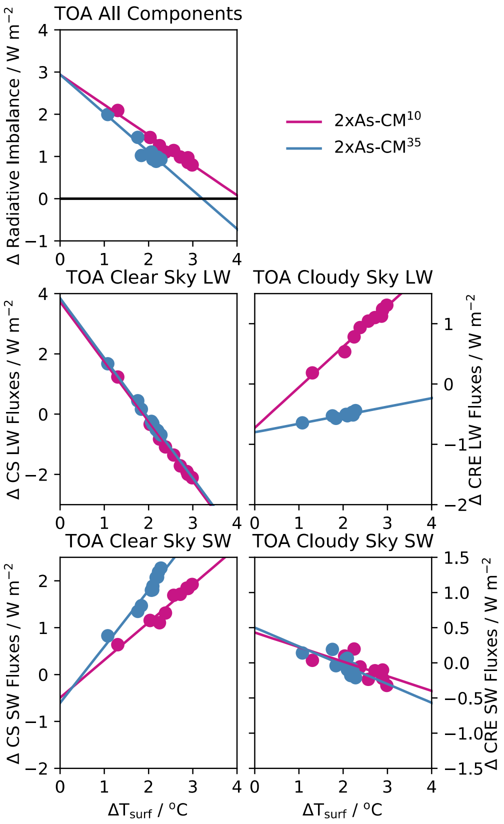


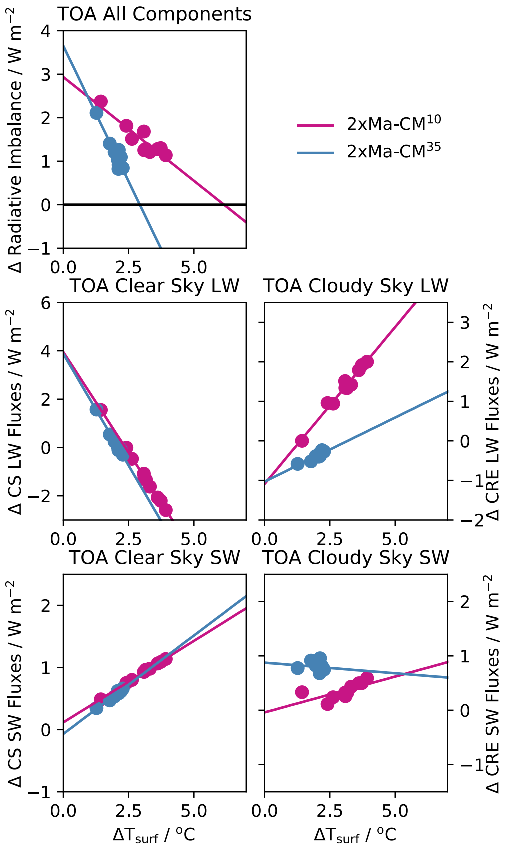
- Good match between EBM and model
- Pressure broadening ↑
- Rayleigh scattering ↑
- Heat transport (Wind stress) ↑
- clear-sky ↑ vs cloudy-sky ↓

Climate sensitivity

- *Interestingly*, whilst ΔpO_2 has a small impact on base climate, there are much larger effects on equilibrium climate sensitivity.
- Decreases in pO_2 lead to increases in ECS
- Higher pO_2 leads to less convection (so at low pO_2 moist feedbacks)

Cloud feedbacks plan an important but uncertain role here





So are the changes in pO_2 important for climate?

- Yes and no. **CO_2 changes are the dominant factor in climate change**.
- Our model results emphasise that there is a need for coupled ocean-atmosphere (and who knows chemistry?) simulations for paleo problems.
- Increases in pO_2 led to:
    - The climate response is state dependent – so case by case analysis needed
    - Reduction in the seasonal cycle of temperature
    - Reduction in equator-to-pole temperature gradient
    - Reduction in global precipitation
- We have run further simulations which suggest that pO_2 can be important for snowball Earth

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Thanks!

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Model evaluation

- Focus on the Maastrictian (70 Ma).
- Comparison to proxy reconstructions of temperature from Upchurch et al. (2015) using var monthly mean as model *error.*
- Overall a good comparison with the reconstructions with worst performance at high latitudes.