

Radiative and dynamic controls of global scale energy fluxes



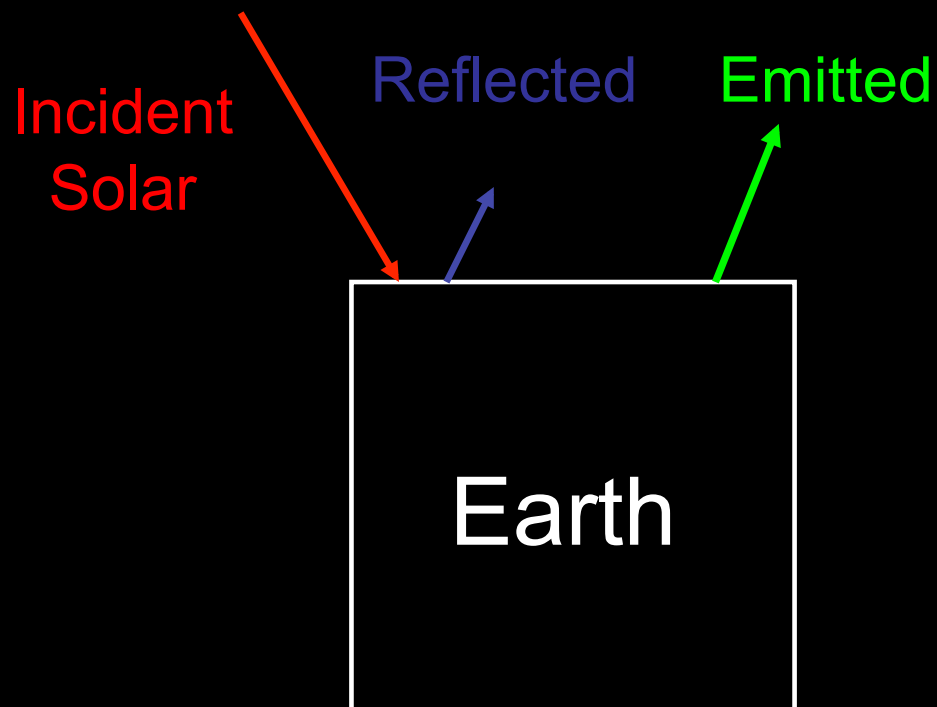
Aaron Donohoe, Ph.D. defense

April 8th 2011

Beginners guide to climate part I :

Global average energy balance

- The Earth receives energy from the sun (and reflects back some portion of it)
- To come into energy balance (equilibrium) the Earth must emit the same amount of energy it receives

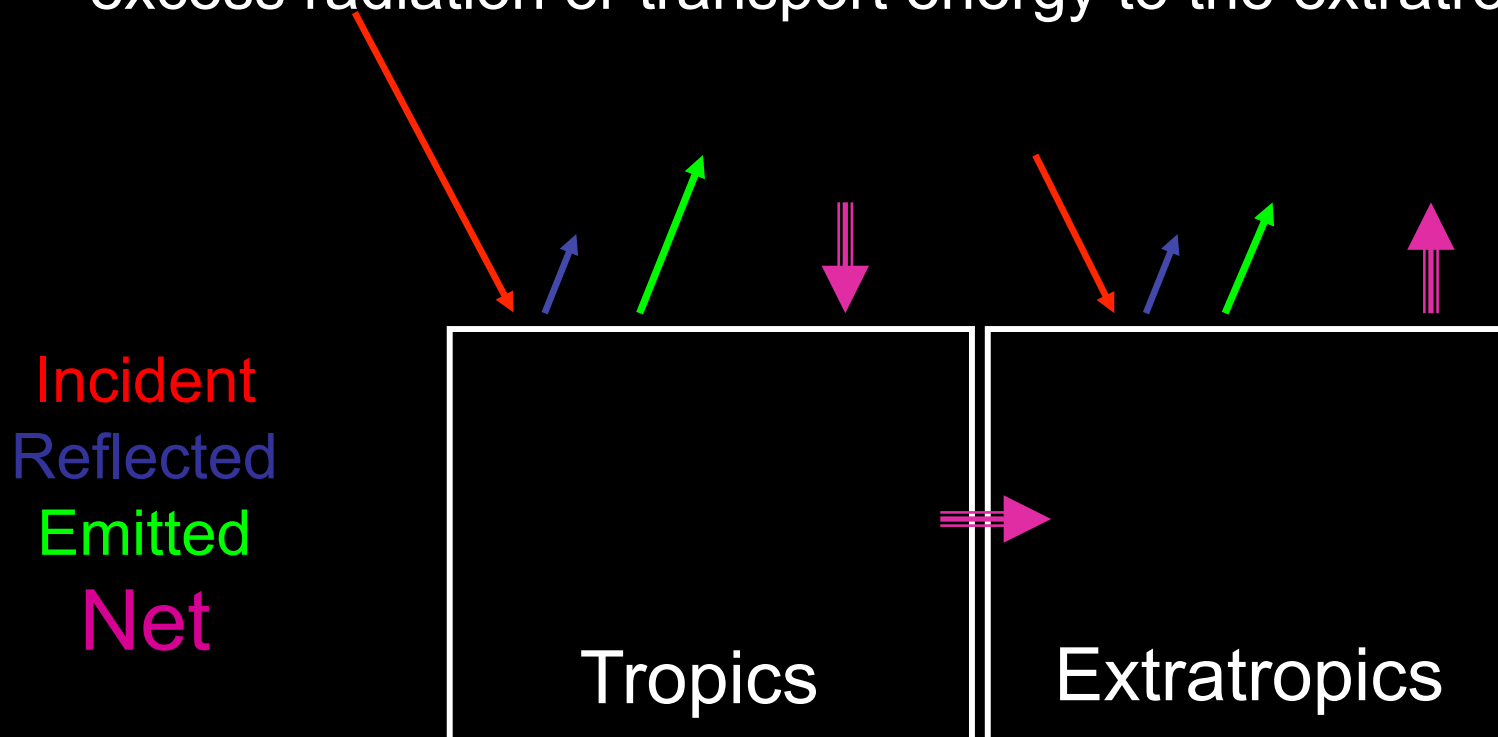


$$\text{Incident} - \text{Reflected} = \text{Emitted}$$

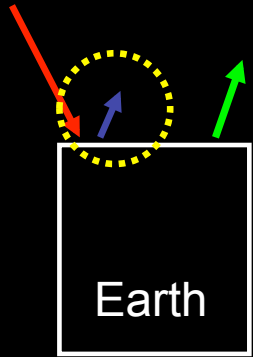
$$S(1-\alpha_p) = \sigma T_e^4$$

Beginners guide to climate part II : Equator-to-pole contrast

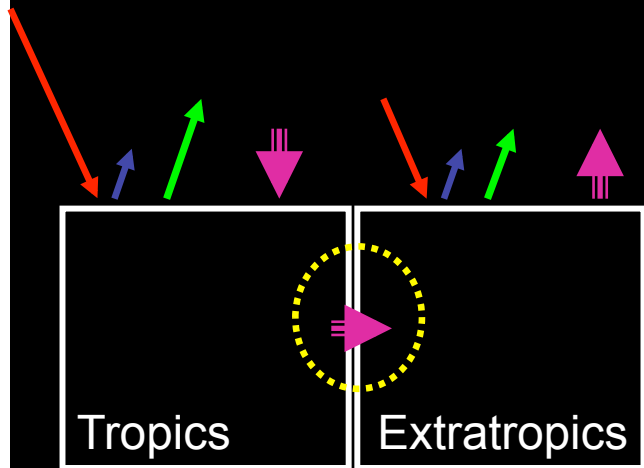
- The tropics receive more solar radiation than the high latitudes (extratropics)
- To come to equilibrium, the tropics must either emit excess radiation or transport energy to the extratropics



Thesis Outline



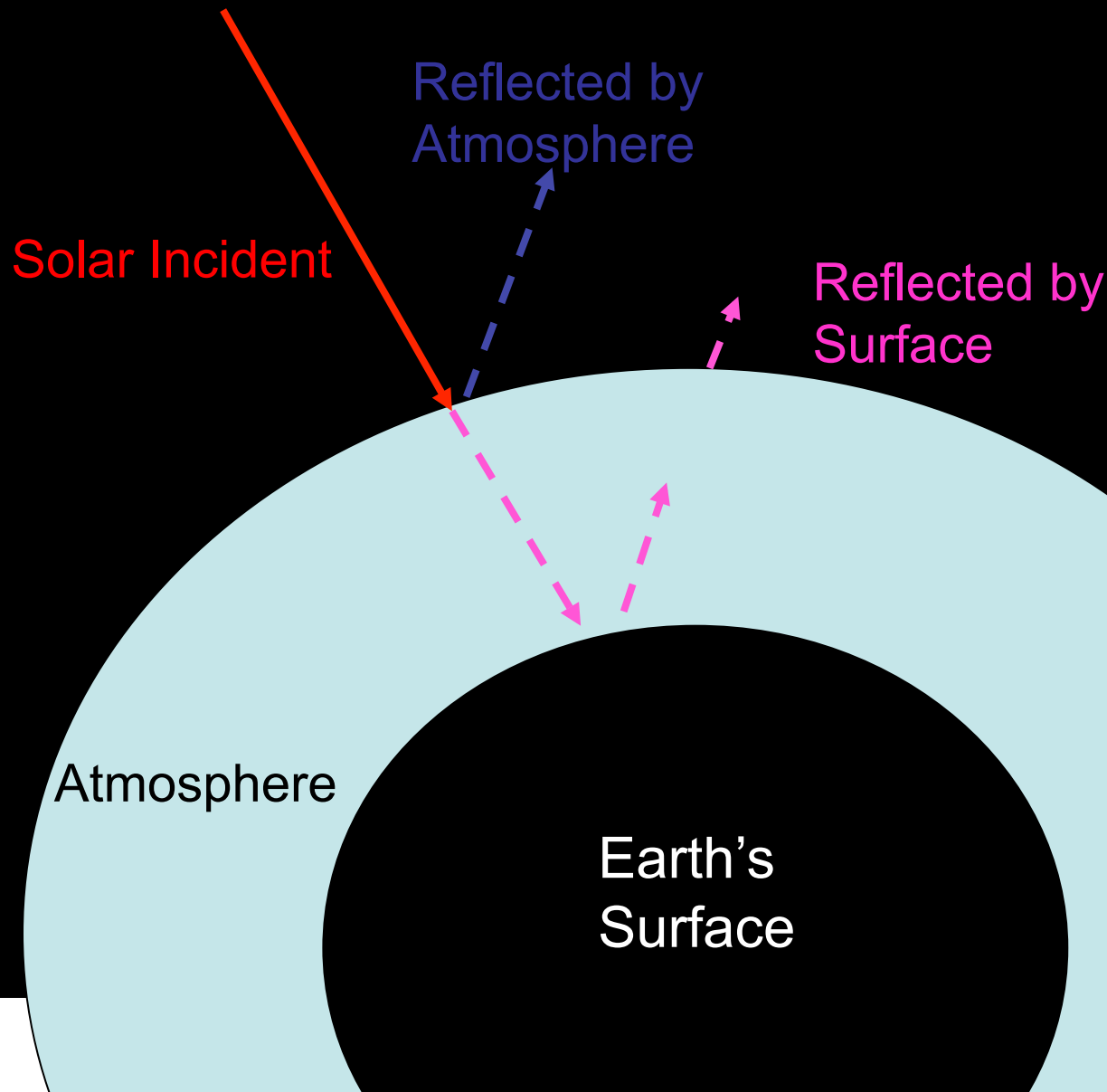
1. What determines the Earth's planetary albedo? (How much solar radiation gets reflected)



2. What determines the meridional heat transport in the climate system?

3. What controls the seasonal amplitude of energy fluxes on the equator-to-pole scale?

I : What determines the Earth's planetary albedo? (solar radiation reflected at top of atmosphere)



Simplified (isotropic) shortwave radiation model

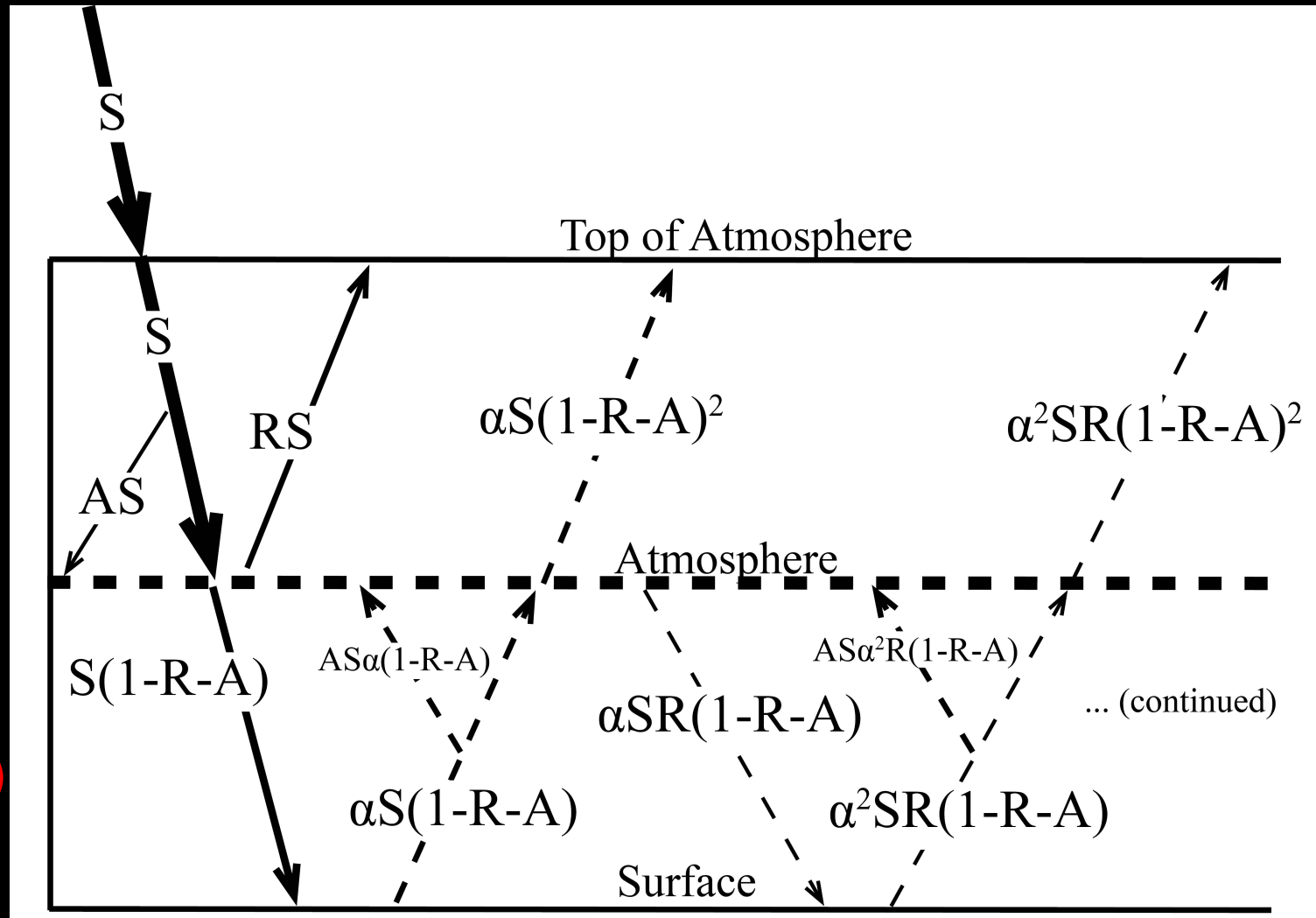
S = incident

R = cloud reflection

A = absorption

α = surface albedo

(UNKNOWN)

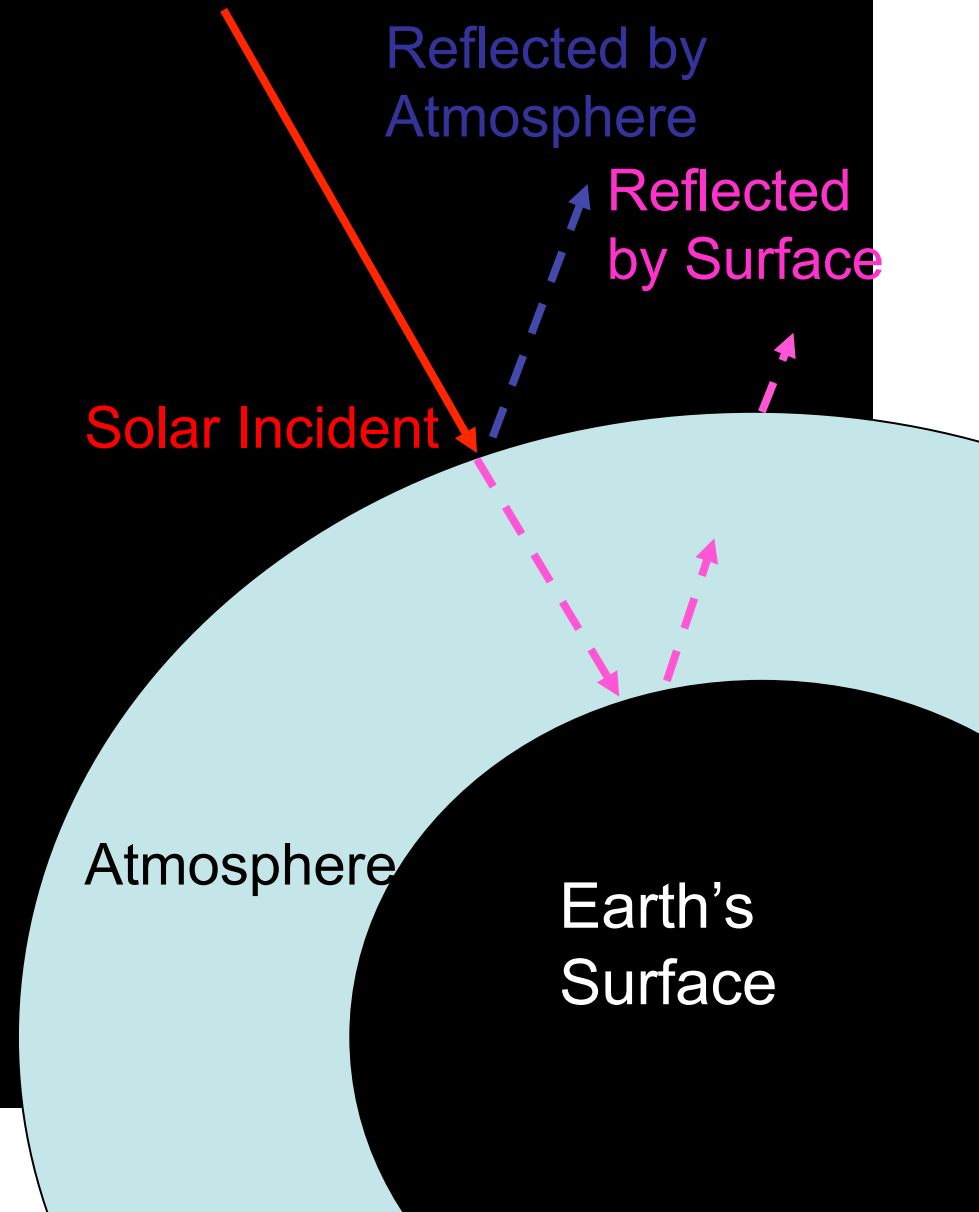


Partitioning of planetary albedo into atmospheric and surface components

$$\alpha_P = \alpha_{P,ATMOS} + \alpha_{P,SURF}$$

$$\alpha_{P,ATMOS} = R$$

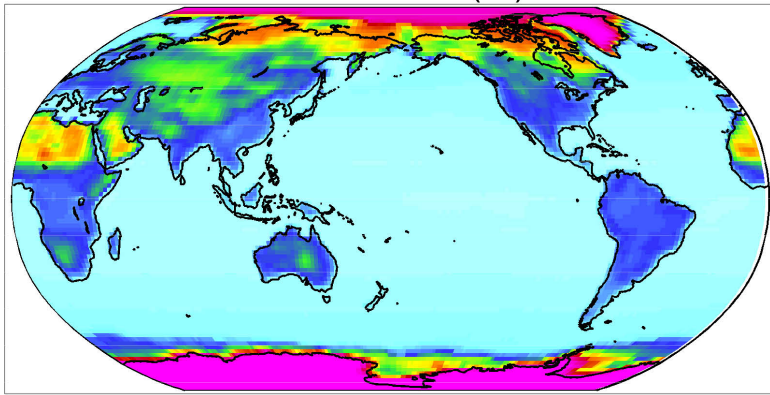
$$\alpha_{P,SURF} = \frac{\alpha(1-R-A)^2}{(1-\alpha R)}$$



Observed (CERES) surface and atmospheric contribution to planetary albedo

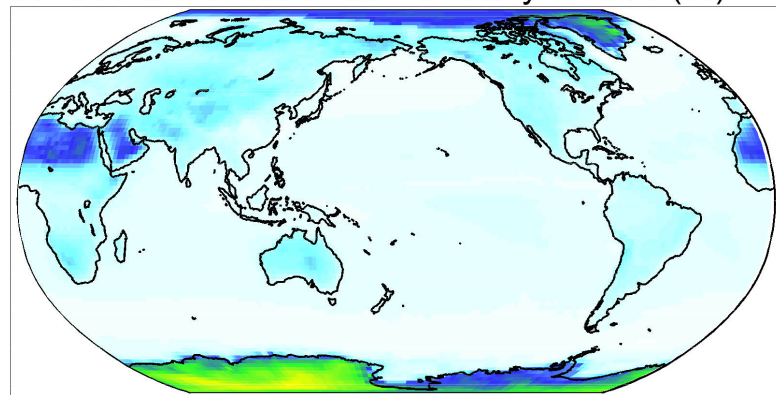
a

Surface Albedo (%)



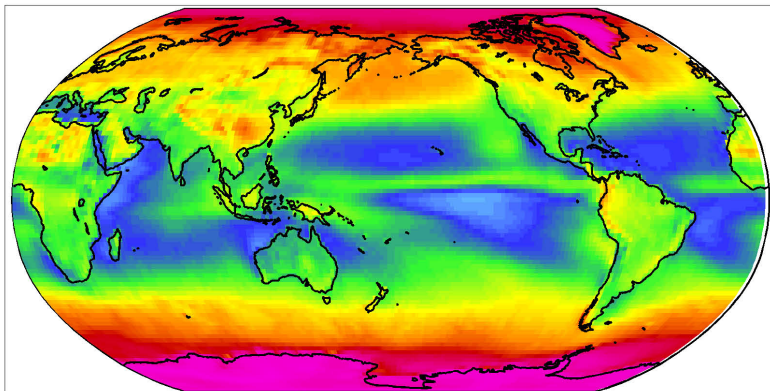
b

Surface Contribution to Planetary Albedo (%)



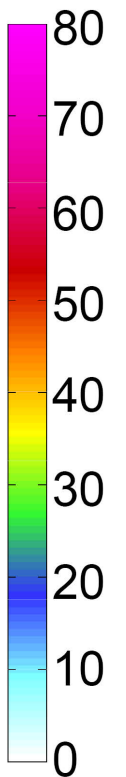
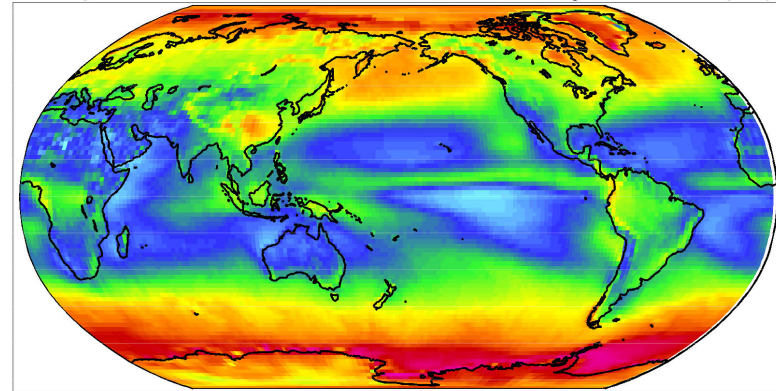
c

Planetary Albedo (%)

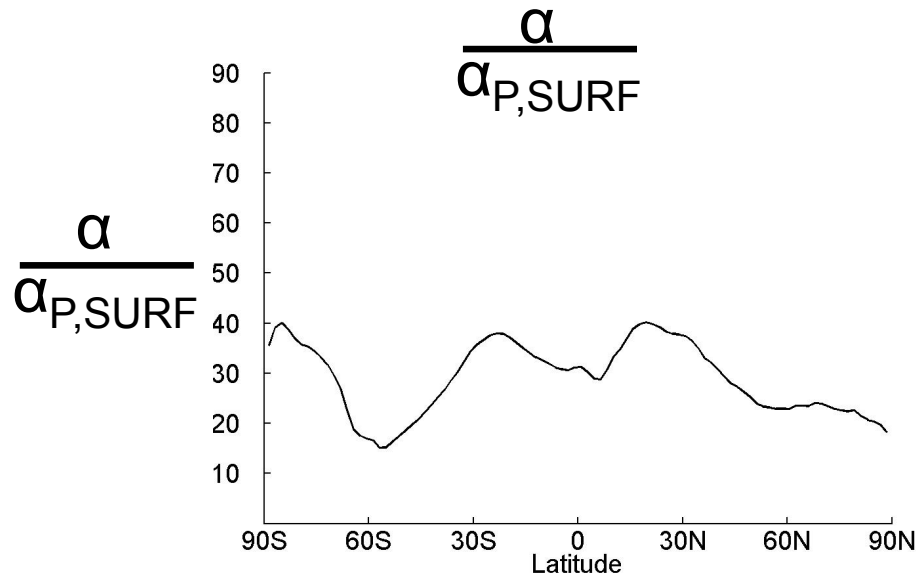
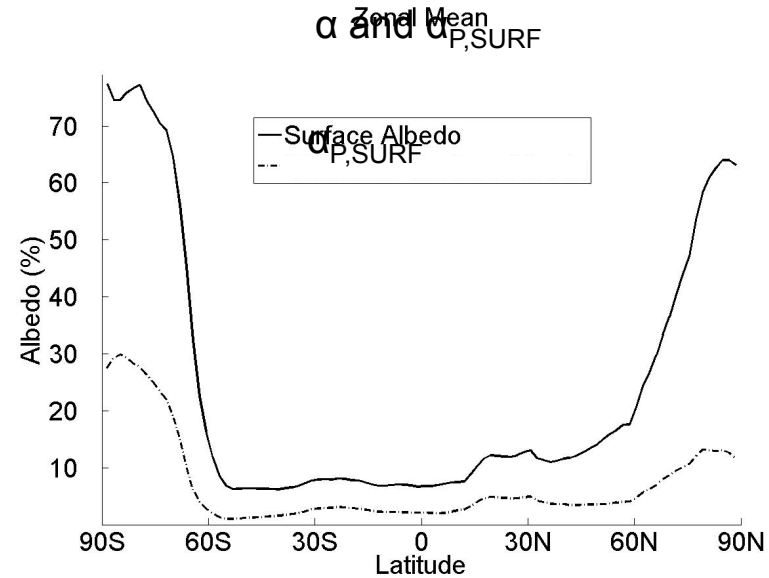
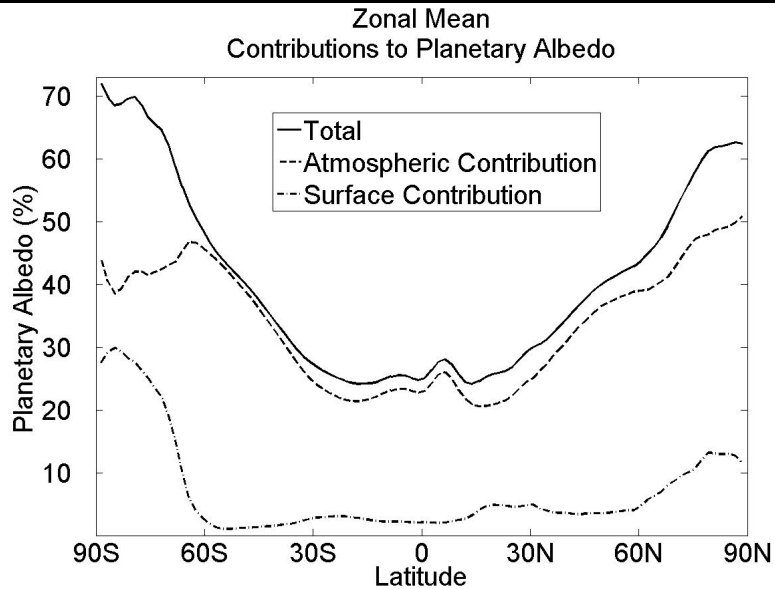


d

Atmospheric Contribution to Planetary Albedo (%)

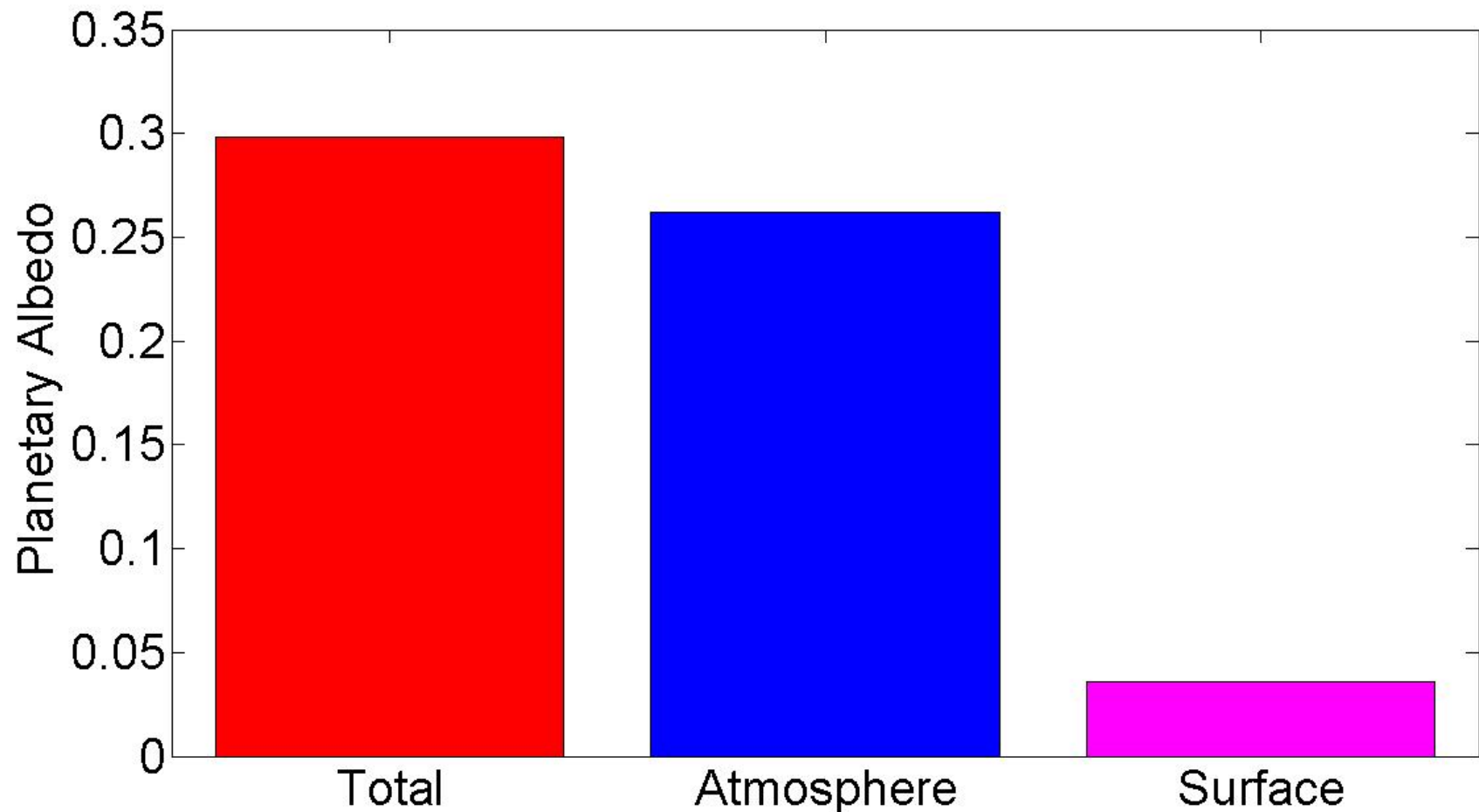


Observed Surface and atmospheric contribution to planetary albedo

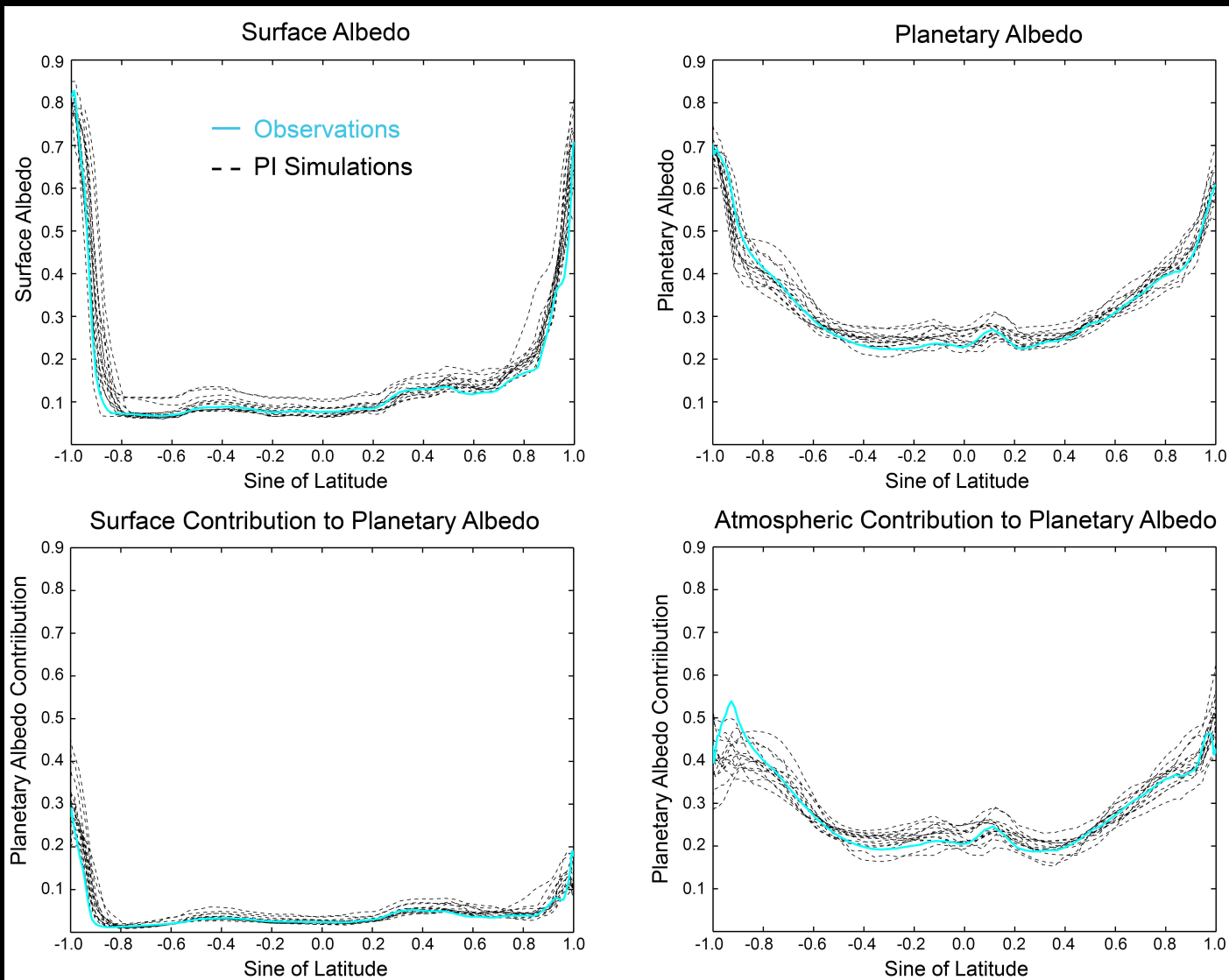


$$\alpha_{P,SURF} = \frac{\alpha(1-R-A)^2}{(1-\alpha R)}$$

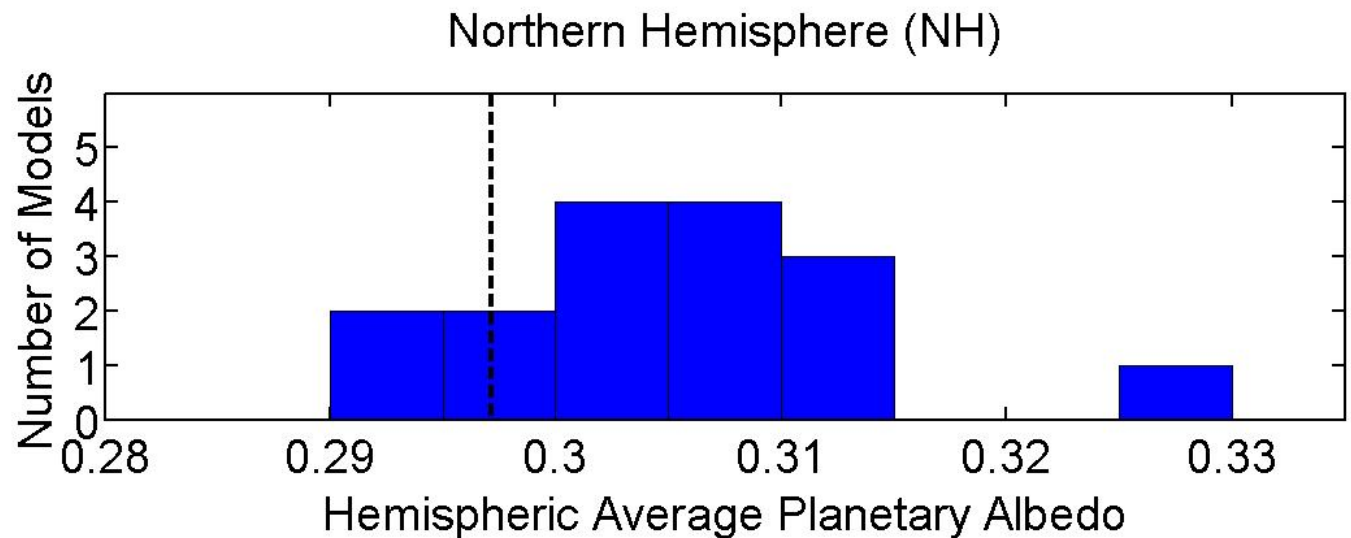
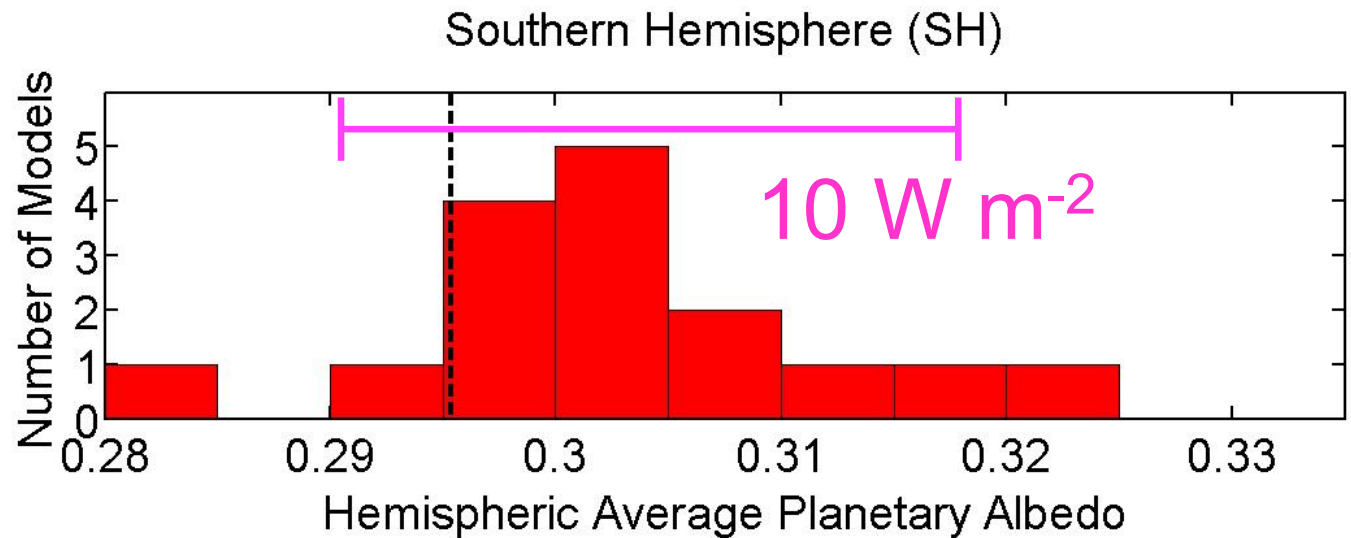
Observed Global Mean Planetary Albedo and its atmospheric/surface Partitioning



Planetary Albedo Partitioning in Climate Models (CMIP3)

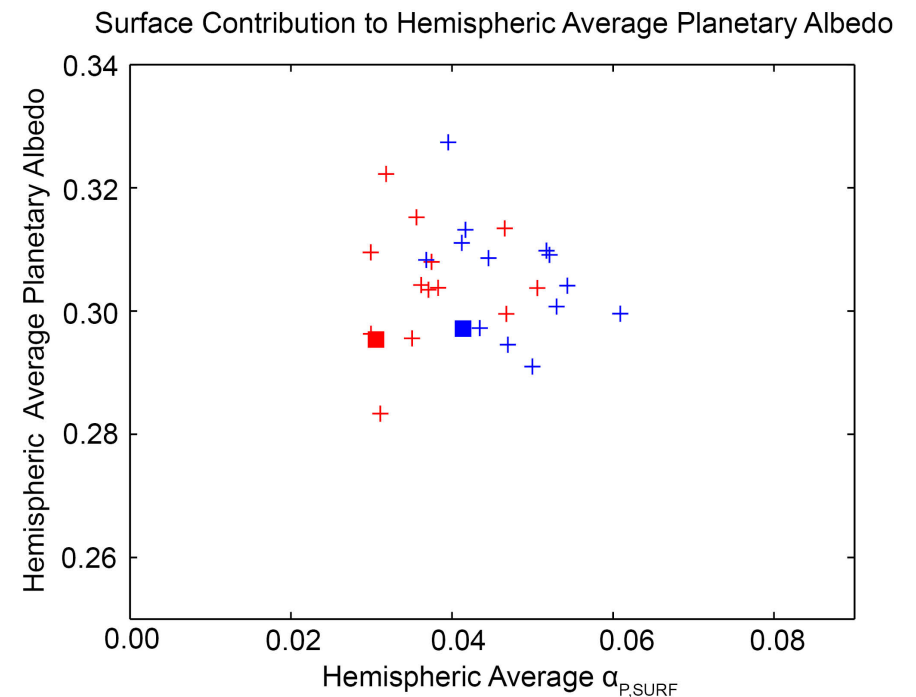
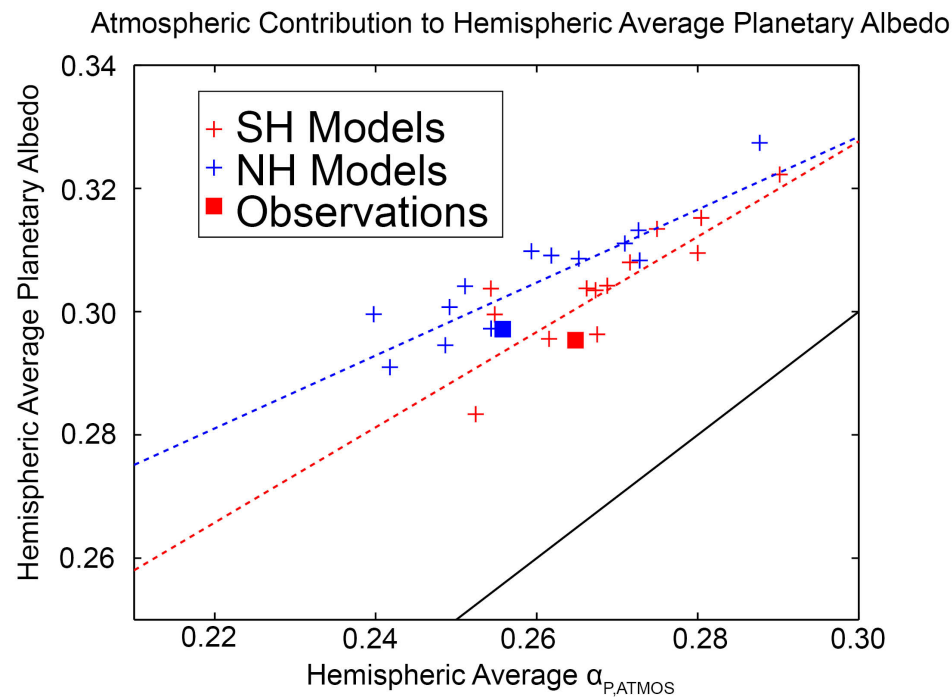


Histogram of hemispheric average planetary albedo

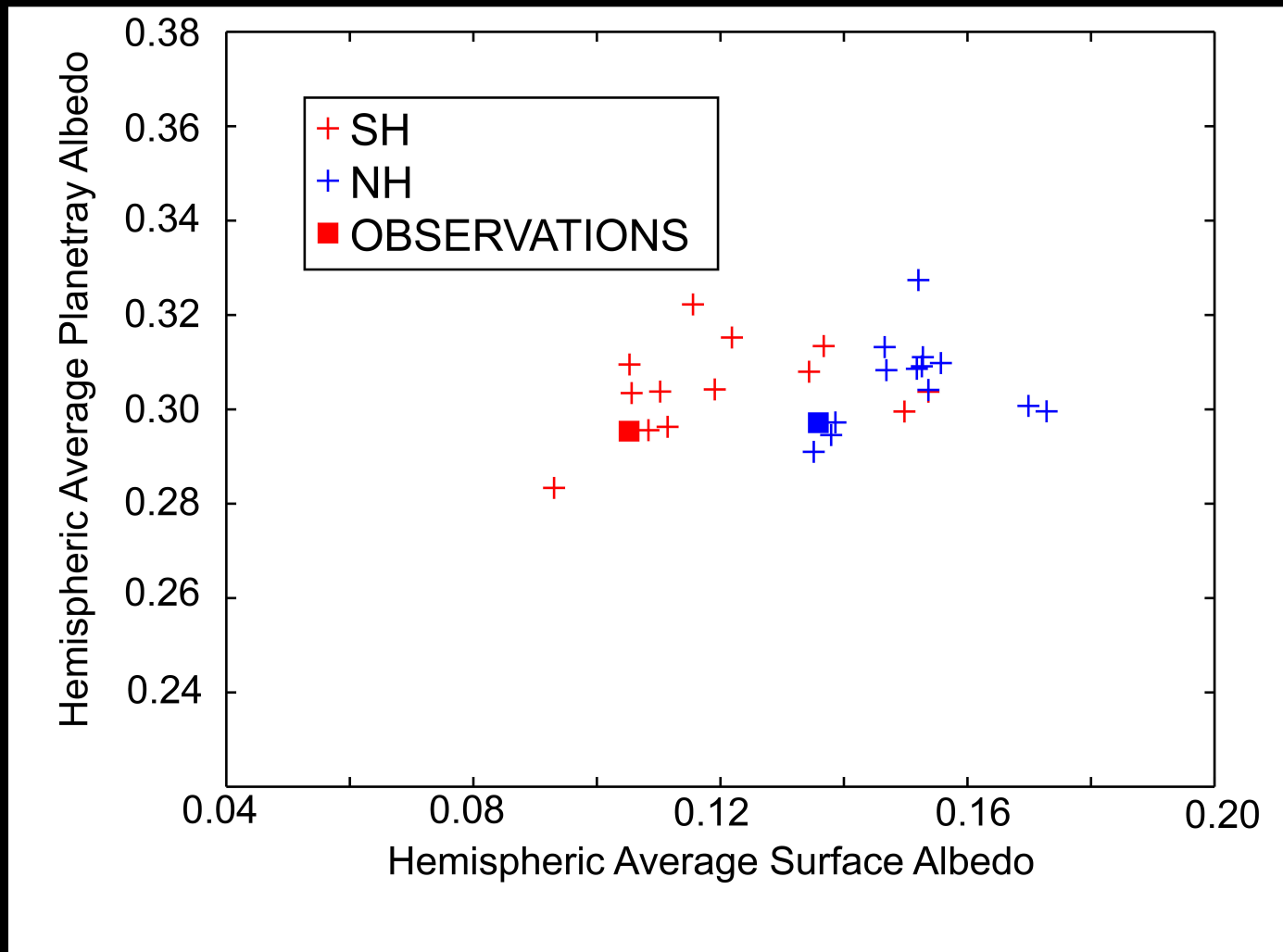


.....
Observations
(CERES)

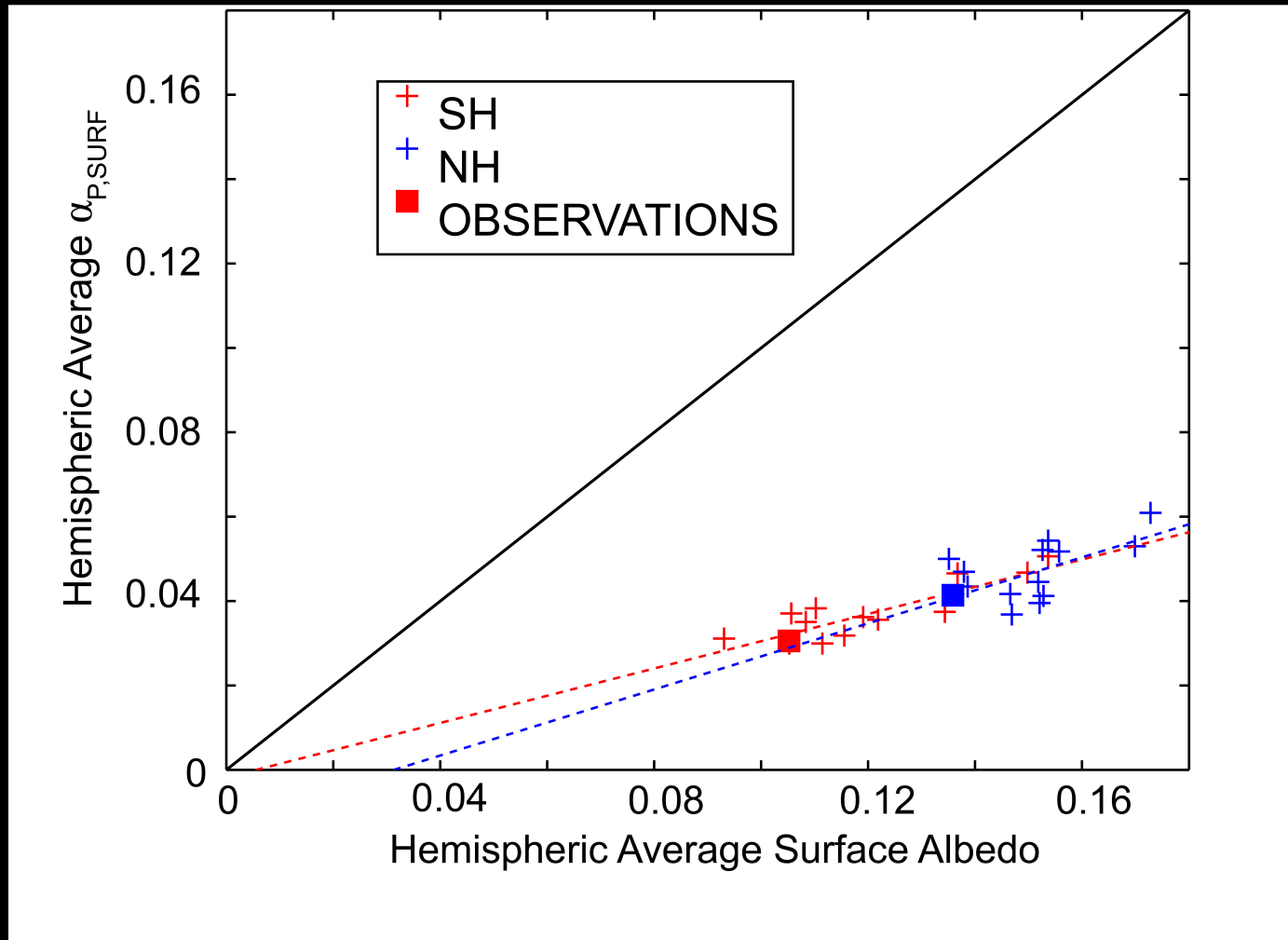
Partitioning of hemispheric average planetary albedo



Hemispheric Average Surface Albedo and Planetary Albedo



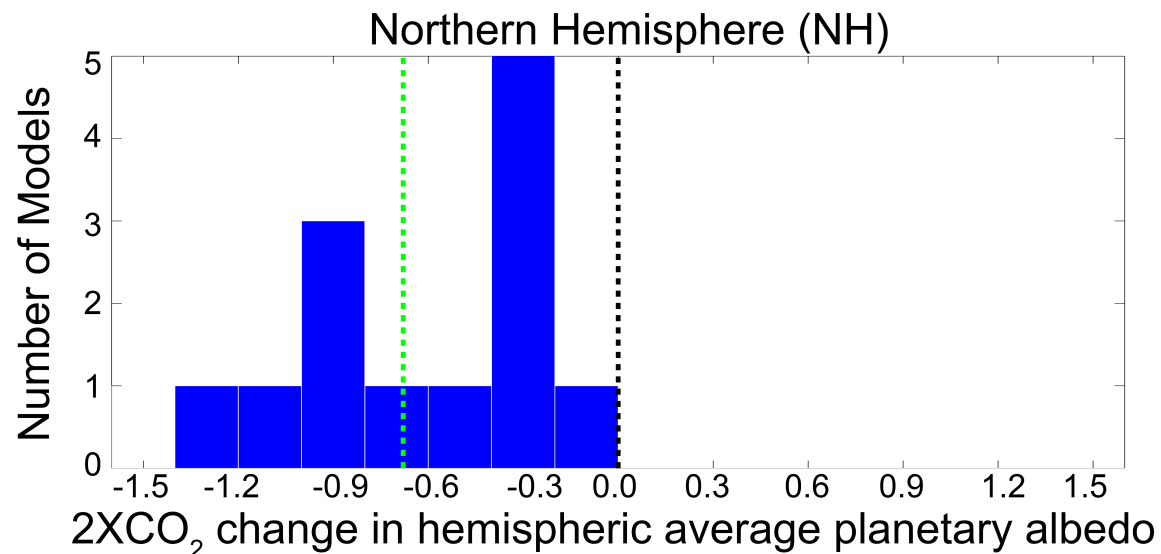
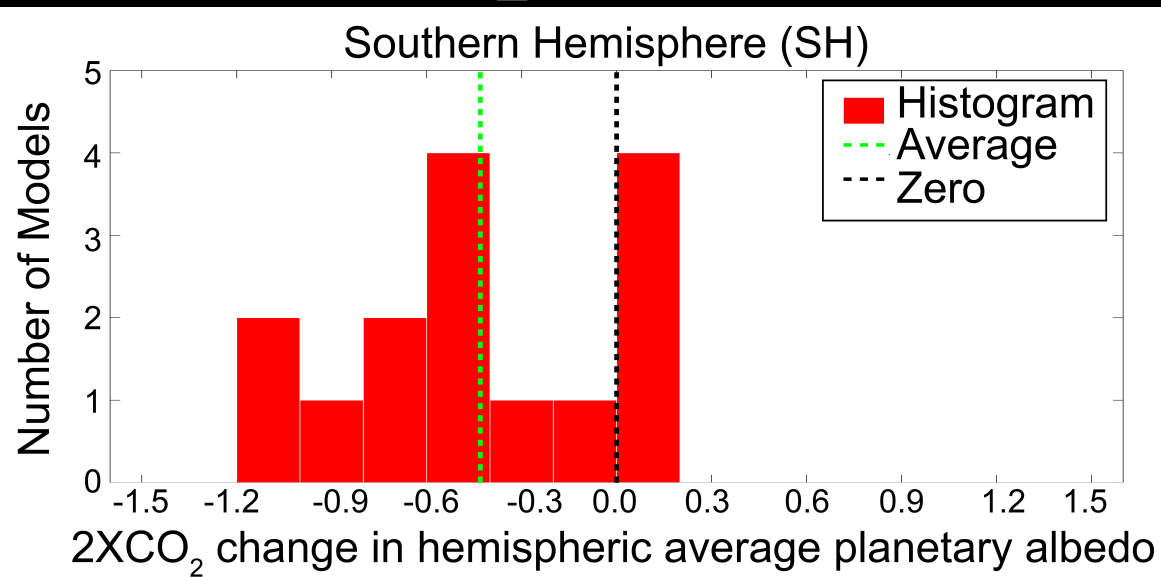
Hemispheric Average Surface Albedo and Surface Contribution to Planetary Albedo



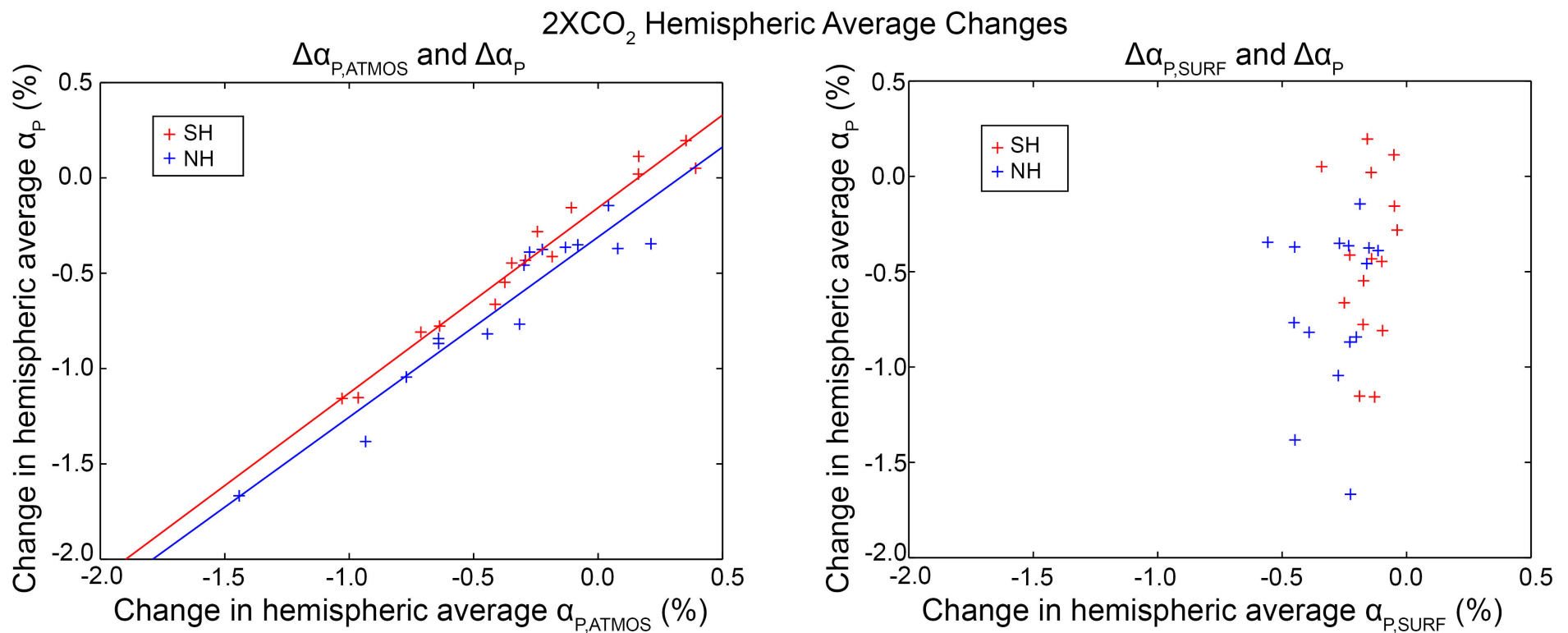
Changes due to CO₂ doubling

- 1% CO₂ increase to doubling experiments
- CO₂ doubles at year 69, we average data from years 200-220
- Compare with pre-industrial simulation in the same model

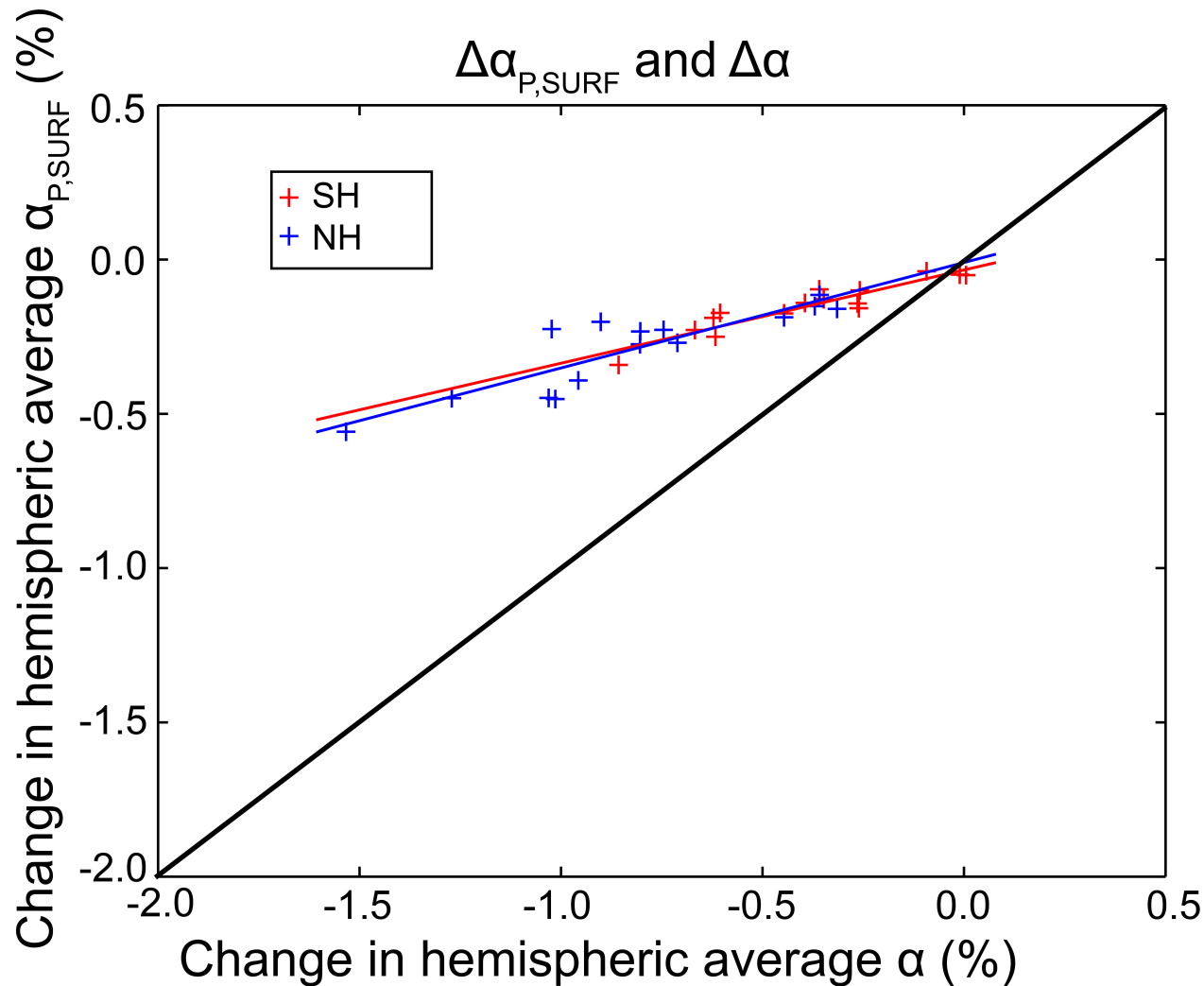
Change in planetary albedo due to CO₂ doubling



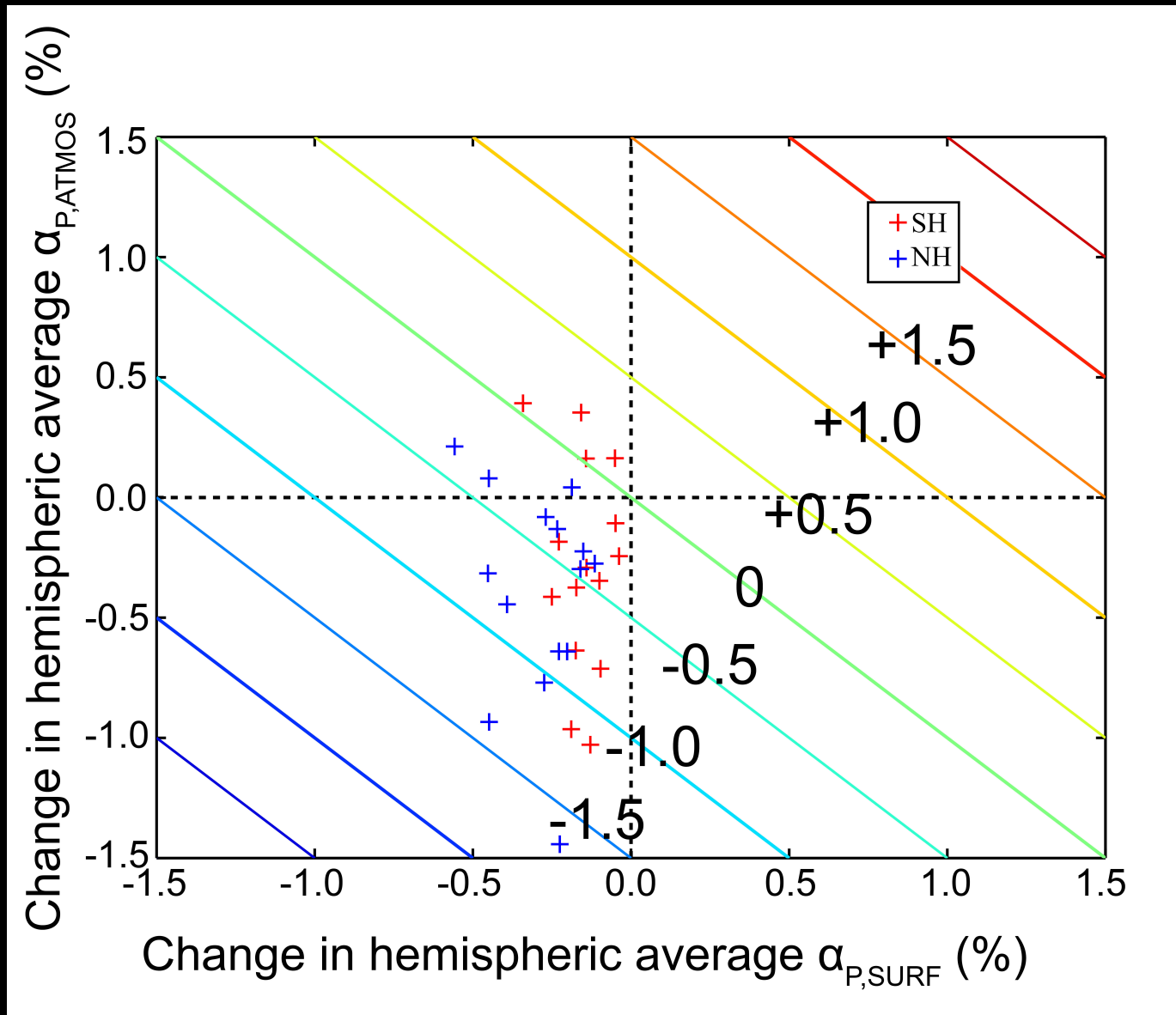
2 X CO₂ change in planetary albedo and partitioning



2 X CO2 change in surface contribution to planetary albedo



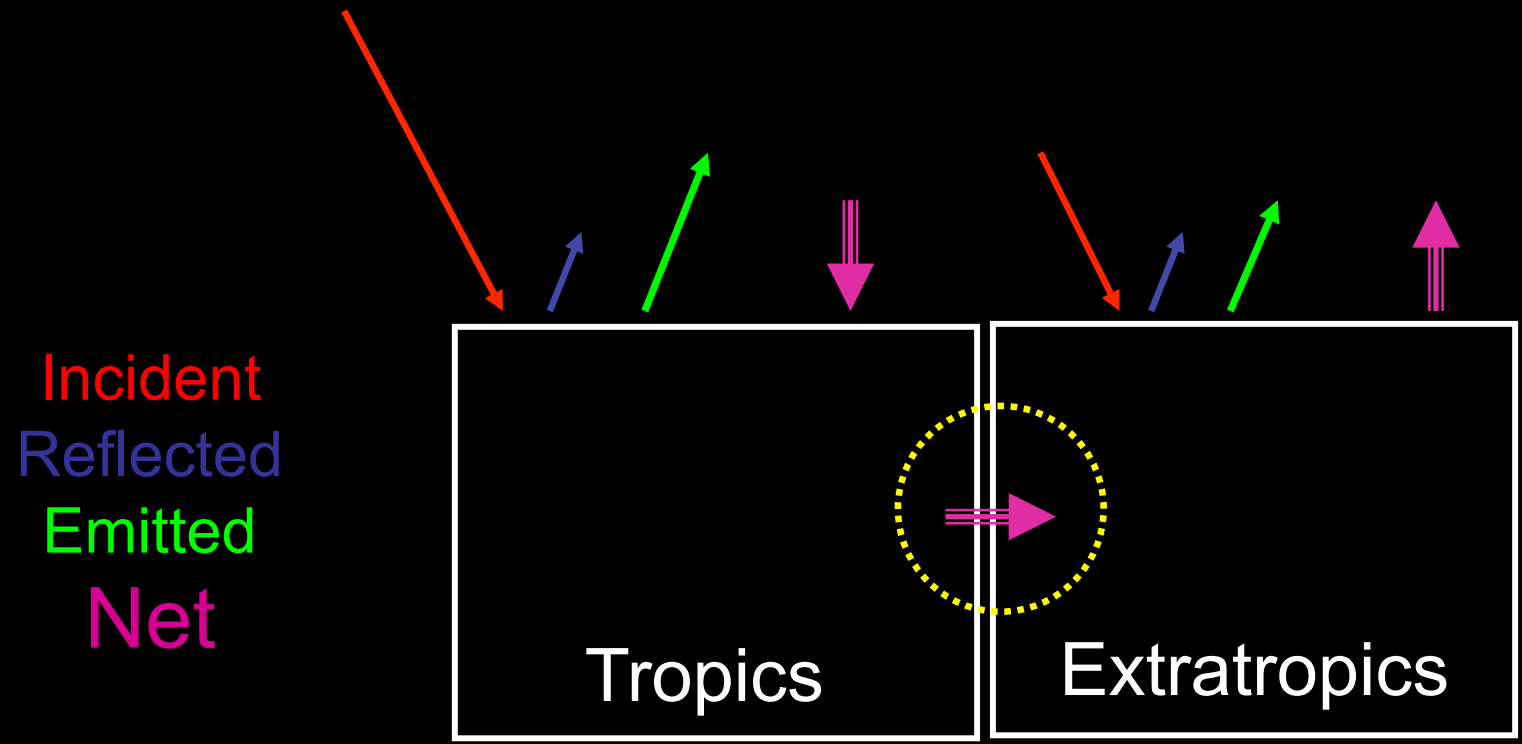
2 X CO2 planetary albedo change



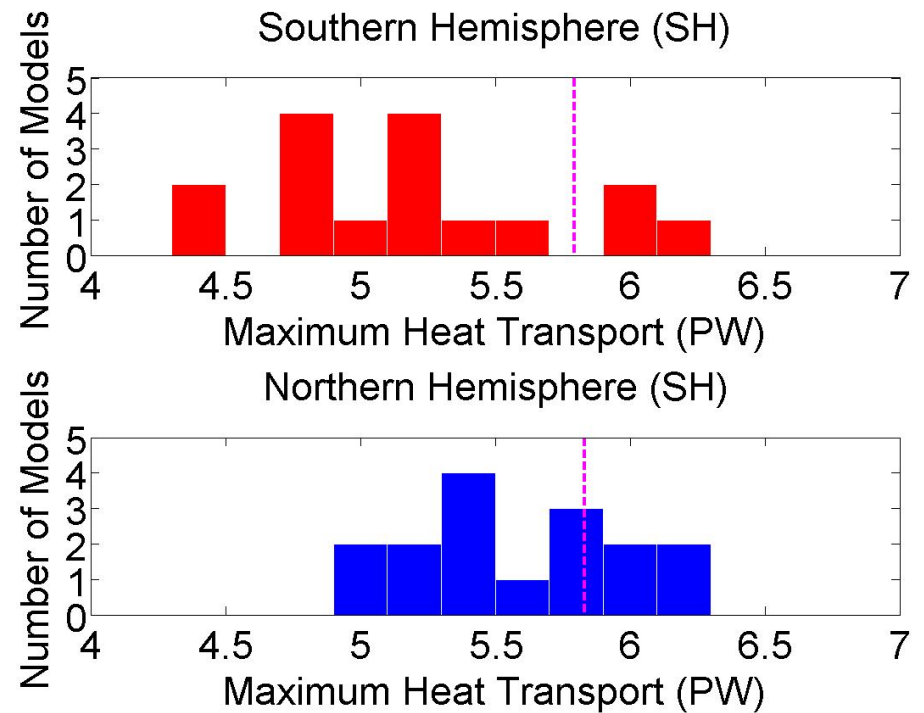
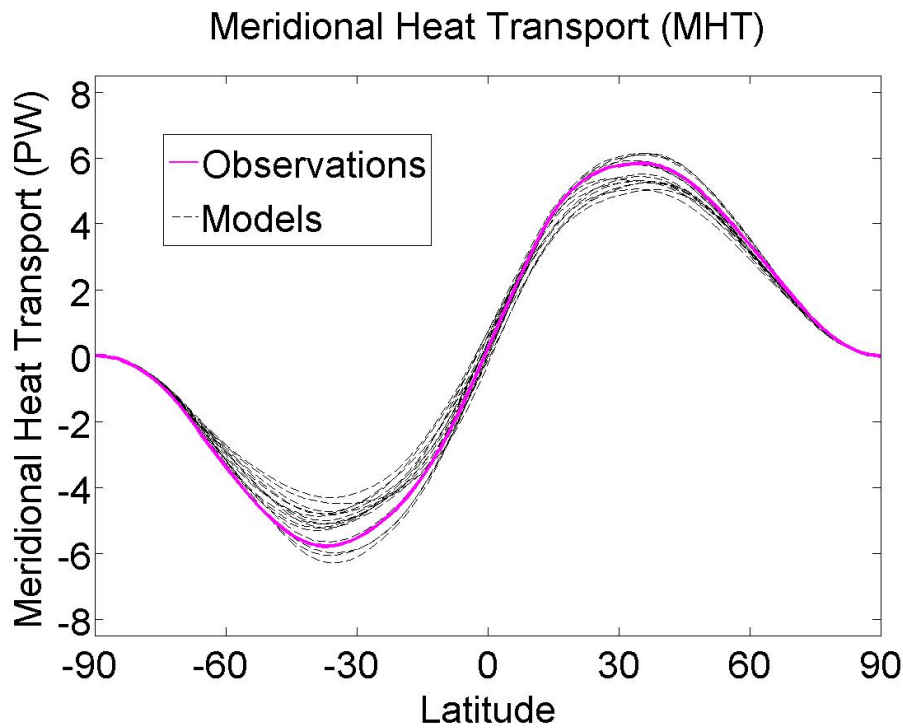
Conclusions: Section I

- The vast majority (88%) of the global average planetary albedo is due to atmospheric as opposed to surface reflection
- The atmosphere attenuates the surface contribution to planetary albedo by a factor ~ 3
- Inter-model differences in planetary albedo are primarily due to differences in cloud reflection
- Changes in planetary albedo due to CO_2 doubling are primarily due to cloud changes and secondarily to changes in surface albedo (both the inter-model average and spread)

II : What determines meridional heat transport?



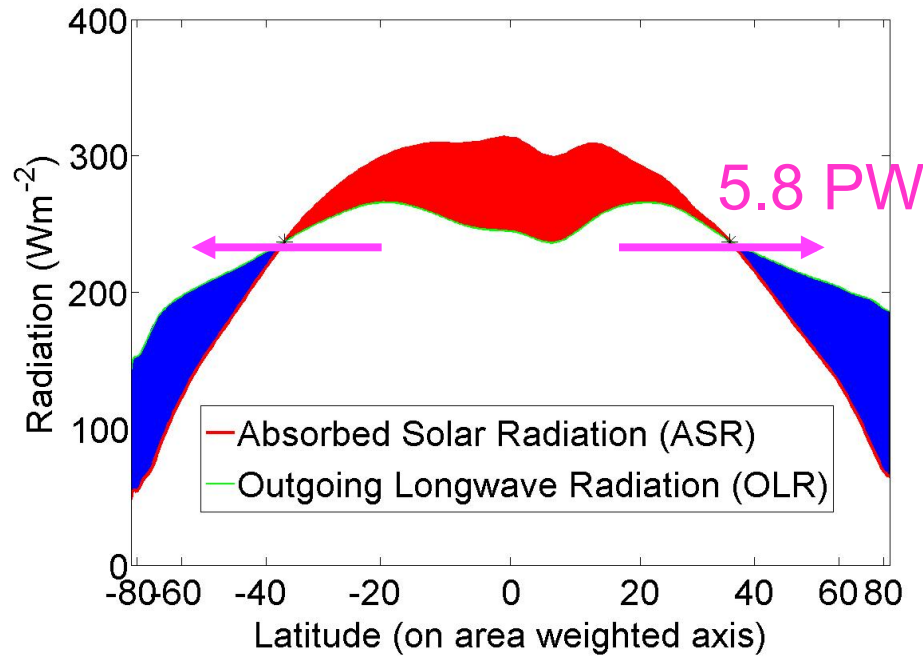
Heat Transport In Climate Models (CMIP3 Pre-industrial)



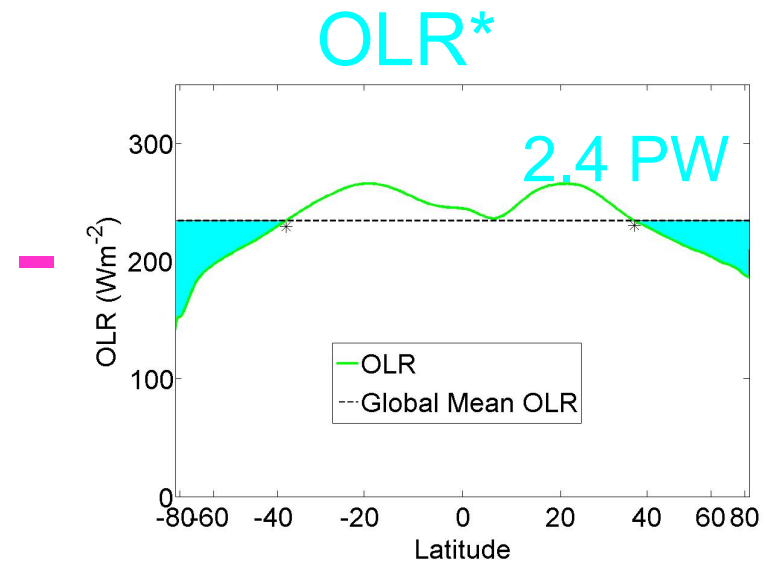
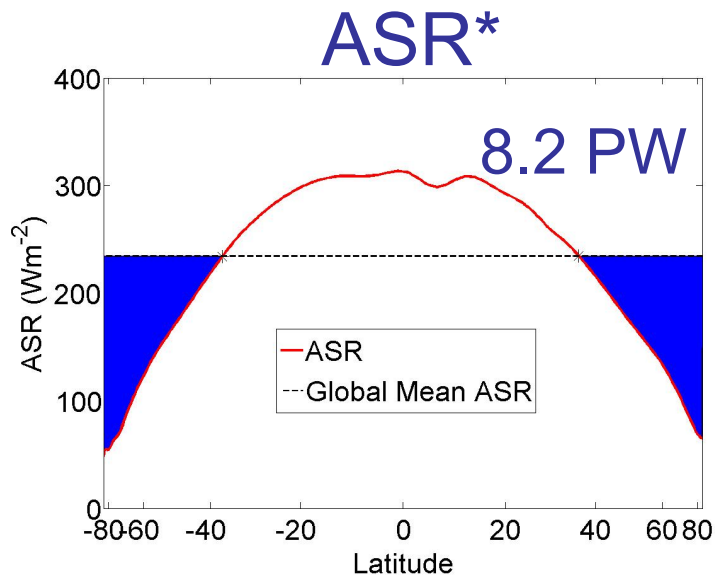
--- Observations

Understanding heat transport

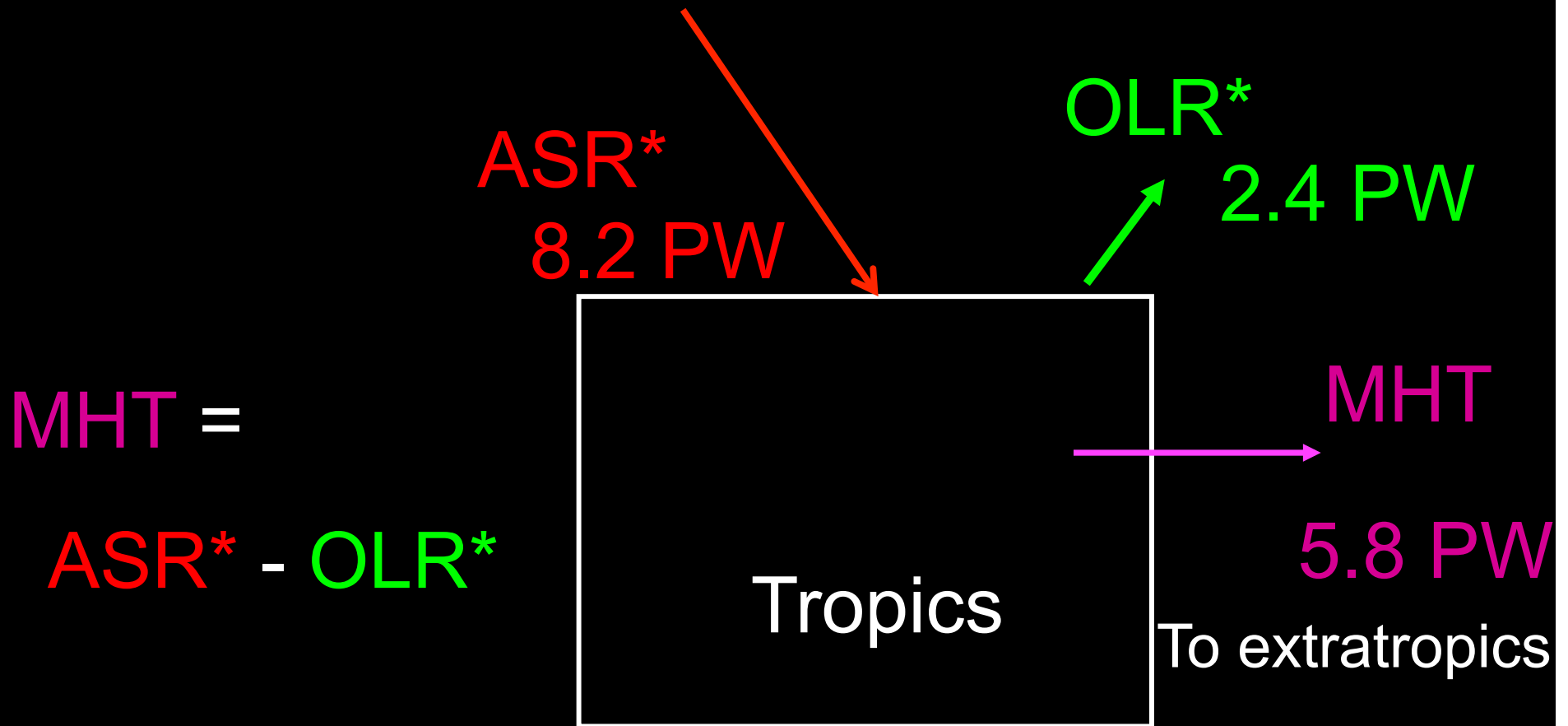
Heat Transport From Radiation Imbalance



Heat Transport =

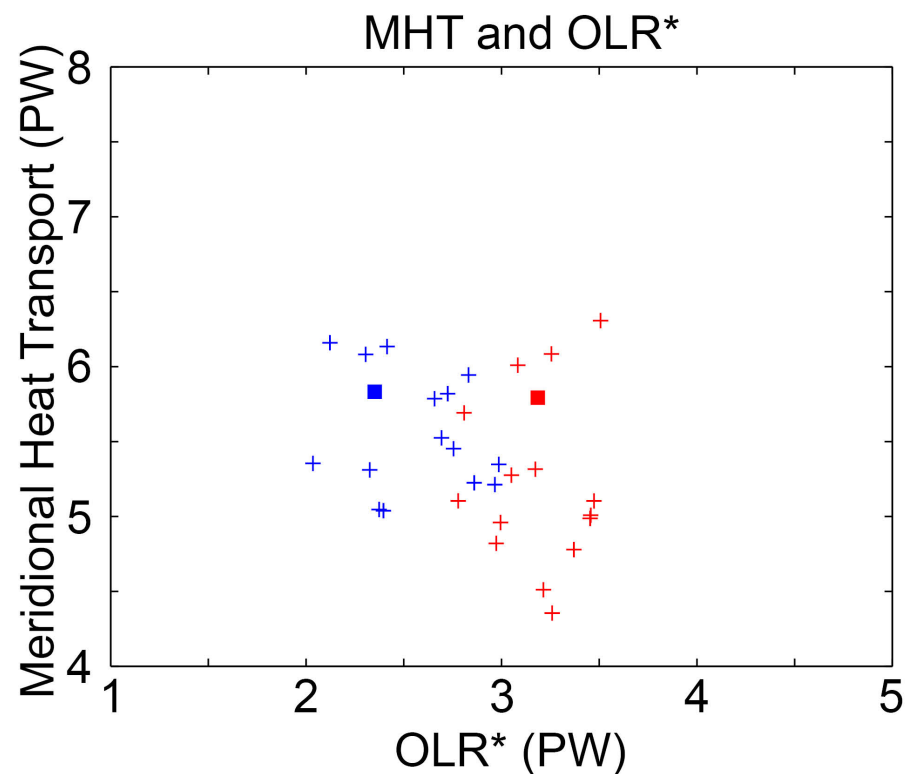
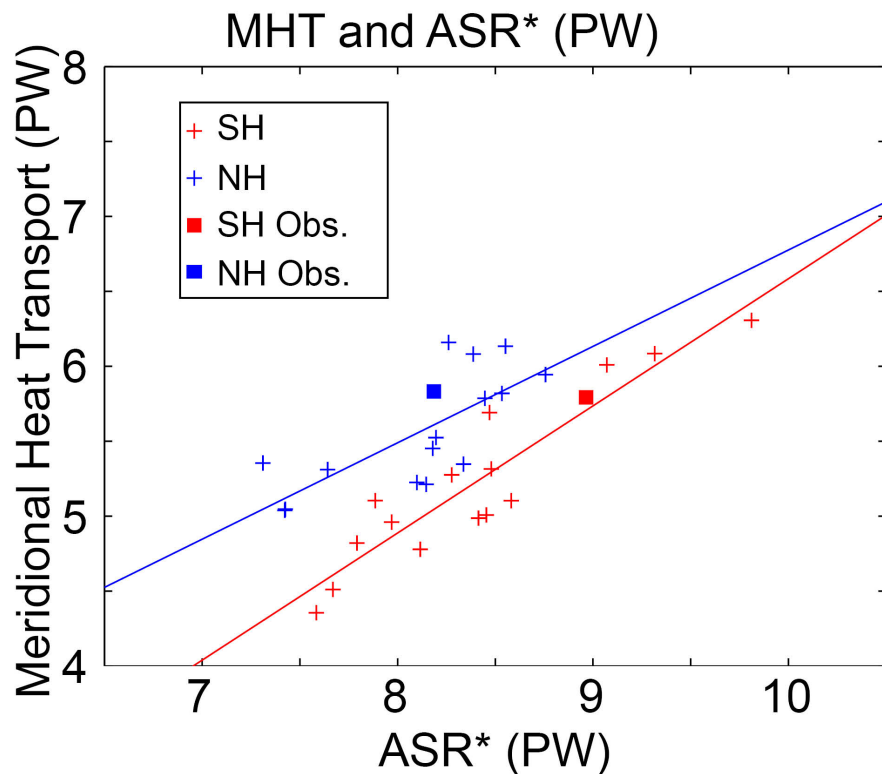


ASR*, OLR*, MHT, and the tropical/ extratropical energy budget



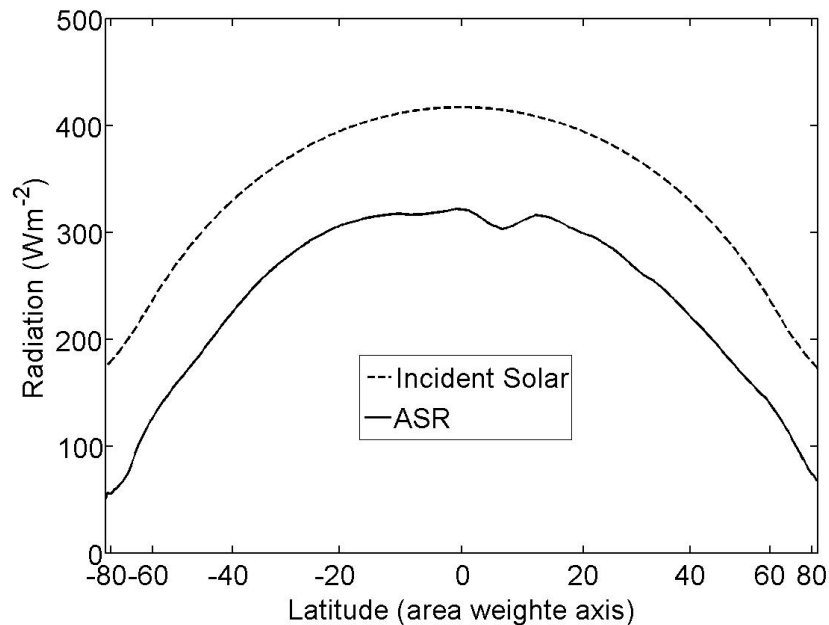
All arrows are relative to the global average

Model heat transport spread in terms of OLR^* and ASR^*

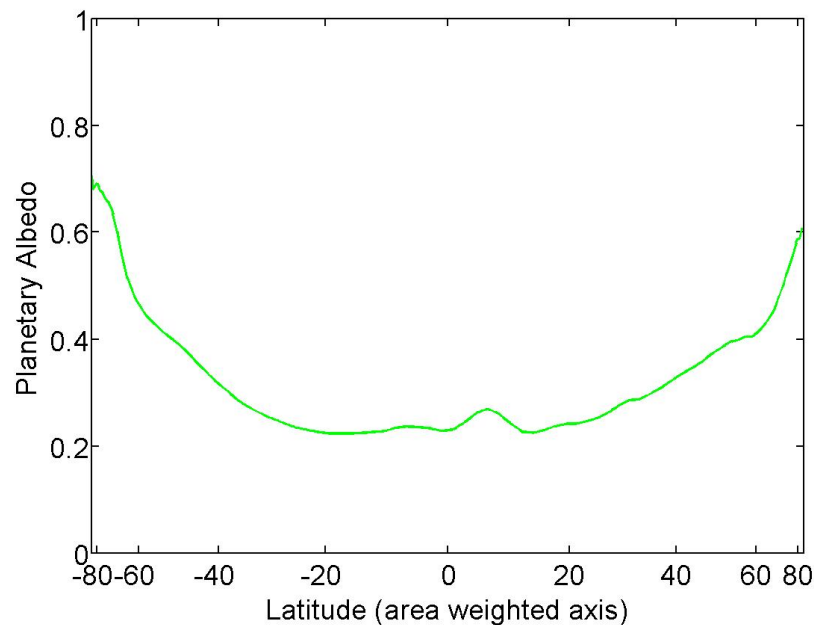


Understanding ASR*

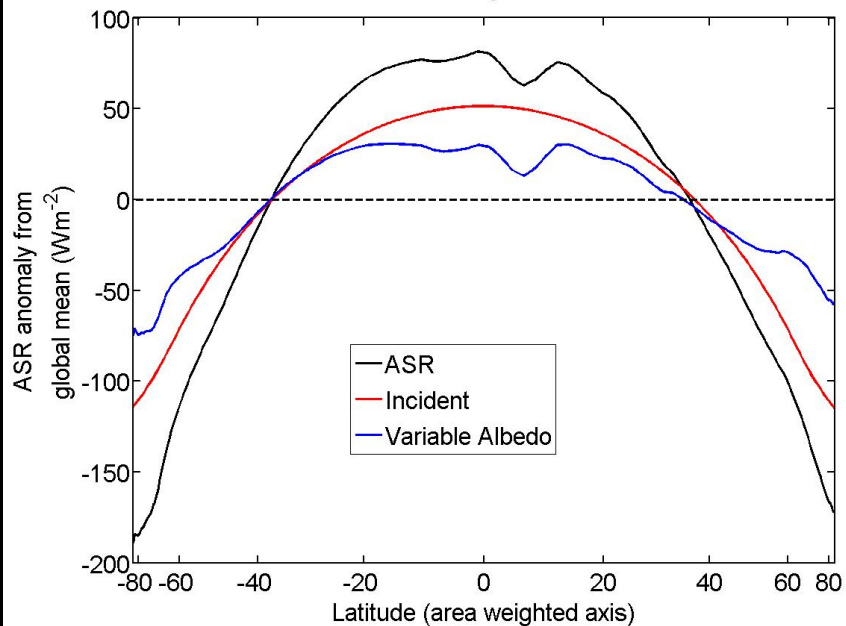
Incoming and Net Solar Radiation



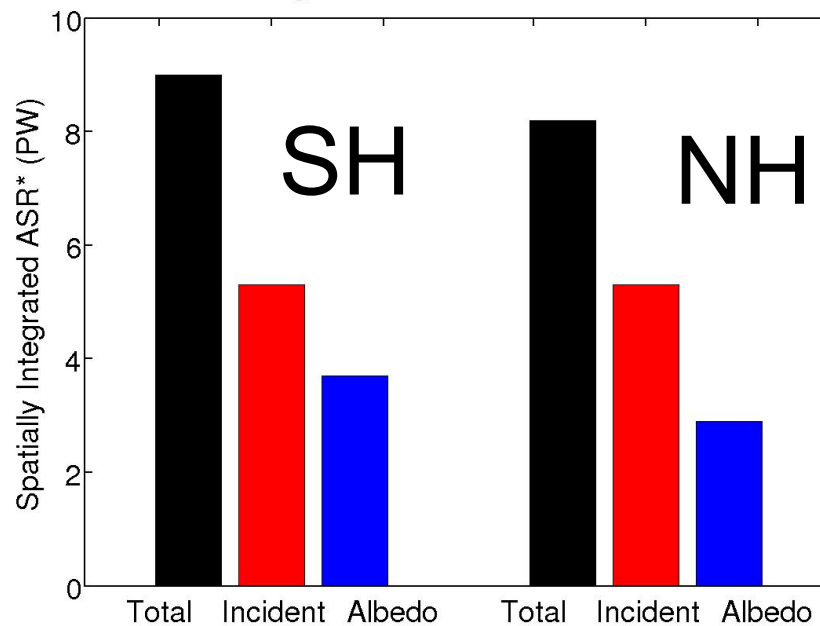
Planetary Albedo



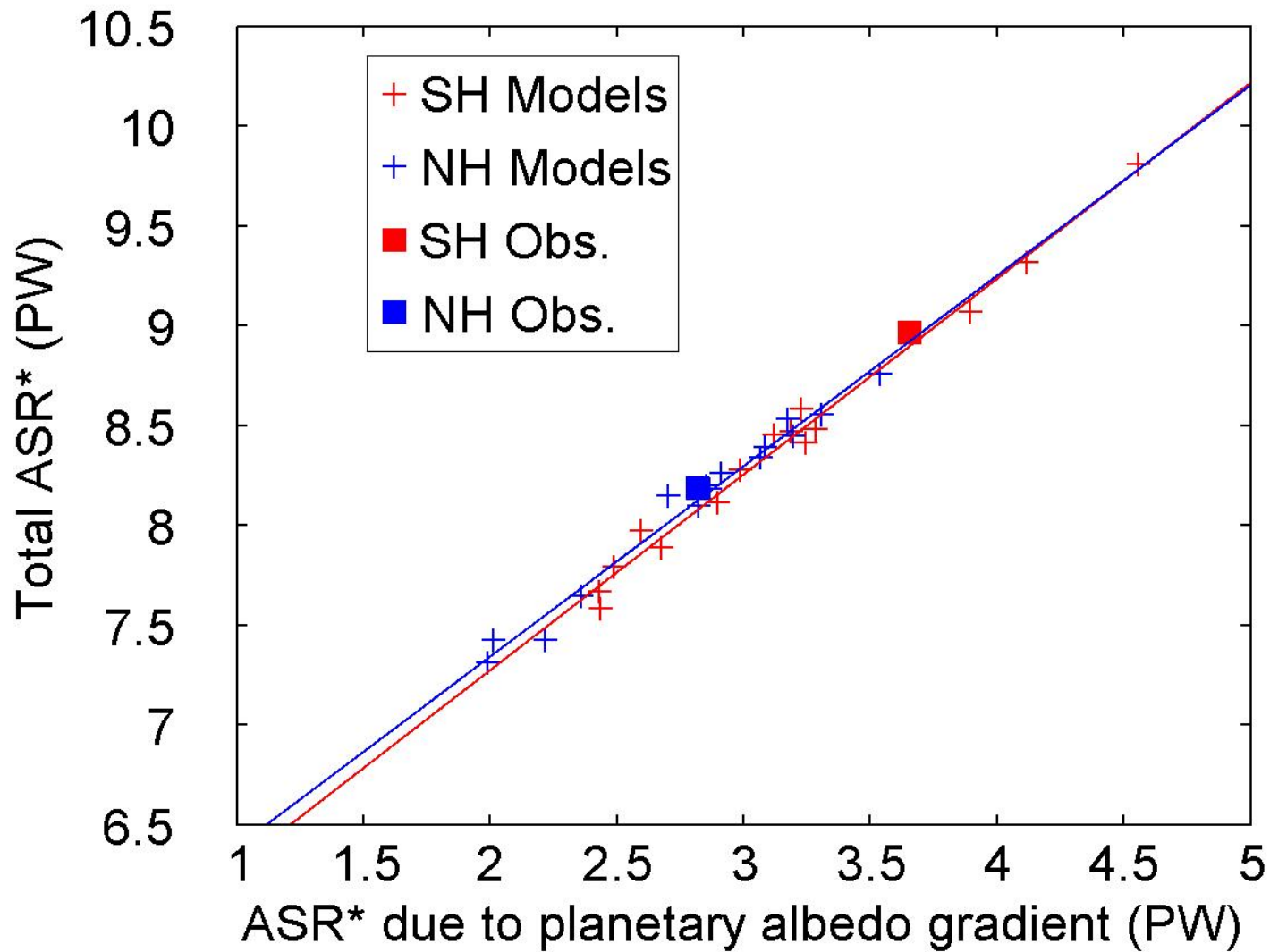
Partitioning of ASR



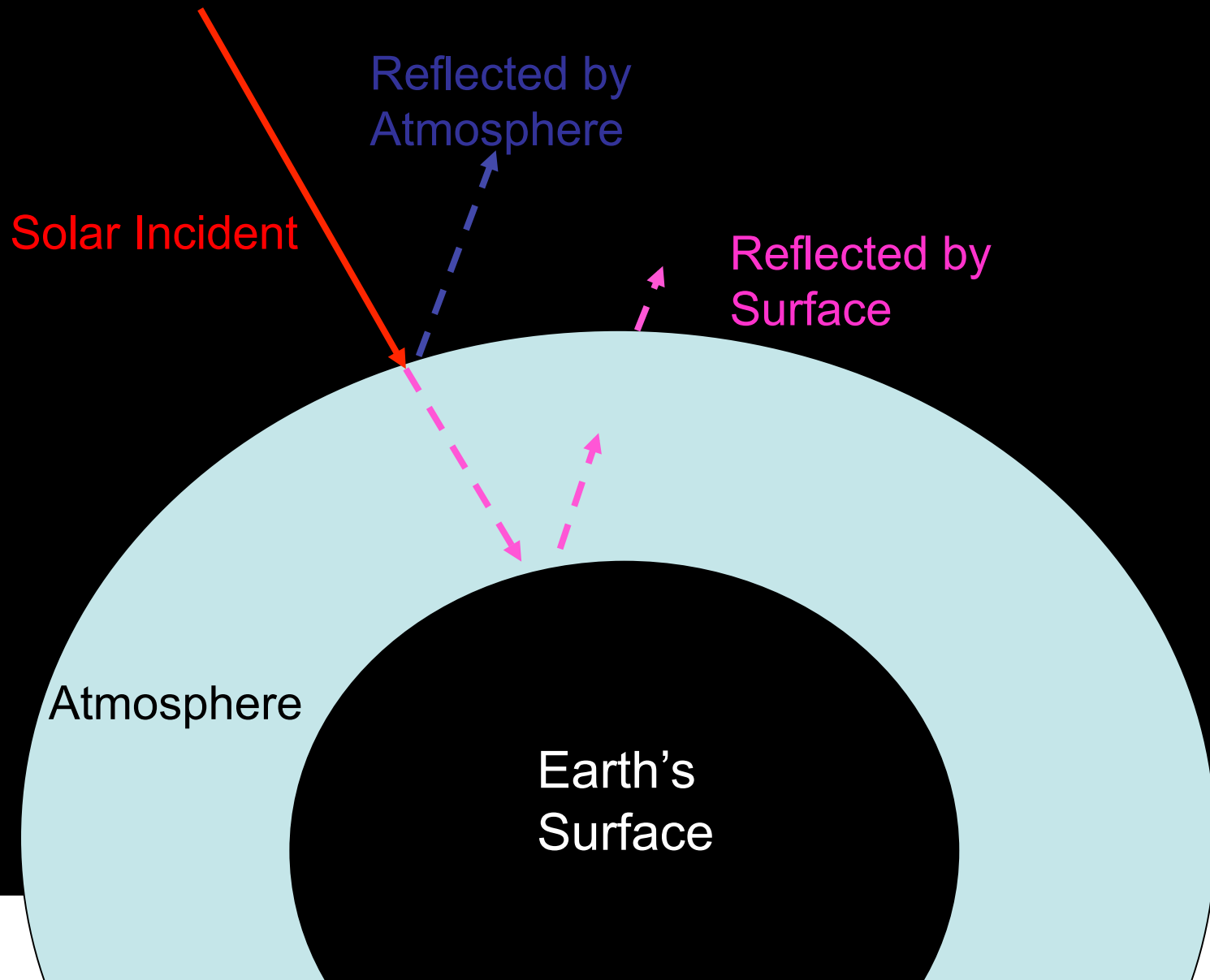
Integrated Contributions to ASR*



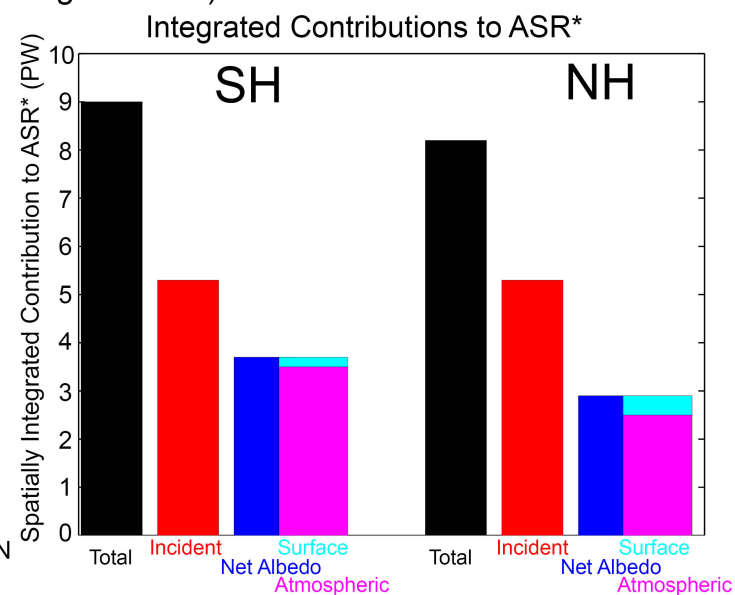
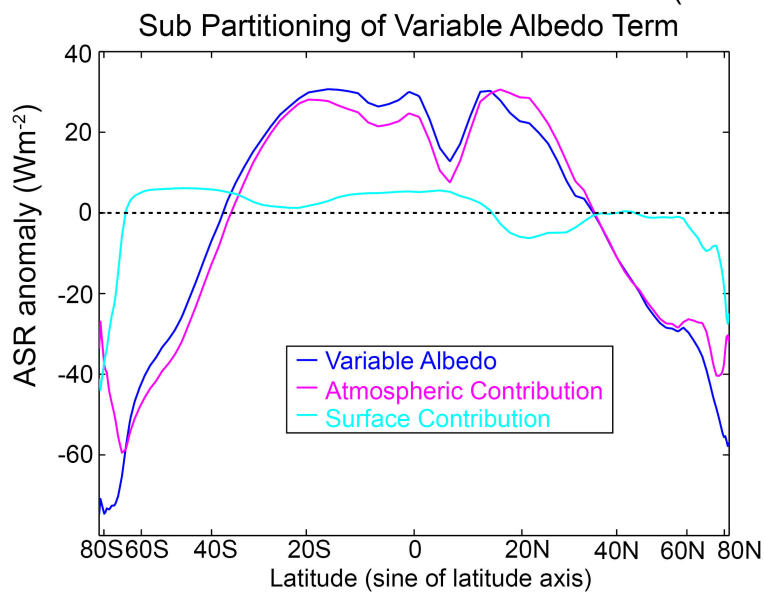
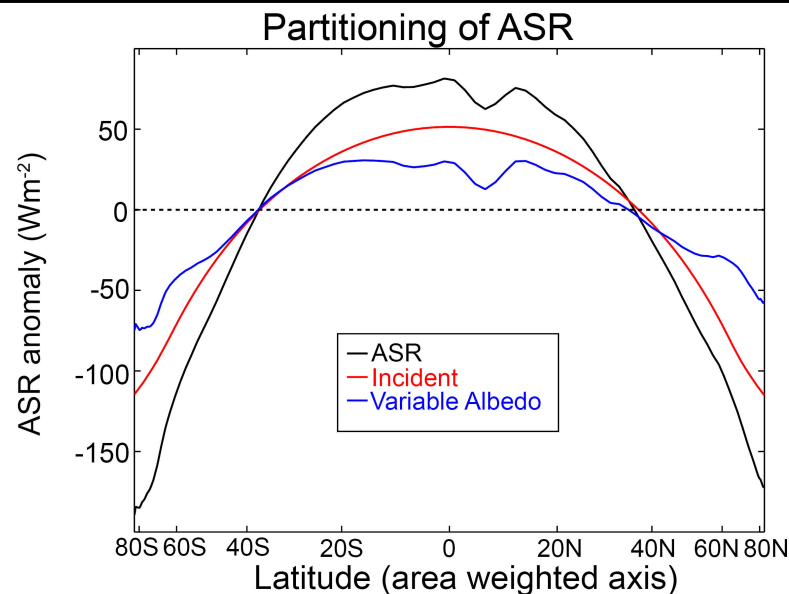
ASR* and planetary albedo



What determines the equator-to-pole contrast of planetary albedo?

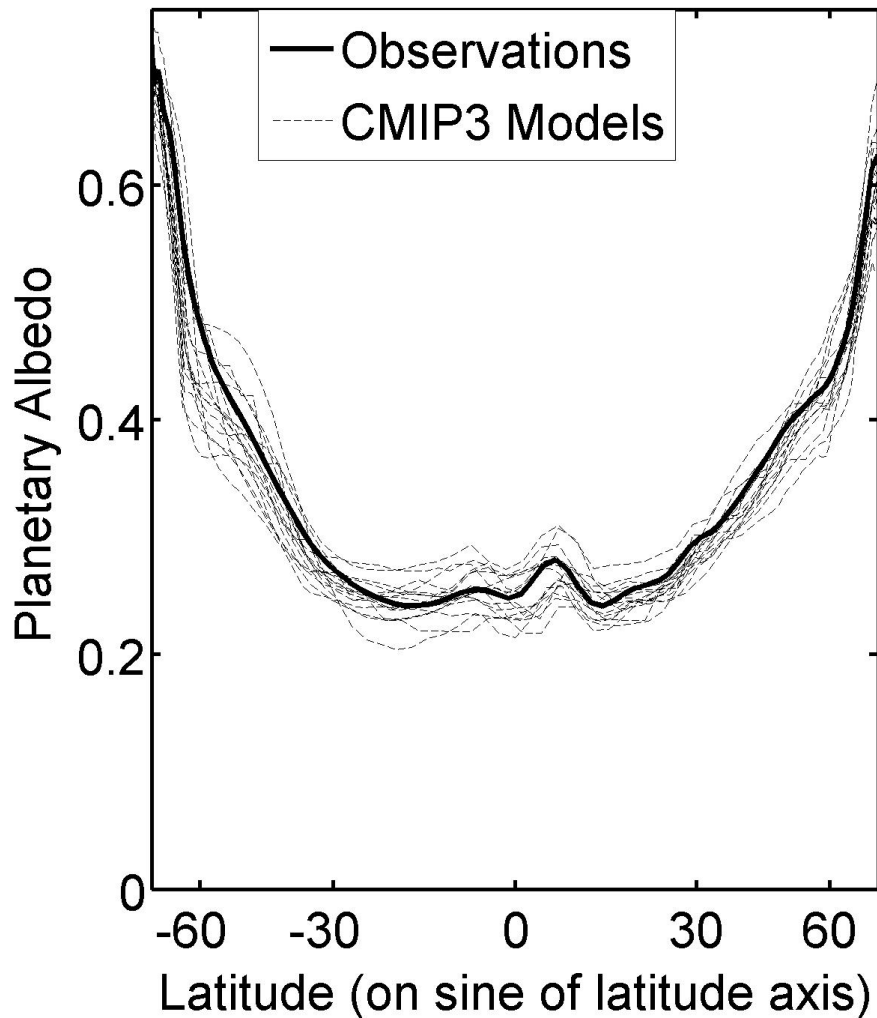


The surface and atmospheric reflection contributions to ASR*

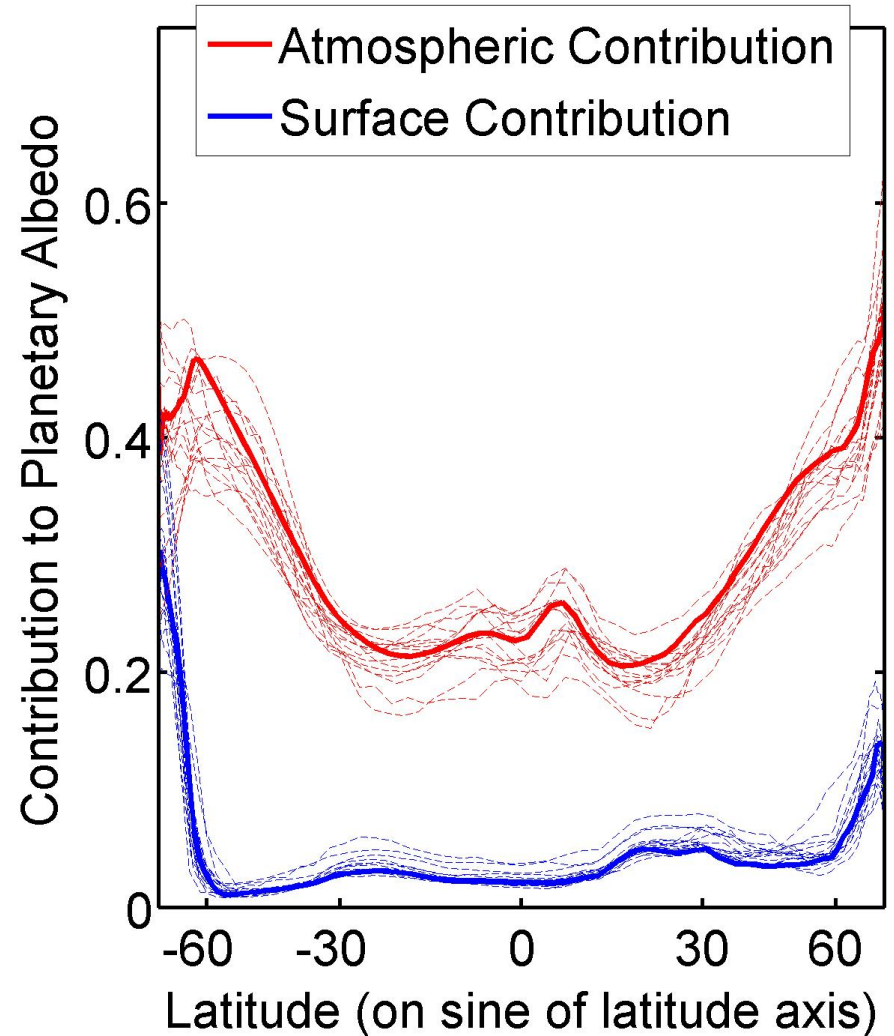


Planetary Albedo Partitioning

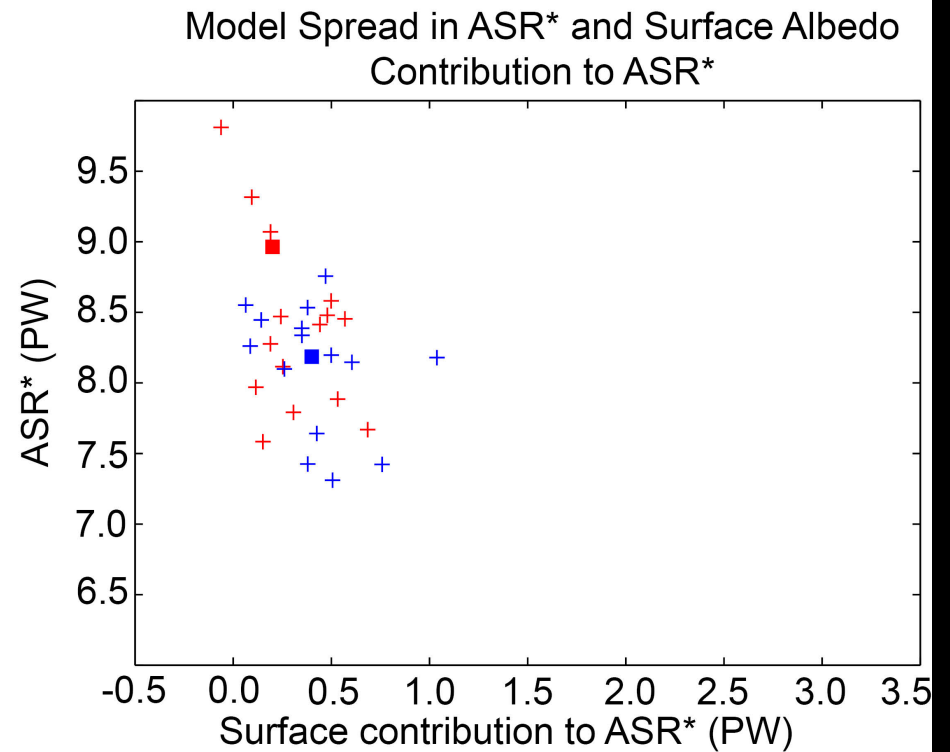
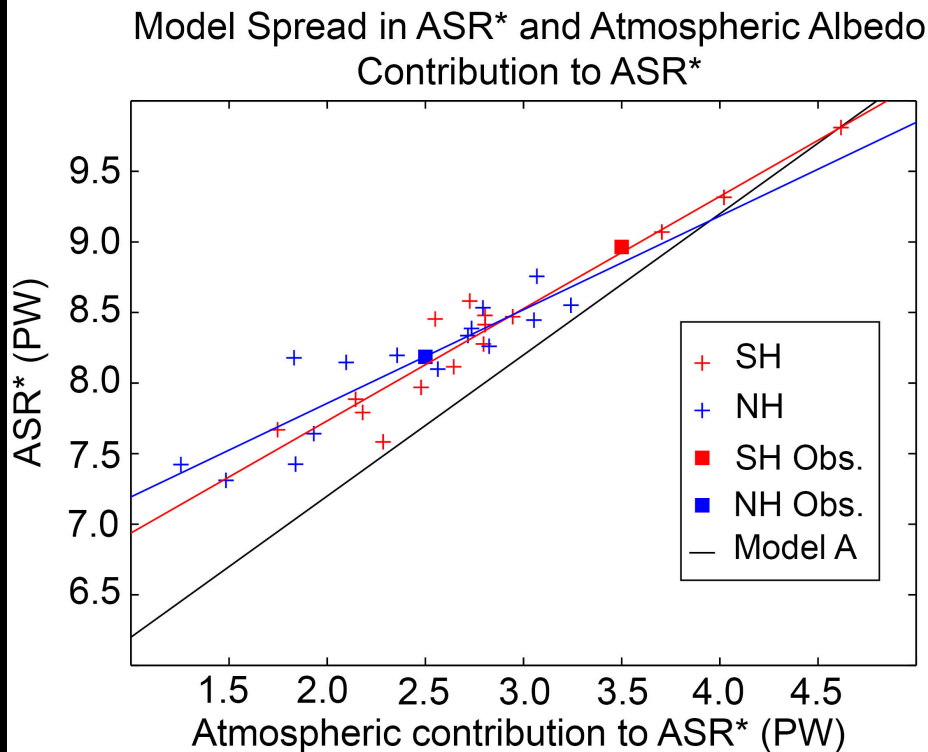
Zonal Average
Planetary Albedo



Zonal Average
Planetary Albedo Partitioning

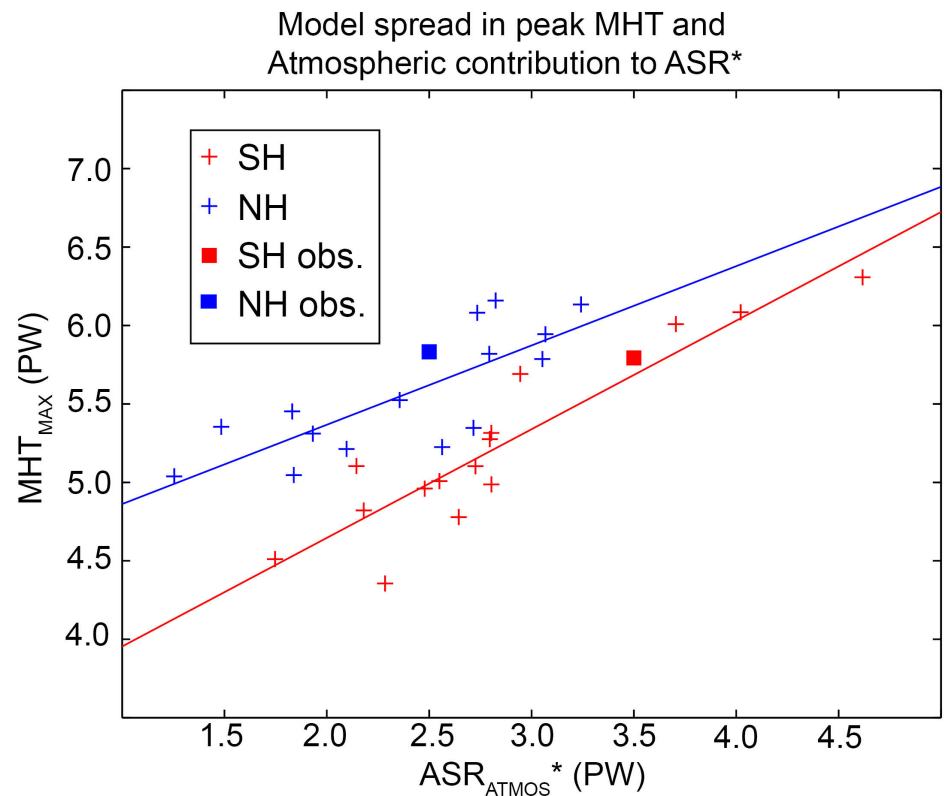


Atmospheric and Surface reflection contribution to ASR*



Summary thus far

- Inter-model differences in MHT are due to differences in ASR^*
- Differences in ASR^* are due to planetary albedo differences
- Planetary albedo differences are due to cloud reflection differences
- Therefore, clouds determine MHT

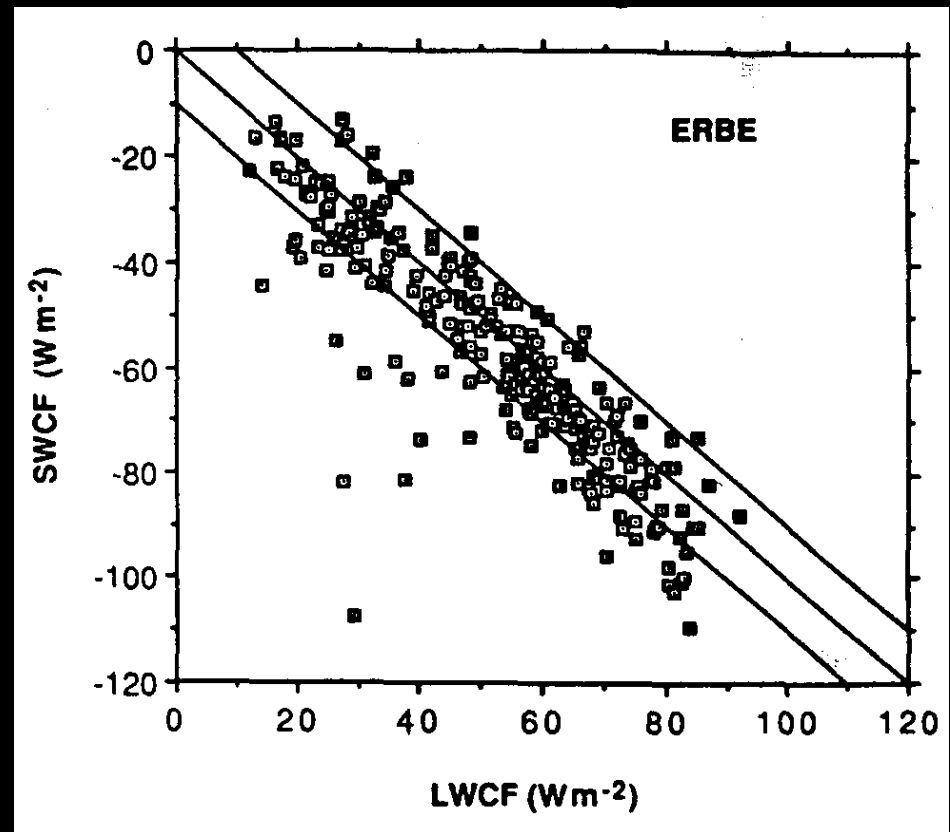


What determines OLR*?

Why don't differences in ASR* and OLR* compensate for each other?

Longwave Cloud Forcing

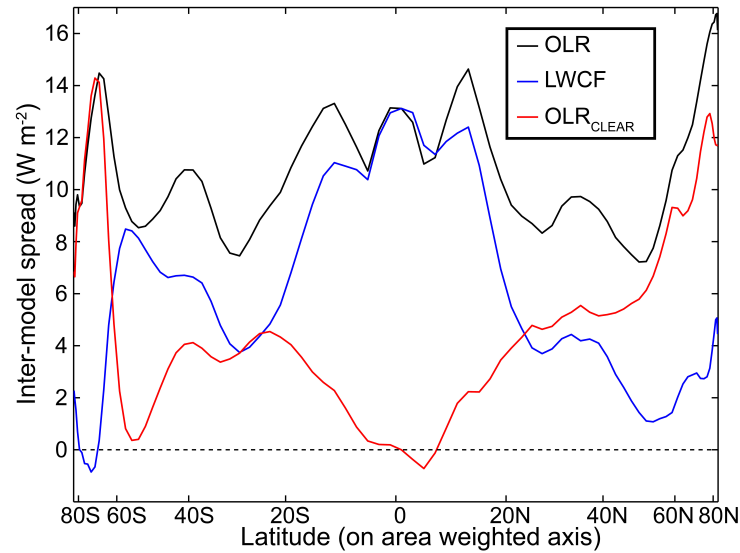
$$\text{LWCF} = \text{OLR}_{\text{CLEAR}} - \text{OLR}$$



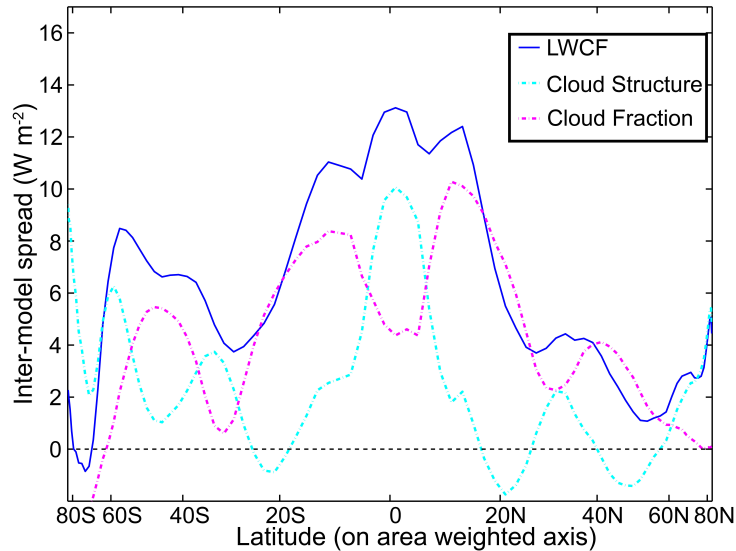
(Kiehl, 1994)

Inter-model differences in OLR

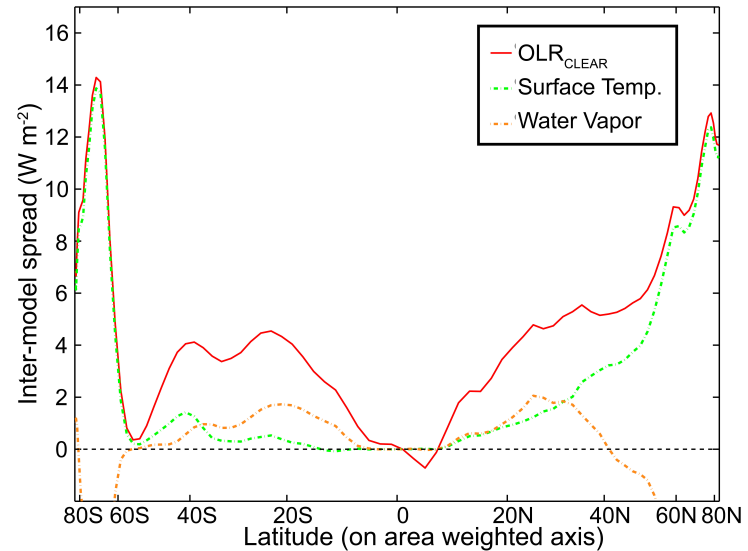
Clear-sky and cloud contributions to OLR spread



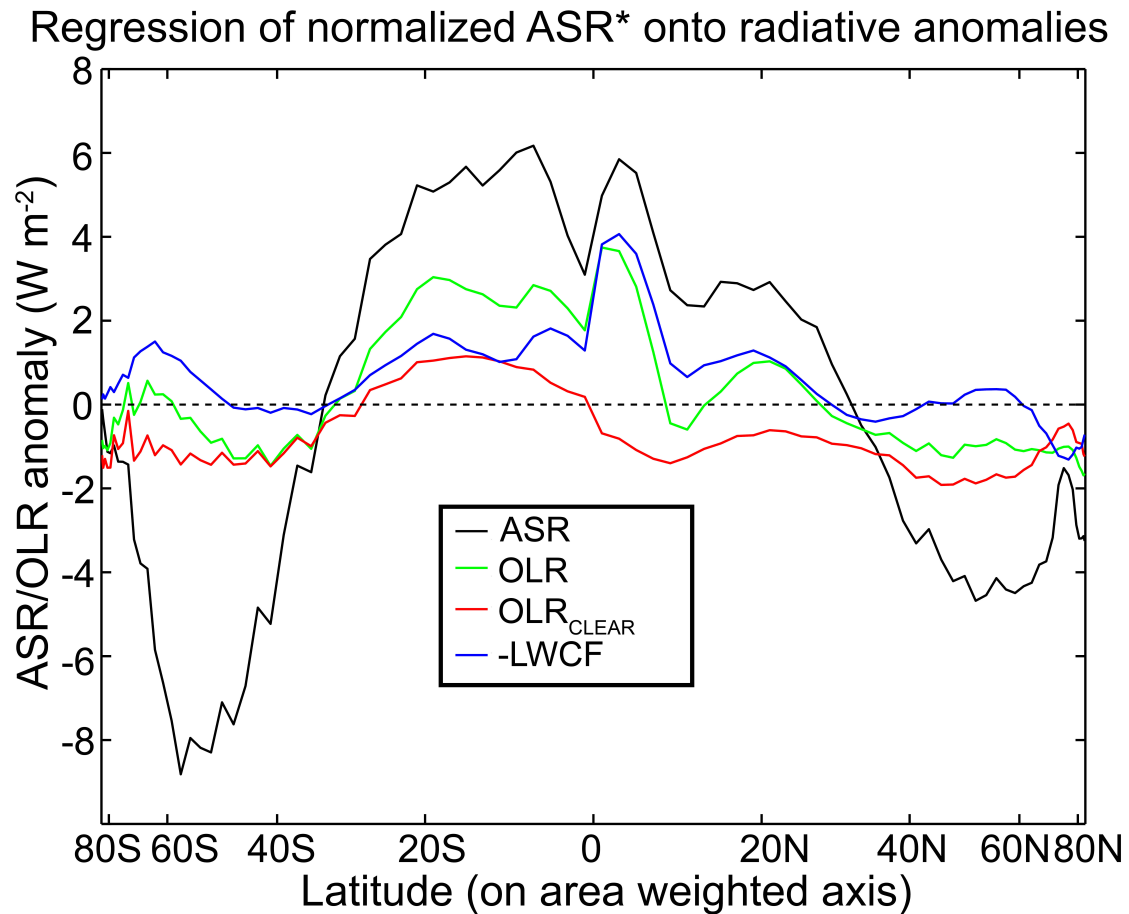
Cloud fraction and cloud structure contributions to LWCF spread



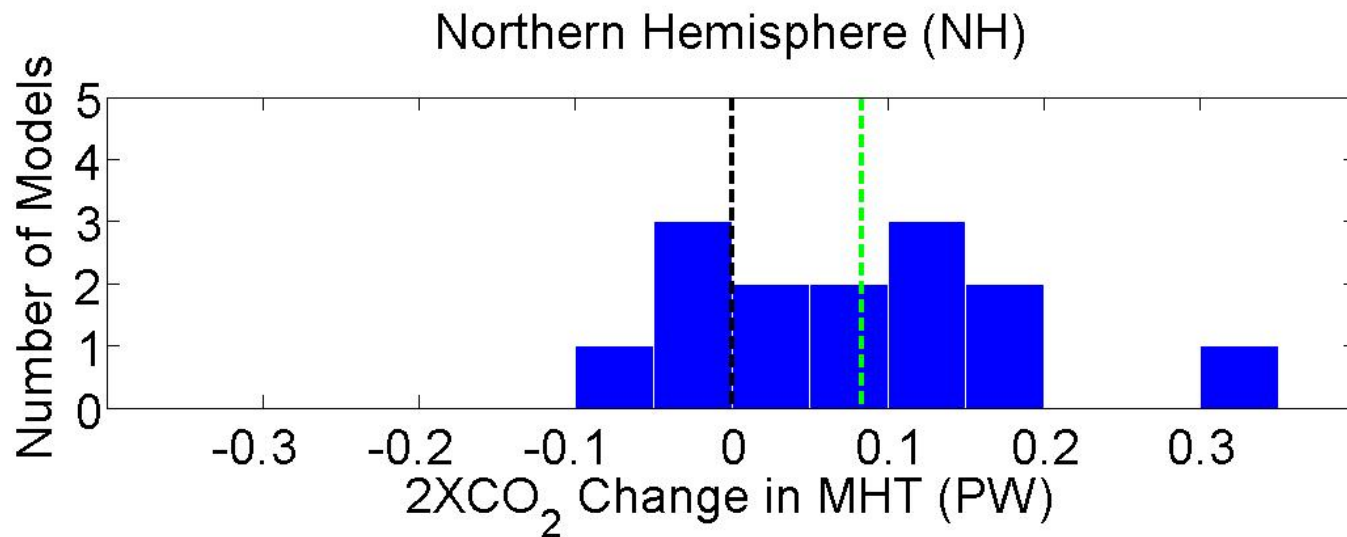
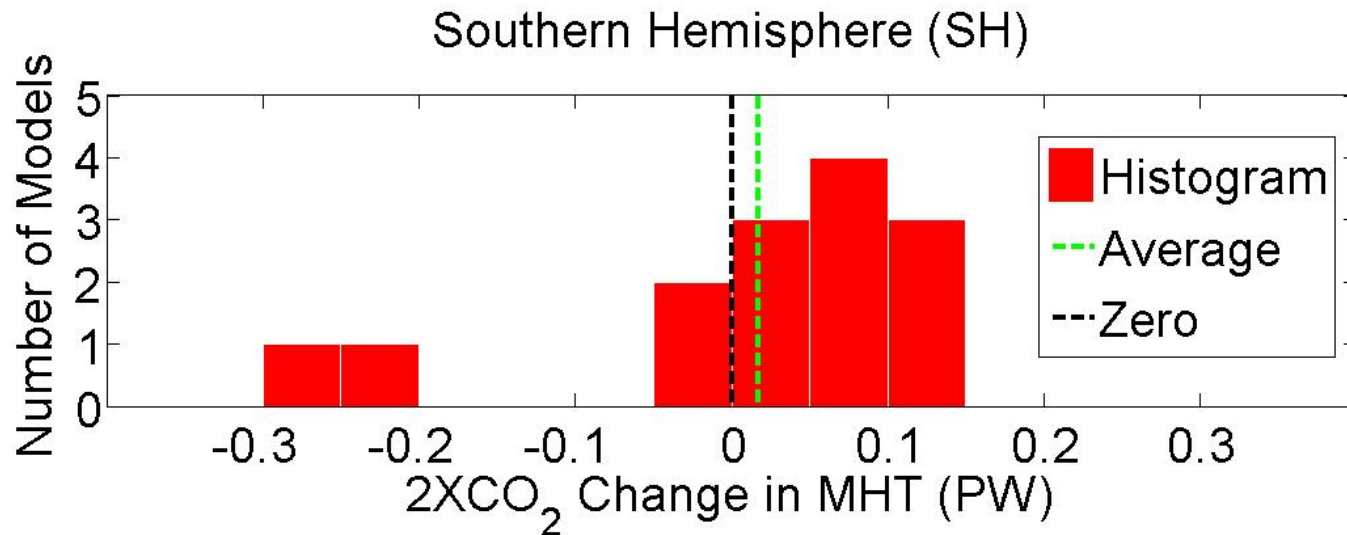
Surface temperature and specific humidity contributions to $\text{OLR}_{\text{CLEAR}}$ spread



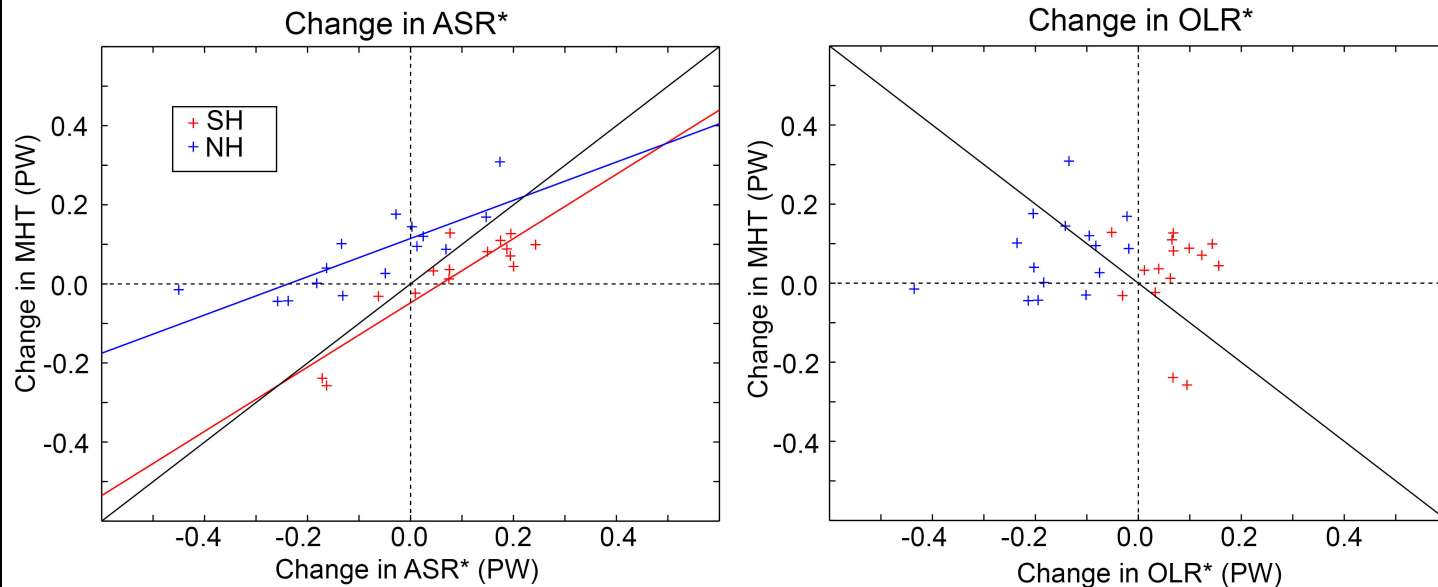
Meridional structure of a “typical” ASR* anomaly



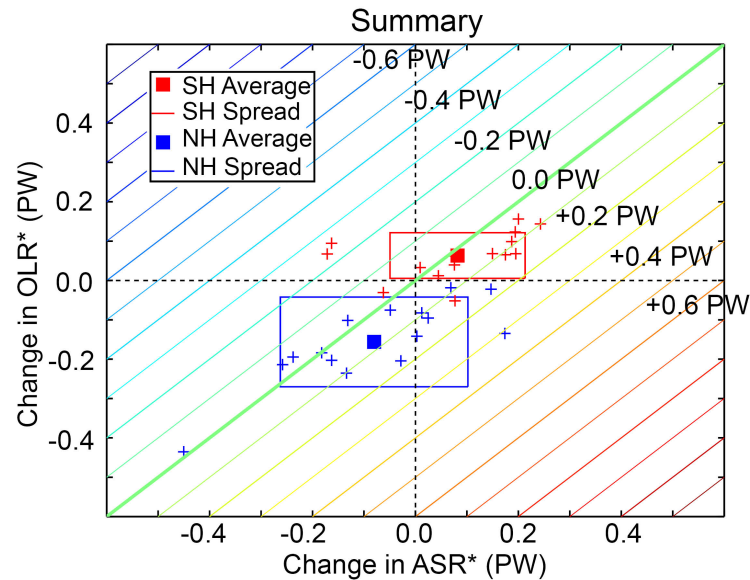
Change in MHT due to CO₂ doubling



Change in MHT due to CO₂ doubling



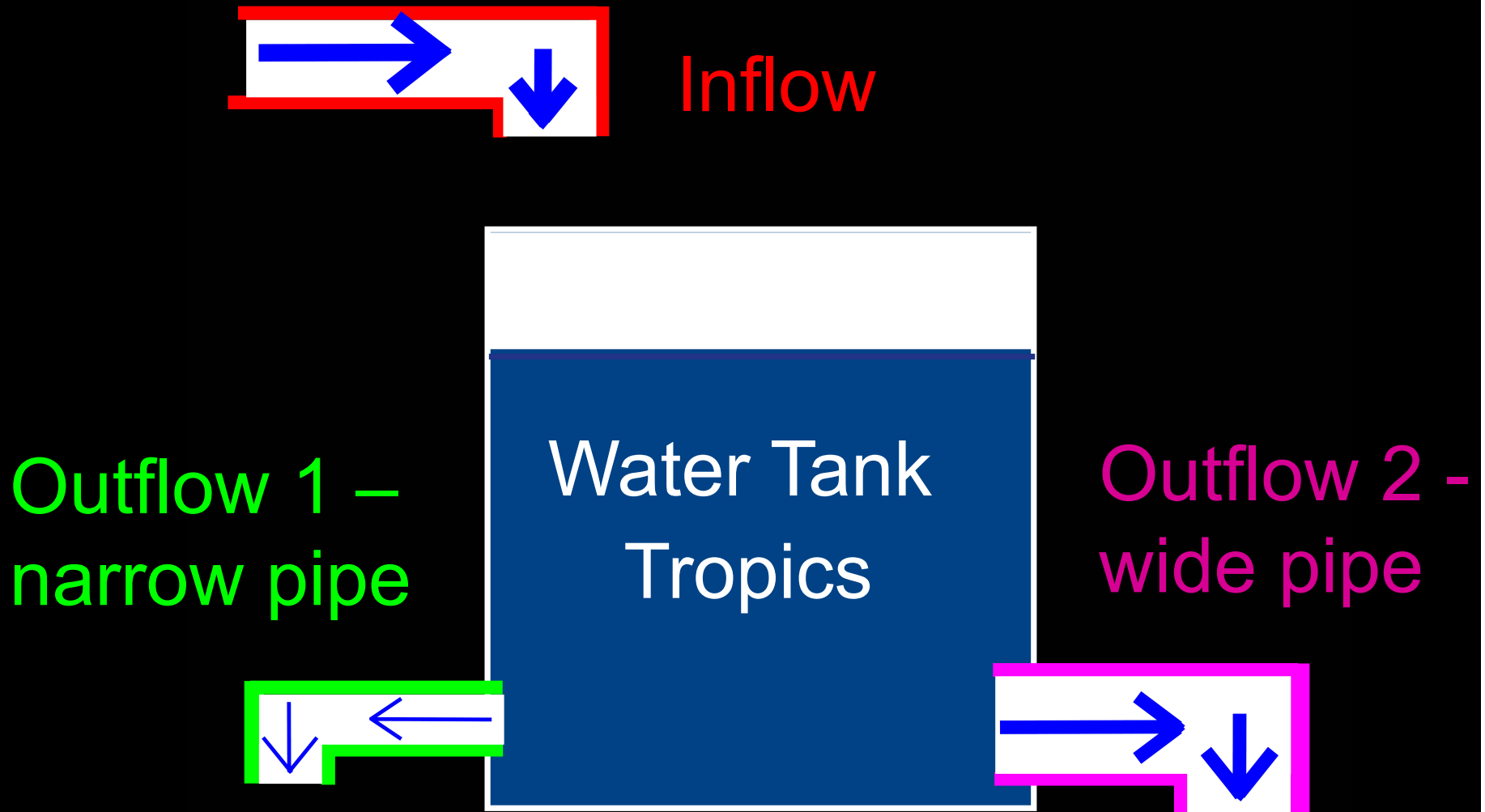
Contours =
Change in
MHT



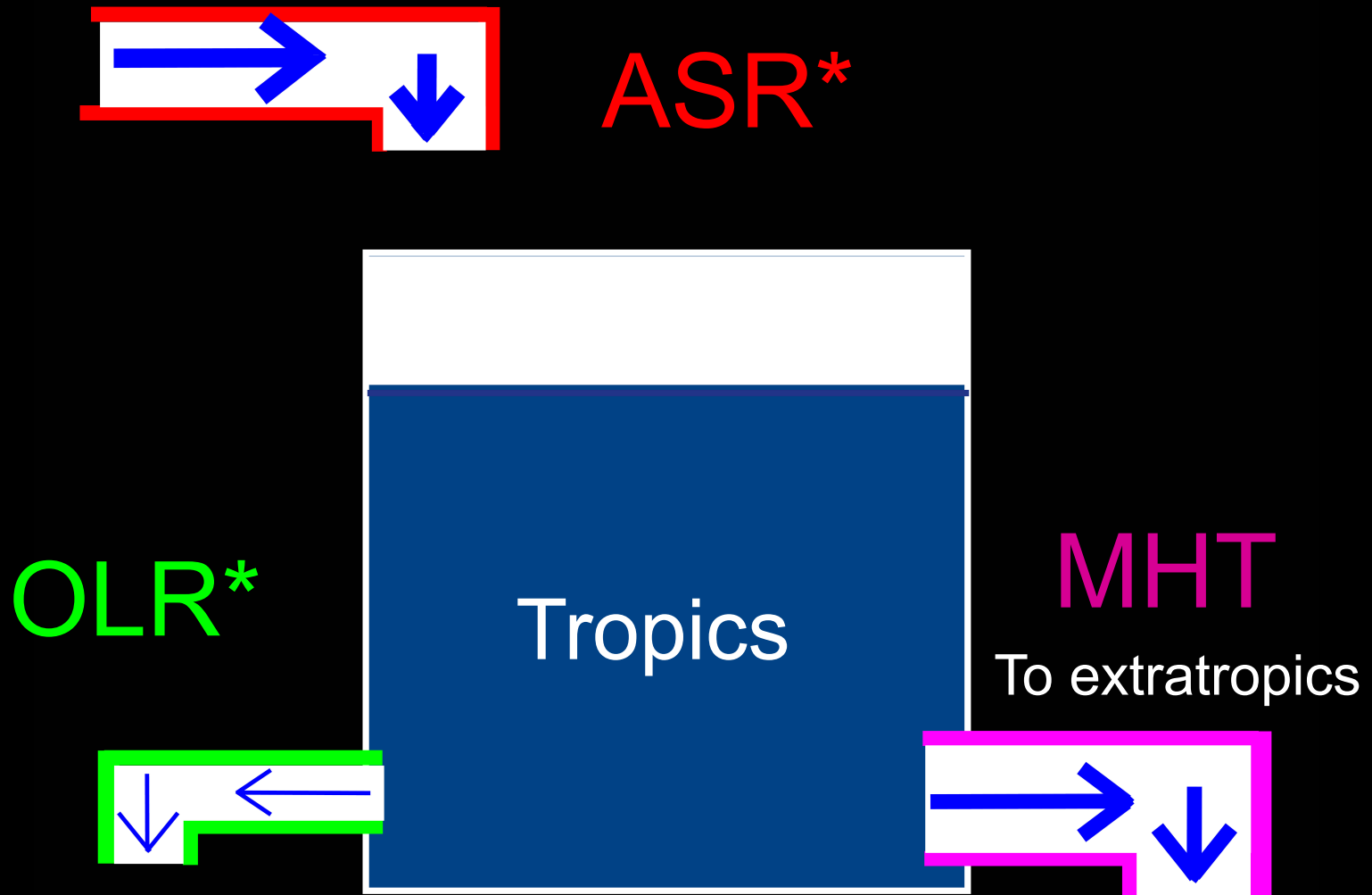
Conclusions this section

- In the extratropical energy budget, ASR^* is balanced by approximately one part OLR^* and two parts MHT
- ASR^* varies widely between models due to cloud differences
- OLR^* varies less than ASR^* and is due to both clouds and temperature
- As a result, MHT varies widely between models and is well correlated with the cloud reflection
- Changes in MHT due to CO_2 are not significant in either hemisphere; the robust changes in surface albedo and OLR^* are overwhelmed by the uncertainty in the cloud reflection contribution to ASR^*

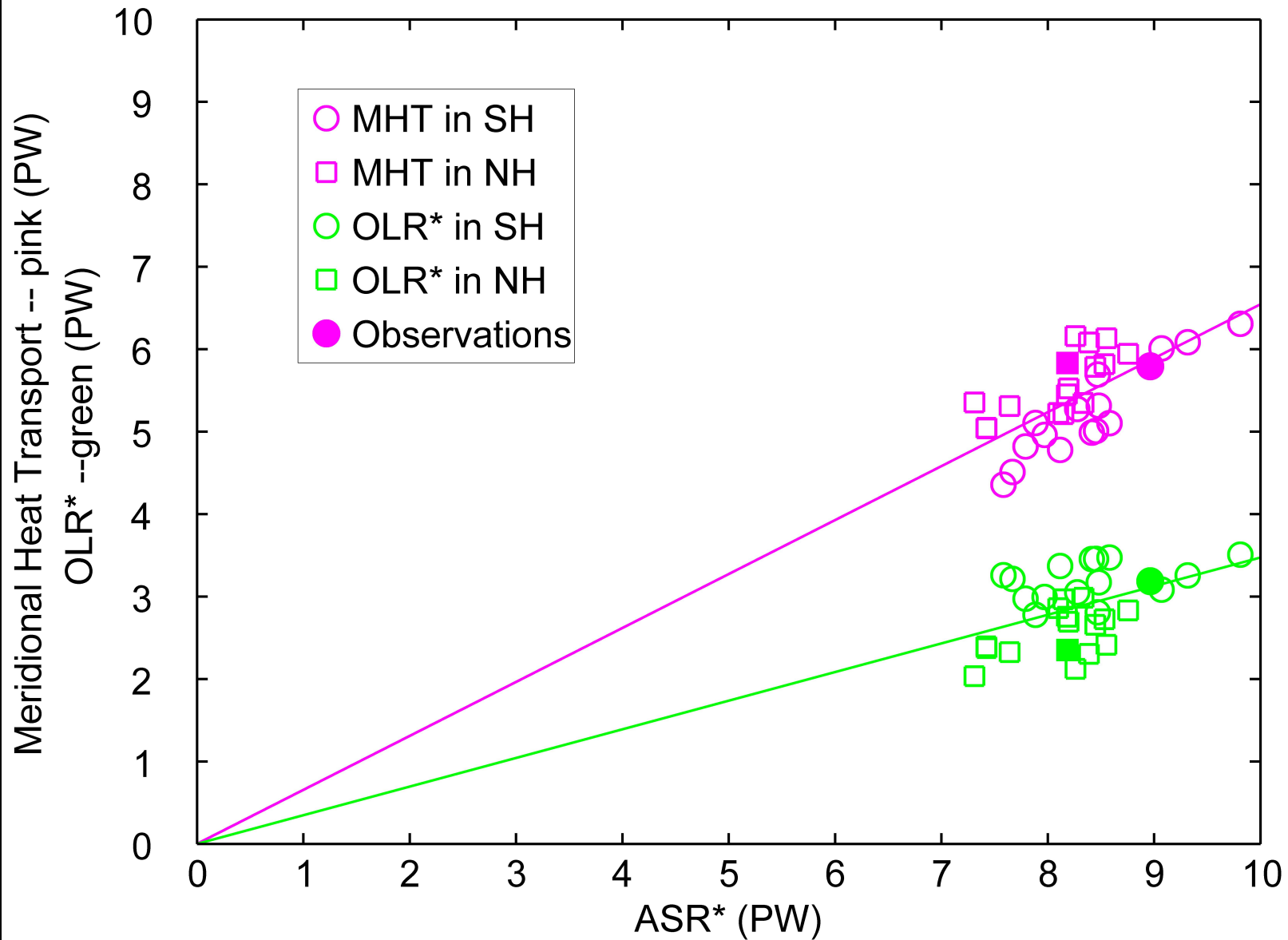
Why are ASR* anomalies associated strongly with MHT and weakly with OLR*?



Why are ASR* anomalies associated strongly with MHT and weakly with OLR*?



ASR* and heat export efficiency

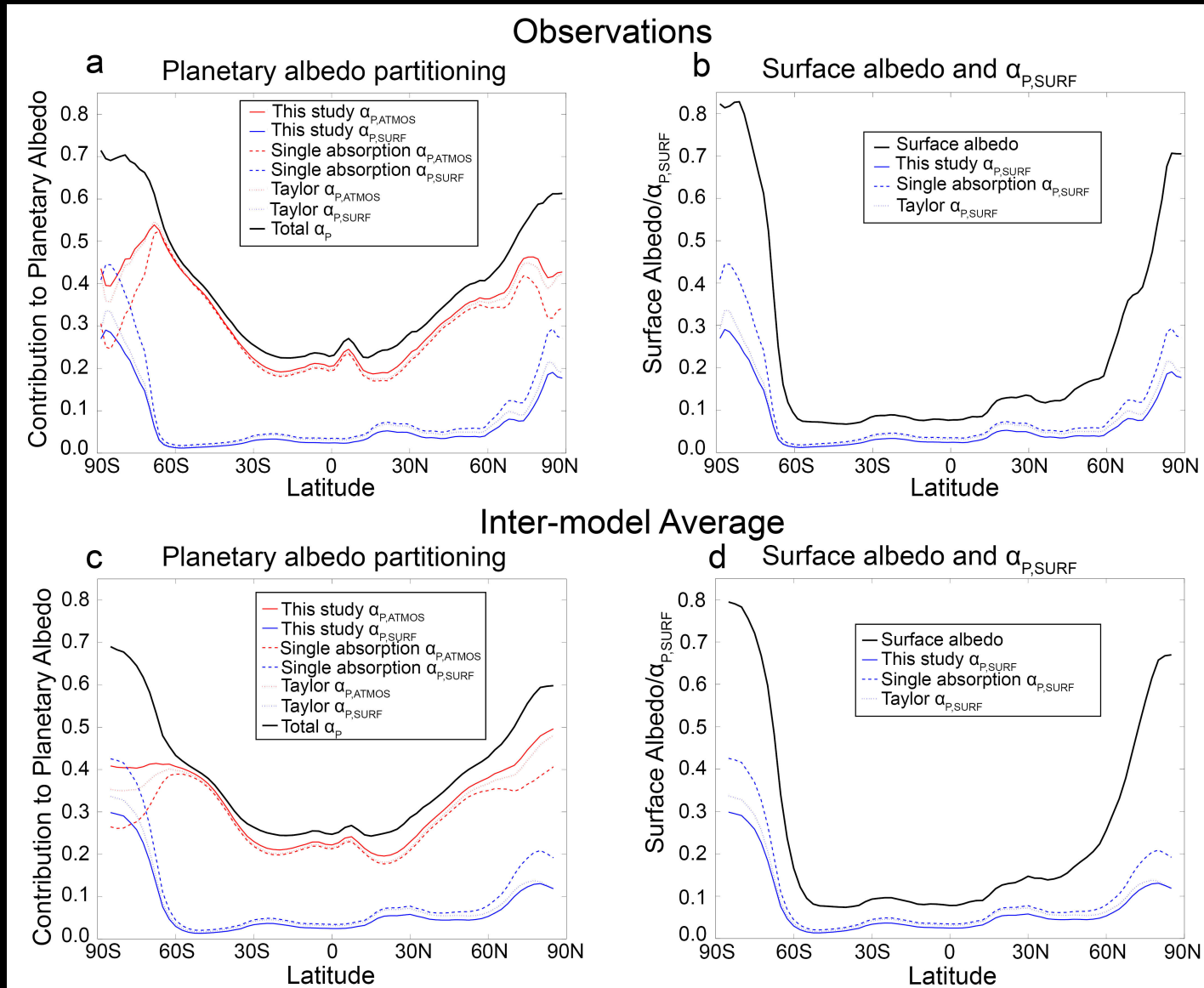


Conclusions

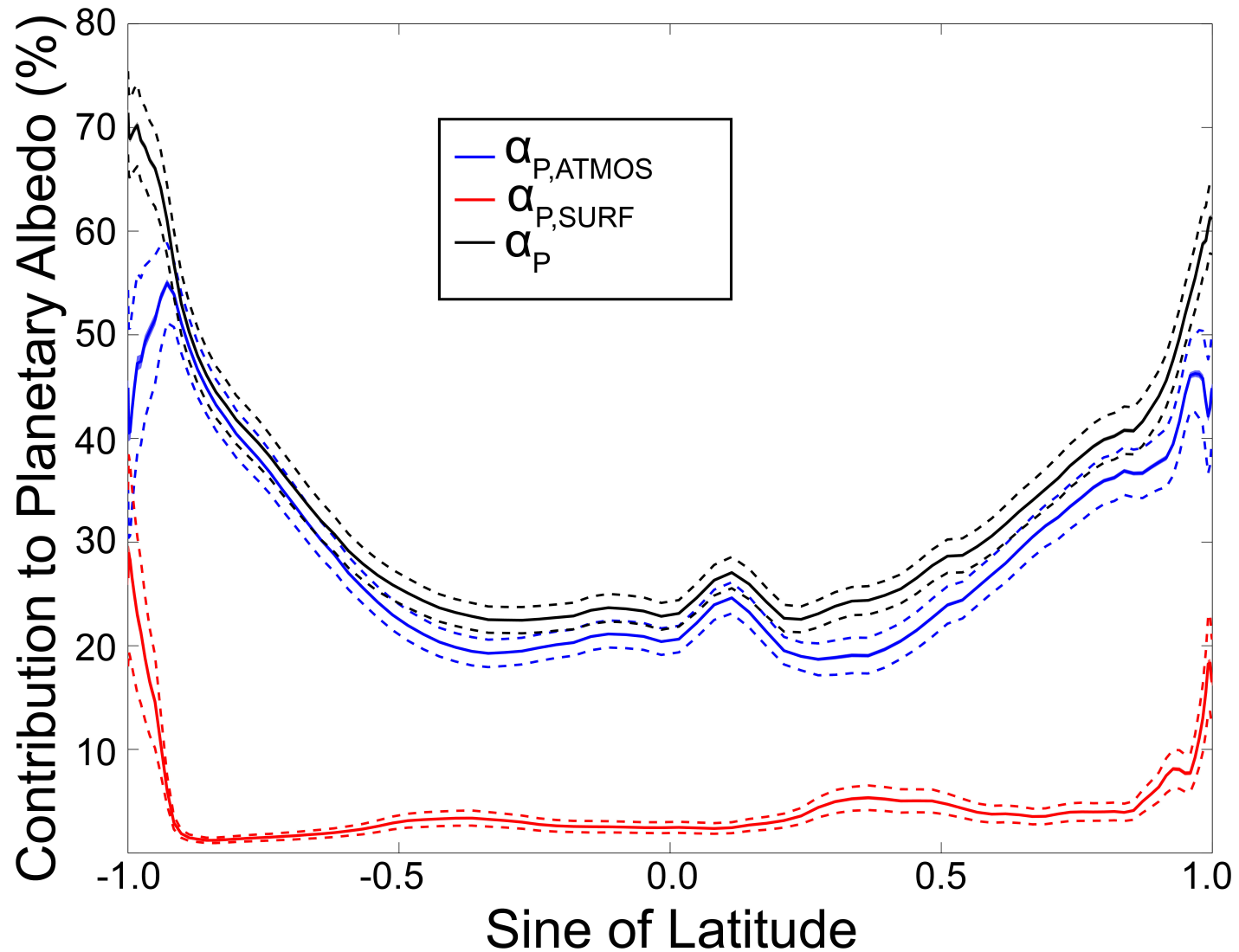
- Heat fluxes in the climate system are a consequence of (A) the spatial (temporal) distribution of energy absorbed from the sun and (B) the efficiency of energy export processes
- ASR is strongly controlled by clouds (and Earth sun geometry) and weakly controlled by surface albedo
- Dynamic energy exports are approximately twice as efficient as radiative energy exports on the equator-to-pole scale

EXTRAS

Sensitivity of planetary albedo partitioning to assumption made in the simplified radiation model

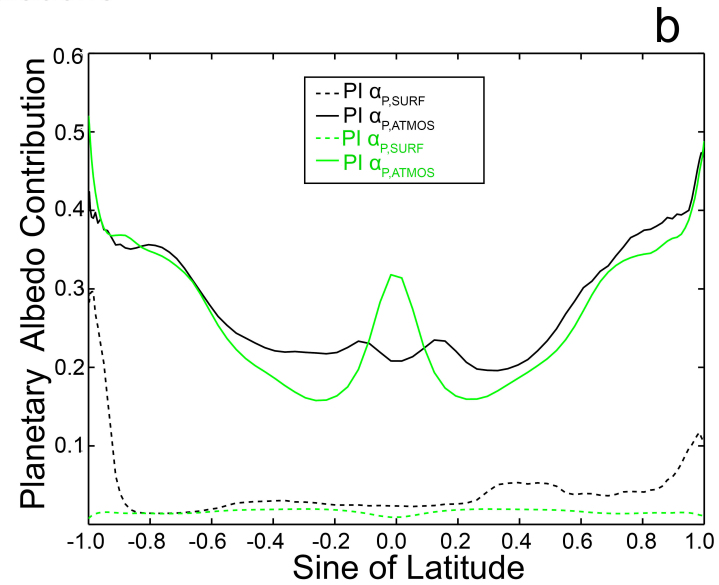
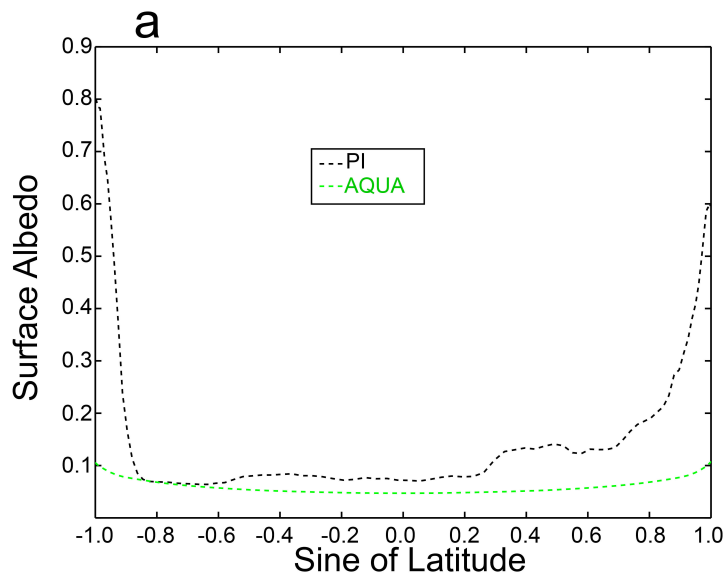


Errors in planetary albedo due to Observational uncertainty

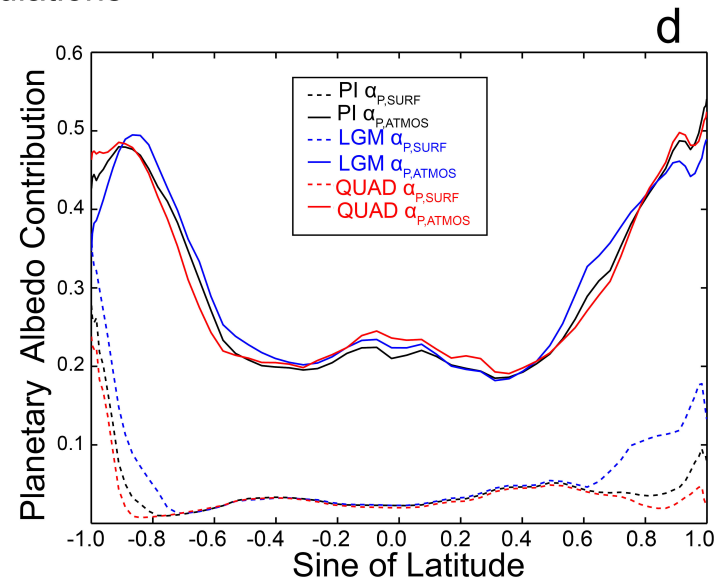
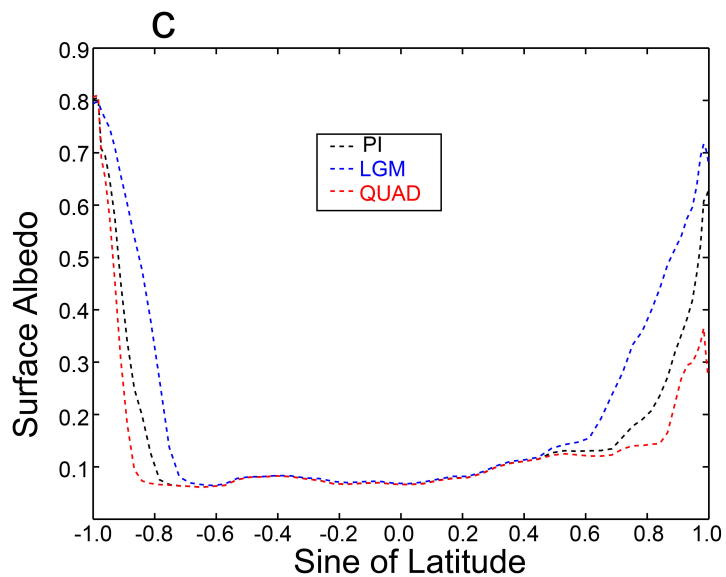


Altered climates states

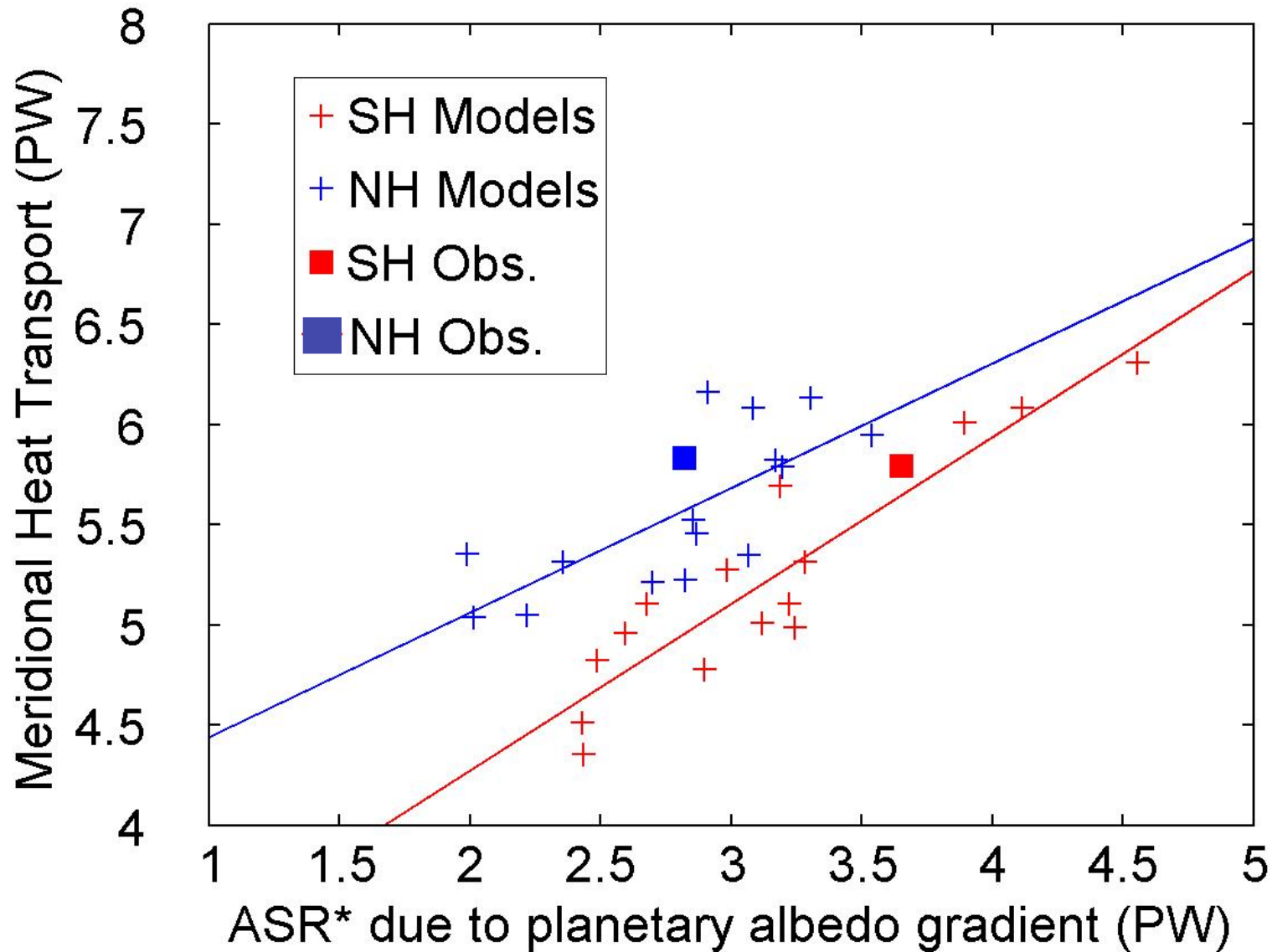
GFDL Simulations

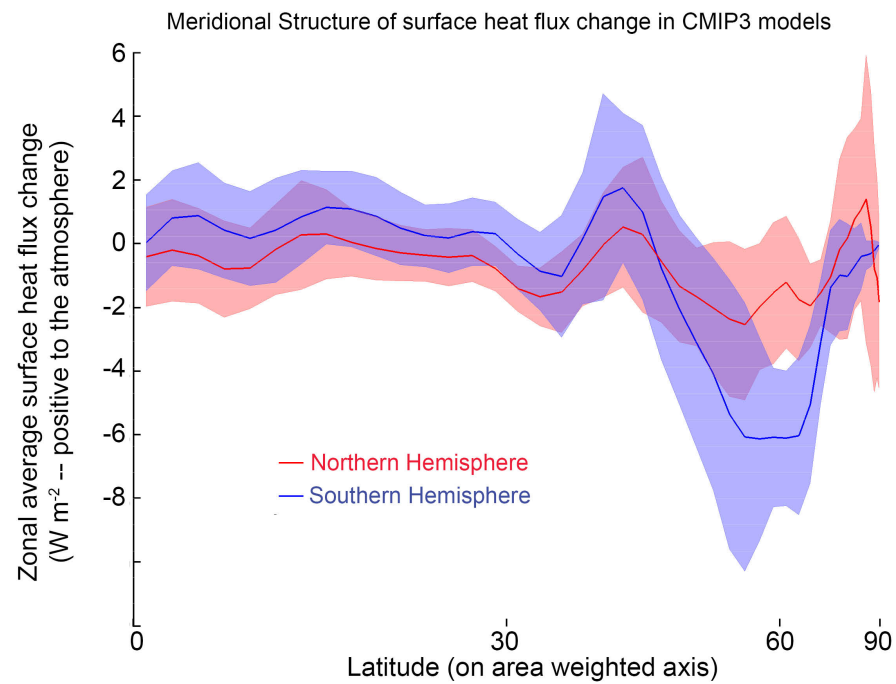
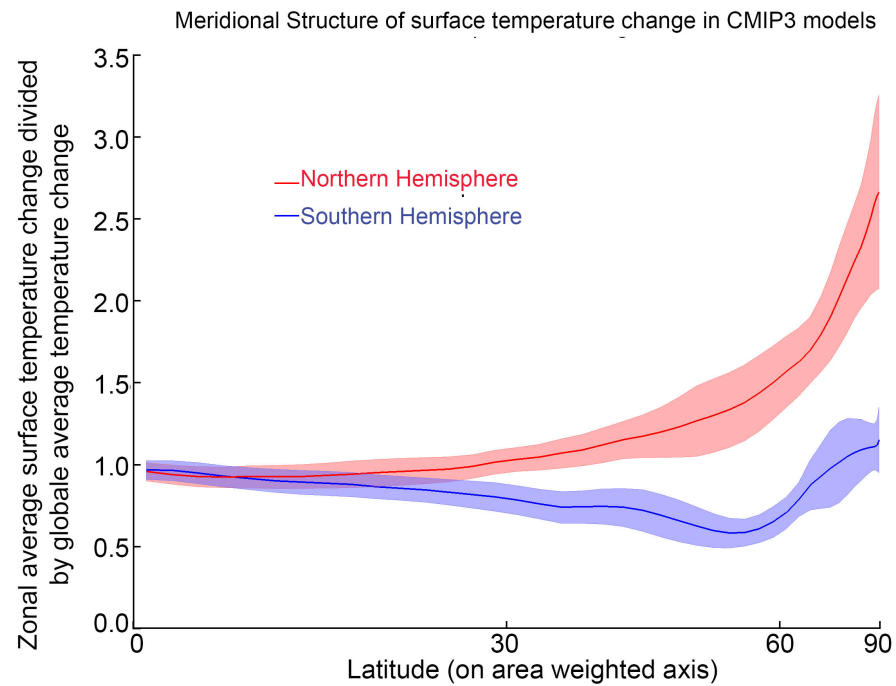


NCAR Simulations

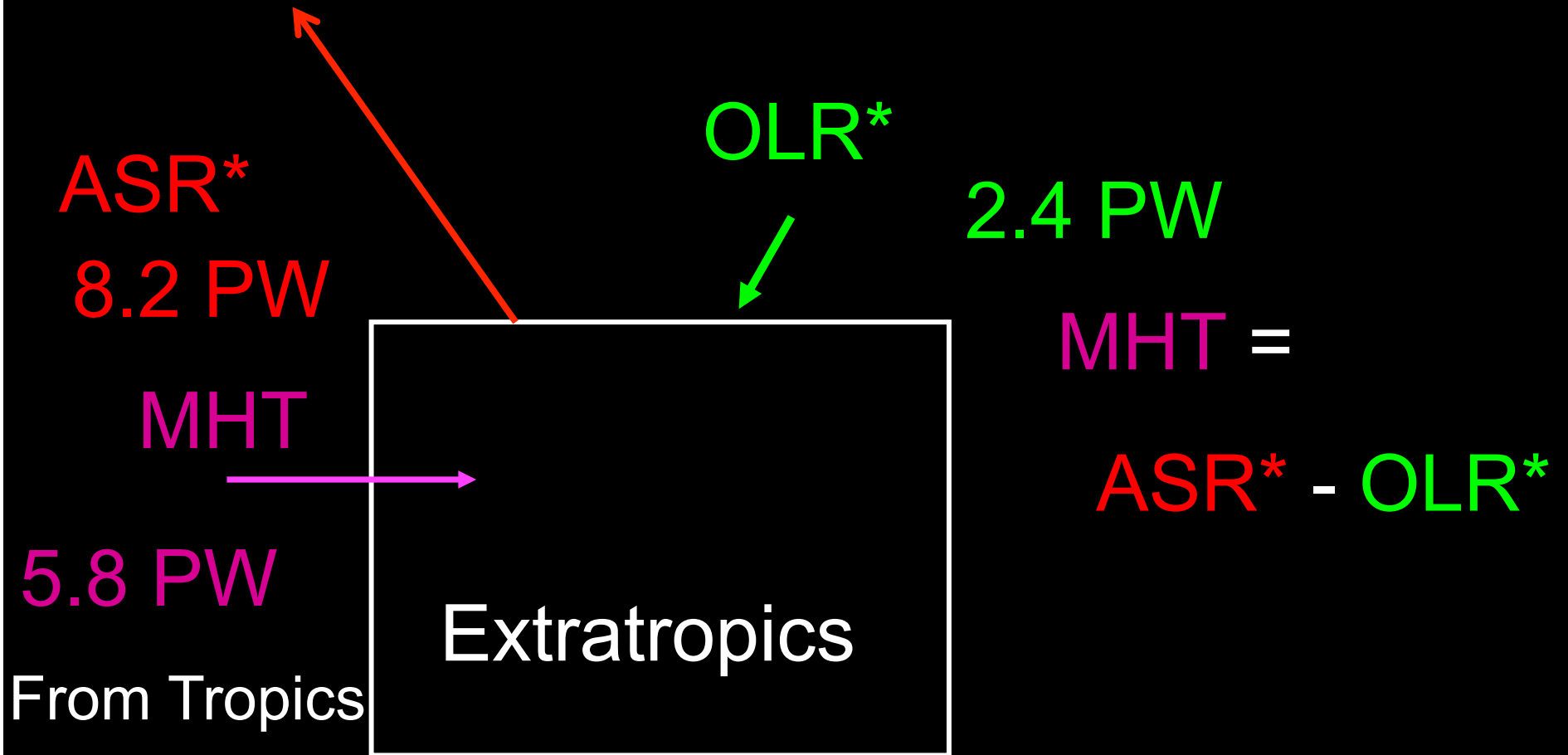


Heat transport and planetary albedo





ASR*, OLR*, MHT, and the extratropical energy budget



All arrows are relative to the global average