

# Radiative and dynamic controls of global scale energy fluxes



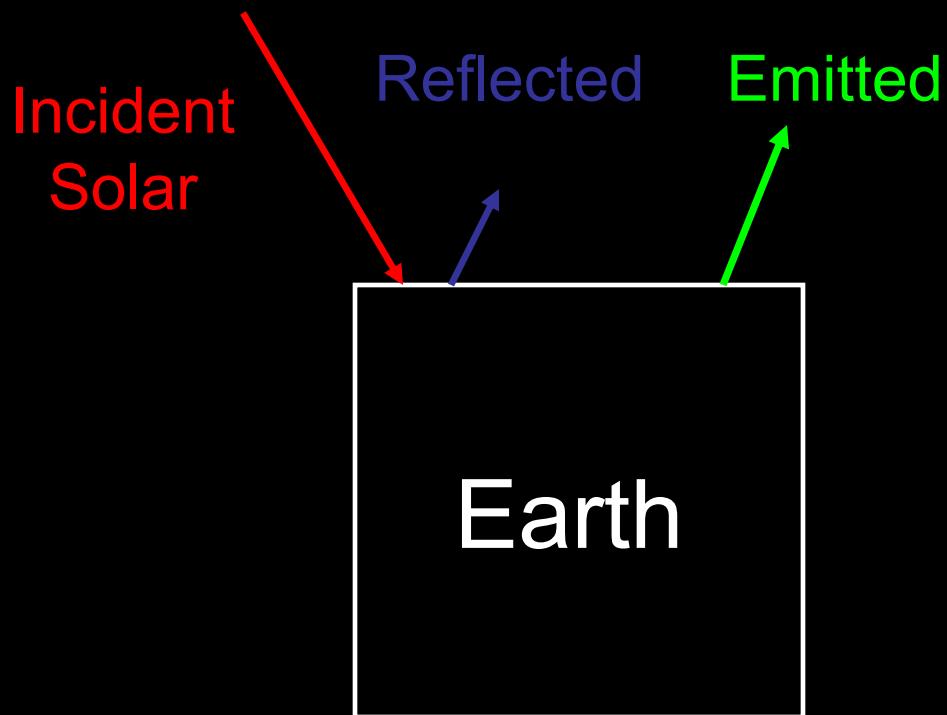
Aaron Donohoe, Ph.D. defense

April 8<sup>th</sup> 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

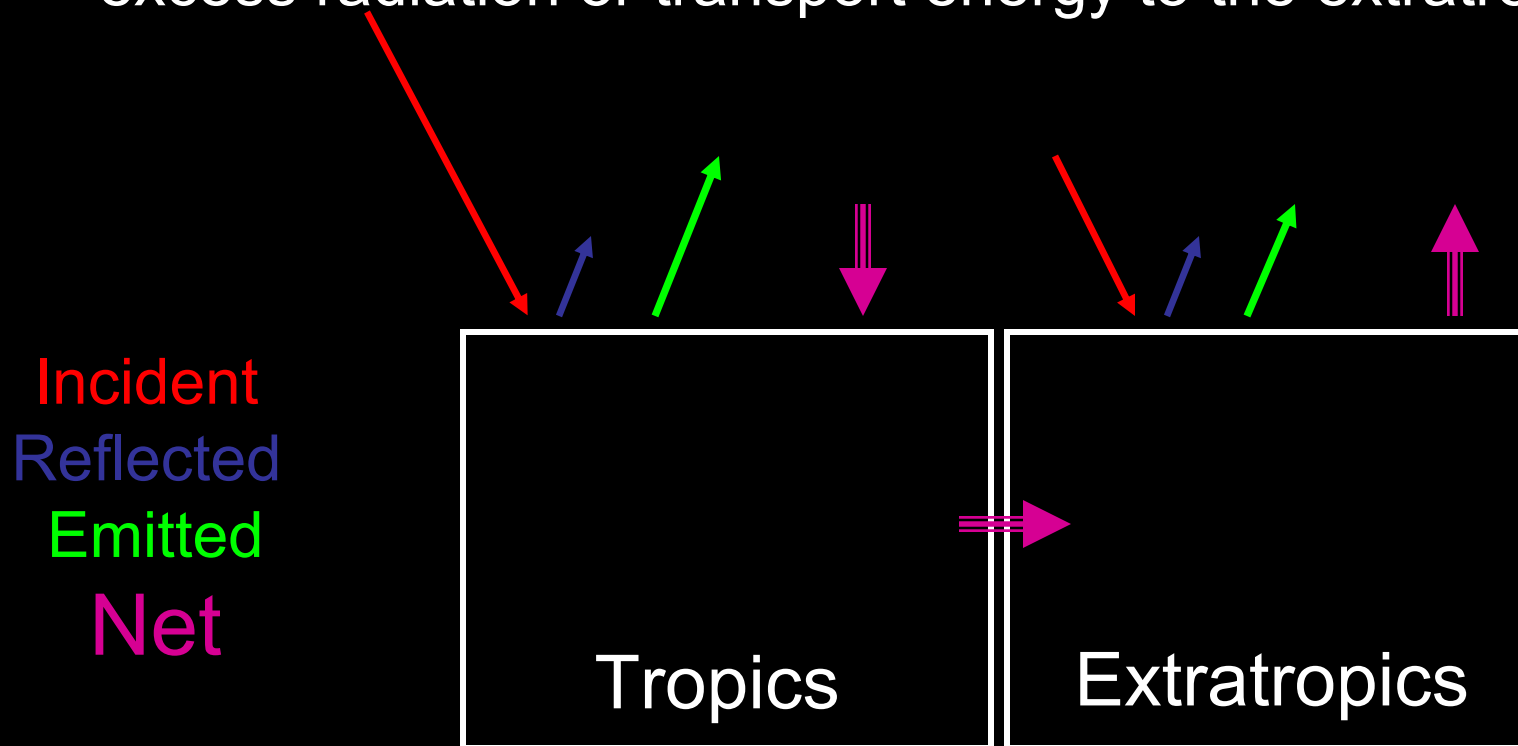


$$\text{Incident} - \text{Reflected} = \text{Emitted}$$

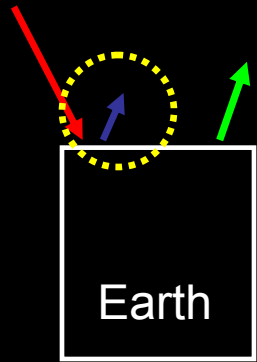
$$S(1 - \alpha_p) = \sigma T_e^4$$

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

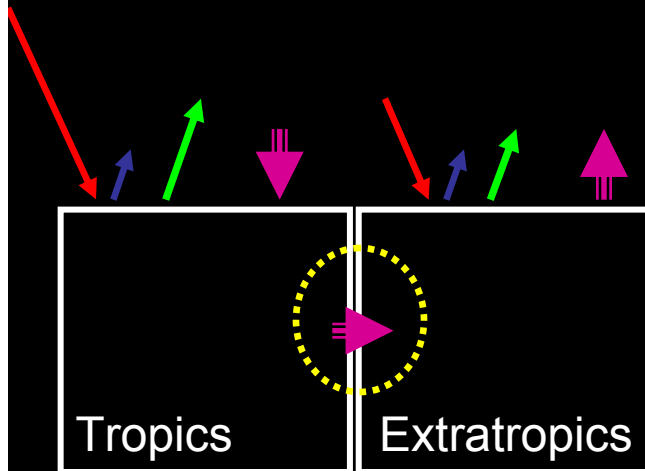
- The tropics receive more solar radiation than the high latitudes (extratropics)
- To come to equilibrium, the tropics must either emit excess radiation or transport energy to the extratropics



# Thesis Outline



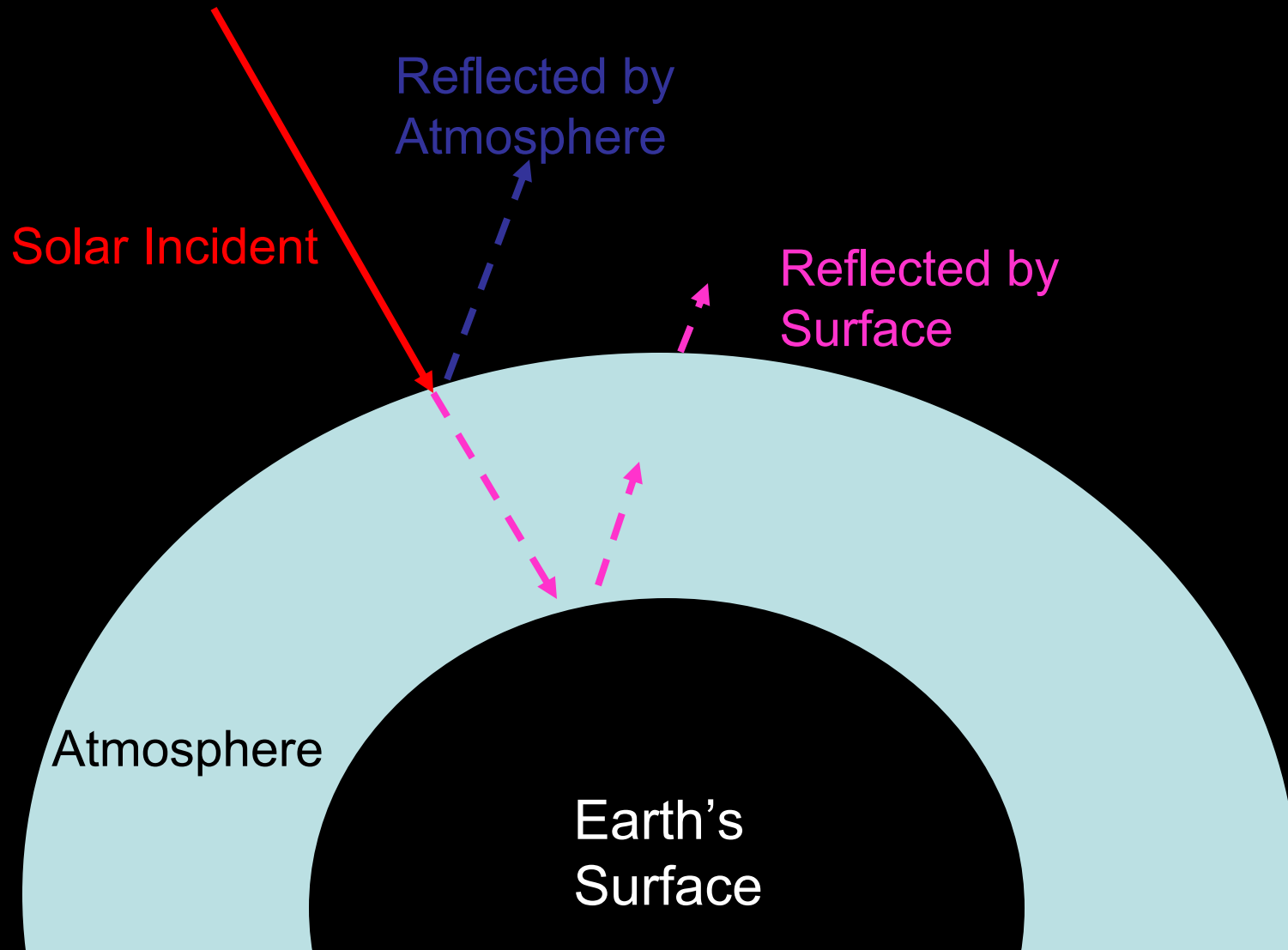
1. What determines the Earth's planetary albedo? (How much solar radiation gets reflected)



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

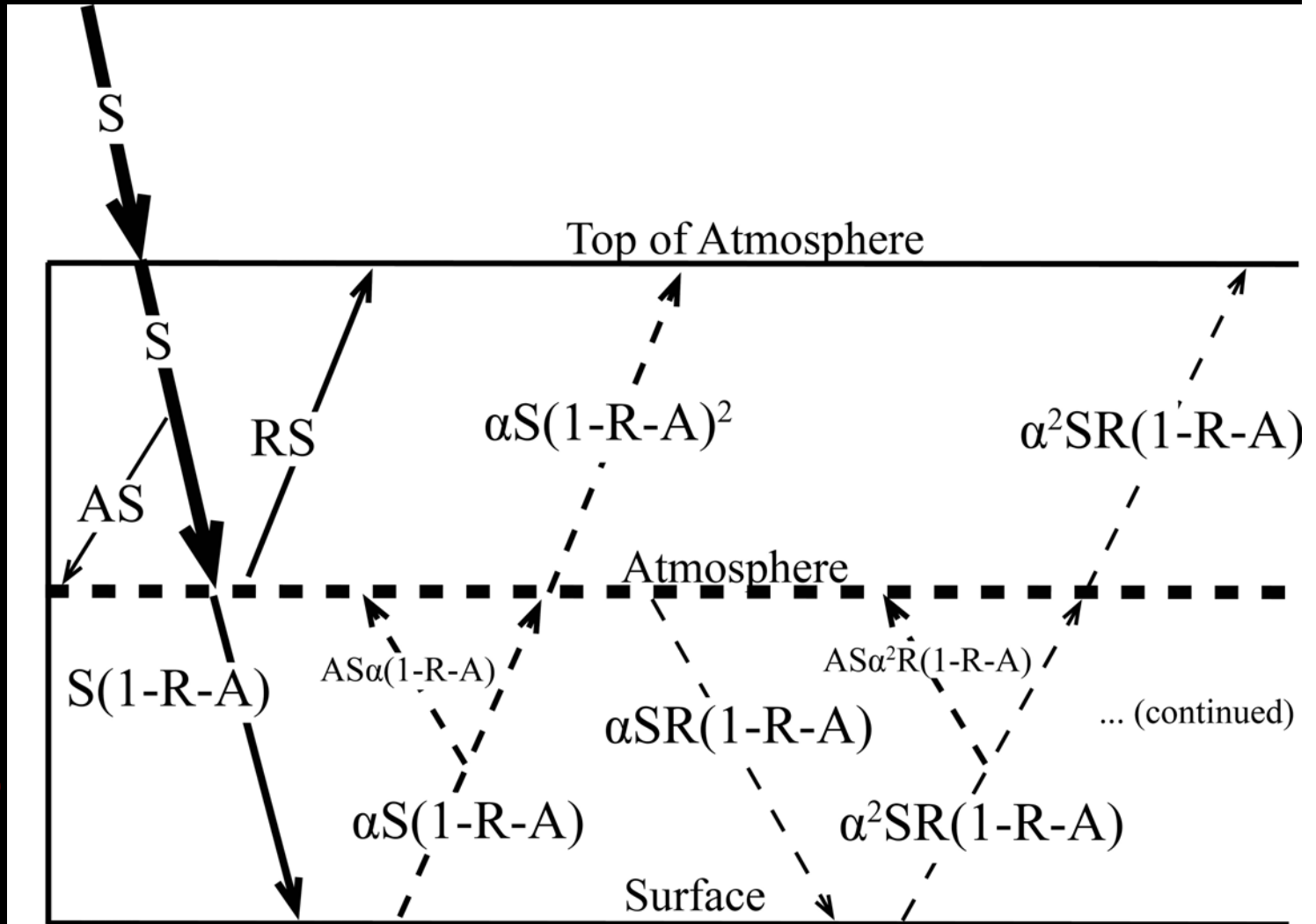
S = incident

R = cloud reflection

A = absorption

$\alpha$  = surface albedo

(UNKNOWN)

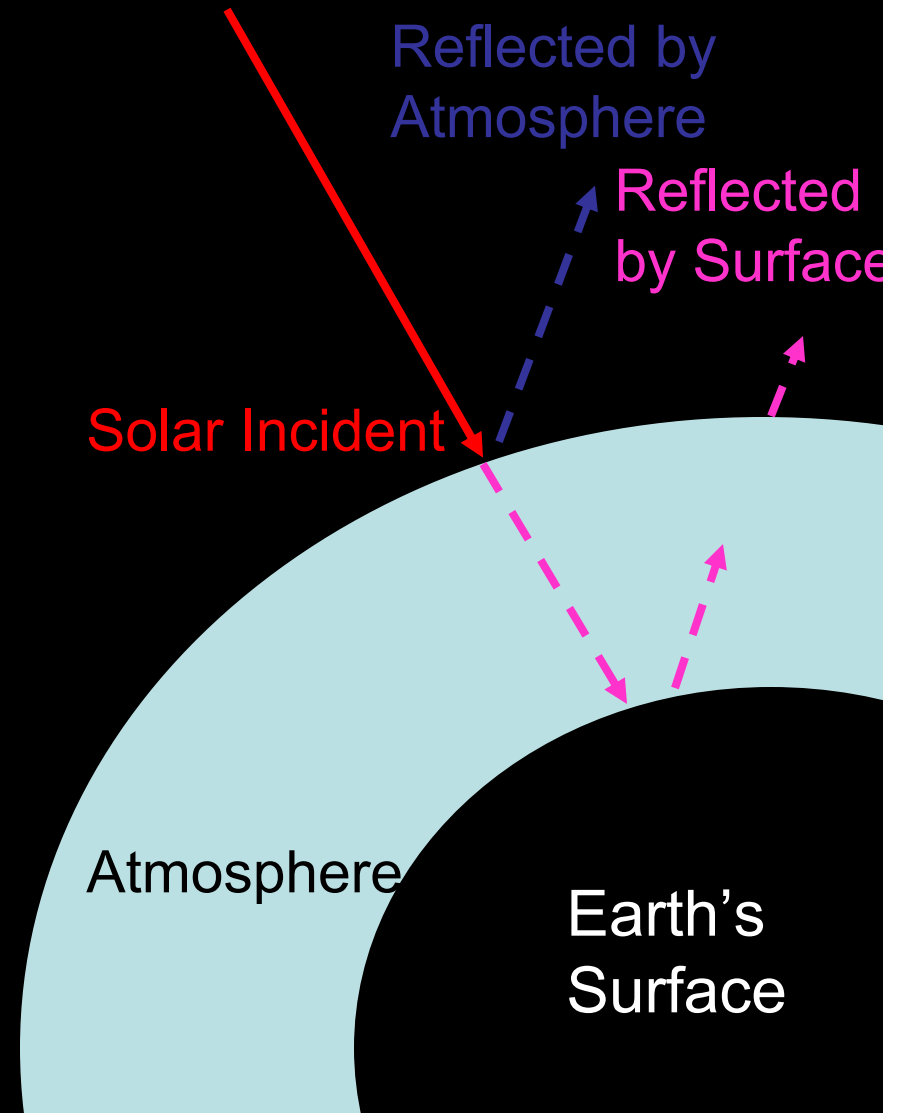


# Partitioning of planetary albedo into atmospheric and surface components

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

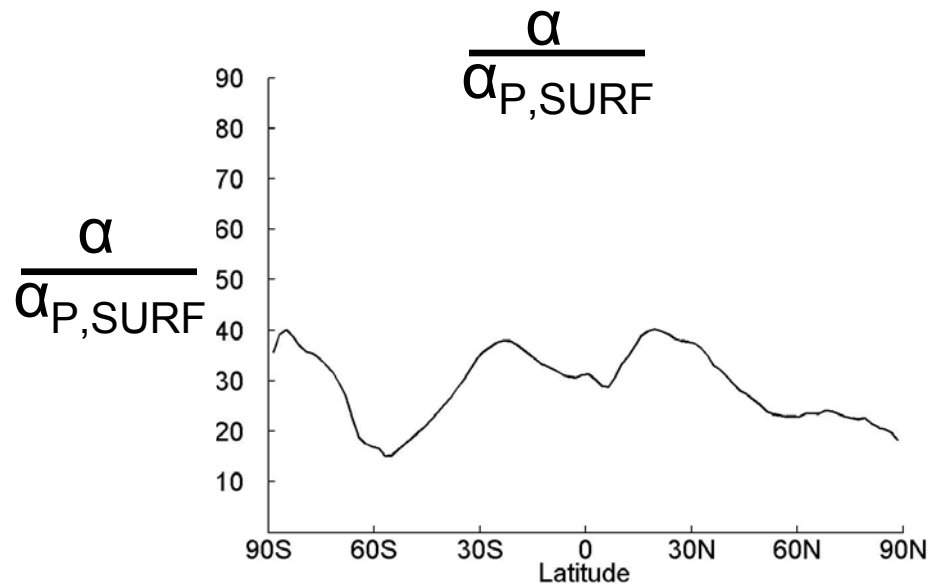
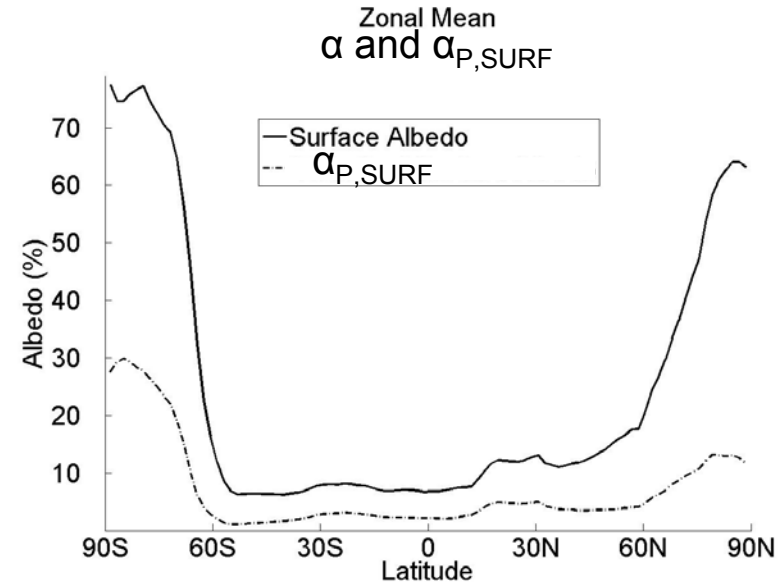
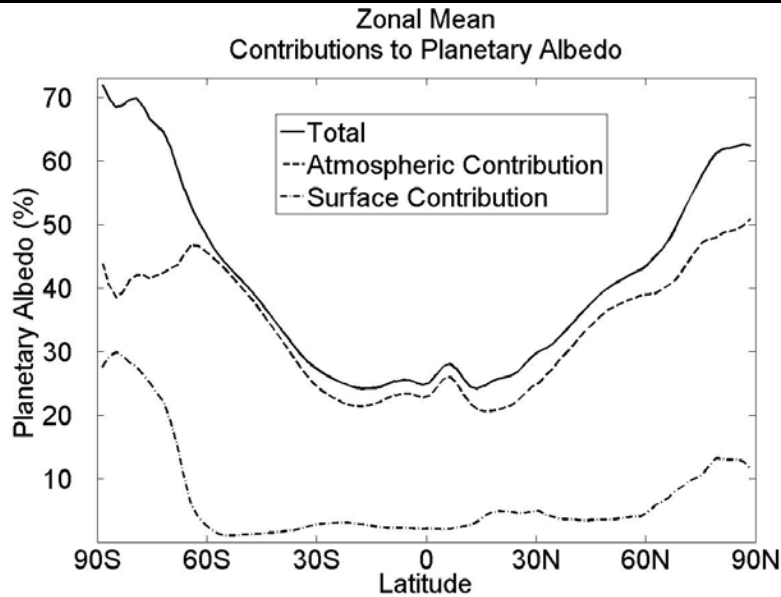
$$\alpha_{P,ATMOS} = R$$

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



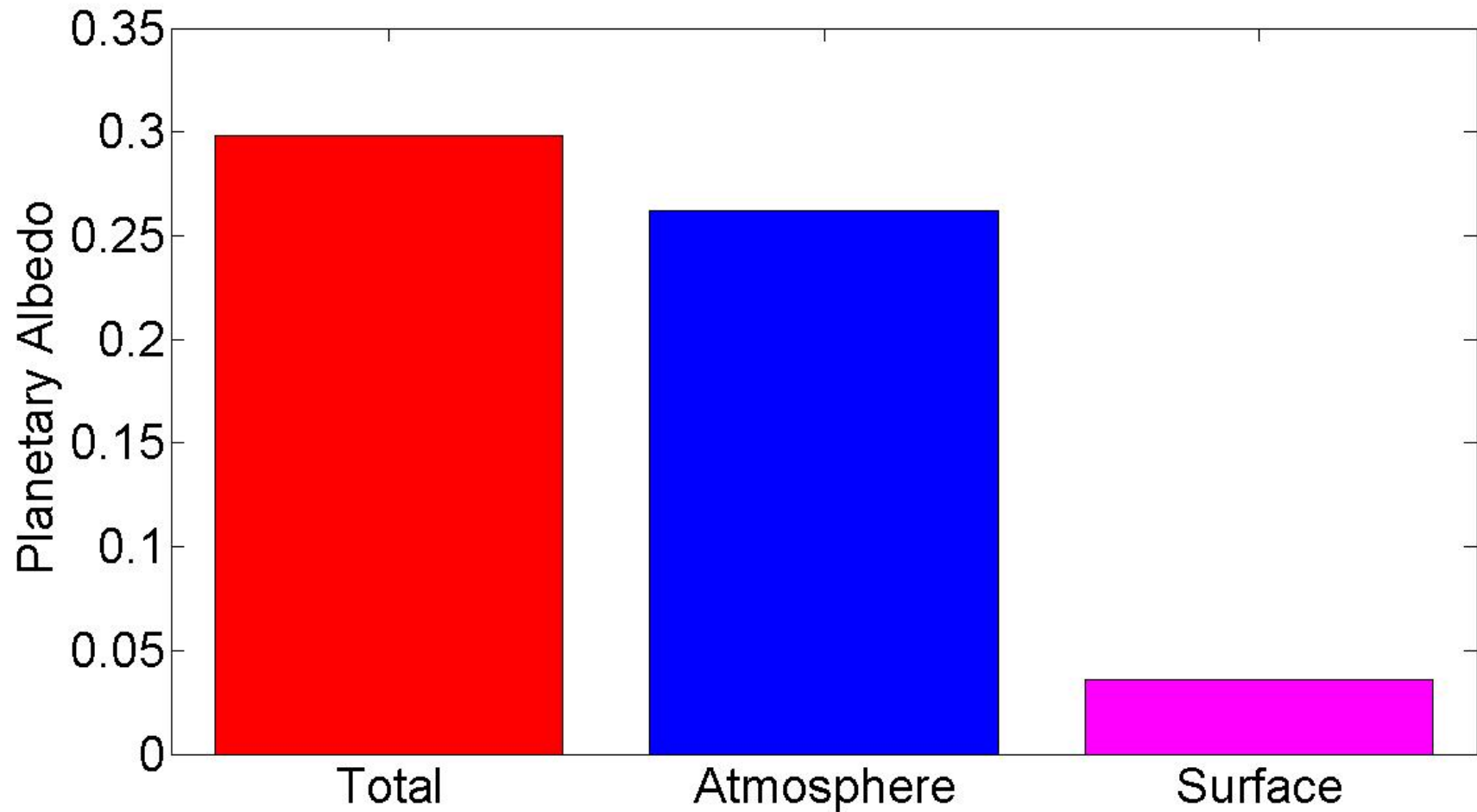
# Observed (CERES) surface and atmospheric contribution to planetary albedo

# Observed Surface and atmospheric contribution to planetary albedo



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

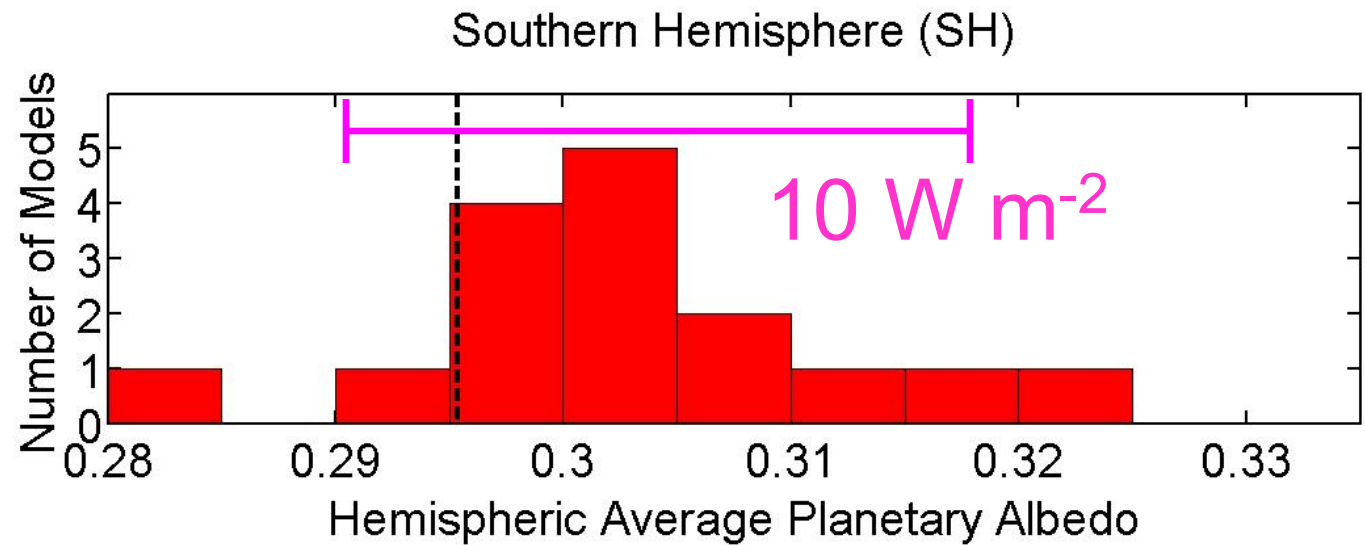
# Observed Global Mean Planetary Albedo and its atmospheric/surface Partitioning



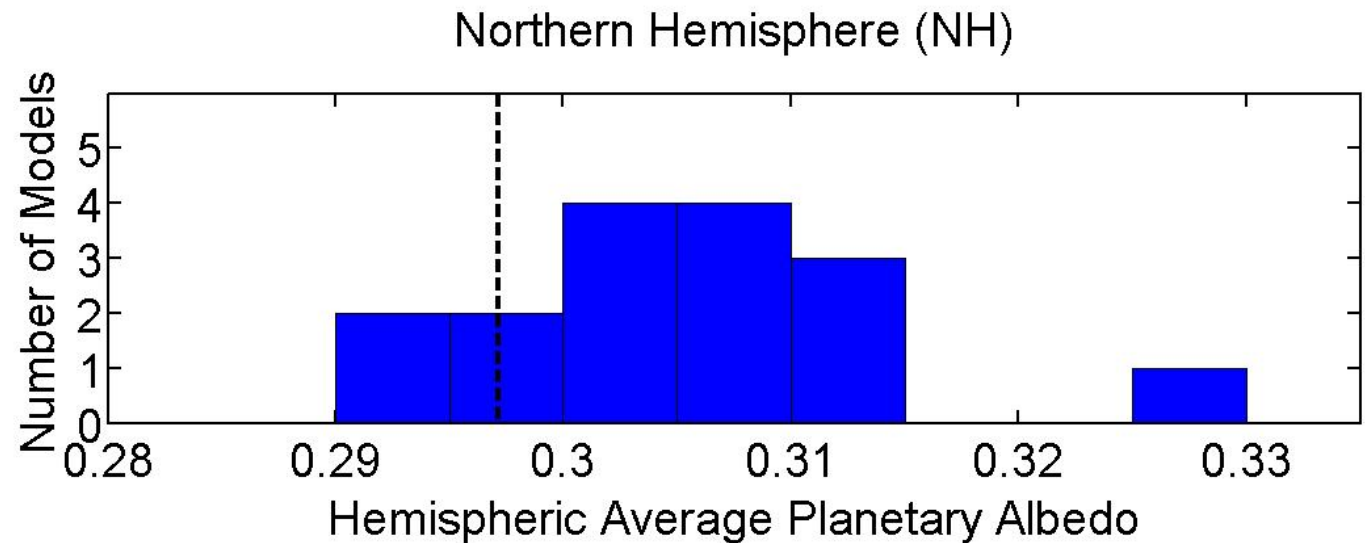
# Planetary Albedo Partitioning in Climate Models (CMIP3)



# Histogram of hemispheric average planetary albedo

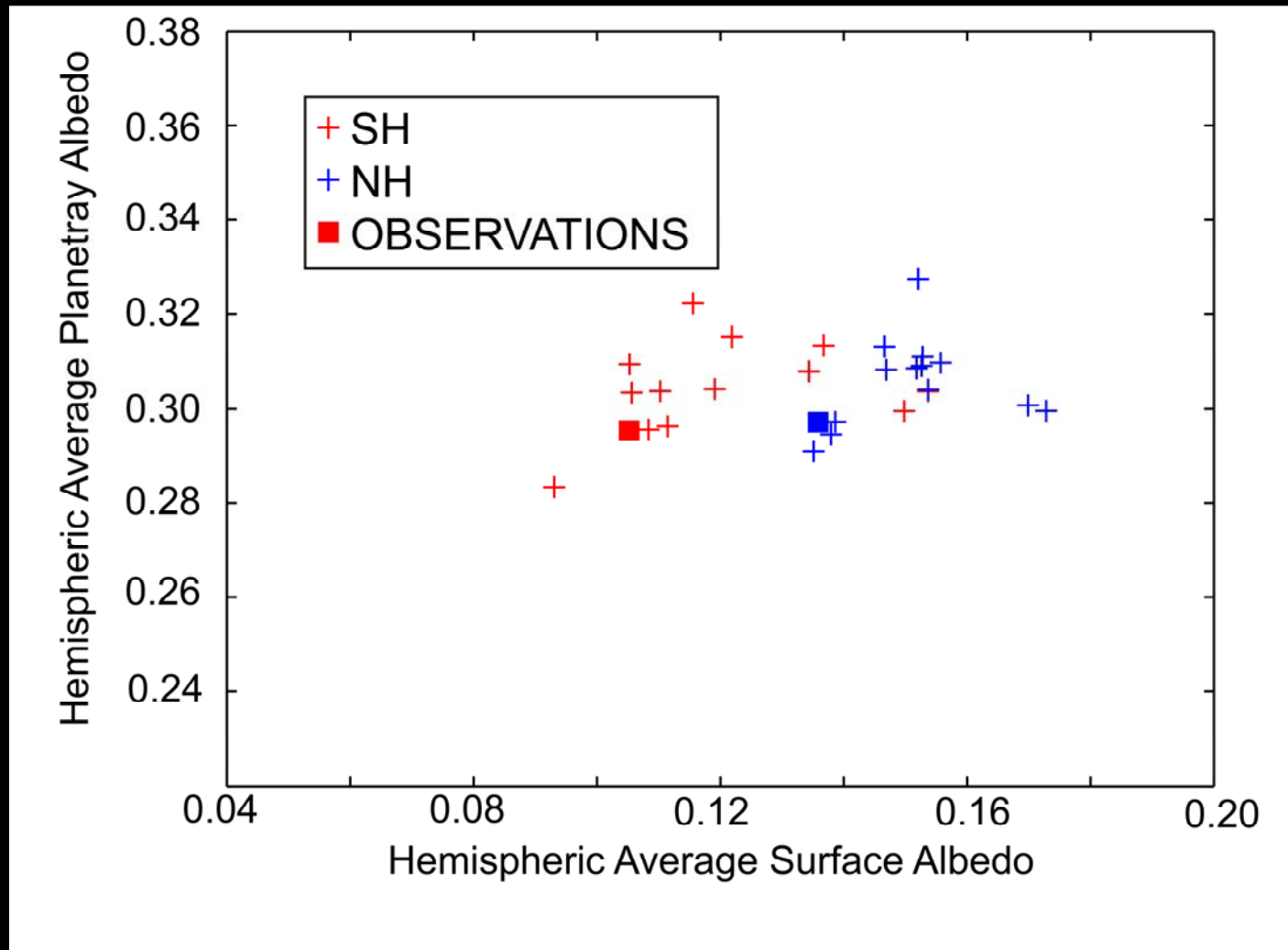


.....  
Observations  
(CERES)

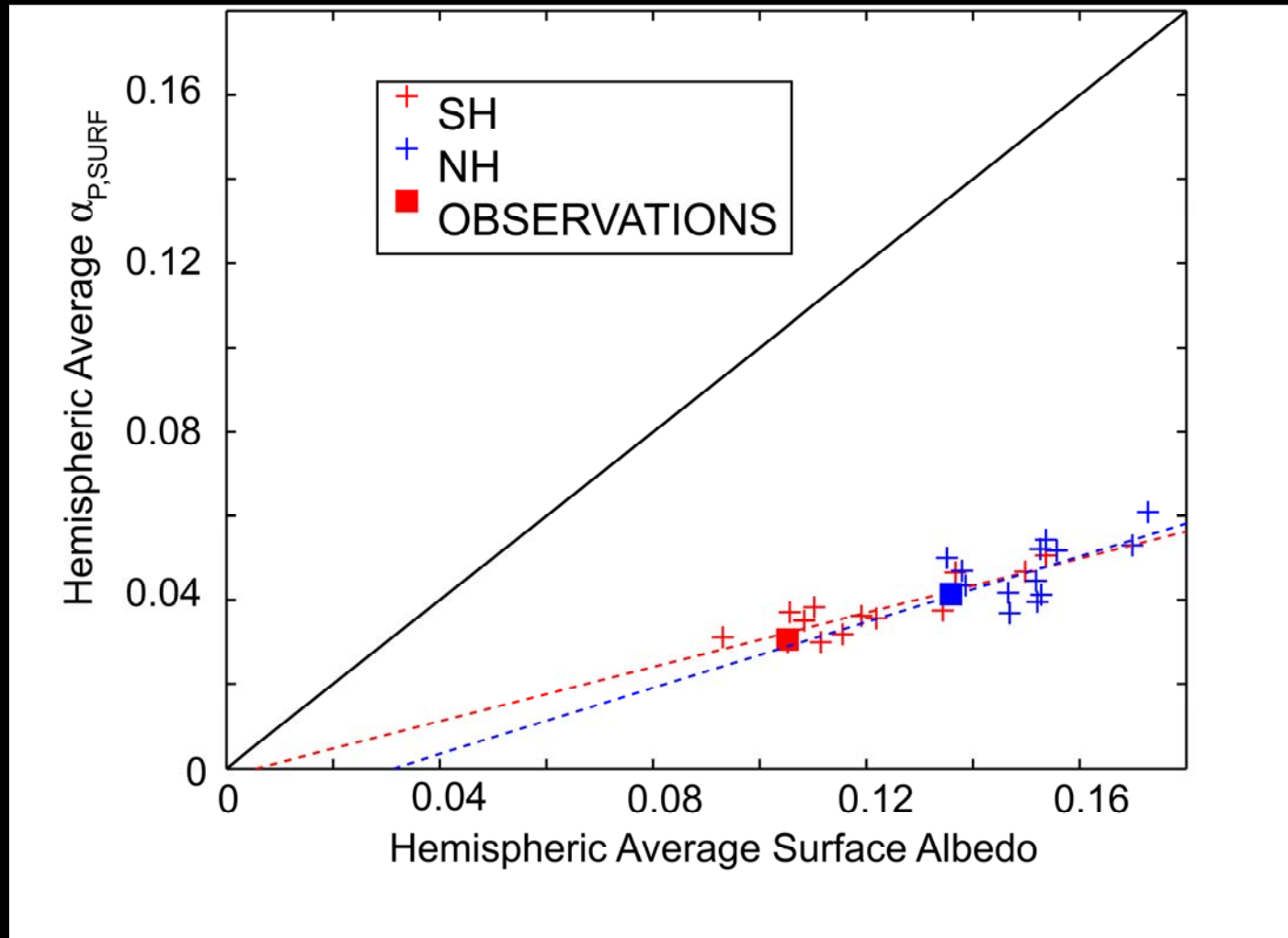


# Partitioning of hemispheric average planetary albedo

# Hemispheric Average Surface Albedo and Planetary Albedo



# Hemispheric Average Surface Albedo and Surface Contribution to Planetary Albedo



# Changes due to CO<sub>2</sub> doubling

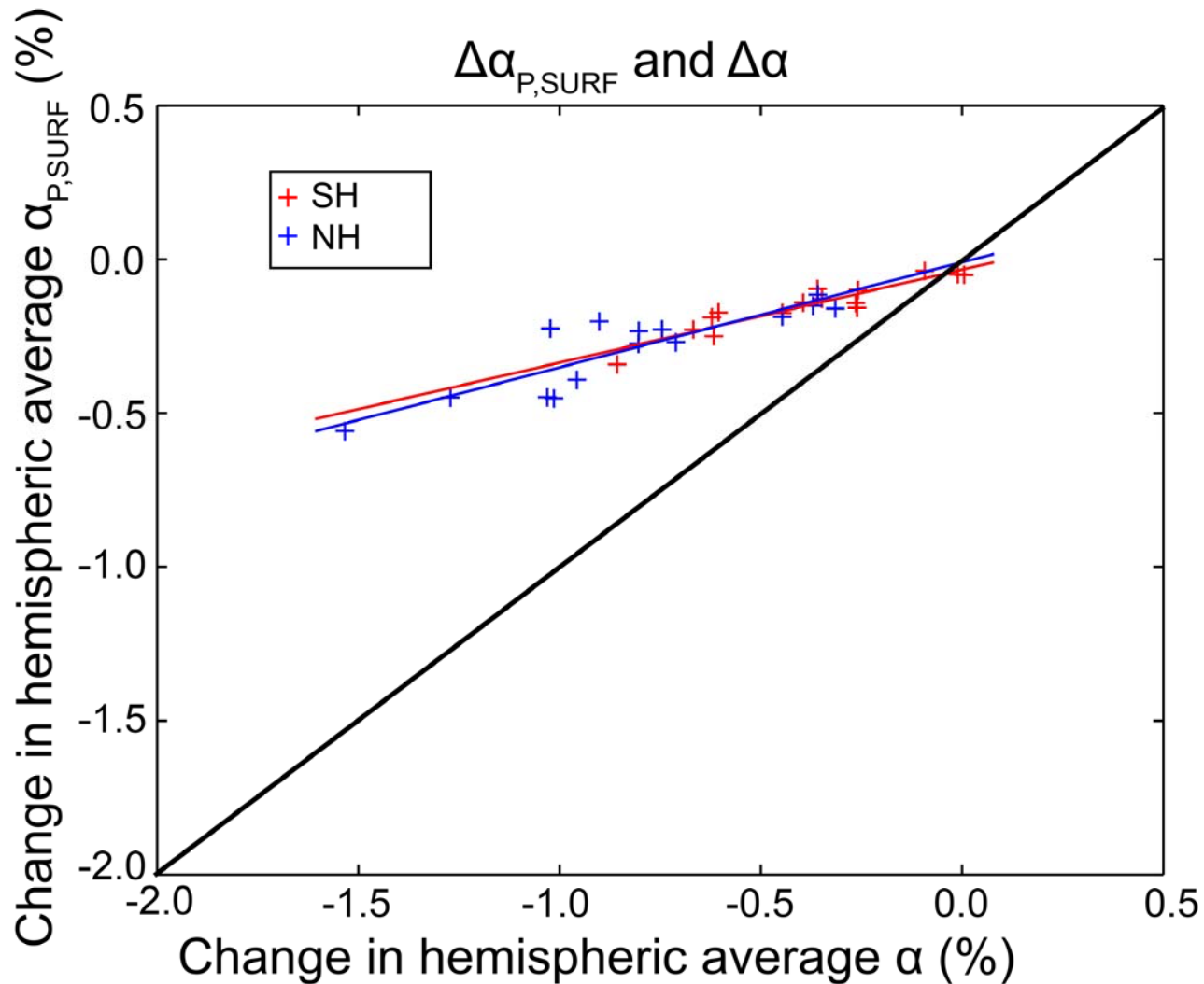
- 1% CO<sub>2</sub> increase to doubling experiments
- CO<sub>2</sub> doubles at year 69, we average data from years 200-220
- Compare with pre-industrial simulation in the same model

# Change in planetary albedo due to CO<sub>2</sub> doubling

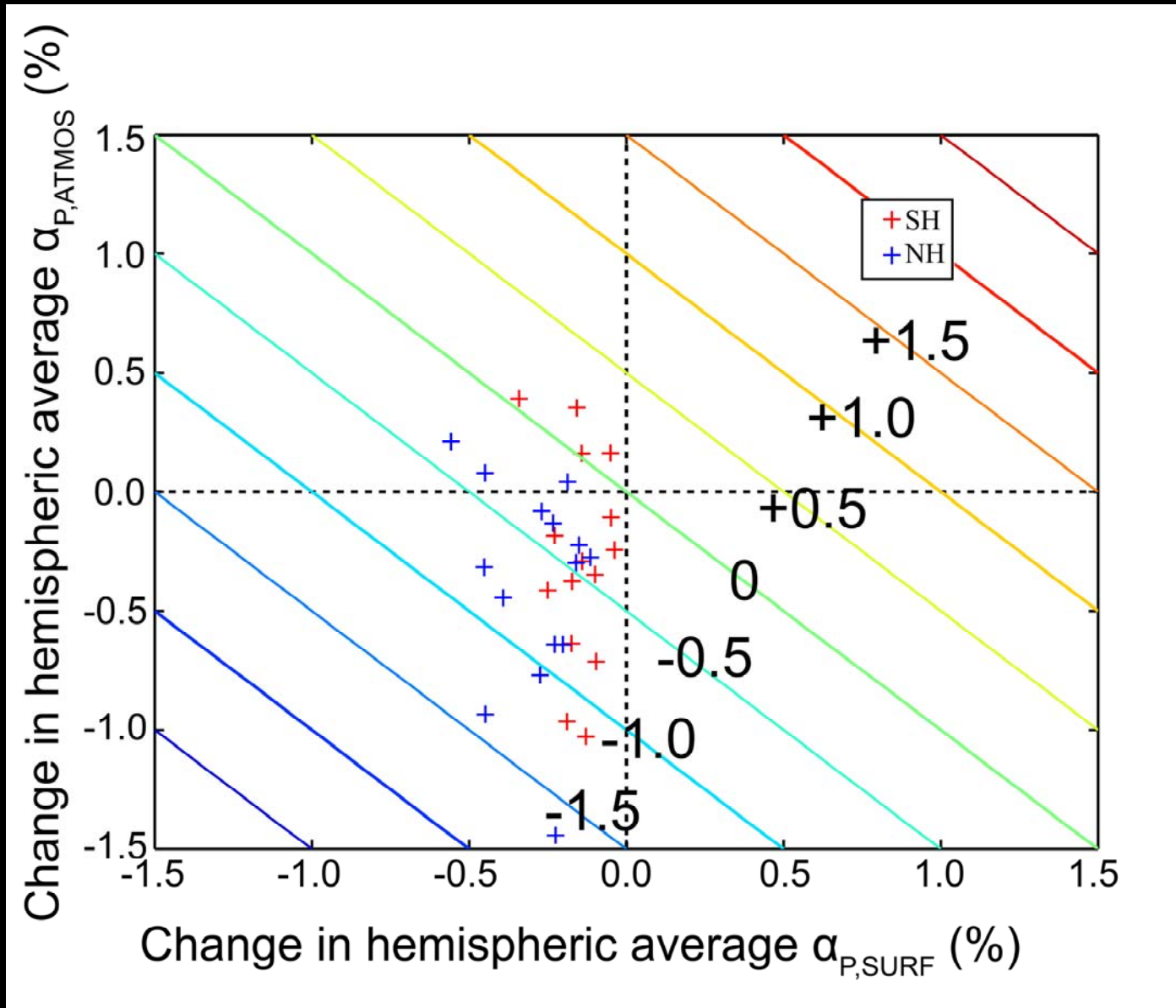


2 X CO<sub>2</sub> change in planetary  
albedo and partitioning

# 2 X CO2 change in surface contribution to planetary albedo



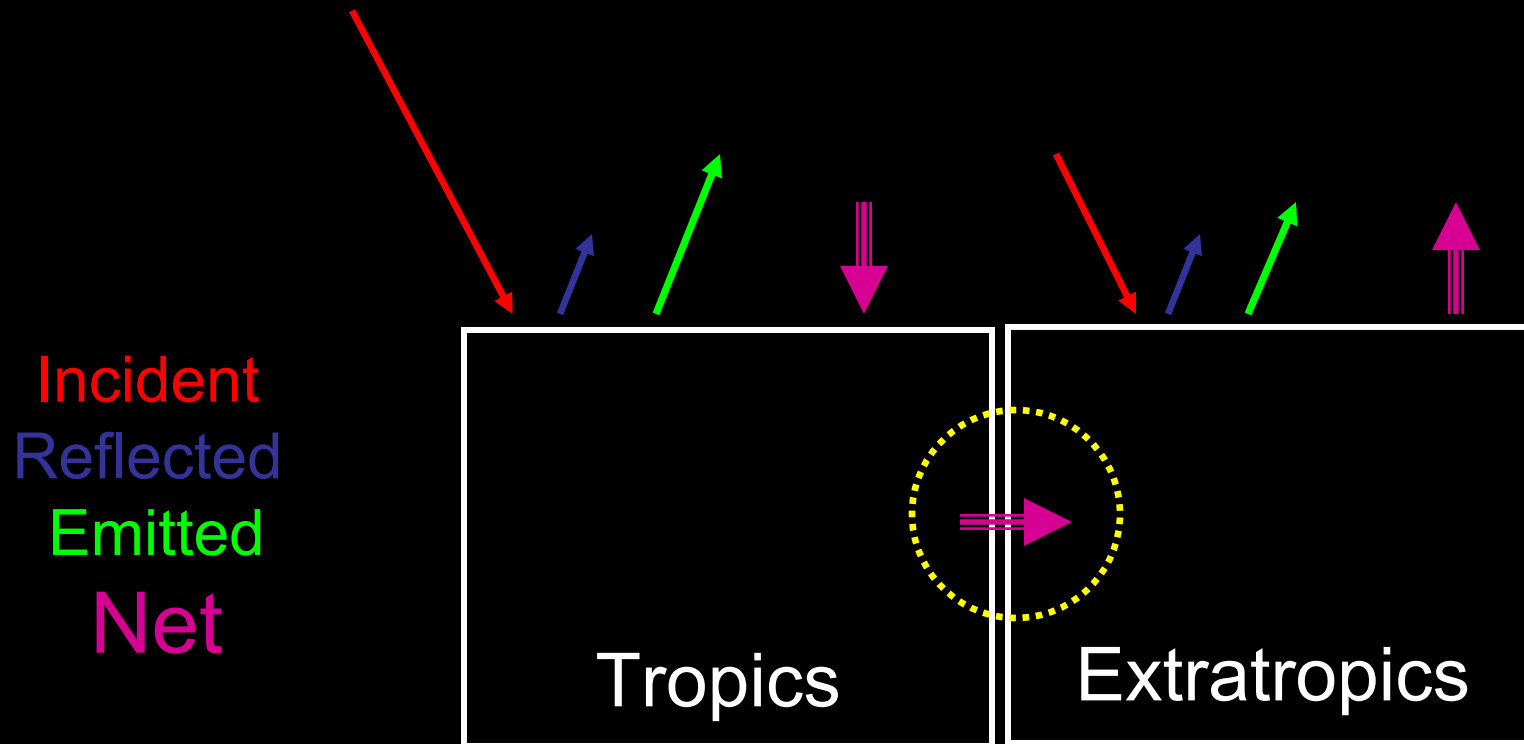
# 2 X CO2 planetary albedo change



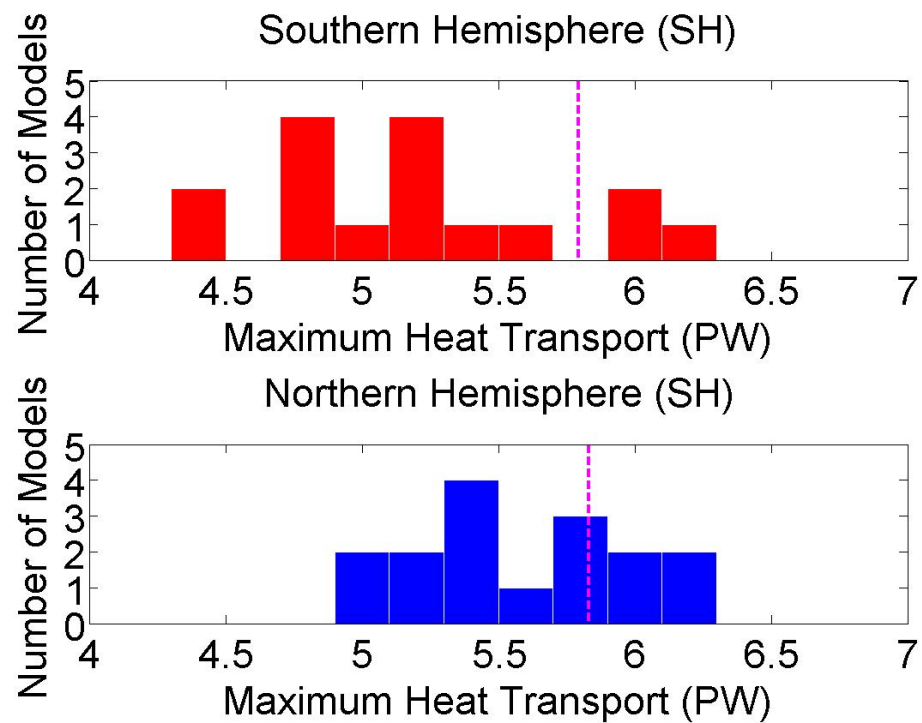
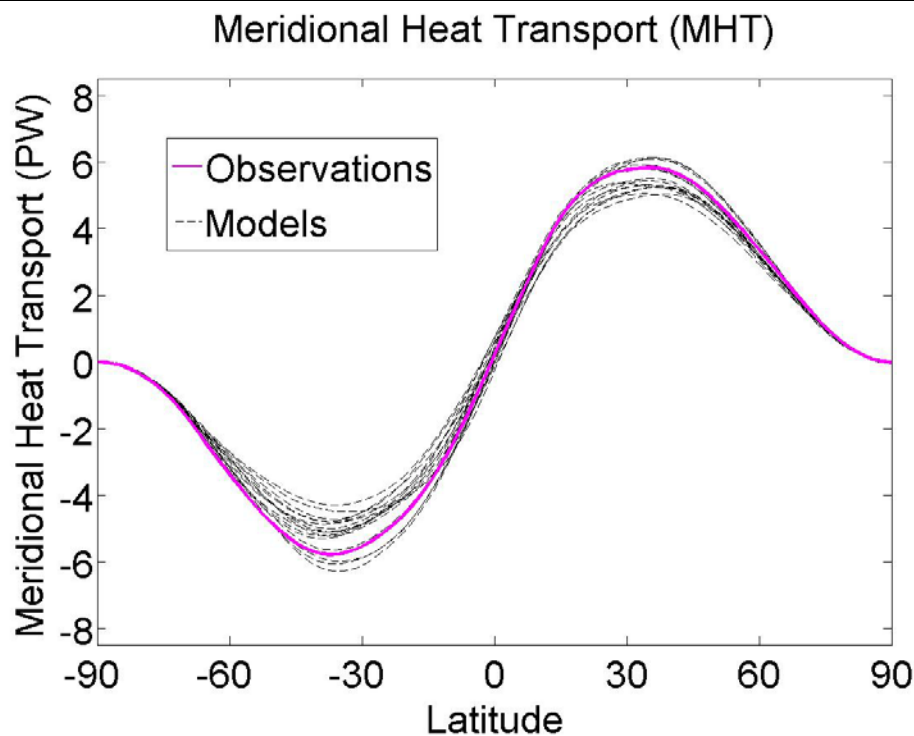
# Conclusions: Section I

- 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  $\sim 3$
- Inter-model differences in planetary albedo are primarily due to differences in cloud reflection
- Changes in planetary albedo due to CO<sub>2</sub> 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?



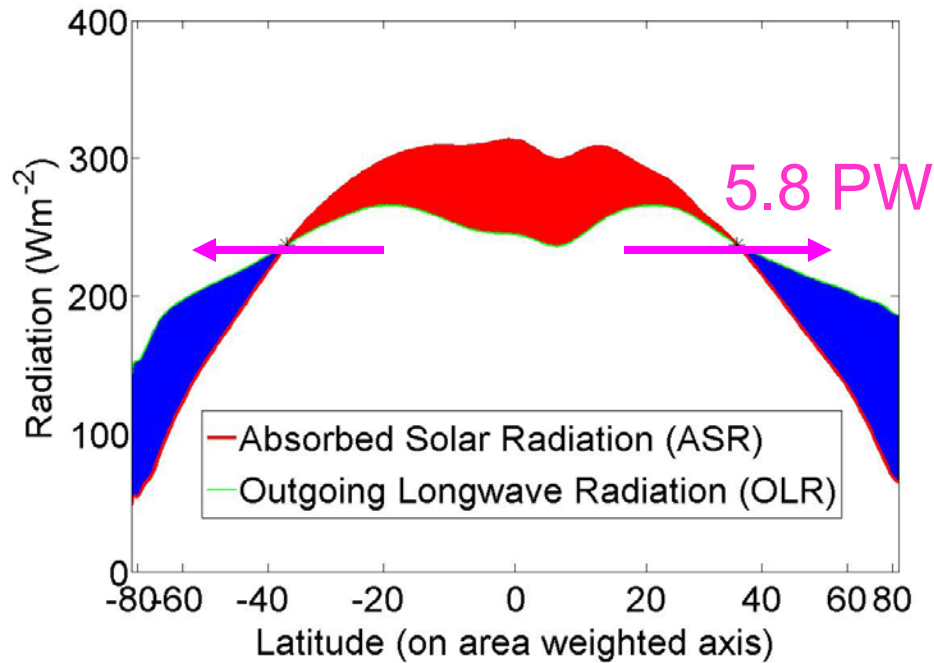
# Heat Transport In Climate Models (CMIP3 Pre-industrial)



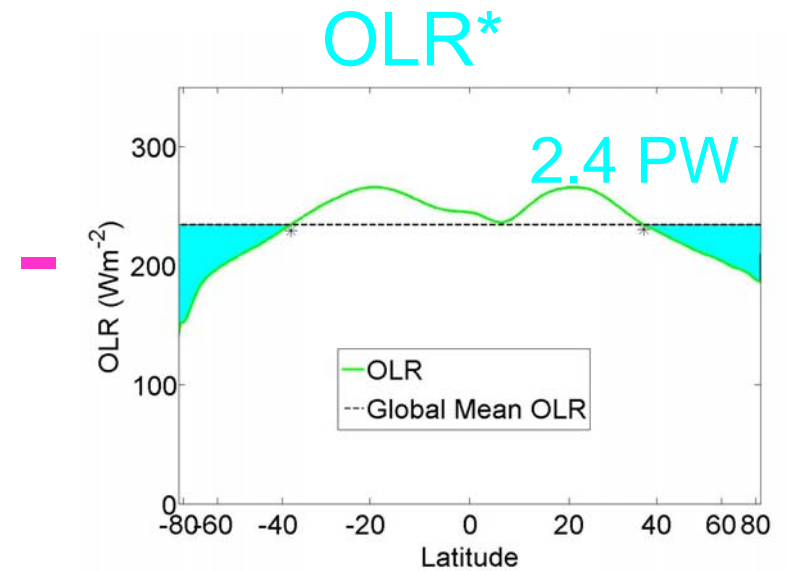
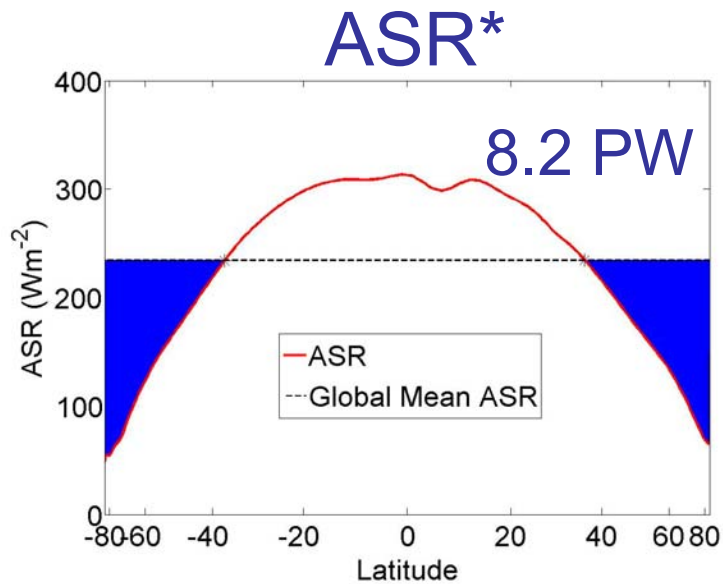
--- Observations

# Understanding heat transport

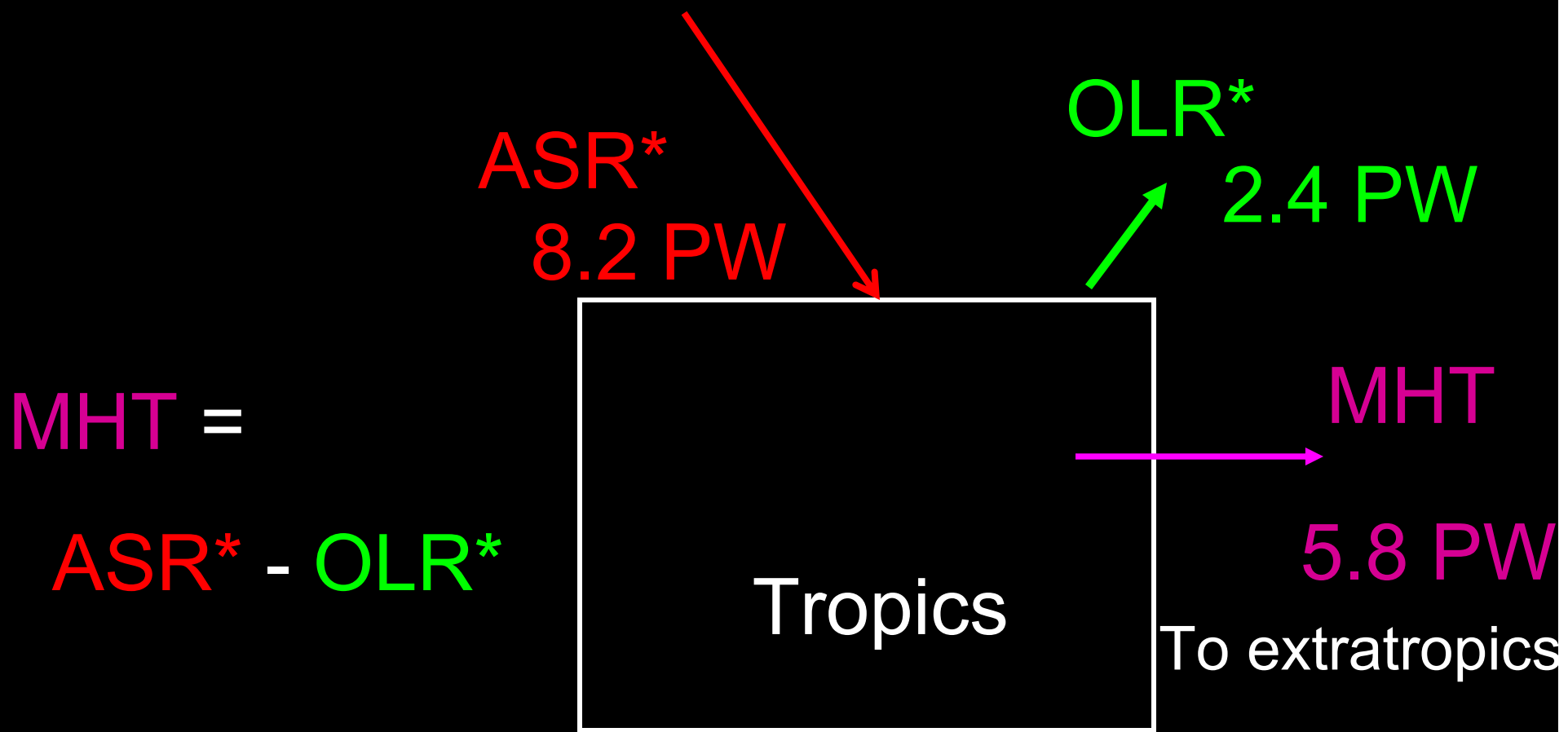
Heat Transport From Radiation Imbalance



Heat Transport =



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



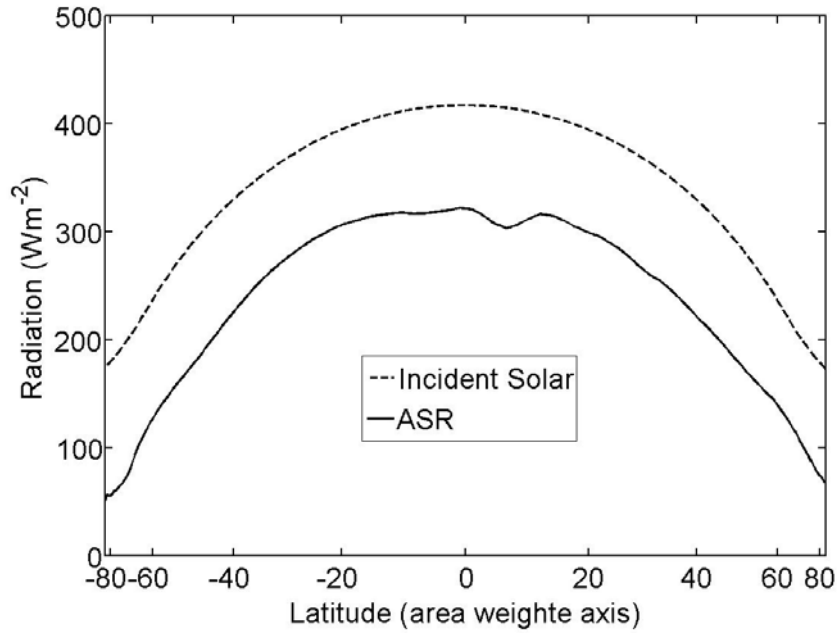
All arrows are relative to the global average

# Model heat transport spread in terms of OLR\* and ASR\*

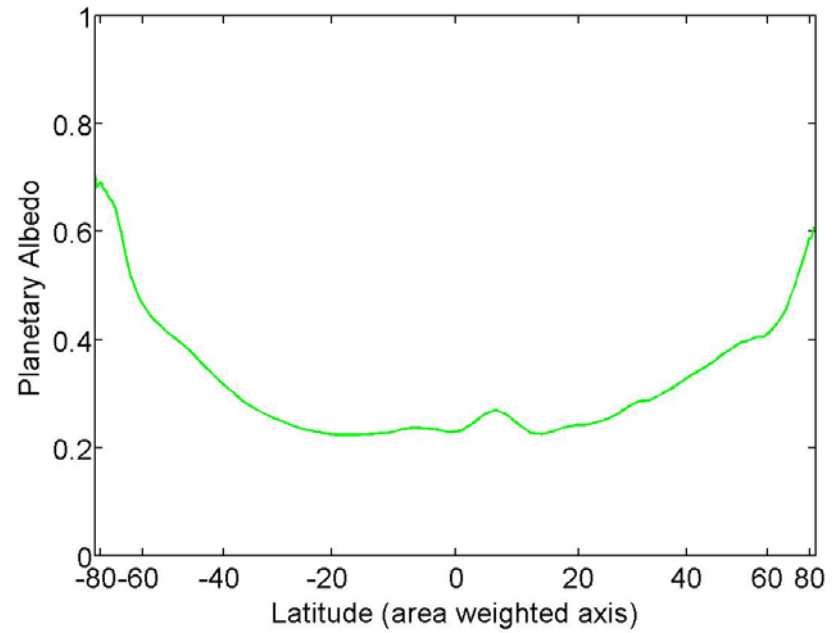


# Understanding ASR\*

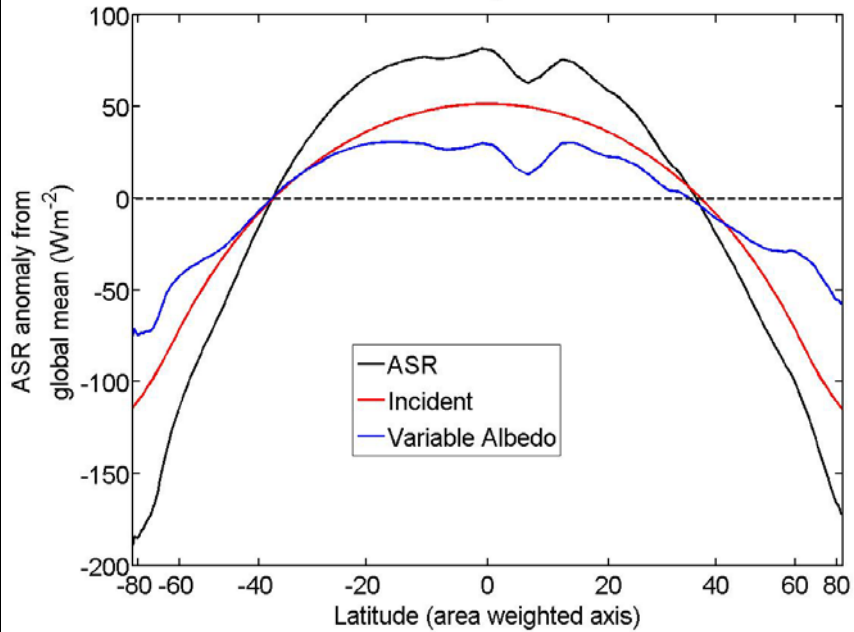
Incoming and Net Solar Radiation



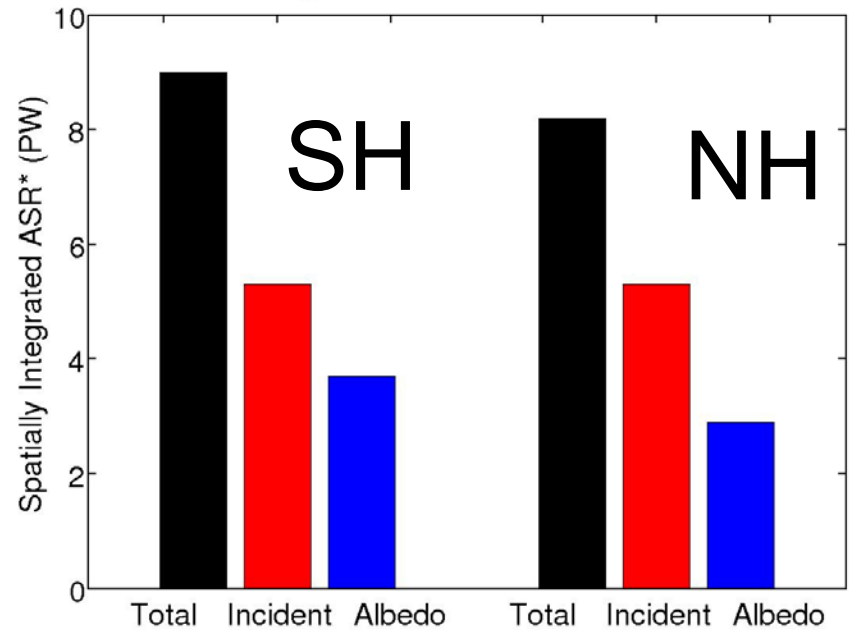
Planetary Albedo



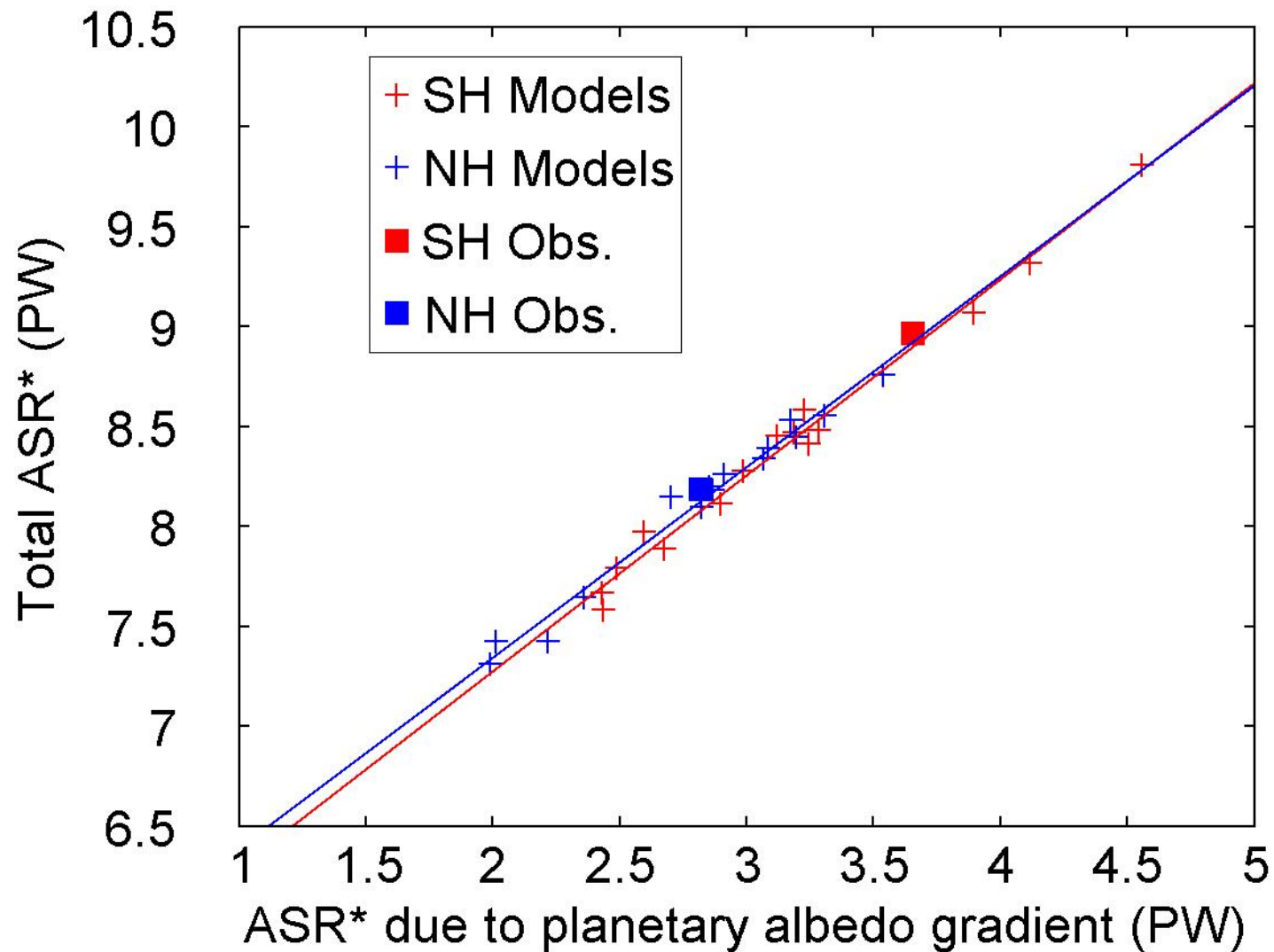
Partitioning of ASR



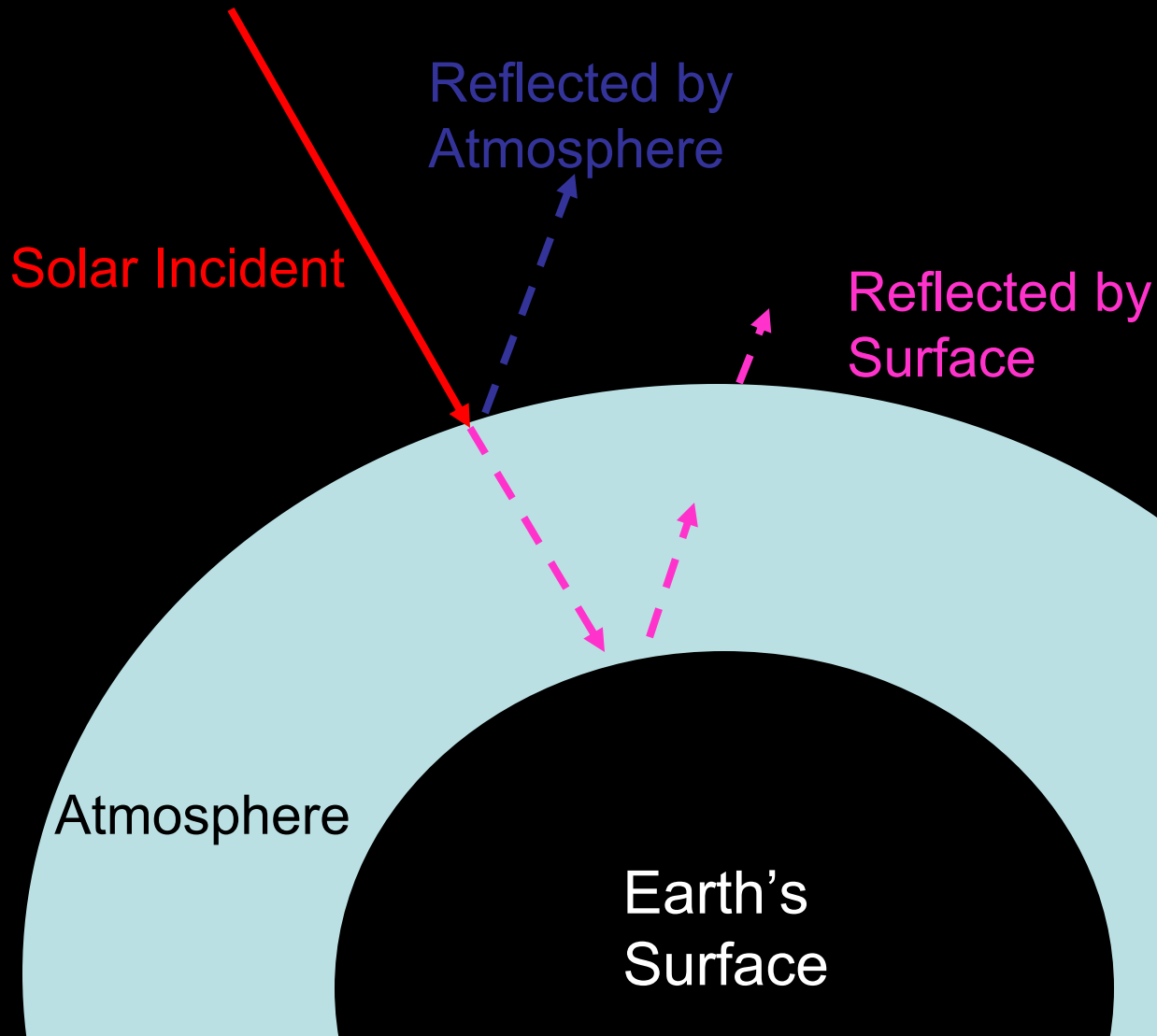
Integrated Contributions to ASR\*



# ASR\* and planetary albedo



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

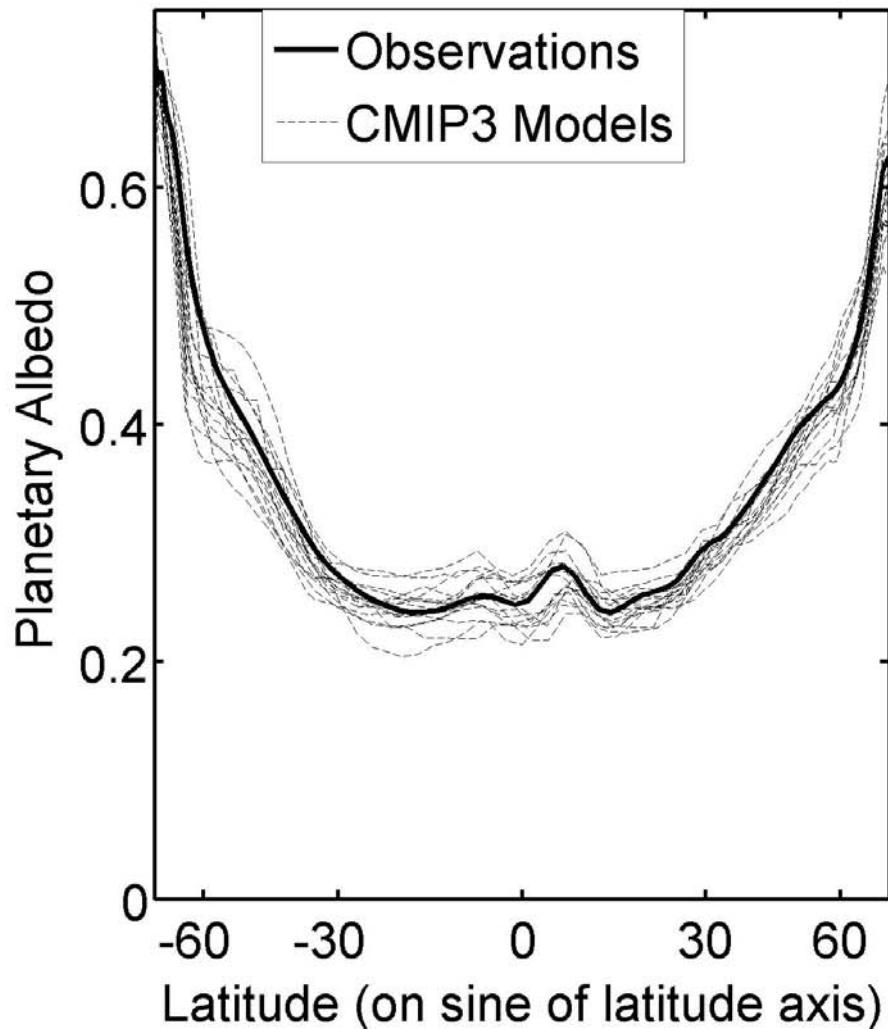


# The surface and atmospheric reflection contributions to ASR\*

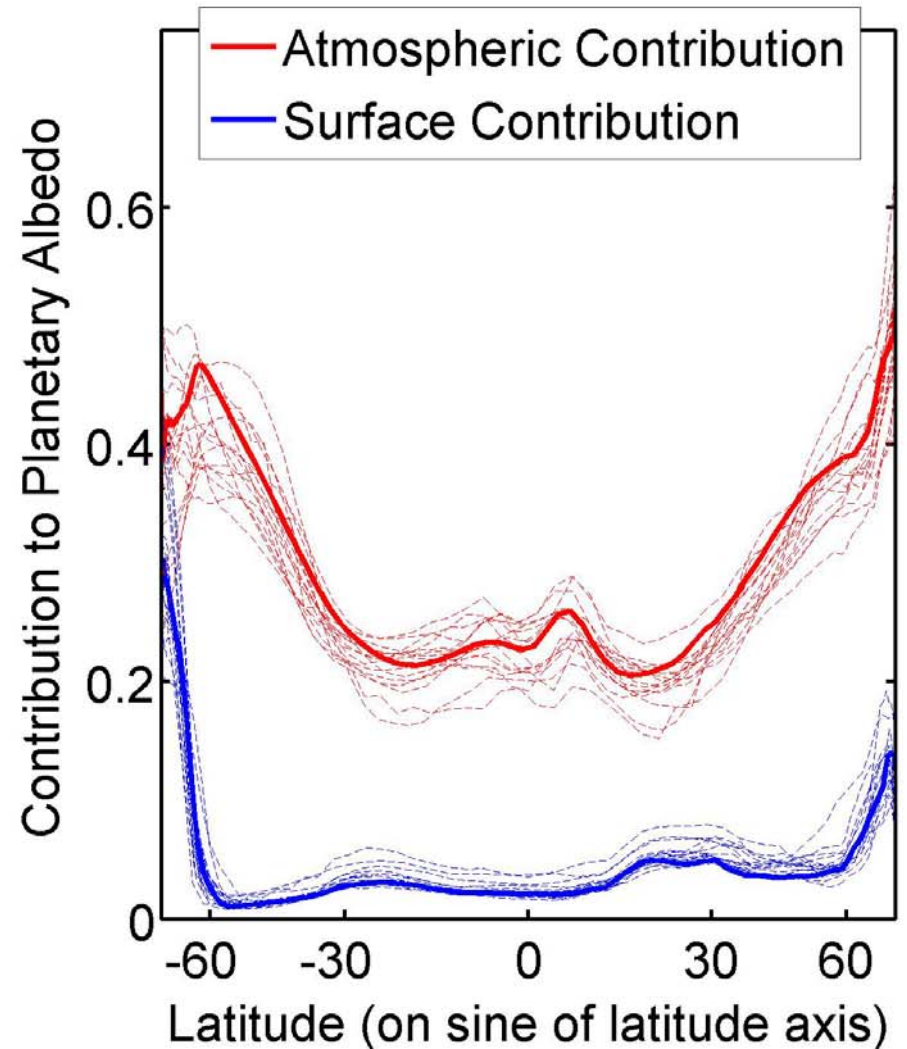


# Planetary Albedo Partitioning

Zonal Average  
Planetary Albedo




Zonal Average  
Planetary Albedo Partitioning



# Atmospheric and Surface reflection contribution to ASR\*

x

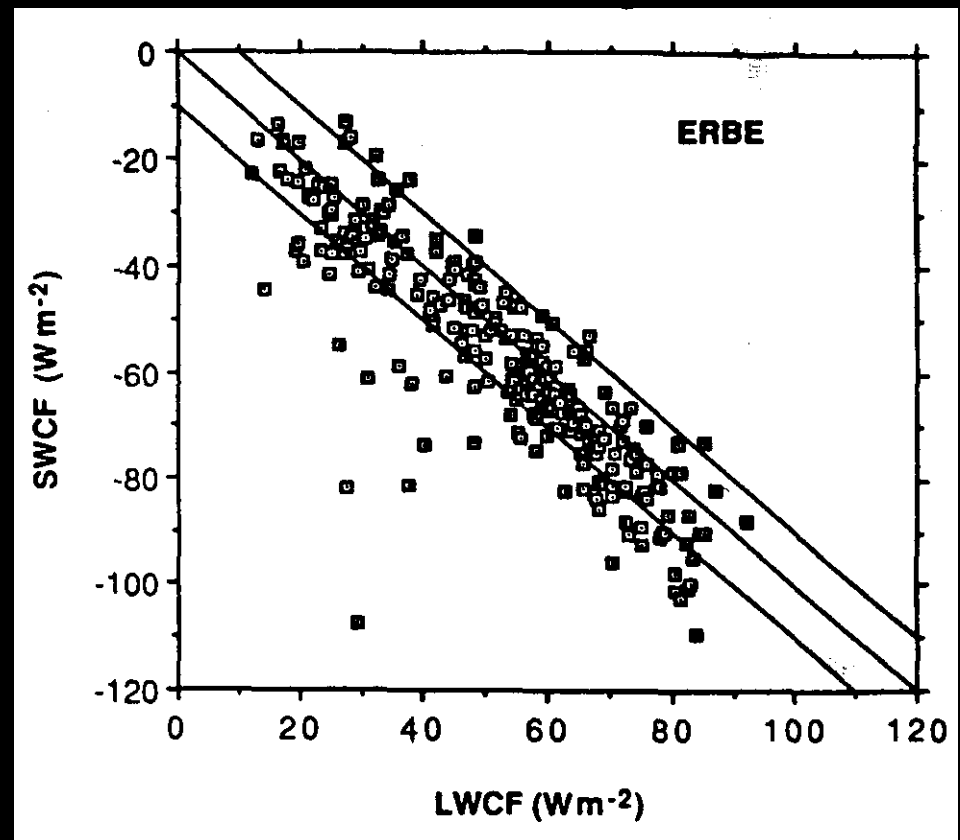
# Summary thus far

- 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  
 $LWCF = OLR_{CLEAR} - OLR$



(Kiehl, 1994)

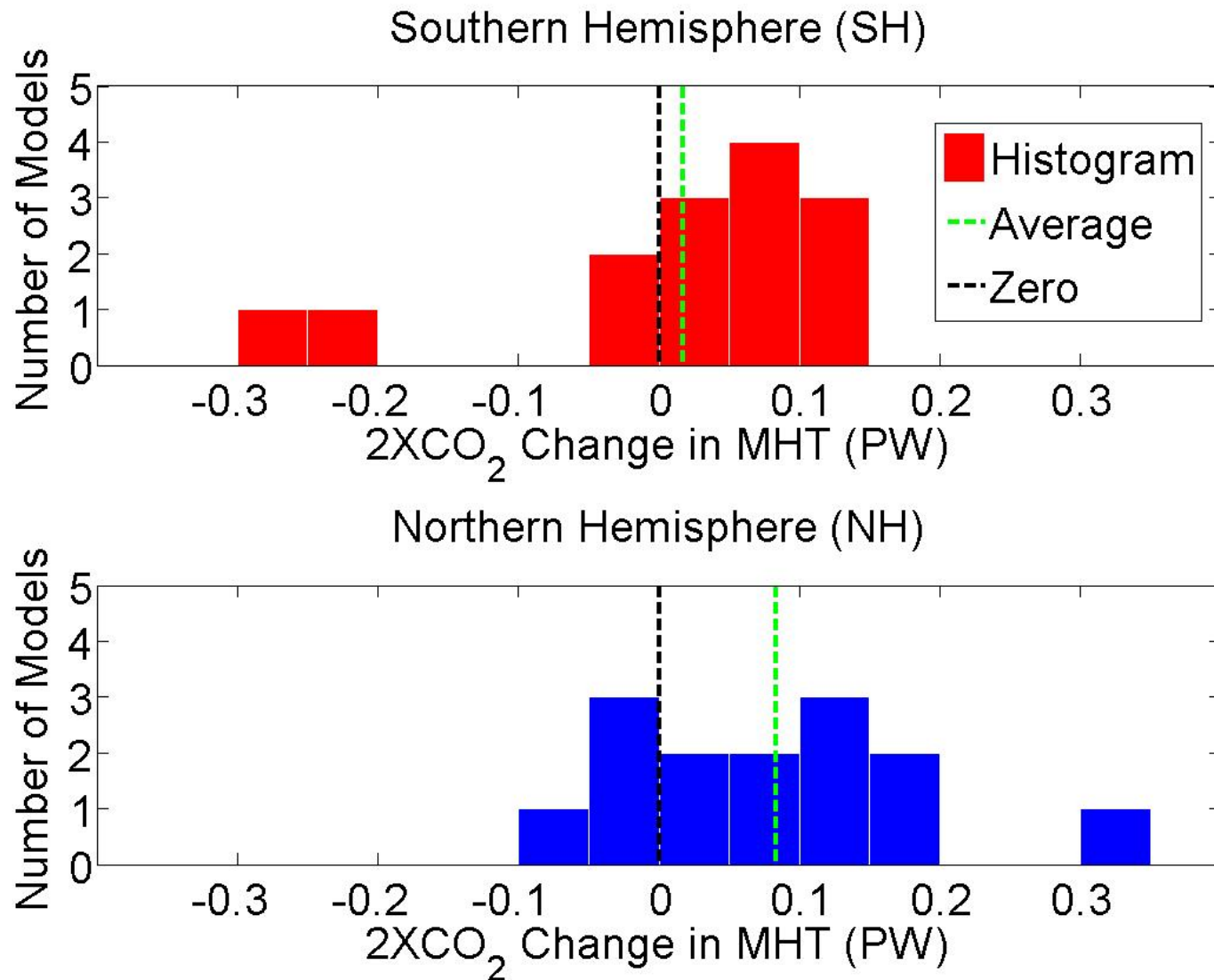
# Inter-model differences in OLR



# Meridional structure of a “typical” ASR\* anomaly

x

# Change in MHT due to CO<sub>2</sub> doubling



# Change in ASR\* due to CO<sub>2</sub> doubling

Contours =  
Change in  
ASR\*

# Change in MHT due to CO<sub>2</sub> 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\*?

Inflow

Outflow 1 –  
narrow pipe

Water Tank  
Tropics

Outflow 2 -  
wide pipe

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

ASR\*

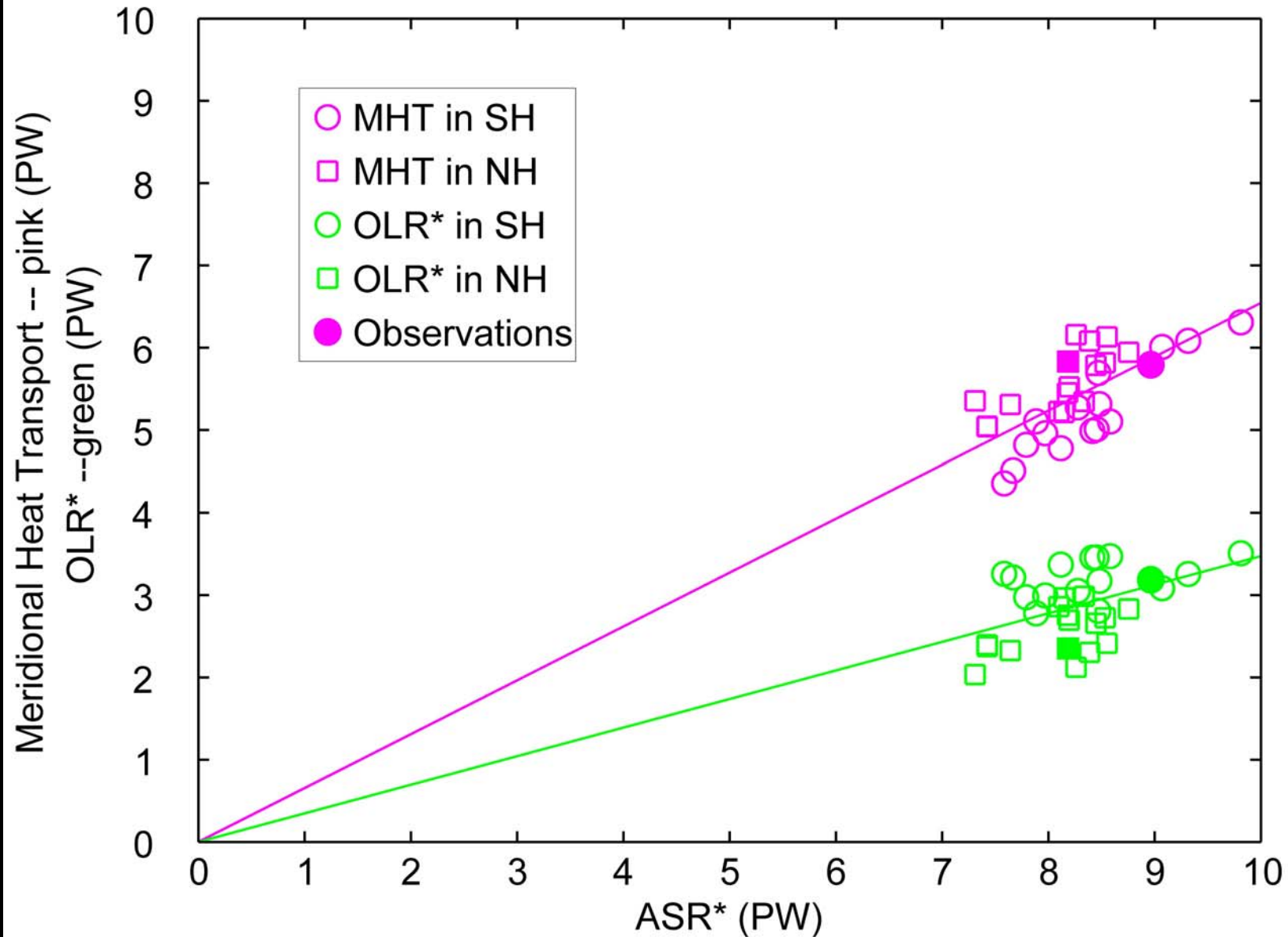
OLR\*

Tropics

MHT

To extratropics

# ASR\* and heat export efficiency



# Conclusions

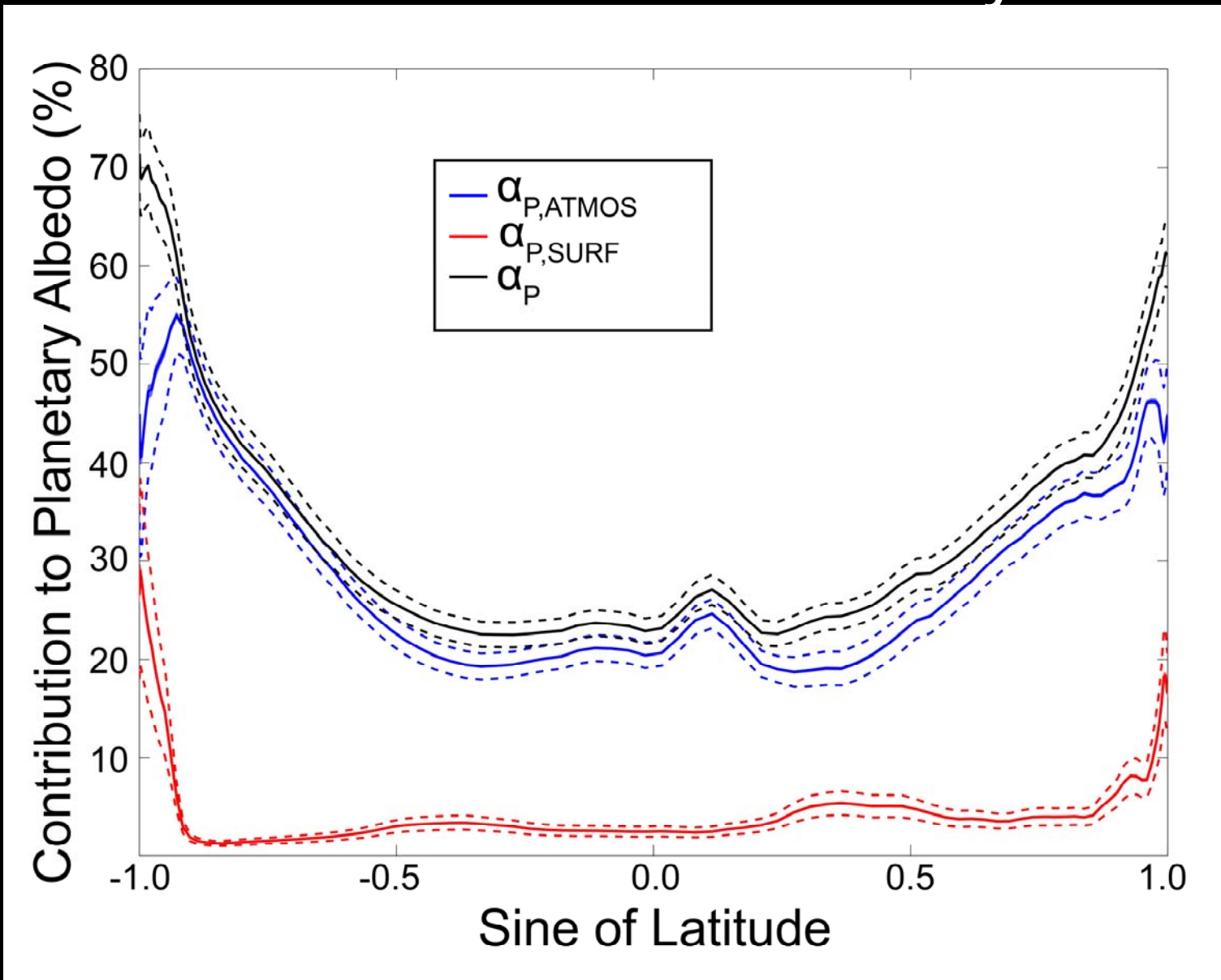
- Heat fluxes in the climate system are a consequence of (A) the spatial (temporal) distribution of energy absorbed from the sun and (B) the efficiency of energy export processes
- ASR is strongly controlled by clouds (and Earth sun geometry) and weakly controlled by surface albedo
- Dynamic energy exports 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

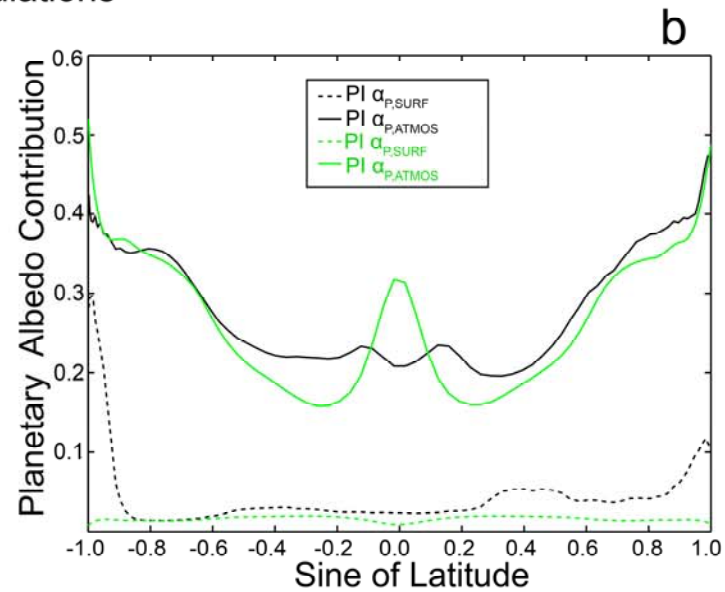
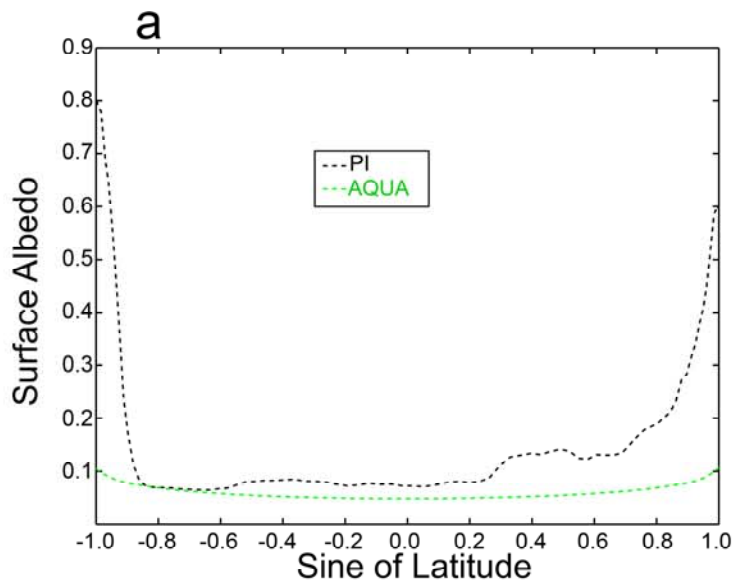


# Errors in planetary albedo due to Observational uncertainty

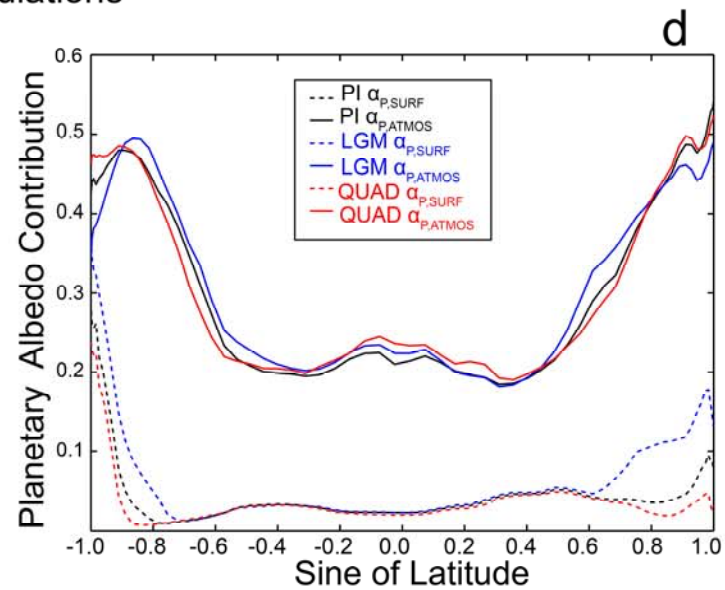
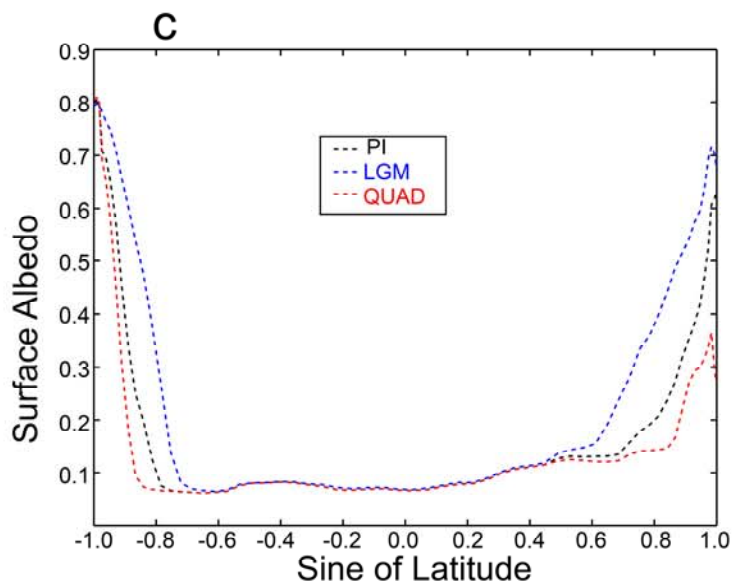


# Altered climates states

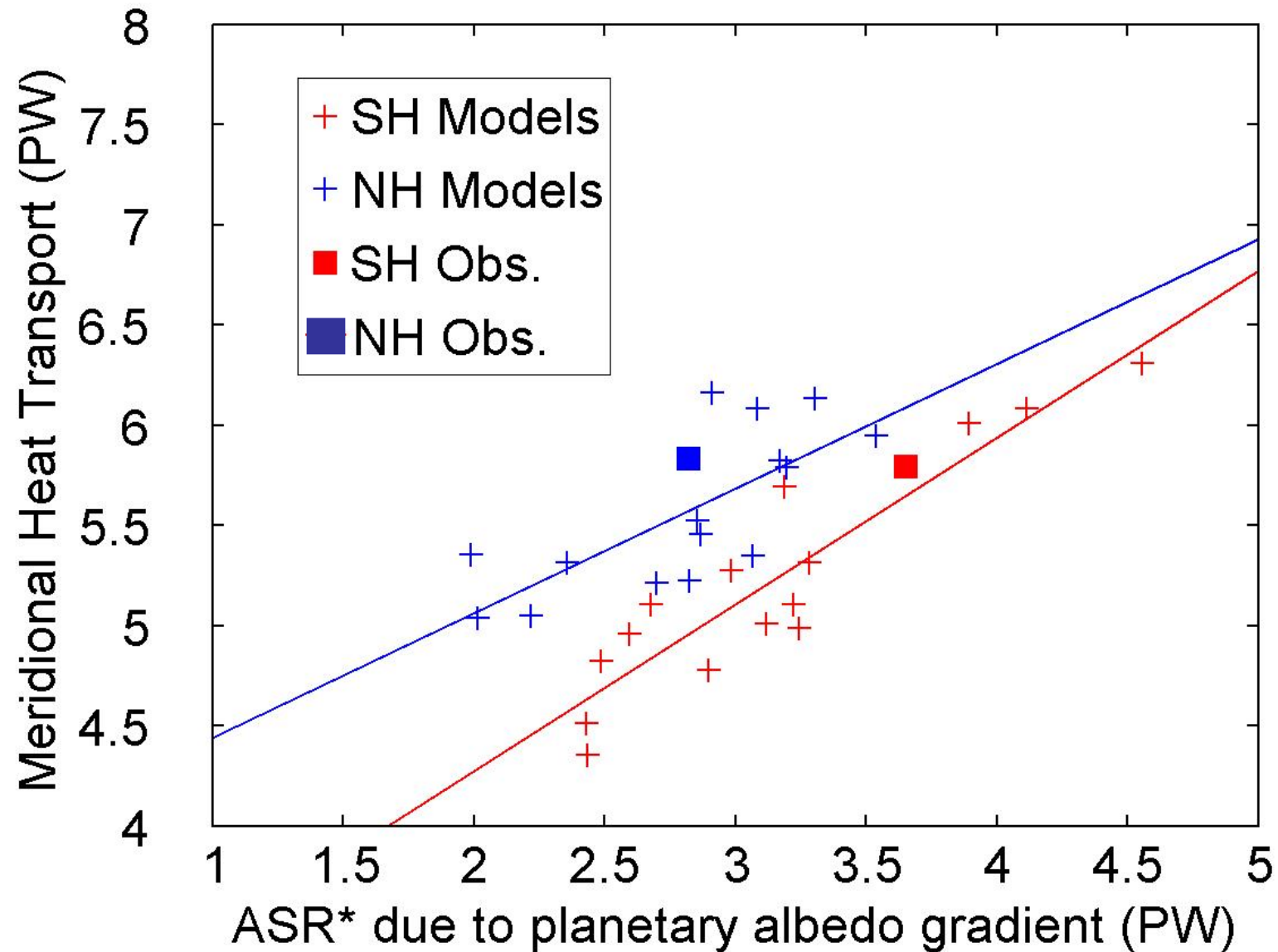
GFDL Simulations



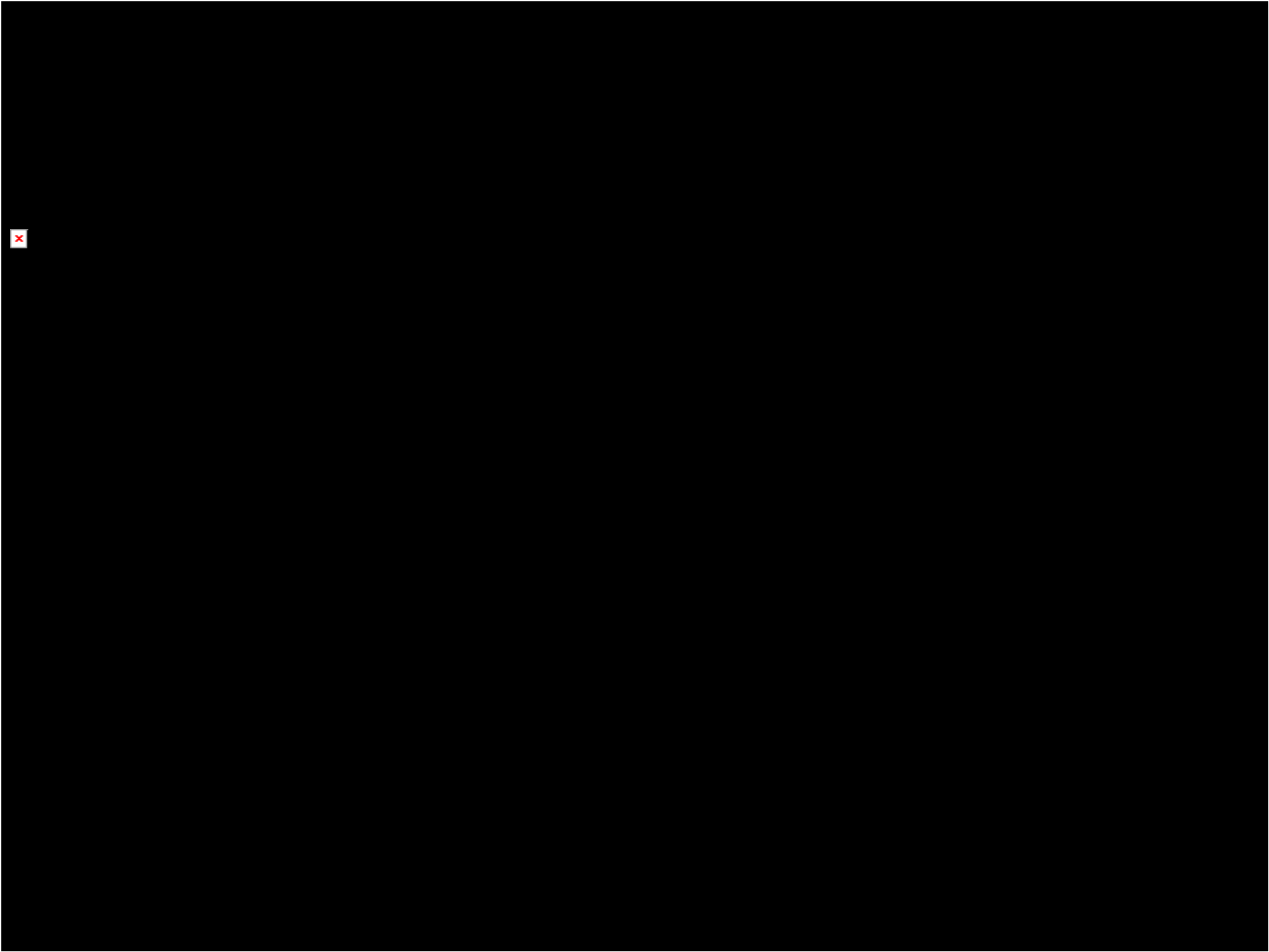
NCAR Simulations



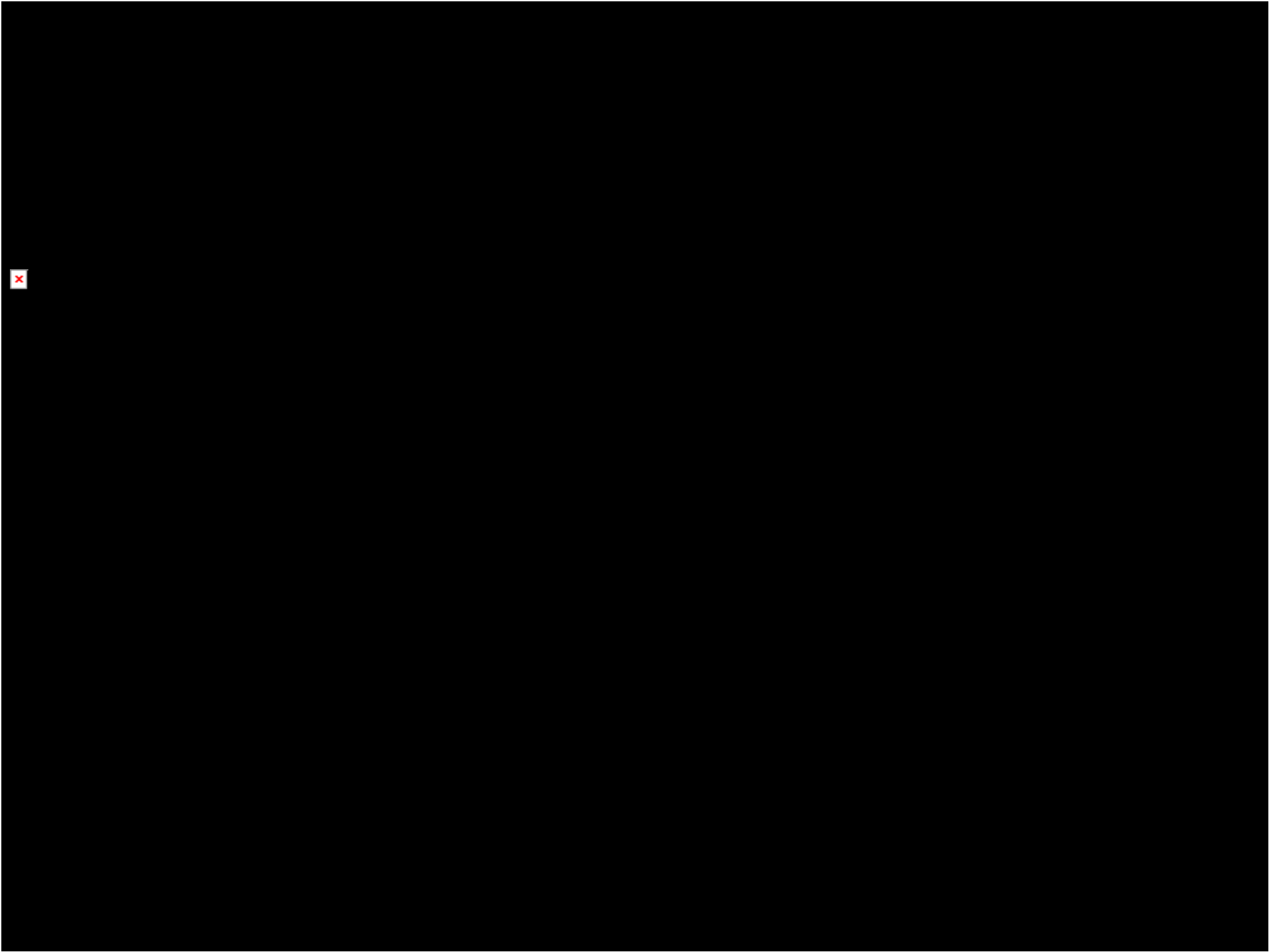
# Heat transport and planetary albedo



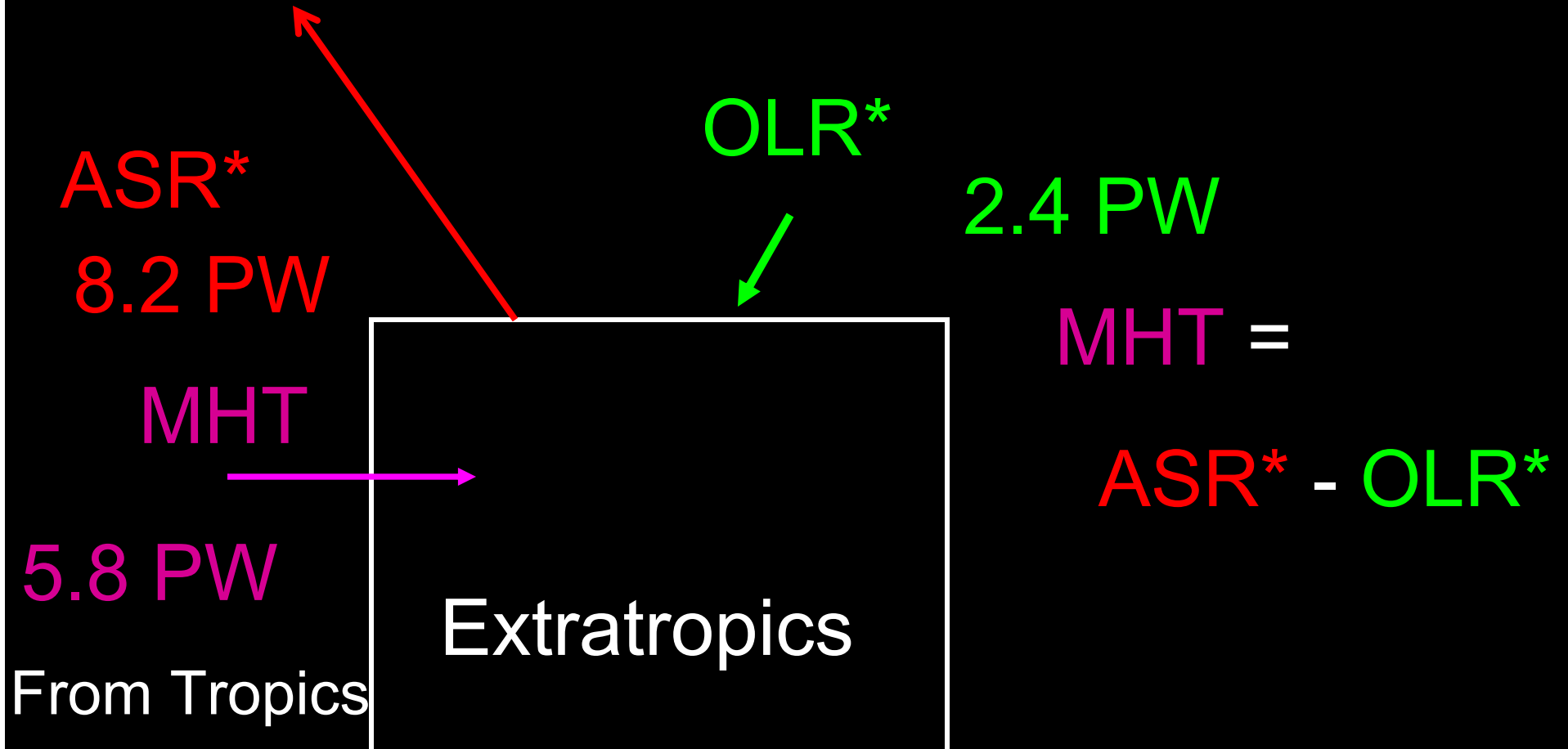




x



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



All arrows are relative to the global average