What (on land) does the atmosphere care (most) about?

Isolating surface property effects on atmospheric responses using an idealized land model.

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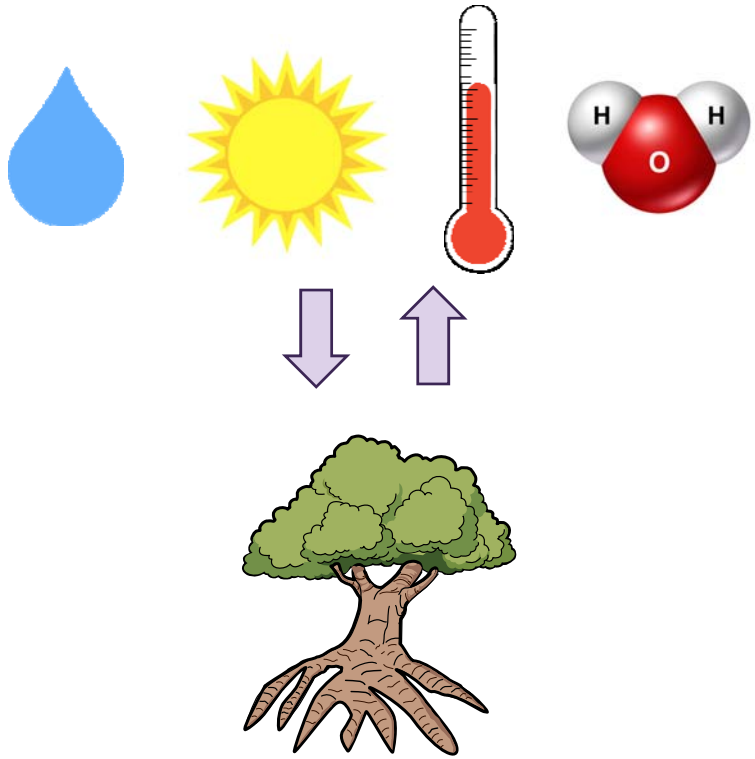
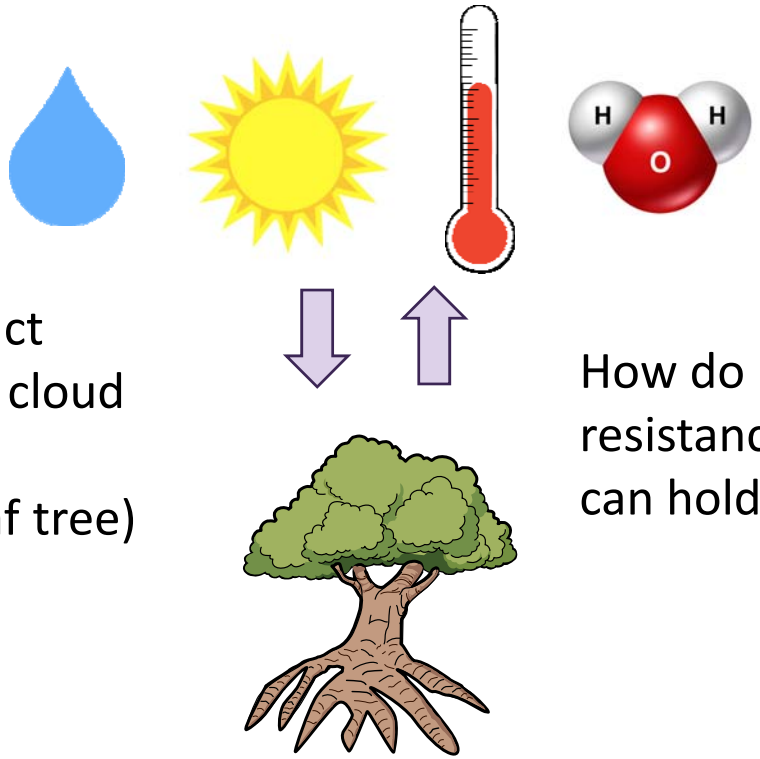
Collaborators: Abigail Swann (UW), Gordon Bonan (NCAR)

Motivation: identify how changes on land drive responses from the atmosphere



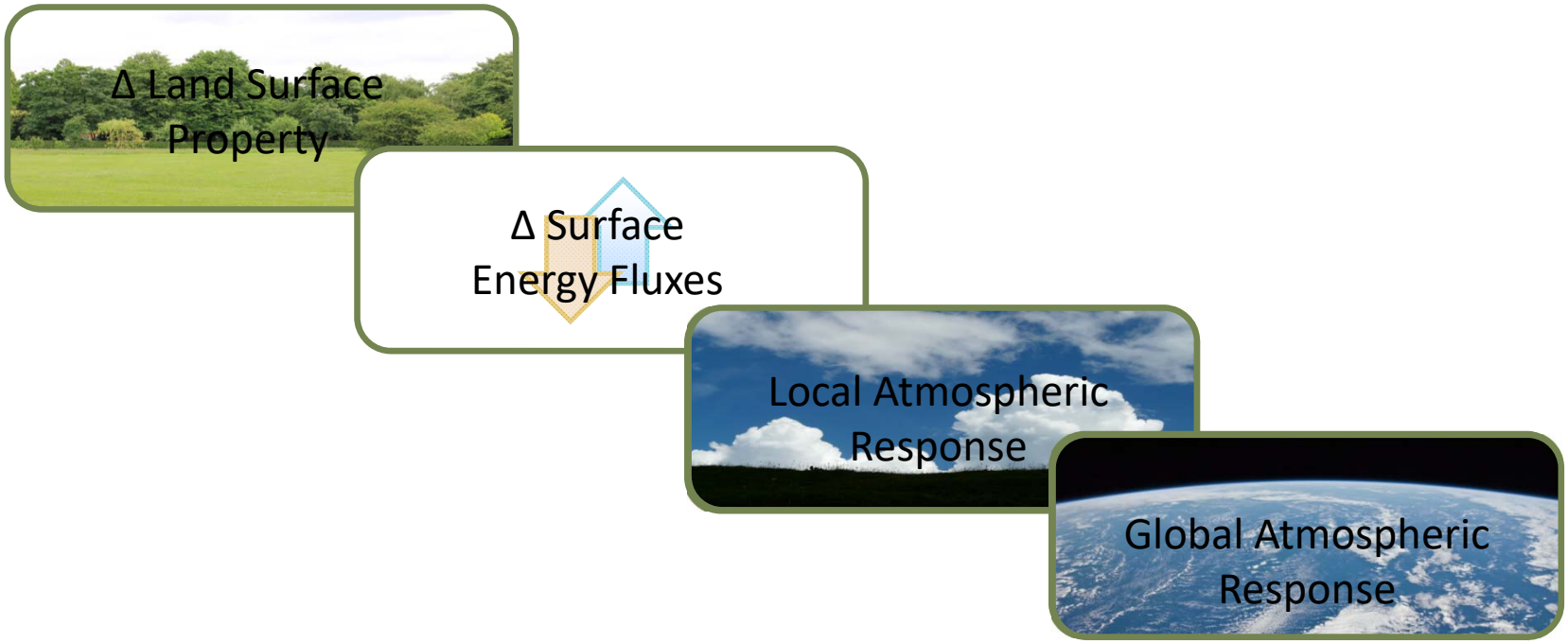
In particular, separate the impact of individual surface properties on the total atmospheric response



How does *albedo* alone impact temperature, or humidity, or cloud cover? (e.g. changing from a broadleaf tree to a needleleaf tree)

How do roughness, or evaporative resistance, or how much water the soil can hold impact the atmosphere?

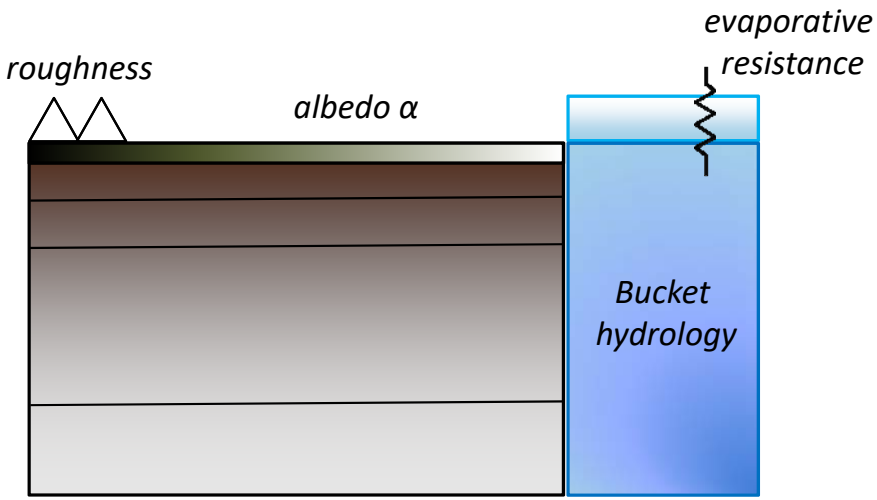
Changes in the land surface drive responses in the atmosphere



Which surface properties are dominating the atmospheric response to land cover change?

Independently modify each surface property and test!

Simple Land Model (coupled into CESM)



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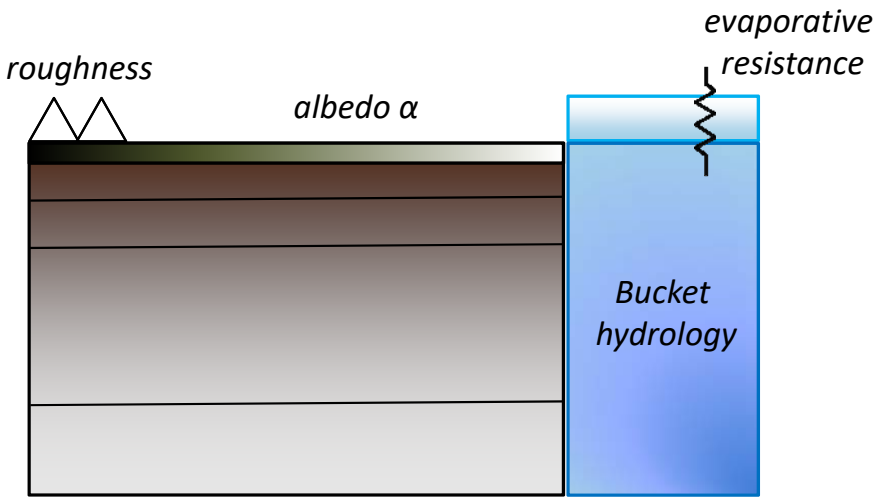

Prescribed surface properties, e.g.

- Albedo
- Roughness (vegetation height) [m]
- Evaporative resistance [s/m]
- Water bucket capacity [kg/m^2]
- Snow masking depth [kg/m^2]
- Soil heat capacity

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Two big questions:

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   e.g. does a change in roughness over North America have the same effect as a change in roughness over the Sahara Desert?

2. How large a change in that land property is required to drive a fixed change in the atmosphere at any given location?

   e.g. how big a Δ albedo is needed to warm the local atmosphere by 1K, and does the Δ albedo required vary spatially?

Experiment: individually perturb 3 separate surface properties, and evaluate the atmospheric response

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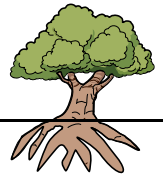
Property	*Low value*	*Medium value*	*High value*
Albedo	0.1 (Forest) 	0.2 (Grass) 	0.3 (Desert) 
Roughness	0.5 m (short grass / bare ground) 	1 m (shrubs) 	2 m (trees) 
Evaporative Resistance	30 s/m (well watered crops, daytime) 	100 s/m 	200 s/m (nigthttime, mostly close stomata) 

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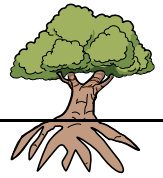
Roughness	0.5 m (short grass / bare ground) 	1 m (shrubs) 	2 m (trees) 
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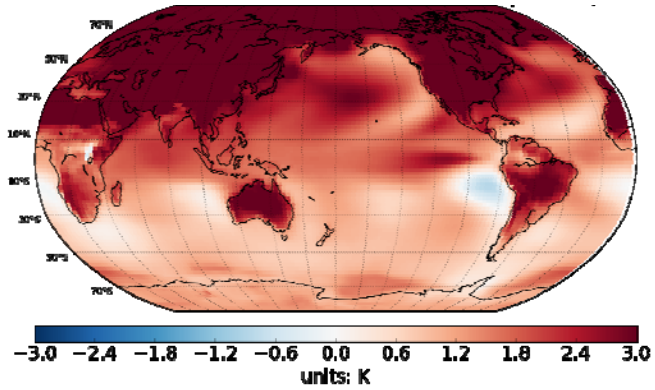
Only change **one** variable at a time; modify all non-glaciated land points; run coupled to CAM & a slab ocean for 50 years

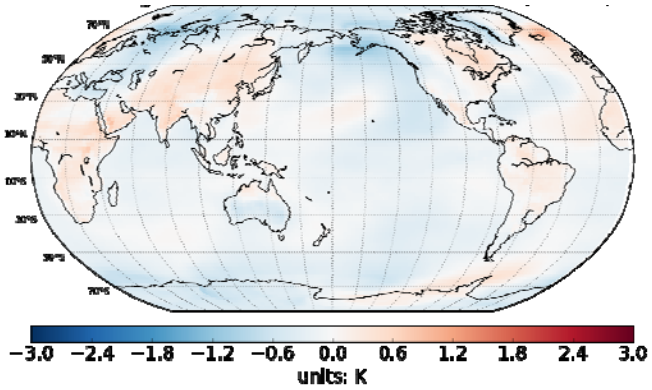
Example atmospheric response: 2m air temperature

Δ 2m Air Temperature for:

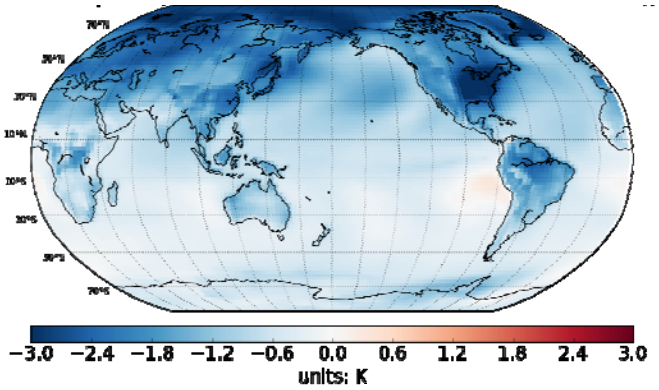
Δ Albedo (low – high)



Δ Roughness (low – high)



Δ Evaporative resistance (low – high)



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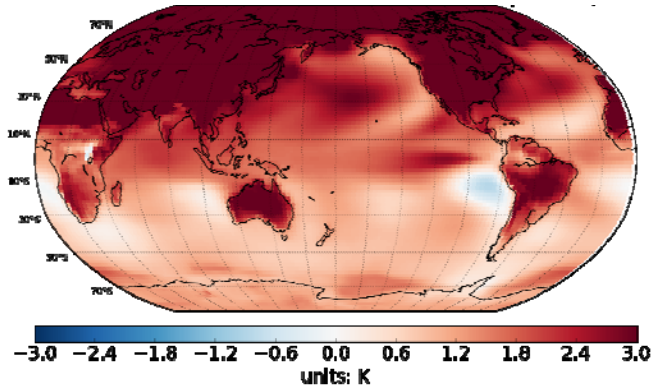

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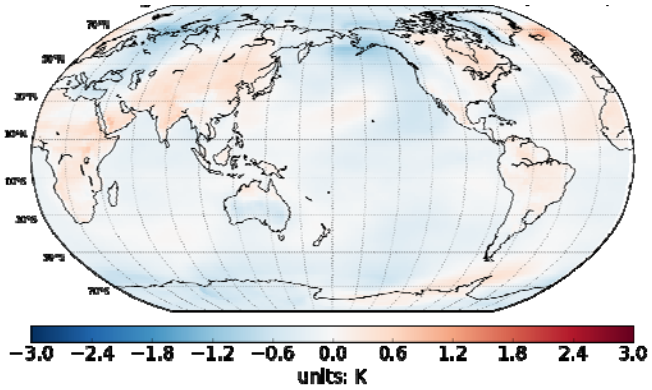

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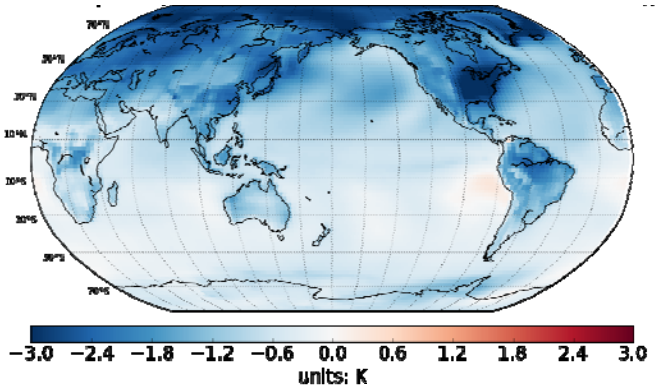
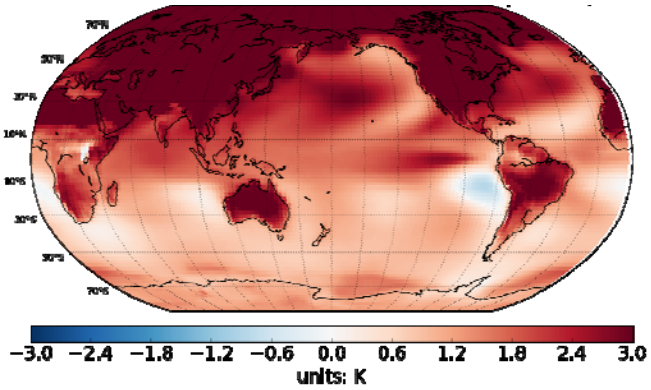


For each property, actually have 3 simulations (low, medium, & high value)

→ Calculate a *slope* of $\frac{\partial(\mathrm{atm})}{\partial(\mathrm{land})}$

2m Air Temperature

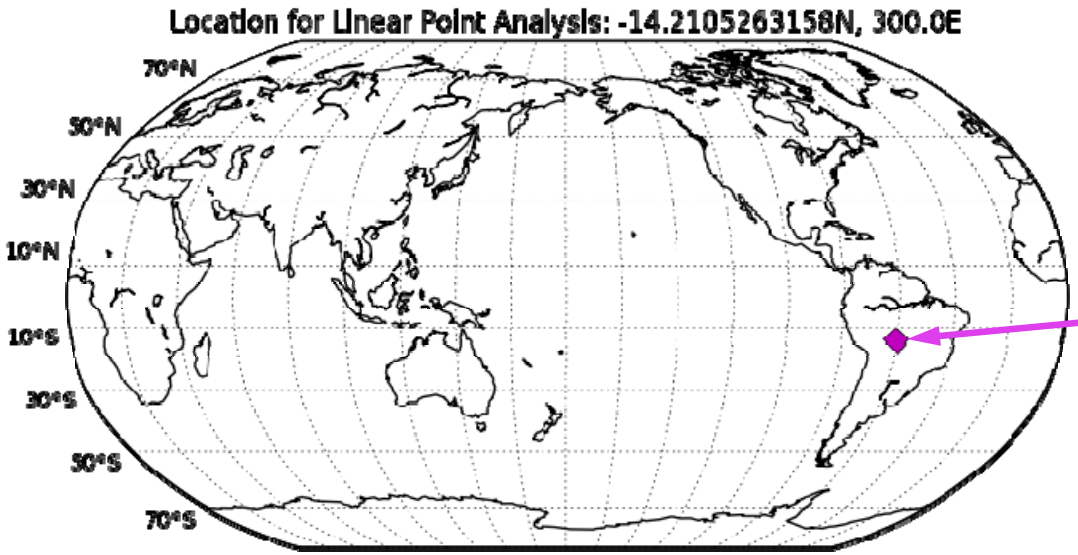
Δ Albedo (low – high)



e.g. $\frac{\partial(\mathrm{T}_{2m})}{\partial(\mathrm{albedo})}$

For each property, actually have 3 simulations (low, medium, & high value)

→ Calculate a *slope* of $\frac{\partial(\mathrm{atm})}{\partial(\mathrm{land})}$ for some land point:



Like right here.

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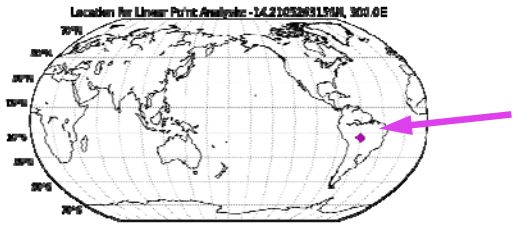

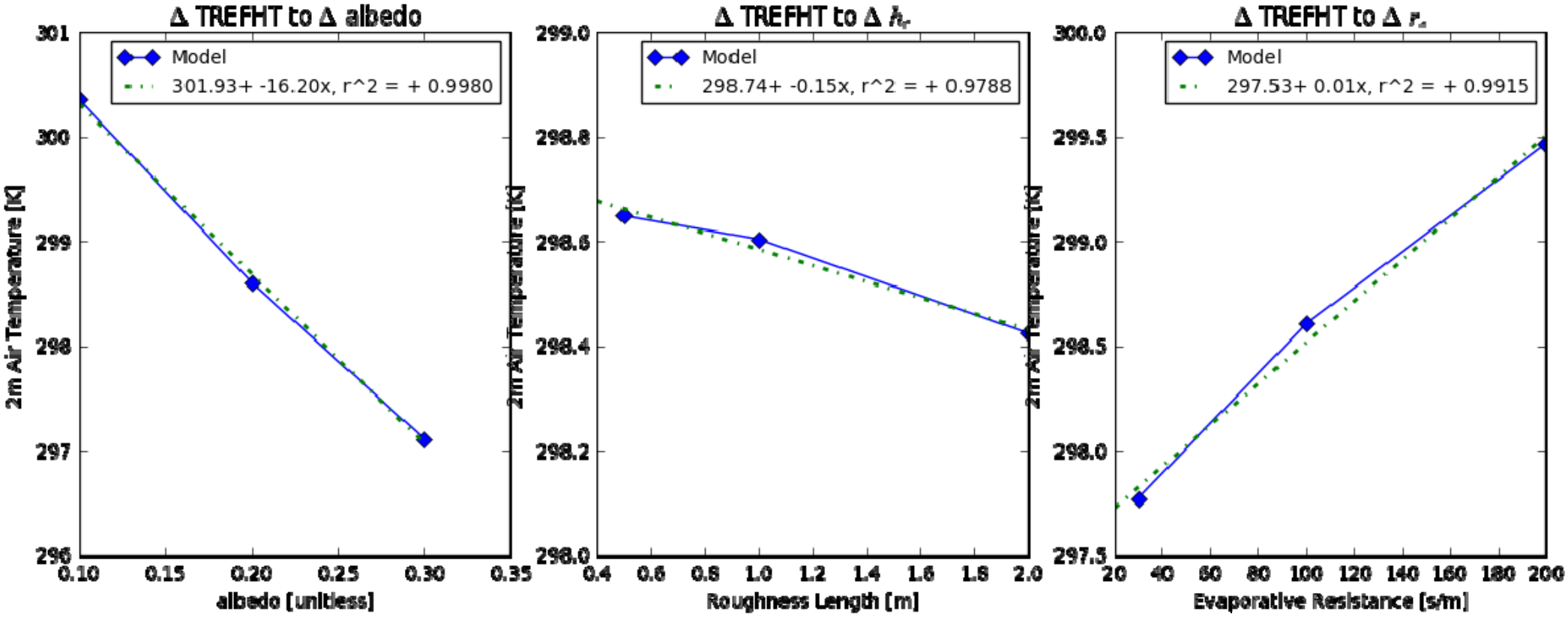

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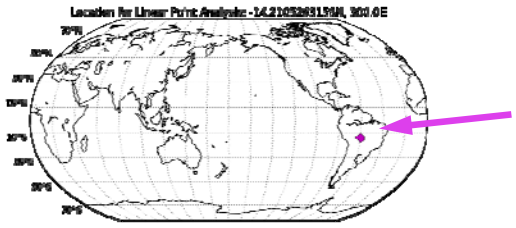
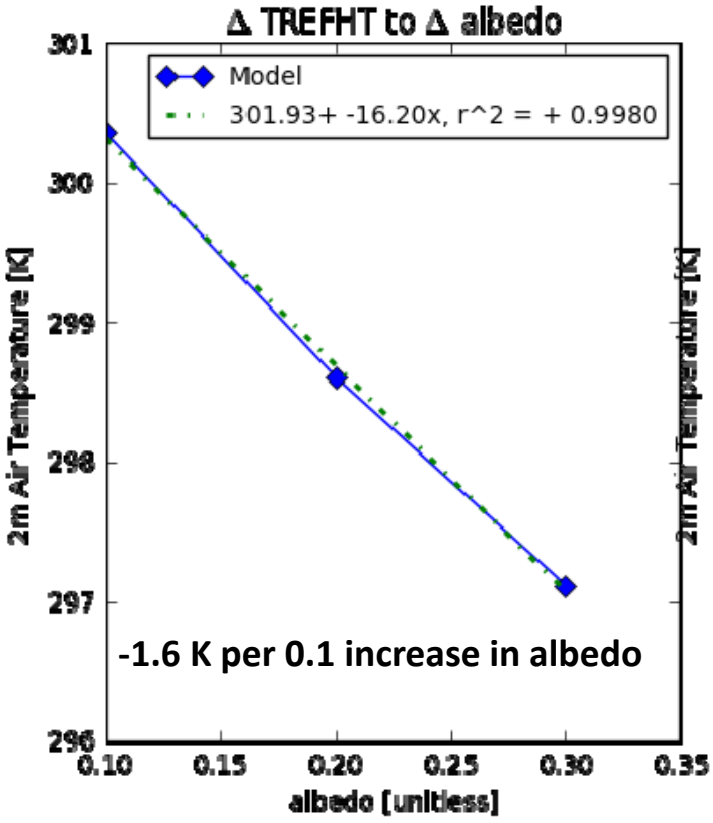
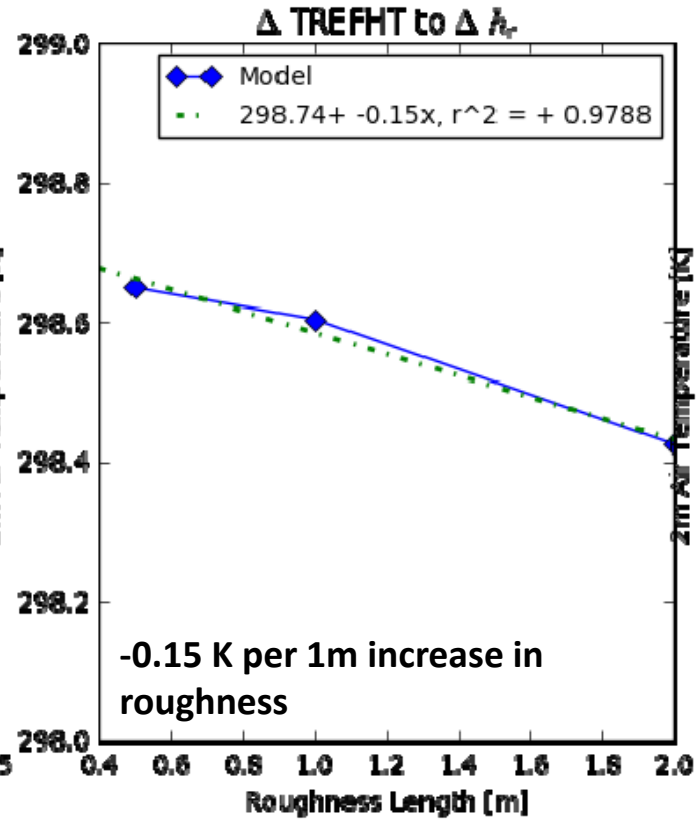
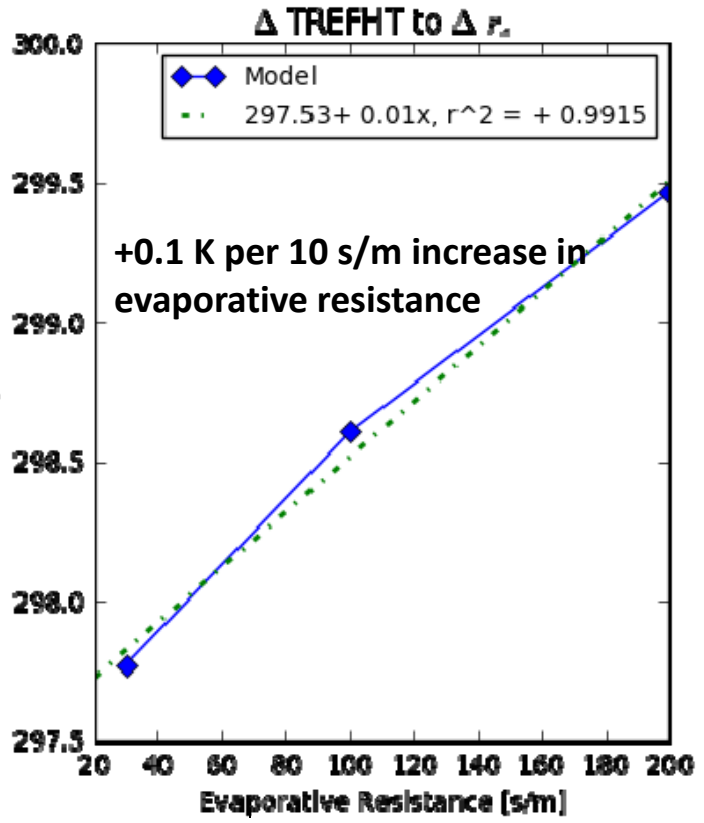
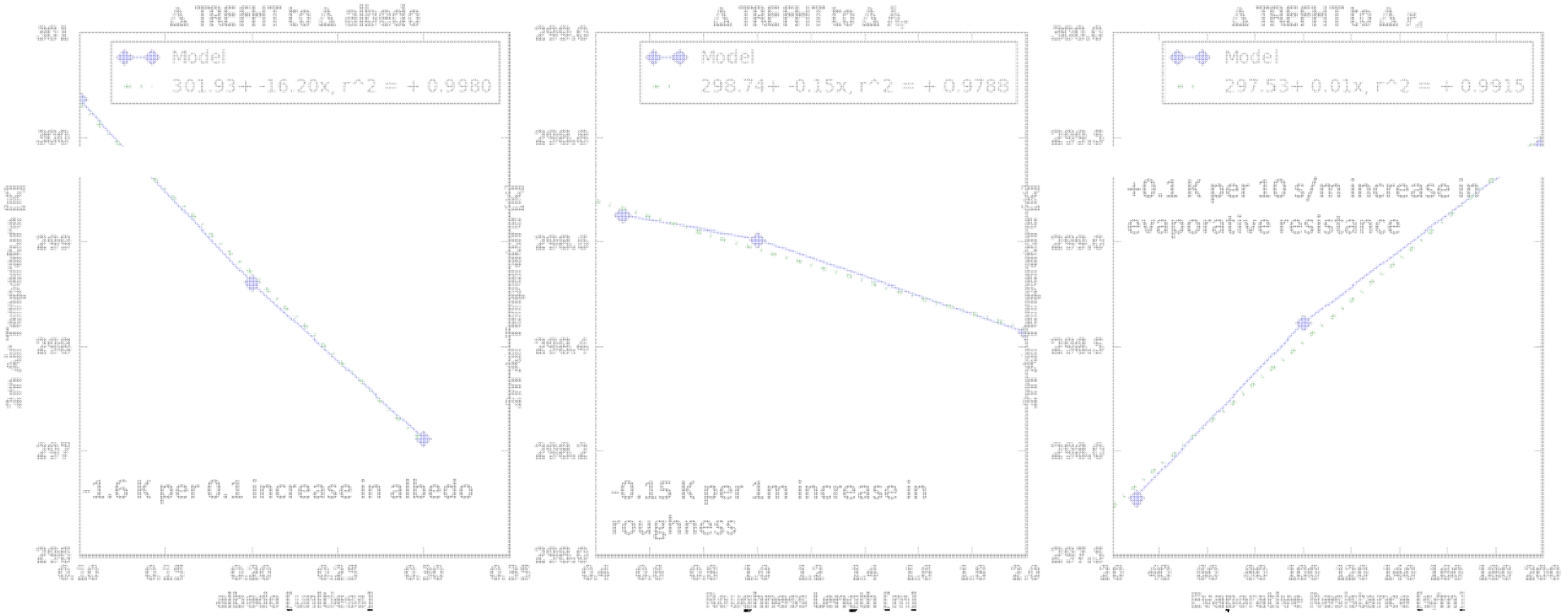








We have $\frac{\partial(\text{atm})}{\partial(\text{land})}$ … take its inverse to get $\frac{\partial(\text{land})}{\partial(\text{atm})}$:



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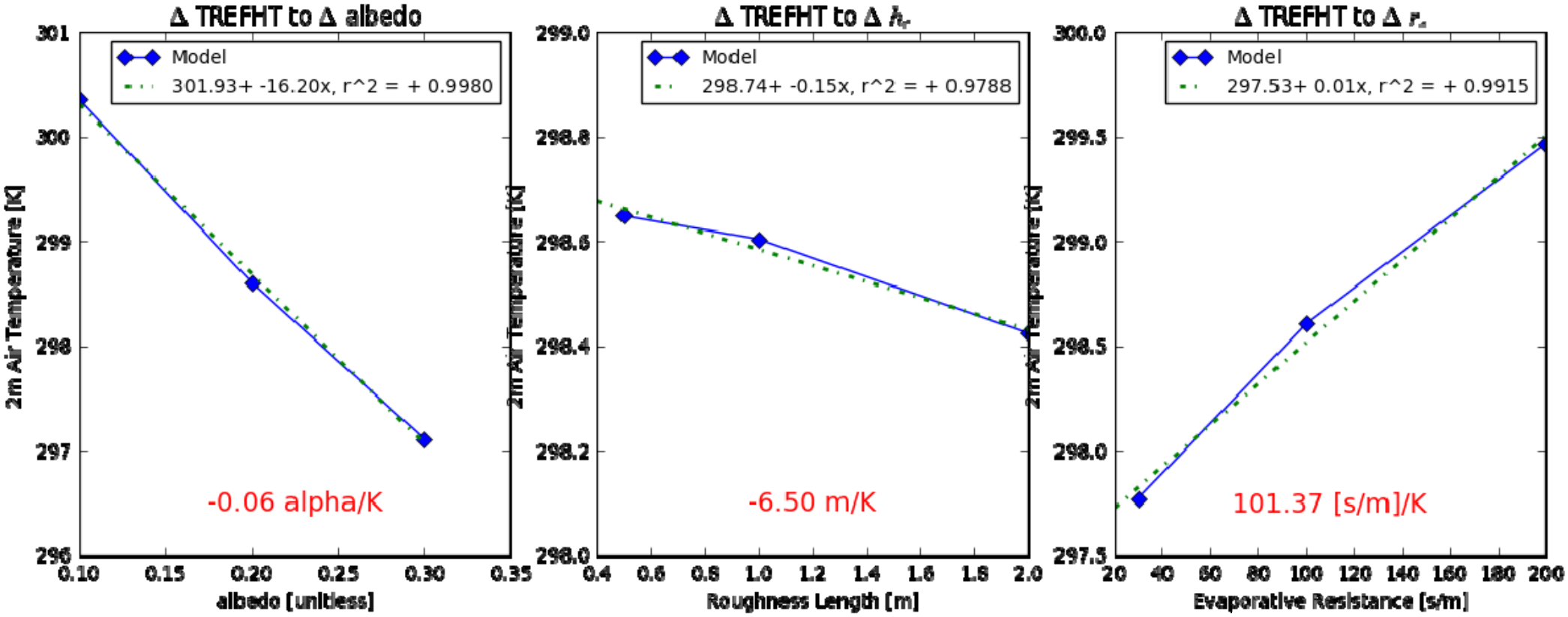
$$\left(\frac{\partial(\mathrm{atm})}{\partial(\mathrm{land})}\right)^{-1} = \frac{\partial(\mathrm{land})}{\partial(\mathrm{atm})} =$$

How large a change in land property is required to drive a fixed change in the atmosphere (e.g. a 1K increase in 2m air temperature)

We have $\frac{\partial(\text{atm})}{\partial(\text{land})}$ … take its inverse to get $\frac{\partial(\text{land})}{\partial(\text{atm})}$ (values in red)



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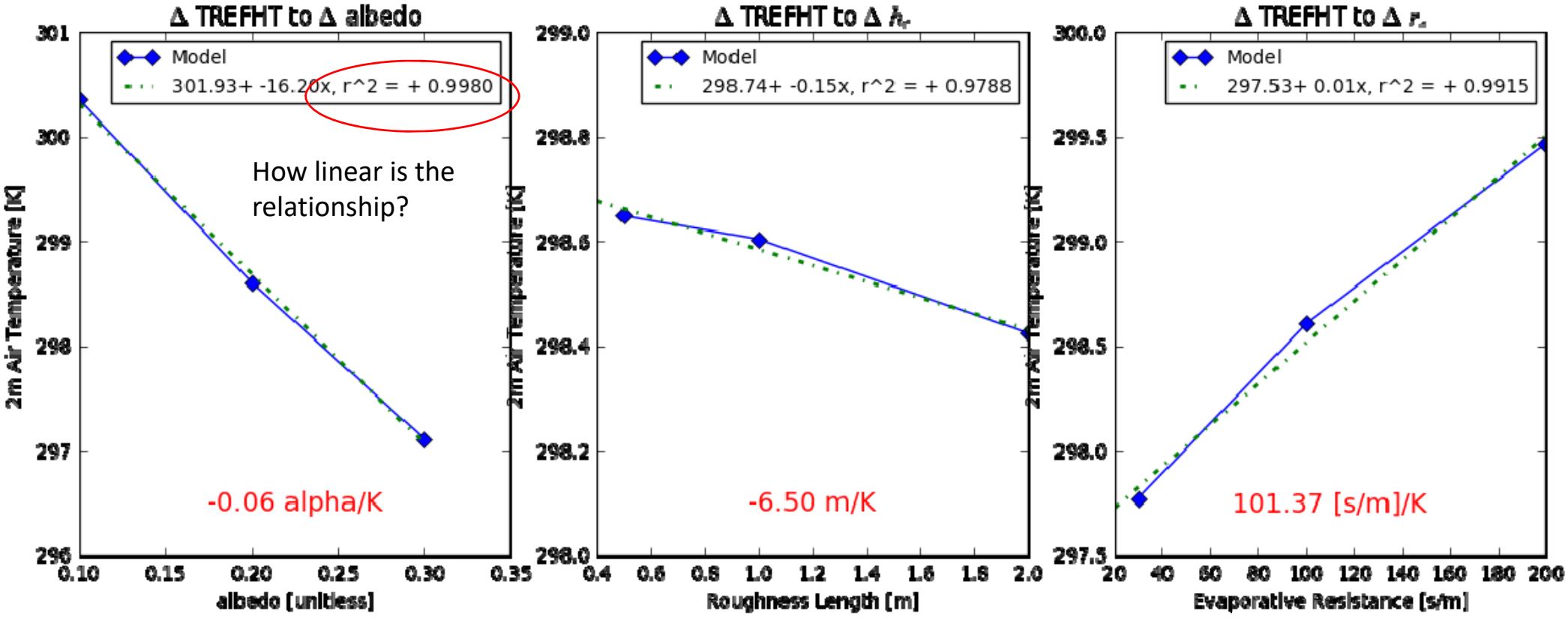
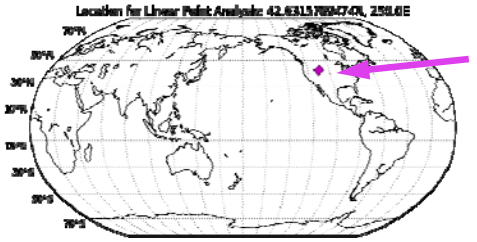
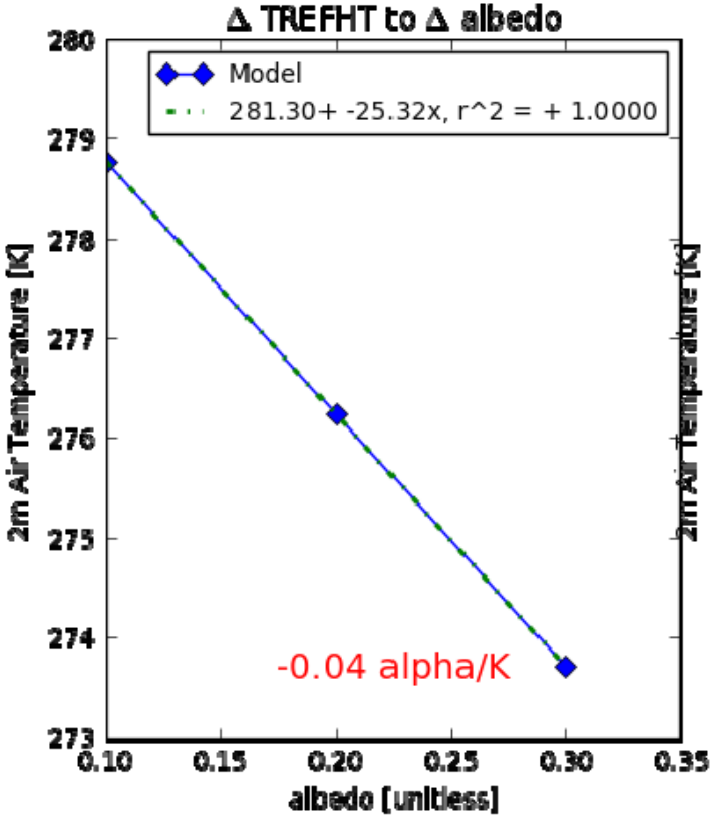
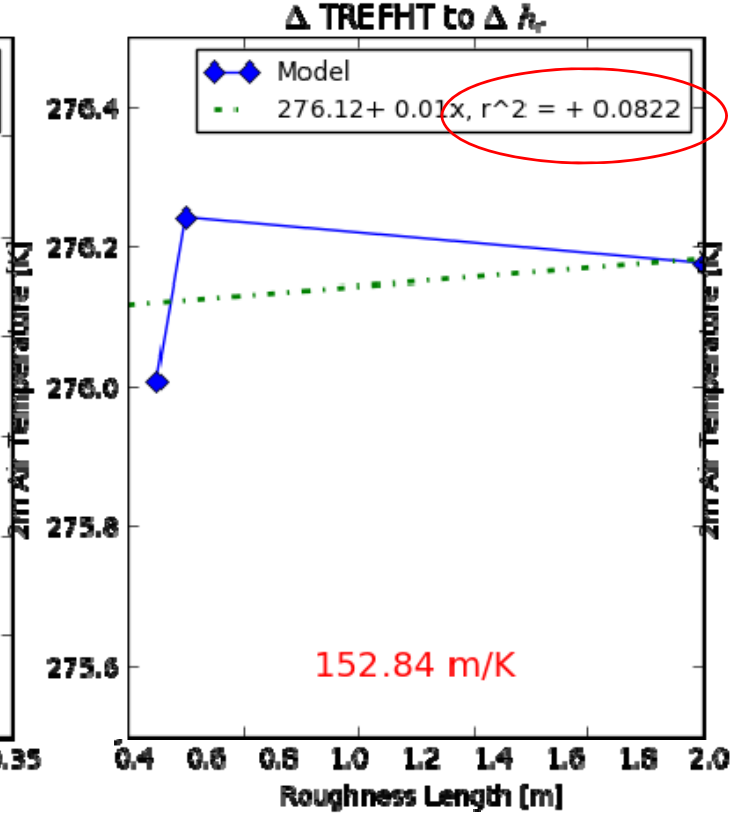
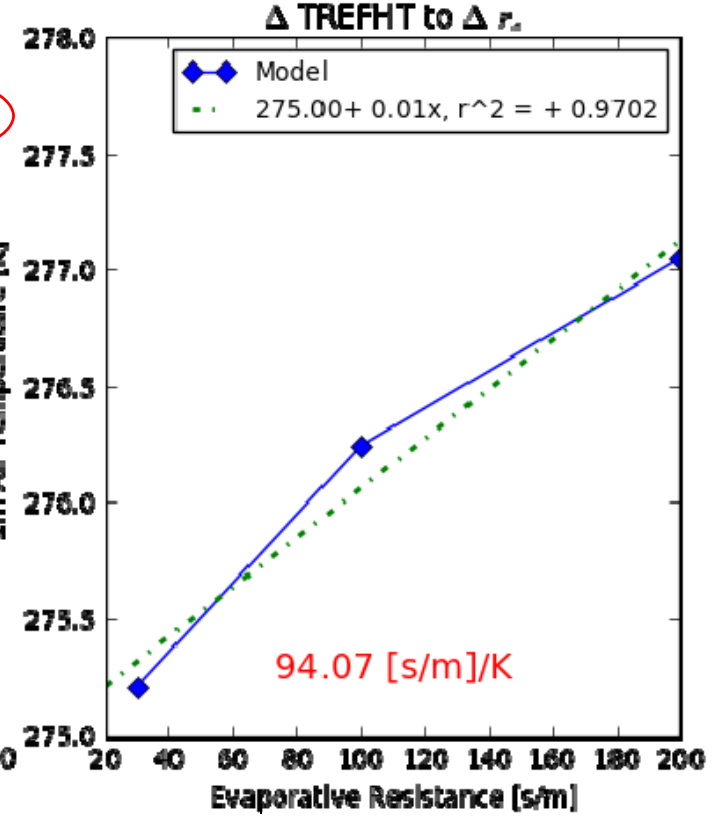


Albedo relationship is always pretty linear; roughness is less so, over many regions.



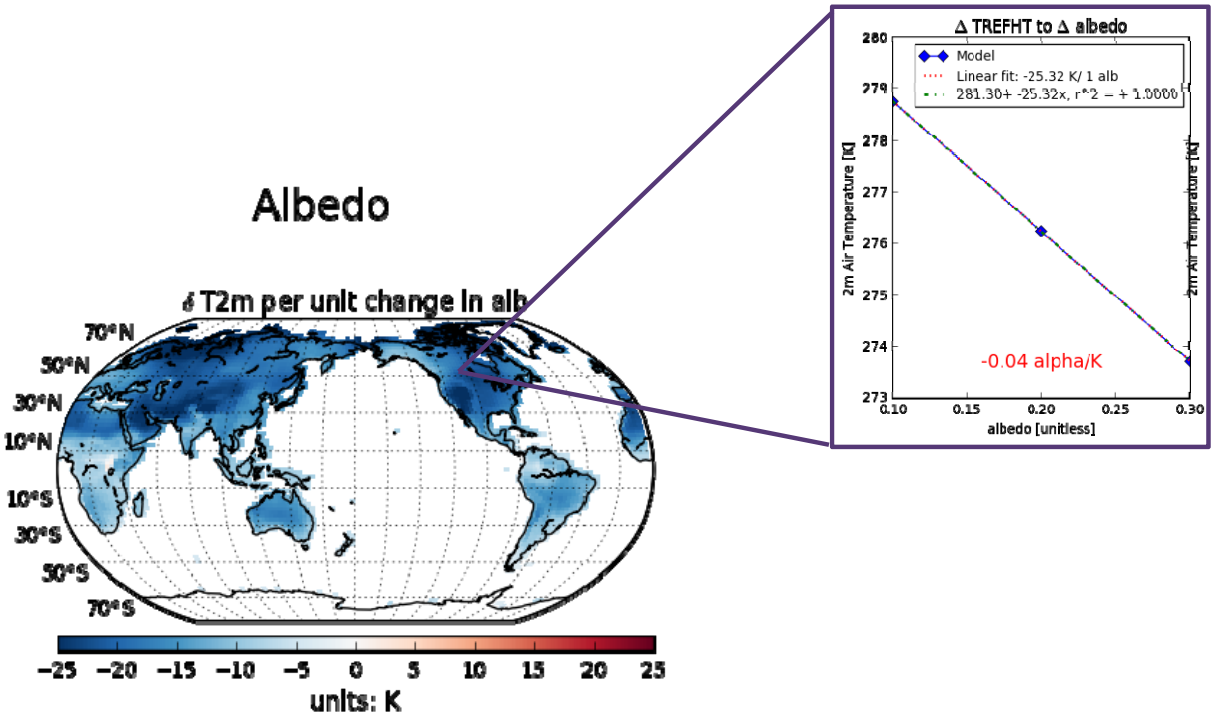






Sensitivity Analysis:

Do that sort of thing for every point on land, and plot the slope on a map…



$$\frac{\partial(\text{atm})}{\partial(\text{land})}$$

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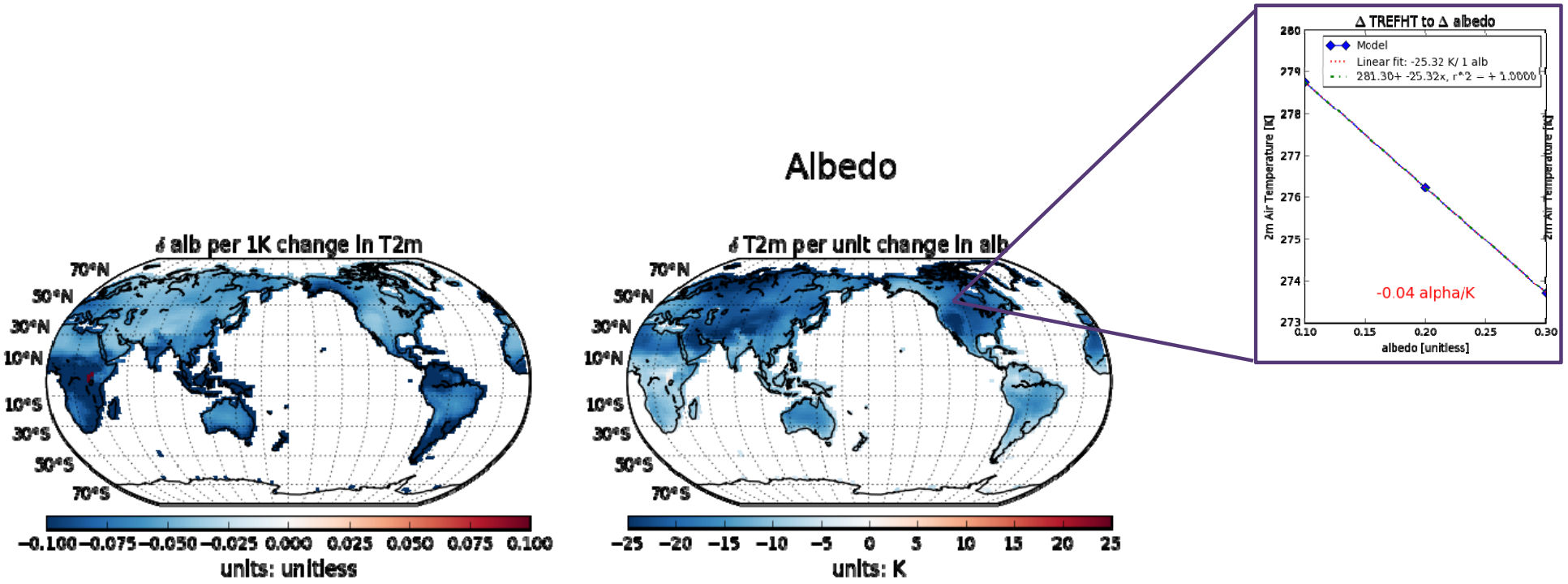

$$\frac{\partial(\text{land})}{\partial(\text{atm})} \qquad \frac{\partial(\text{atm})}{\partial(\text{land})}$$

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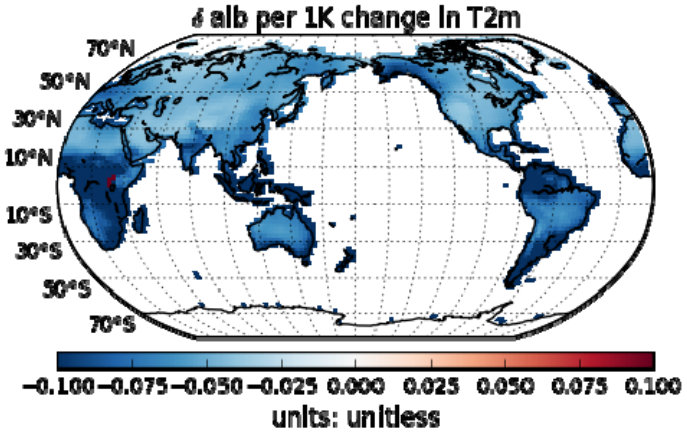
Albedo



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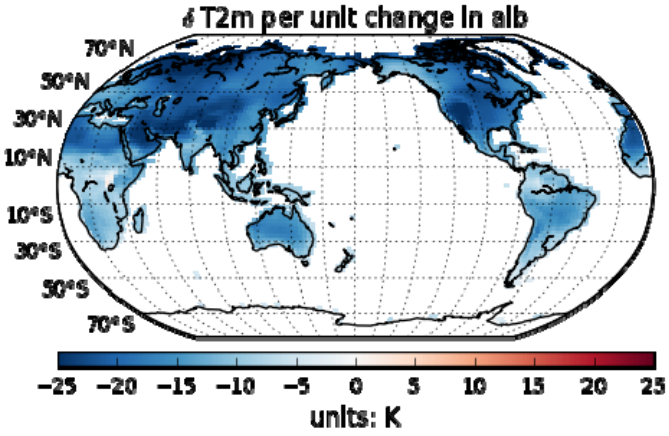

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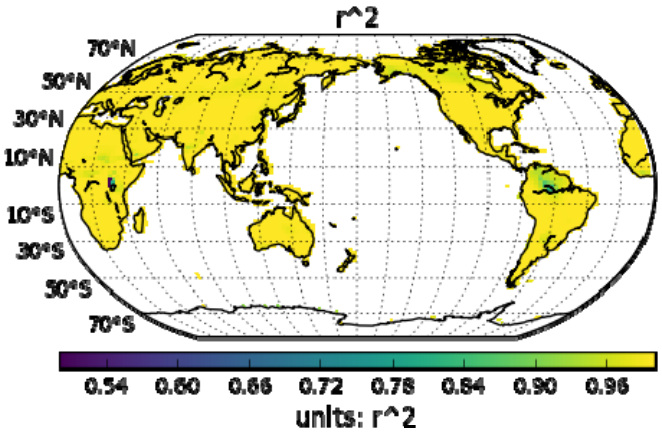
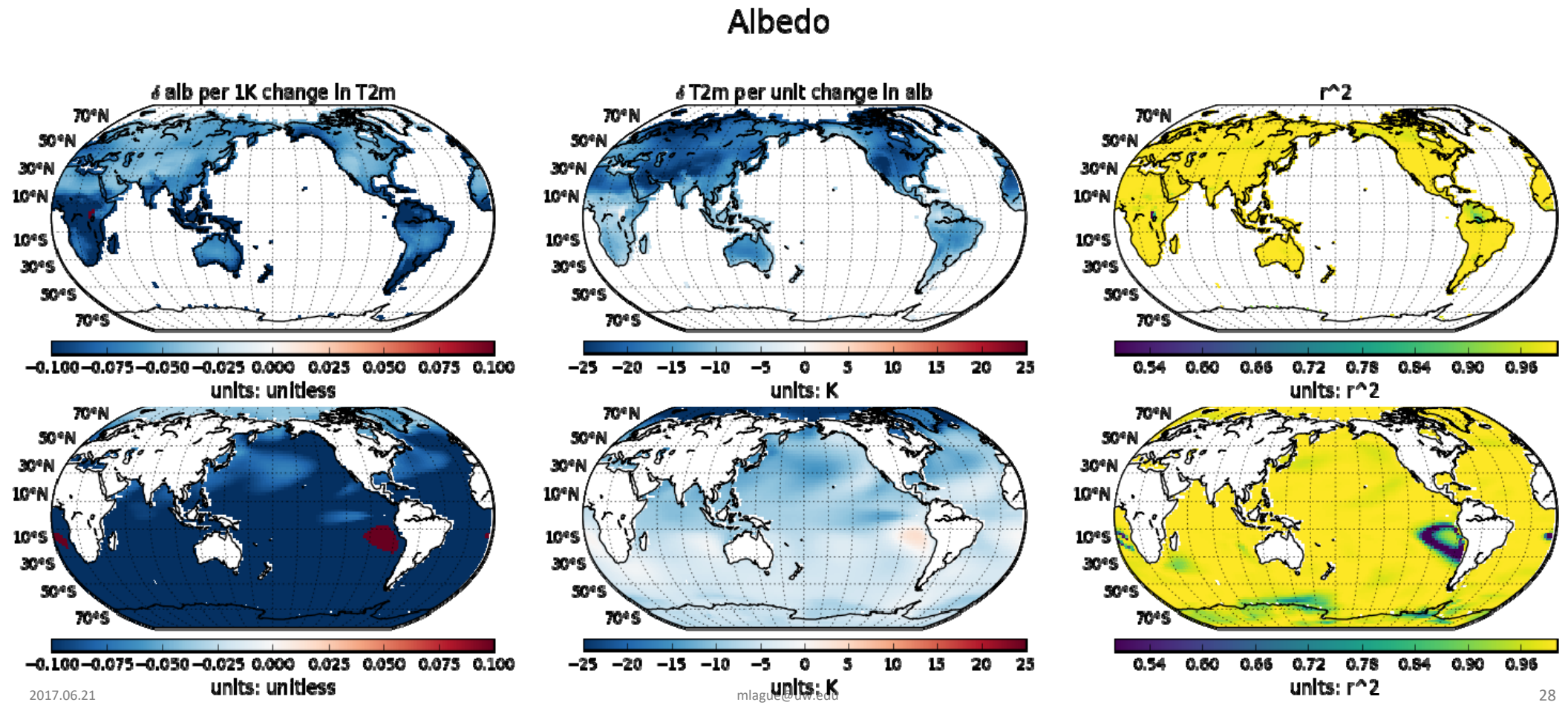


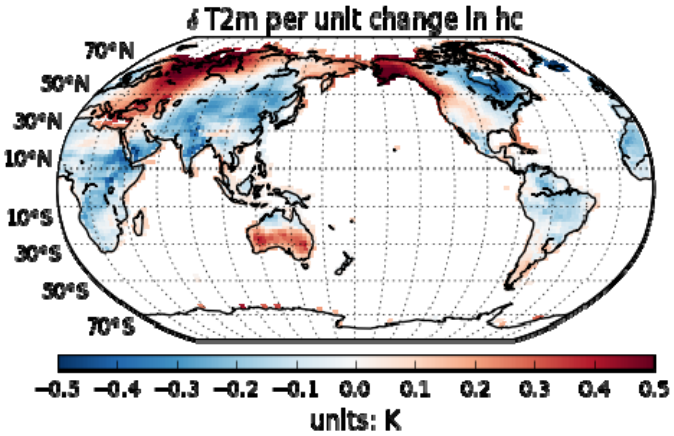
How linear the relationship is

Land response is a combination of local and remote effects (running coupled to CAM).
Ocean response is ALL remote (no land changes over the ocean)



Sensitivity Analysis

Sensitivity to Roughness



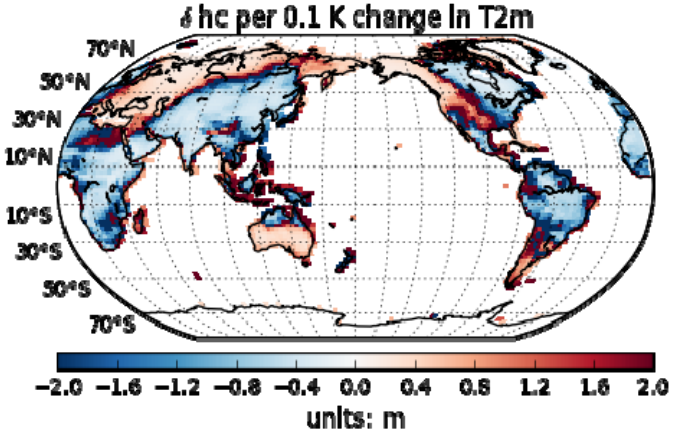
$$\frac{\partial(\mathrm{atm})}{\partial(\mathrm{land})}$$

Red regions: surface air warms with increased roughness

Blue regions: surface air cools with increased roughness

Sensitivity Analysis

Sensitivity to Roughness



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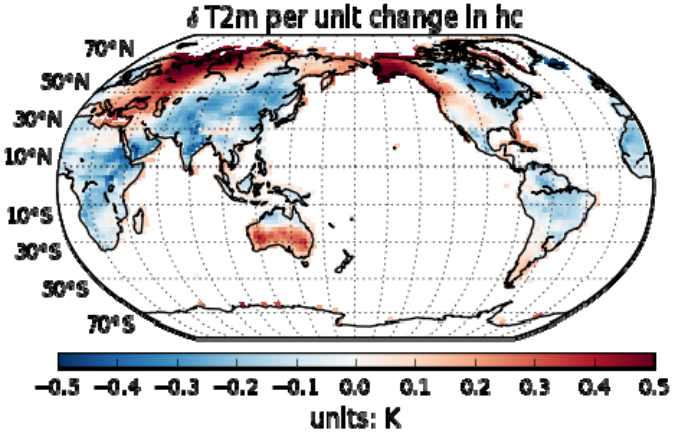


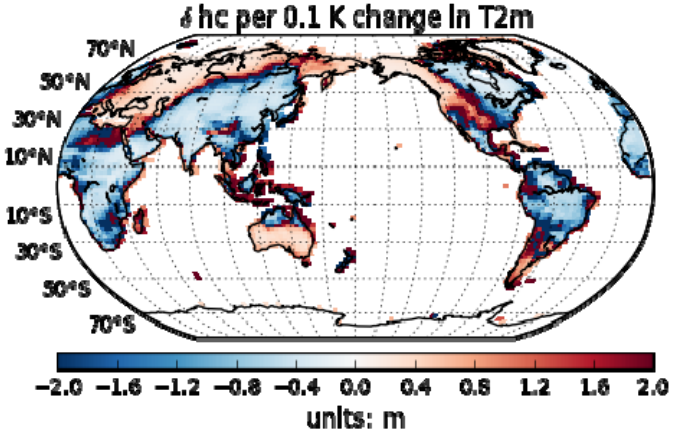
$$\frac{\partial(\text{atm})}{\partial(\text{land})}$$

Red regions: make surface rougher to warm

Blue regions: make surface smoother to warm

Sensitivity Analysis

Sensitivity to Roughness



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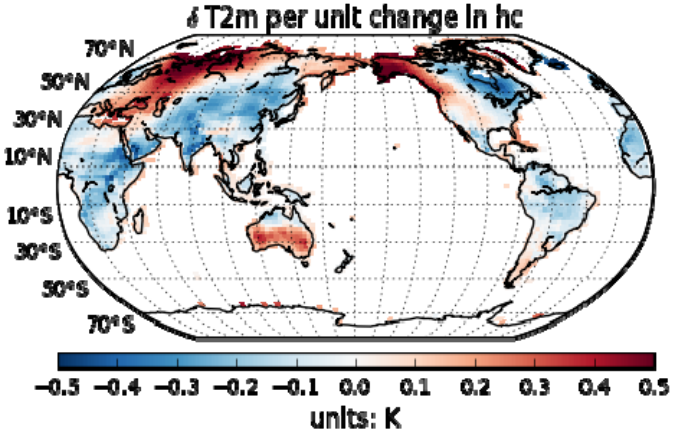

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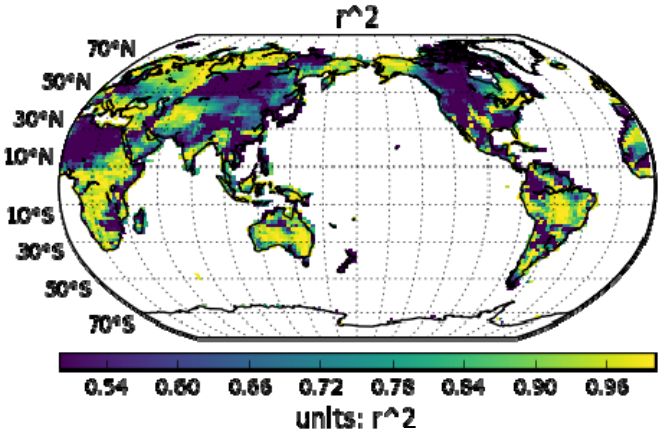

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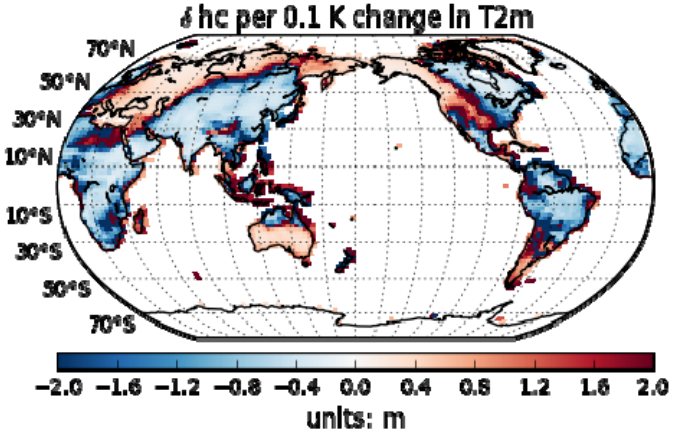
Sensitivity Analysis

Sensitivity to Roughness



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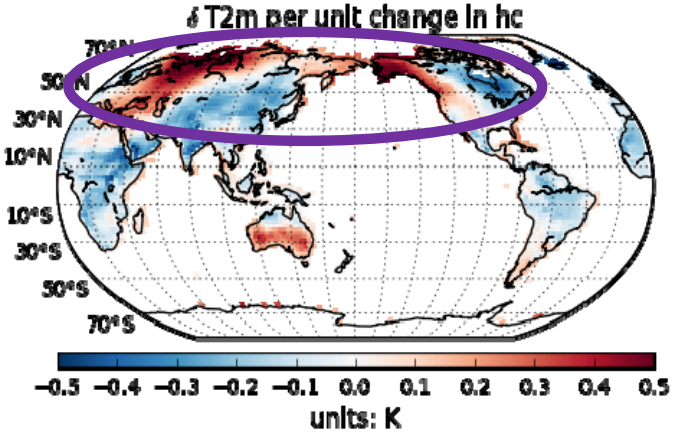

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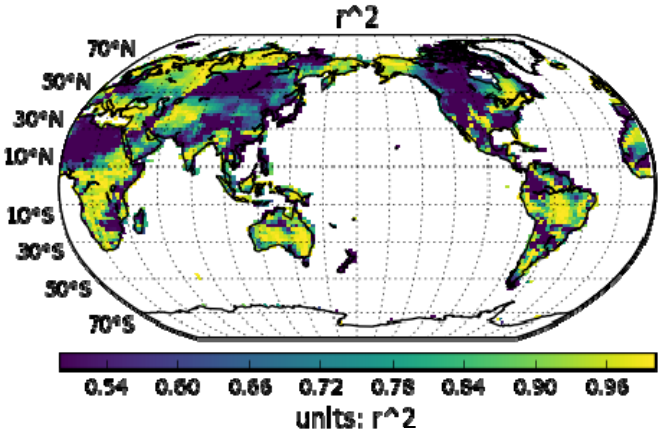
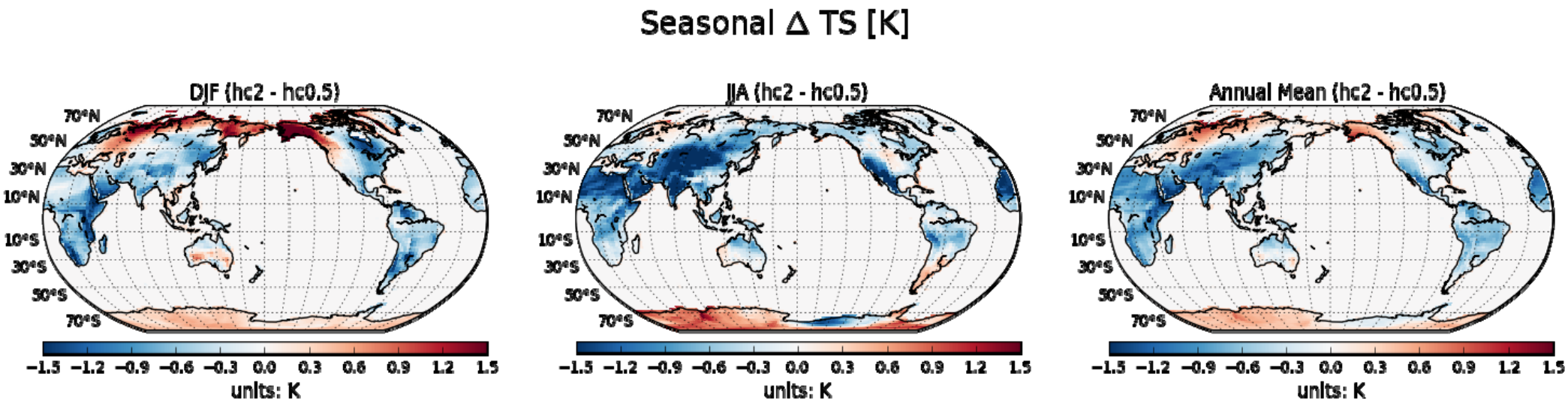


How linear the relationship is

Generally: making land rougher leads to cooler land (more energy goes into turbulent heat fluxes, less into warming the surface).

But, this is **not** the case everywhere!

Warming with *increased* roughness at high latitudes is a **winter** phenomena



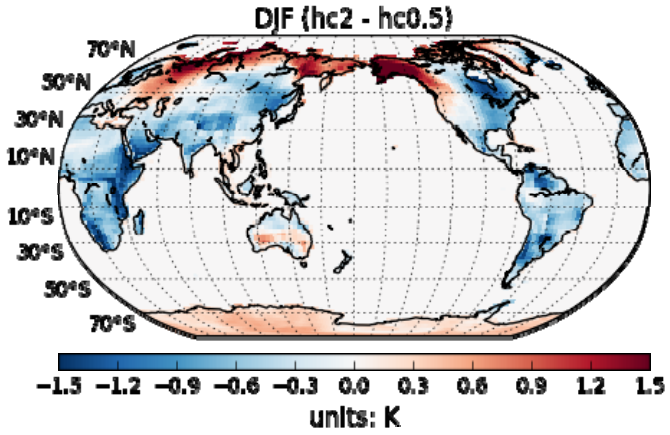
Sign change in winter

Dominates sign in annual mean

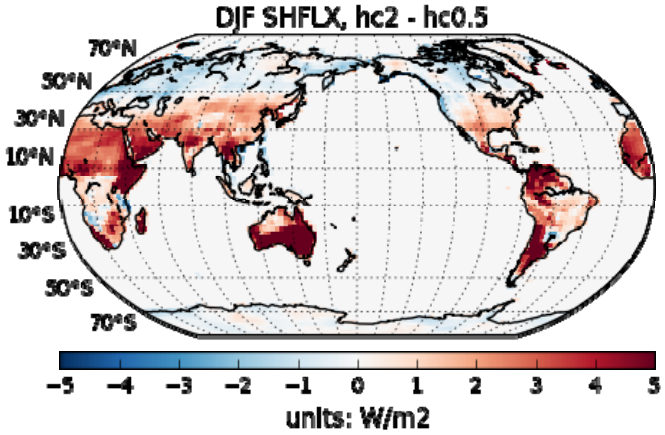
Warming with *increased* roughness at high latitudes is a **winter** phenomena

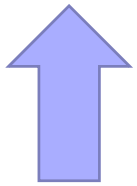
Sensible heat fluxes have opposite sign over regions where rougher = warmer

Δ Surface Temperature



Δ Sensible Heat Flux





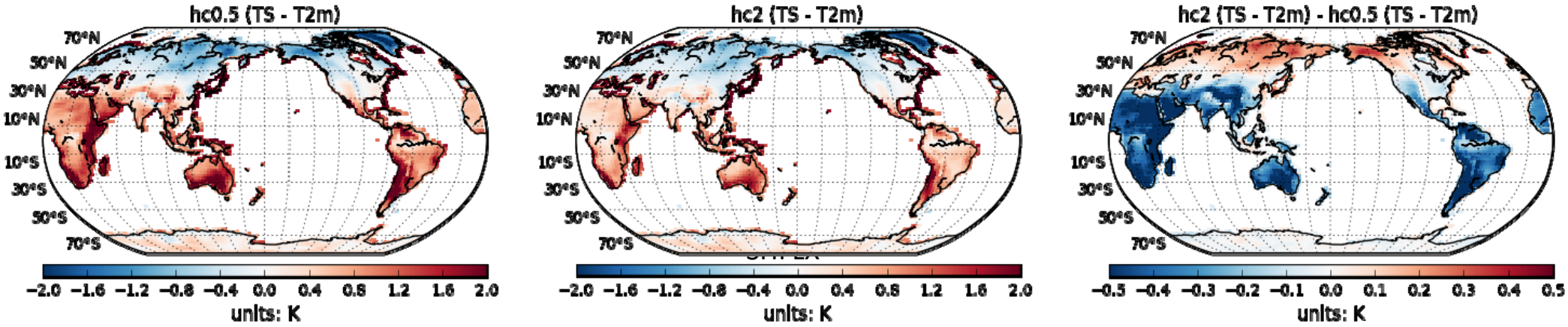
"Decrease" in sensible heat flux is actually an *increase* in *negative (downwards)* sensible heat flux as the ground gets rougher

Sensitivity Analysis: Roughness

The air is warmer than the ground over high latitude land regions: sensible heat fluxes go *from* the air *to* the land

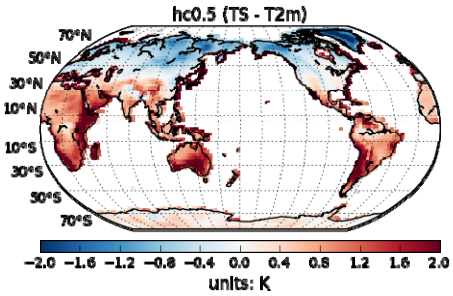
Sensitivity to Roughness

DJF Δ (TS - TREFHT) [K]



Blue: air is warmer than surface (sensible heat flux should go *downwards*)
Red: surface is warmer than air (sensible heat flux should go *upwards*)

Normal conditions
(red locations)



Cool air

Warm ground

smooth **rough**

$Sh_{smooth} > 0$

$Sh_{rough} > 0$

	smooth	rough
TS:	warmer	cooler
SH:	lower (and +)	higher (and +)

$|Sh_{smooth}| < |Sh_{rough}|$, $Sh_{rough} - Sh_{smooth}$ *looks* positive

Normal conditions
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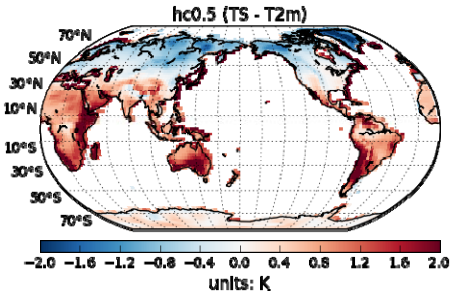

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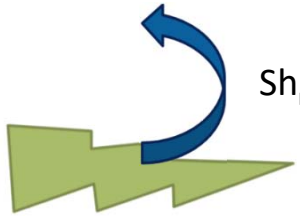

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Cold land
(blue locations)

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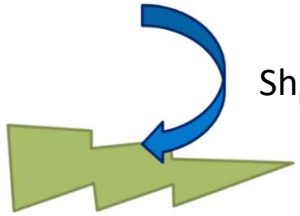


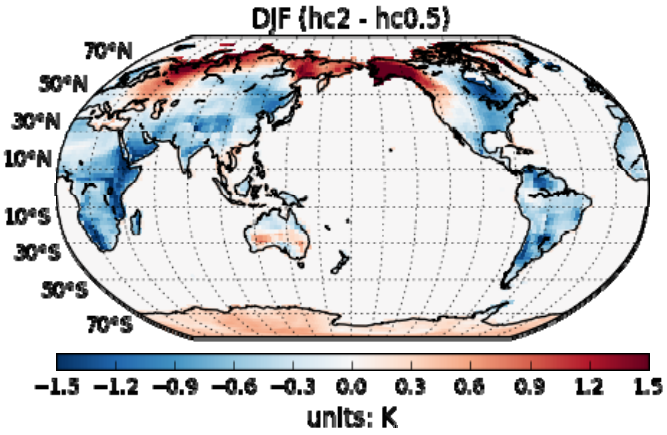
$Sh_{rough} < 0$

Big - Small -
$(Sh_{rough} - Sh_{smooth}) < 0$

TS: warmer cooler
SH: lower (and -) higher (and -)

$|Sh_{smooth}| < |Sh_{rough}|$, but both are negative… so $Sh_{rough} - Sh_{smooth}$ *looks* negative

Δ Surface Temperature



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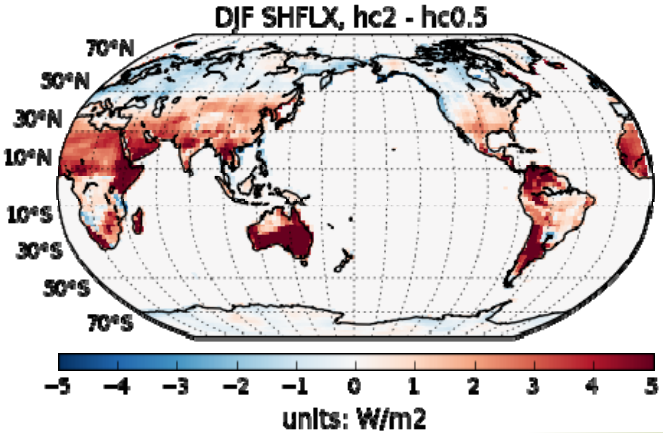

Cold land
(blue locations)

smooth **rough**

Warm air

Cold ground

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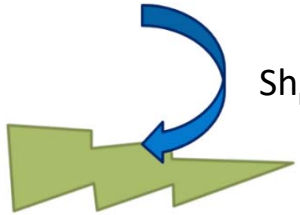

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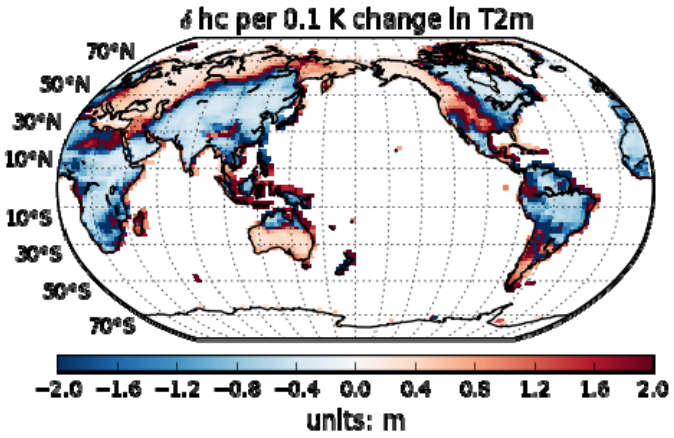
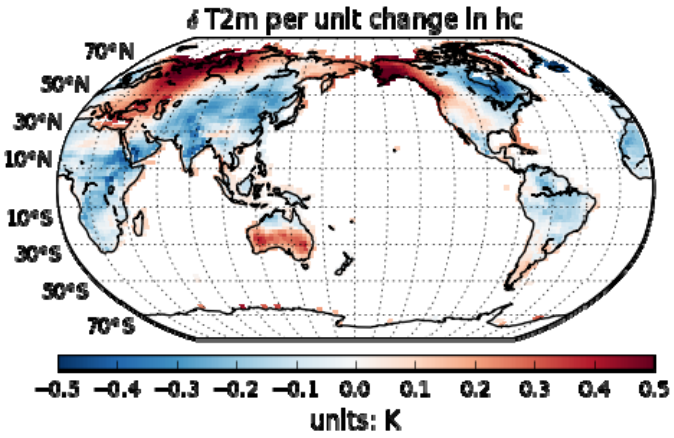
Wintertime reversal of sensible heat fluxes dominates sensitivity of air temperature to roughness at high latitudes

Sensitivity to Roughness



$$\frac{\partial(\text{land})}{\partial(\text{atm})}$$



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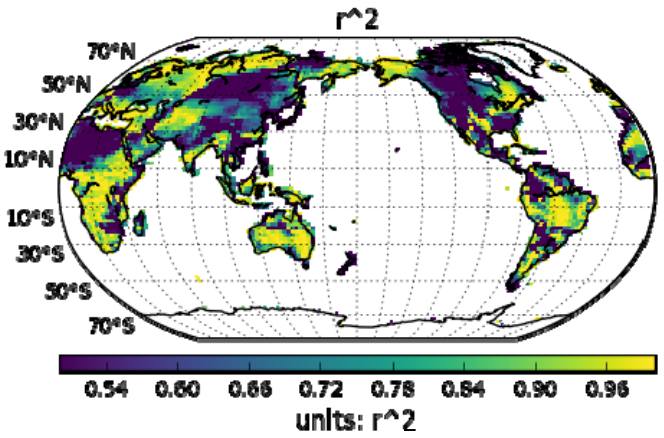
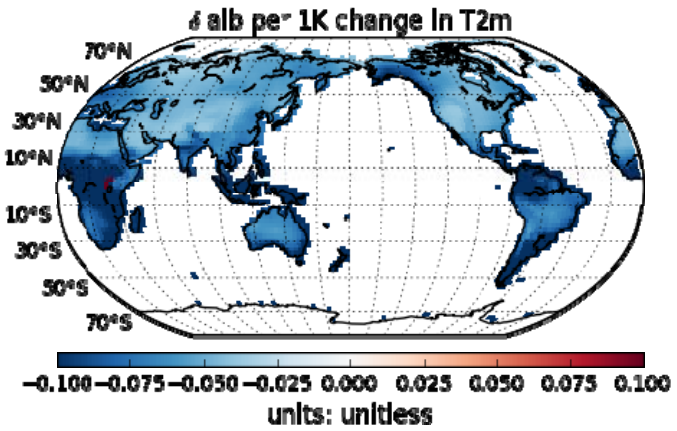


How linear the relationship is

Red regions: make surface rougher to warm
Blue regions: make surface smoother to warm

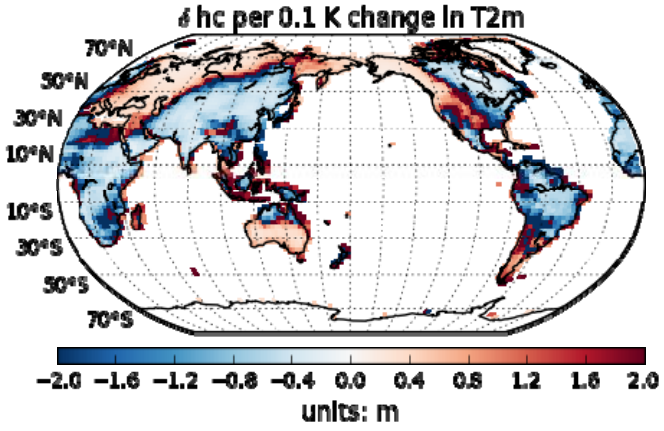
Over realistic ranges of albedo / roughness / evaporative resistance perturbations, the largest responses by far come from albedo.

Sensitivity to Albedo



$$\frac{\partial(\text{land})}{\partial(\text{atm})}$$

Sensitivity to Roughness



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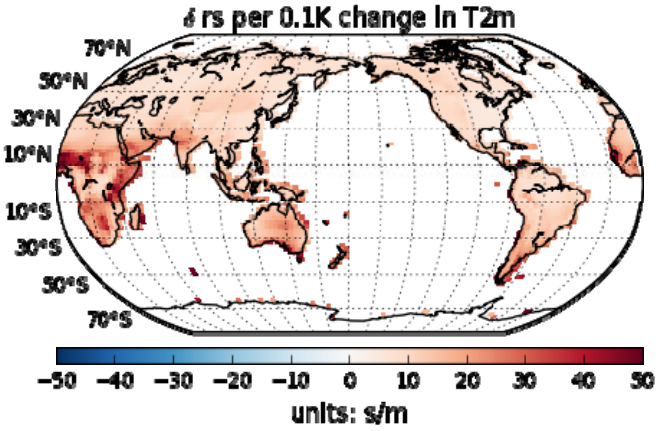
Sensitivity to Evaporative Resistance



$$\frac{\partial(\text{land})}{\partial(\text{atm})}$$

Note: only looking for a 0.1 K change in temperature for roughness / evaporative resistance! (Weaker forcing)

Summary

- Perturbed 3 variables: albedo, roughness, and evaporative resistance.
  - Calculate $\frac{\partial(\mathrm{atm})}{\partial(\mathrm{land})}$ (how sensitive the atmosphere is to a given increment of land change),

    invert to find $\frac{\partial(\mathrm{land})}{\partial(\mathrm{atm})}$ (how large a change in land is required to drive an increment of atmospheric response, e.g. a 1K warming)

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Questions?

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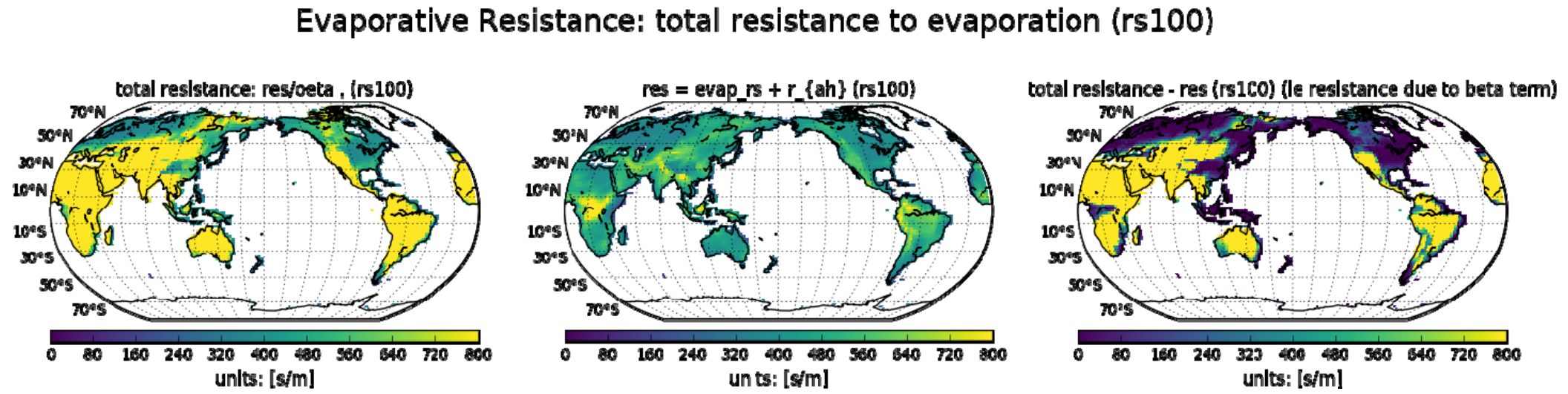
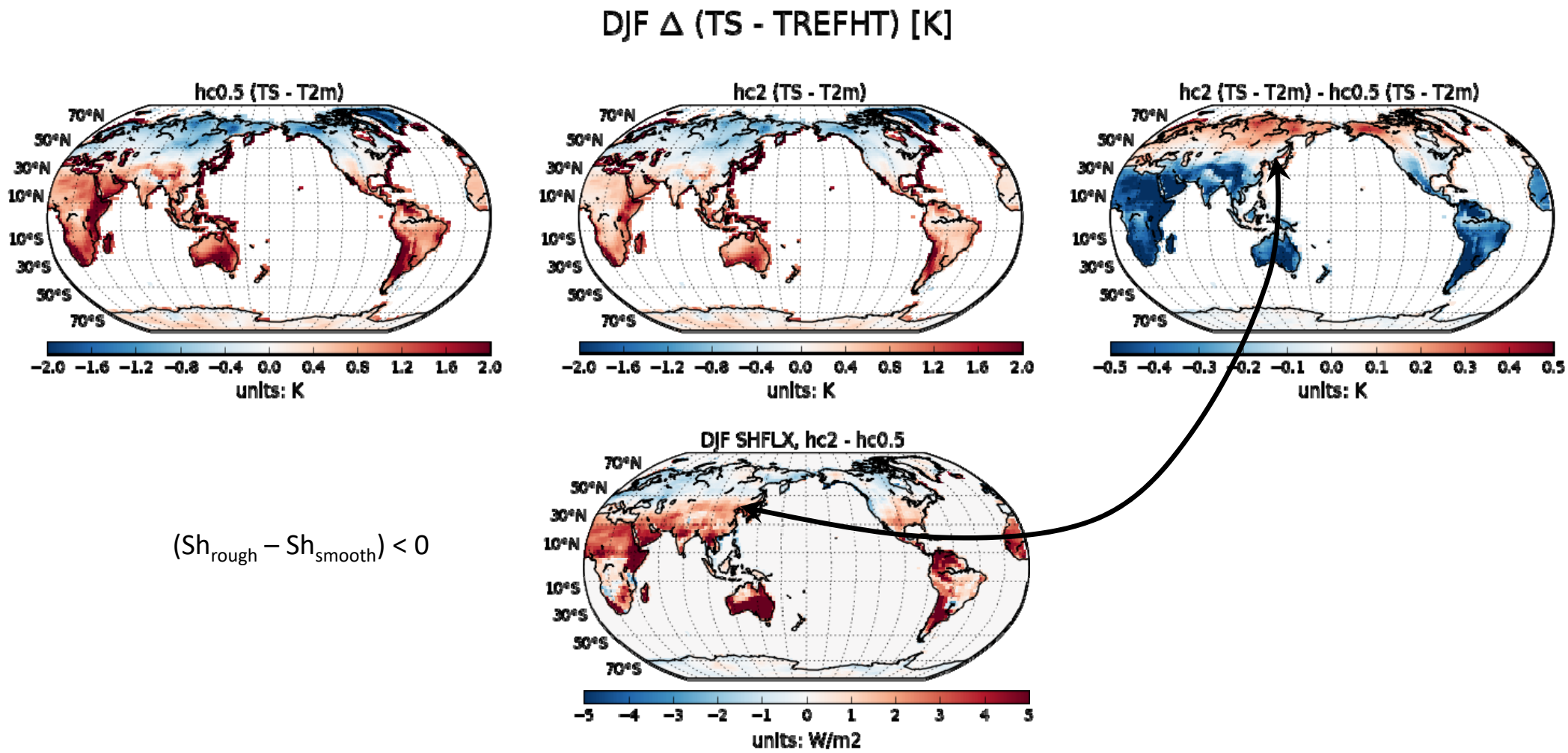
Evaporative resistance is sometimes dominated by the β term (how full the bucket is), rather than the “lid” resistance. Most, but not *all* of these places are dry… (exception: the Amazon)

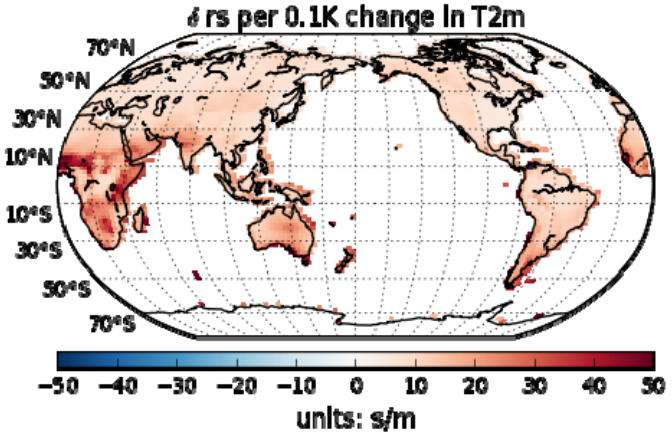


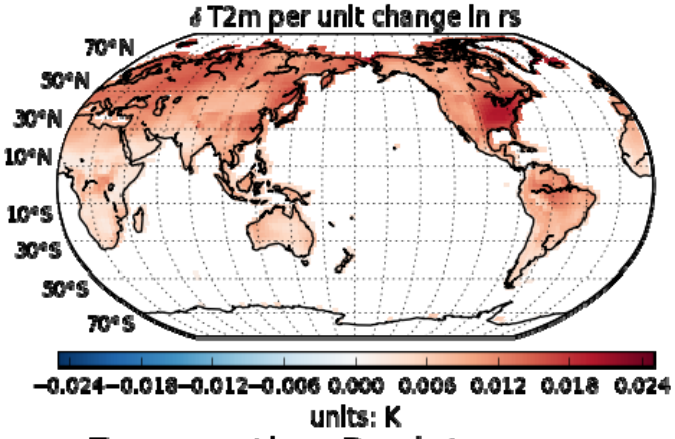


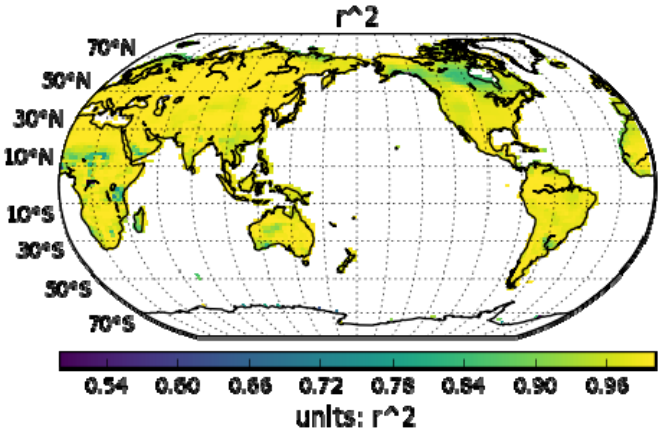
$(Sh_{rough} - Sh_{smooth}) < 0$

Sensitivity Analysis

Evaporative Resistance







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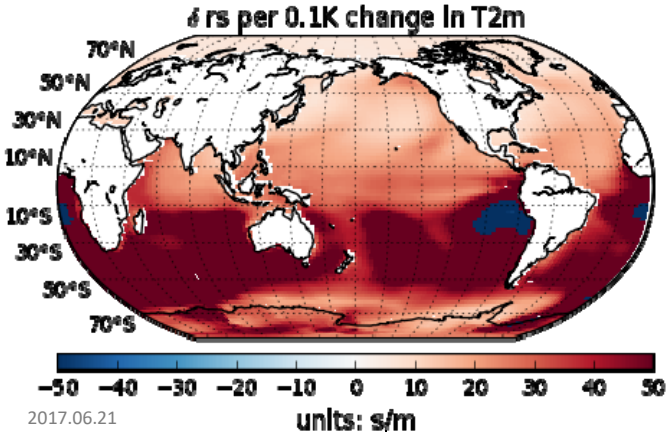
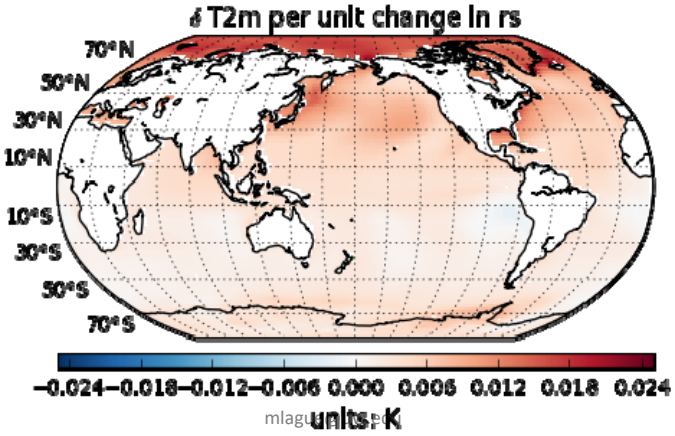
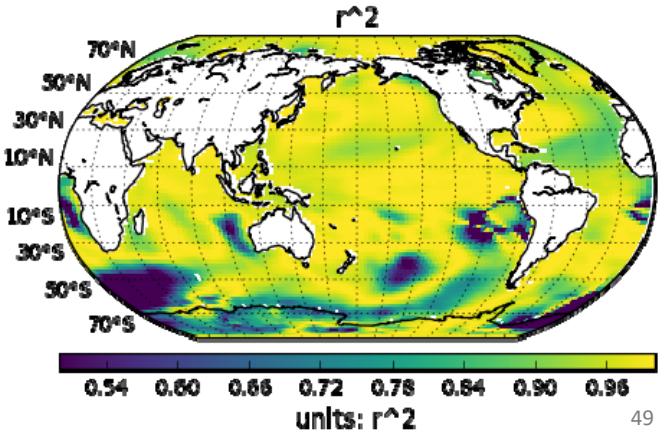
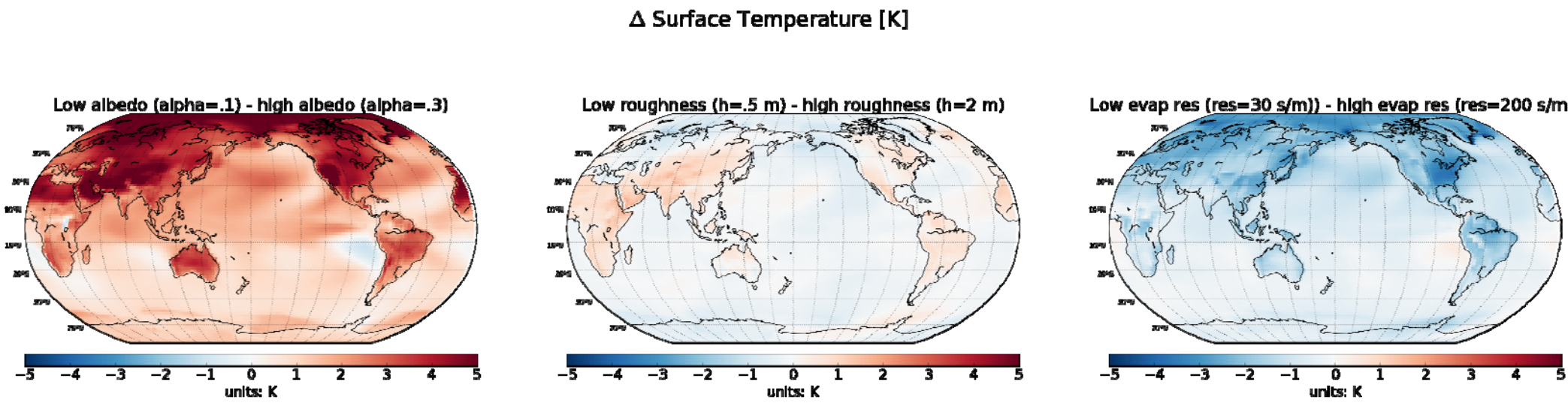






Temperature response range for physically realistic range of surface perturbations



Sensitivity Analysis