ATS 301:

Understanding & Analyzing the Land Surface Energy Balance

Dr. Marysa Laguë
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Learning goals:

Theory:

- Understand the components of the surface energy budget over land
  - Predict which fluxes should dominate based on land cover

Application:

- Analyze the surface energy budget using climate model output
  - Interpret bar graphs of surface fluxes and predict how they might change with warming

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  - **Predict which fluxes should dominate based on land cover**

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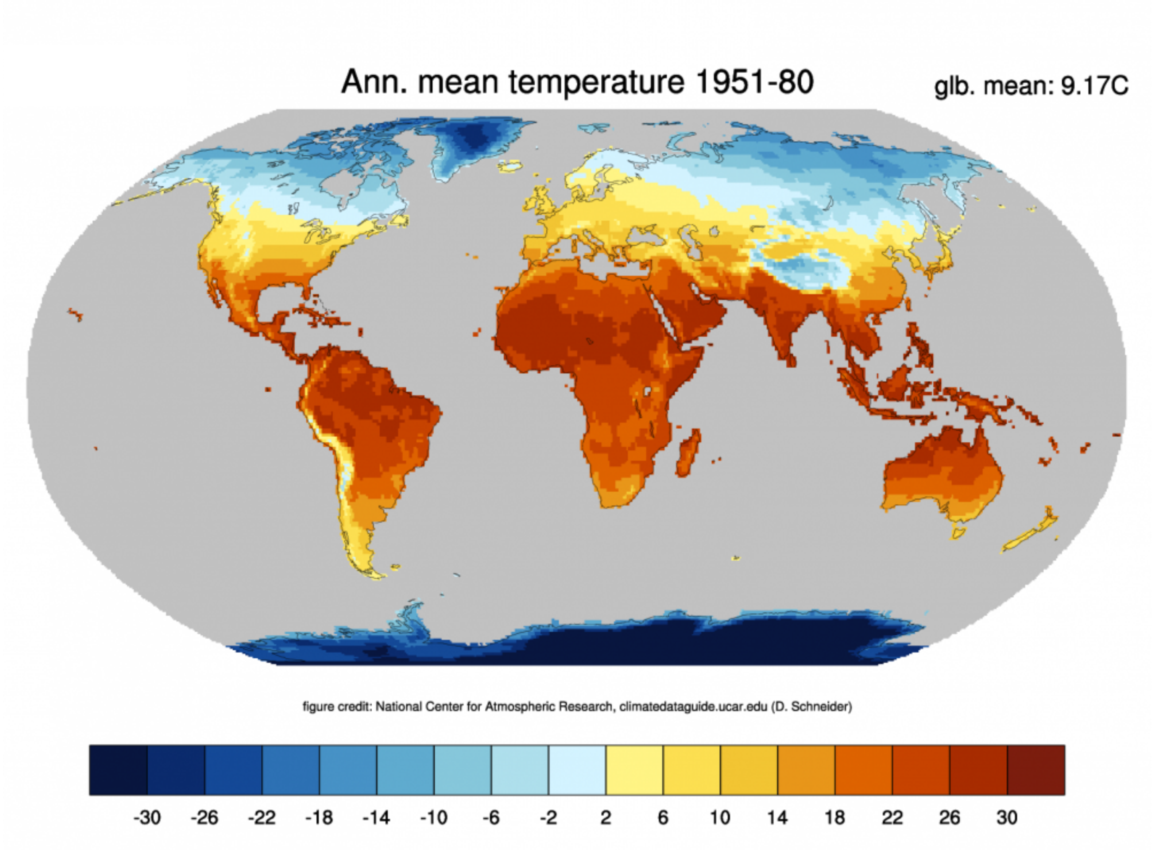
What is the land surface energy balance, and why do we care about it?



Fluxes of energy and water between the land and the atmosphere determine surface temperatures on land – where most people live!

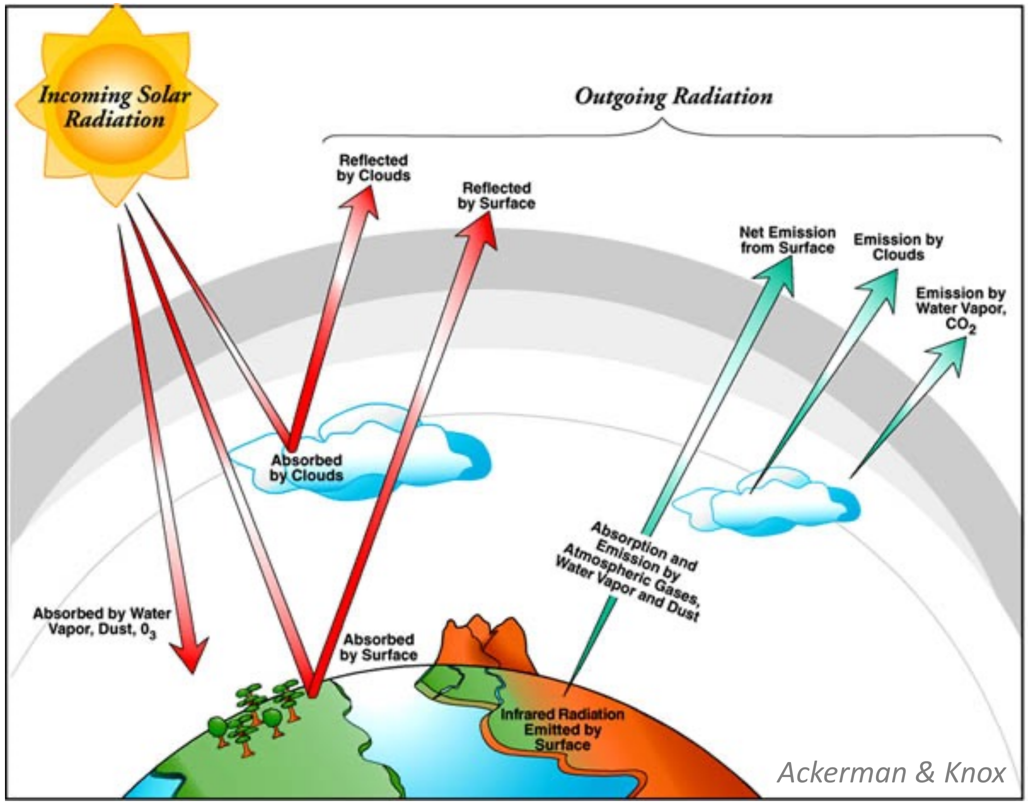
Earth's global energy budget:

Energy In = Energy Out

- This is true of the planet as a whole

Energy In:

- Incoming solar radiation



Energy Out:

- Reflected solar radiation
- Emitted longwave radiation

Longwave radiation
(or infrared radiation)

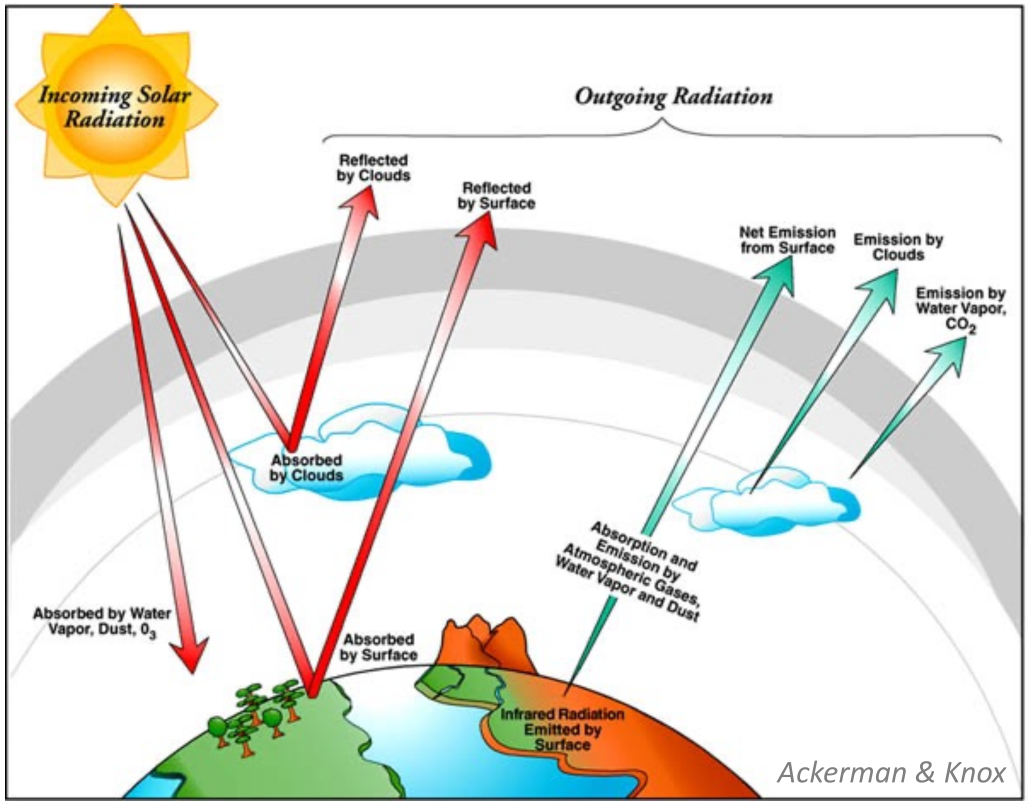
$$LW = \varepsilon\sigma T^4$$

Energy emitted by anything with a temperature > 0 K

Earth's global energy budget:

Energy In = Energy Out

- Within the Earth system, the atmosphere and oceans can move energy around



Earth's global energy budget:

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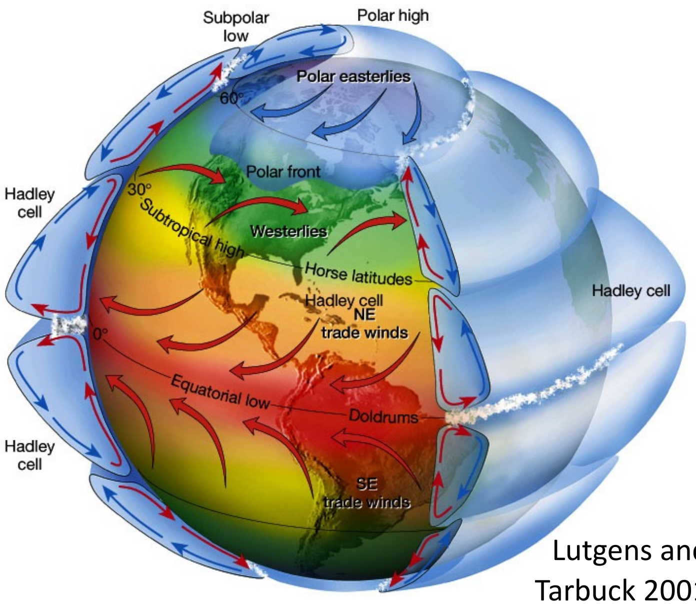
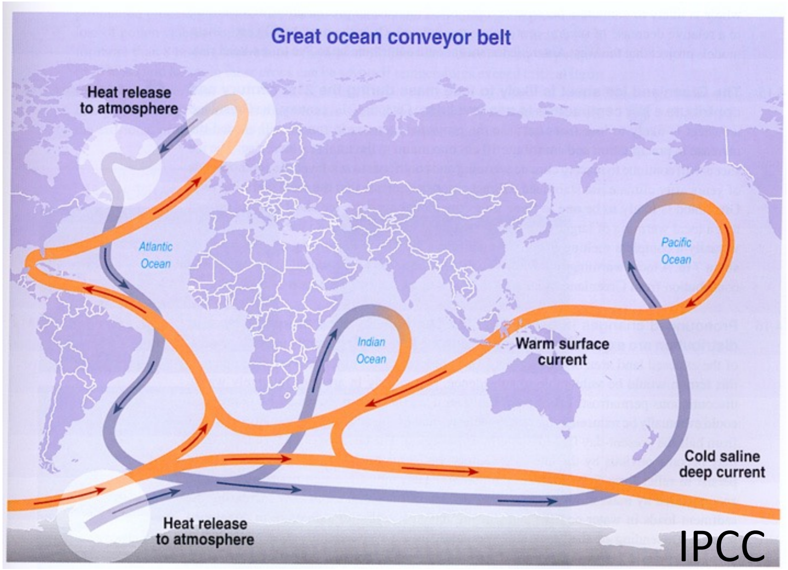
Atmospheric circulation / winds



Lutgens and Tarbuck 2001

Ocean circulation / currents

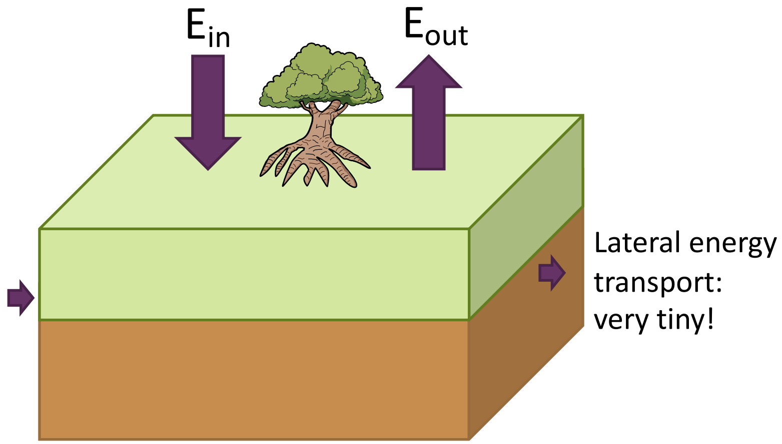


IPCC

Earth's global energy budget:

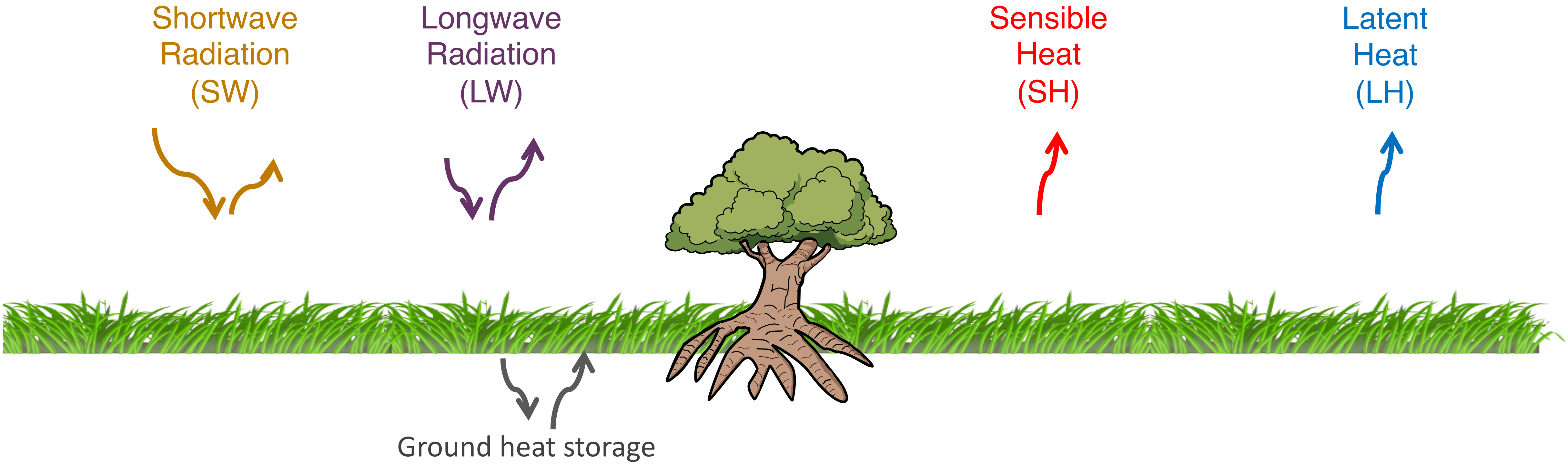
Energy In = Energy Out

- Within the Earth system, both the atmosphere and oceans can move energy around
- Land doesn't move energy around sideways very efficiently – which means that at any point on land, energy in = energy out over long enough time scales



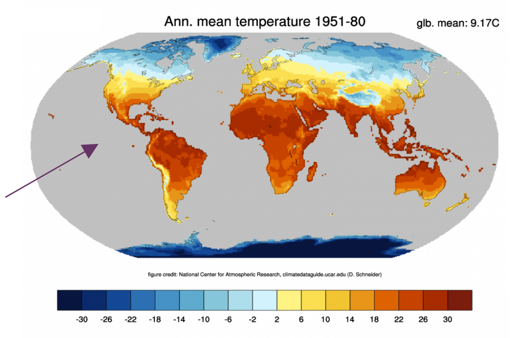
(Another way of saying this is that the land surface energy budget is "closed")

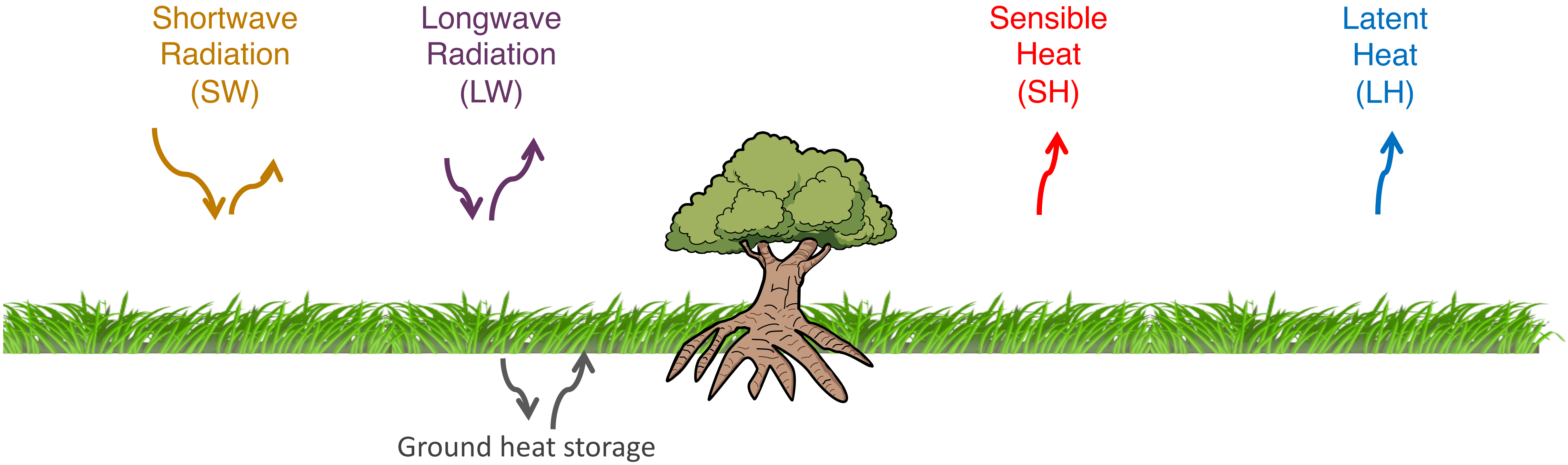
The land surface energy budget is made up of 5 pieces



The land surface energy budget is made up of 5 pieces

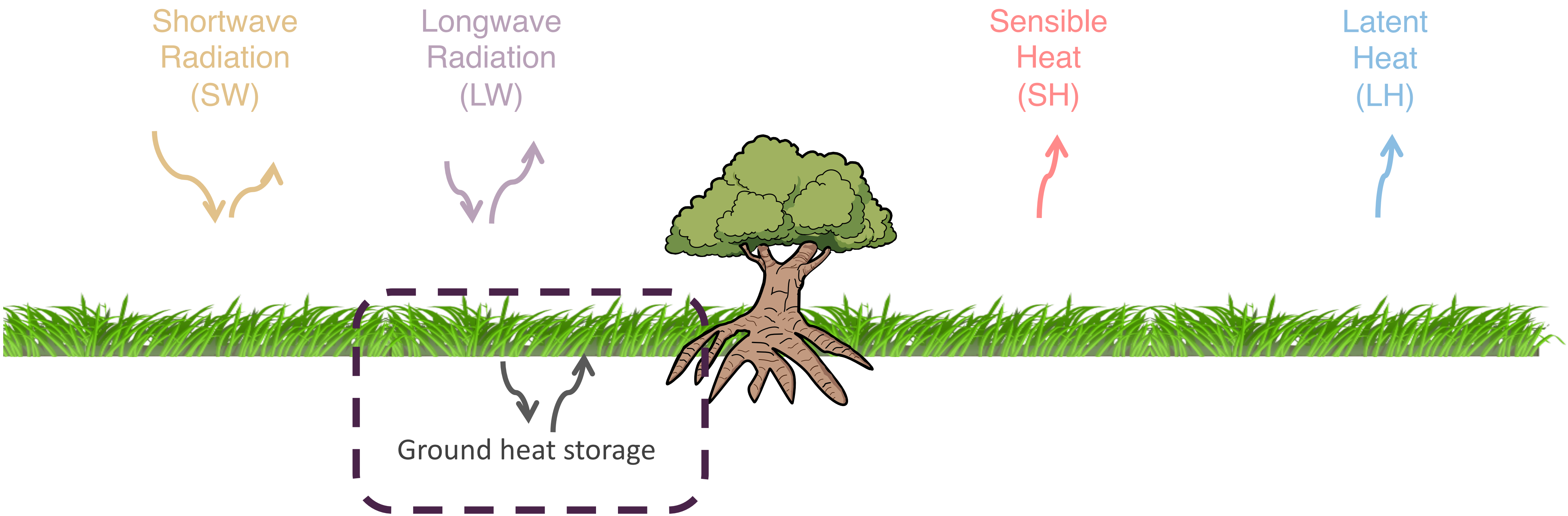
Balance of these fluxes determine surface temperature





The land surface energy budget is made up of 5 pieces

- Land has a small heat capacity, so ground heat storage is much smaller* than the other 4 terms



* exceptions: places where permafrost is thawing or ice sheets are melting

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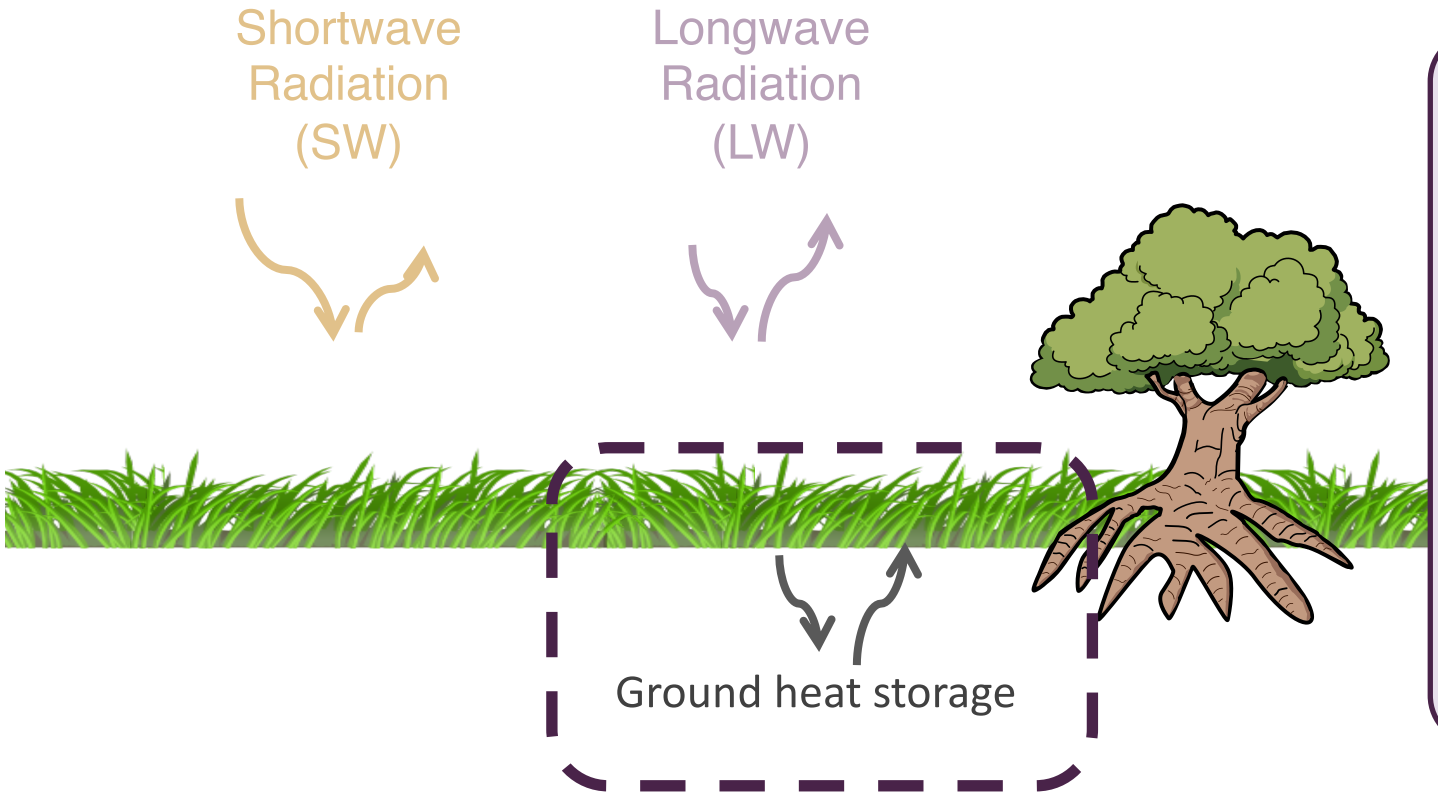


Definition:

Heat capacity:

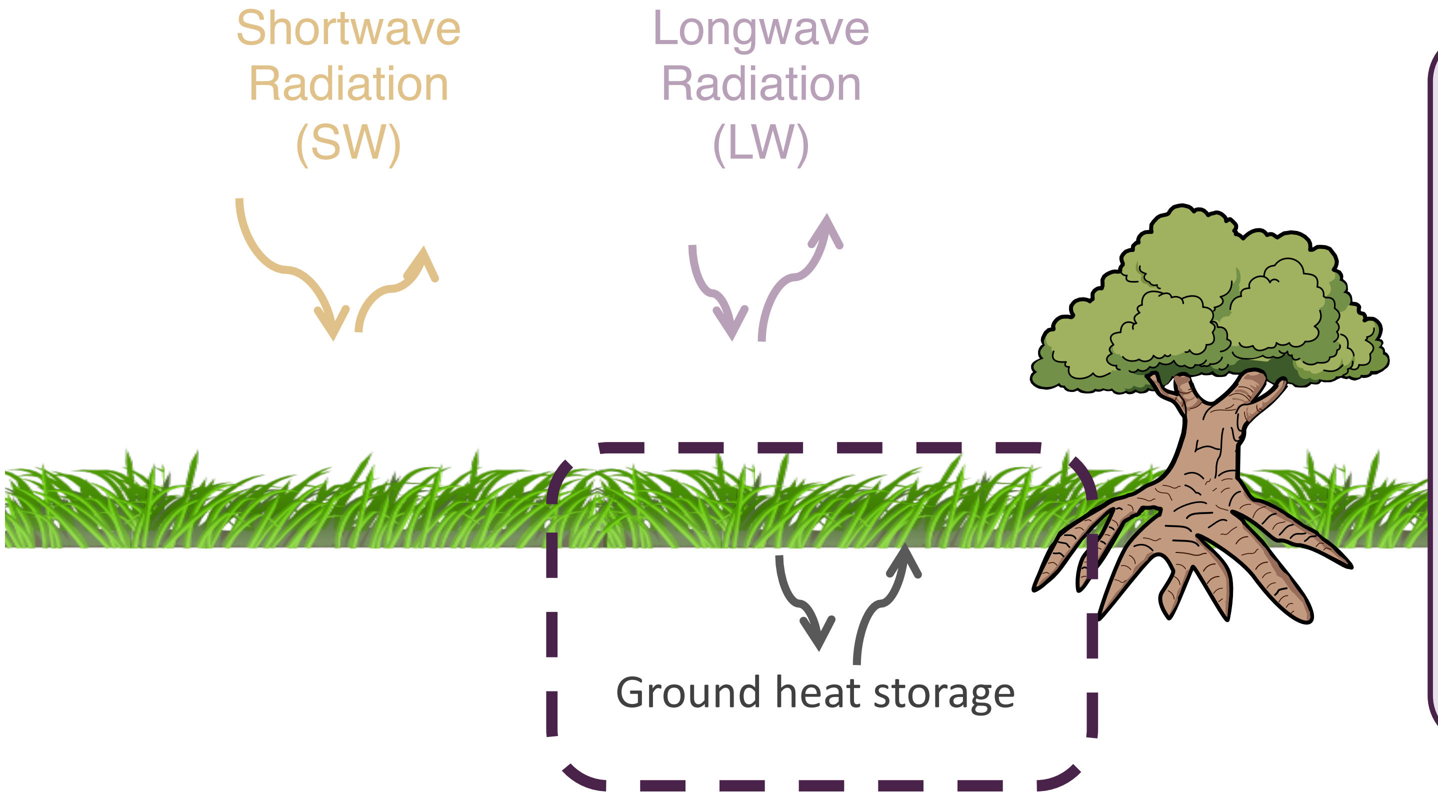
How much energy you have to add to an object for it to change temperature

Water (the oceans) has a much larger heat capacity than land

* exceptions: places where permafrost is thawing or ice sheets are melting

The land surface energy budget is made up of 5 pieces

- Land has a small <u>heat capacity</u>, so ground heat storage is much smaller* than the other 4 terms
- Over the annual cycle, average ground heat storage is ≈ 0 (takes up heat in summer, releases heat in winter, doesn't move energy sideways very well)



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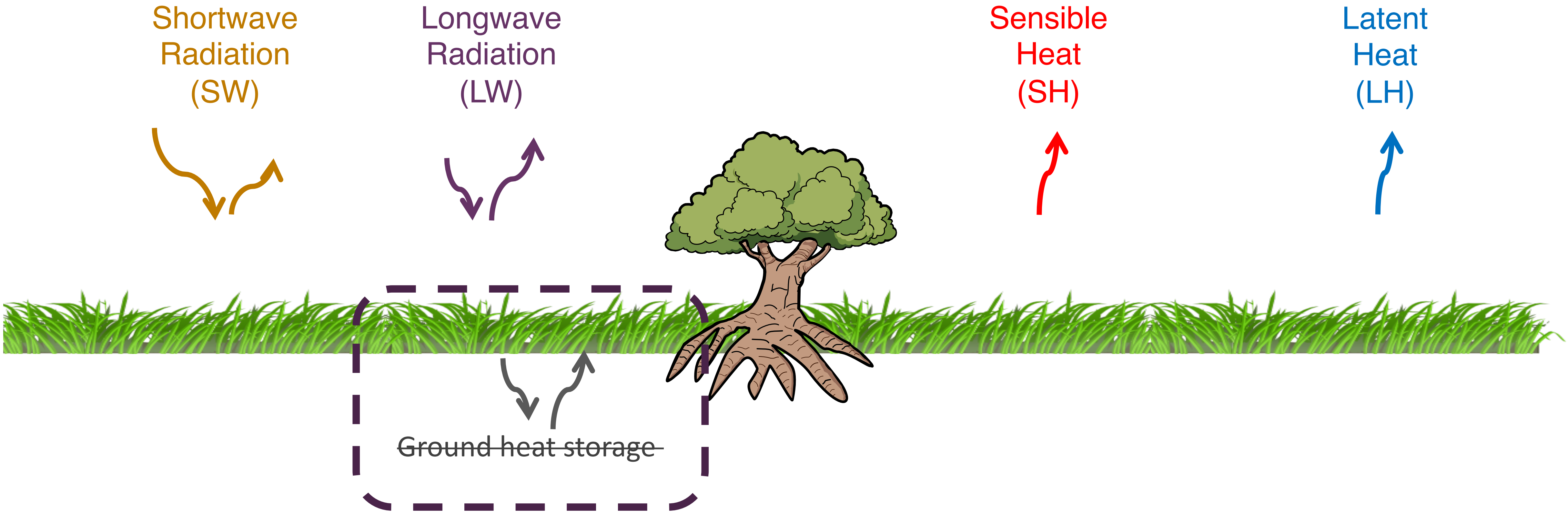
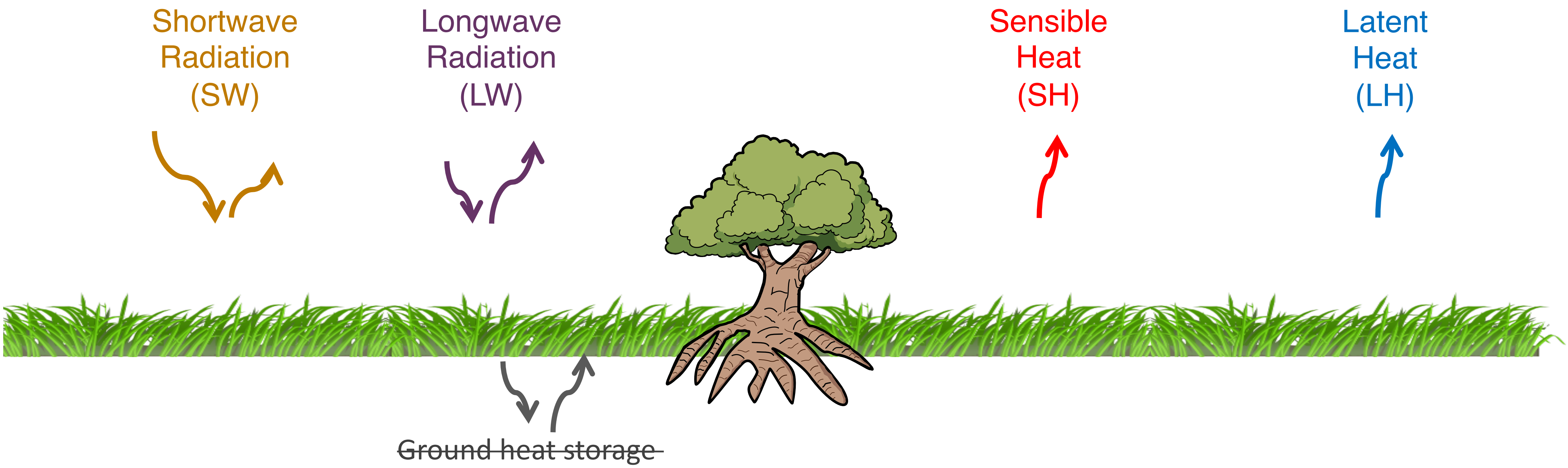


The land surface energy budget is made up of 5 pieces

Radiative Energy

Turbulent Energy



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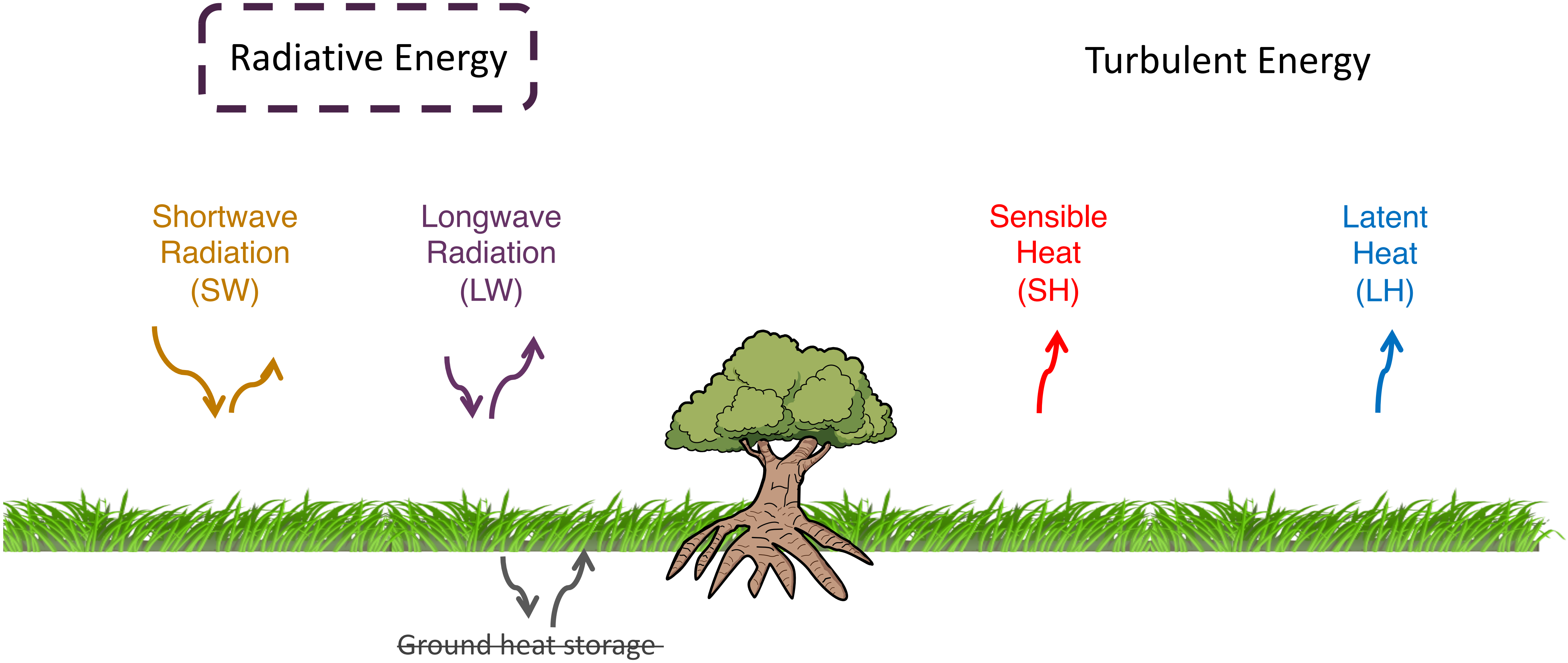


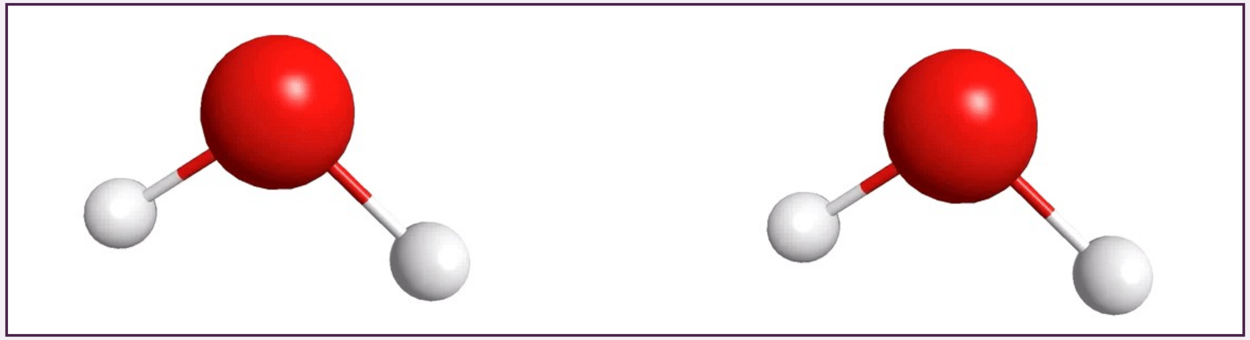
The land surface energy bu

Radiative Energy

Shortwave Radiation (SW)

Longwave Radiation (LW)

Anything warming than 0 K emits energy because of molecules jiggling around



Cold molecules:
- Jiggle more slowly
- Emit less energy

Vs.

Hot molecules:
- Jiggle more quickly
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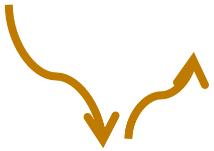

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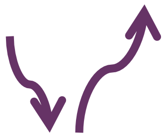

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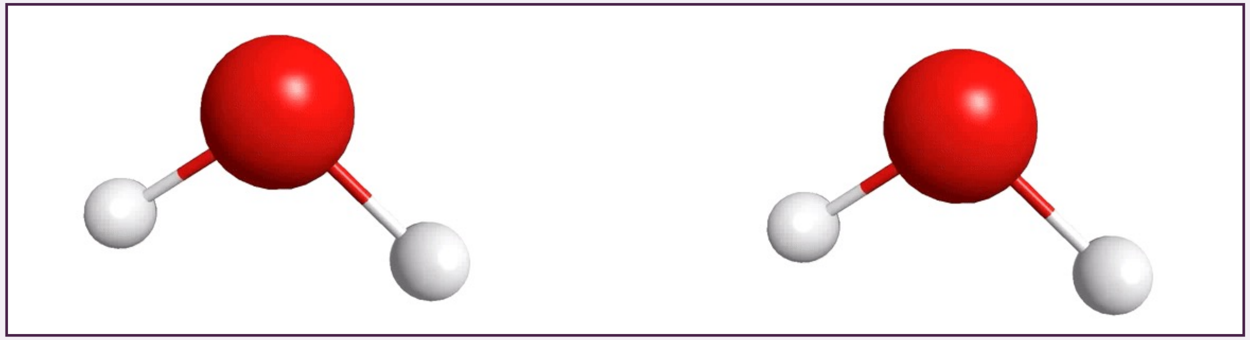

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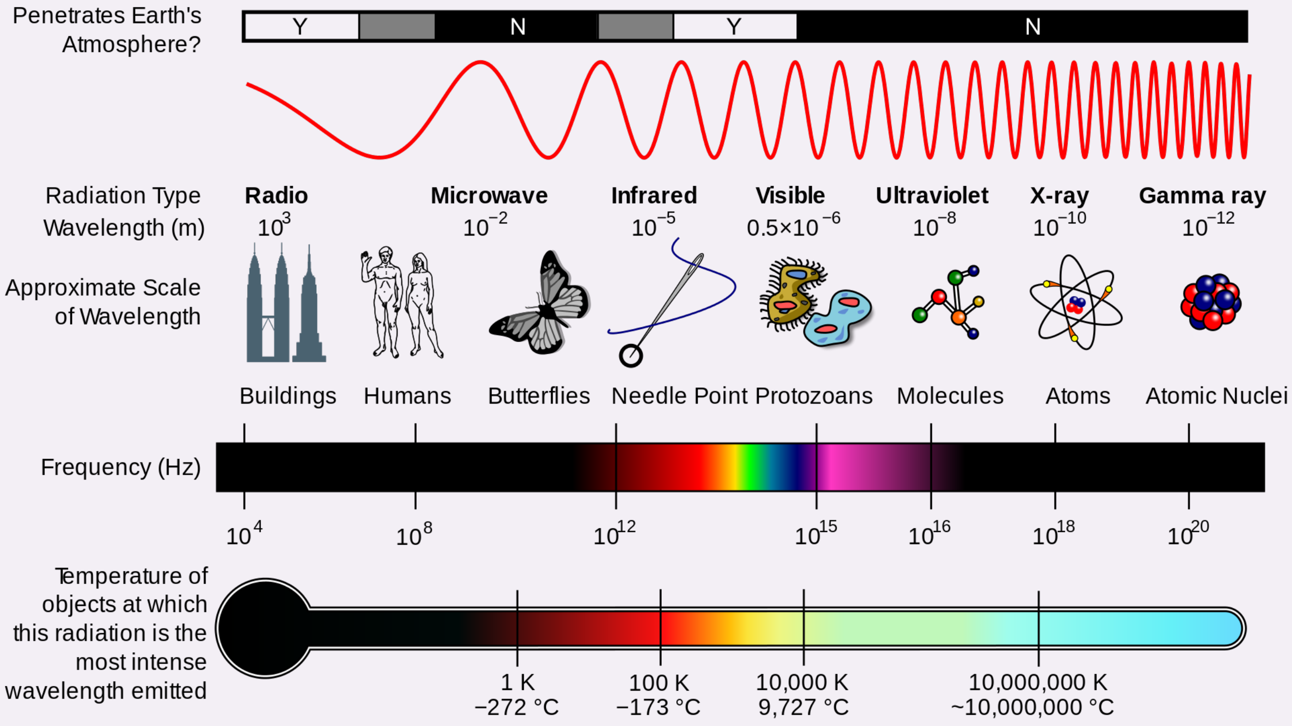

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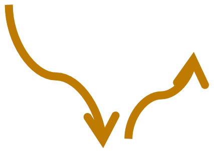

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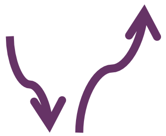

- For climate, we care about two ranges of wavelength, and we lump these into two bins: “shortwave” and “longwave” radiation

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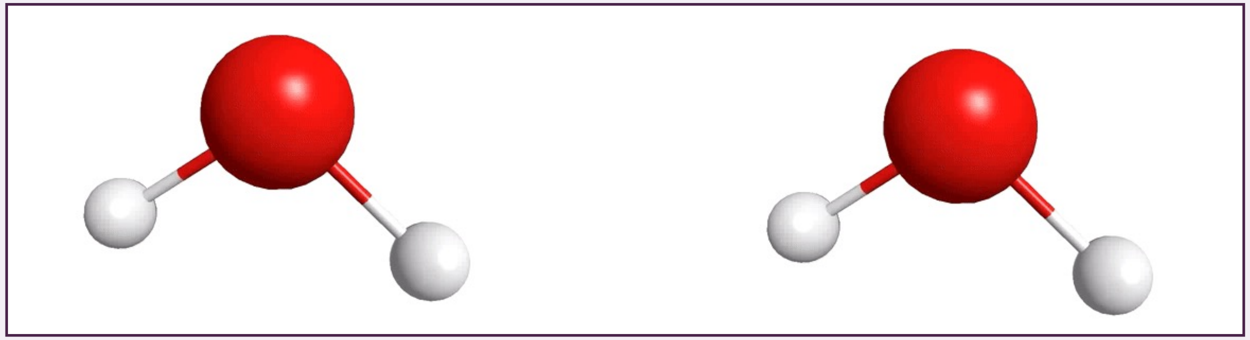

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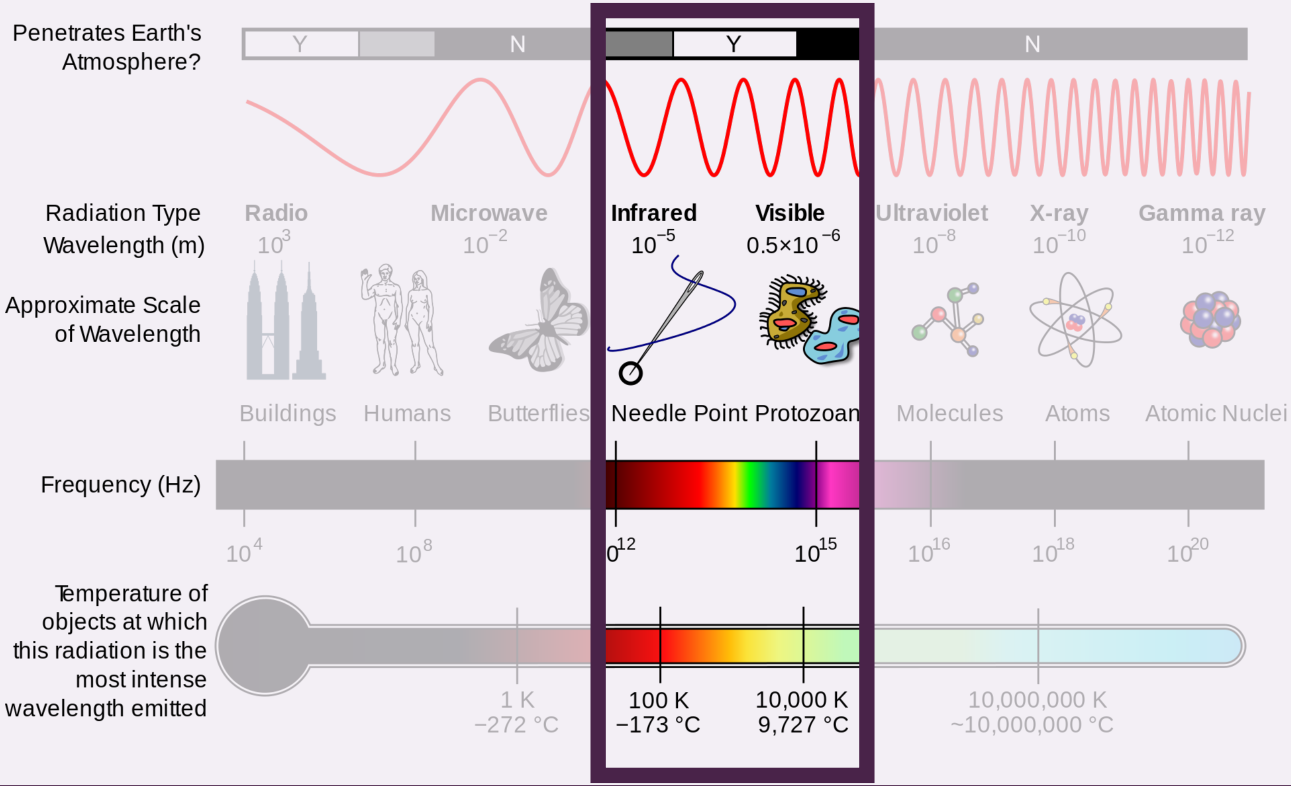

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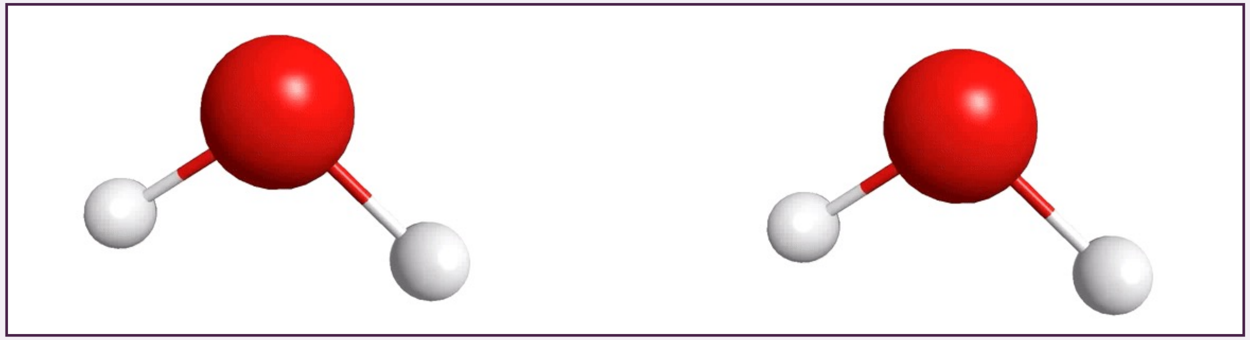

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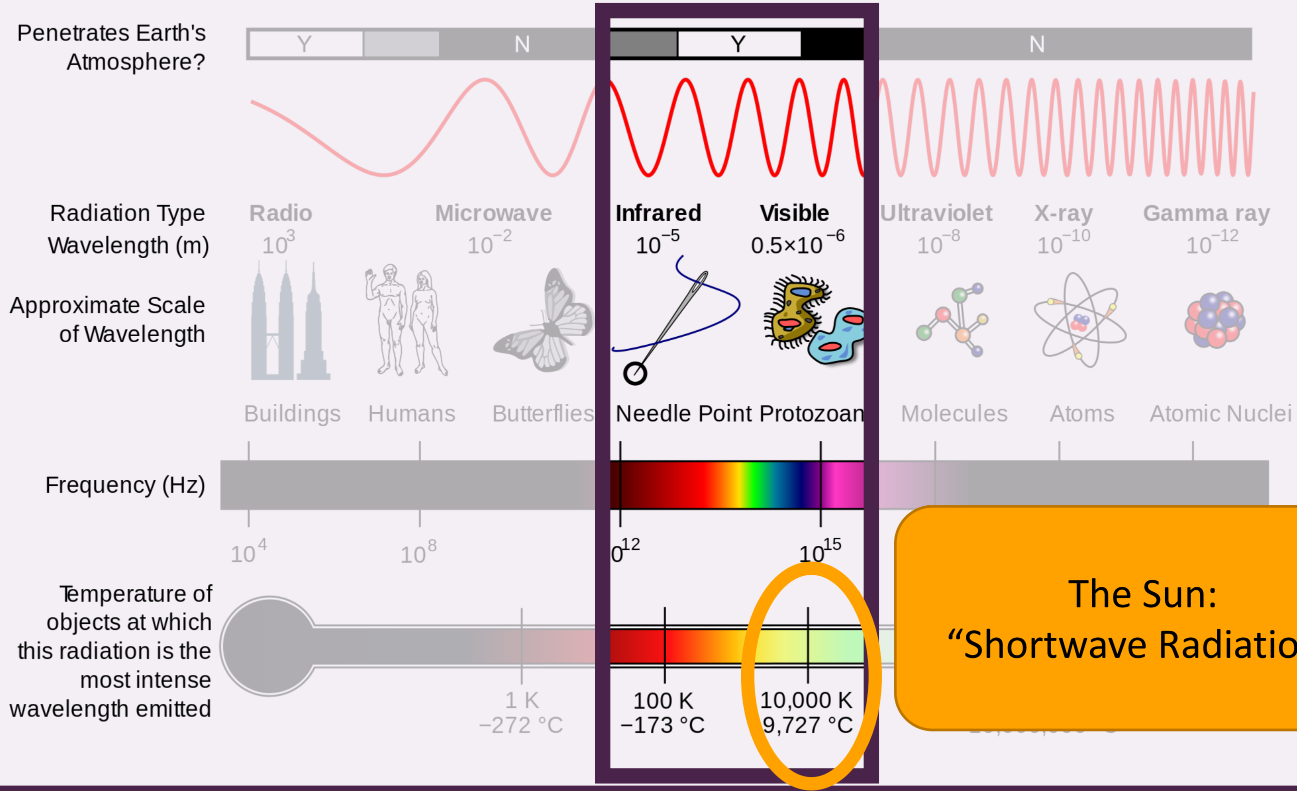
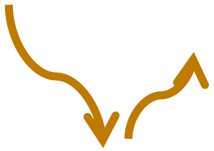


The Sun:
“Shortwave Radiation”

The land surface energy bu

Radiative Energy

Shortwave Radiation (SW)



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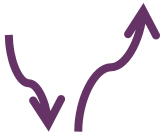

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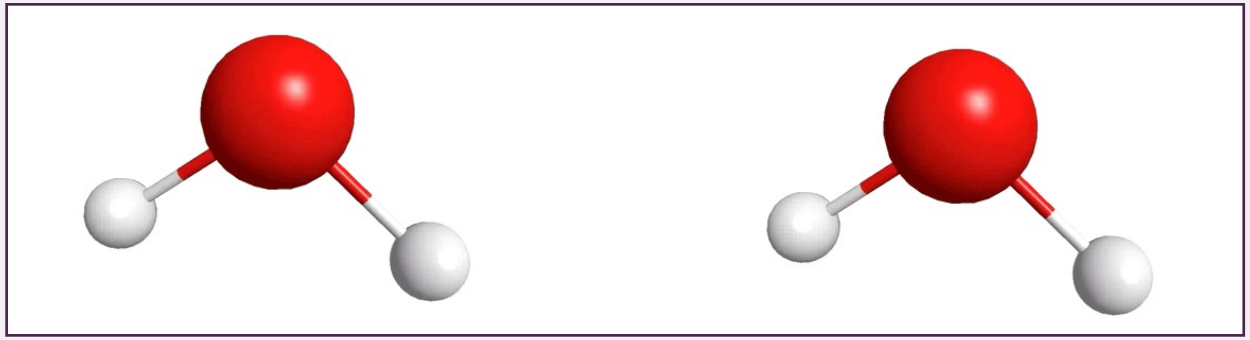

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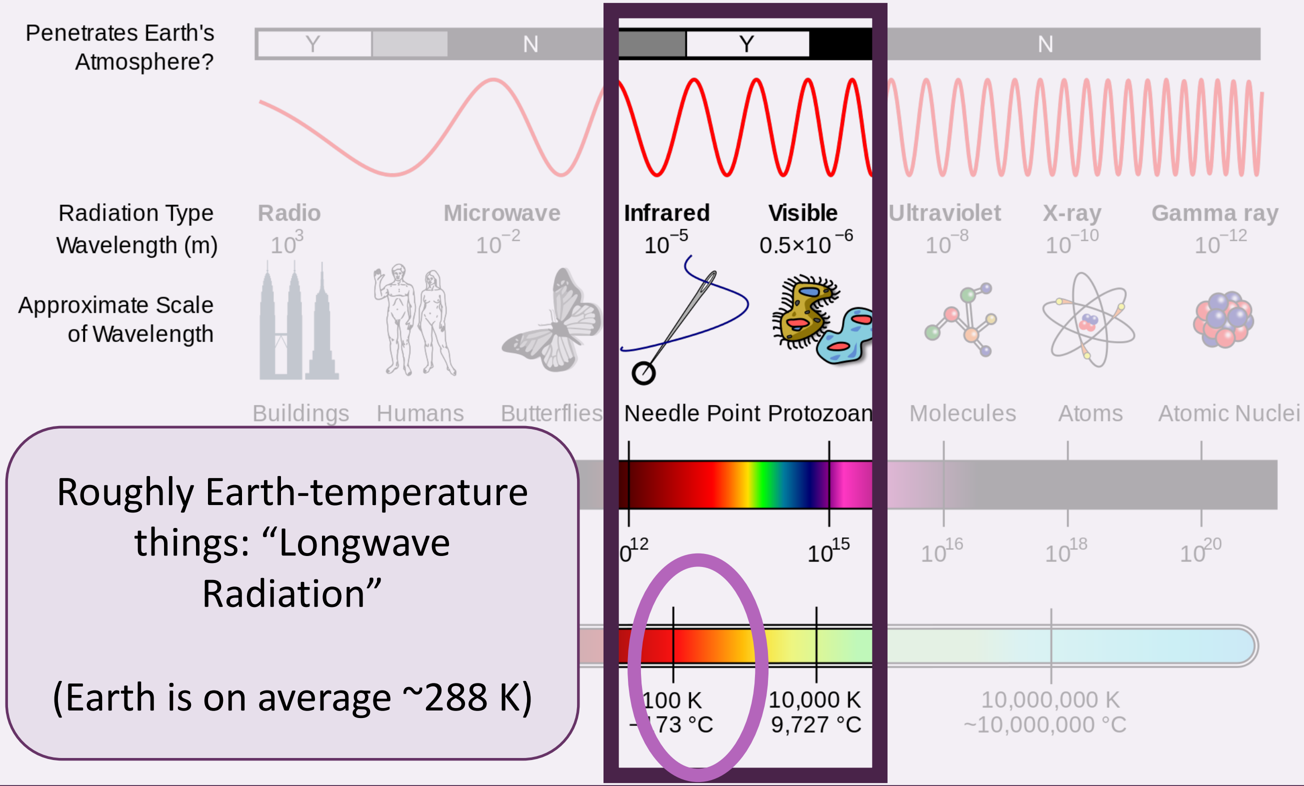
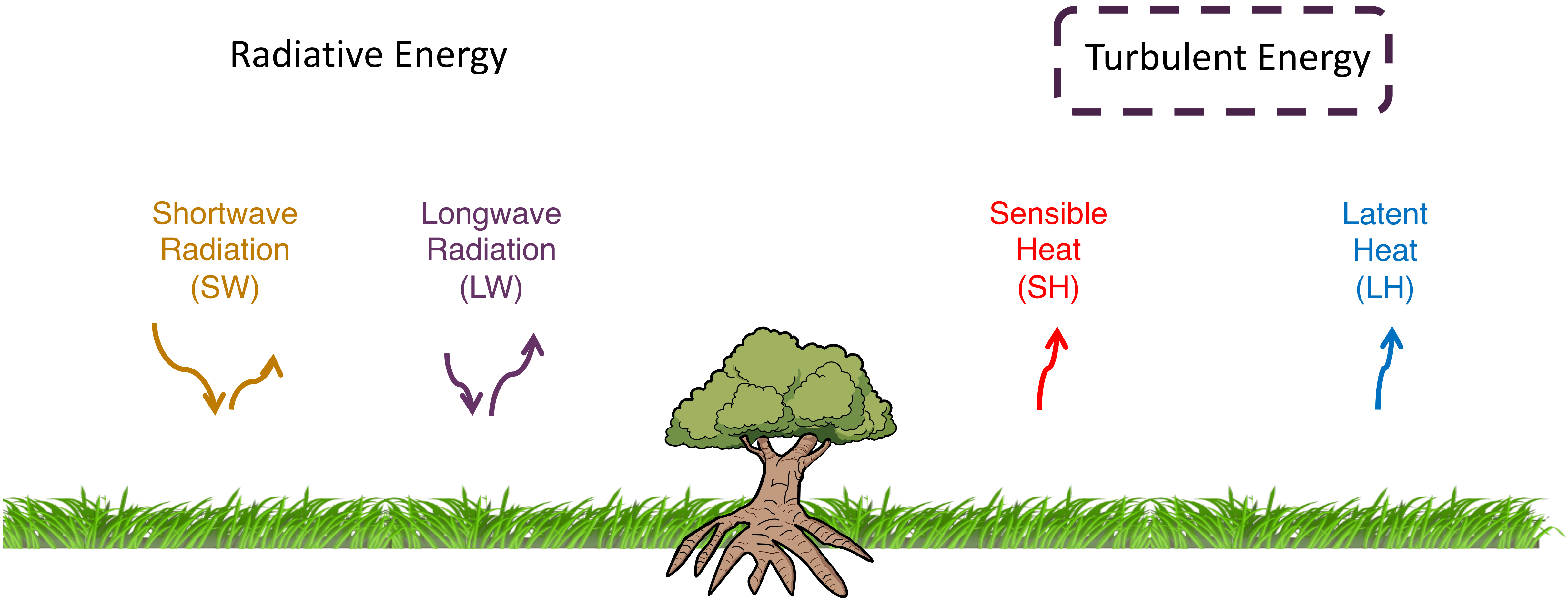


Roughly Earth-temperature things: “Longwave Radiation”

(Earth is on average ~288 K)

The land surface energy budget is made up of 5 pieces



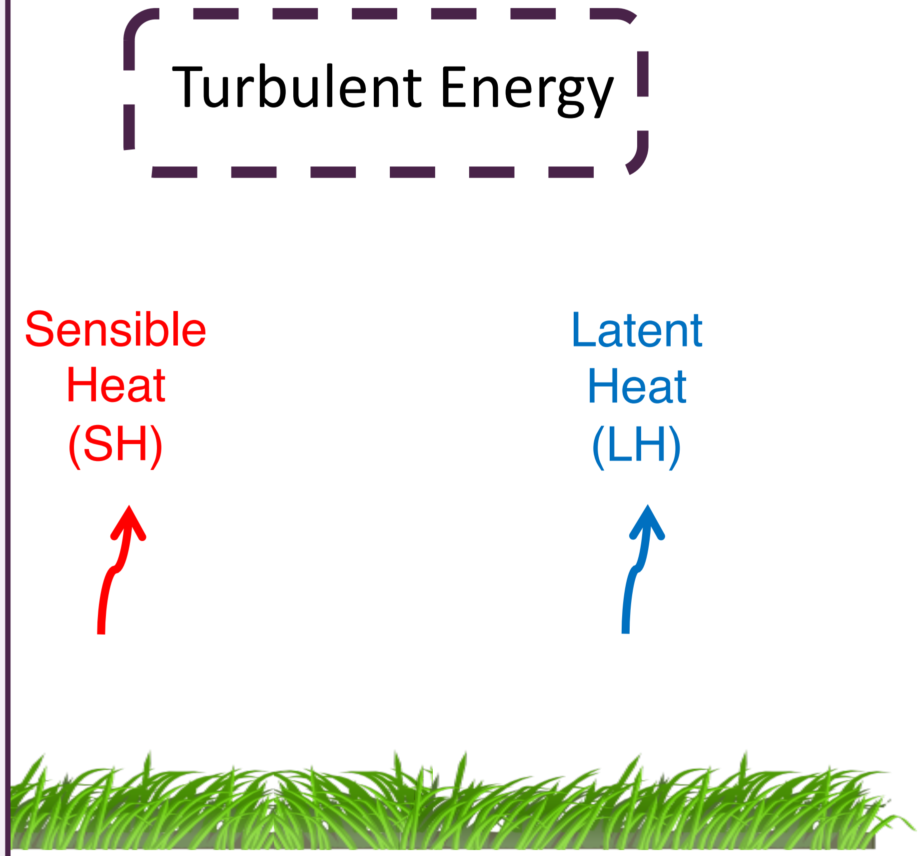
of 5 pieces

Turbulent energy = physically mixing air that is in contact with the surface with air from the rest of the atmosphere

Blowing on something hot to cool it down works because of turbulent energy exchange

Sensible heat:
Physically mixing air of a different temperature to be in contact with a surface

Latent heat:
Evaporating water takes energy, so you can cool a surface by using energy to do the phase change from liquid water to gas (water vapor), rather than using that energy to heat the surface.
Air needs to not be saturated with water for this to be efficient.



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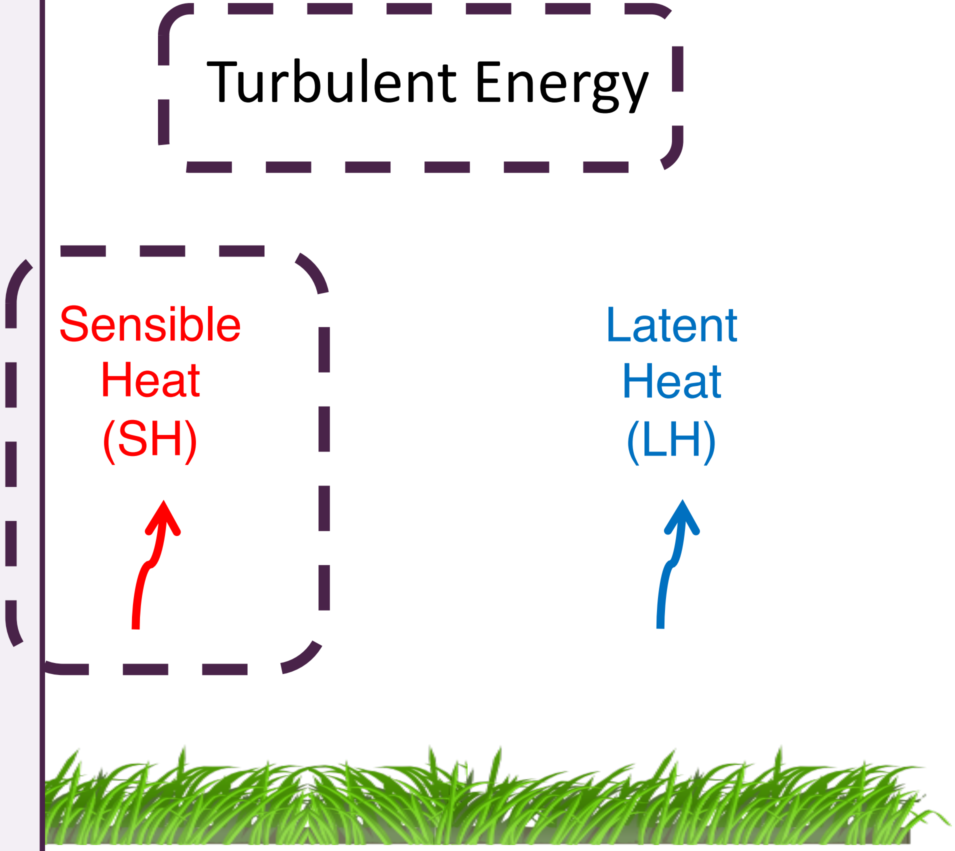

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Turbulent Energy

Sensible Heat (SH)

Latent Heat (LH)

The land surface energy budget is made up of ~~5~~ 4 pieces

Radiative Energy

Turbulent Energy

Shortwave Radiation (SW)

Longwave Radiation (LW)

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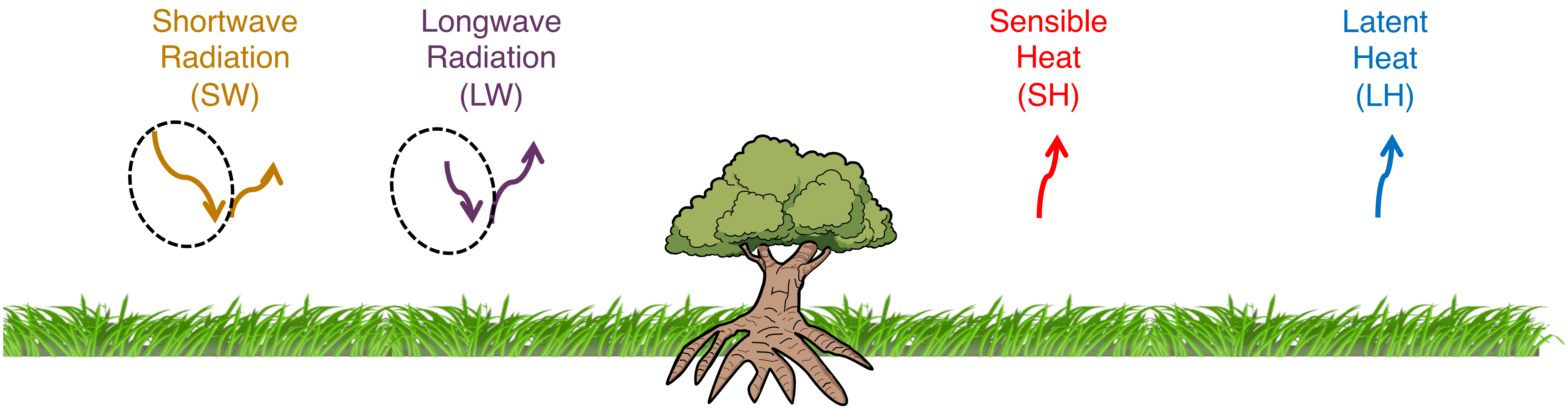
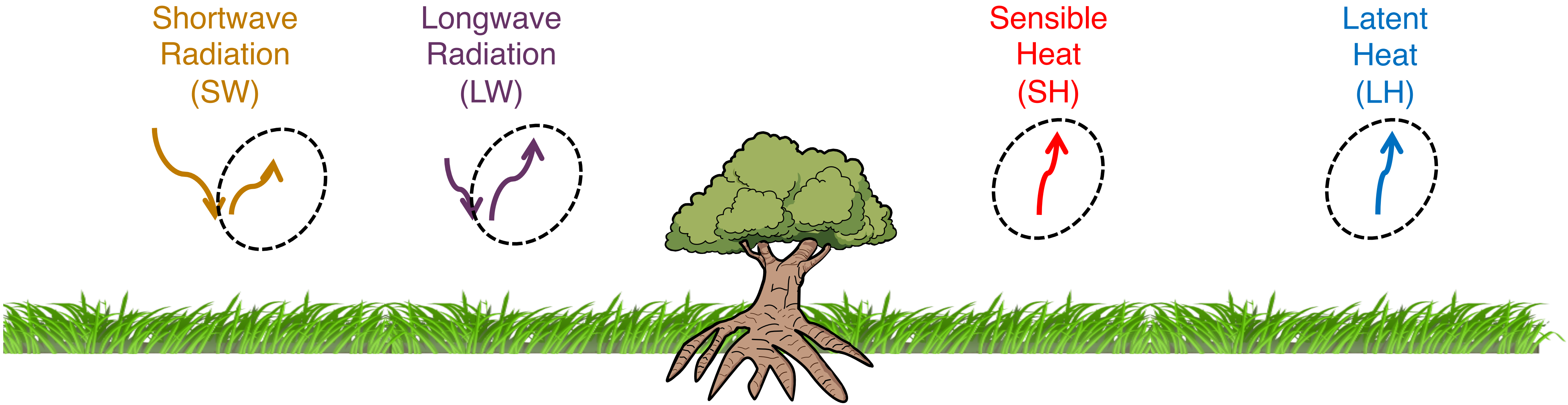
Energy In ≈ Energy Out

(downwards arrows) (upwards arrows)



The land surface energy budget is made up of ~~5~~ 4 pieces

$\boxed{\text{Energy In} \approx \text{Energy Out}}$



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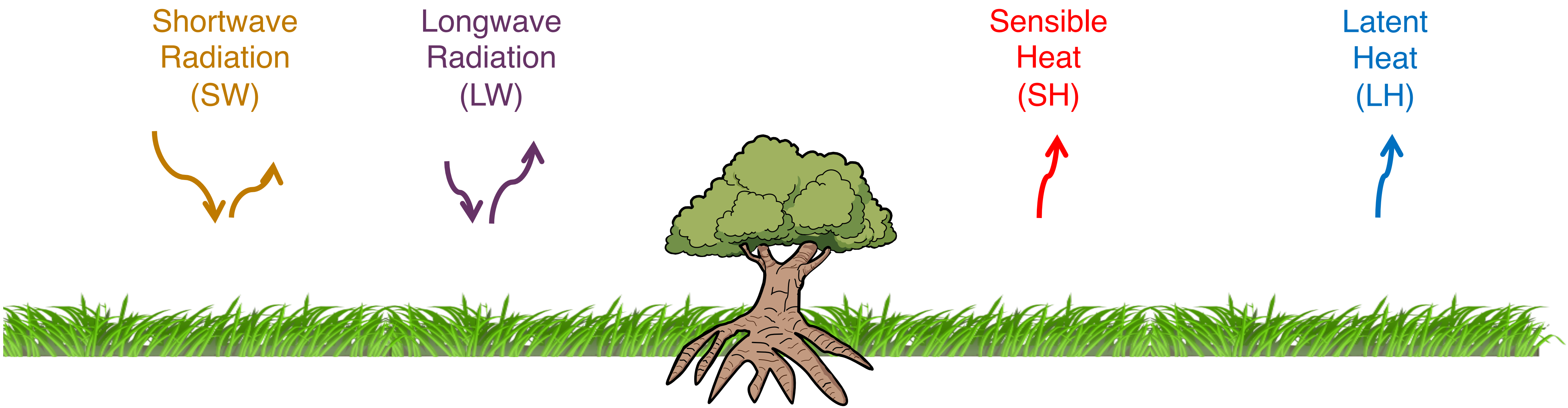
$$\boxed{\text{Energy In} \approx \text{Energy Out}}$$

Land surface properties & climate determine how energy gets divided between these fluxes



Balance of fluxes determine the land surface temperature

The land surface energy budget is made up of ~~5~~ 4 pieces

Energy In ≈ Energy Out

Land surface properties & climate determine how energy gets divided between these fluxes

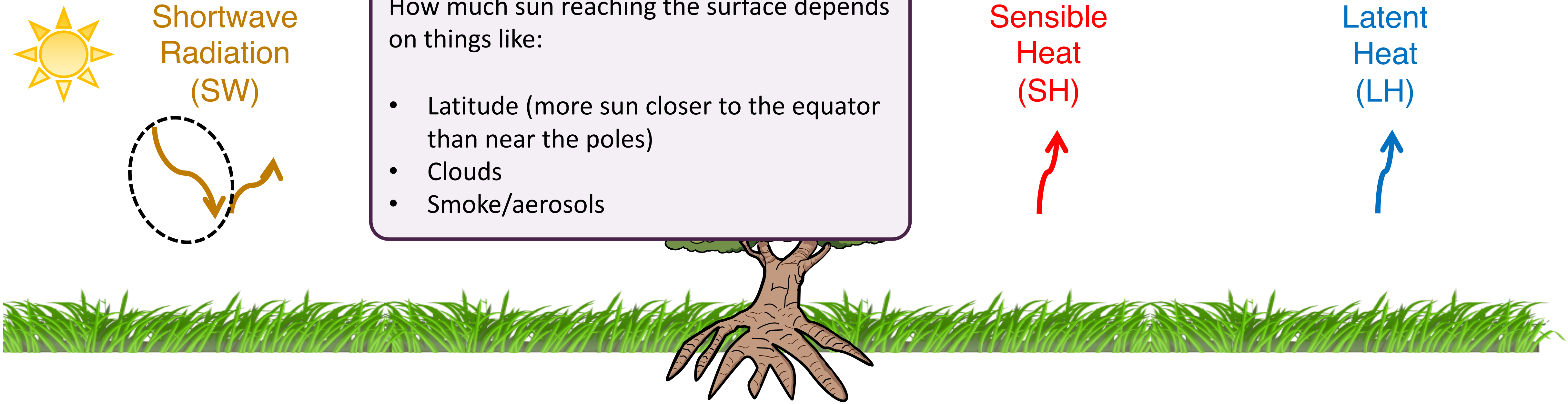
Shortwave Radiation (SW)

How much sun reaching the surface depends on things like:

- Latitude (more sun closer to the equator than near the poles)
- Clouds
- Smoke/aerosols

Sensible Heat (SH)

Latent Heat (LH)



Balance of fluxes determine the land surface temperature

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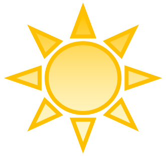
Energy In ≈ Energy Out

Land surface properties & climate determine how energ



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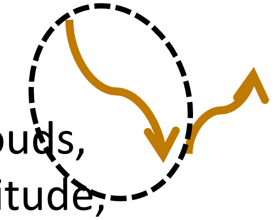

Clouds, latitude, aerosols

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Dark, smoky skies above San Francisco, Sept 2020, 1pm

The Wong Couple Photographers via SFGate

Balance of fluxes determine the land surface temperature

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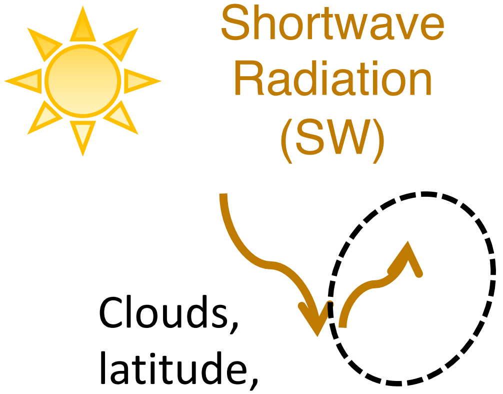

Shortwave Radiation (SW)

Clouds, latitude, aerosols

albedo

How much sun reaching the surface depends on things like:

- Latitude (more sun closer to the equator than near the poles)
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- Smoke/aerosols

How much sun the surface absorbs depends on albedo:

$$albedo = \frac{reflected\ SW}{incoming\ SW}$$

Sensible Heat (SH)

Latent Heat (LH)

The land surface energy budget is made up of ~~5~~ 4 pieces

Energy In ≈ Energy Out

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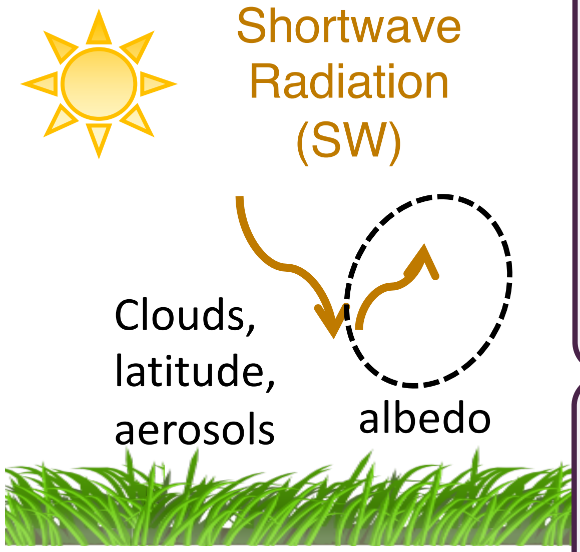

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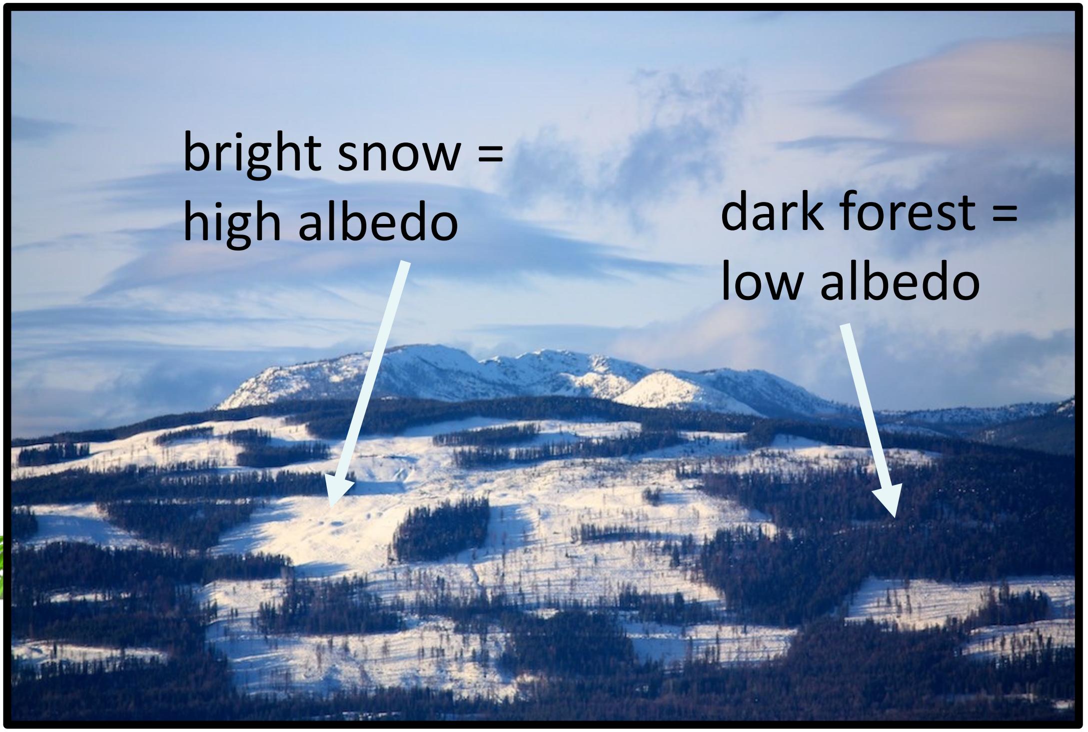
How much sun the surface <u>absorbs</u> depends on <u>albedo:</u>

$$albedo = \frac{reflected\ SW}{incoming\ SW}$$



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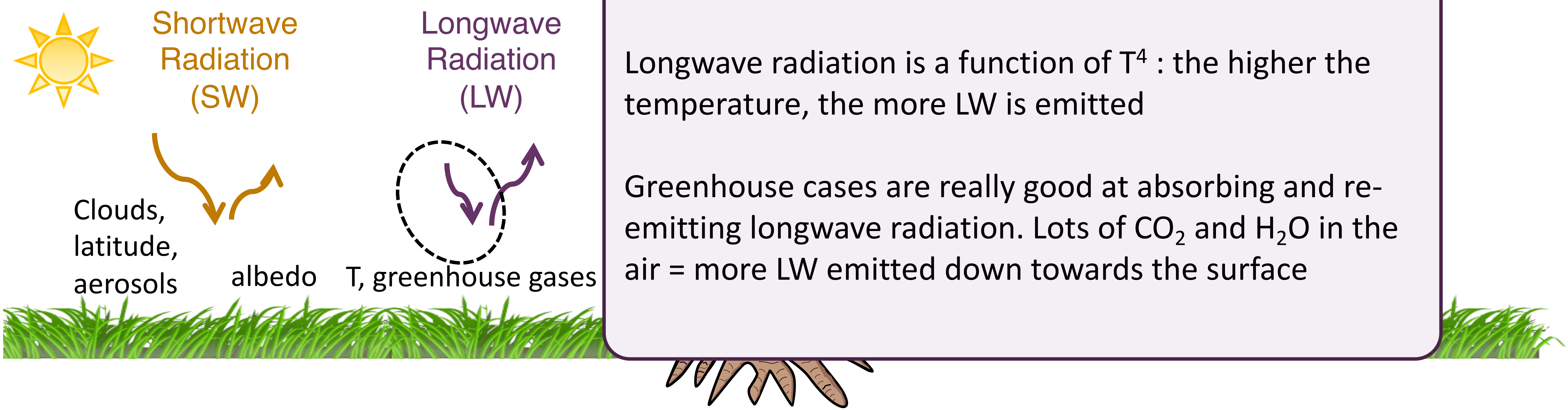

Longwave radiation is a function of T^4 : the higher the temperature, the more LW is emitted

Greenhouse cases are really good at absorbing and re-emitting longwave radiation. Lots of CO_2 and H_2O in the air = more LW emitted down towards the surface

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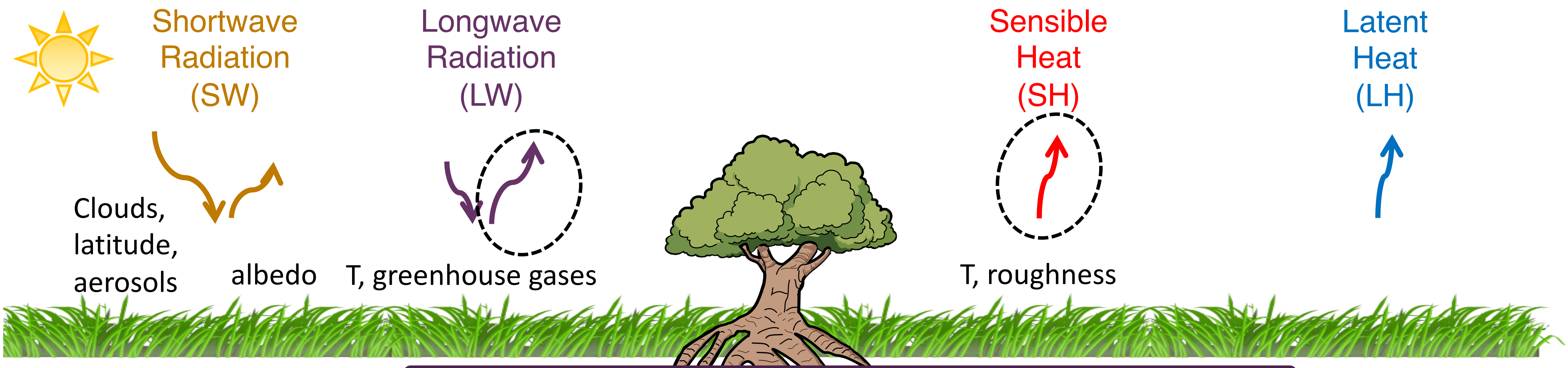
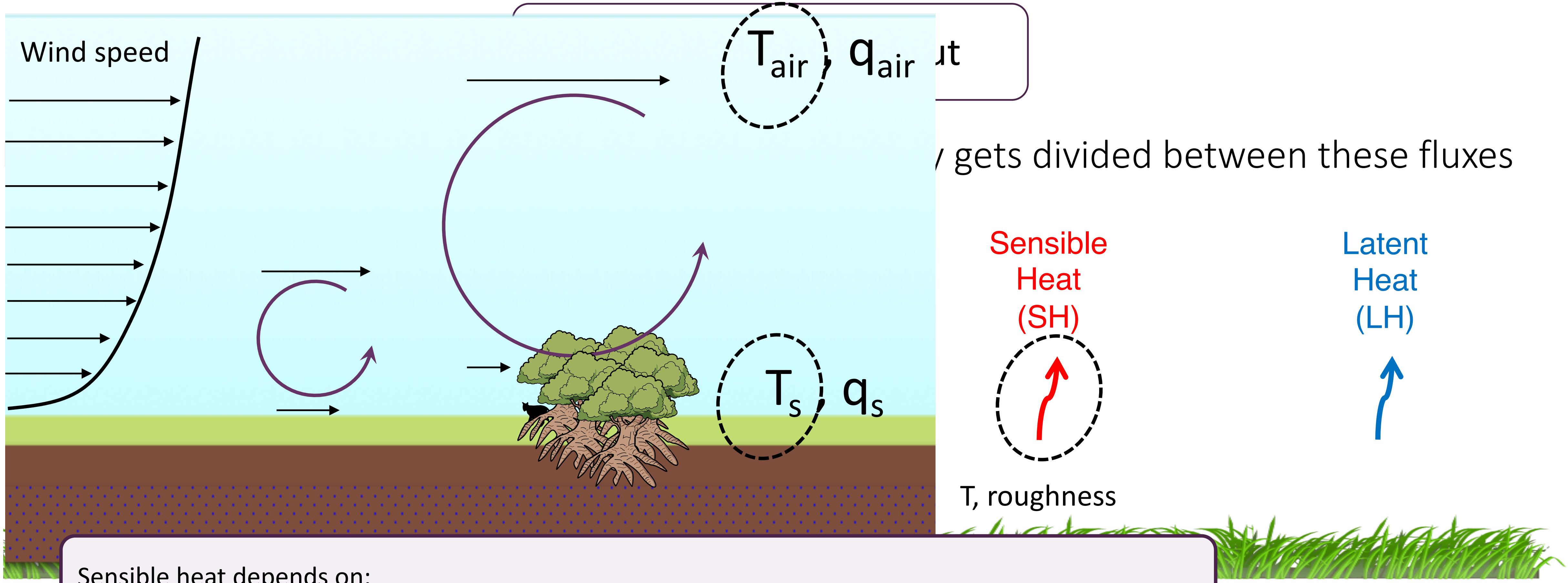


Both LW↑ and SH increase with higher surface temperatures

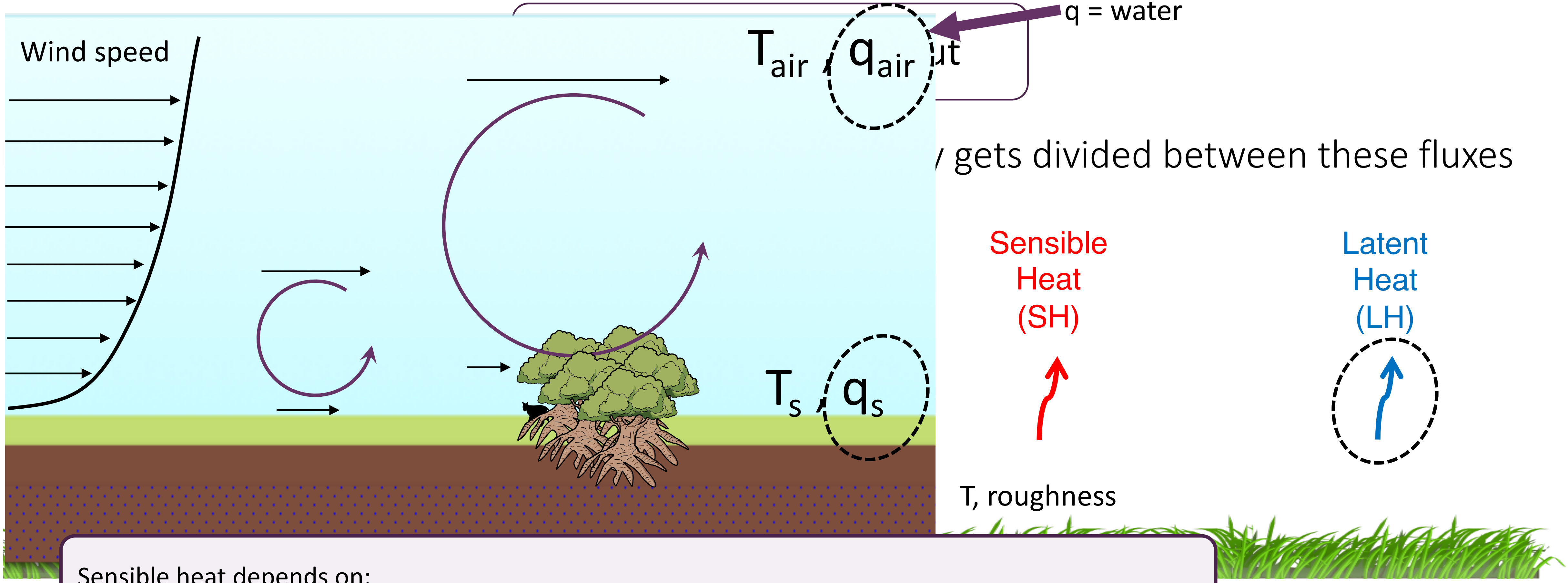
The land surface energy budget is made up of ~~5~~ 4 pieces



Sensible heat depends on:

- How well wind can mix air from the surface with the atmosphere (surface roughness)
- Wind speeds
- Difference in temperature between surface air and air higher up

The land surface energy budget is made up of 4 ~~5~~ pieces



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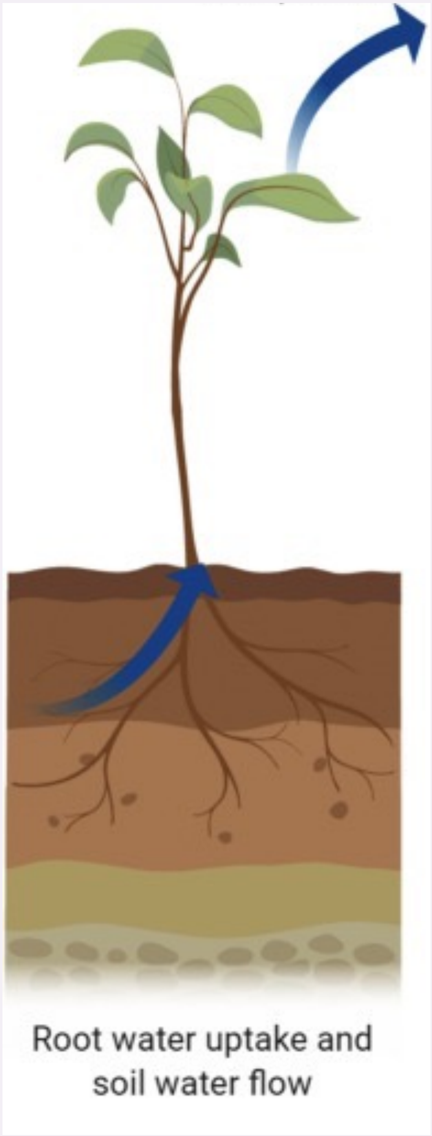
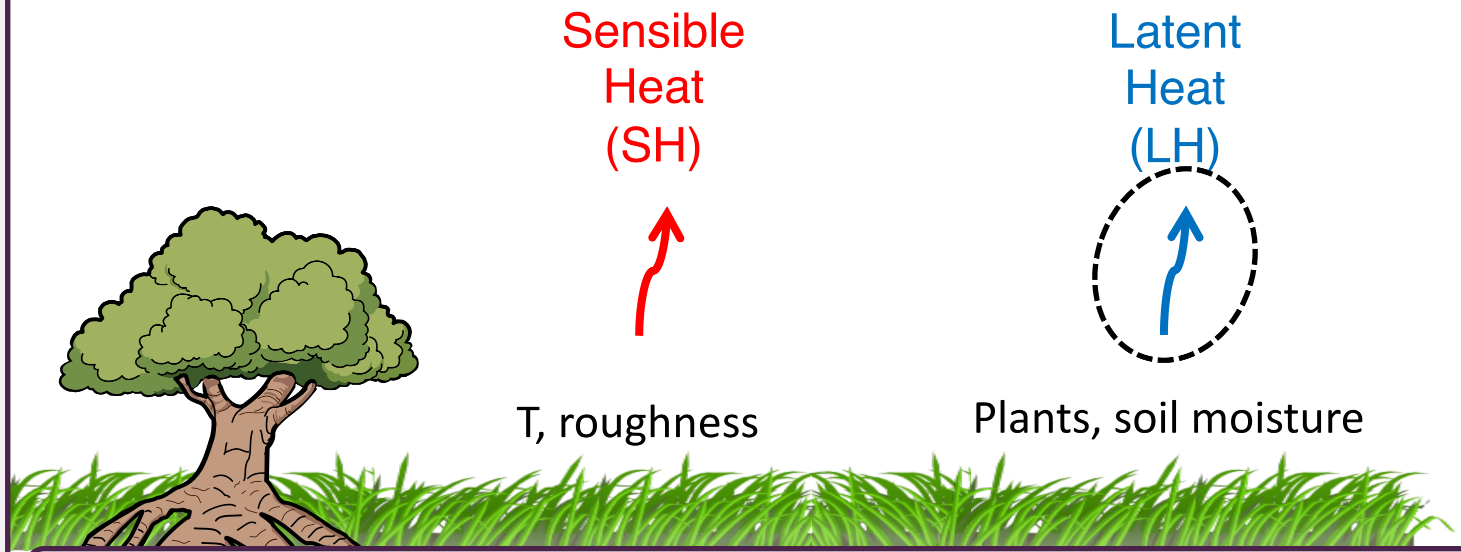


Carminati et al. 2020



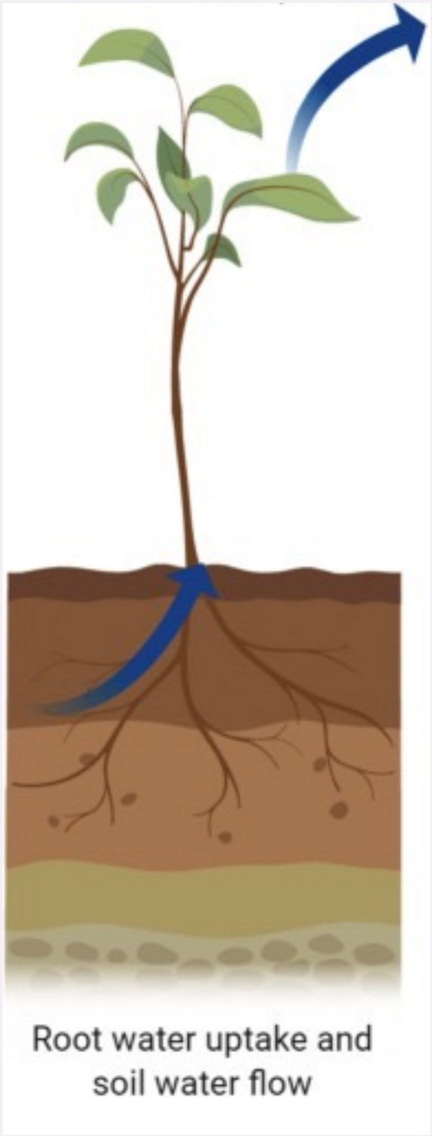
Latent heat (evaporation) <u>cools</u> the surface because it removes energy from the land without needing surface temperatures to go up

4

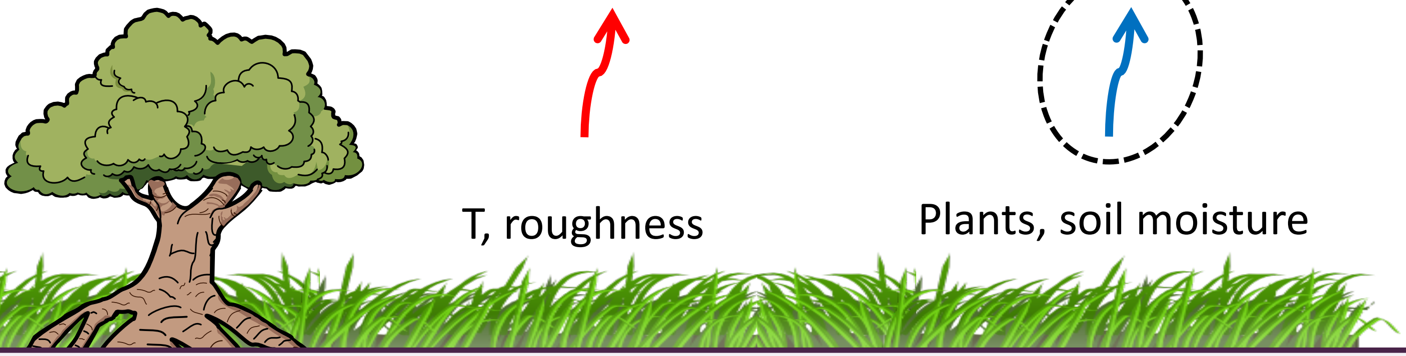
Th get is made up of ~~5~~ pieces

ergy In ≈ Energy Out

La ermine how energy gets divided between these fluxes



Carminati et al. 2020



Sensible Heat (SH)

T, roughness

Latent Heat (LH)

Plants, soil moisture

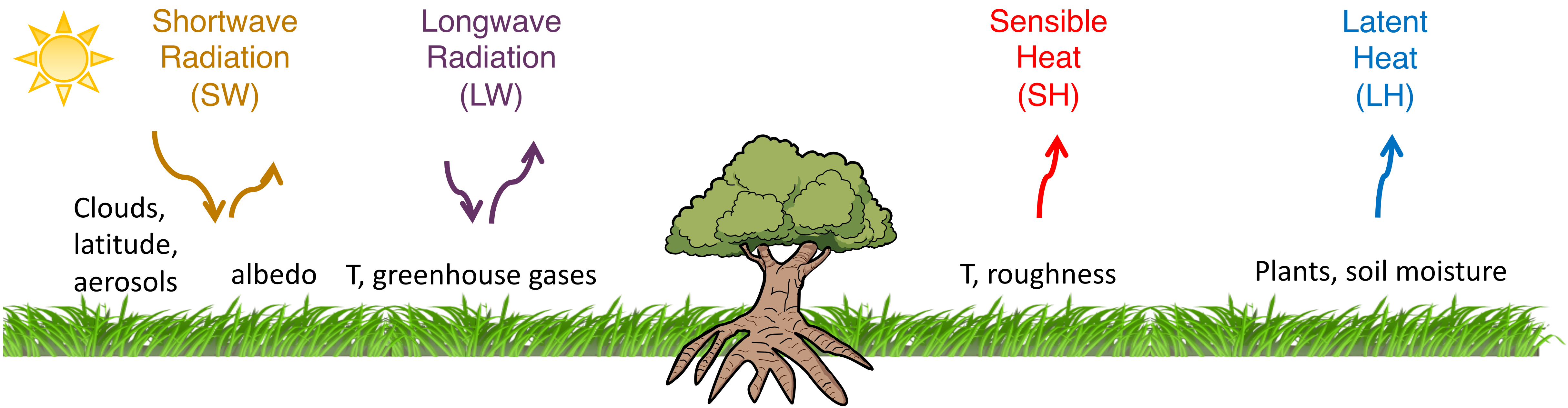
Latent heat (evaporation) <u>cools</u> the surface because it removes energy from the land without needing surface temperatures to go up

Important note: evaporation doesn’t cool the whole PLANET, because energy (heat) is released when the water vapor condenses to form clouds

The land surface energy budget is made up of ~~5~~ 4 pieces

$\boxed{\text{Energy In} \approx \text{Energy Out}}$

Land surface properties & climate determine how energy gets divided between these fluxes

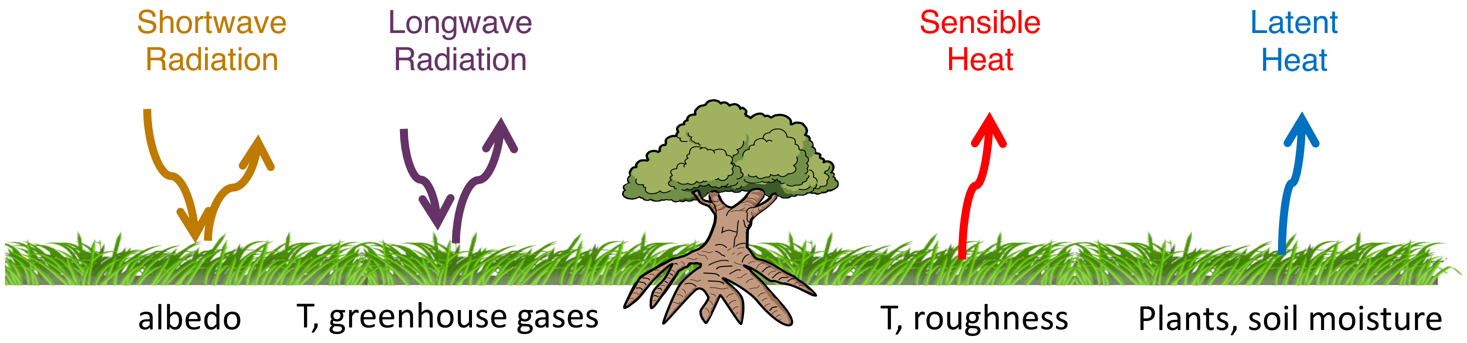


Balance of fluxes determine the land surface temperature

Based on what we've learned about the surface energy budget:

pollev.com/marysalague767

Which land surface below will absorb the most shortwave energy?



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Based on what we’ve learned about the surface energy budget:

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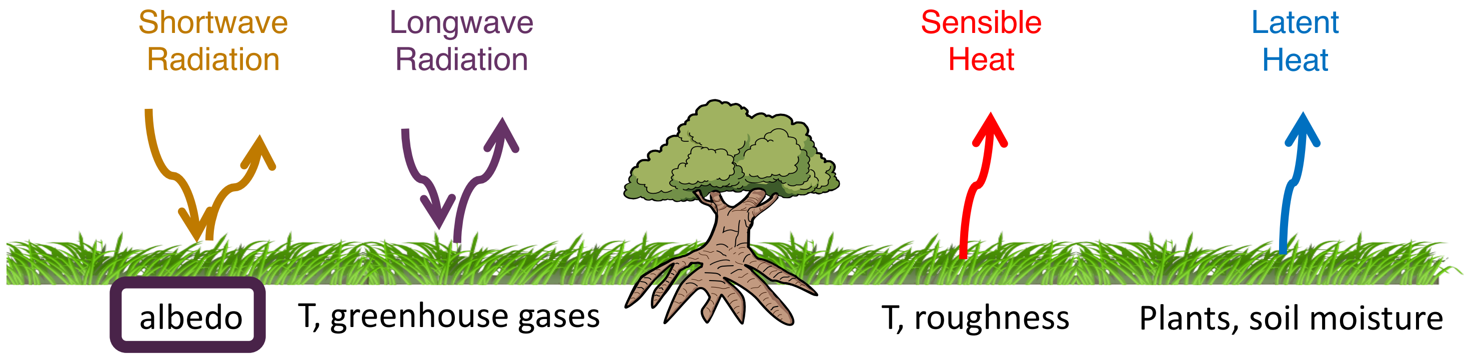
a

b

c



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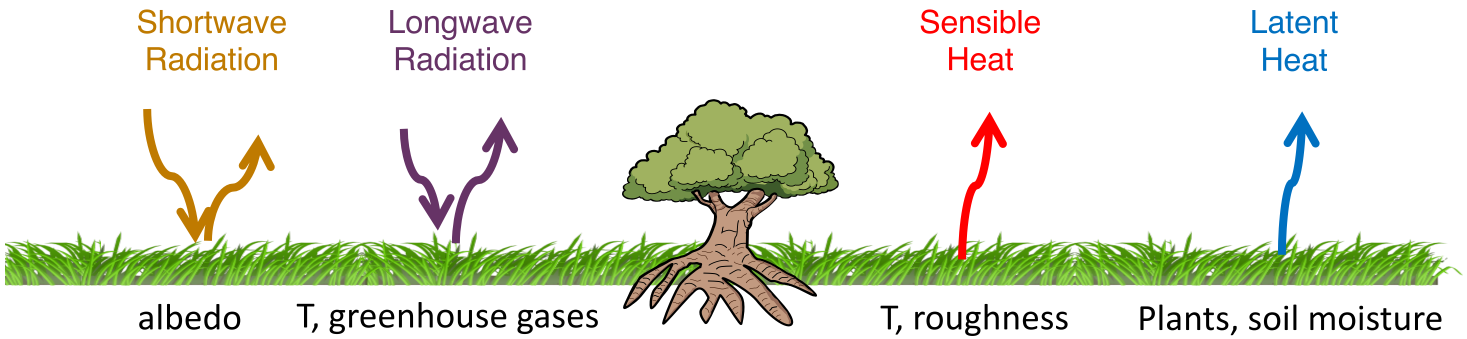

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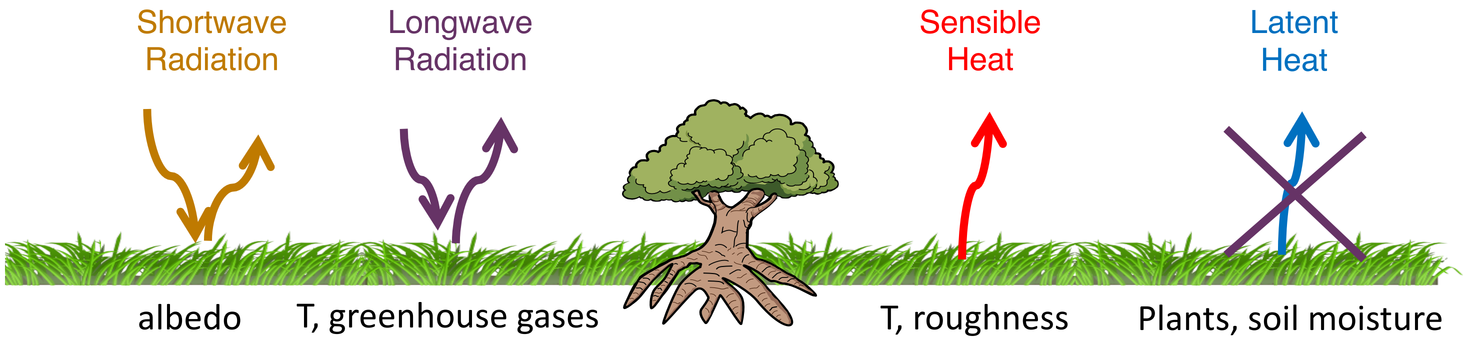

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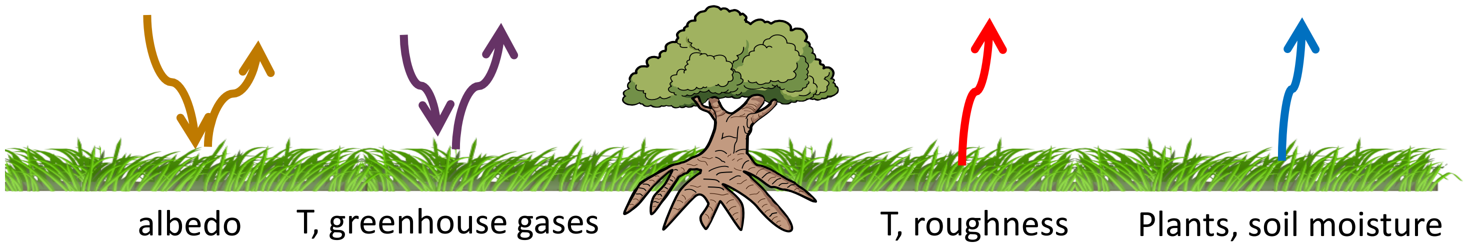

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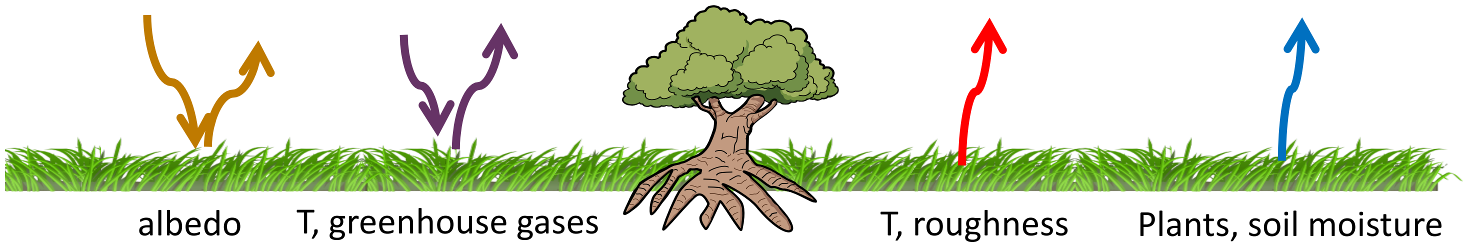

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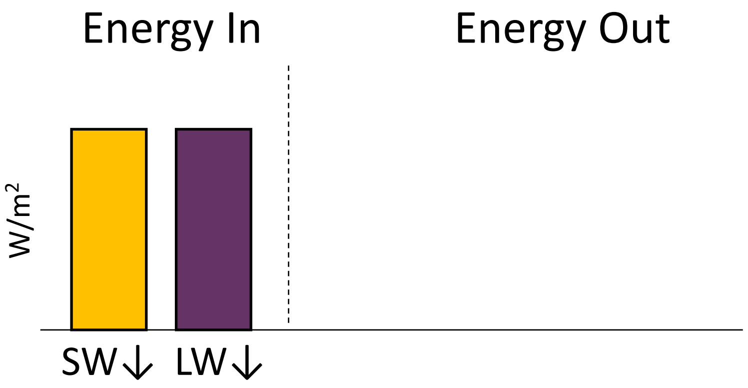

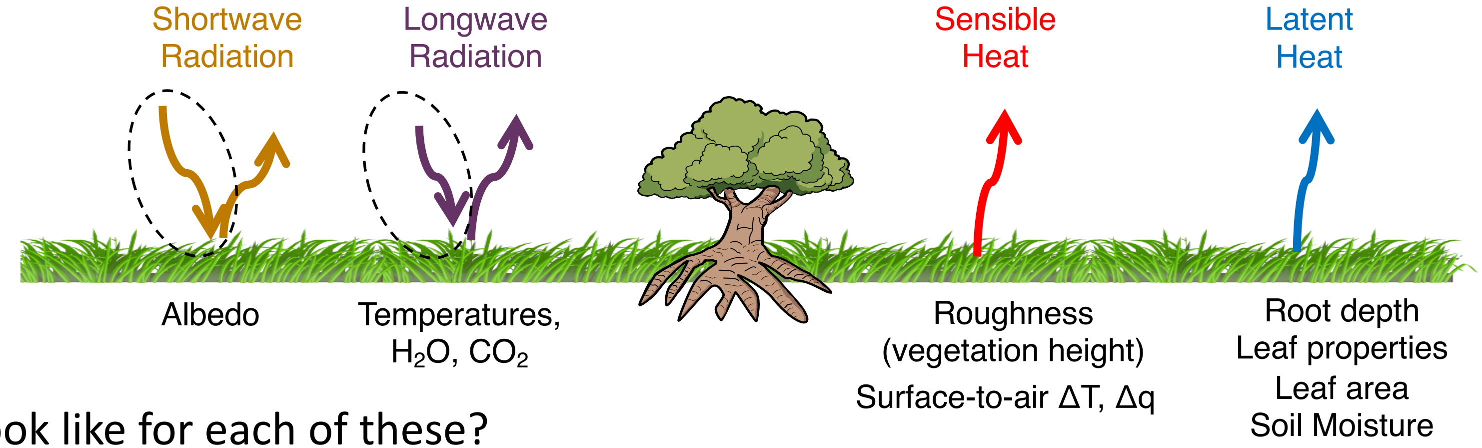

What might the surface energy budgets look like for each of these?

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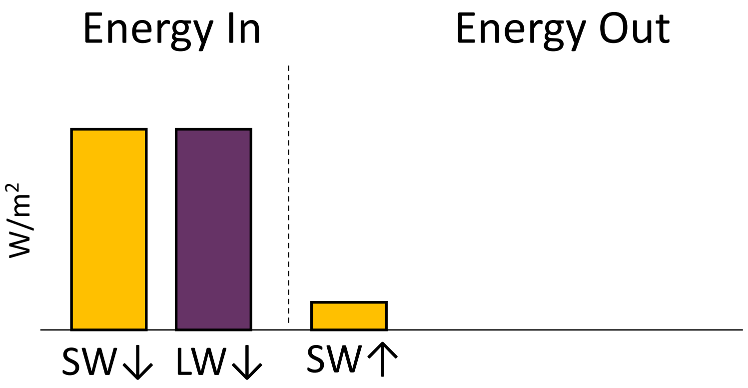

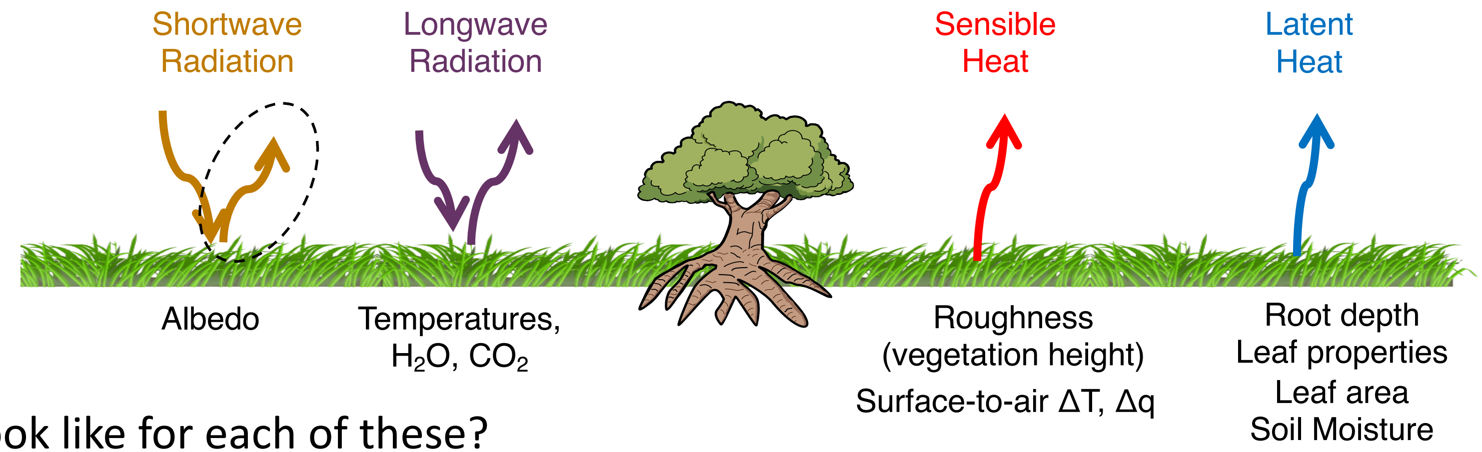

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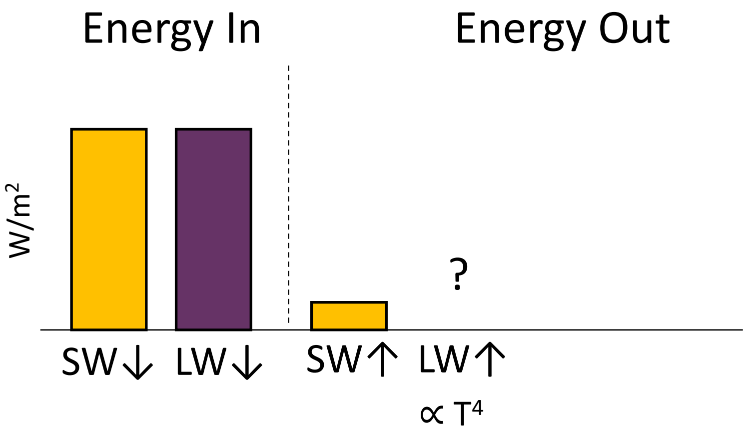

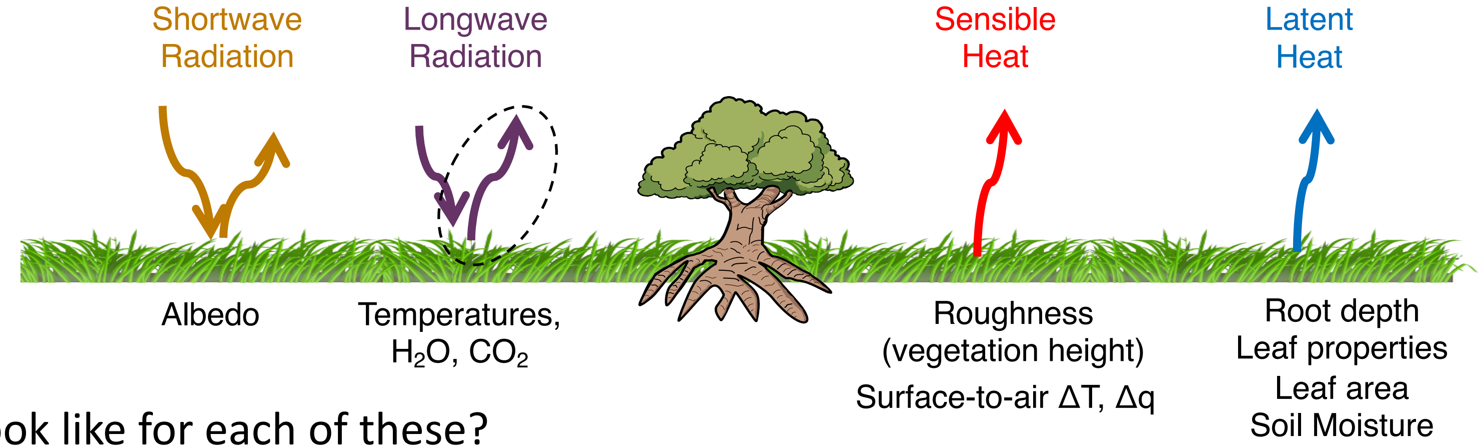

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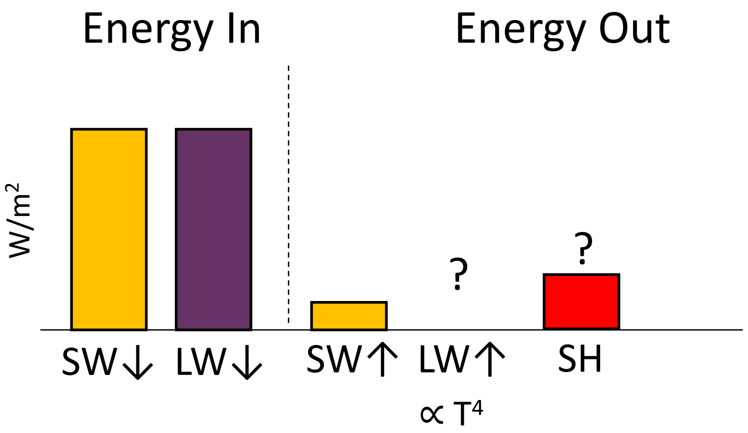

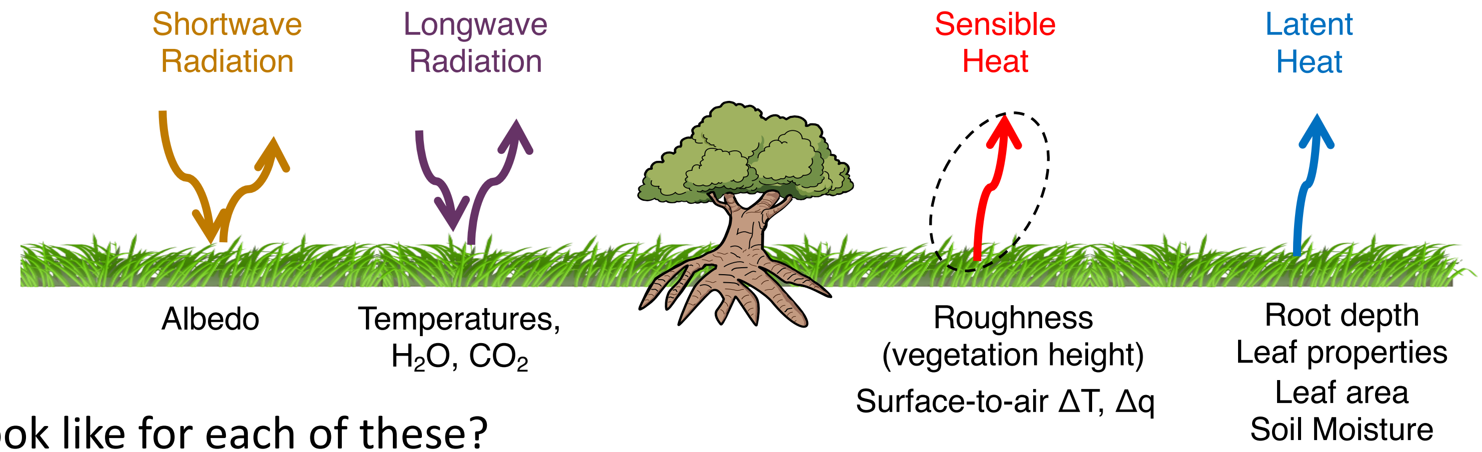

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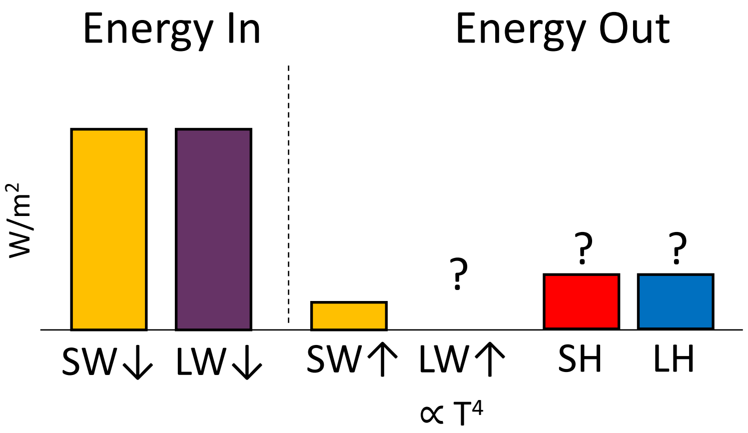

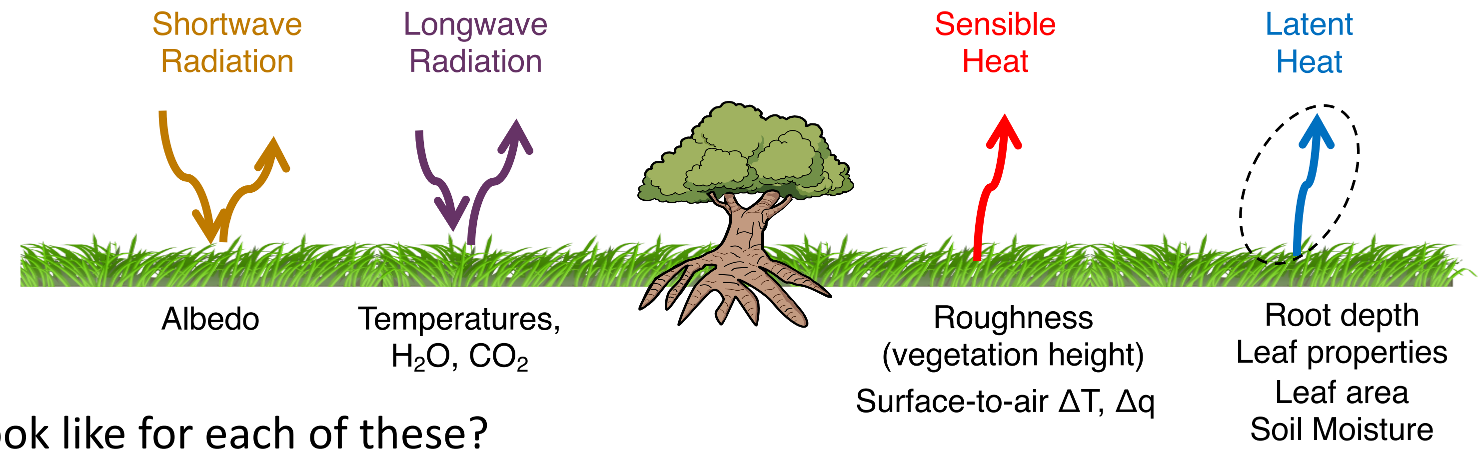

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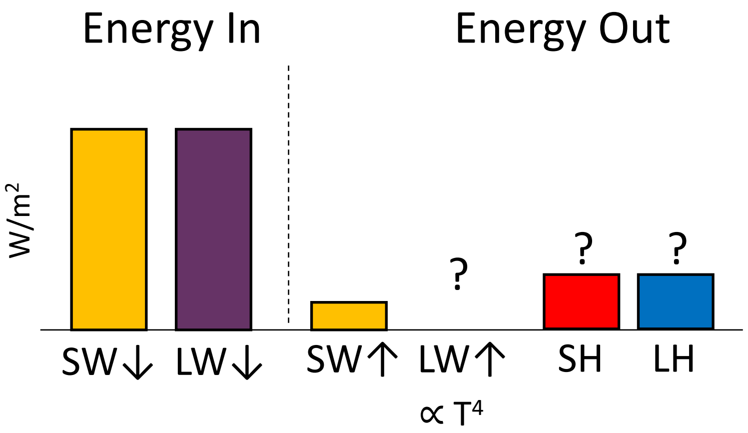

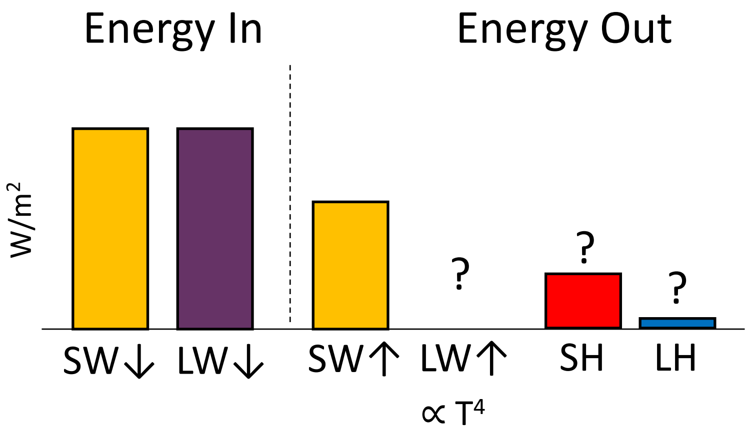

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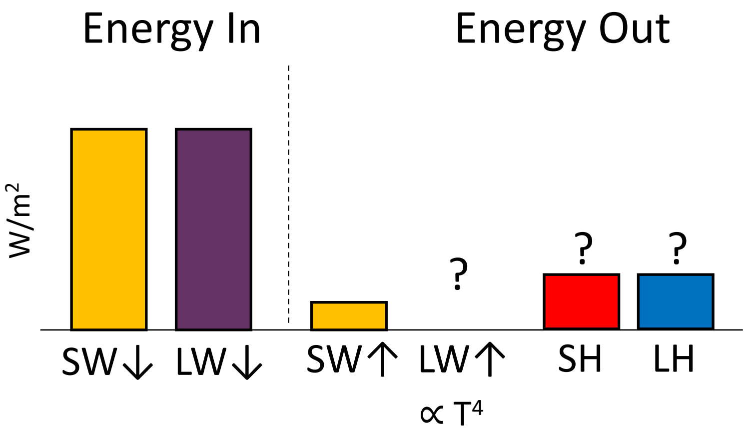

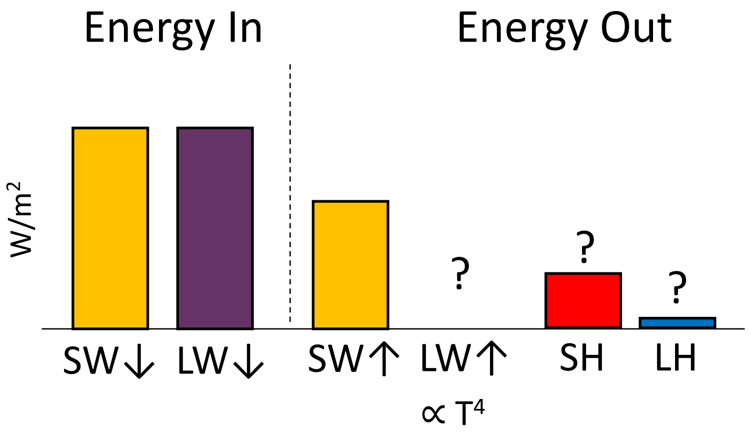

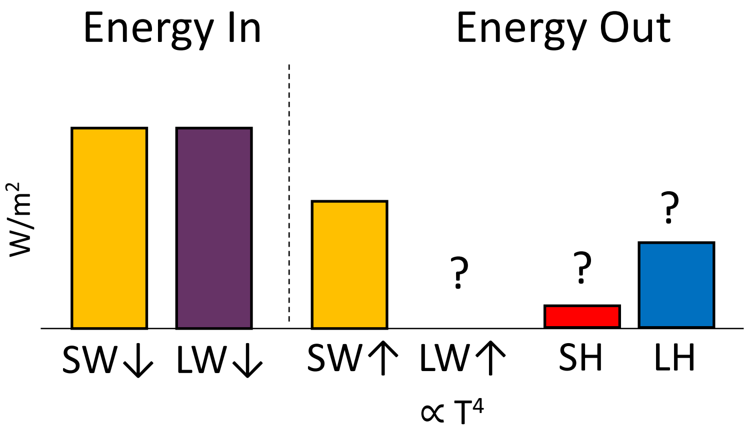

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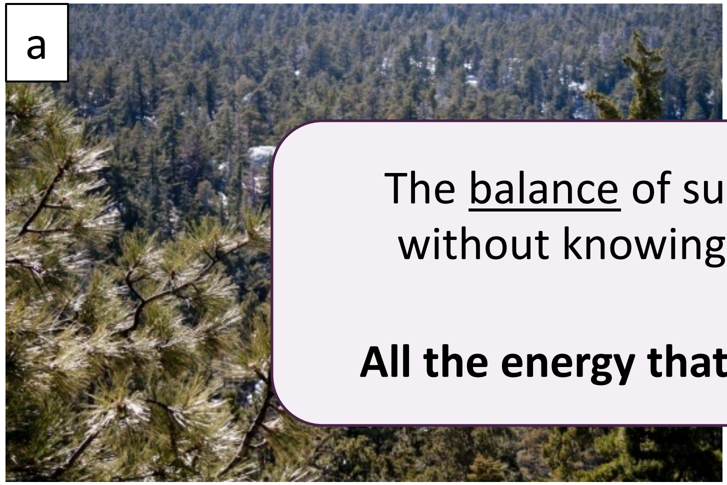

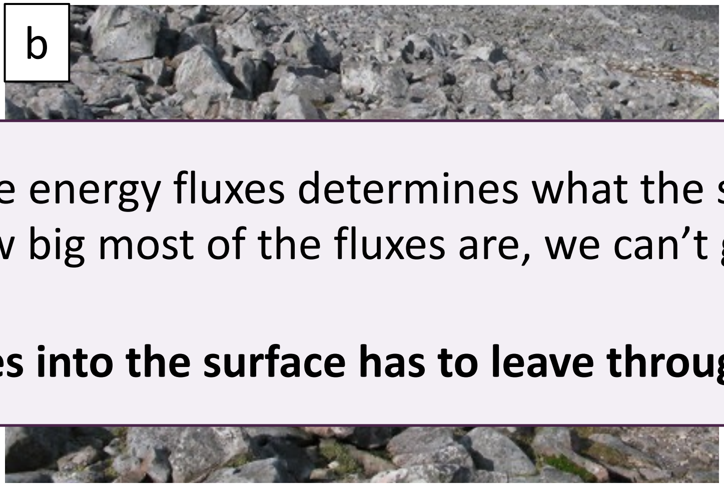

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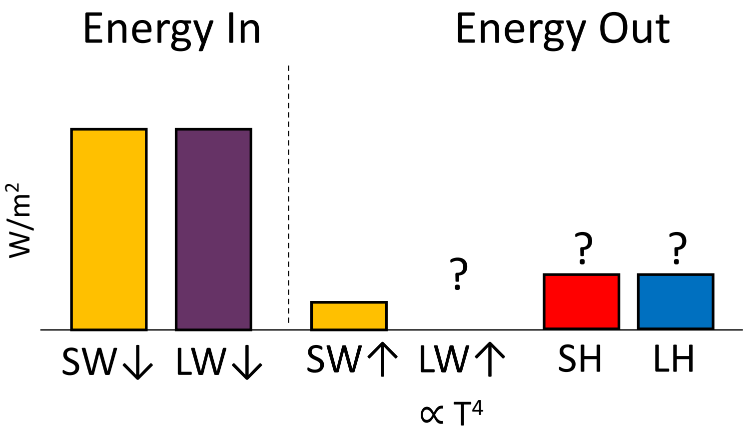
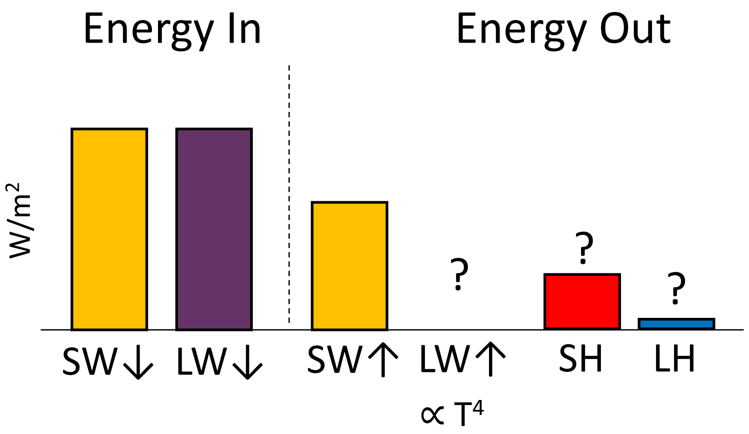
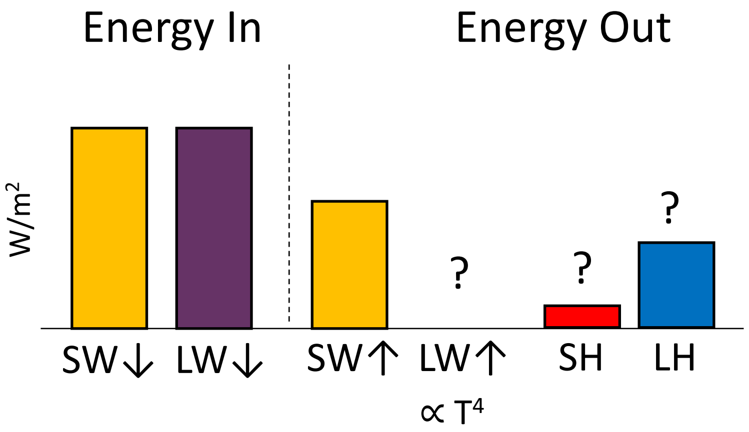
All the energy that goes into the surface has to leave through one of the 4 pathways







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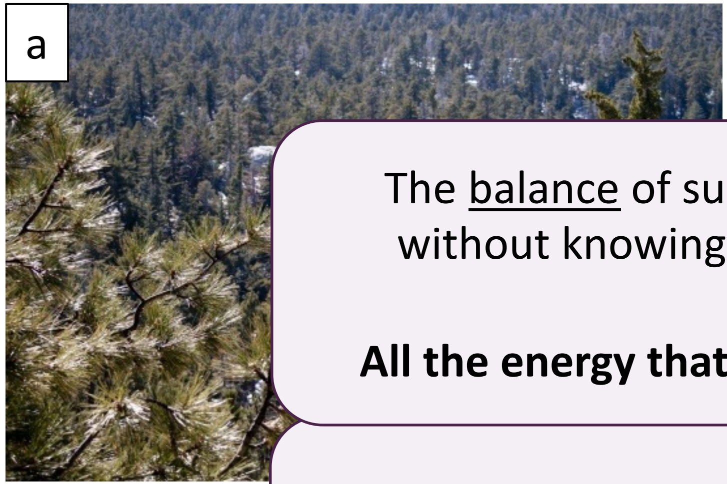

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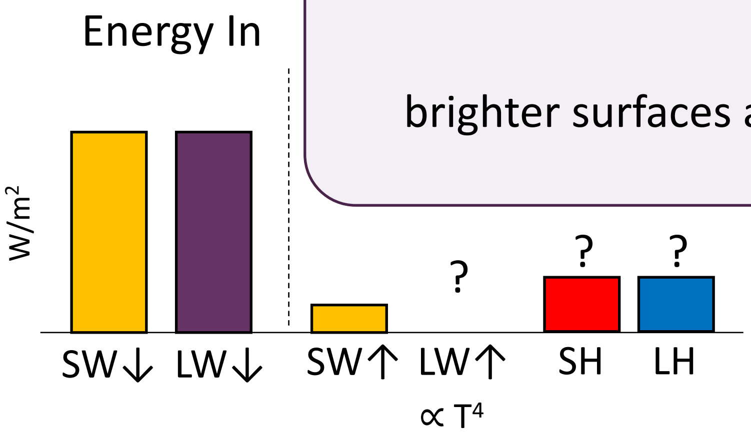
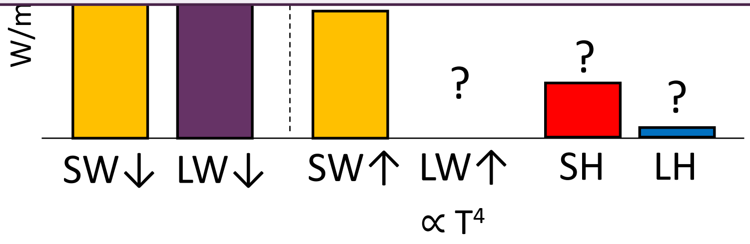
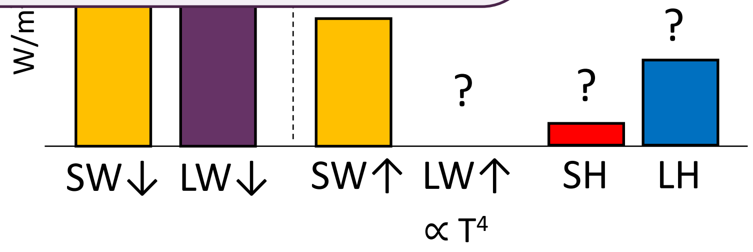
Generally:

brighter surfaces are cooler, and surfaces that can evaporate lots of water are cooler







Learning goals:

Theory:

- **Understand the components of the surface energy budget over land**

Energy In ≈ Energy Out

Exact breakdown of the terms in the surface energy balance determine the surface temperature

Application:

- Analyze the surface energy budget using climate model output
    - Interpret bar graphs of surface fluxes and predict how they might change with warming

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Climate data comes in many forms:

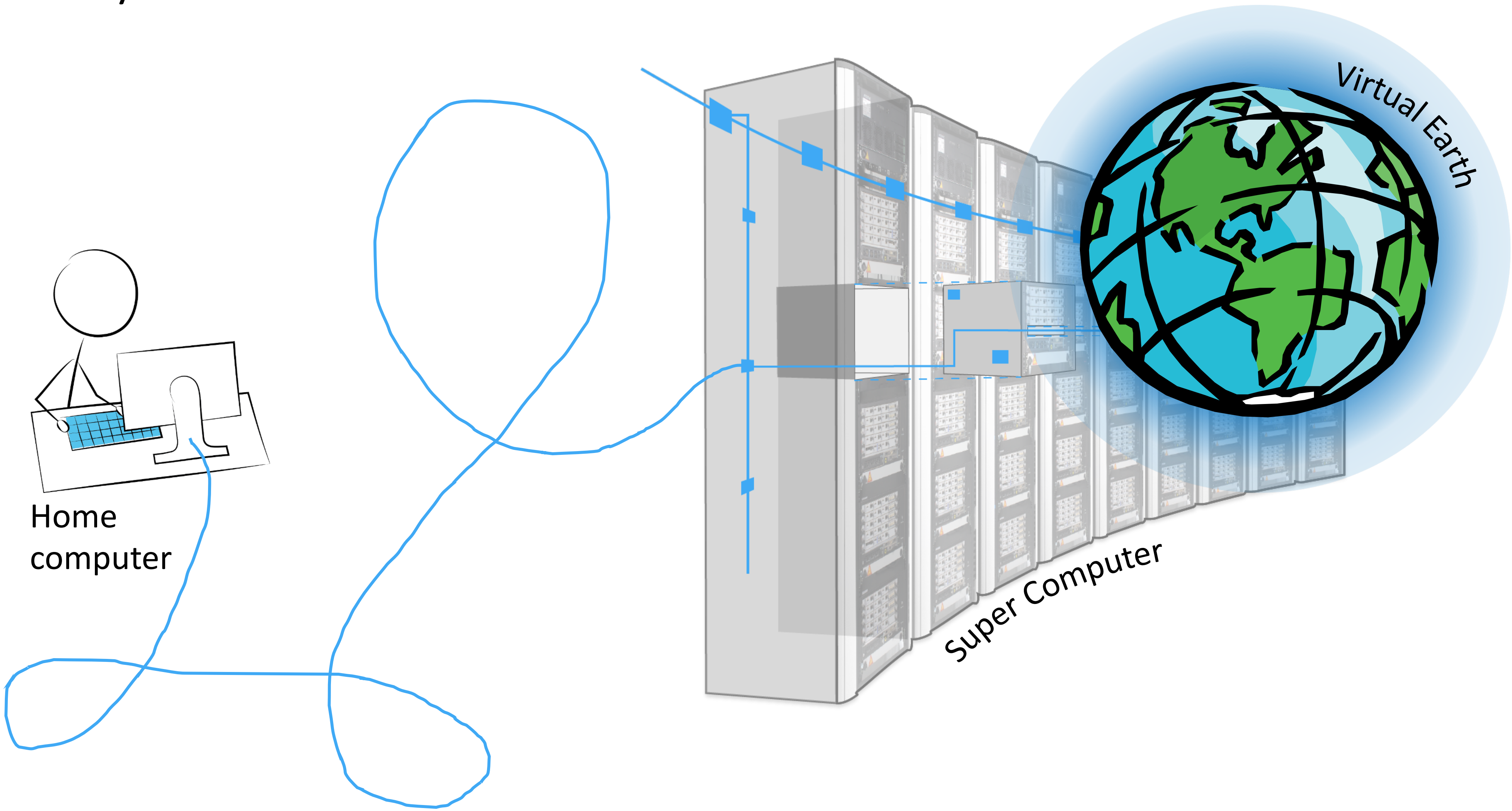
e.g. Satellite Observations

Ground Observations

Models

Climate data comes in many forms

Today: data from climate models



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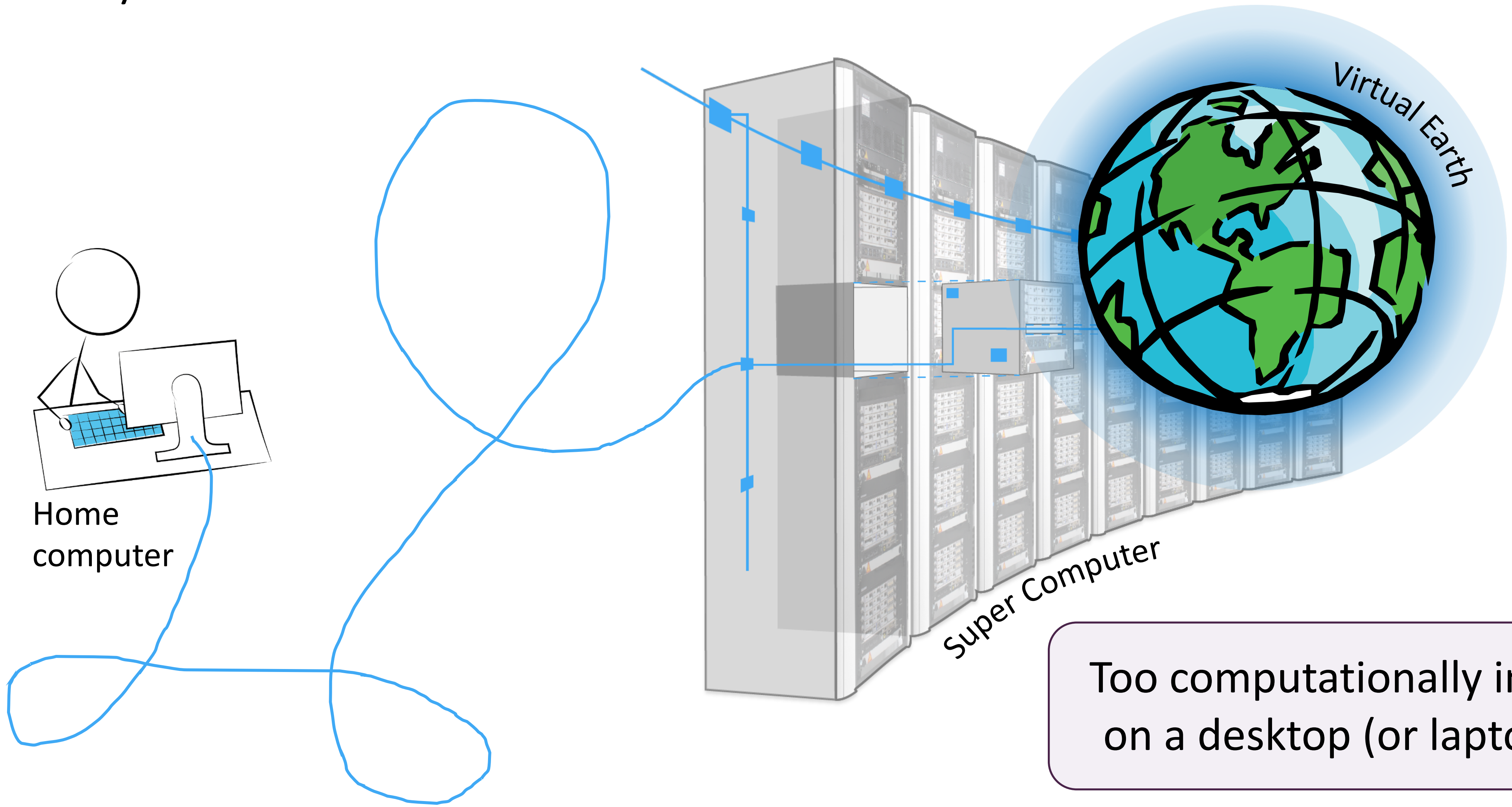

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Today's data: "1pctCO2" experiment: every year, increase CO_2 by 1%

- At the start of the run, looks like the pre-industrial Earth
- At the end of the run, has 4x as much CO_2 as the pre-industrial era

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File format:
"netcdf" files – a common data format for storing large, gridded datasets like climate model output

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Pros/cons of climate data (vs observations):

Pros:
Self consistent!
Energy is conserved!*
Let us test how the Earth would respond to forcings without experimenting on our actual home planet.

Cons:
Can differ from observations due to: variability, missing physics
Fairly coarse resolution (each "point" is ~1 degree wide, or ~100 km)

* Energy is also conserved in the real world, but *measuring* it accurately can be really hard

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Today: data from climate models

Climate model data analysis has many steps:

Get the data (run the climate model) → Write some code → Make some figures → Interpret the figures

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Activity:

In groups, compare climate model data for the surface energy balance at two distinct land locations:
Oregon and the Sahara desert

www.github.com/marysa/surface_energy_budget/ (link)

Click on "SurfaceEnergyBudgetAnalysis.ipynb"

Data analysis:

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Done!

Compare the surface energy budget breakdown of two different ecosystems

Activity:

In groups, compare climate model data for the surface energy balance at two distinct land locations:
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From the differences in surface fluxes, what can you infer about what the two locations actually look like, and how they might respond to global warming?

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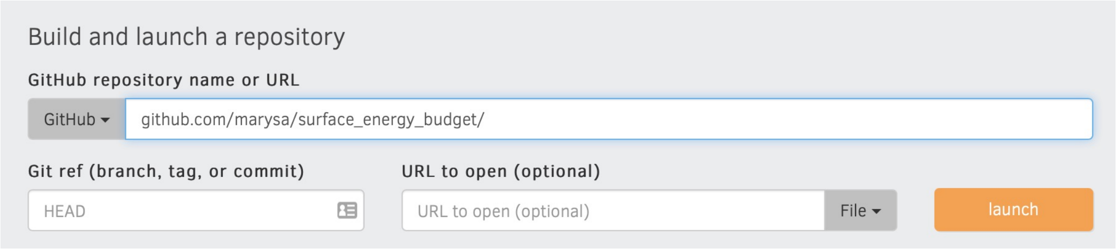
If you want to run this code interactively later, go to: mybinder.org
In the "launch a repository" field, choose "GitHub" and enter the path to our repository (github.com/marysa/surface_energy_budget/)



Then click "launch" to launch an interactive JupyterLab session. It can take a few minutes to start up.
Important note: changes you make won't be saved! You'll need to download your own copy of the code to save changes.

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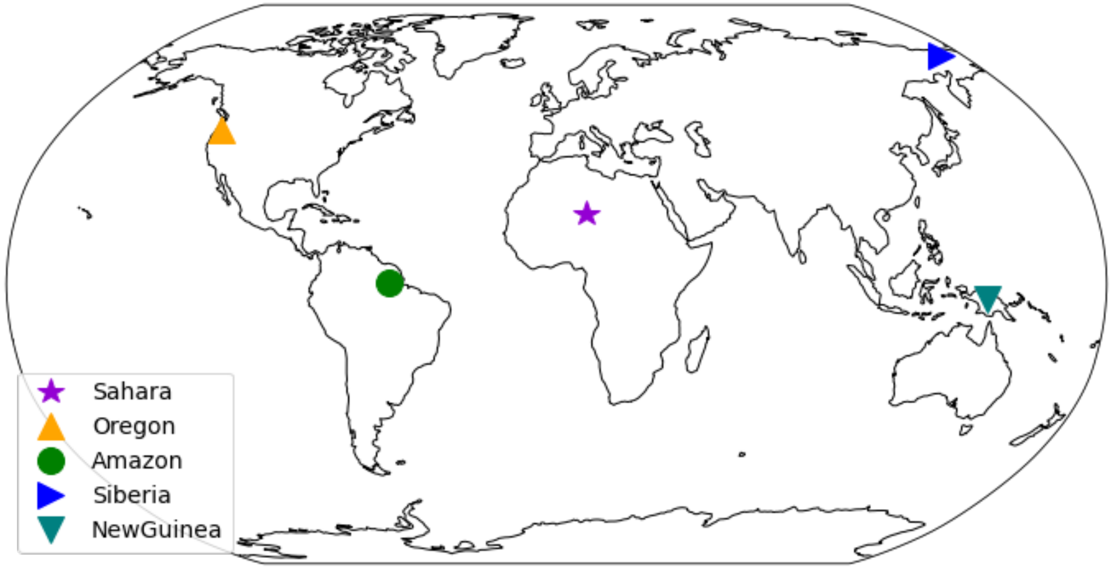

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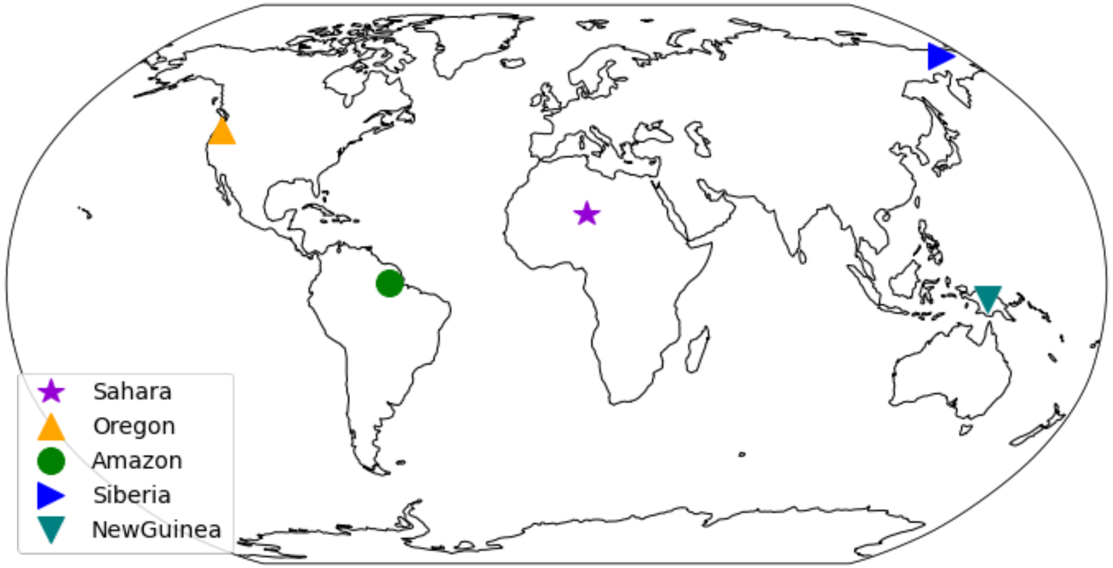
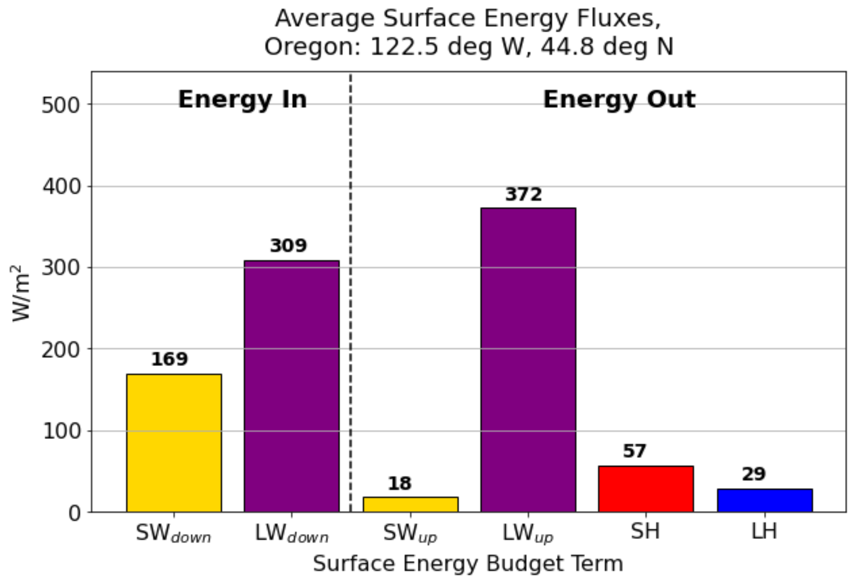


For each location, the surface energy budget is plotted:



Your task:

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In groups, compare the surface energy budget bar graphs for any two locations (I suggest Oregon & the Sahara) to address the following questions:

1. Does Energy In = Energy Out?
2. Which region has more Energy In?
3. Which region gets more sun? Does this fit with what you expect of the climate there?
4. Which region absorbs more shortwave radiation (albedo = SW_{up} / SW_{down}). Does this make sense for the land cover of the two regions (feel free to use google maps here!)
5. Which region has more evaporation (latent heat flux)?

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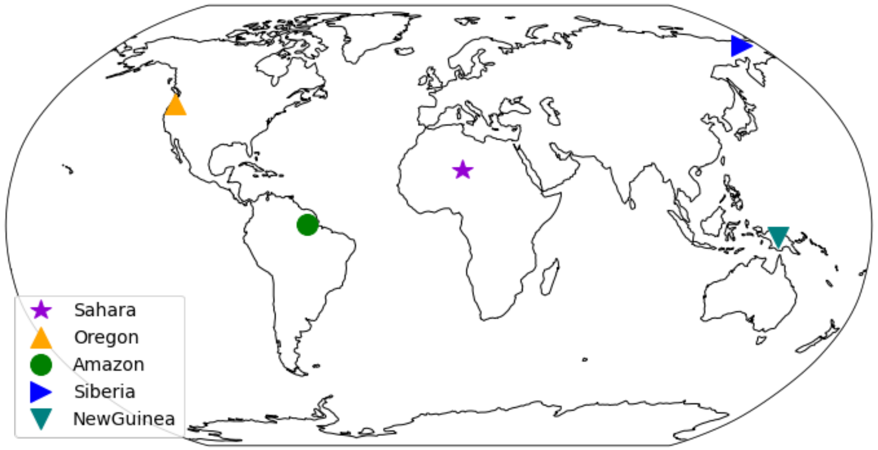

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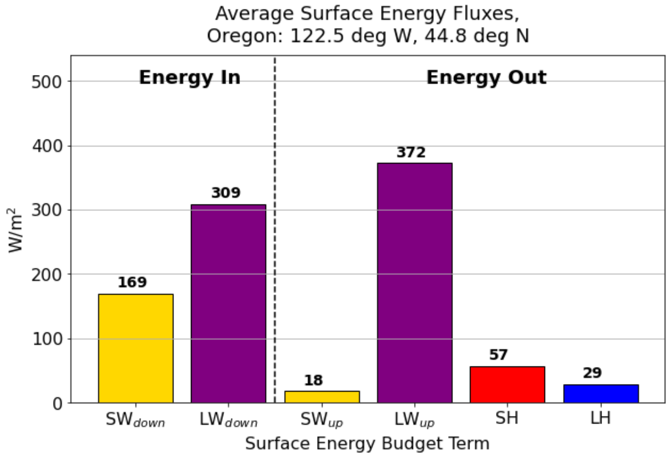

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Click on "SurfaceEnergyBudgetAnalysis.ipynb"

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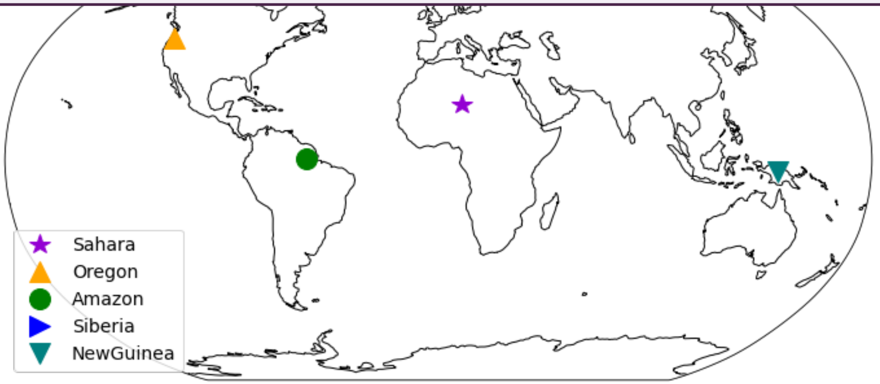
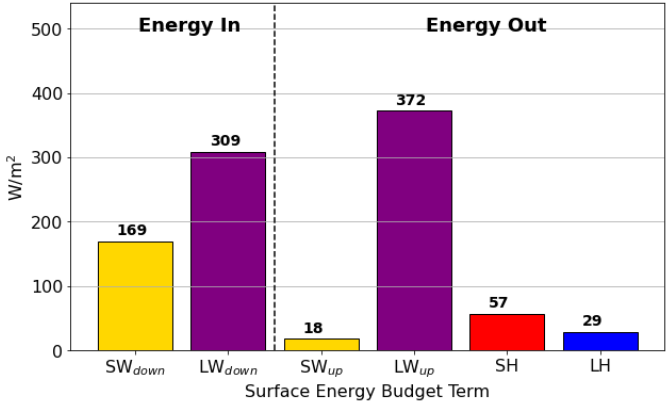
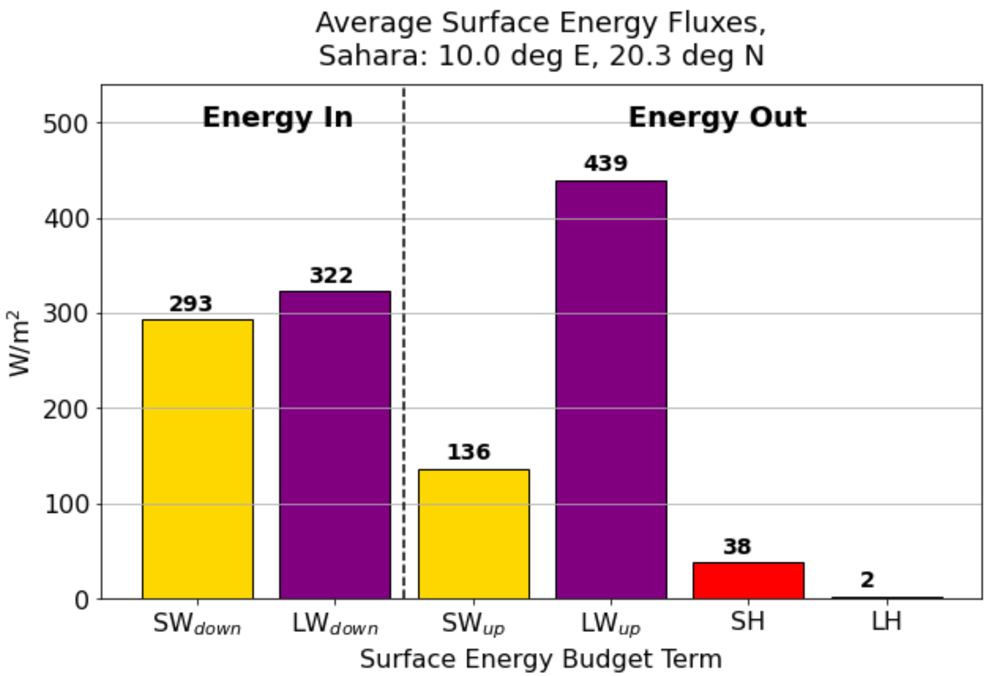
1. Does Energy In = Energy Out?
2. Which region has more Energy In?
3. Which region gets more sun? Does this fit with what you expect of the climate there?
4. Which region absorbs more shortwave radiation (albedo = SW_{up} / SW_{down}). Does this make sense for the land cover of the two regions (feel free to use google maps here!)
5. Which region has more evaporation (latent heat flux)?

6. With ↑ atmospheric CO_2, we expect longwave radiation into the surface (LW_{down}) to go up (because the atmosphere is hotter). How do you think that will impact the surface fluxes – and thus surface temperature – in your two locations?

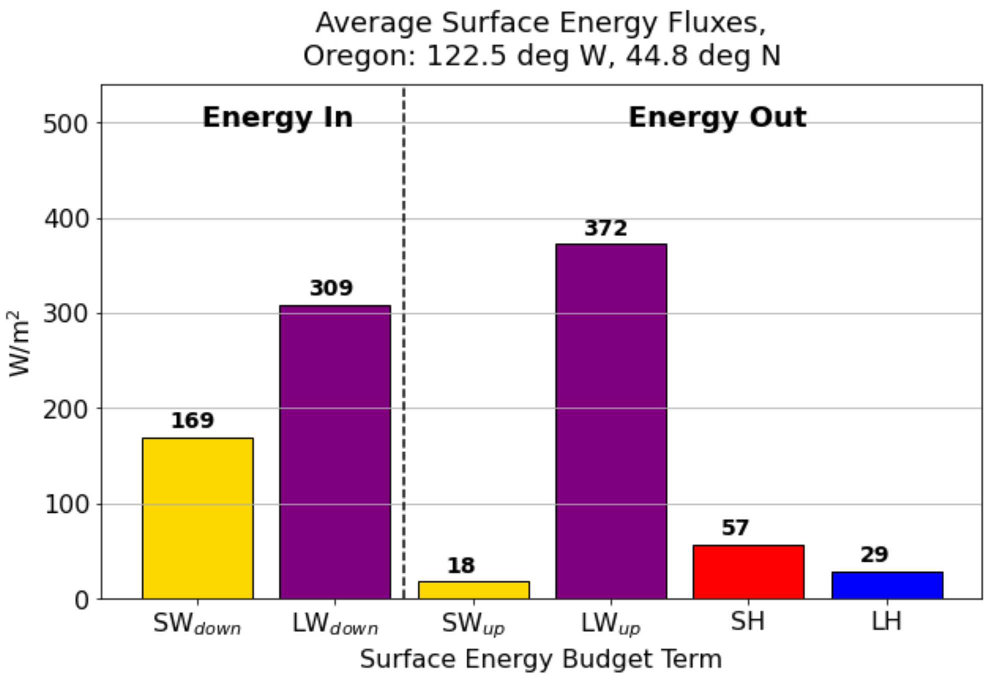


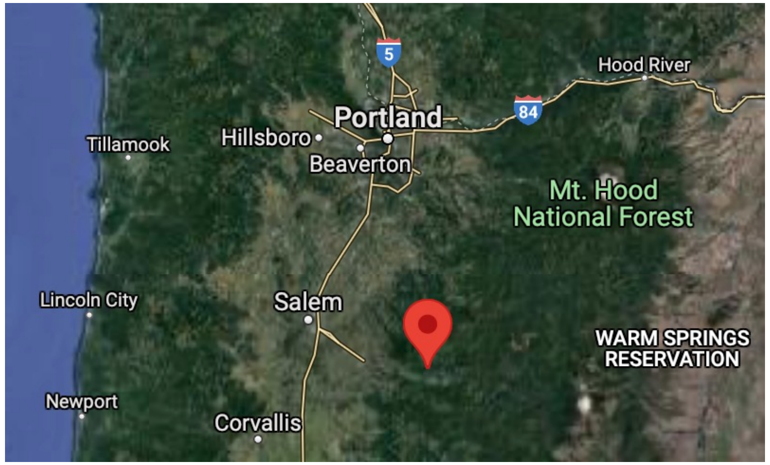


Sahara



Oregon





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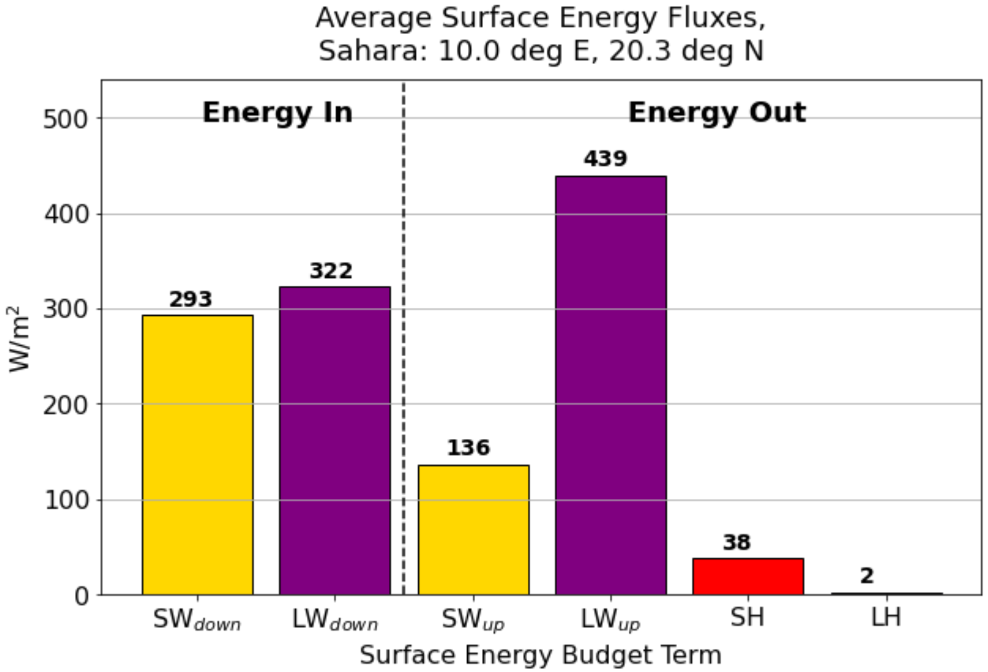

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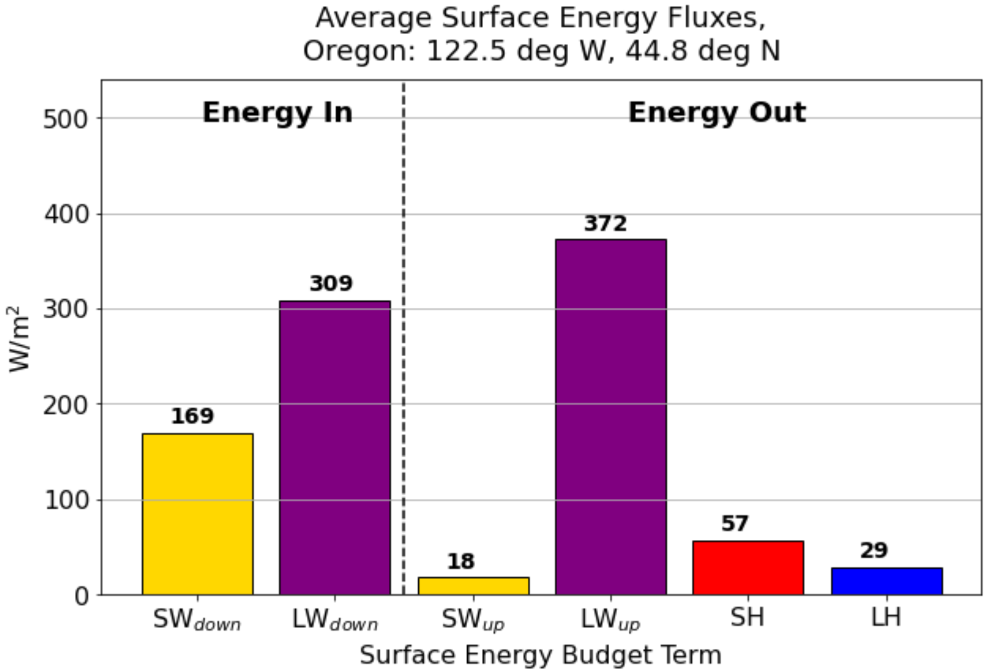

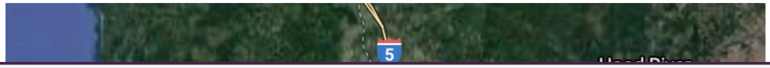

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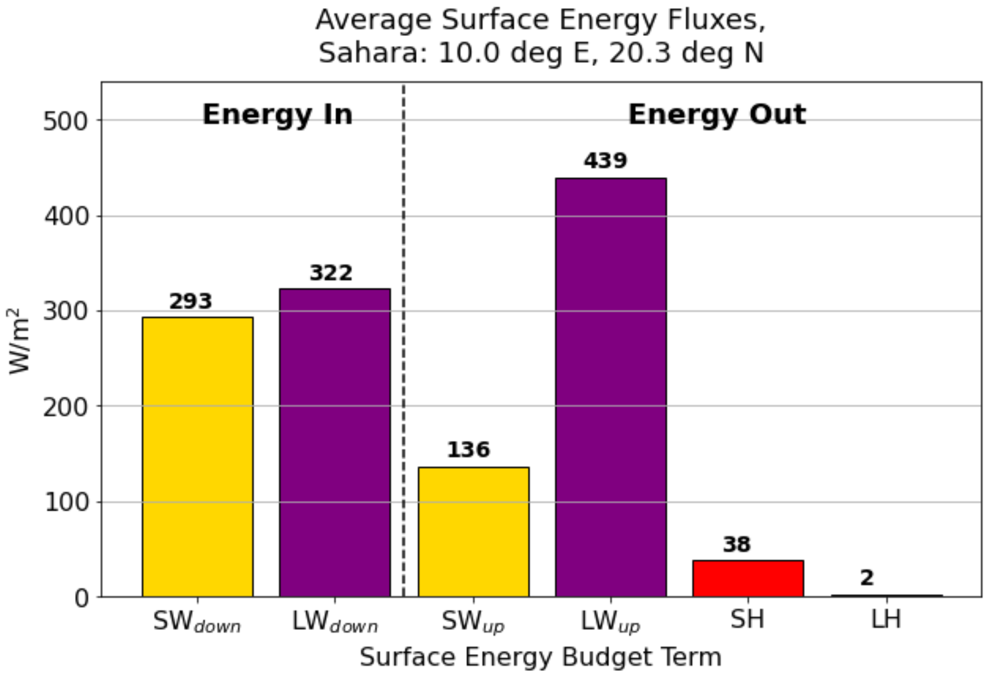
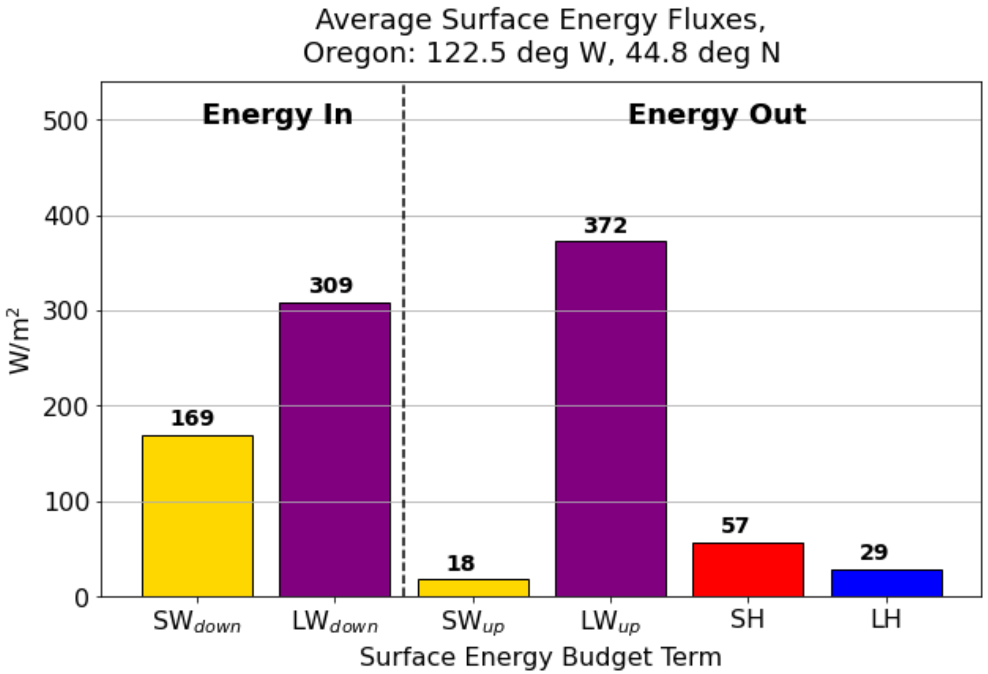
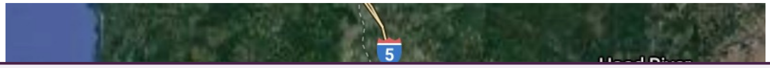


Albedo = 136/293 = 0.46

Oregon



Albedo = 18/169 = 0.11



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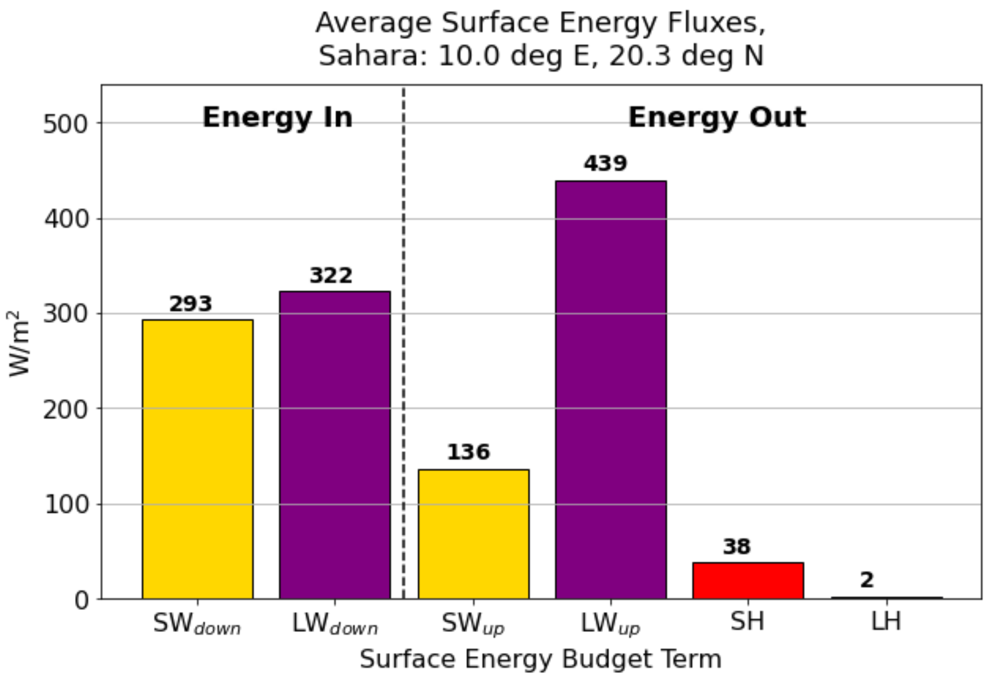

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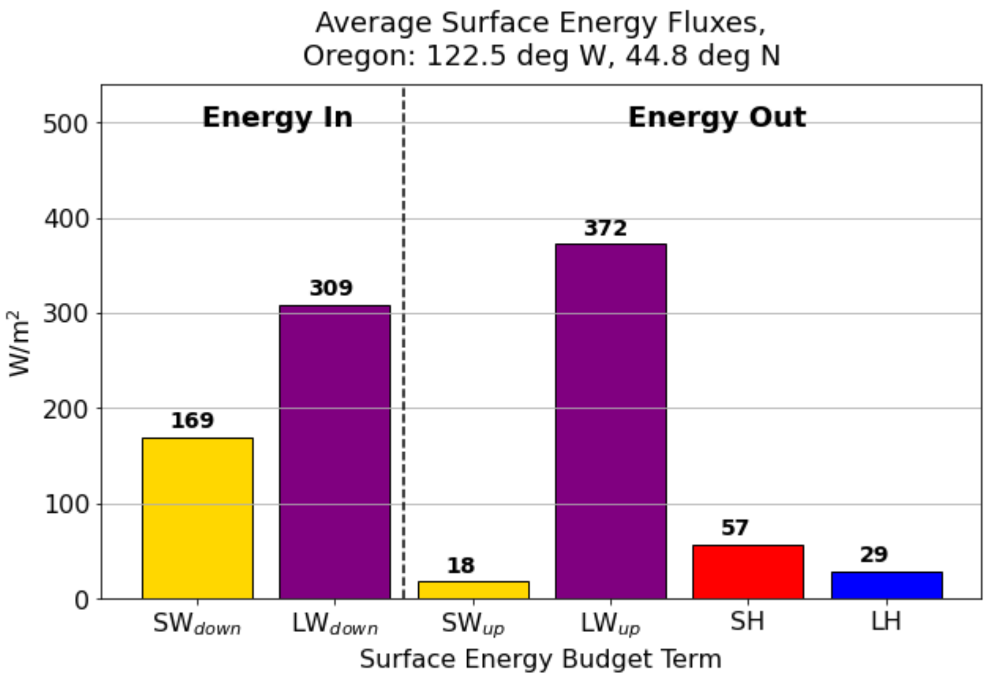

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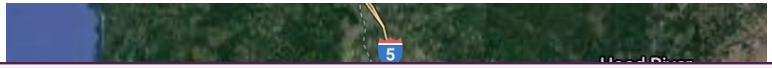

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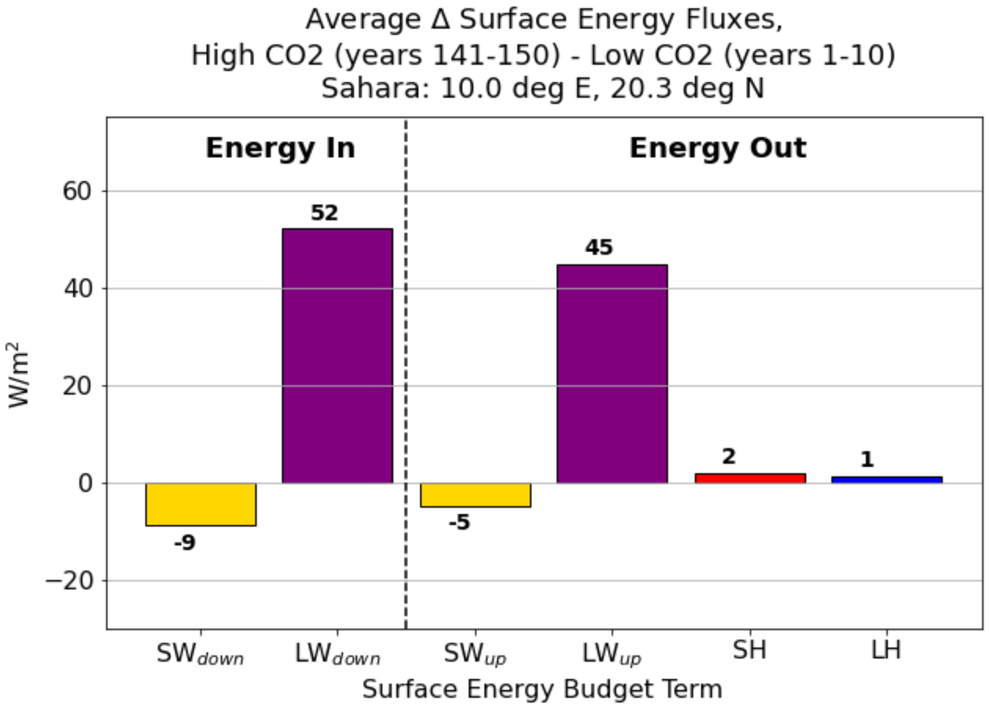

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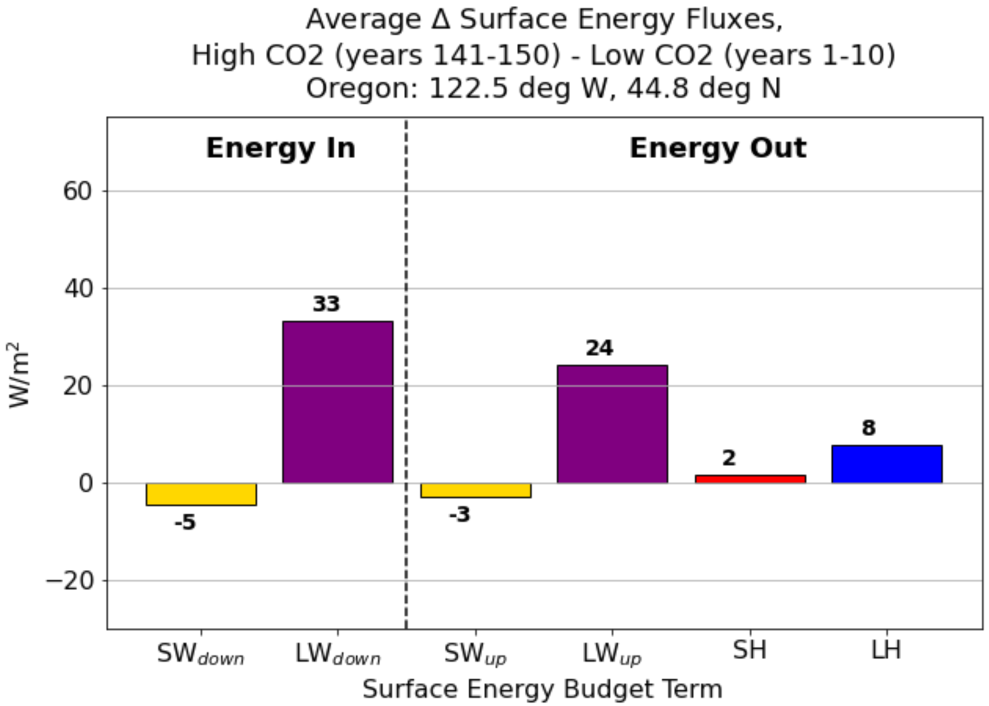

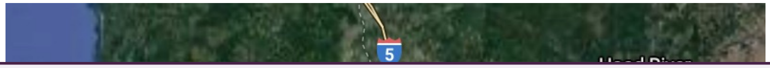

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Objectives:

Theory:

- Understand the components of the surface energy budget over land

$$\boxed{\text{Energy In} \approx \text{Energy Out}}$$

Exact breakdown of the terms in the surface energy balance determine the surface temperature

Application:

- **Analyze the surface energy budget using climate model output**

Different regions have different breakdowns of surface energy fluxes, and will respond differently to CO_2-induced warming