# Land–Atmosphere Interactions

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# Approaching Land–Atmosphere Interactions

- We will approach the land-atmosphere interactions question from a ***biogeophysical*** perspective

**Biogeophysics** = how **energy** and **moisture** move through the earth system including the role of the biosphere

# A Brief History of L-A Interactions

1800 1900 1940 1980 2000 2020

# A Brief History of L-A Interactions

**"Rain follows the plow…"**


- Some researchers later found correlations between precipitation and time when western settlement was rapidly increasing
- Was thought to be discredited in the 1940s but there is still research being done regarding irrigation and its influence on precipitation over the Plains
- Holzman 1939 from USDA
  - "The conclusion that an increase in atmospheric moisture must necessarily… increase precipitation can now definitely be shown to be erroneous"

1800 1900 1940 1980 2000 2020

# A Brief History of L-A Interactions

- Richardson (1922) was calculating things by hand to predict weather!
- He even described the importance of stomatal conductance

"Rain follows the plow…"

**Numeric Models**

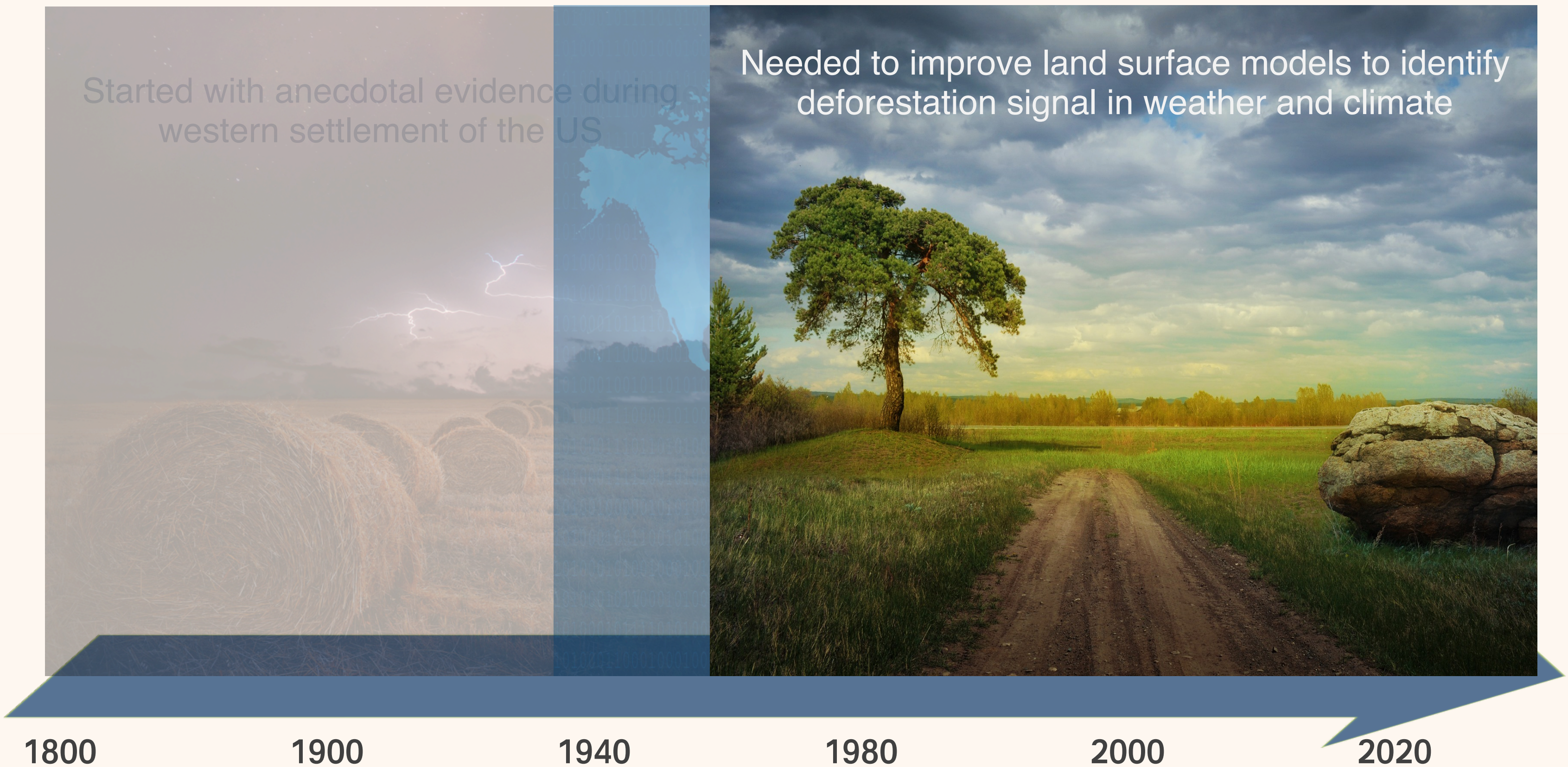

1800 1900 1940 1980 2000 2020

# A Brief History of L–A Interactions

- Earlier papers focused on albedo as a surrogate for deforestation (Charney 1972)
- Recommend review Garratt (1993) outlining the importance of the land surface

“Rain follows the plow…”

**Land Cover Change and Deforestation**

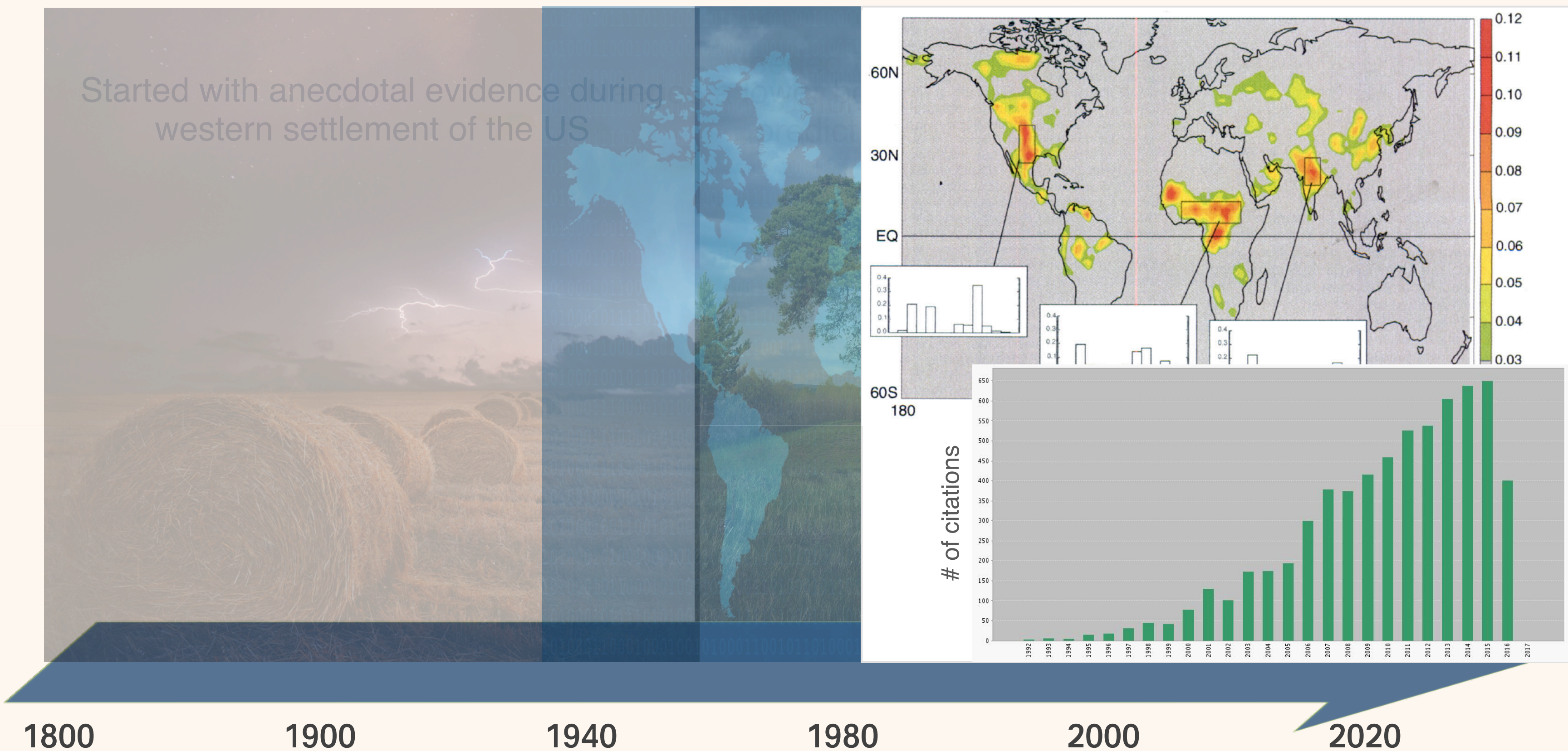


# A Brief History of L-A Interactions

- Shift in discourse looking at soil moisture-precipitation interactions (Koster et al. 2004)
- Review by Seneviratne (2010) outlining the “current” works; but fast moving field

“Rain follows the plow…”

**Climate and Surface Feedbacks**



# Approaching Land–Atmosphere Interactions

If you have ever asked questions like…

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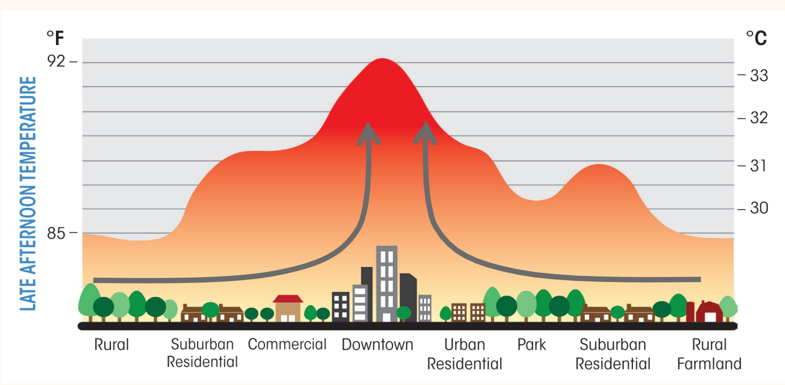
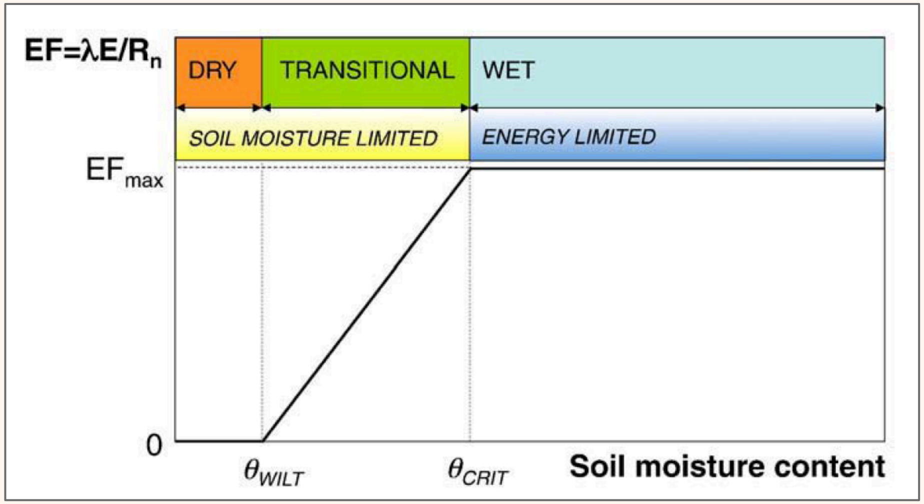
- When do changes in soil moisture/LAI effect surface flux partitioning?
- How sensitive is the climate to increased urbanization?  Are there down-wind effects?



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- How does deforestation/reforestation influence temperature and precipitation extremes?

# Approaching Land–Atmosphere Interactions

How can we quantify ***Coupling*** and ***Feedbacks***?

Description of physical processes and defining terminology
Common metrics and measures

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How can we quantify ***Coupling*** and ***Feedbacks***?

Description of physical processes and defining terminology
Common metrics and measures

Land-Atmosphere interactions in ***CESM*** (CAM and ***CLM***)

Change in coupling and feedbacks across model version
Model-world versus Real-world

# Physical Processes: Land–Atmosphere Interactions

If you have ever asked questions like…

- When do changes in soil moisture/LAI effect surface flux partitioning?
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**Biogeophysics** = how **energy** and moisture move through the earth system including the role of the biosphere

We will begin from the **surface energy budget**

$$SW^{\downarrow} - SW^{\uparrow} + LW^{\downarrow} - LW^{\uparrow} = \lambda E + SH + G + H$$

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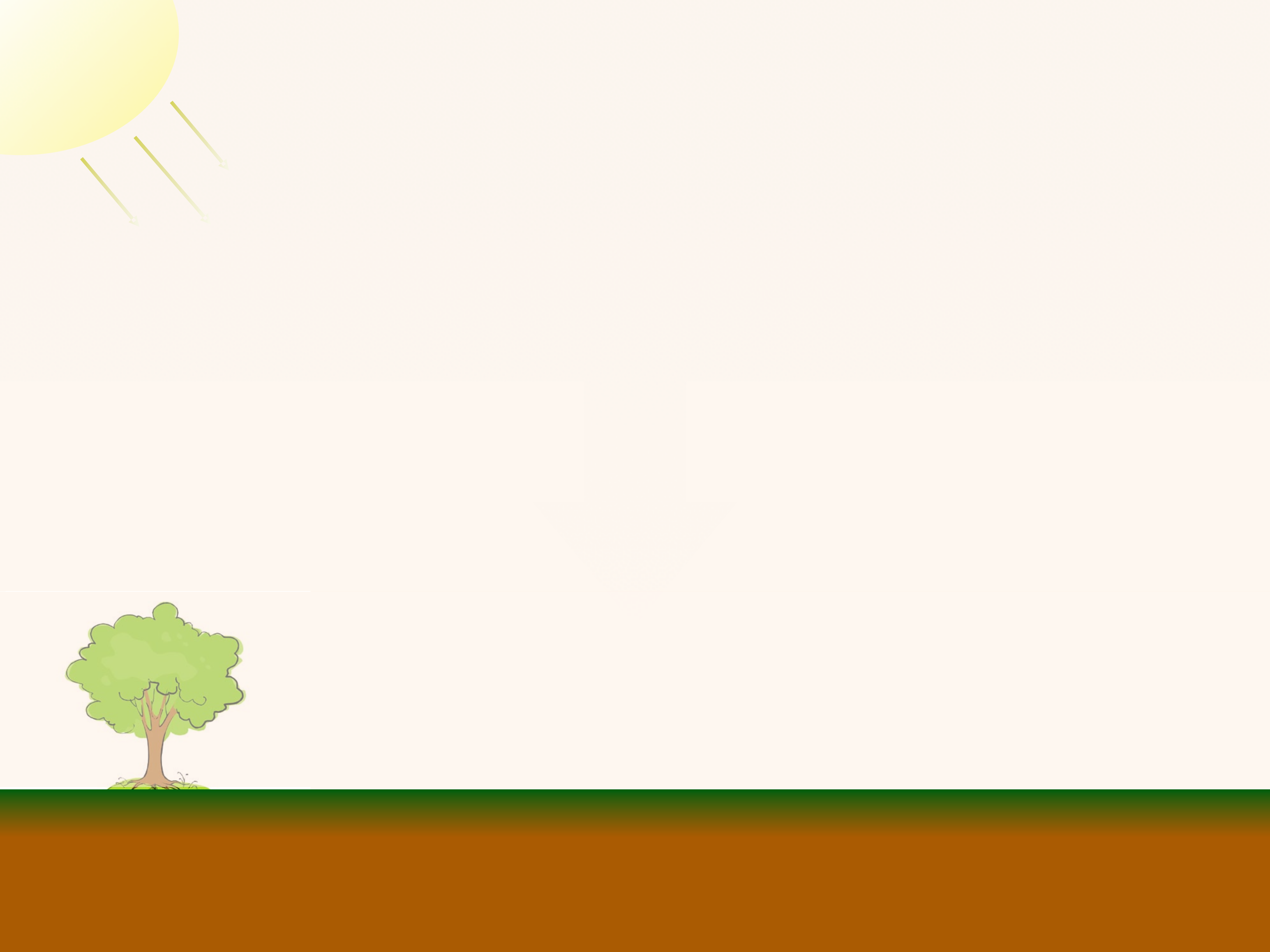
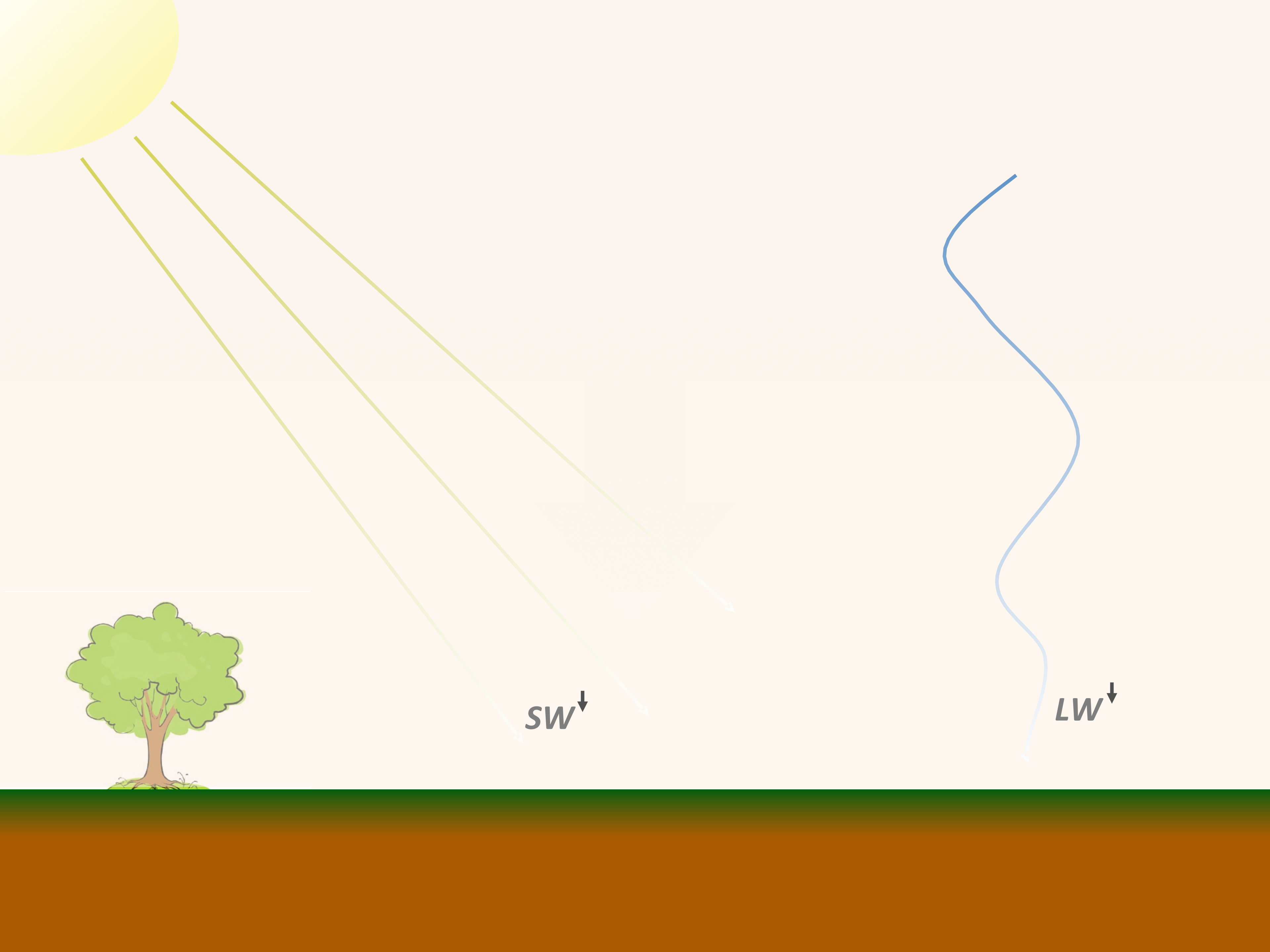
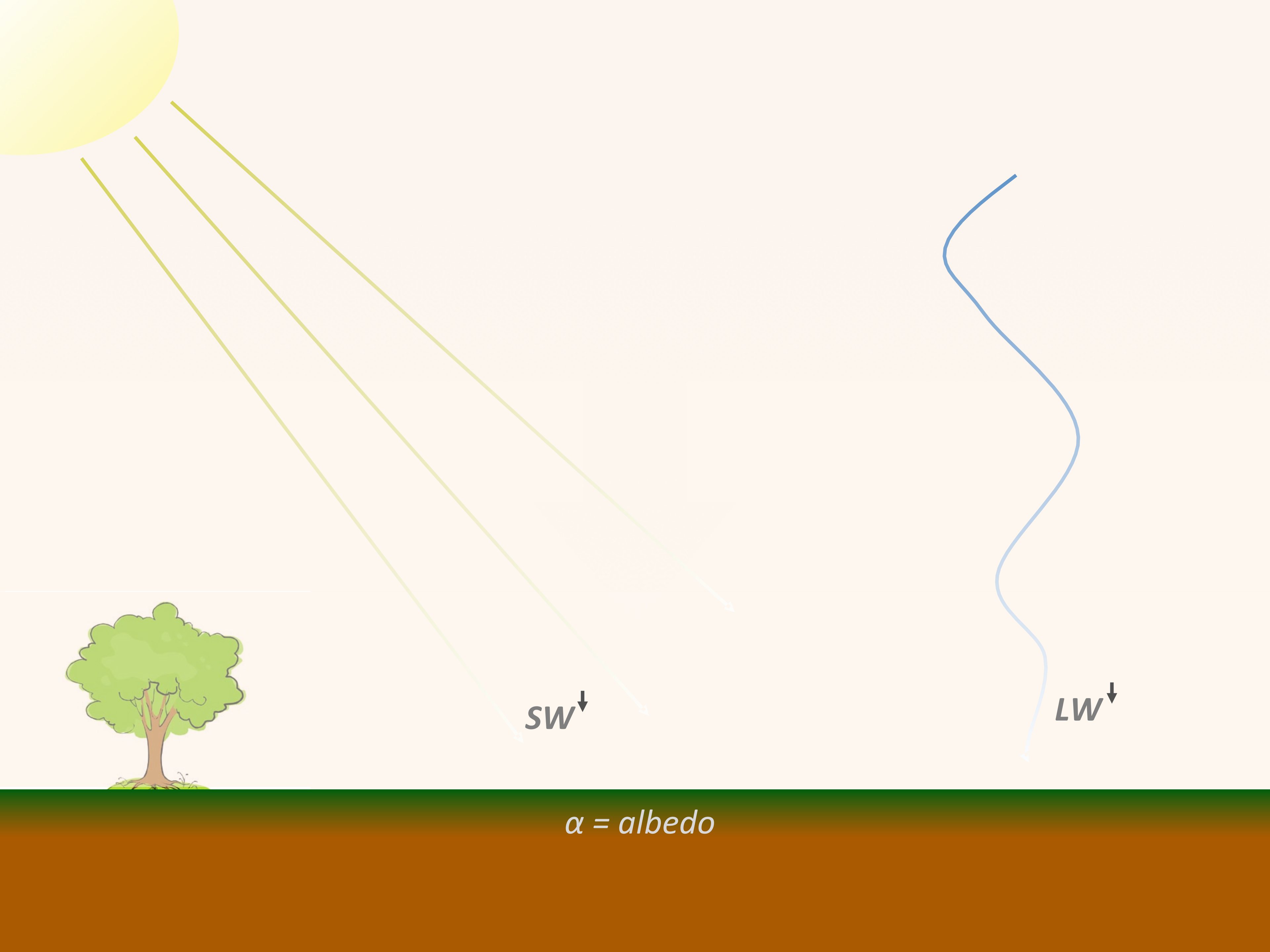
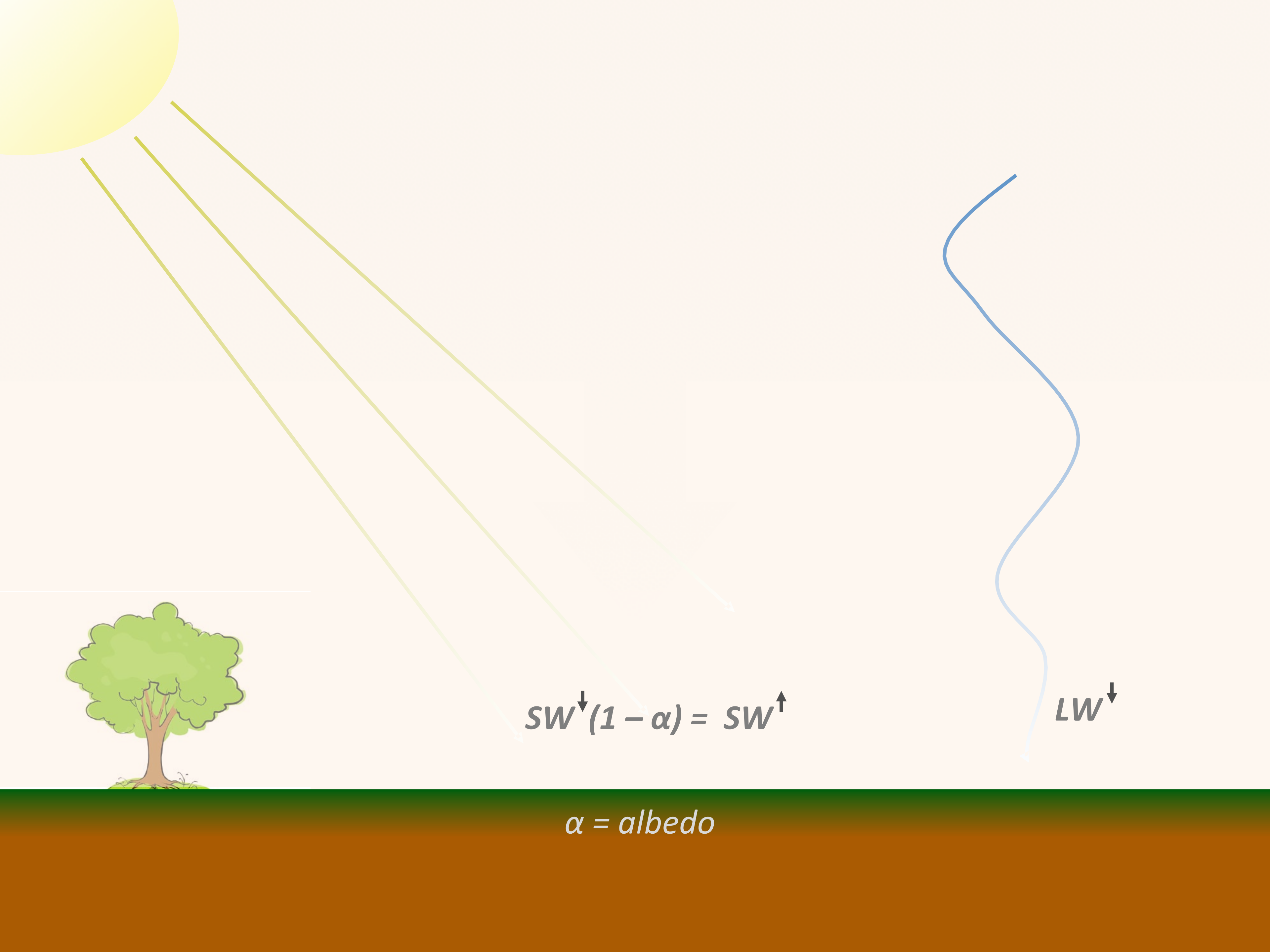
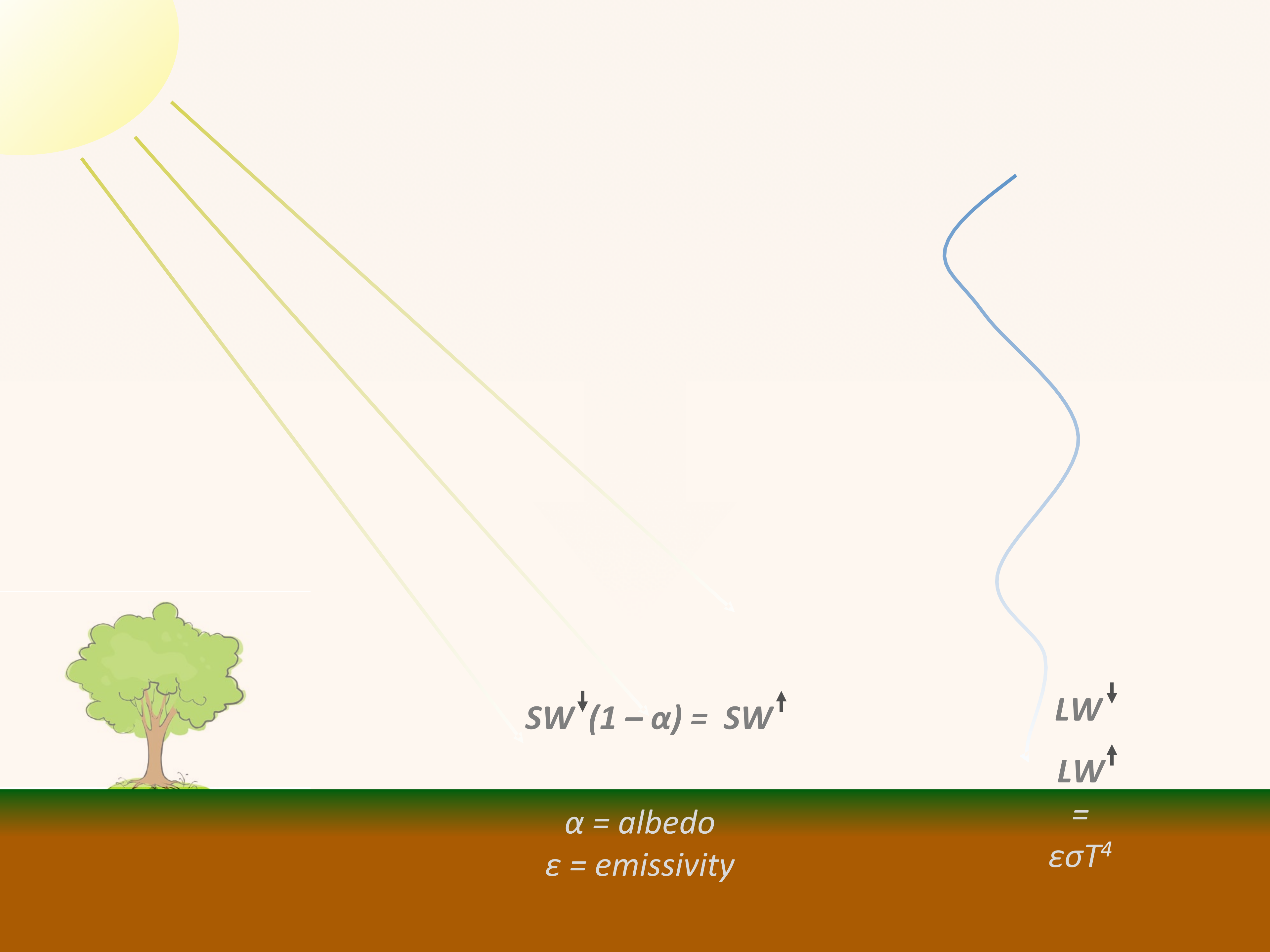
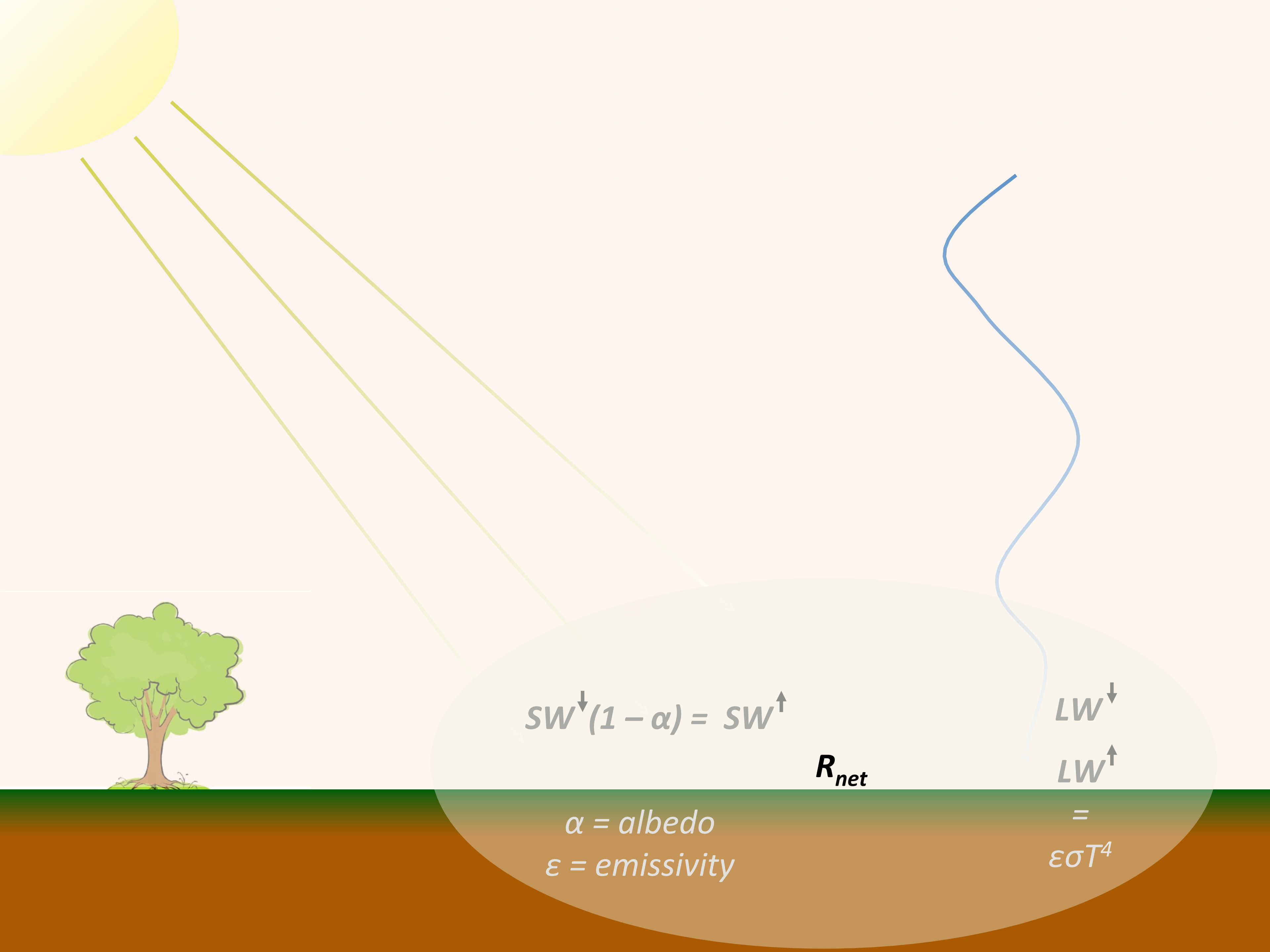


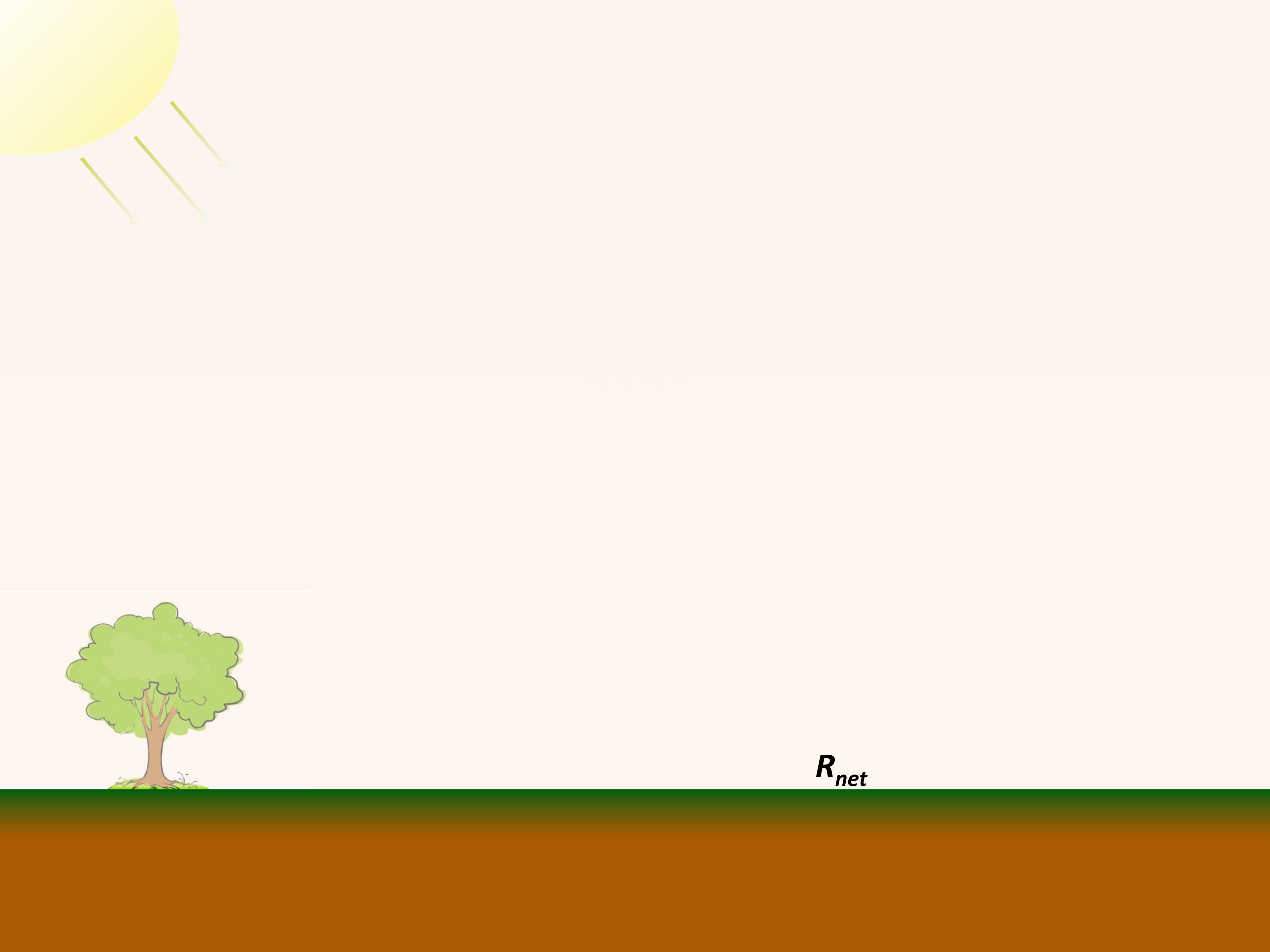

SW↓
LW↓

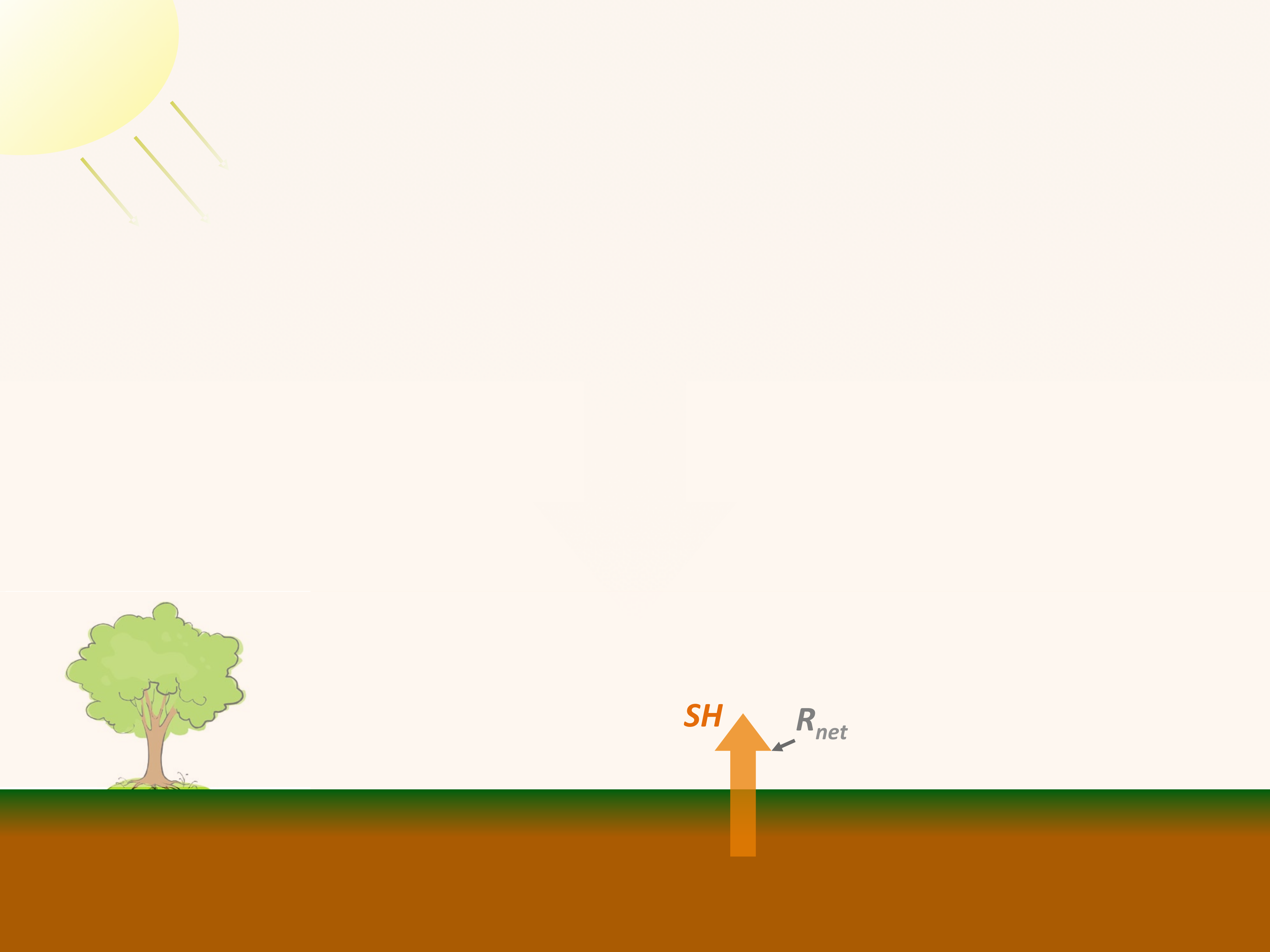

SW↓
LW↓
α = albedo

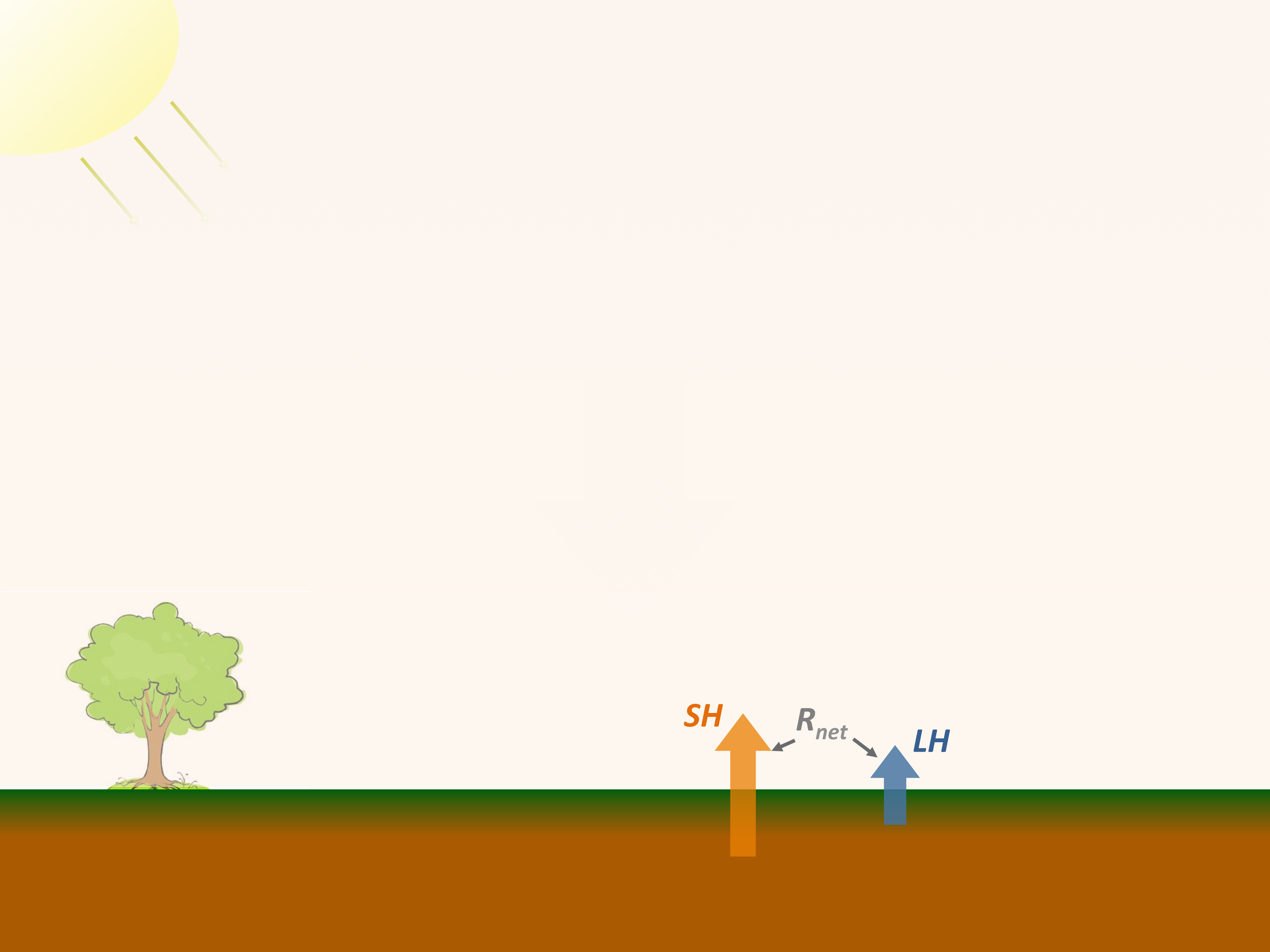

$SW^{\downarrow}(1 - \alpha) = SW^{\uparrow}$
$LW^{\downarrow}$
$\alpha$ = albedo

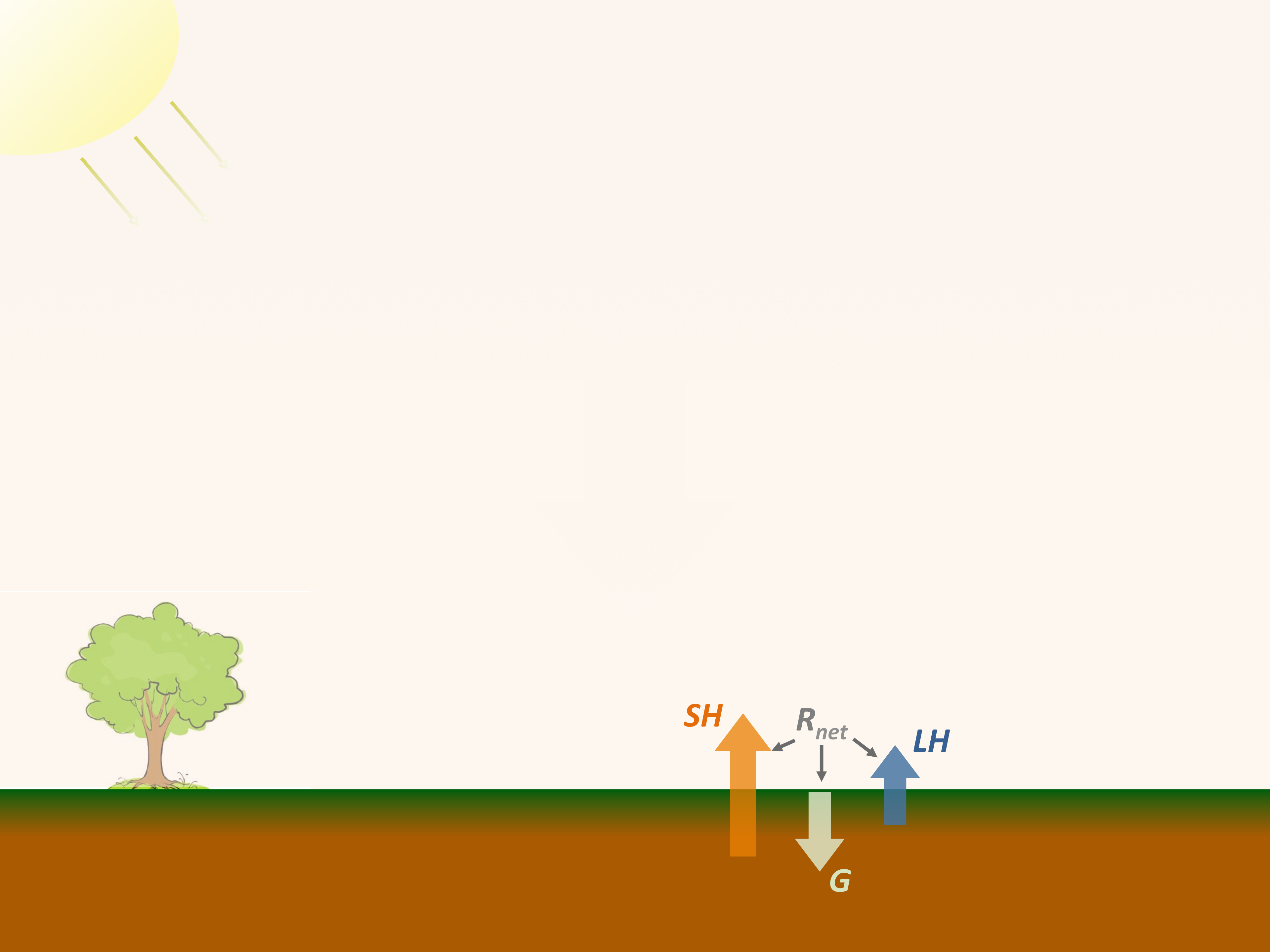

SW↓(1 – α) = SW↑
LW↓
LW↑
=
εσT4
α = albedo
ε = emissivity

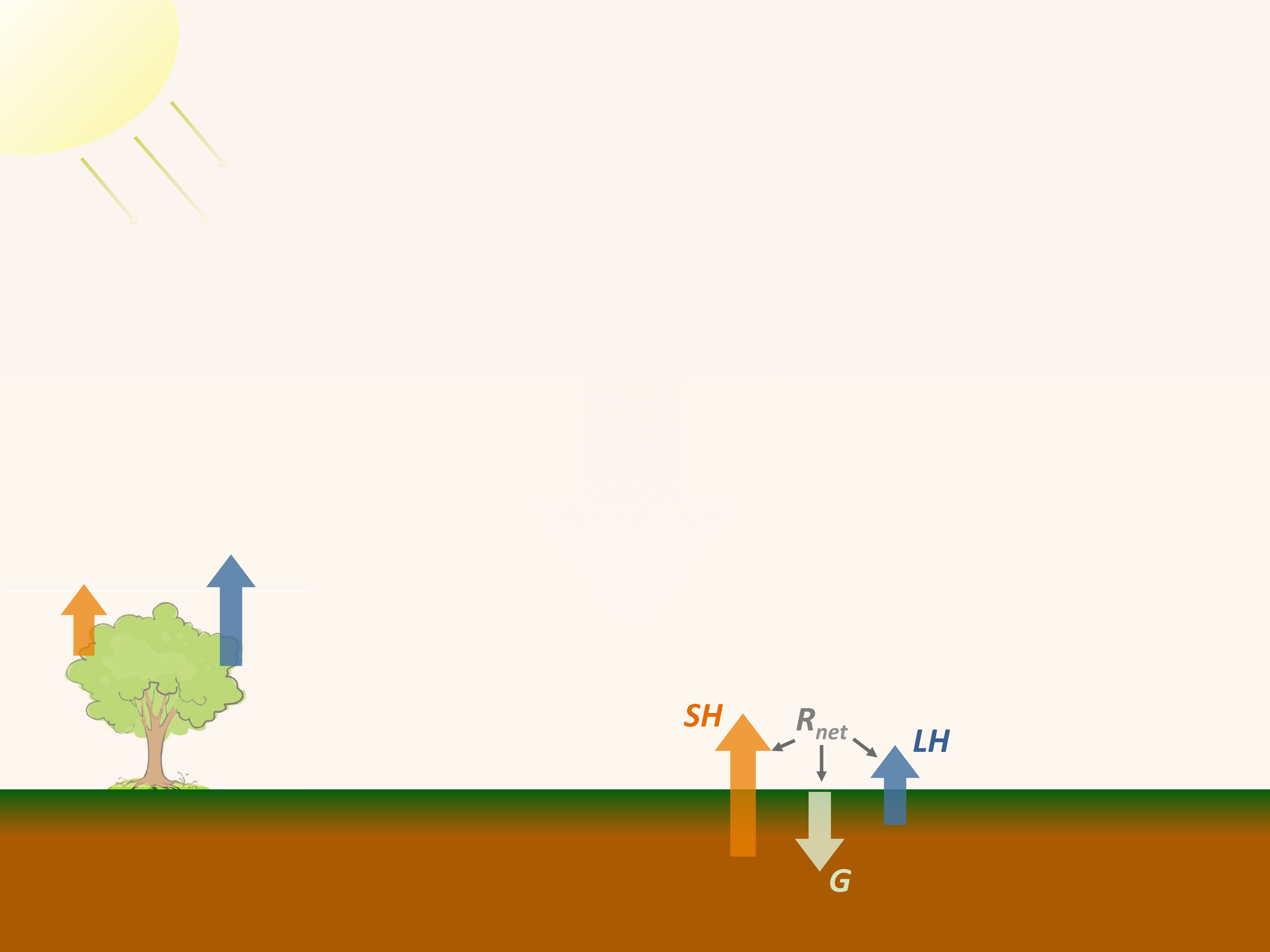

$SW^{\downarrow}(1 - \alpha) = SW^{\uparrow}$
$LW^{\downarrow}$
$R_{net}$
$LW^{\uparrow}$
=
$\varepsilon\sigma T^4$
α = albedo
ε = emissivity


$R_{net}$


SH
$R_{net}$

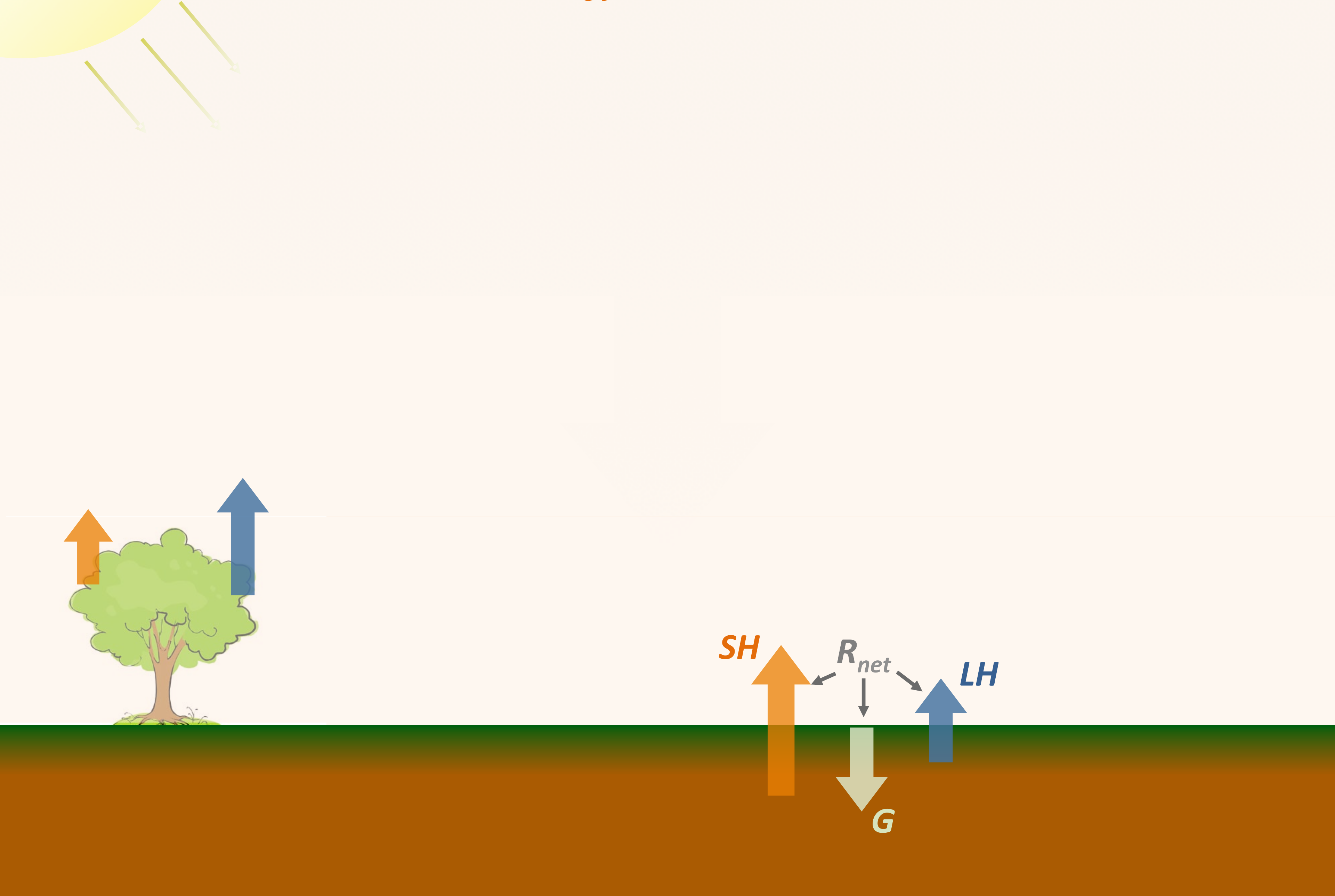

SH
Rnet
LH

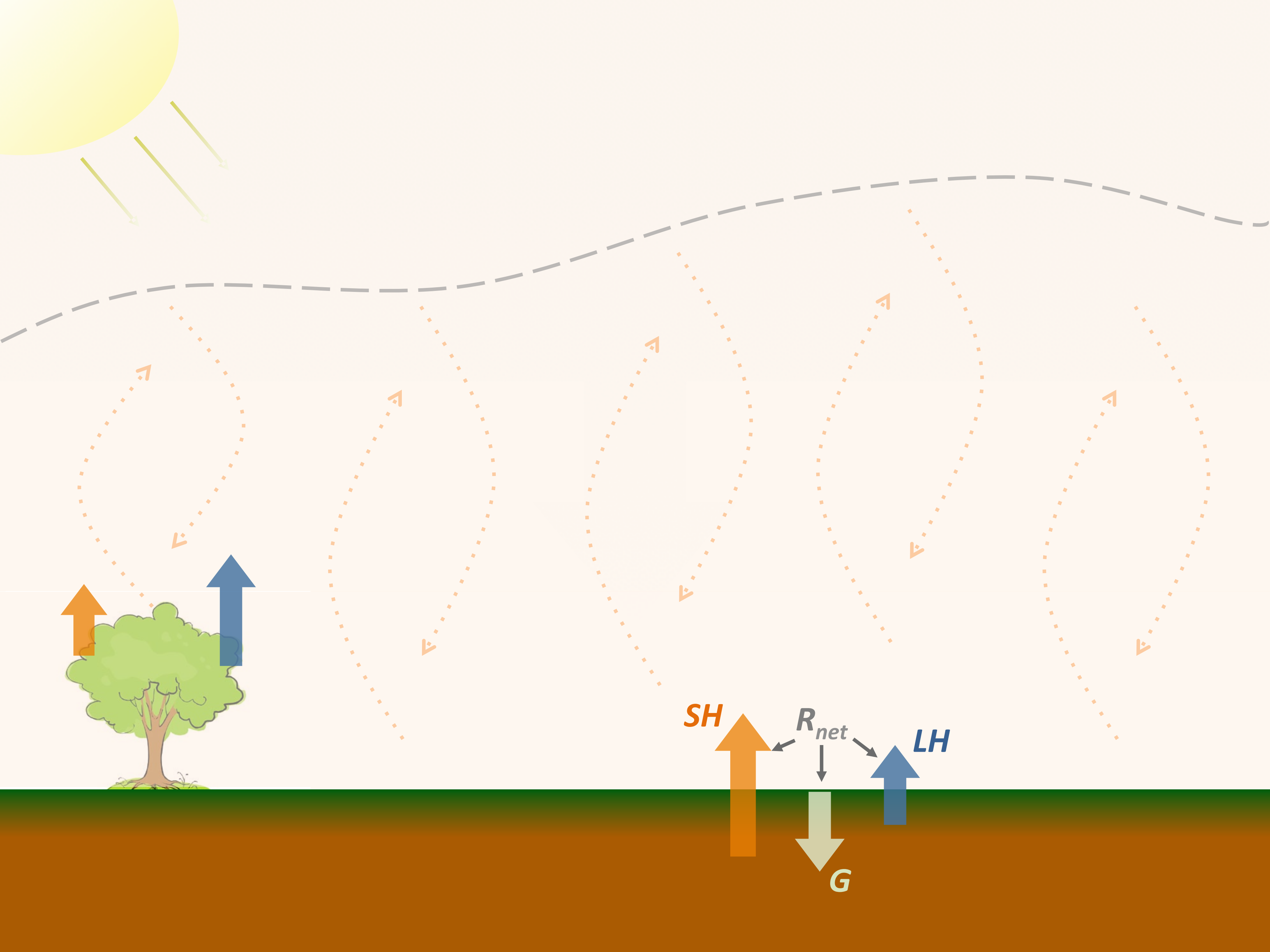

SH
$R_{net}$
LH
G



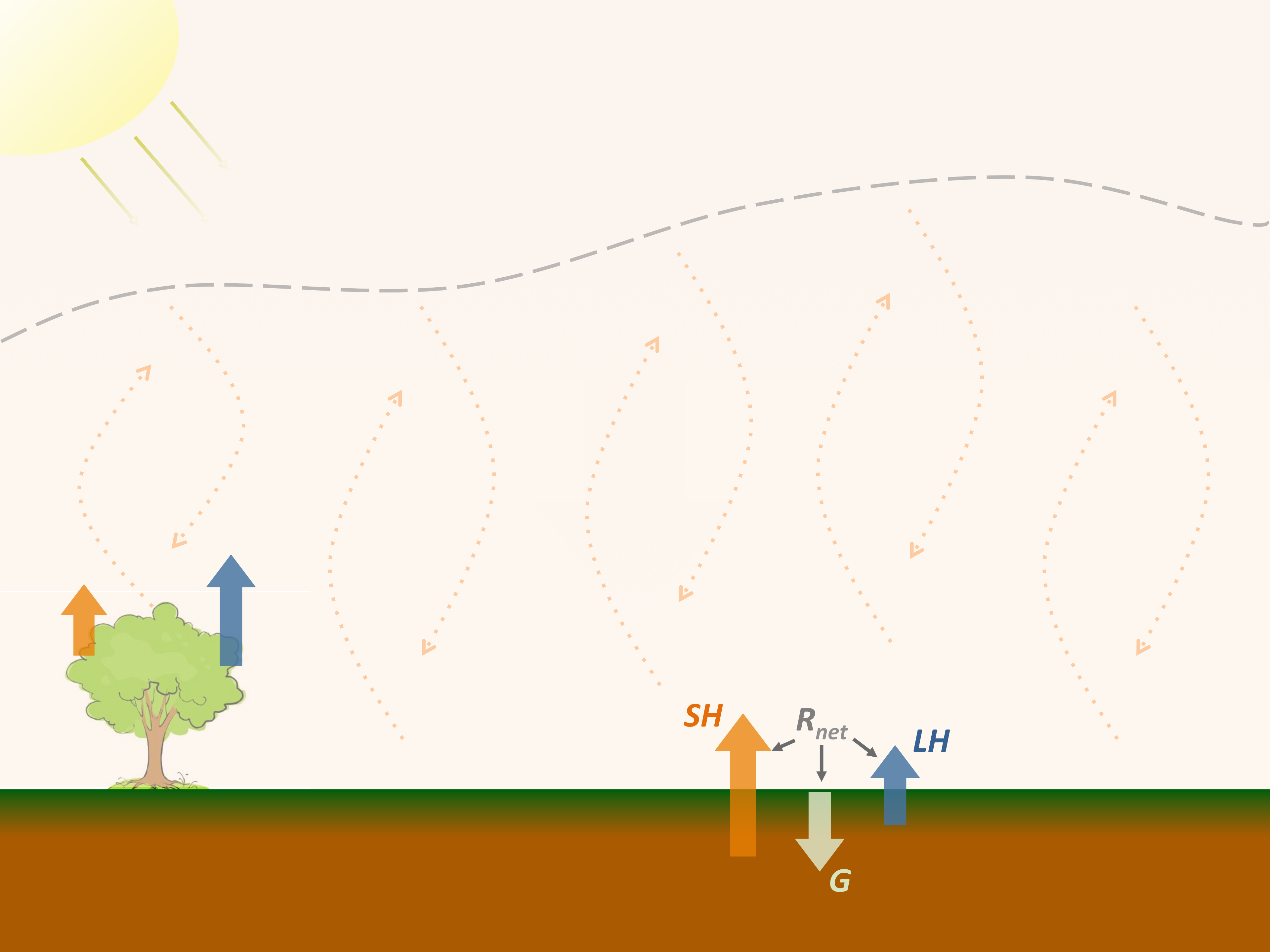
SH
$R_{net}$
LH
G

How does the atmosphere respond to the new **energy** and **moisture**?

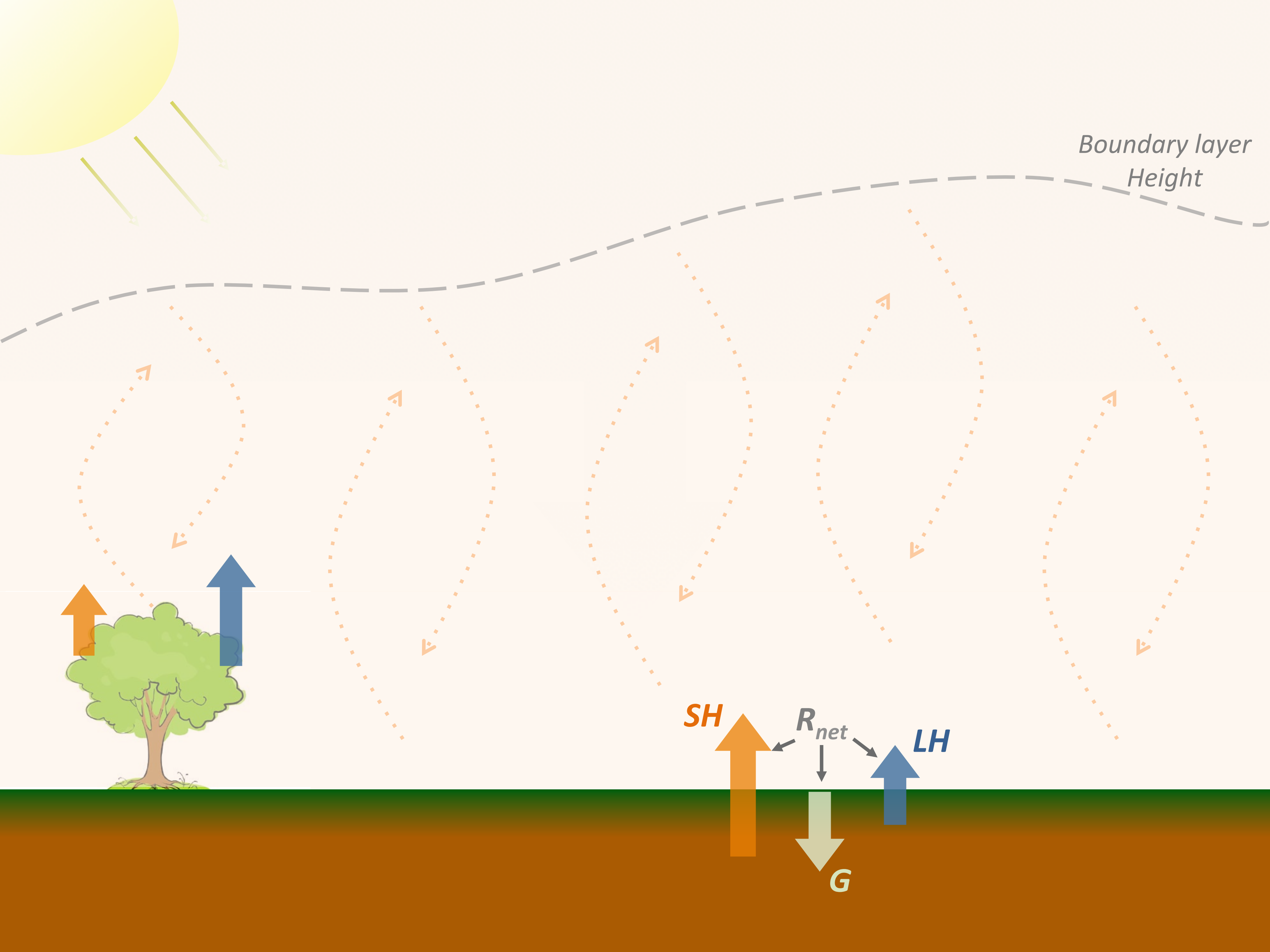


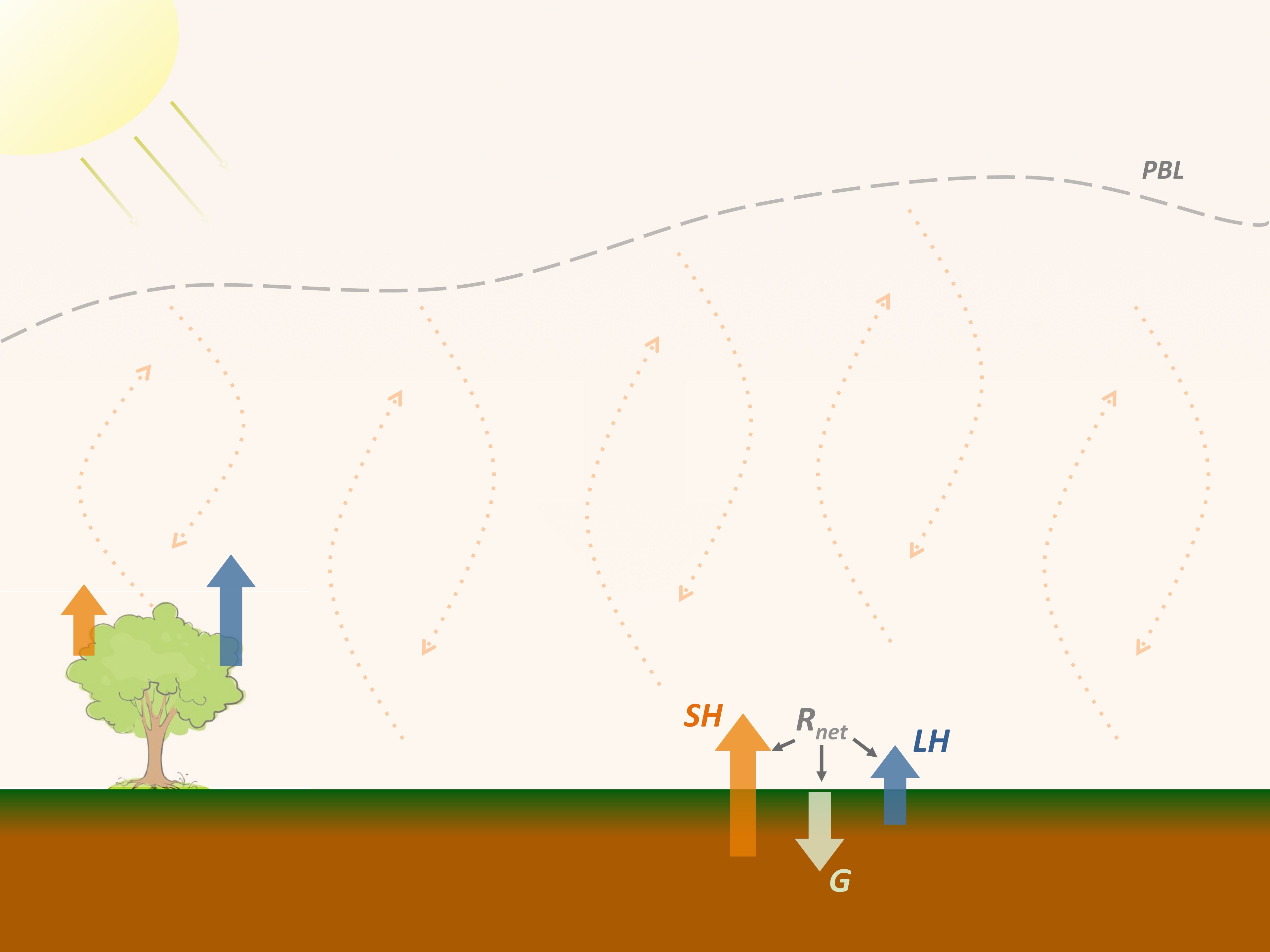


SH
$R_{net}$
LH
G



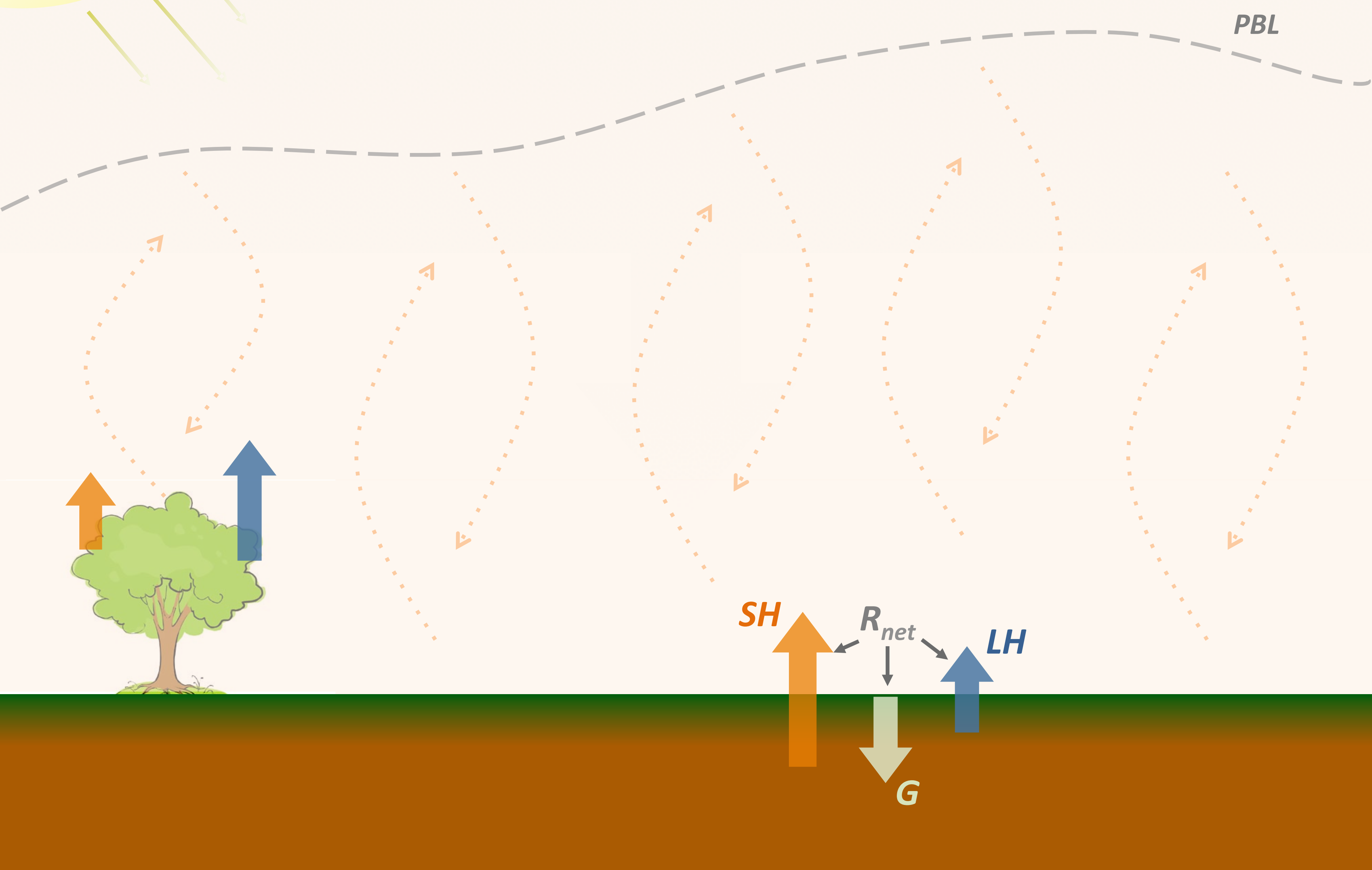
SH
$R_{net}$
LH
G


Boundary layer Height
SH
$R_{net}$
LH
G



PBL
SH
$R_{net}$
LH
G

Note that **SH** builds the **PBL** mixing
and
**LH** is a gas being mixed



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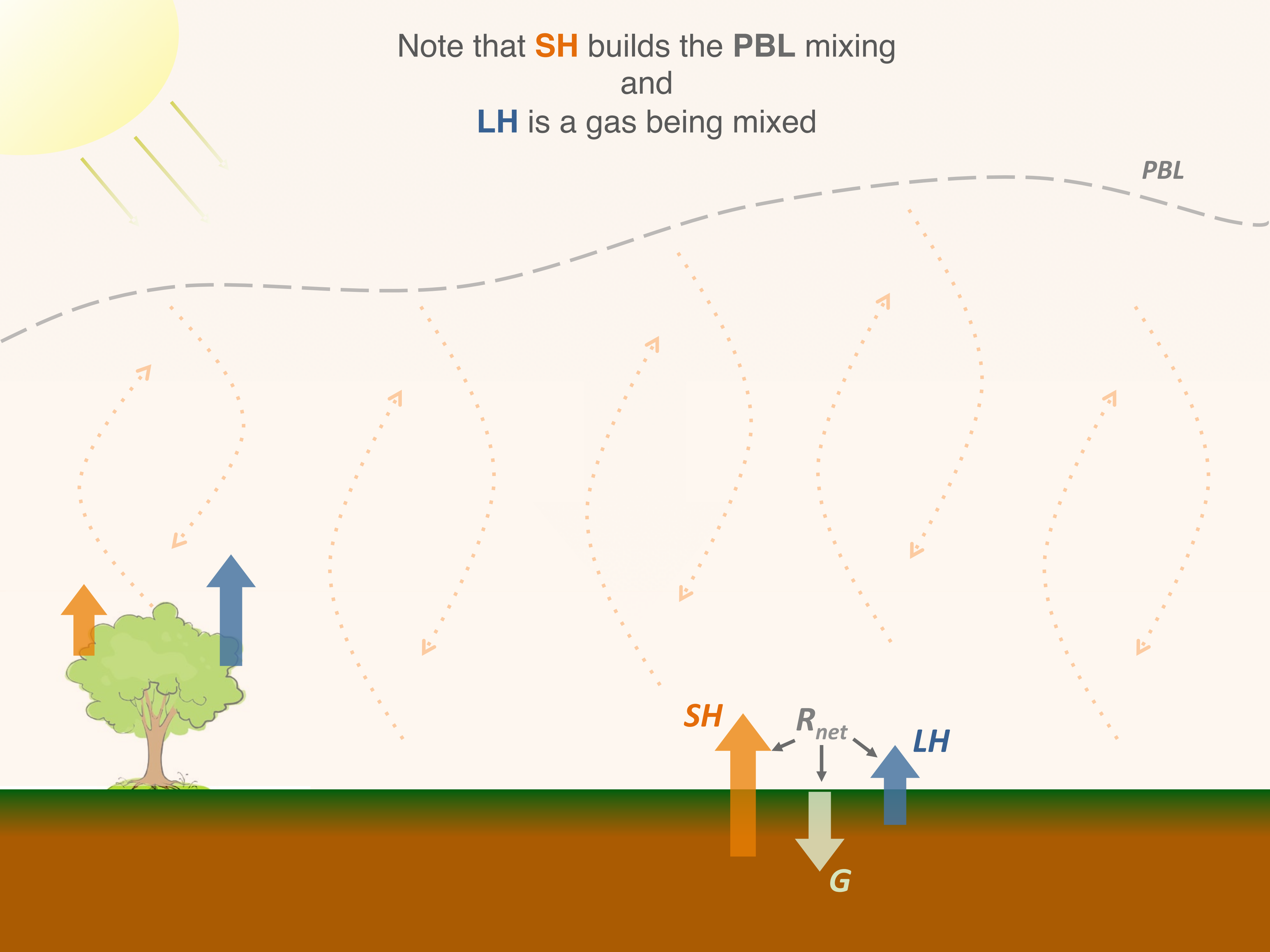
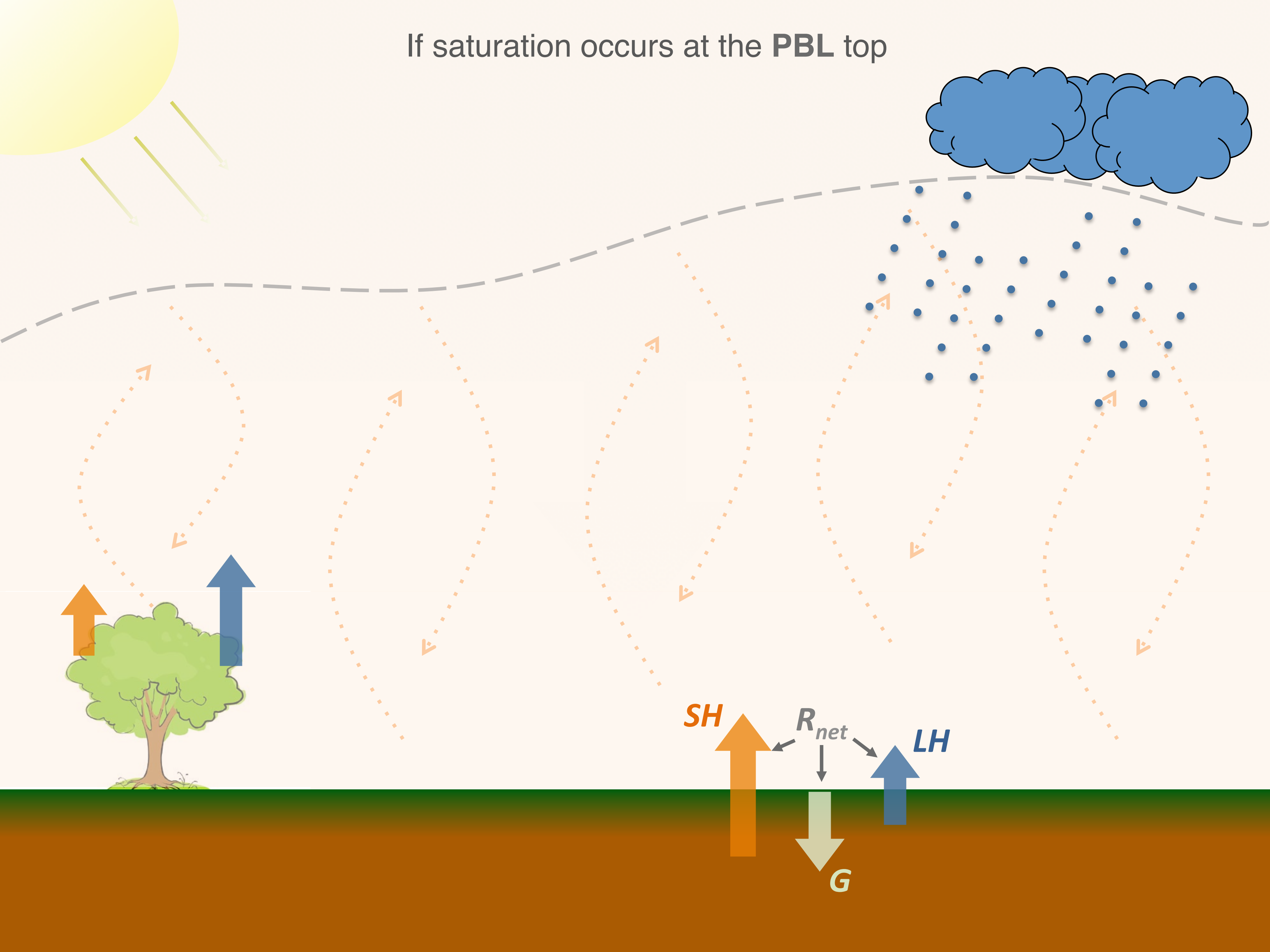
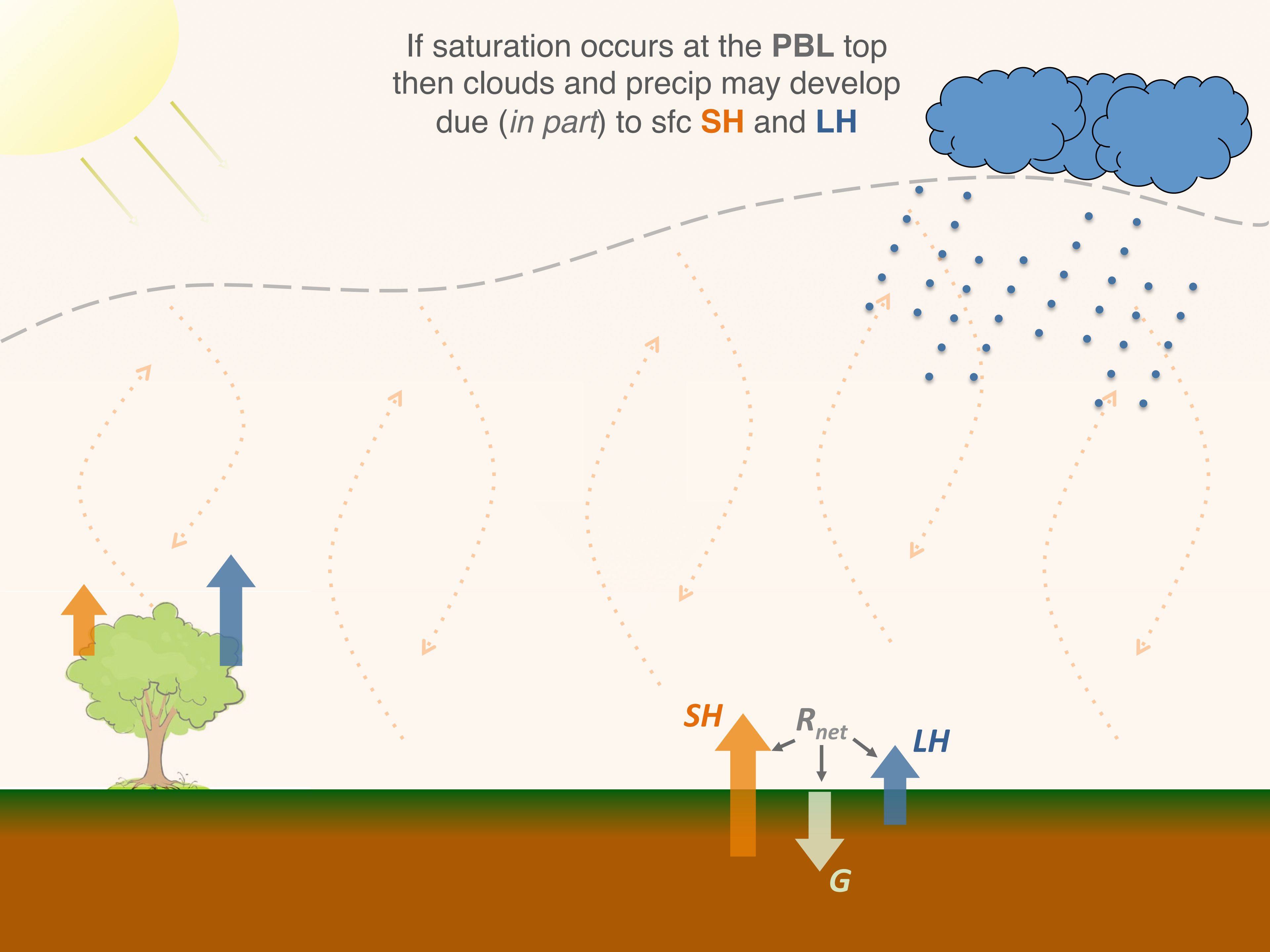


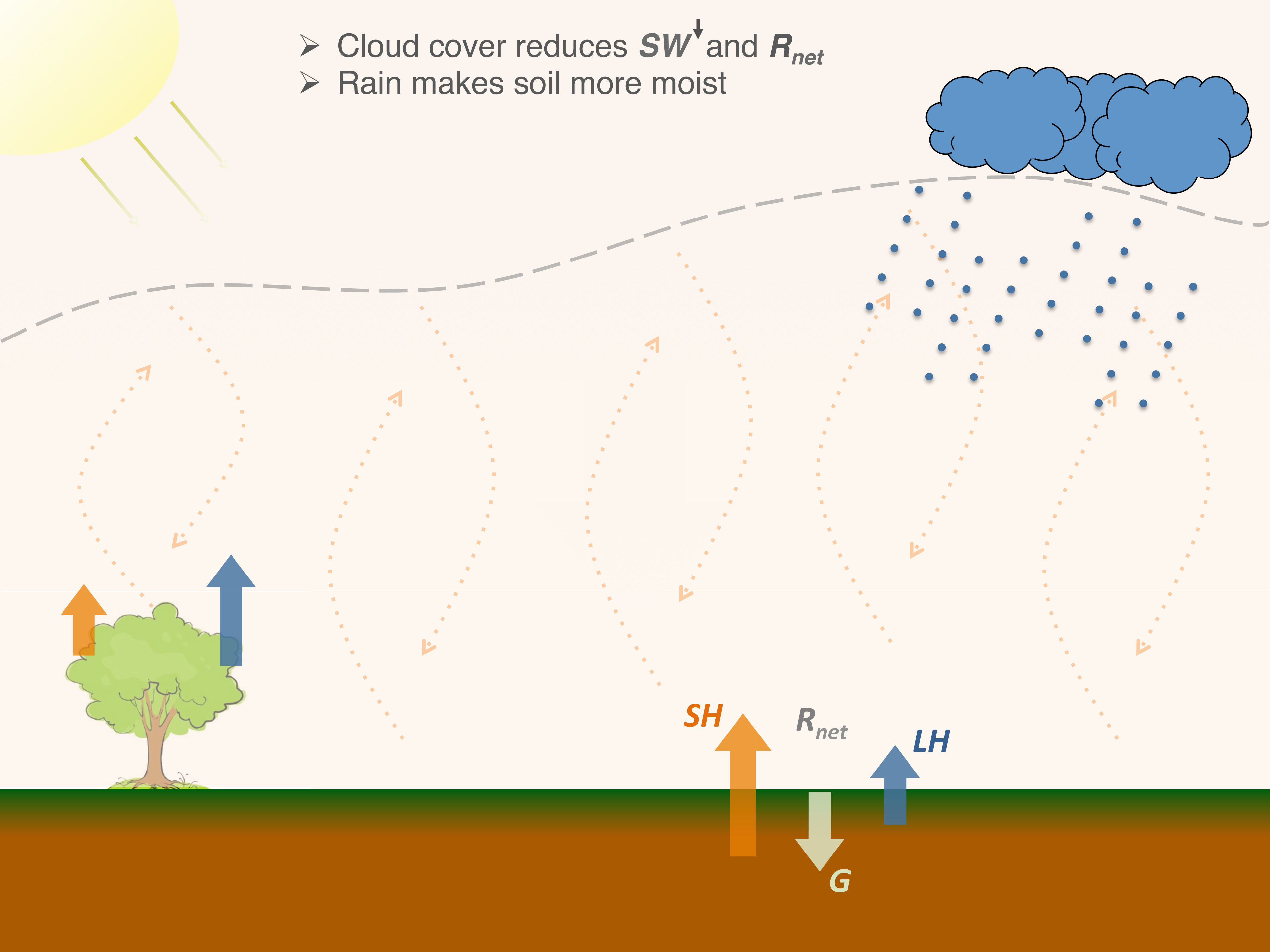
If saturation occurs at the **PBL** top



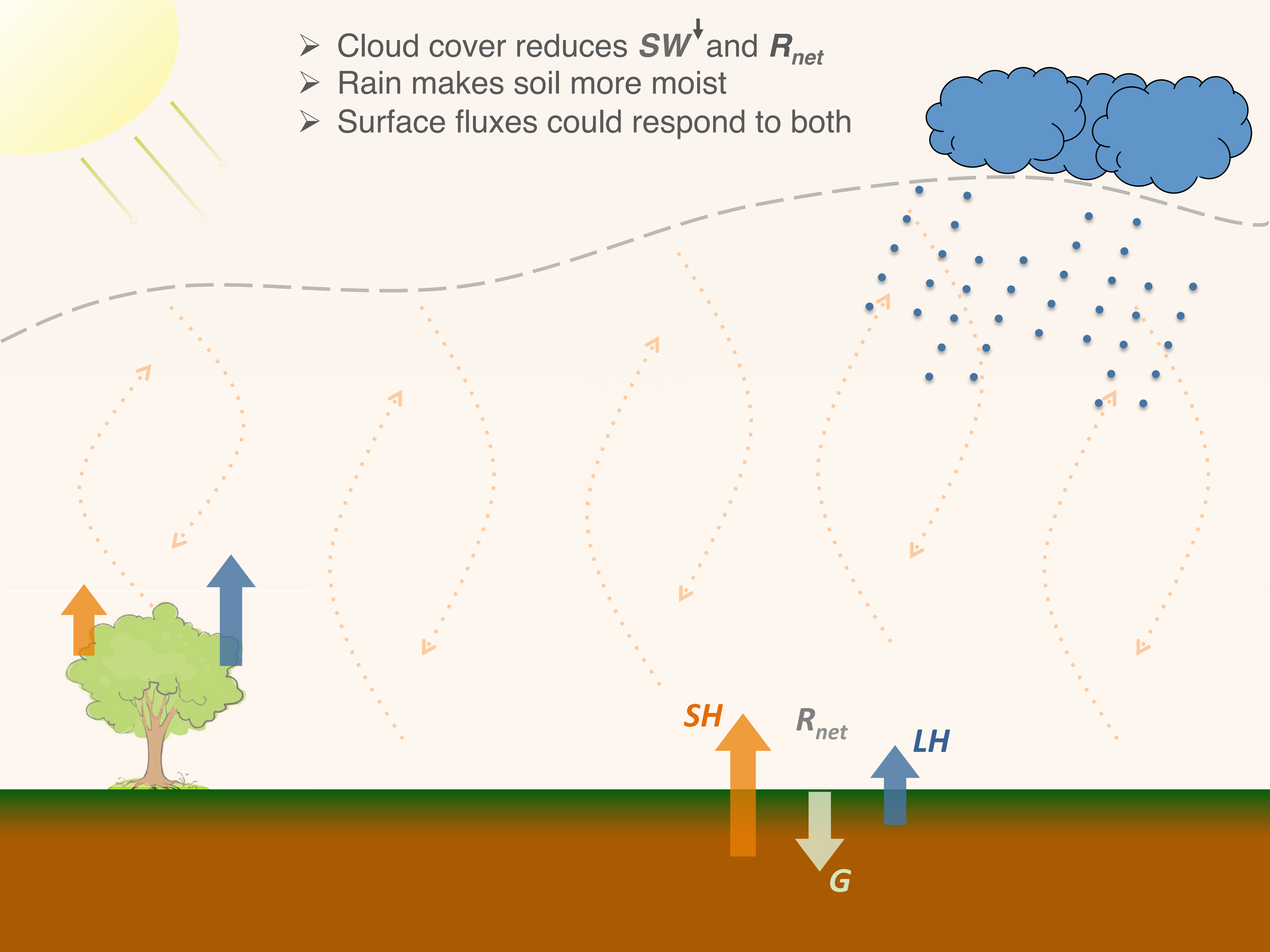
If saturation occurs at the **PBL** top then clouds and precip may develop due (*in part*) to sfc **SH** and **LH**



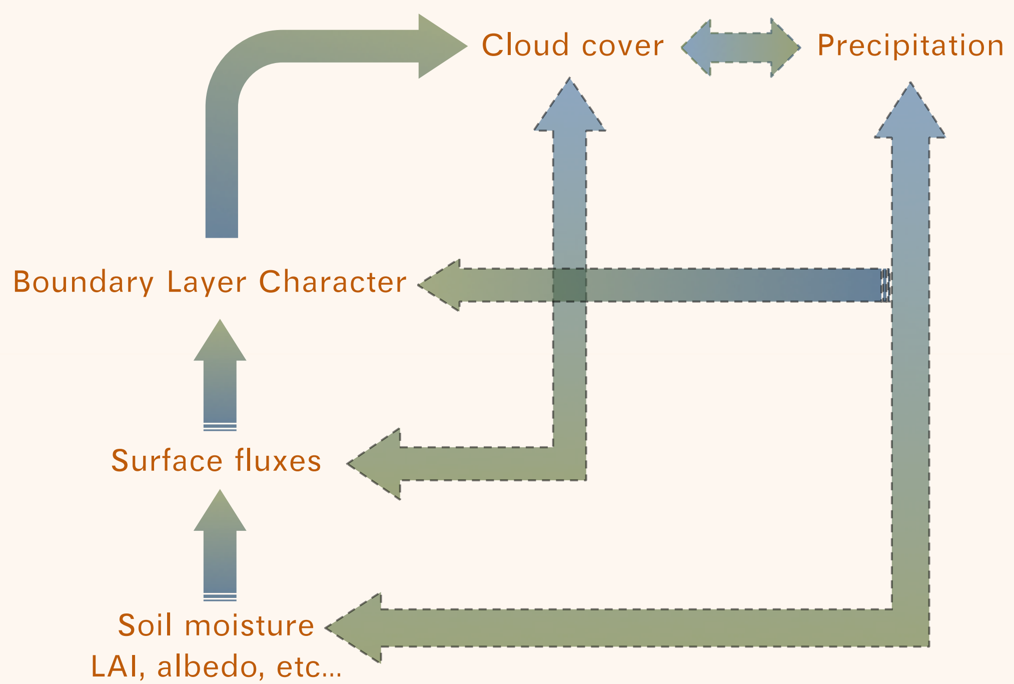
- Cloud cover reduces $SW^{\downarrow}$ and $R_{net}$
- Rain makes soil more moist



- Cloud cover reduces $SW^{\downarrow}$ and $R_{net}$
- Rain makes soil more moist
- Surface fluxes could respond to both



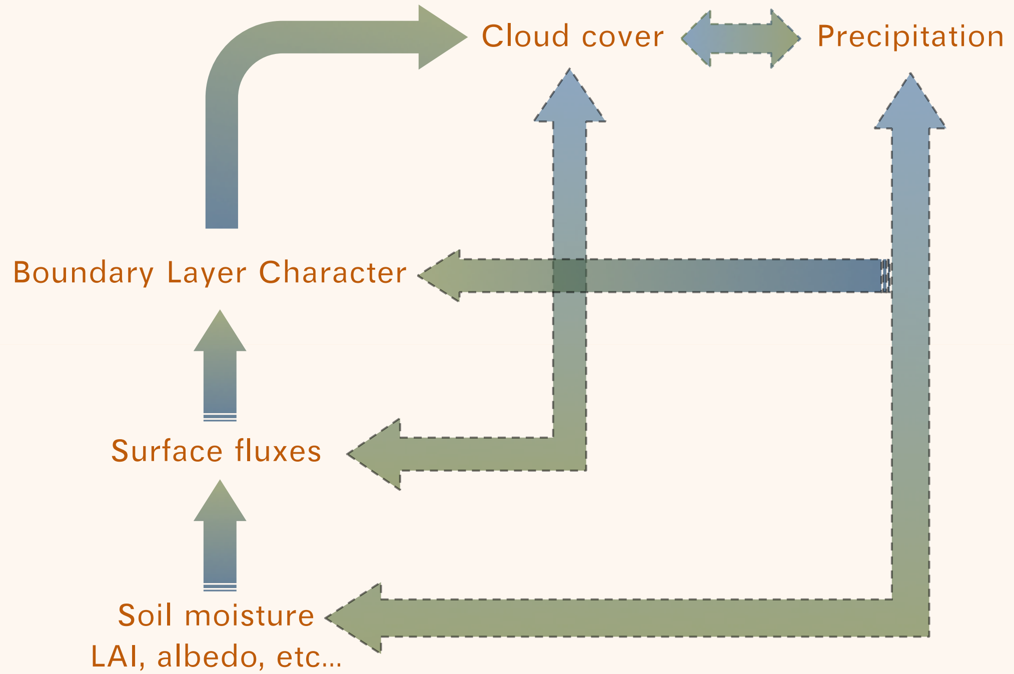
# Cascade of processes leading to **local** land-atmosphere interactions



# Cascade of processes leading to **local** land-atmosphere interactions

***Coupling*** = how closely controlled is one variable by another

- *Example:* ***Latent Heat*** *changes due to variations in* ***Soil Moisture***



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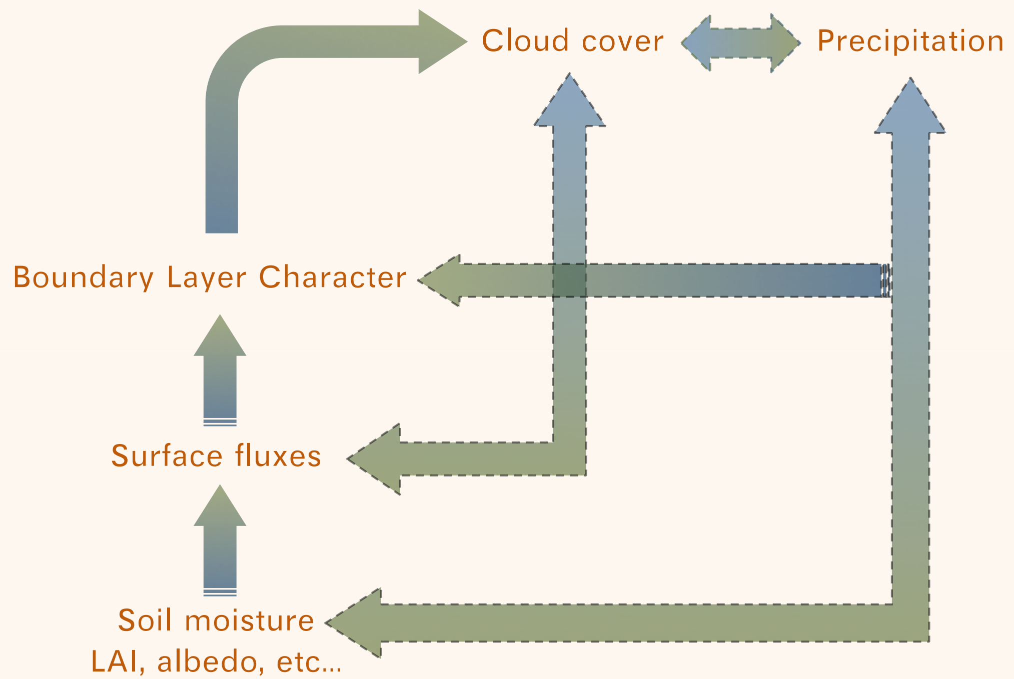
***Coupling*** = how closely controlled is one variable by another

- *Example: **Latent Heat** change due to variations in **Soil Moisture***

***Feedback*** = perturbation of a variables results in further perturbation

- *Example: **Wet soil** produces **more rain** further wetting the soil* **(+)**



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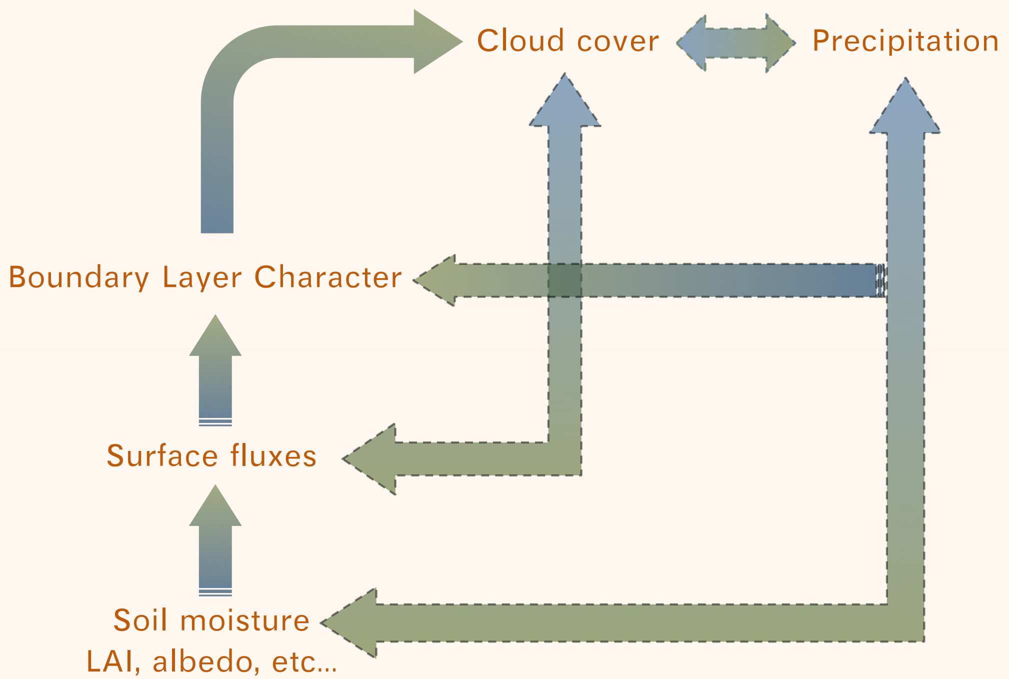
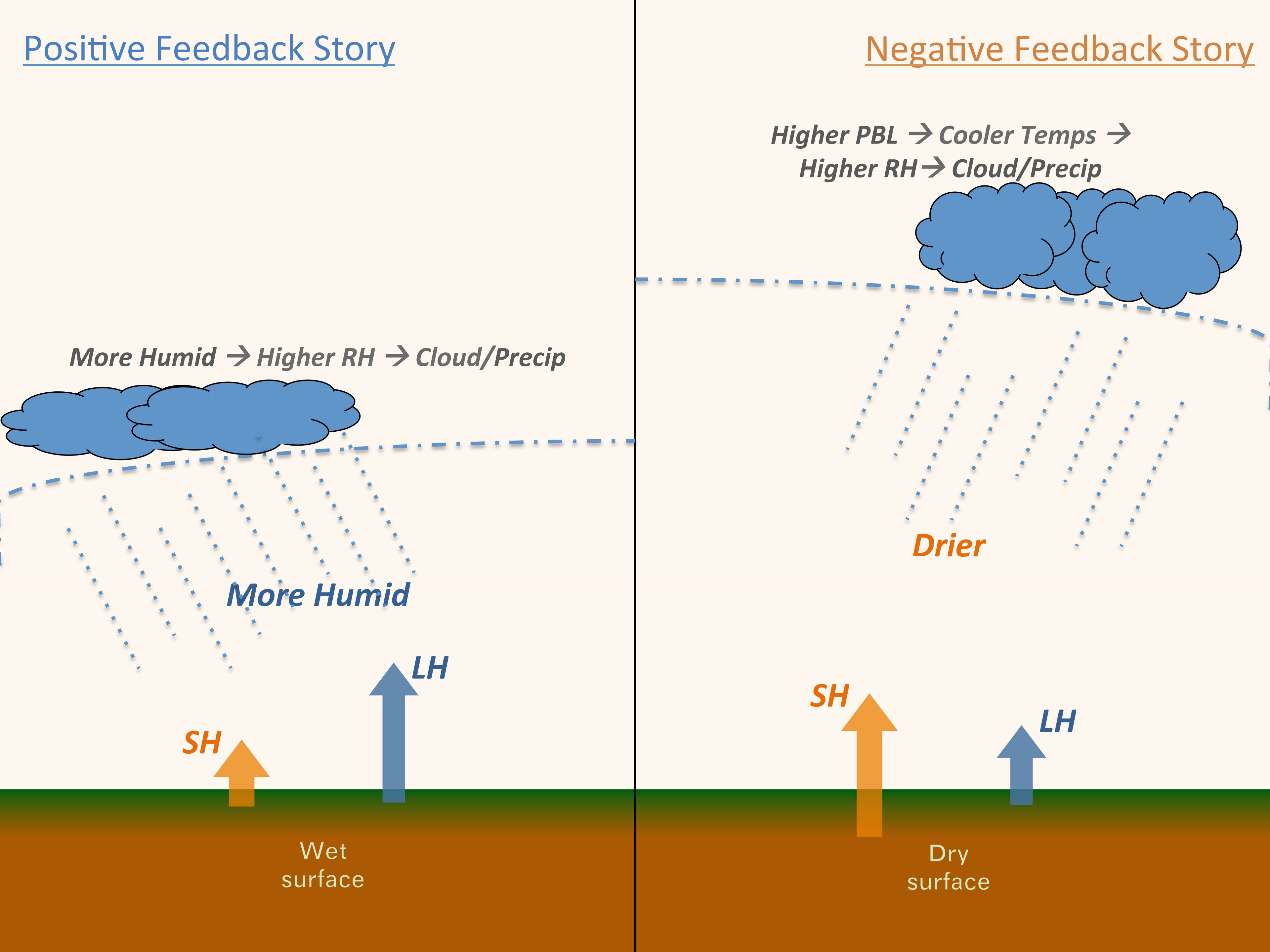
***Coupling*** = how closely controlled is one variable by another

- *Example: **Latent Heat** change due to variations in **Soil Moisture***

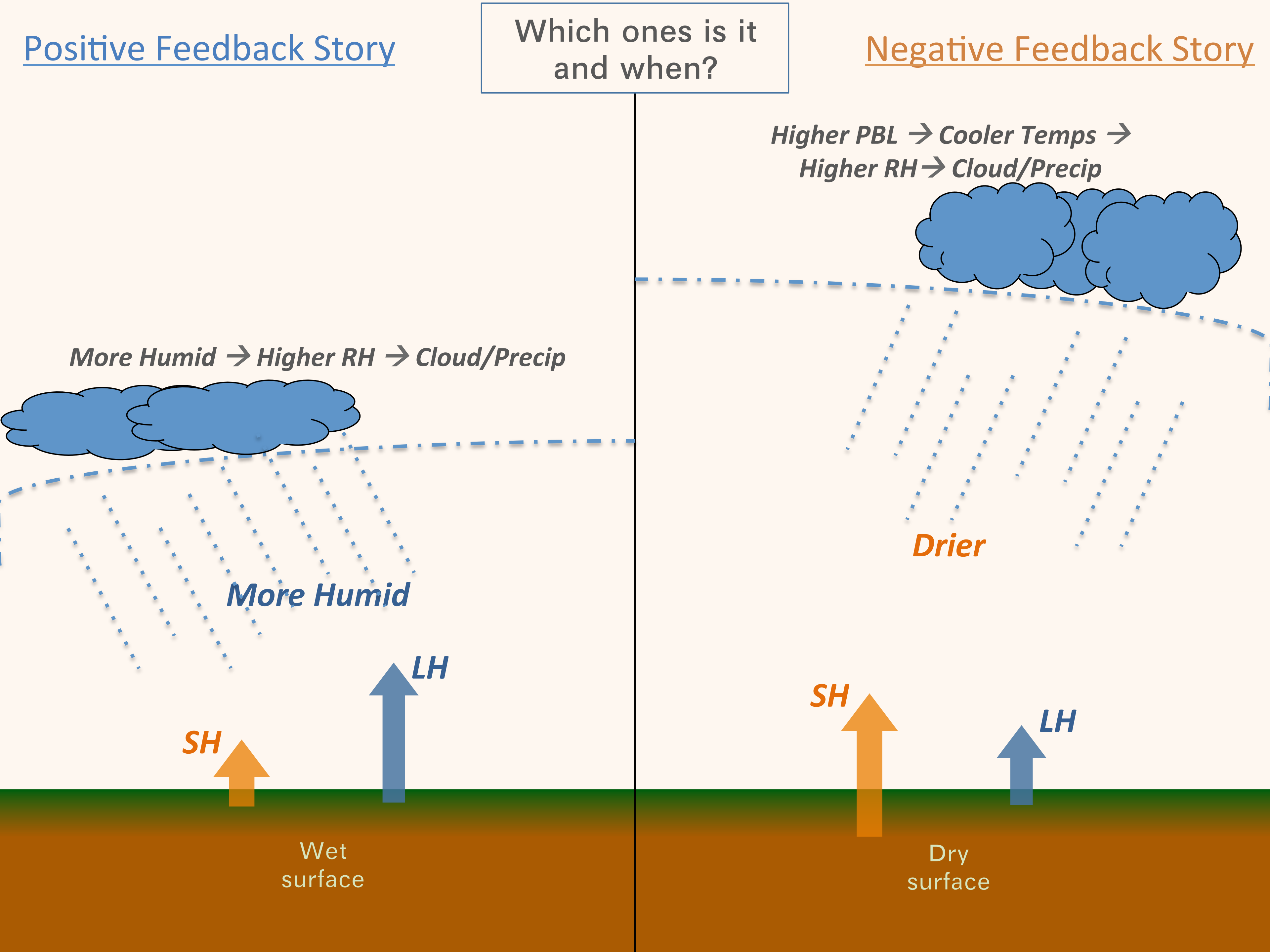
***Feedback*** = perturbation of a variables results in further perturbation

- *Example: **Wet soil** produces **less rain** results in soil drying* **(-)**





Positive Feedback Story
More Humid → Higher RH → Cloud/Precip
More Humid
LH
SH
Wet
surface
Negative Feedback Story
Higher PBL → Cooler Temps →
Higher RH → Cloud/Precip
Drier
SH
LH
Dry
surface



Positive Feedback Story
Which ones is it and when?
Negative Feedback Story
Higher PBL → Cooler Temps → Higher RH → Cloud/Precip
More Humid → Higher RH → Cloud/Precip
Drier
More Humid
LH
SH
SH
LH
Wet surface
Dry surface

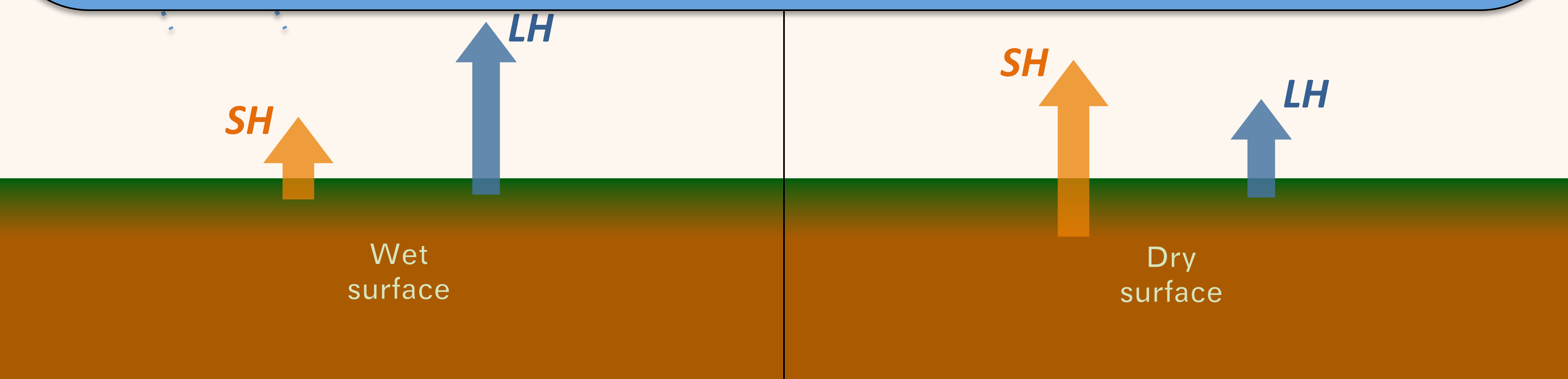
Positive Feedback Story

Which ones is it and when?

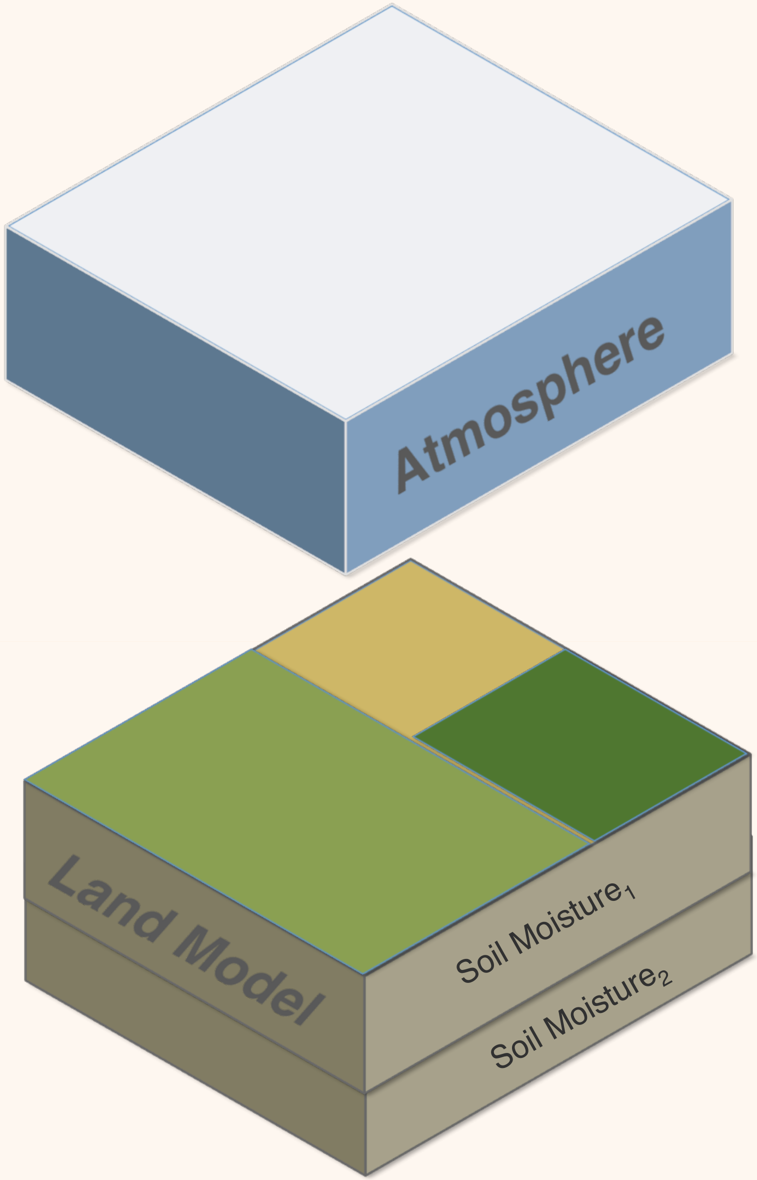
Negative Feedback Story

***Higher PBL → Cooler Temps → Higher RH → Cloud/Precip***

Need a way to quantify ***coupling*** and ***feedbacks*** in order to answer this question and others



# Clever Model Design for Coupling and Feedback




In model world we can just prescribe or adjust soil moisture to explore L-A

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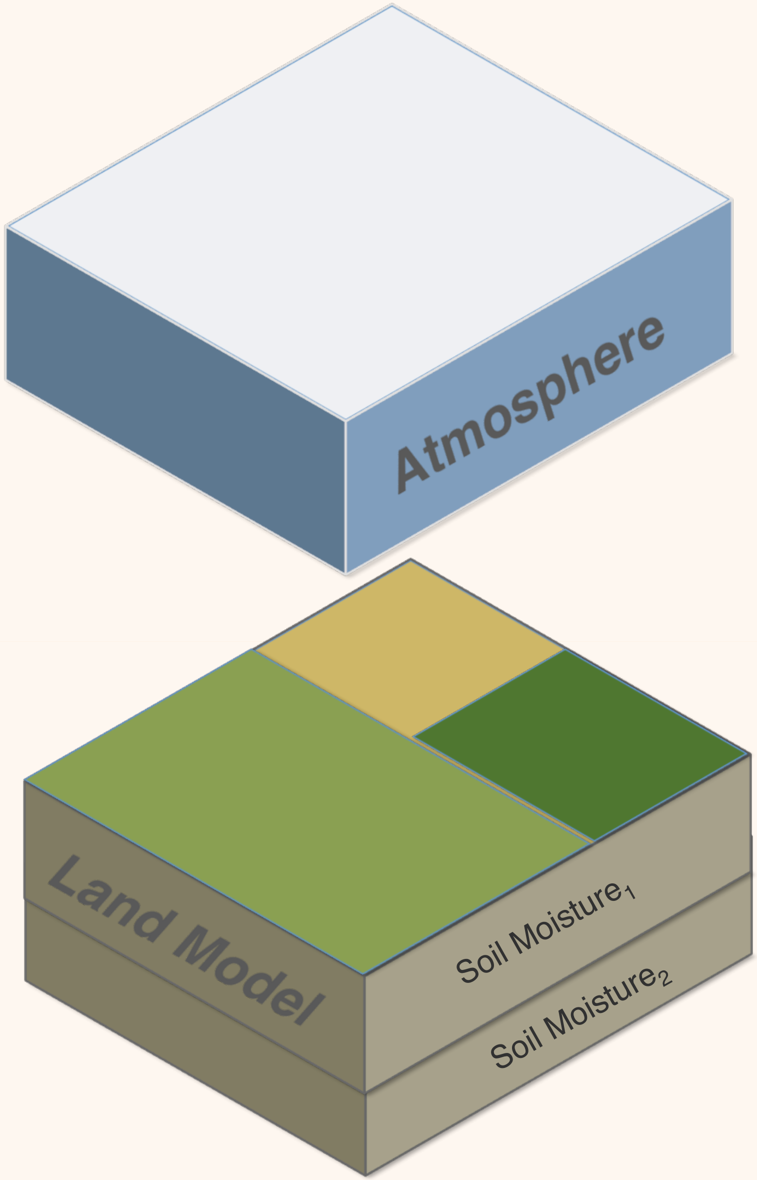


In model world we can just prescribe or adjust soil moisture to explore L-A

- ***Seasonal predictability:*** A popular method was to initialize to dry or wet soil moisture and see how the model evolves (Betts et al. 1996; Fennessy and Shukla 1999; Pal and Eltahir 2001; Betts 2004; Wu et al. 2007; Kim and Wang 2007)

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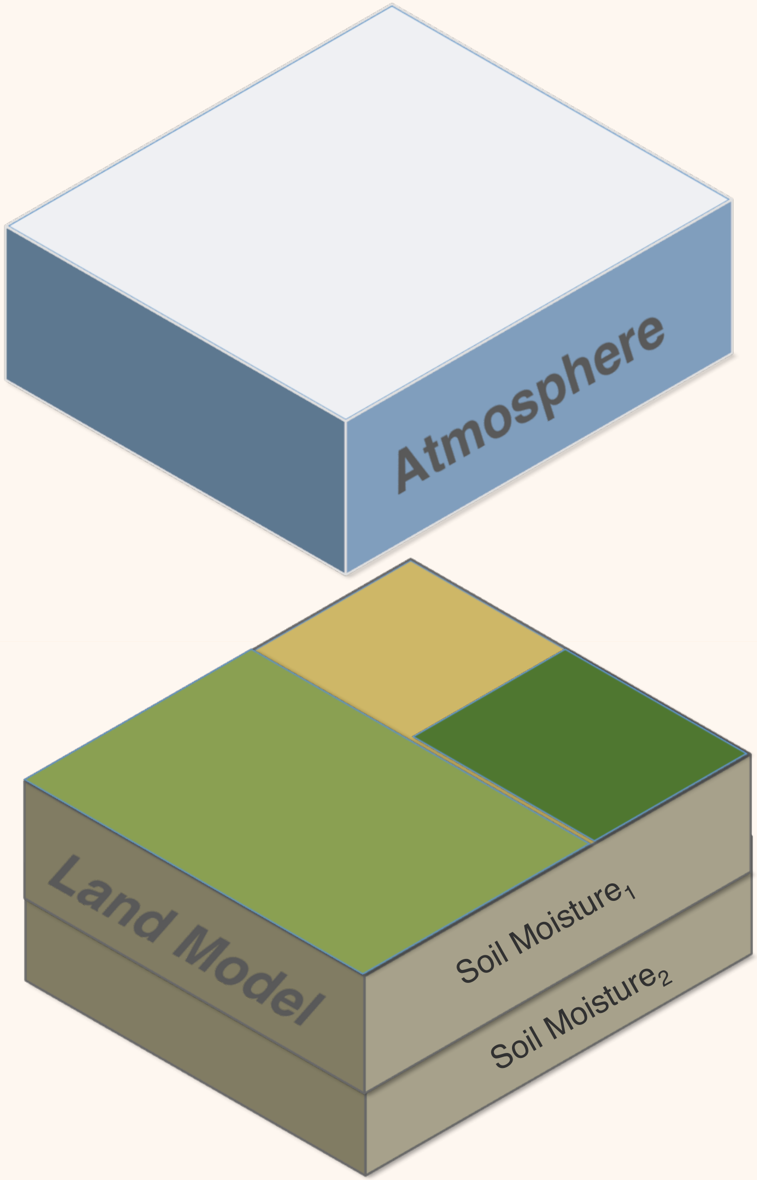


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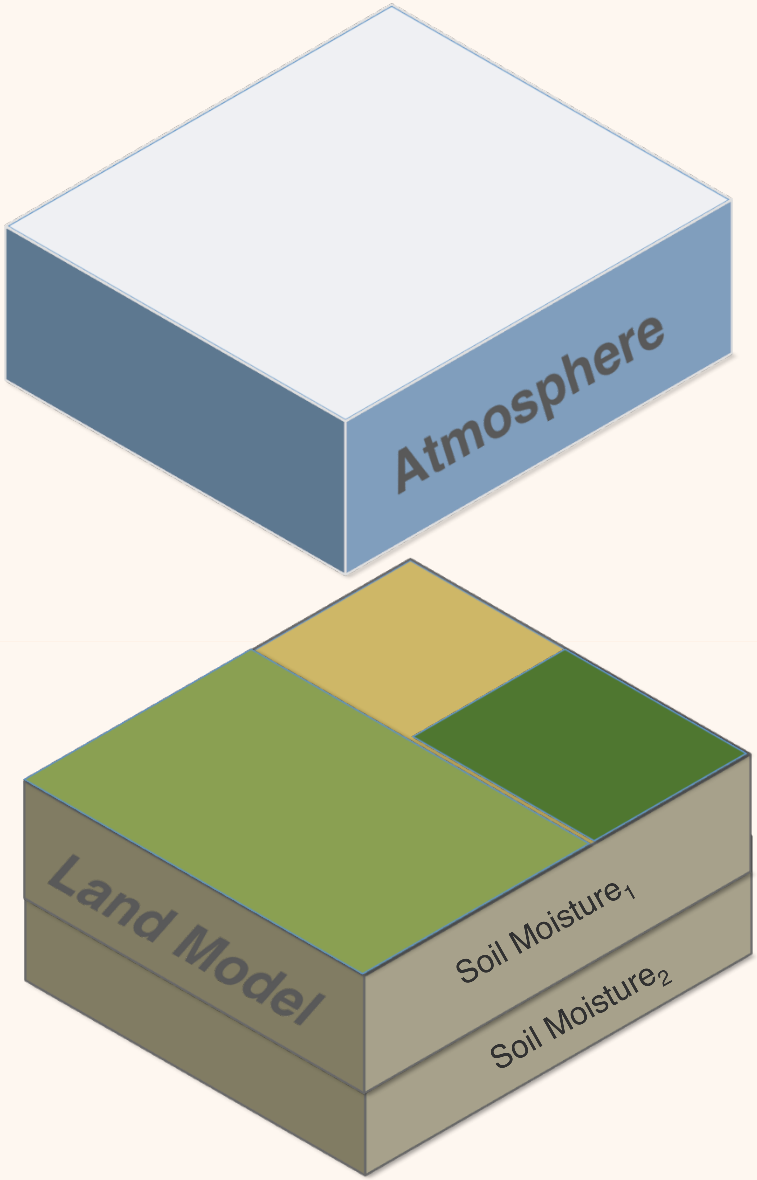
- ***Climate Feedbacks:*** The Global Land Atmosphere Experiment (GLACE) explored soil moisture-precipitation interactions in 12 GCMs by performing two sets of ensembles for each model. A metric was then be derived to isolate variations in precipitation due solely to soil moisture (Koster et al. 2004, 2006; Guo et al. 2006)

$$\Omega_P = \frac{16\sigma_{\hat{P}}^2 - \sigma_P^2}{15\sigma_P^2}.$$

# Clever Model Design for Coupling and Feedback

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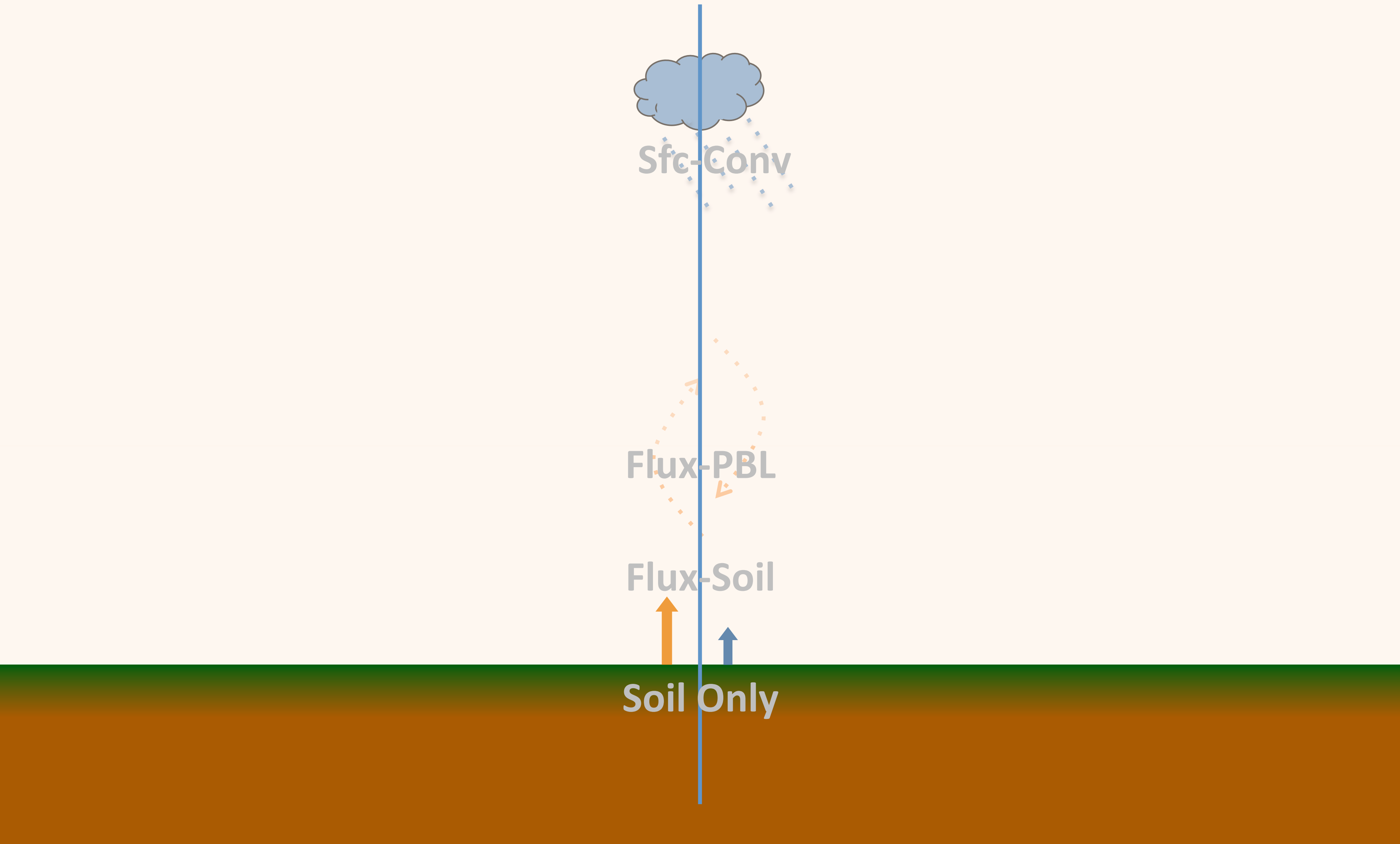
- ***Real-World:*** Unfortunately, in the real-world you cannot just prescribe soil moisture in a massive controlled way. Need metrics that can be calculated from both models and observations

# Common Metrics for L-A Coupling and Feedbacks



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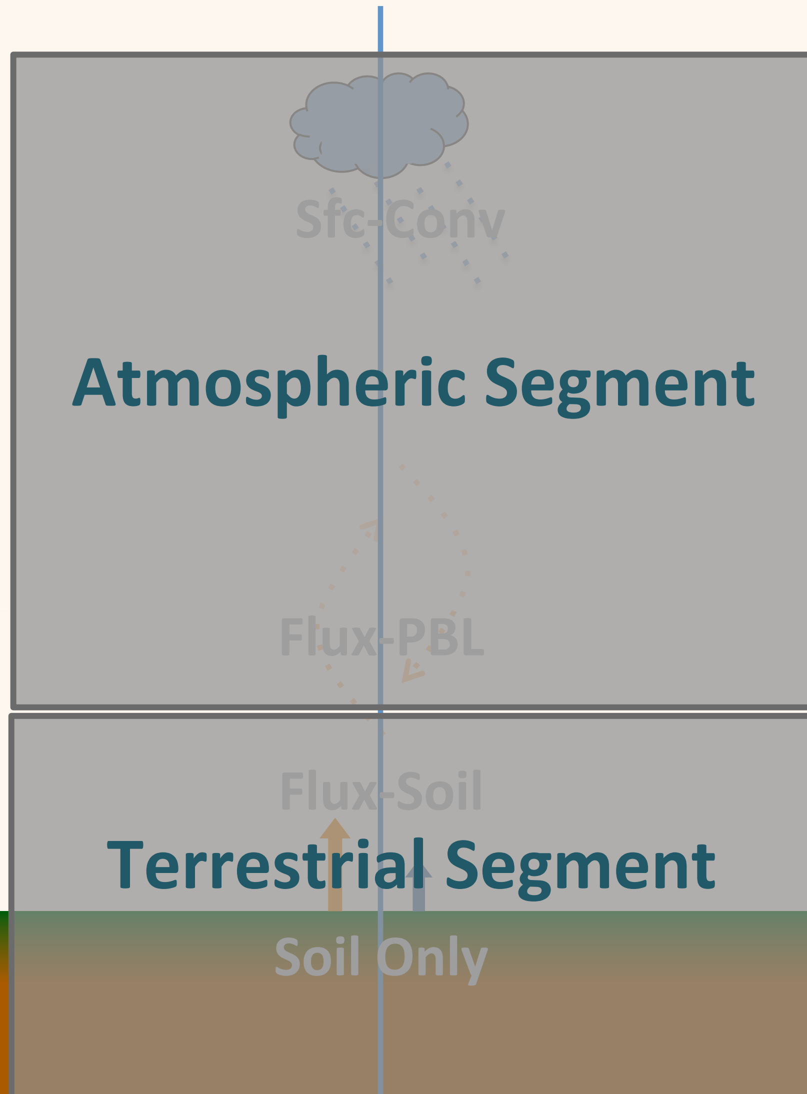
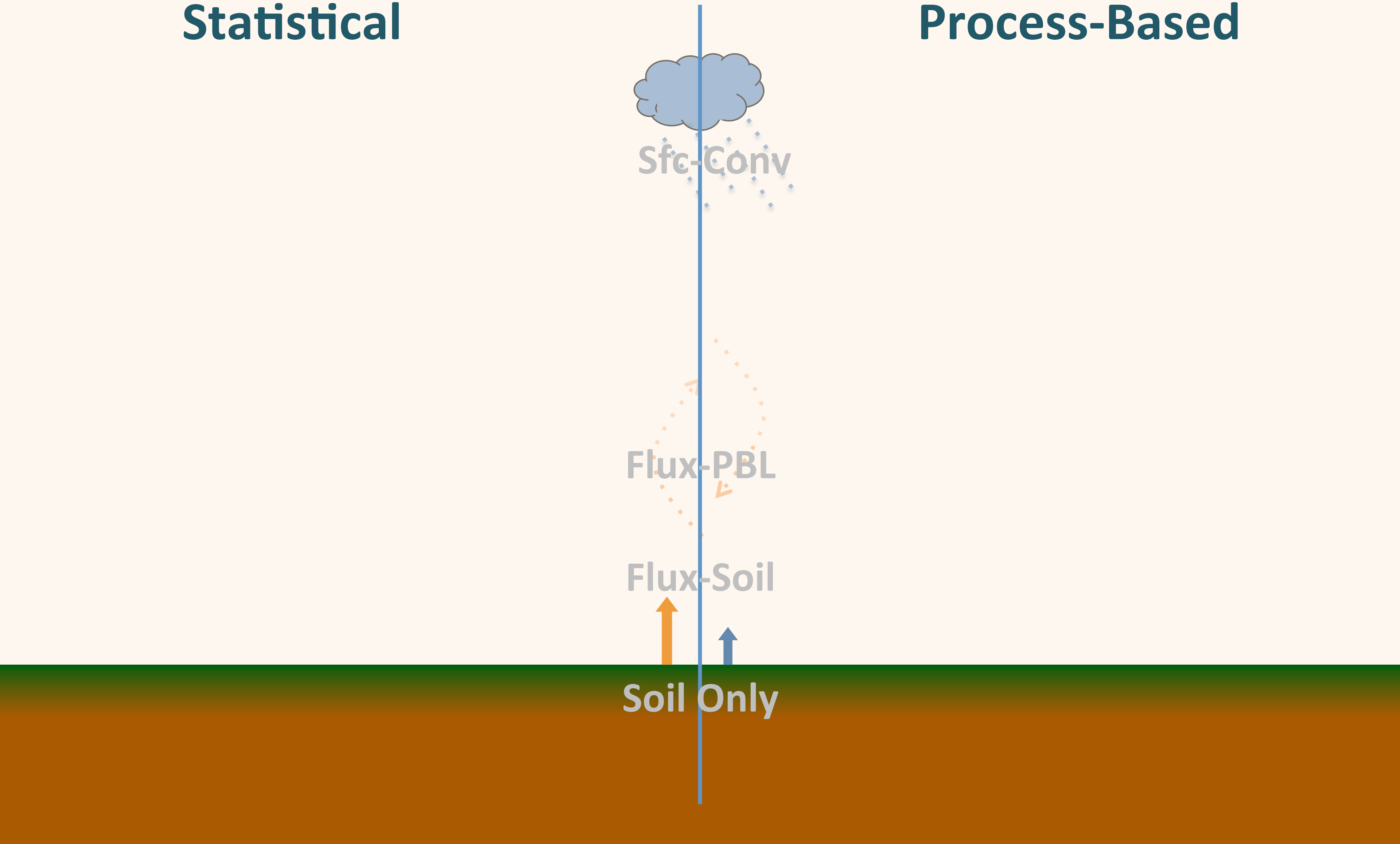


# Common Metrics for L-A Coupling and Feedbacks

**Statistical** | **Process-Based**



# Common Metrics for L–A Coupling and Feedbacks

## Statistical

Trigger/Amplification Feedback Strength

Two-legged Metric

Terrestrial Coupling Parameter

Soil Moisture Memory

## Process-Based

Convective Triggering Potential

Heated Condensation Framework

Relative Humidity Tendency

Mixing Diagrams

Intrinsic Biophysical Factors

Soil Moisture Memory

Sfc-Conv

Flux-PBL

Flux-Soil

Soil Only

# Common Metrics for L-A Coupling and Feedbacks

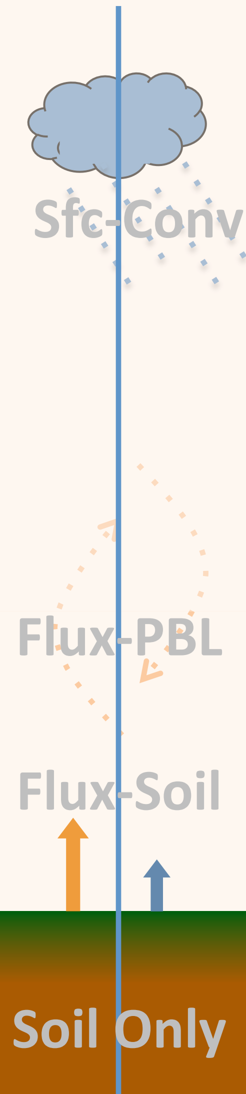
## Statistical

Soil moisture memory

- How long a soil moisture anomaly is retained
- Statistically – using the lagged autocorrelation of soil moisture and identify when the correlation falls below some "information thershold"

Good references:

Dirmeyer 2016 – models versus observations
Seneviratne 2012 – decent review and comprehensive process framework




## Process-Based

- **Why we care?** Because persistence of an anomaly is potential for predictability!
- Process – using water balance equation to estimate the water storage

Soil Moisture Memory

Soil Moisture Memory

# Common L–A Coupling Metrics

## Statistical

Flux-Soil Moisture

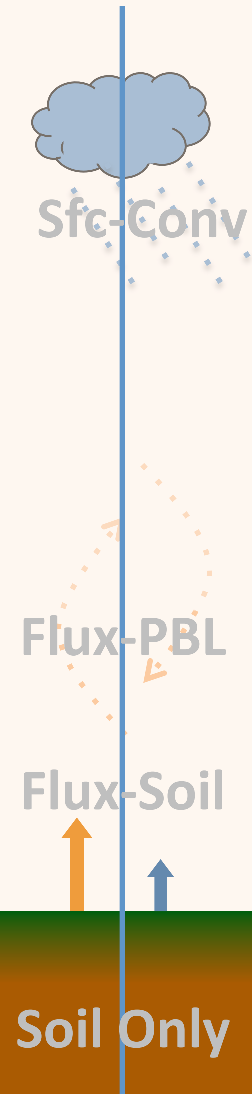
- How changes in soil moisture control variations in latent and sensible heat flux
- TCP – standard deviation of soil moisture x linear slope of sm-sfc flux (Dirmeyer 2011)

Terrestrial Coupling Parameter

## Process-Based

- **Why we care?** Because fluxes are the info being passed to the atmosphere so to know the surface control is to know the importance of the land surface
- IBF – makes assumptions about transfer process to back out contribution of roughness, bowen ratio and radiation to temperature change (Lee et al. 2011)

Intrinsic Biophysical Factors




Soil Moisture Memory

Soil Moisture Memory

# Common Metrics for L–A Coupling and Feedbacks

## Statistical

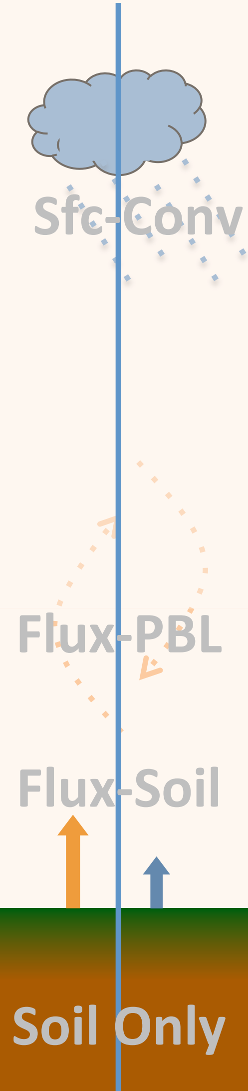
Flux-PBL Character

- How changes in fluxes control variations in PBL properties
- TWO – standard deviation of soil moisture x linear slope of sm-sfc flux (Dirmeyer 2014)

Two-legged Metric

Terrestrial Coupling Parameter

Soil Moisture Memory




## Process-Based

- **Why we care?** Same reason as before but continuing along the process-chain
- MIX – Takes the diurnal evolution of T, q, and fluxes to see how much surface fluxes contribute to changes in T and q in the PBL (Santanello et al. 2009, 2011, 2013)

Mixing Diagrams

Intrinsic Biophysical Factors

Soil Moisture Memory

# Common Metrics for L–A Coupling and Feedbacks

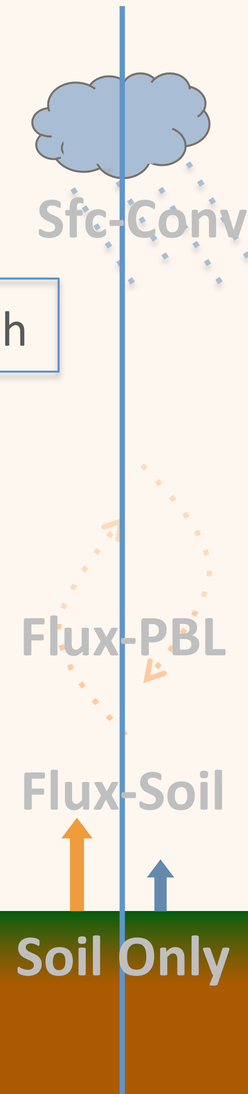
## Statistical

**Trigger/Amplification Feedback Strength**

Surface-Convection

- Gets at ***feedbacks***. How changes in fluxes control cloud cover and/or precipitation

- TFS/AFS – probabilistic way to estimate how surface fluxes contribute to triggering or intensification of precipitation (Findell et al. 2011)




## Process-Based

**Convective Triggering Potential**

**Heated Condensation Framework**

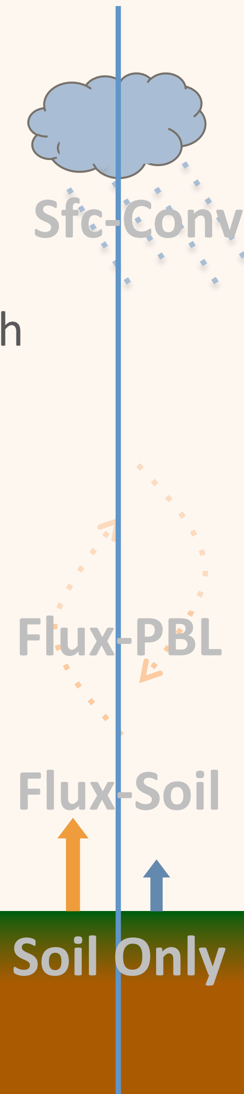
**Relative Humidity Tendency**

- RH-Tend – uses mixed layer model assumption to derive an equation for top of PBL relative humidity in terms of evaporative fraction (Ek and Holtslag 2004)

- CTP – evaluates morning conditions to determine whether wet or dry conditions favor convection (Findell and Eltahir 2003)

- HCF – asses atmospheric background state and identifies local versus non-local convection (Tawfik and Dirmeyer 2013, 2014)

# Common Metrics for L-A Coupling and Feedbacks




## Statistical

Trigger/Amplification Feedback Strength

Two-legged Metric

Terrestrial Coupling Parameter

Soil Moisture Memory

## Process-Based

Convective Triggering Potential

Heated Condensation Framework

Relative Humidity Tendency

Mixing Diagrams

Intrinsic Biophysical Factors

Soil Moisture Memory

# Common Metrics for L-A Coupling and Feedbacks

[www.coupling-metrics.com](http://www.coupling-metrics.com)

To get Fortran 90 subroutines that calculate some of these metrics

Heated Condensation Framework

Trigger/Amplification Feedback Strength

Relative Humidity Tendency

Two-legged Metric

Flux-PBL

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Which metrics can we calculate using ***CLM***?

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# Common Metrics for L-A Coupling and Feedbacks

**Statistical** | **Process-Based**

Which metrics can we calculate using ***CLM***?

*these* ***coupling*** *metrics*

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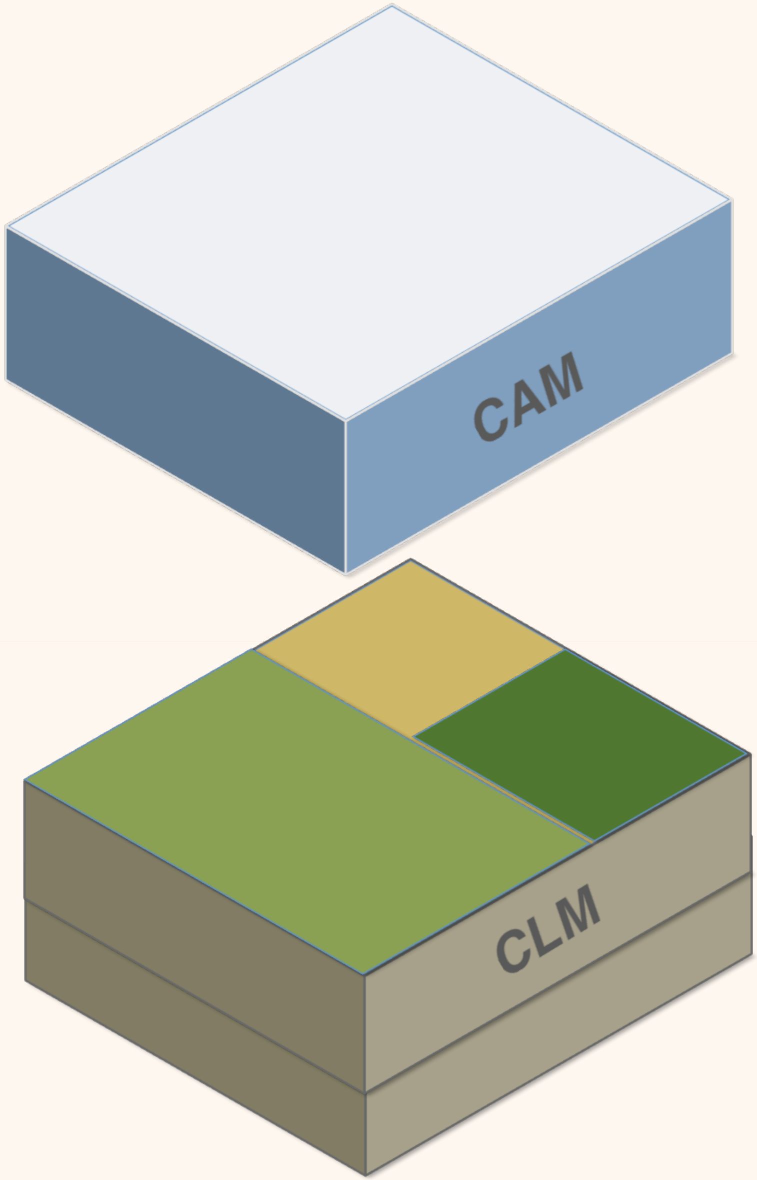
Soil Moisture Memory

# The Community Earth System Model (CESM)




***CESM:*** Stands for the Community Earth System Model

- CESM has ocean, atmosphere, land, sea ice, and wave component models; other features include atmospheric chemistry among others…
- These components when all run together are called "fully coupled"
- CAM is the atmosphere component of the CESM and there is a component set that includes just using CAM and CLM; the ocean temperatures are prescribed in this case
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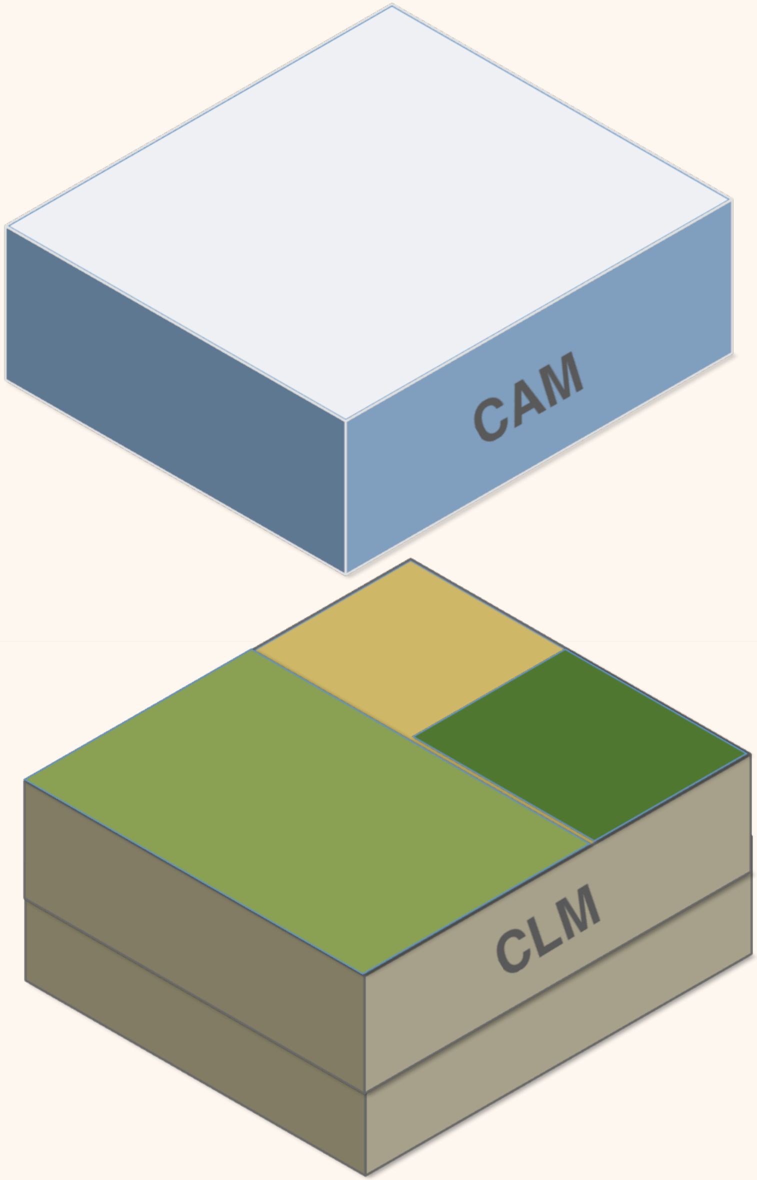


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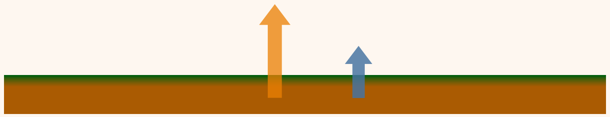
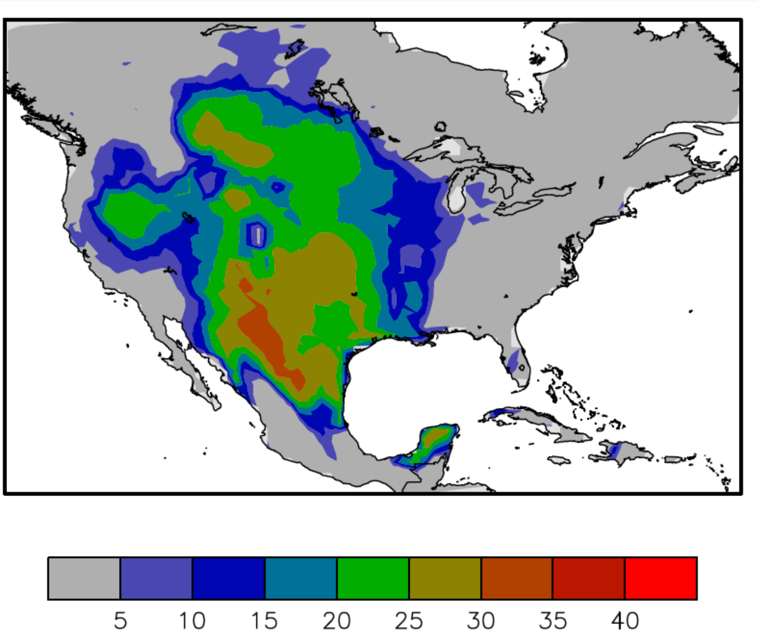
## How does **terrestrial coupling** vary with model configuration?

Refresher: soil moisture control on latent heat flux



# Terrestrial Coupling and CESM

**CLM 4.0 and CAM 5.3**




**latent heat flux not sensitive to soil moisture variation**
(weak coupling)

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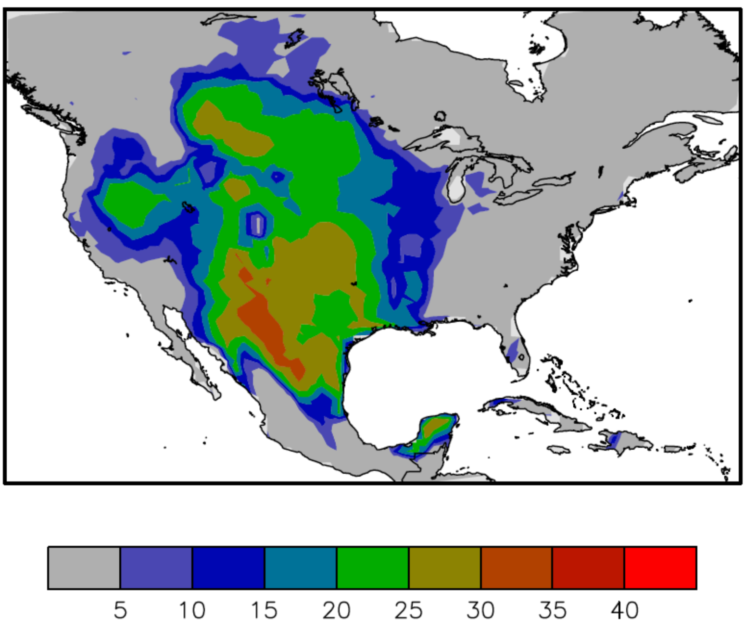


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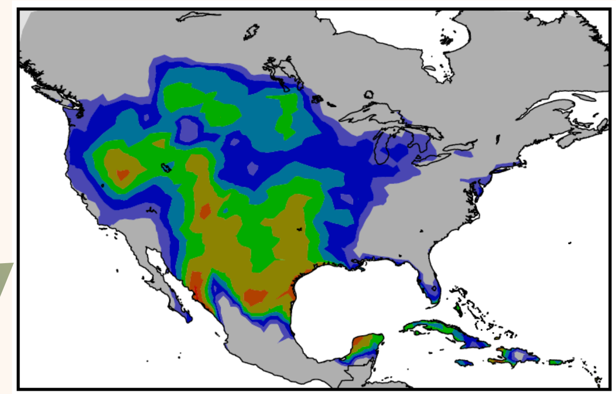
**CLM 4.5 effect**



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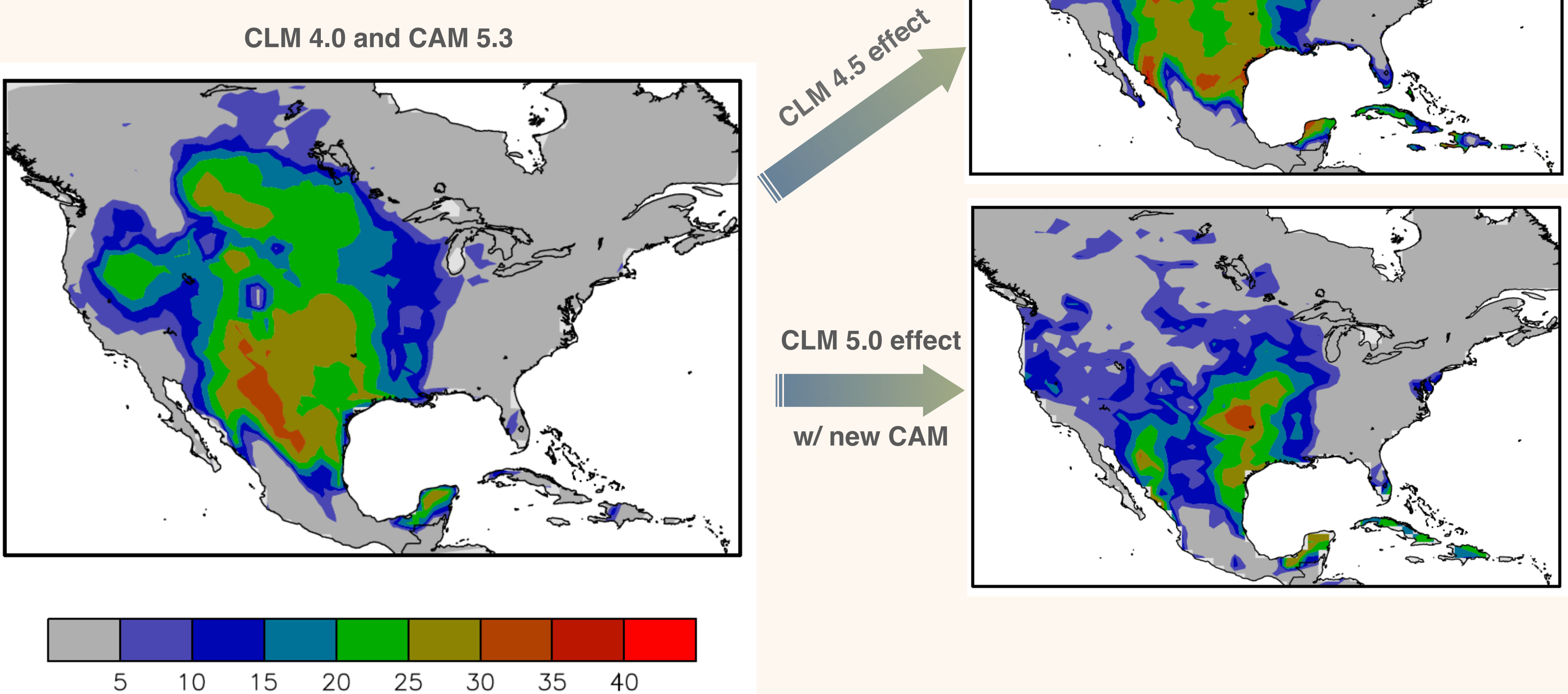


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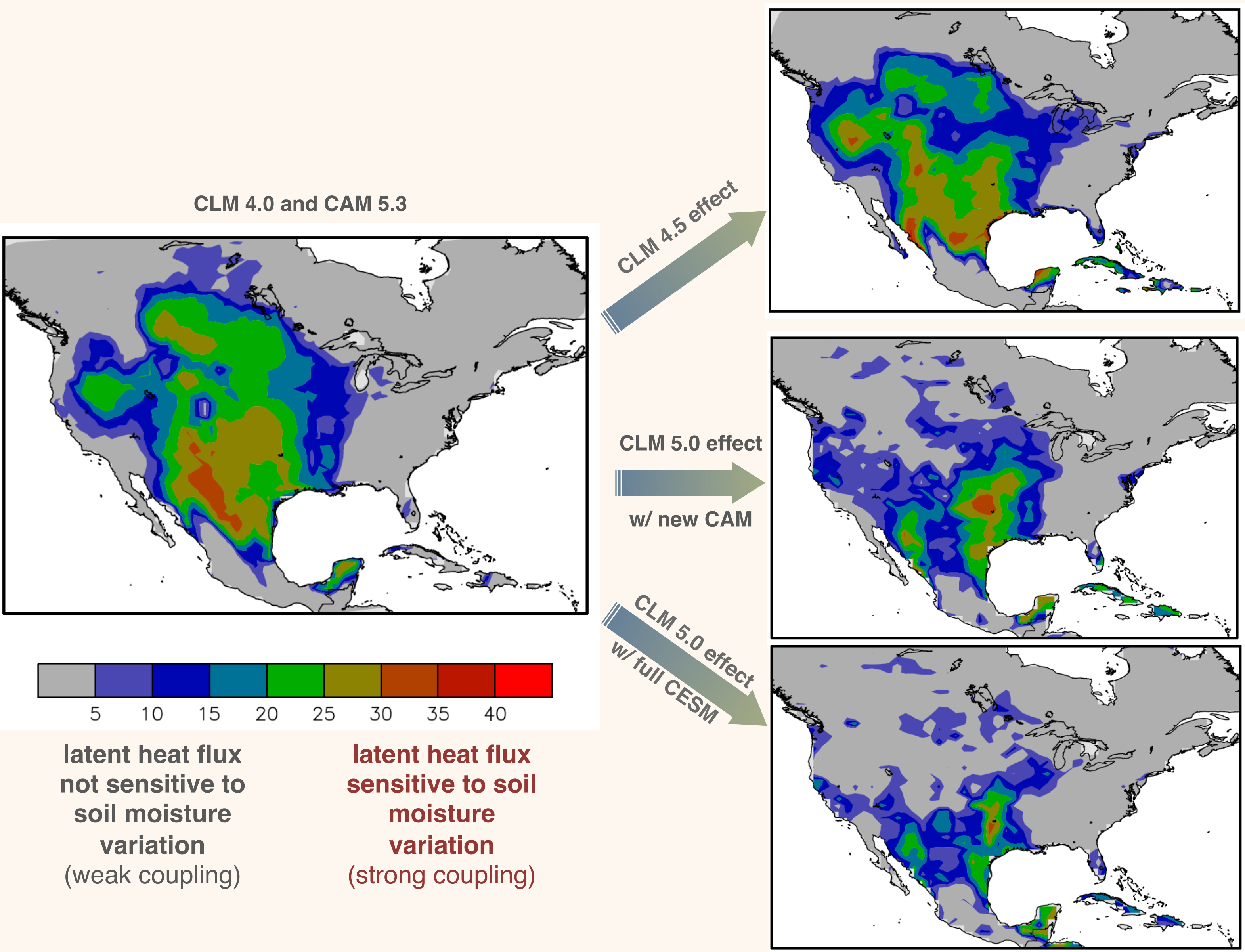
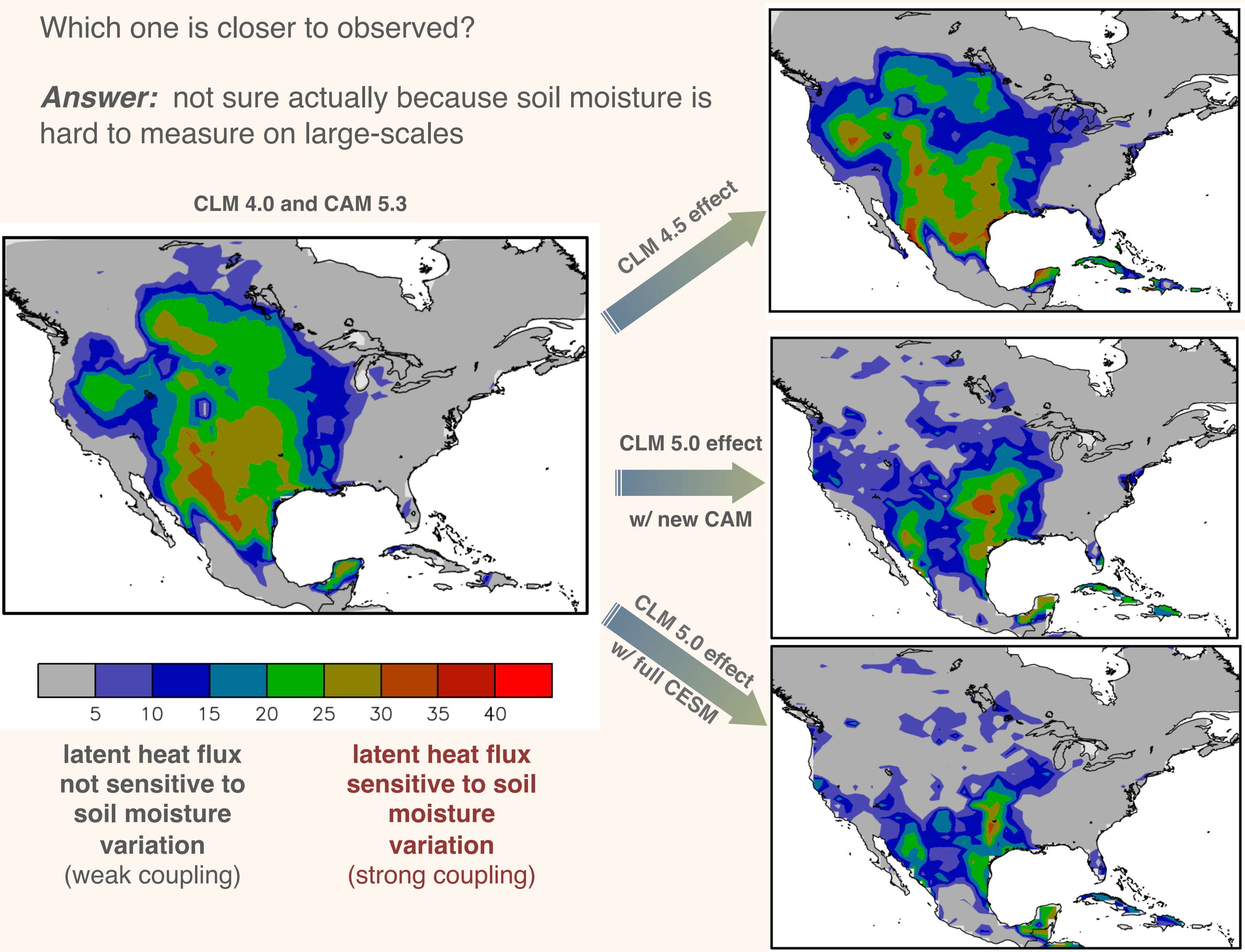


# Terrestrial Coupling and CESM

Which one is closer to observed?

***Answer:*** not sure actually because soil moisture is hard to measure on large-scales



# Terrestrial Coupling and CESM

Comparison can be done against limited flux observations and **other models** that are given observed precipitation

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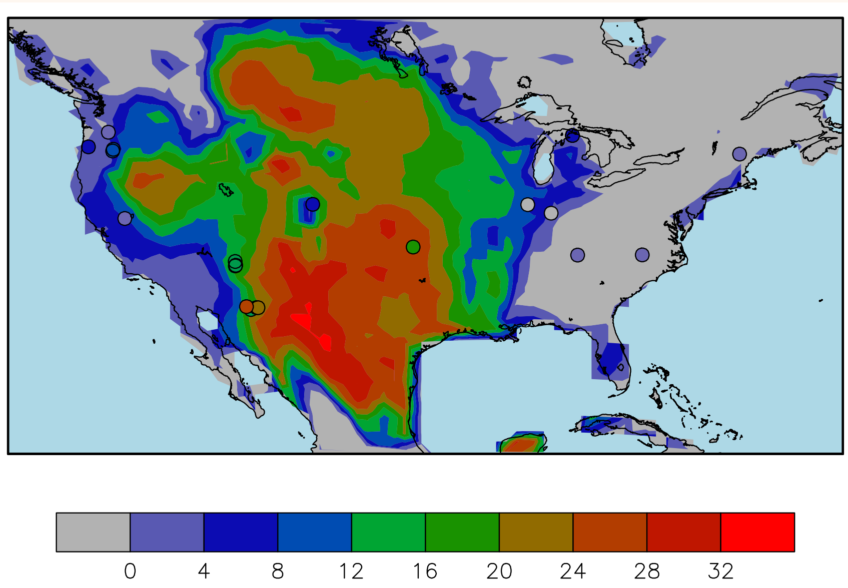


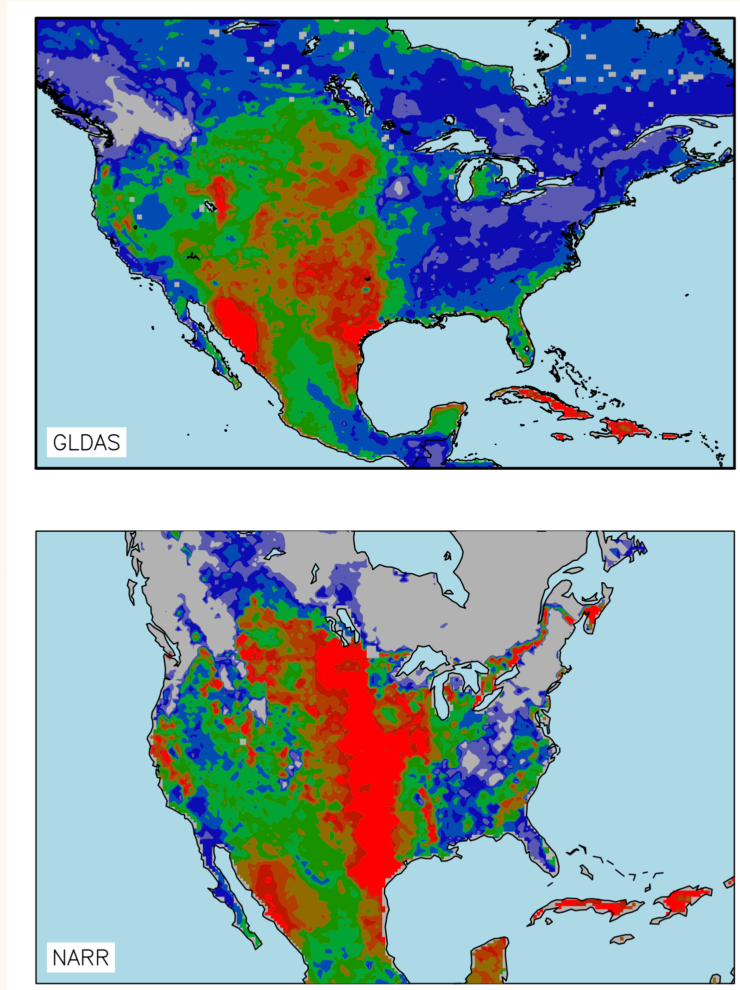


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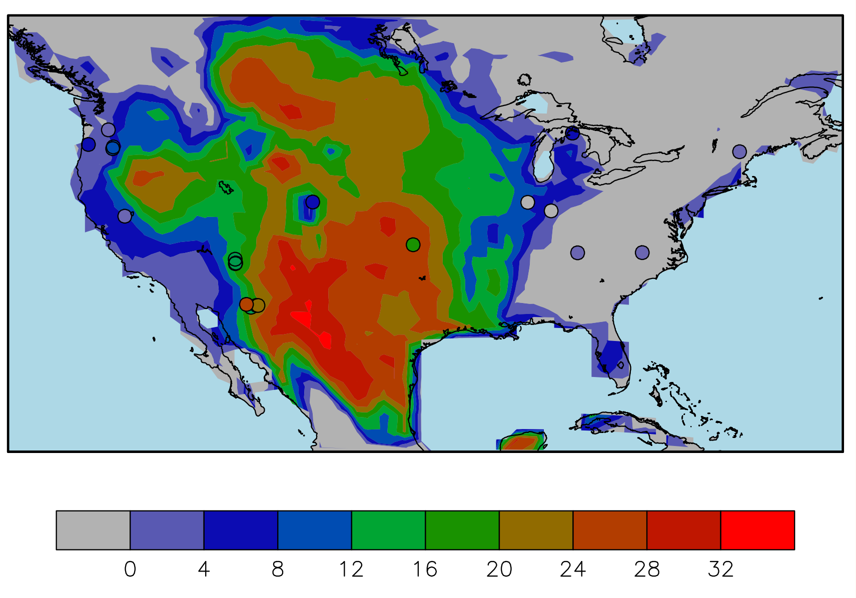


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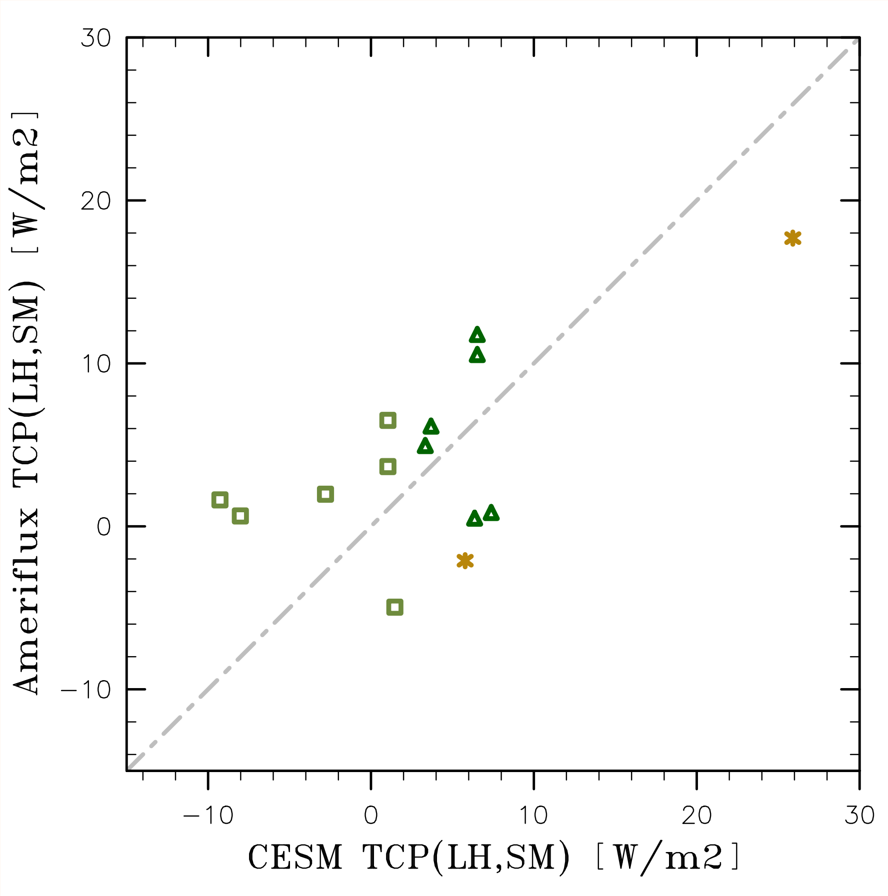
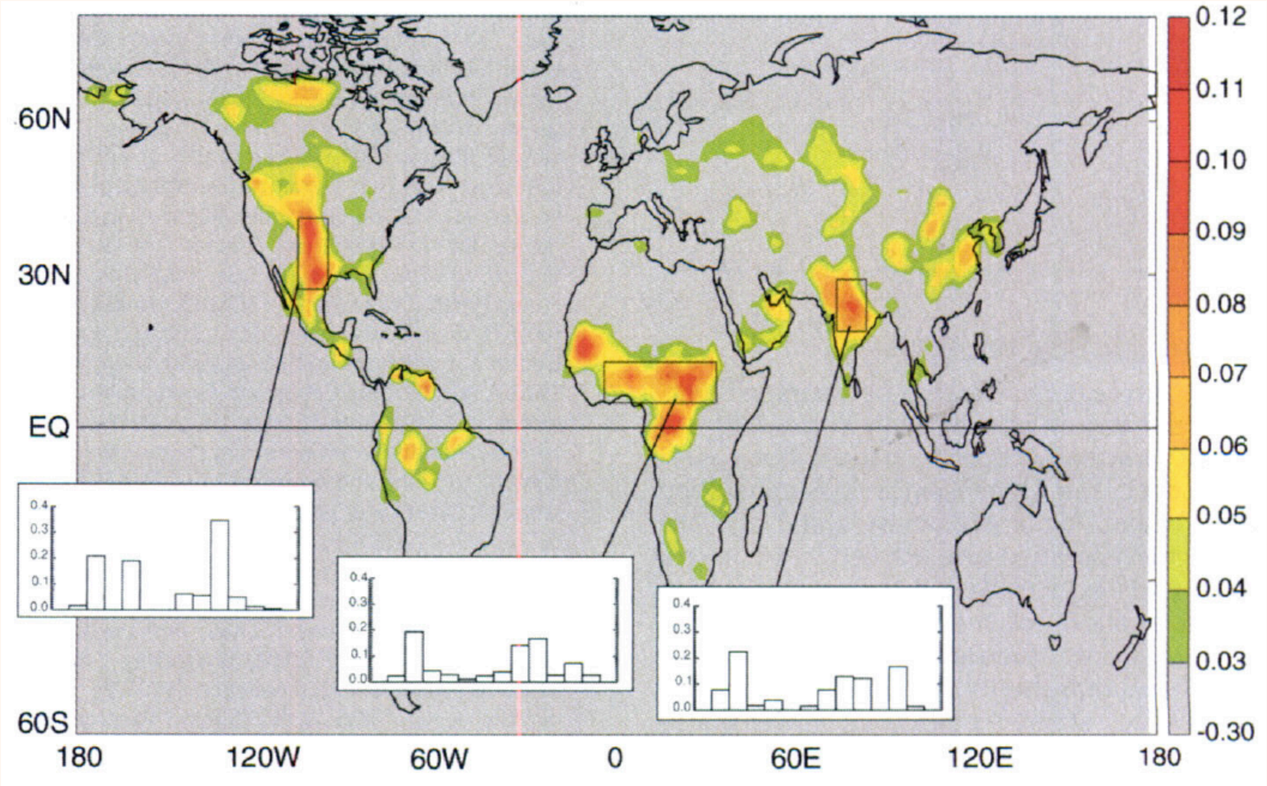


# Models: SM–Precipitation Feedback

Warm colors show positive soil moisture-precipitation feedback
Models show wet soil → more rain




(Koster et al. 2004, Science)

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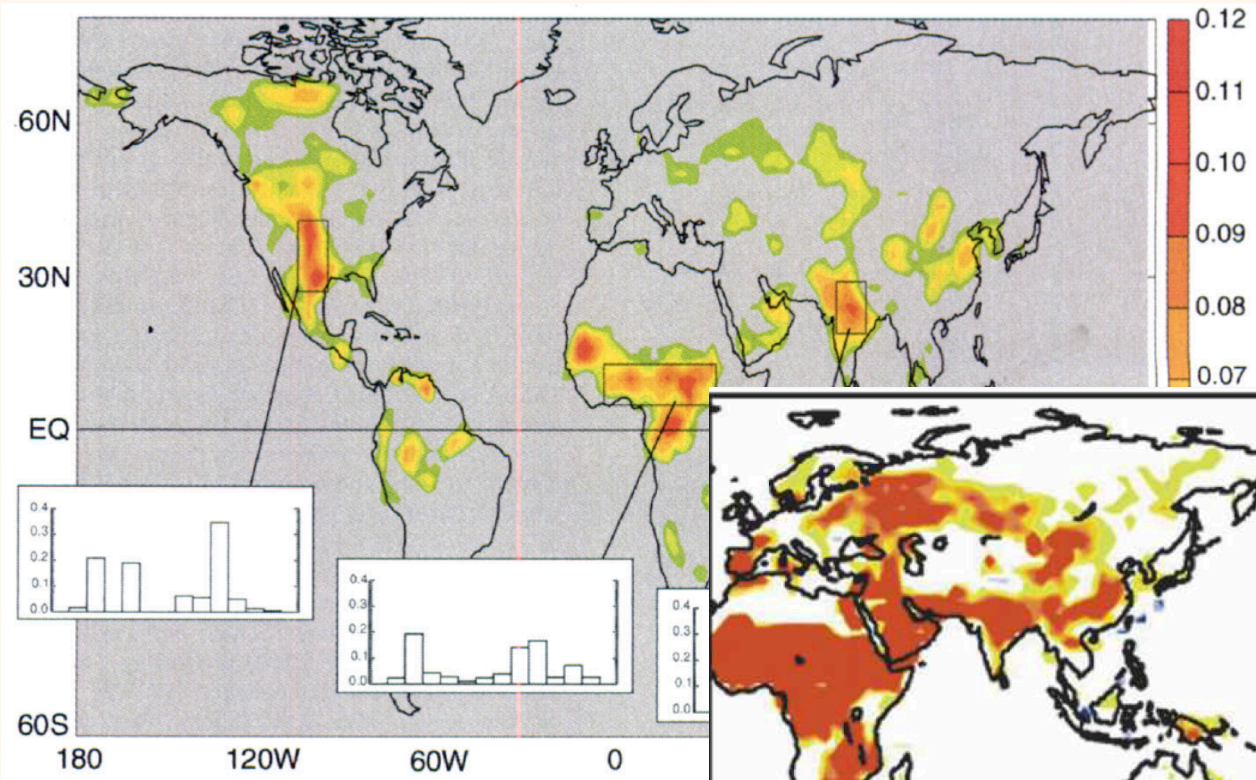


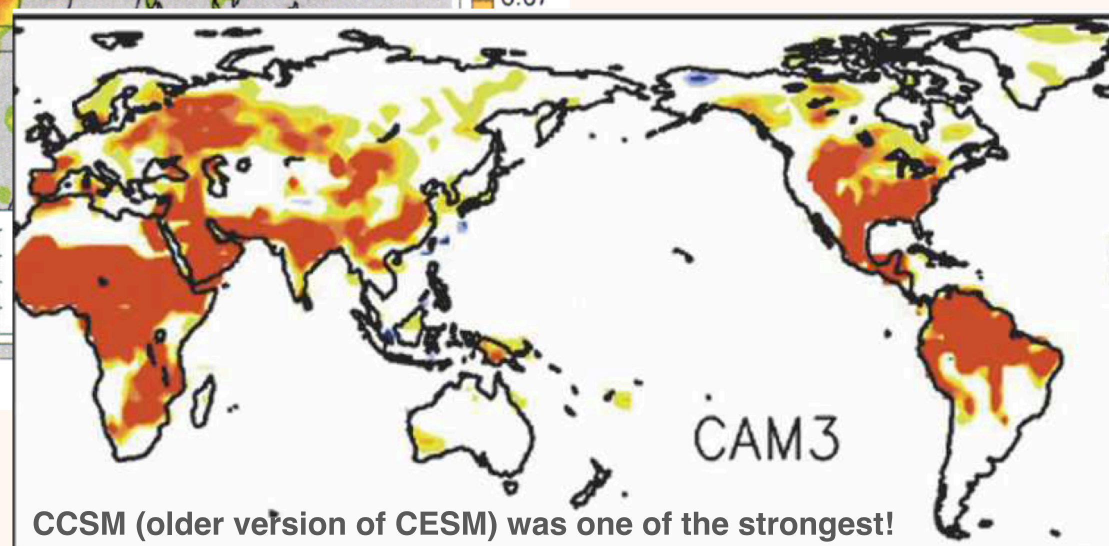


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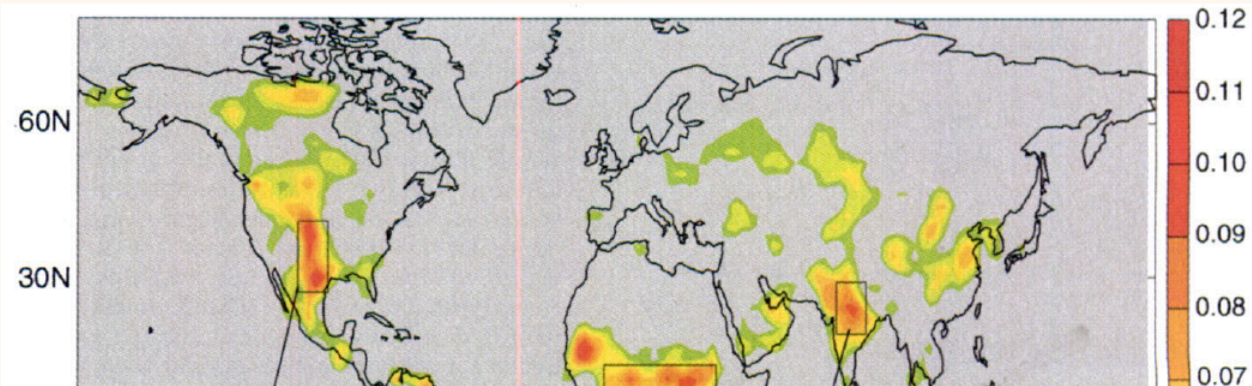
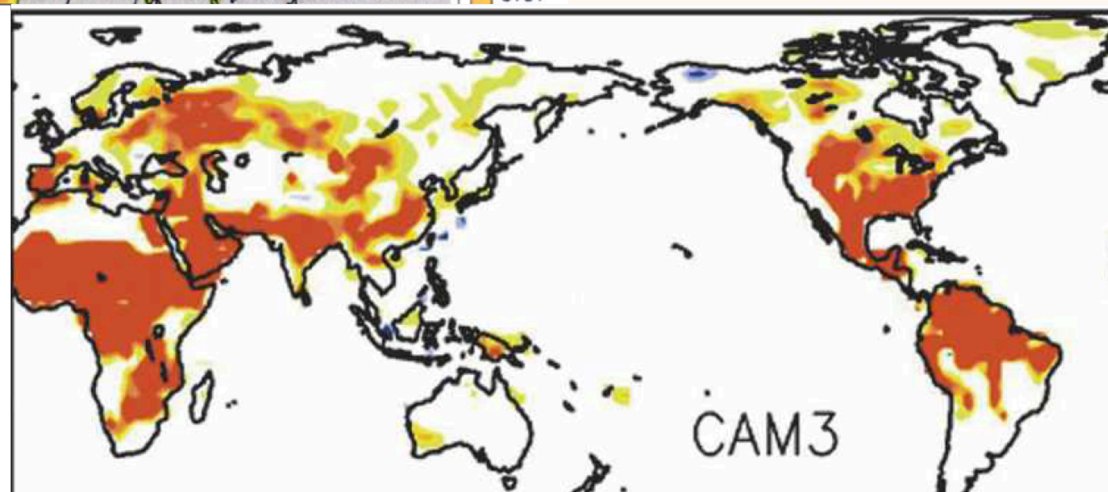



- Feedback has been shown to be most sensitive to things happening in CAM and is likely ***not*** from CLM (Mei and Wang 2012)

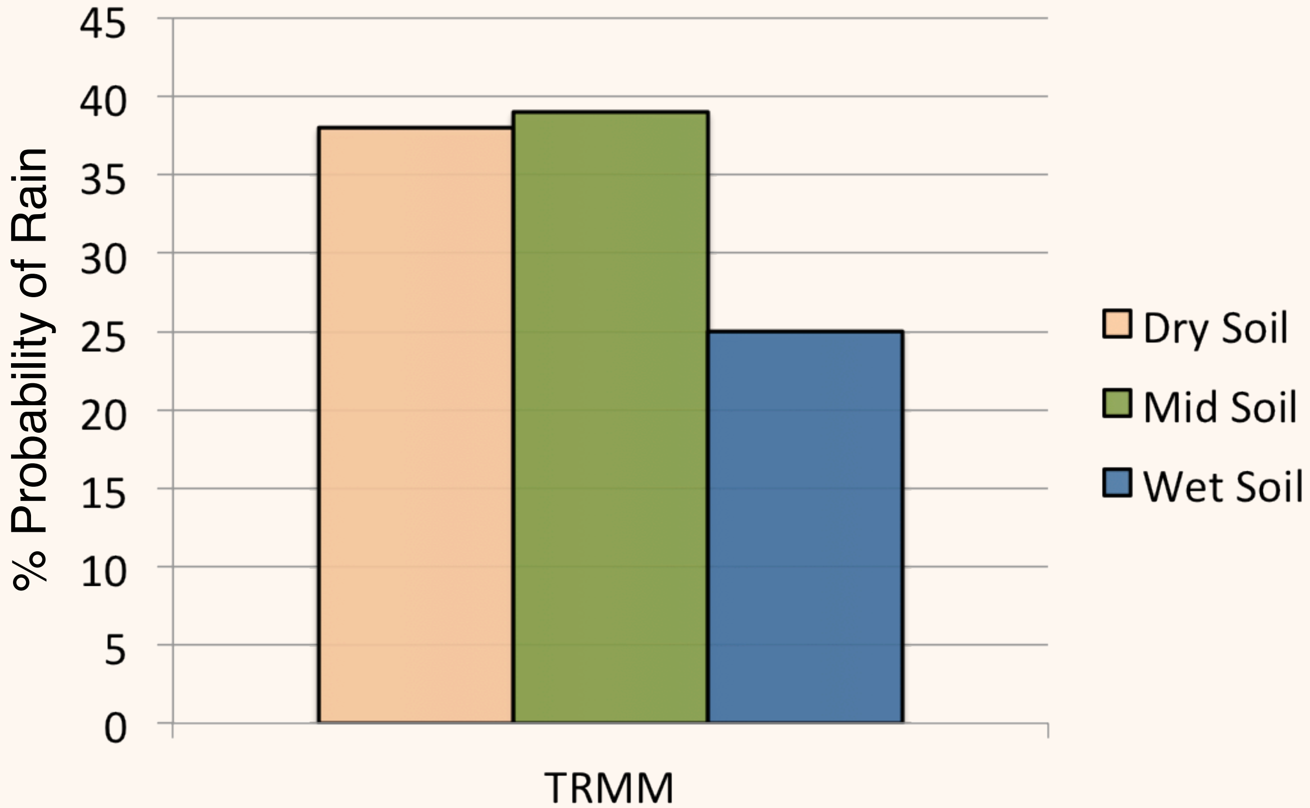



**CCSM (older version of CESM) was one of the strongest!**

**(Koster et al. 2004, 2006)**

# SM-Precip Feedbacks in the Real-world

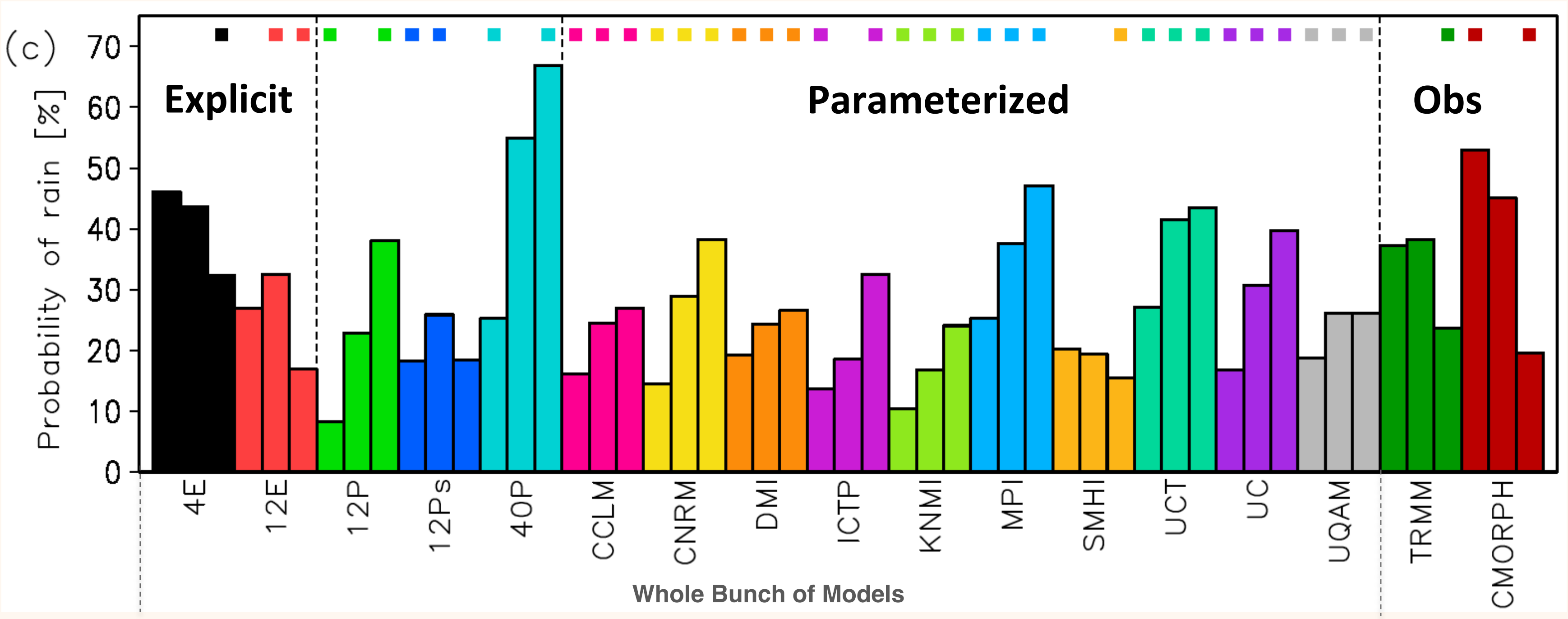
Drier soils have a higher probability of triggering rain in obs…




(Taylor et al. 2013, GRL)

# SM-Precip Feedbacks in the Real-world

But models show the **opposite** signal

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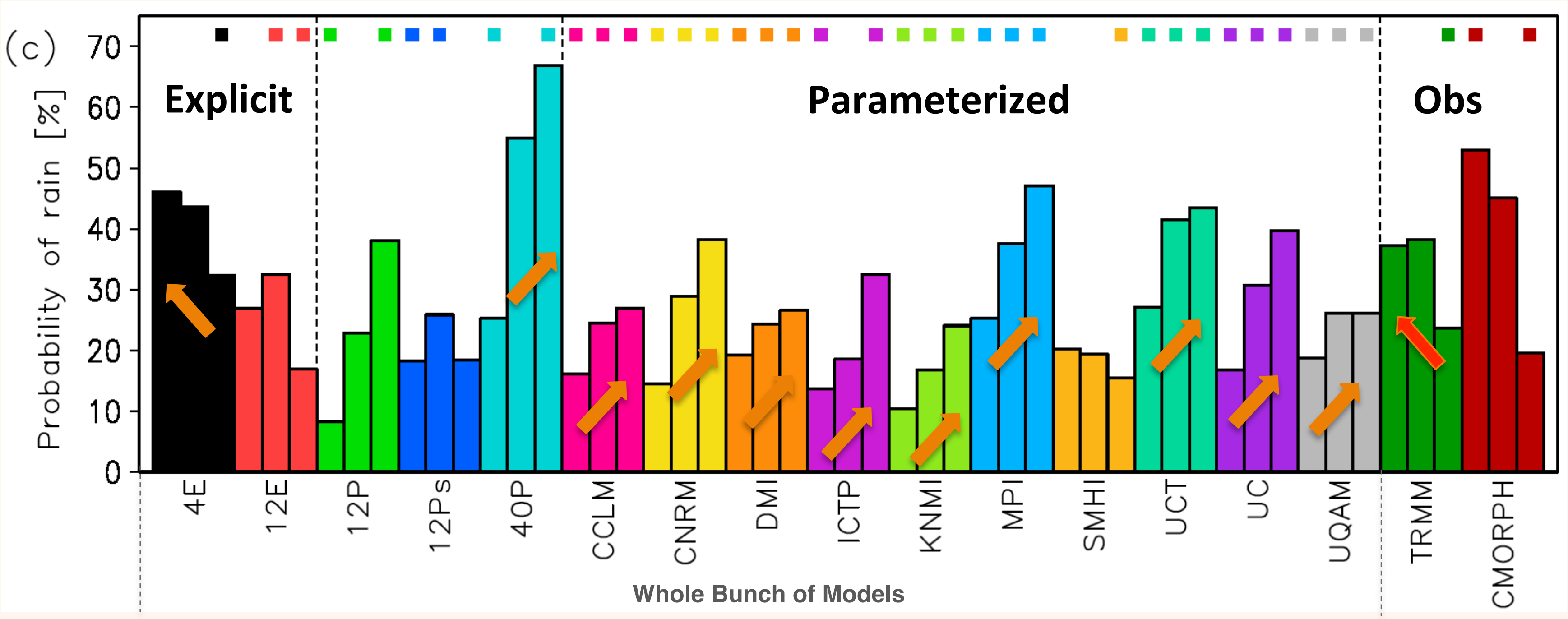


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# Take–home points

How can we quantify ***Coupling*** and ***Feedbacks***?

Description of physical processes and defining terminology:

Common metrics and measures:

Land-Atmosphere interactions in ***CESM*** (CAM and ***CLM***)

Change in coupling and feedbacks across model version

Model-world versus Real-world

# Take-home points

<u>How can we quantify ***Coupling*** and ***Feedbacks***?</u>

Description of physical processes and defining terminology:

- It's a complicated coupled system and coupling is different from a feedback

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- There are a lot of metrics depending on what you want to quantify
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<u>Land-Atmosphere interactions in ***CESM*** (CAM and ***CLM***)</u>

Change in coupling and feedbacks across model version

- Changing model component sets and versions can modify the coupling signal

Model-world versus Real-world

- Observations are scarce but limited obs suggest models have the wrong sign of sm-precip feedbacks

# Word of Caution and Optimism

Although models don't seem to look like the "real-world" quantifying model feedbacks and coupling help identify missing or incomplete processes

- "Real-world" is still foggy
- Still much to be learned!