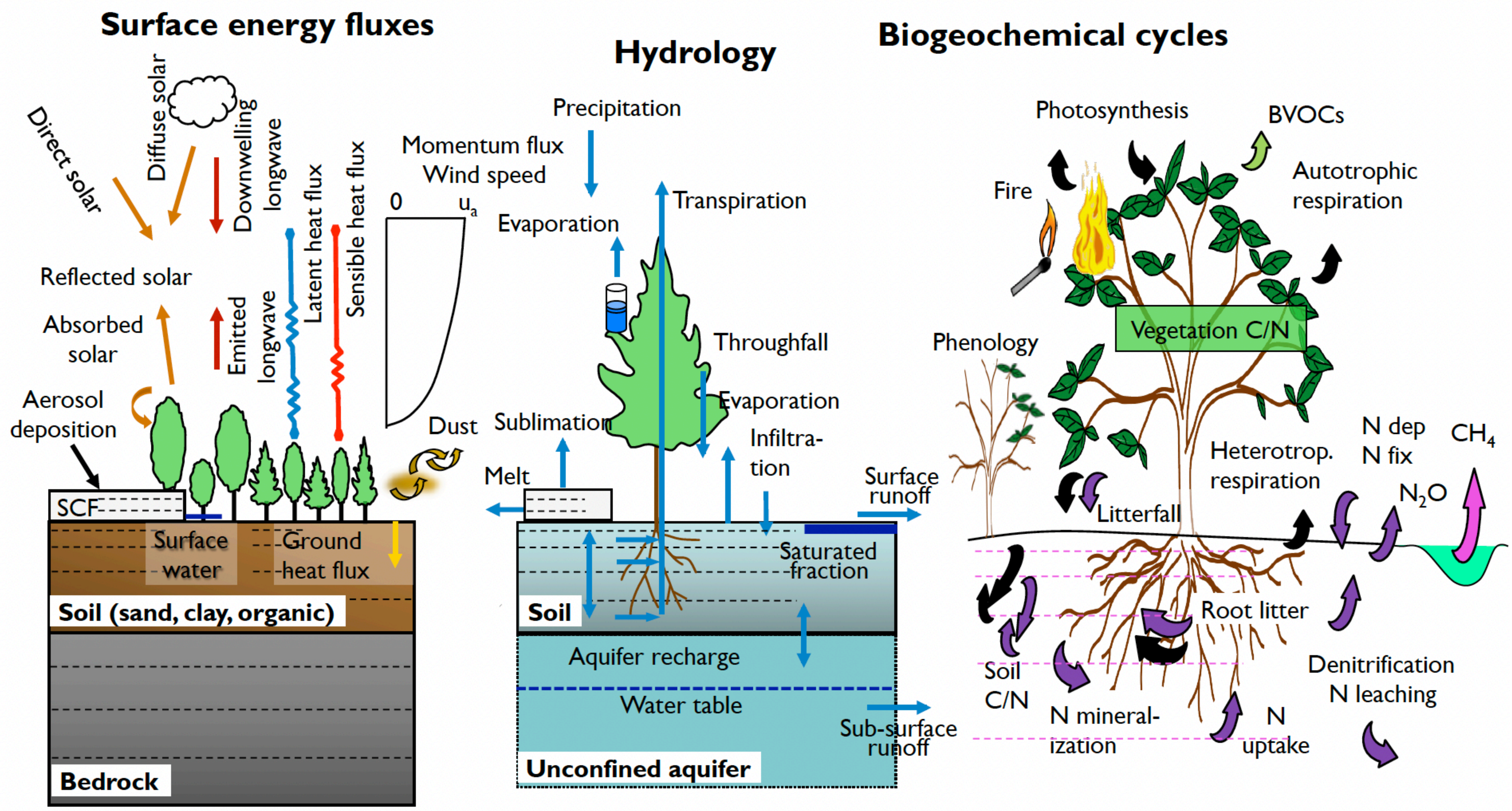
Lecture 8
30 January 2025

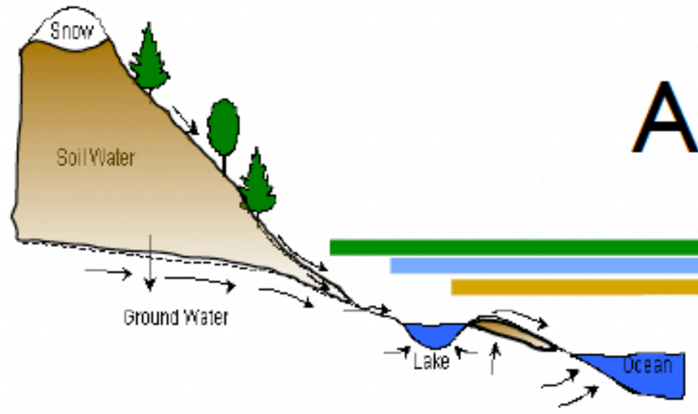
CM 615

Climate change Impacts & Adaptation

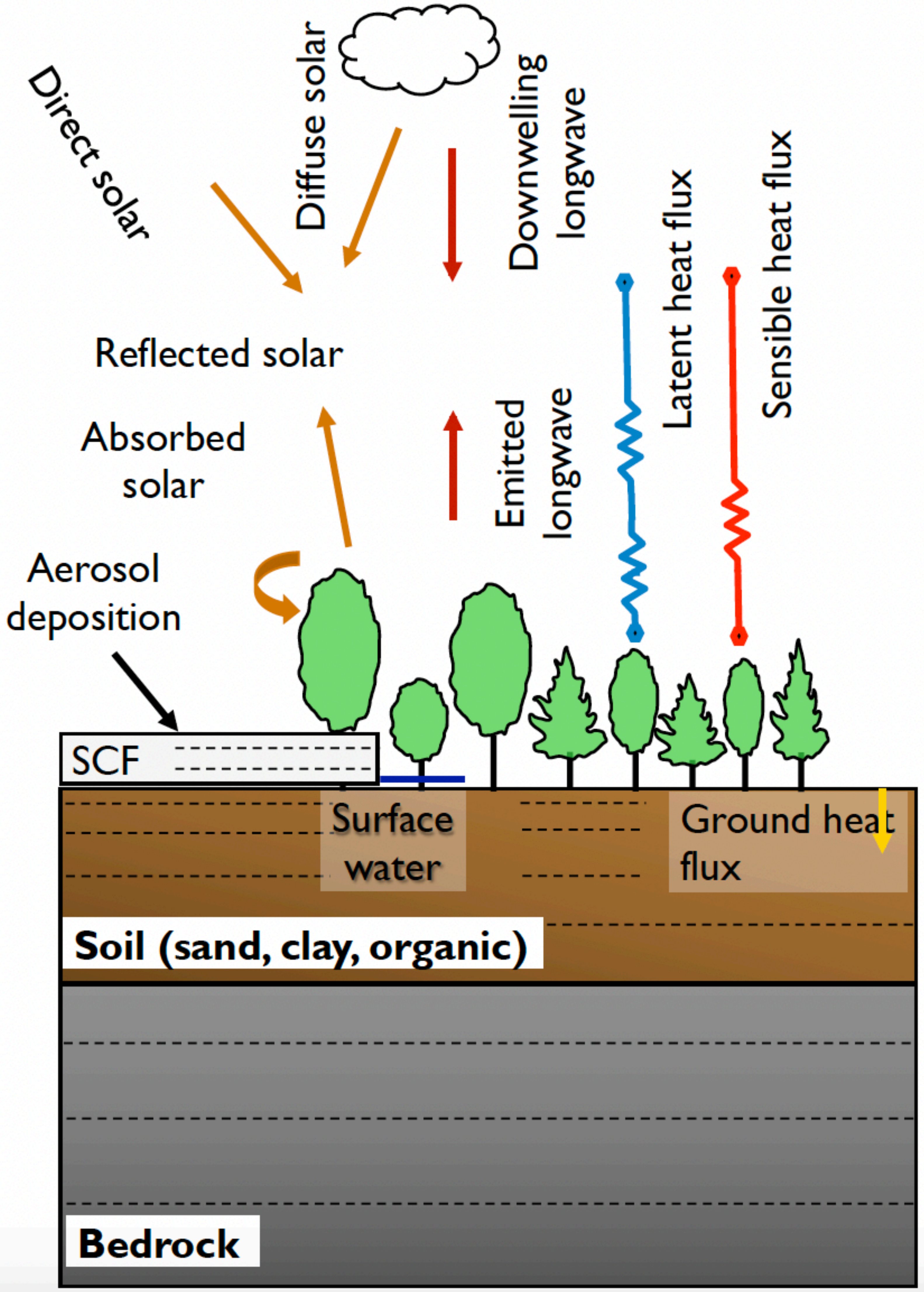
Global Land Model: CLM5.0

Angshuman Modak
Climate Studies, IIT Bombay


Surface energy fluxes
Hydrology
Biogeochemical cycles
Direct solar
Diffuse solar
Downwelling longwave
Latent heat flux
Sensible heat flux
Reflected solar
Absorbed solar
Emitted longwave
Aerosol deposition
SCF
Surface water
Ground heat flux
Soil (sand, clay, organic)
Bedrock
Momentum flux
Wind speed
0
u_a
Dust
Precipitation
Evaporation
Transpiration
Throughfall
Evaporation
Sublimation
Melt
Infiltration
Surface runoff
Saturated fraction
Soil
Aquifer recharge
Water table
Sub-surface runoff
Unconfined aquifer
Photosynthesis
BVOCs
Fire
Autotrophic respiration
Vegetation C/N
Phenology
Heterotrop. respiration
N dep
N fix
CH_4
N_2O
Litterfall
Root litter
Soil C/N
N mineralization
N uptake
Denitrification
N leaching



At each time step the land model solves Surface Energy Balance



$$S^{\uparrow} - S^{\downarrow} + L^{\uparrow} - L^{\downarrow} = \lambda E + H + G$$

$S^{\uparrow}$, $S^{\downarrow}$ are down(up)welling solar radiation,

$L^{\uparrow}$, $L^{\downarrow}$ are up(down)welling longwave rad,

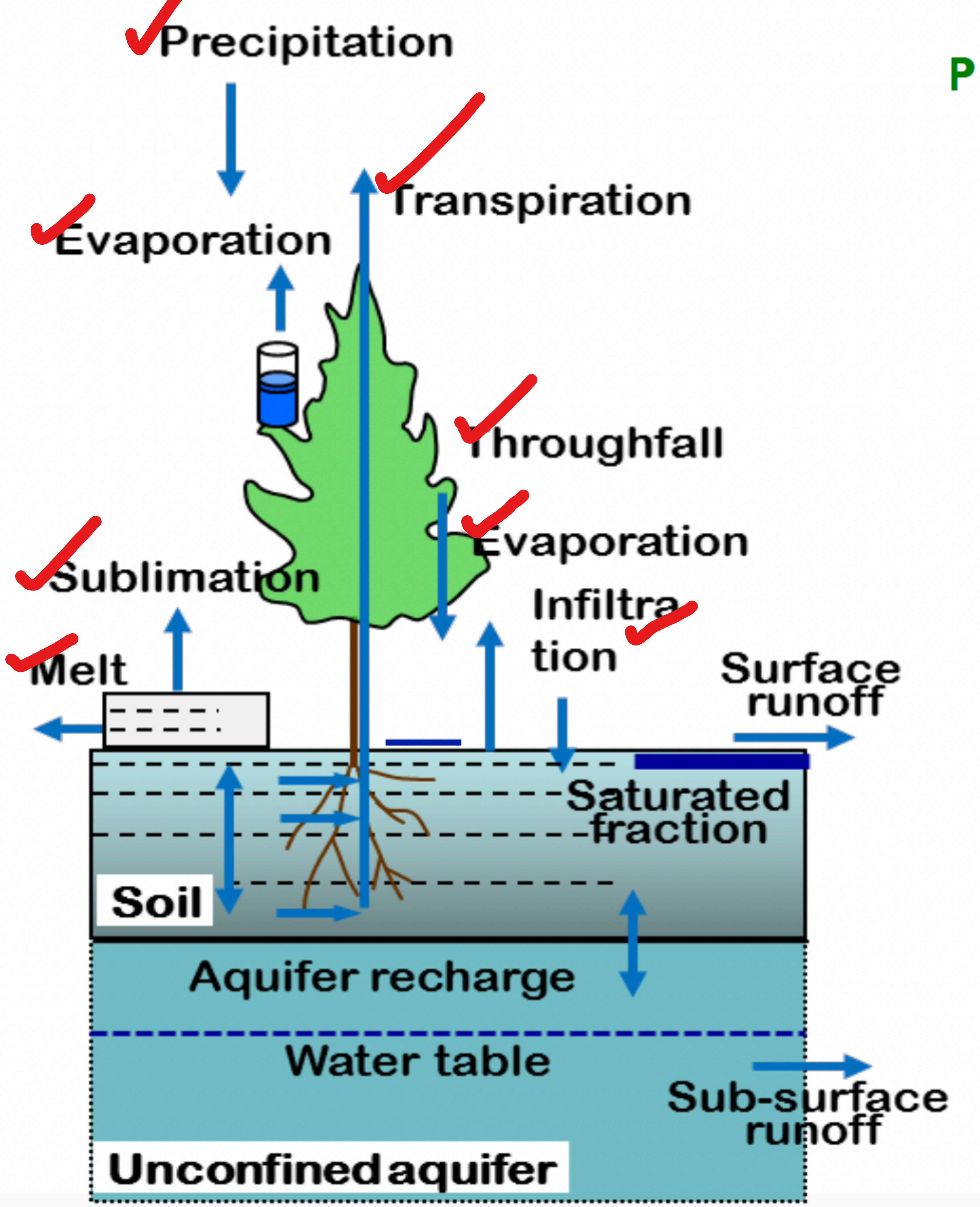
λ is latent heat of vaporization,

E is evaporation,

H is sensible heat flux

G is ground heat flux

… and the Surface Water Balance



$$P = E_S + E_T + E_C + R + (\Delta W_{soi} + \Delta W_{snw} + \Delta W_{sfcw} + \Delta W_{can}) / \Delta t$$

P is rainfall/snowfall,

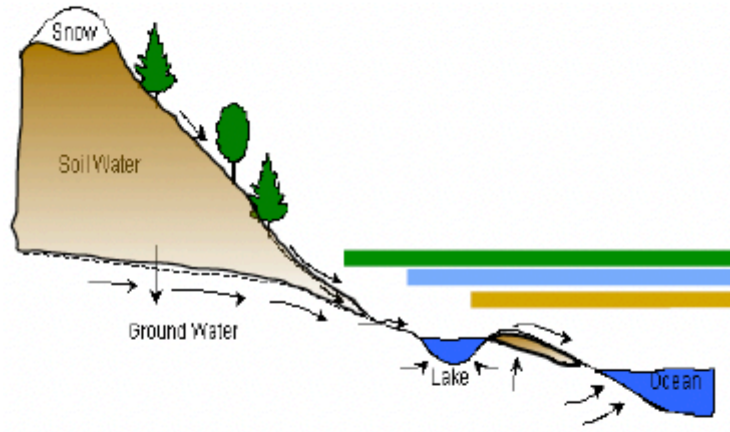
E_S is soil evaporation,

E_T is transpiration,

E_C is canopy evaporation,

R is runoff (surf + sub-surface),

$\Delta W_{soi} / \Delta t$, $\Delta W_{snw} / \Delta t$, $\Delta W_{sfcw} / \Delta t$, $\Delta W_{can} / \Delta t$, are the changes in soil moisture, surface water, snow, and canopy water over a timestep

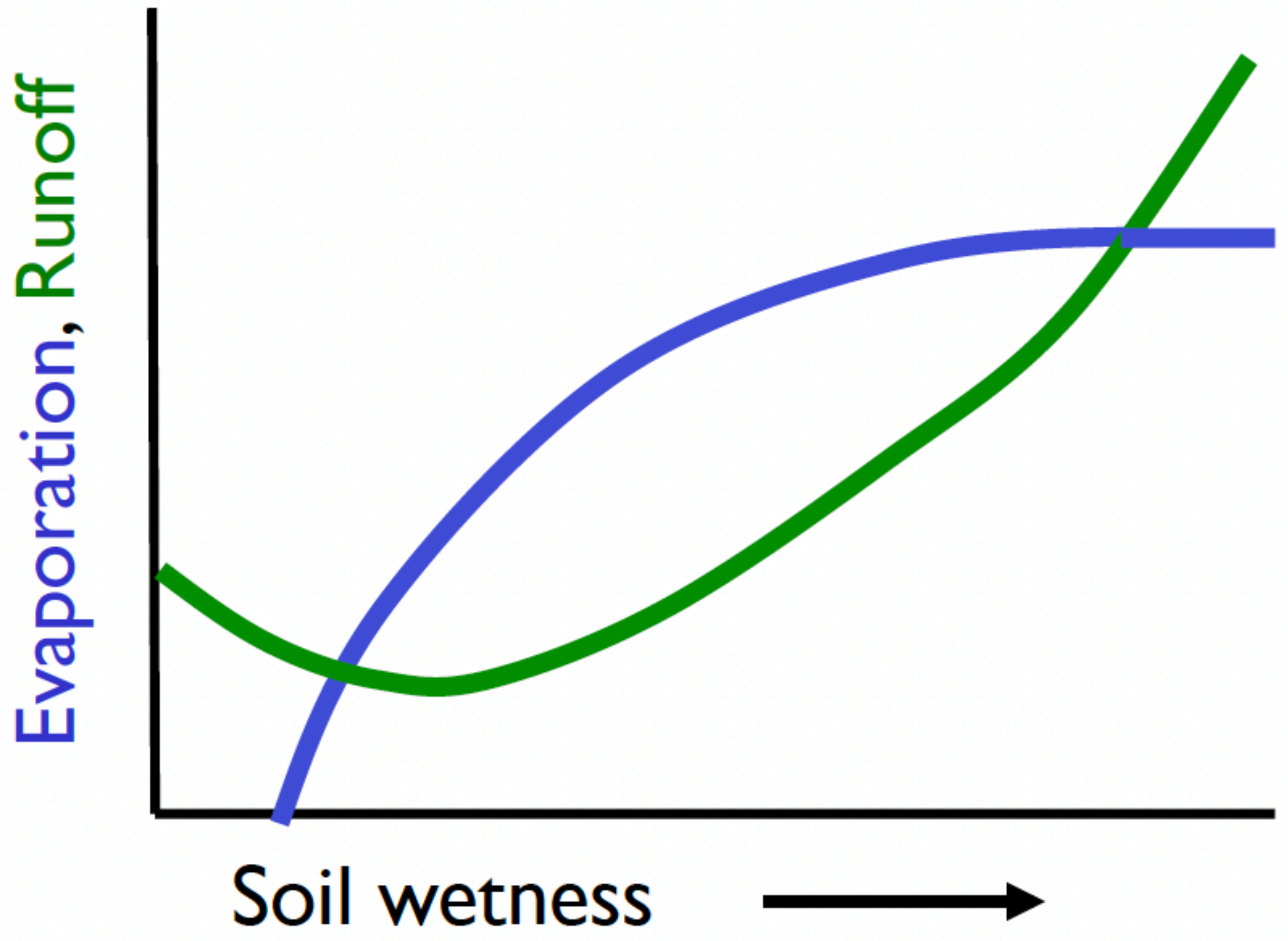


Land water and energy cycles intricately linked

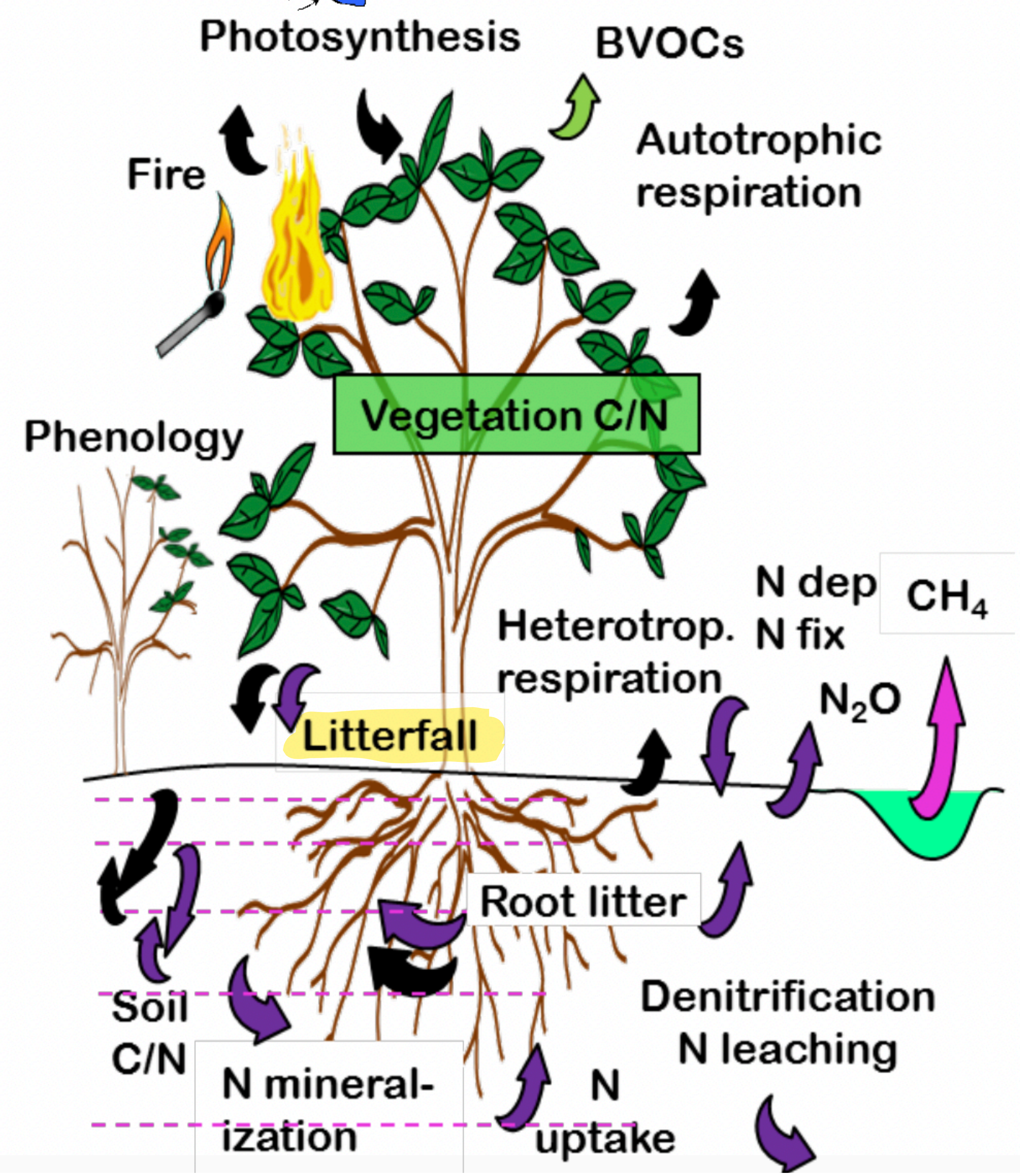
"The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related through soil moisture."

(Koster and Milly, 1997).

Runoff and evaporation vary non-linearly with soil moisture



… and Surface Carbon Exchange

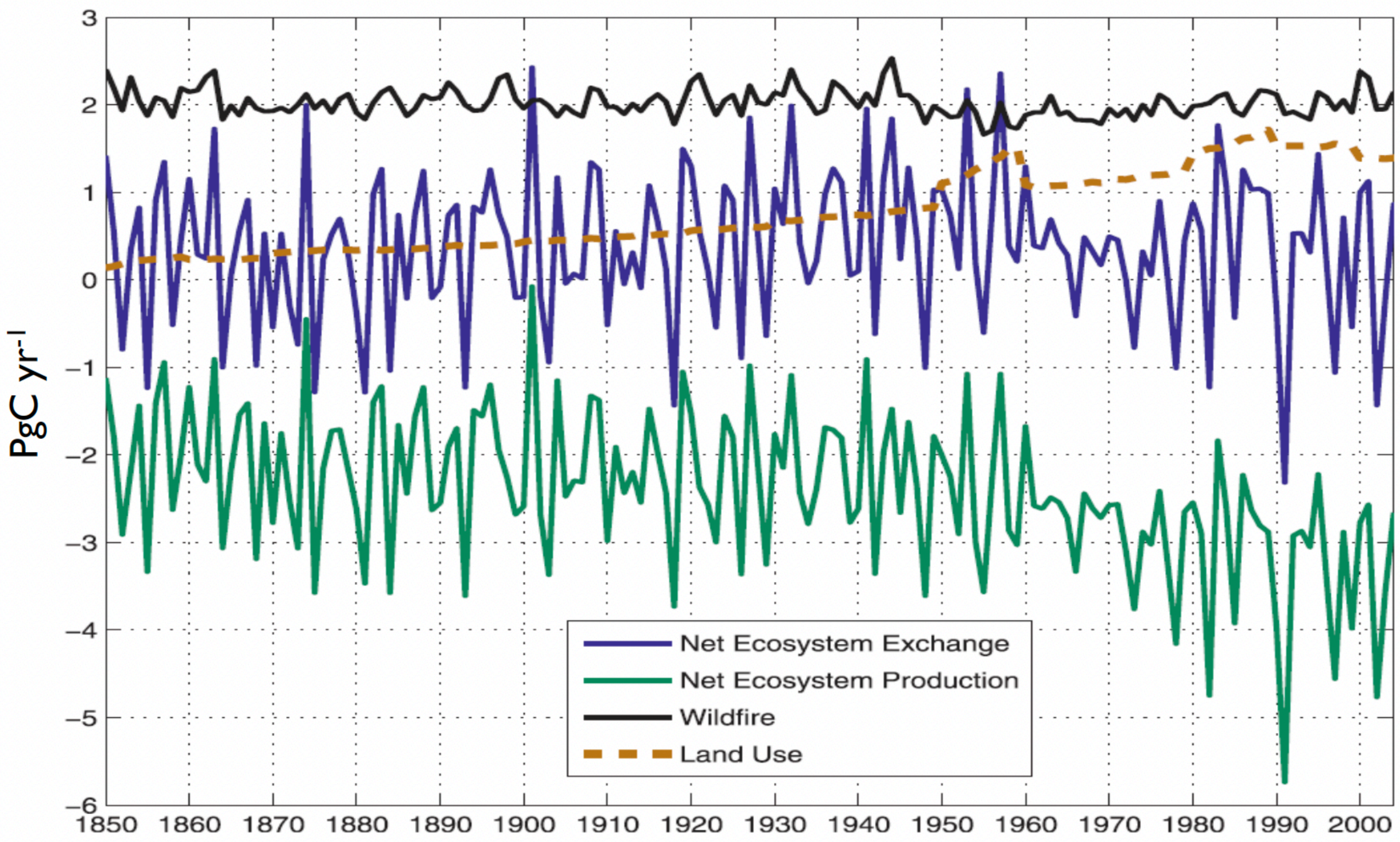


$NEE = GPP - HR - AR - Fire - LUC$

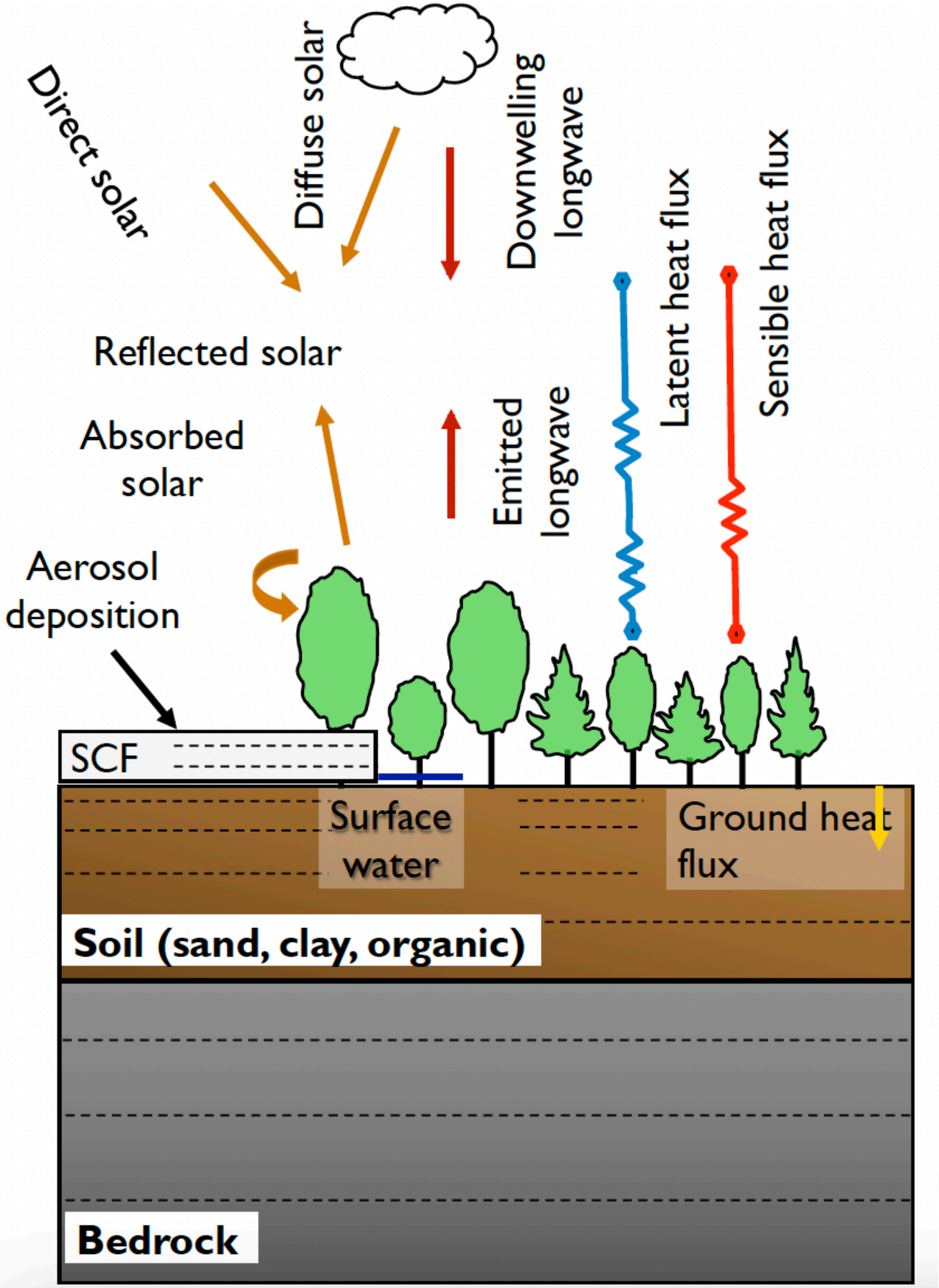
- NEE is net ecosystem exchange
- GPP is gross primary productivity
- HR is heterotrophic respiration
- AR is autotrophic respiration
- Fire is carbon flux due to fire
- LUC is C flux due to land use change

Carbon exchange

NEE = GPP – HR – AR – Fire – LUC



Leaf temperature and fluxes



Leaf energy balance:

$$c_L \frac{\partial T_l}{\partial t} = Q_a - 2\varepsilon_l \sigma T_l^4 + 2c_p (T_l - T_a) g_{bh} + \lambda [q_*(T_l) - q_a] g_l$$

Atmospheric forcing

Q_a - radiative forcing (solar and longwave)

T_a - air temperature

q_a - water vapor (mole fraction)

u - wind speed

P - surface pressure

Leaf properties

λ - latent heat of vaporisation

g_{bh} - leaf boundary layer resistance

g_ℓ - leaf resistance to water vapor

c_L - heat capacity

Up to Stomata level

With atmospheric forcing and leaf properties specified, solve for temperature T_ℓ that balances the energy budget

Gordon Bonan, NCAR, UCAR

Leaf temperature and fluxes

Leaf energy balance:

$$c_L \frac{\partial T_l}{\partial t} = Q_a - 2\varepsilon_l \sigma T_l^4 + 2c_p (T_l - T_a) g_{bh} + \lambda [q_*(T_l) - q_a] g_l$$

sensible heat flux relates to the leaf boundary layer conductance ($g_{bh}, mol\,.\,m^{-2}s^{-1}$) and occurs from both sides of a leaf

Atmospheric forcing

Q_a - radiative forcing (solar and longwave)

T_a - air temperature

q_a - water vapor (mole fraction)

u - wind speed

P - surface pressure

Latent heat flux relates to the vapor pressure deficit between the leaf, assumed to be saturated with moisture, and the surrounding air ($q_*(T_l) - q_a$).

Leaf properties

Up to Stomata level

λ - latent heat of vaporisation

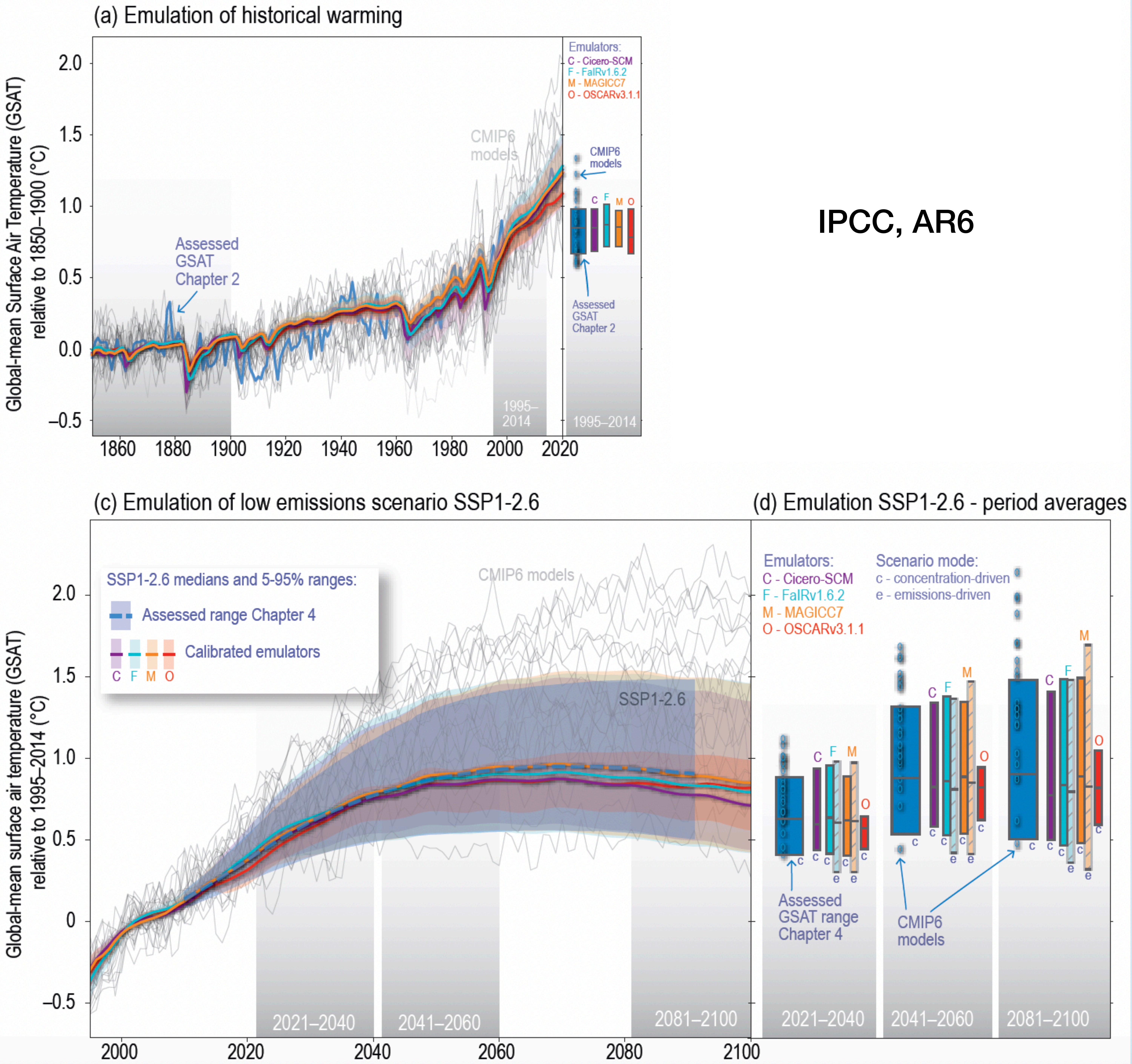
g_{bh} - leaf boundary layer resistance

g_ℓ - leaf resistance to water vapor

c_L - heat capacity

With atmospheric forcing and leaf properties specified, solve for temperature T_ℓ that balances the energy budget

Gordon Bonan, NCAR, UCAR



(a) Emulation of historical warming
Global-mean Surface Air Temperature (GSAT) relative to 1850–1900 (°C)
Emulators:
C - Cicero-SCM
F - FaIRv1.6.2
M - MAGICC7
O - OSCARv3.1.1
CMIP6 models
Assessed GSAT Chapter 2
1995–2014
(c) Emulation of low emissions scenario SSP1-2.6
Global-mean surface air temperature (GSAT) relative to 1995–2014 (°C)
SSP1-2.6 medians and 5-95% ranges:
Assessed range Chapter 4
Calibrated emulators
SSP1-2.6
2021–2040
2041–2060
2081–2100
(d) Emulation SSP1-2.6 - period averages
Scenario mode:
c - concentration-driven
e - emissions-driven
Assessed GSAT range Chapter 4

IPCC, AR6

Shared Socio-economic Pathways (SSPs)

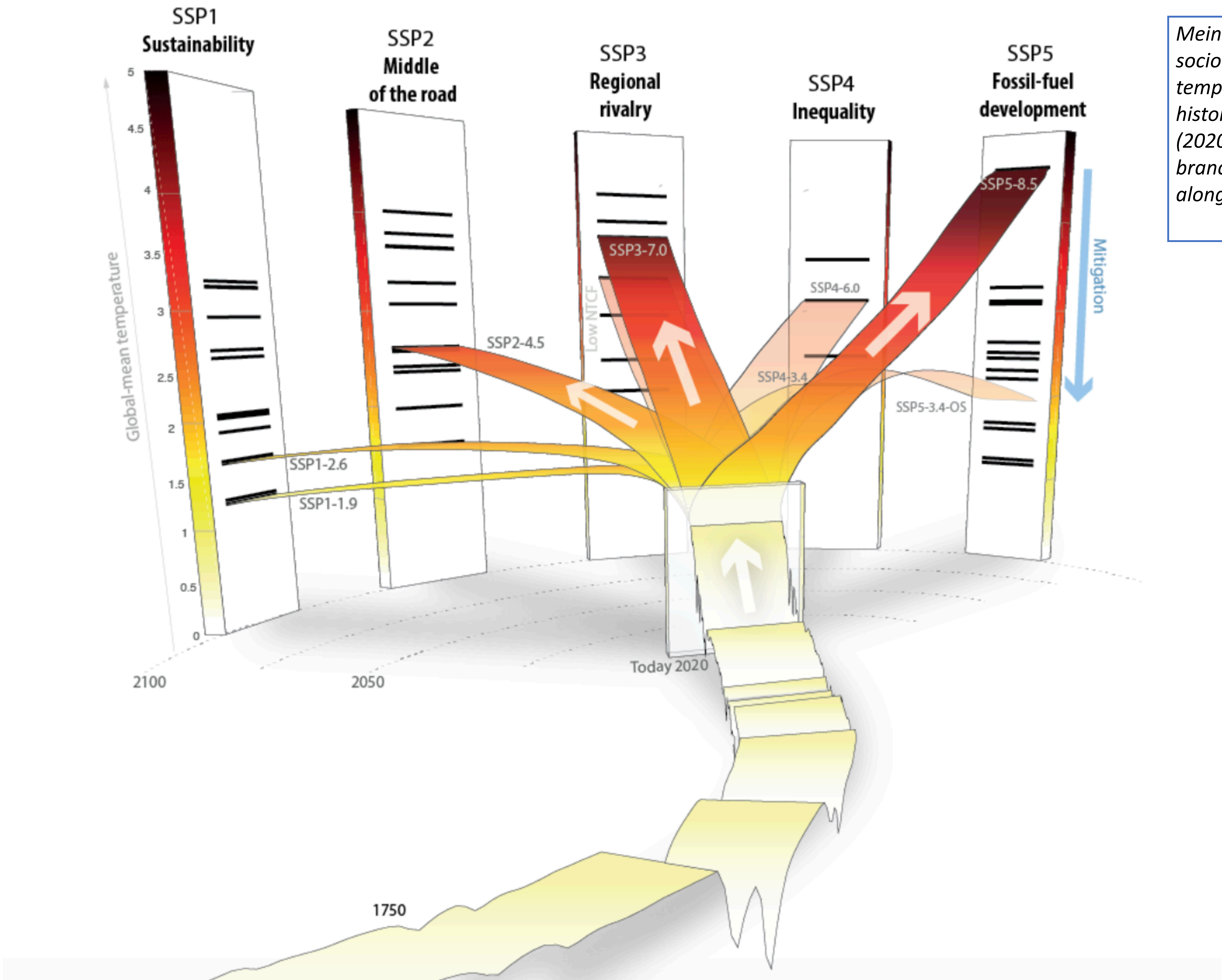
- **The scenarios used to characterize possible future development pathways for human societies are known as Shared Socio-economic Pathways, or SSPs for short.**
  - Created to analyze socio-economic trends and climate change mitigation strategies.

- **Assumptions made while creating these scenarios:**
  - Consider factors like population growth, education, energy use, technological advancements, and other socio-economic changes over the century.
  - Include varying levels of ambition for climate change mitigation, from low to high efforts.

- **Linking Socio-economic Factors to Emissions:**
  - Combine socio-economic trends and mitigation ambitions to generate greenhouse gas emission scenarios and associated atmospheric concentration trajectories.

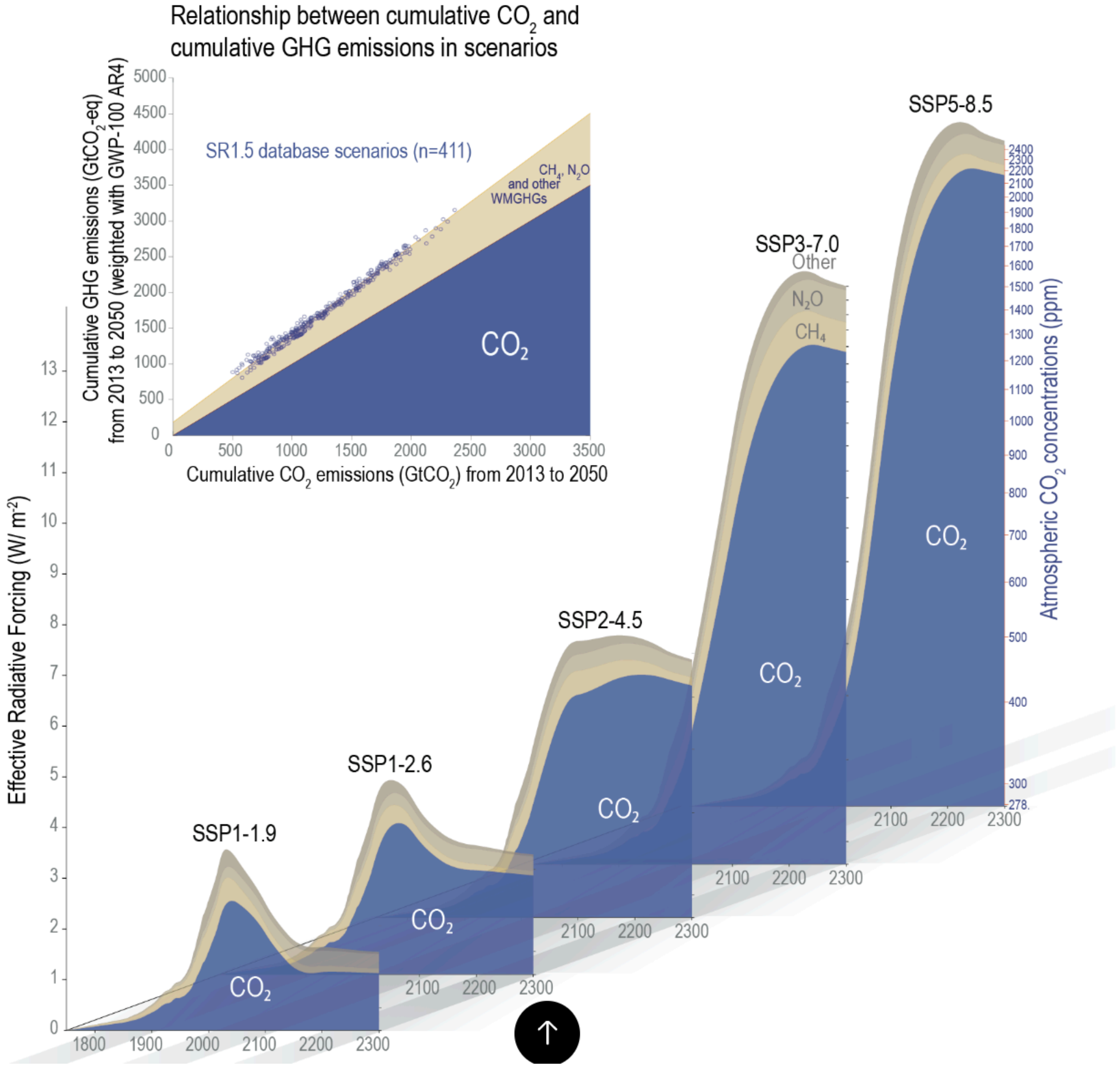
- **Climate Projections from SSPs:**
  - Cover a spectrum of plausible future climates, such as:
    - High-emission scenarios: Limited mitigation leading to significant warming (e.g., SSP5-8.5).
    - Low-emission scenarios: Strong mitigation aligned with the Paris Agreement goals (e.g., SSP1-1.9).

https://climatedata.ca/

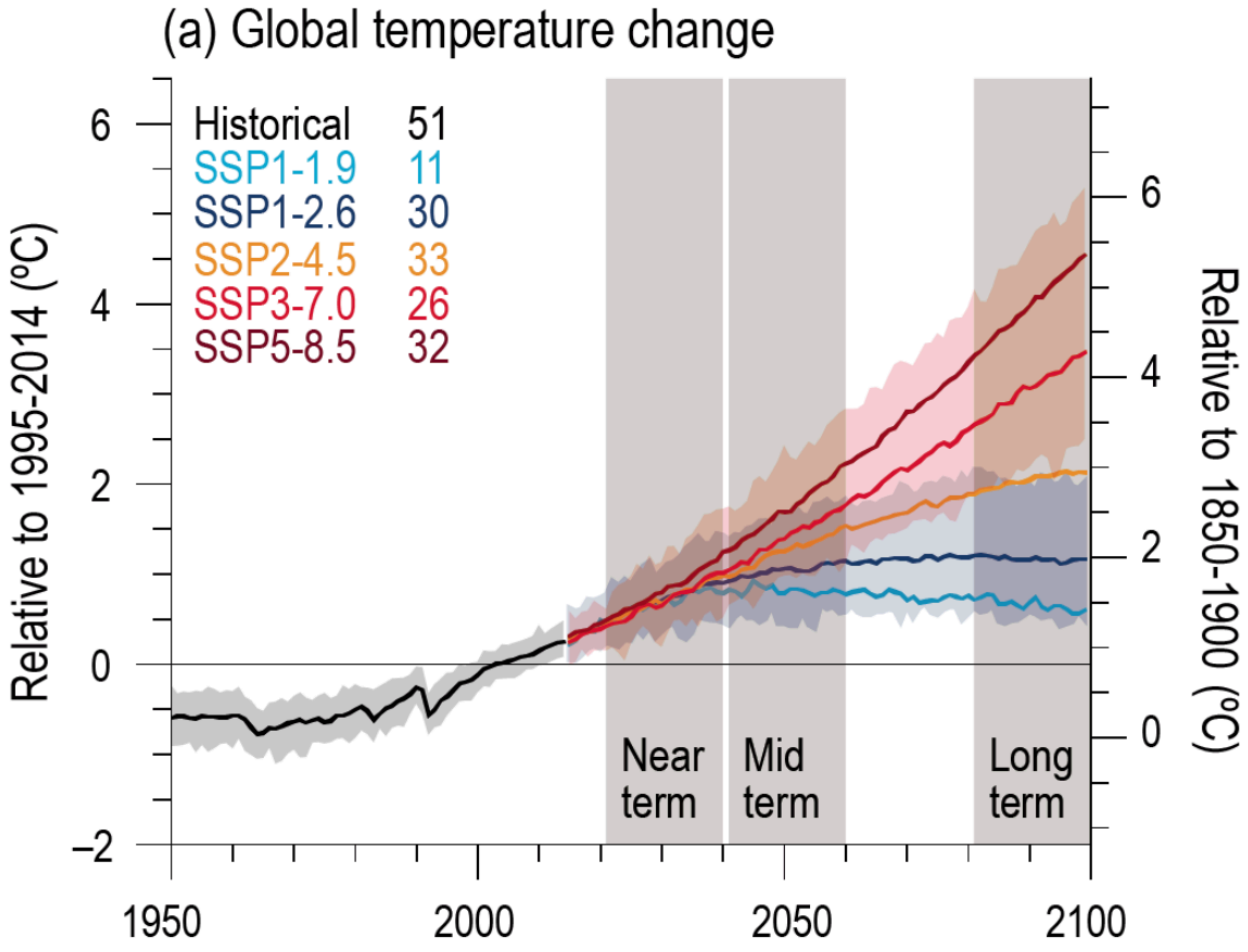


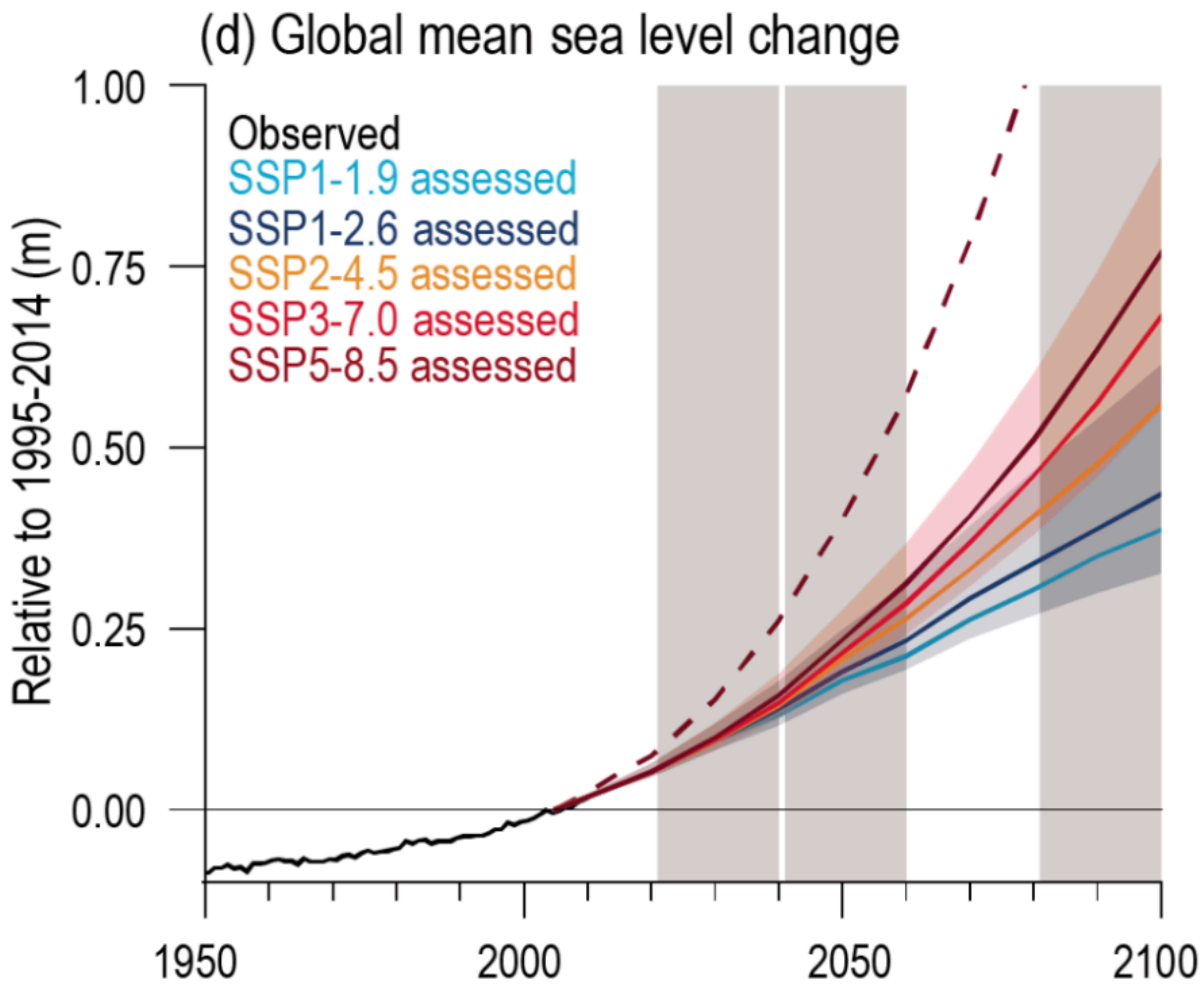
Meinshausen et al. (2020). The SSP scenarios and their five socio-economic SSP families. Shown are illustrative temperature levels relative to pre-industrial levels with historical temperatures (front light yellow band), current (2020) temperatures (white block in the middle), and branching of the respective scenarios over the 21st century along the different socio-economic SSP families.

https://climatedata.ca/



Relationship between cumulative CO_2 and cumulative GHG emissions in scenarios
SR1.5 database scenarios (n=411)
CH_4, N_2O and other WMGHGs
CO_2
Cumulative GHG emissions ($GtCO_2$-eq) from 2013 to 2050 (weighted with GWP-100 AR4)
Cumulative CO_2 emissions ($GtCO_2$) from 2013 to 2050
SSP1-1.9
SSP1-2.6
SSP2-4.5
SSP3-7.0
SSP5-8.5
Other
N_2O
CH_4
Effective Radiative Forcing (W/ m^2)
Atmospheric CO_2 concentrations (ppm)


(a) Global temperature change
Historical 51
SSP1-1.9 11
SSP1-2.6 30
SSP2-4.5 33
SSP3-7.0 26
SSP5-8.5 32
Relative to 1995-2014 (°C)
Relative to 1850-1900 (°C)
Near term
Mid term
Long term
1950
2000
2050
2100


(d) Global mean sea level change
Observed
SSP1-1.9 assessed
SSP1-2.6 assessed
SSP2-4.5 assessed
SSP3-7.0 assessed
SSP5-8.5 assessed
Relative to 1995-2014 (m)
1.00
0.75
0.50
0.25
0.00
1950
2000
2050
2100

Lecture 8
30 January 2025

CM 615

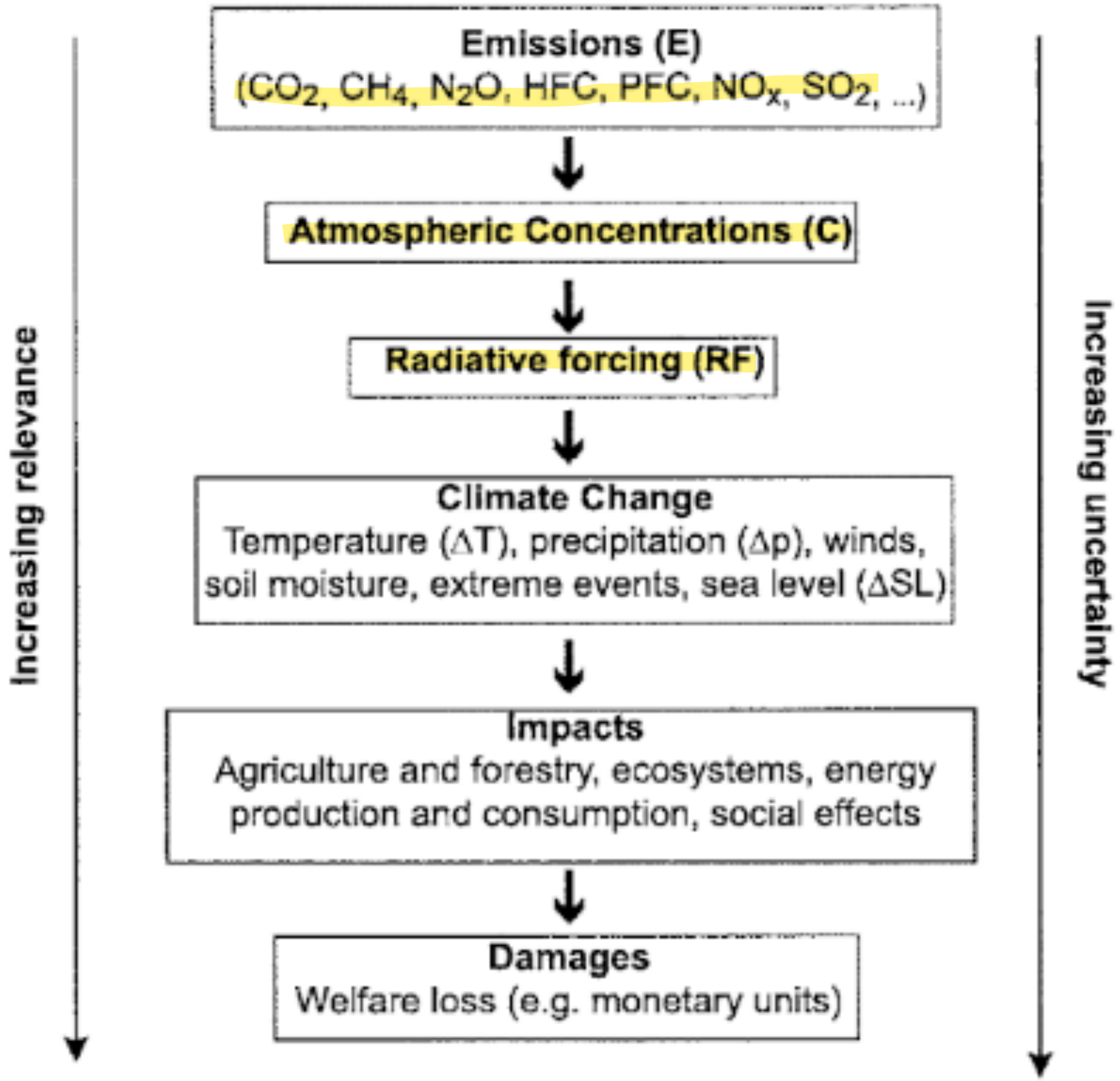
Climate change Impacts & Adaptation

Emission metrics

Angshuman Modak
Climate Studies, IIT Bombay

Concept of emission metrics

The cause-effect chain



Emission metric is a simplified expression that describes the relationship between the emissions (cause) and any of its consequent effect.

It is desirable to link emissions to effects that occur later in the chain as they become more relevant. However, the calculations become more complex and incorporate higher uncertainties.

Global Warming Potential (GWP)

An emission metric representing climate impact by linking emissions to the radiative forcing for a particular pollutant. It is a relative metric that quantifies the climate impact of a pollutant with respect to CO_2.

Definition:

It is defined as the time-integrated radiative forcing over a specific time horizon of an emission pulse of a forcer, divided by the time-integrated radiative forcing over the same time horizon of an emission pulse of CO_2 of equal size (by weight).

Expression:

$$GWP(T)_i = \frac{\int_0^T RF_i(t)dt}{\int_0^T RF_{CO_2}(t)dt} = \frac{\int_0^T a_i c_i(t)dt}{\int_0^T a_{CO_2} c_{CO_2}(t)dt} = \frac{AGWP_i}{AGWP_{CO_2}}$$

T = time horizon (years) ;
i = pollutant;
a = radiative forcing per unit increase in concentration of the pollutant (Wm^{-2} $ppmv^{-1}$) ,
c = time decaying abundance of pulses of the pollutant (ppmv).
RF = radiative forcing ($W\ m^{-2}$)
AGWP = Absolute Global Warming Potential (Joules m^{-2})