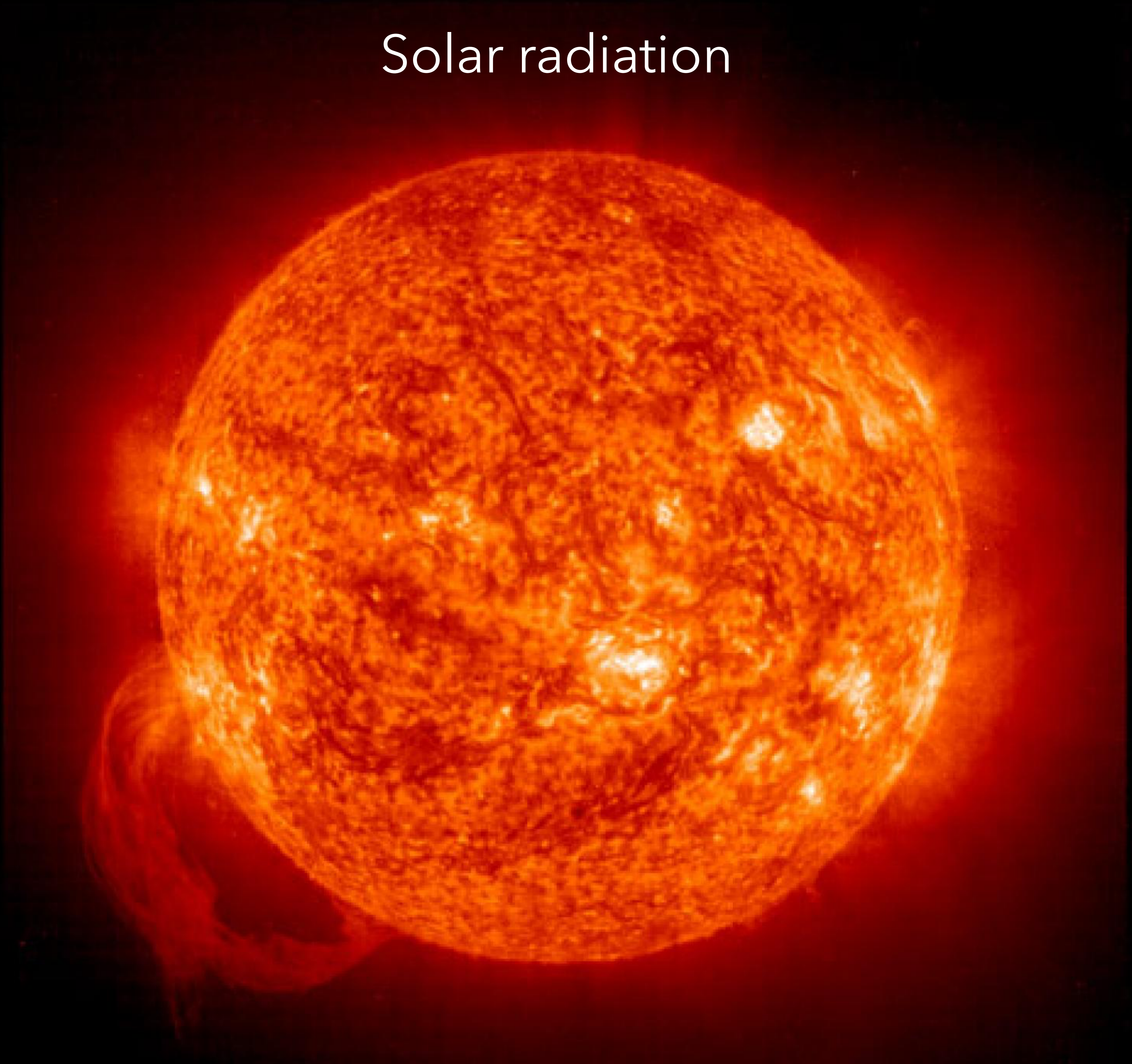
Introduction to the Biosphere-Atmosphere system

Lecture Autumn 2023

Part VI

Steffen M. Noe

Solar radiation



What is the solar radiation?

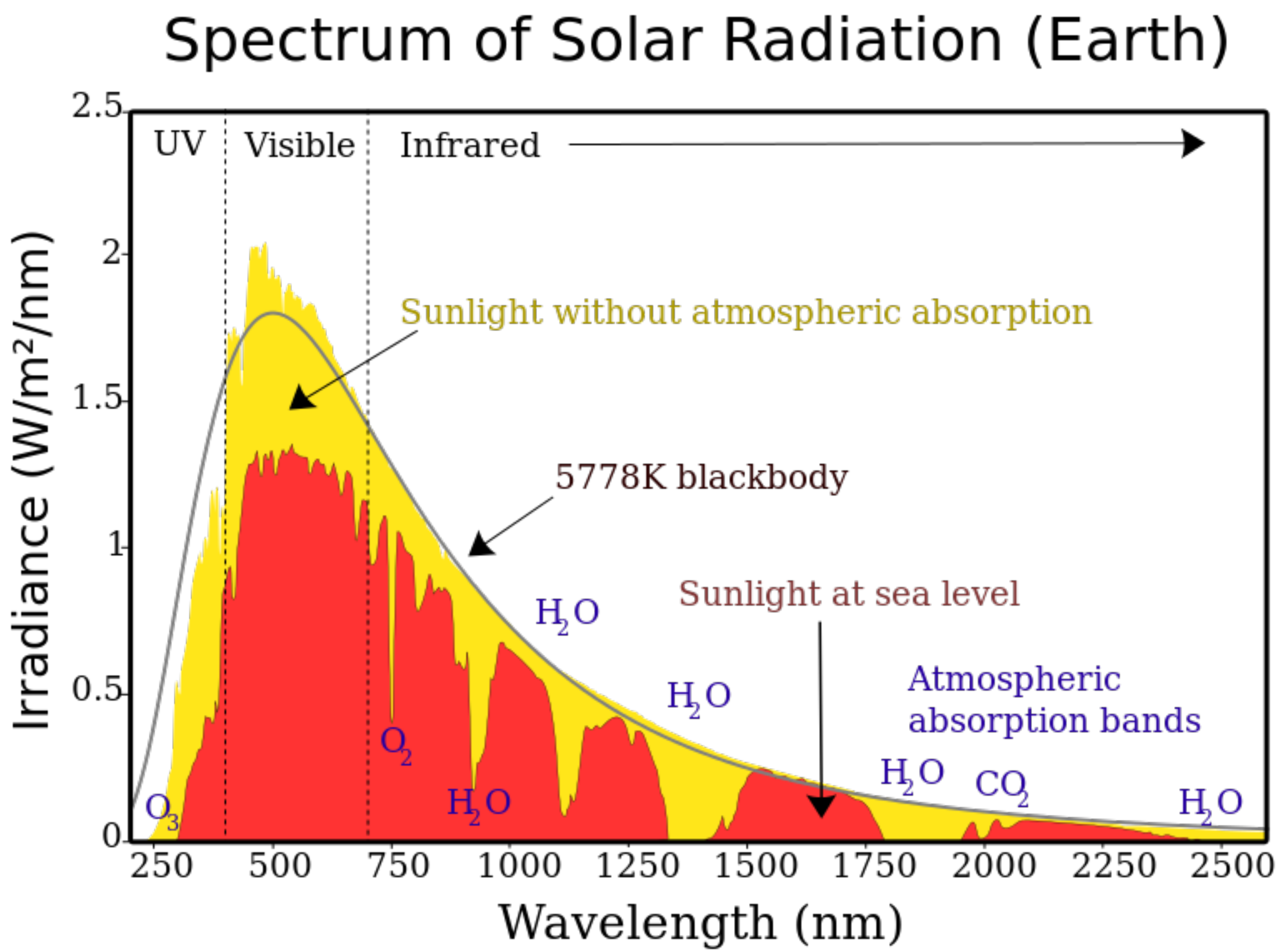
Solar radiation is the electromagnetic energy emitted by the sun.

Solar energy can be expressed as “solar irradiance” which is the power per unit area (Wm^{-2})

Annual average solar radiation arriving on top of the atmosphere is 1361 Wm^{-2}.

That’s what we call the solar constant!

What are we looking for



Atmospheric absorption

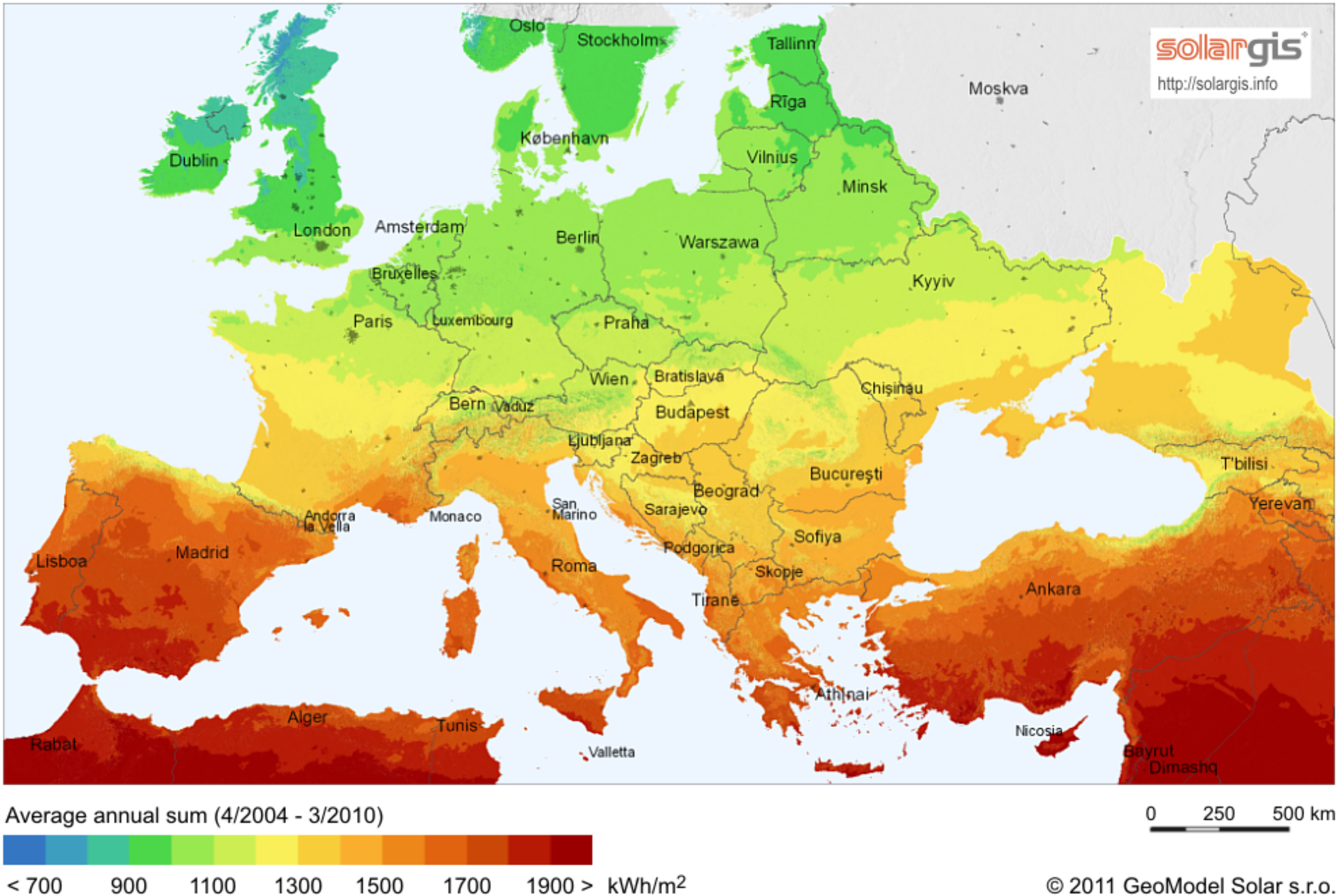
By passing the atmosphere, the solar radiation is attenuated.

Attenuation happens by absorption and scattering.

Scattered light still contributes to the energy budget.

The maximum solar irradiance reaching to the ground at sea level is approx. 1000 Wm^{-2}.

Global horizontal irradiation Europe



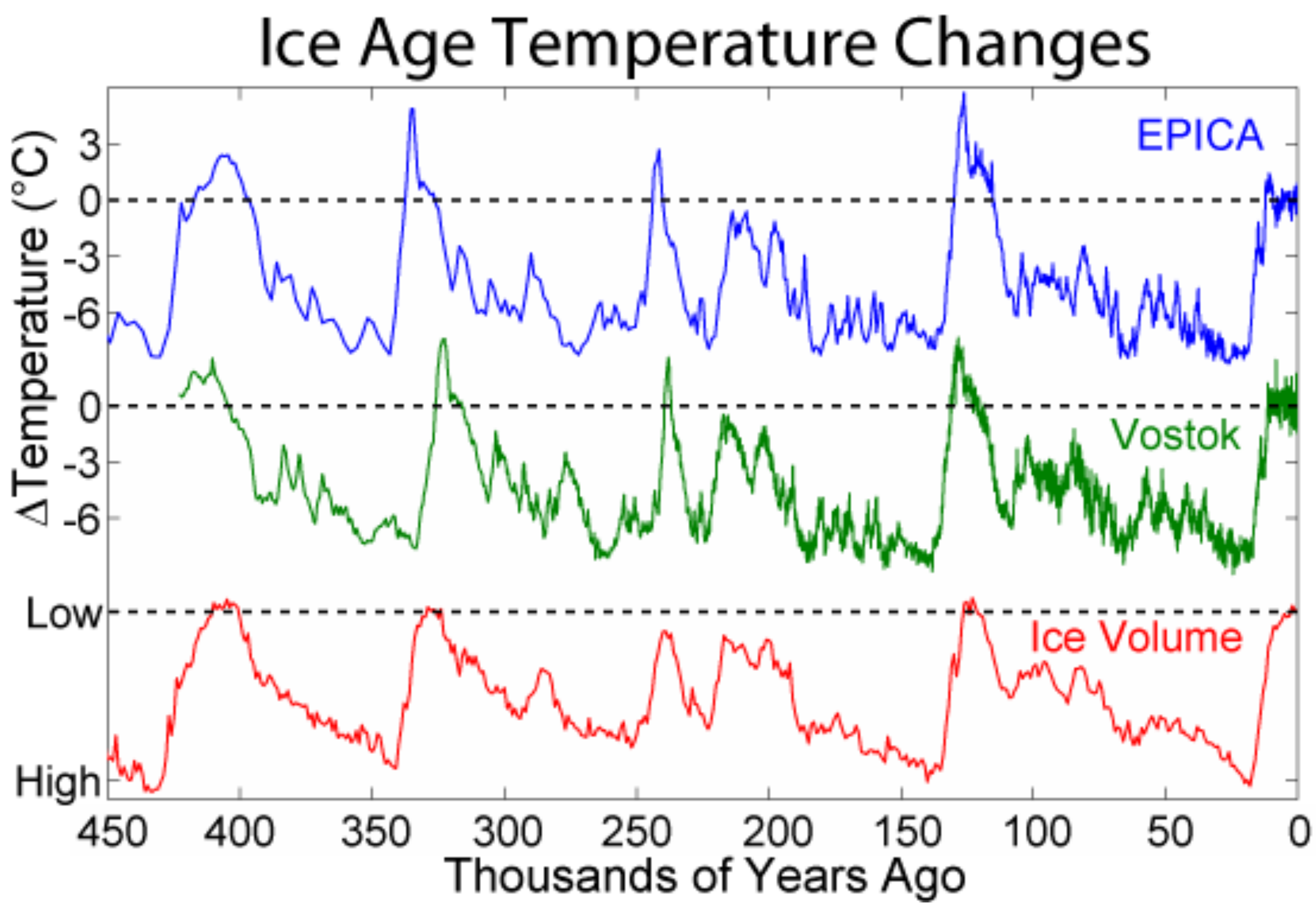
What is sunlight?

Sunlight is the portion of the solar radiation that consist of ultra violet (UV), visible, and infra red (IR) radiation.

It’s the same as we already had! The solar radiation.

But, we experience sunlight as the combination of bright light and radiant heat.

How does the solar system determines long-term dynamics in the Earth system?



Positive feedbacks: Increase in albedo, lower temperature lead to more snow/ice cover and that reflects sunlight which lowers temperature. Reduction of forests further increases albedo.

Negative feedbacks: Ice sheets lead to erosion and less land is available for ice sheets to grow on which reduces albedo. Cold dry air because less evaporation occurs and ice sheet growth stops.

Next glacial period will not occur due to high CO2 concentrations!

Ice age on hold

Determining the natural length of the current interglacial

P. C. Tzedakis[1]*, J. E. T. Channell[2], D. A. Hodell[3], H. F. Kleiven[4,5] and L. C. Skinner[3]

We're at ~420 ppmv today!

No glacial inception is projected to occur at the current atmospheric CO_2 concentrations of 390 ppmv (ref. 1). Indeed, model experiments suggest that in the current orbital configuration—which is characterized by a weak minimum in summer insolation—glacial inception would require CO_2 concentrations below preindustrial levels of 280 ppmv (refs 2–4). However, the precise CO_2 threshold[4–6] as well as the timing of the hypothetical next glaciation[7] remain unclear. Past interglacials can be used to draw analogies with the present, provided their duration is known. Here we propose that the minimum age of a glacial inception is constrained by the onset of bipolar-seesaw climate variability, which requires ice-sheets large enough to produce iceberg discharges that disrupt the ocean circulation. We identify the bipolar seesaw in ice-core and North Atlantic marine records by the appearance of a distinct phasing of interhemispheric climate and hydrographic changes and ice-rafted debris. The glacial inception during Marine Isotope sub-Stage 19c, a close analogue for the present interglacial, occurred near the summer insolation minimum, suggesting that the interglacial was not prolonged by subdued radiative forcing[7]. Assuming that ice growth mainly responds to insolation and CO_2 forcing, this analogy suggests that the end of the current interglacial would occur within the next 1500 years, if atmospheric CO_2 concentrations did not exceed 240 ± 5 ppmv.

The notion that the Holocene (or Marine Isotope Stage 1, MIS1), already 11.6 thousand years (kyr) old, may be drawing to a close has been based on the observation that the duration of recent interglacials was approximately half a precession cycle (~11 kyr; ref. 8). However, uncertainty over an imminent hypothetical glaciation arises from the current subdued amplitude of insolation variations as a result of low orbital eccentricity (Fig. 1). It has thus been proposed that at times of weak eccentricity–precession forcing, obliquity is the dominant astronomical parameter driving ice-volume changes, leading to extended interglacial duration of approximately half an obliquity cycle (~21 kyr; ref. 9). In this view, the next glacial inception would occur near the obliquity minimum ~10 kyr from now[7].

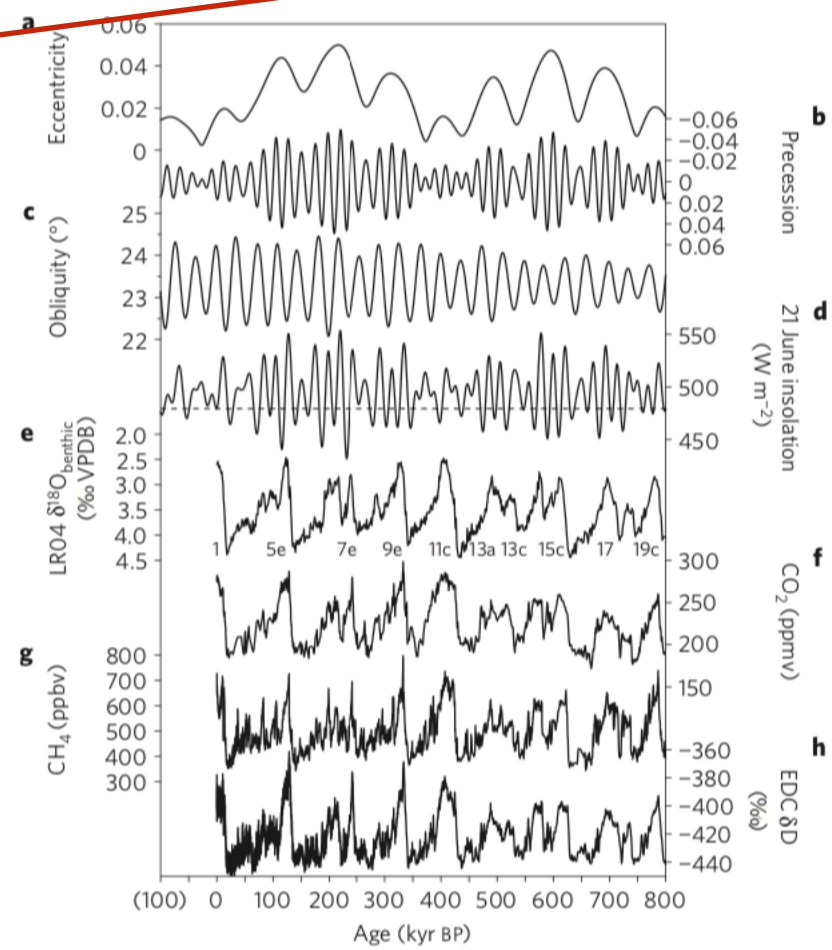
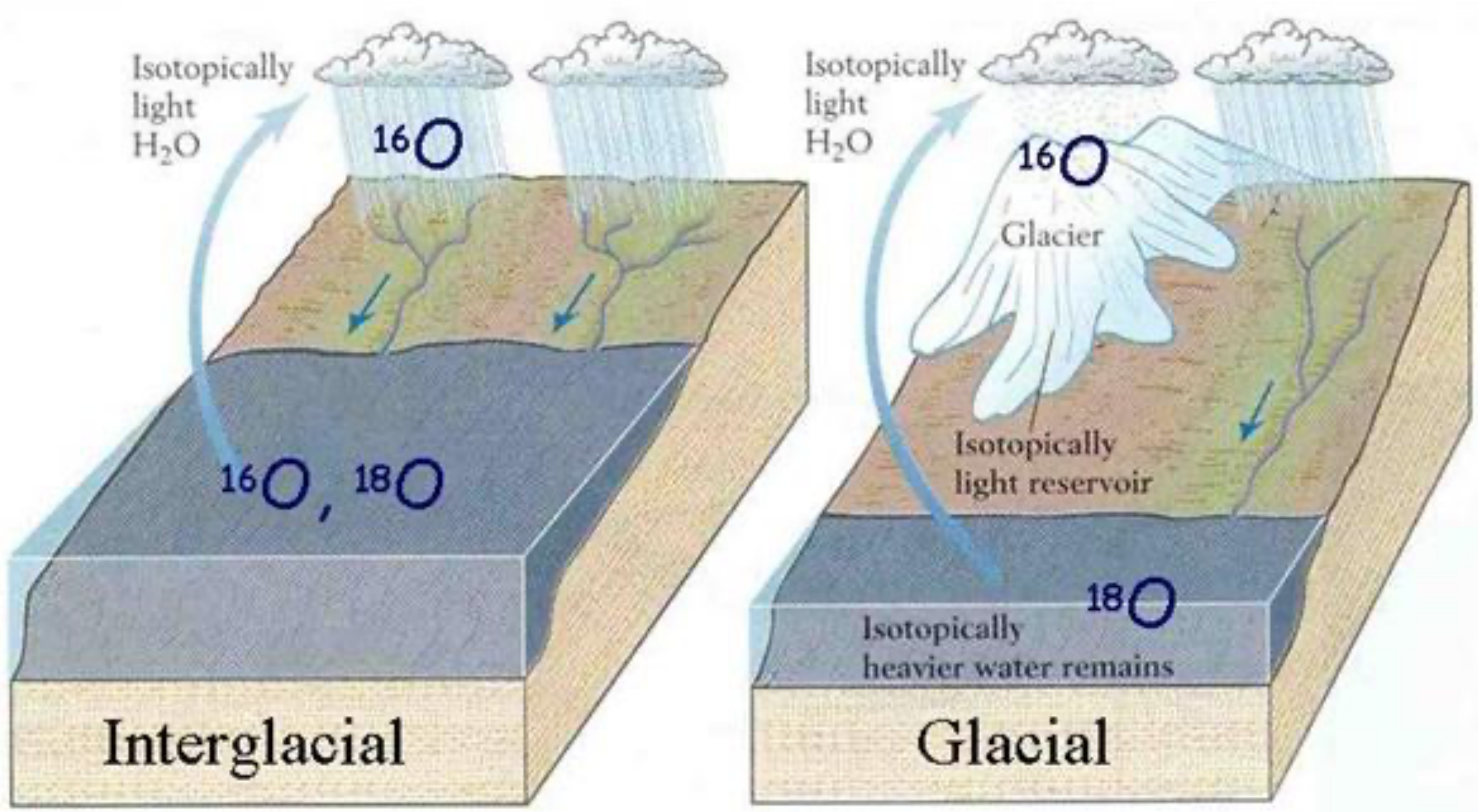


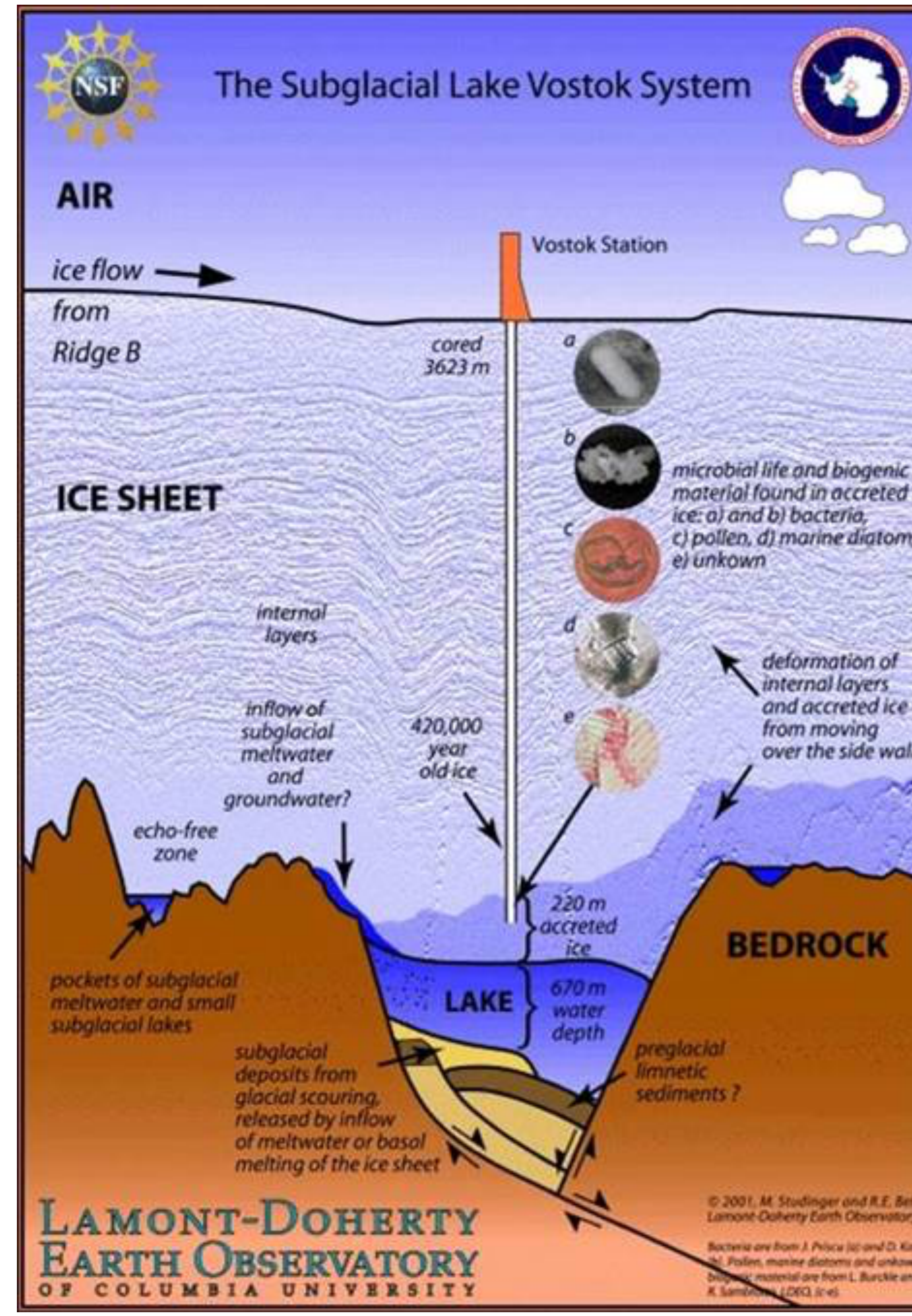
Figure 1 | Astronomical parameters 100 kyr after present—800 kyr BP and palaeoclimatic records 0–800 kyr BP. a, Eccentricity[29]; **b**, precession index, plotted on an inverse vertical axis[29]; **c**, obliquity[29]; **d**, 21 June insolation 65° N (ref. 29); **e**, $\delta^{18}O_{benthic}$ record from the LR04 stack[28]; **f**, atmospheric CO_2 concentration in Antarctic ice cores[12]; **g**, atmospheric CH_4 concentration in the Antarctic EDC ice core[13]; **h**, δD composition of ice in the EDC ice core[18]. Marine Isotopic Stages and sub-Stages corresponding to interglacials are indicated. Ages in parentheses denote years after present. The dashed line indicates the current 21 June insolation level at 65° N.

Vostok ice cores since 1970'ties used to assess Paleoclimate



Isotopically light water evaporates from the ocean and returns via rivers: the system is in balance

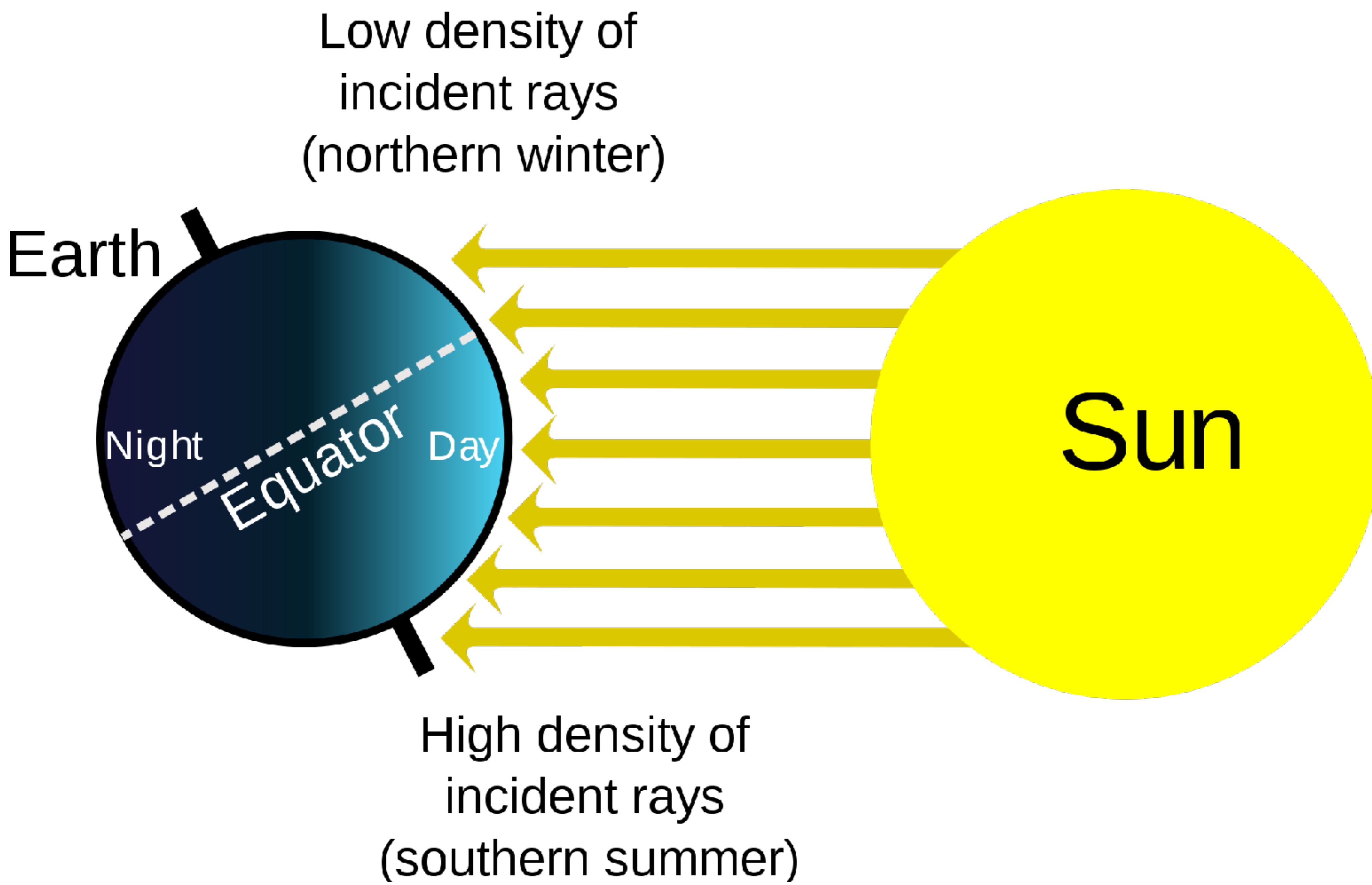
Glaciers expand, forming a new reservoir of isotopically light water on the land: sea level drops and the ocean becomes isotopically heavy



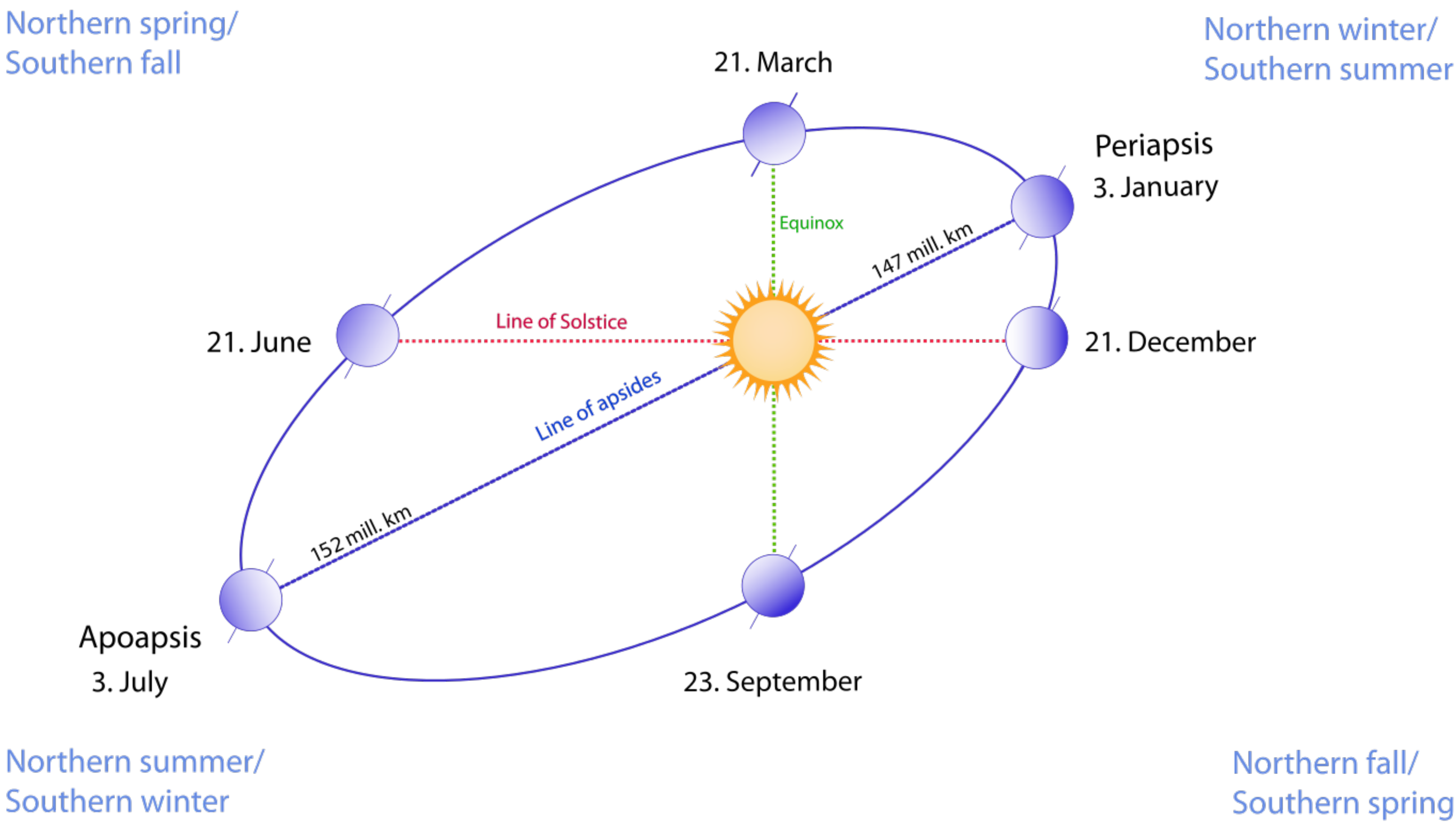
How to assess temperature from ice cores?

- Air bubbles that contain CO_2 and methane
- Oxygen isotopes H_2O^{16} (99.7%), H_2O^{18} (0.2%) and HDO^{16} (0.03%)
- Layers with no bubbles -> meltwater!

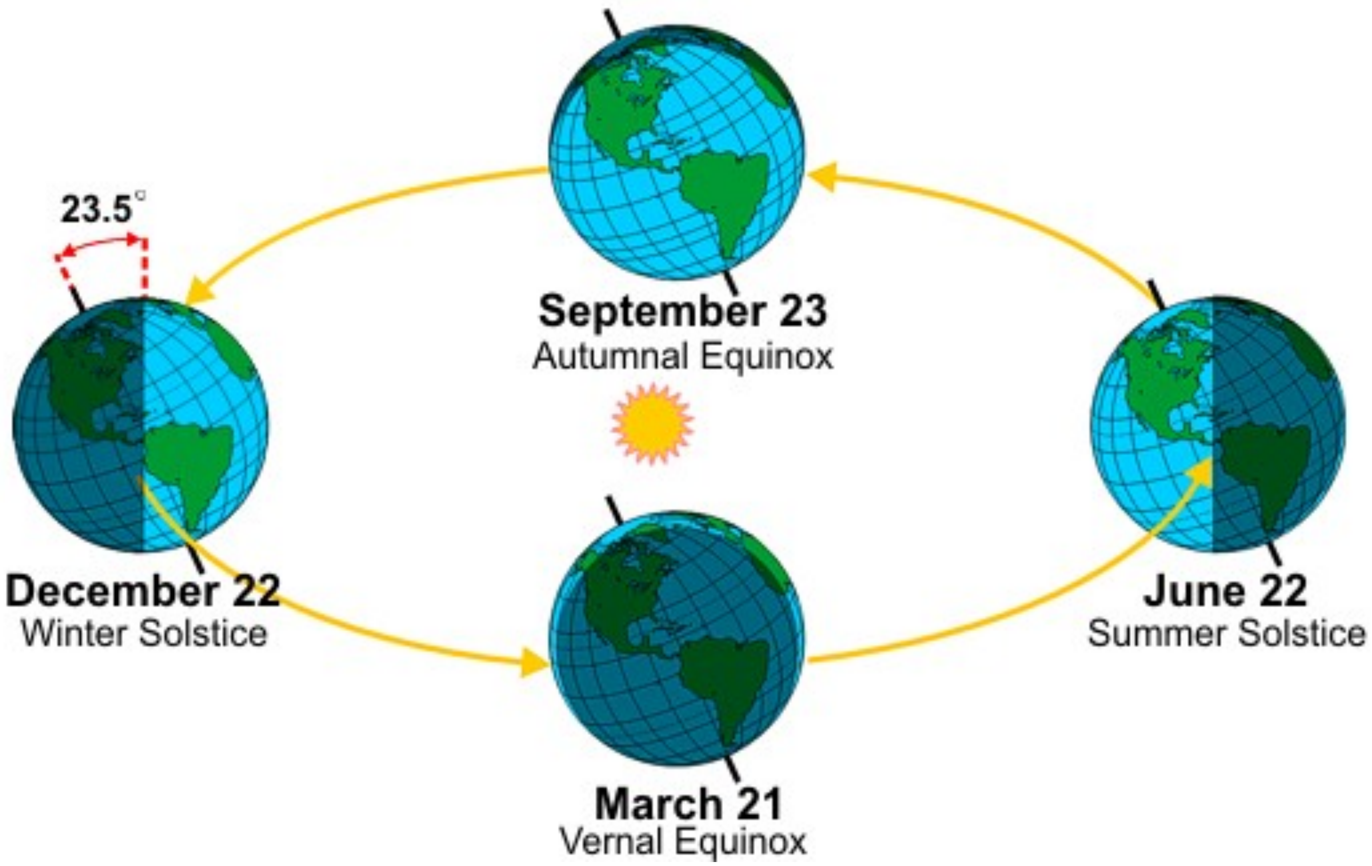
Daily and seasonal rhythms



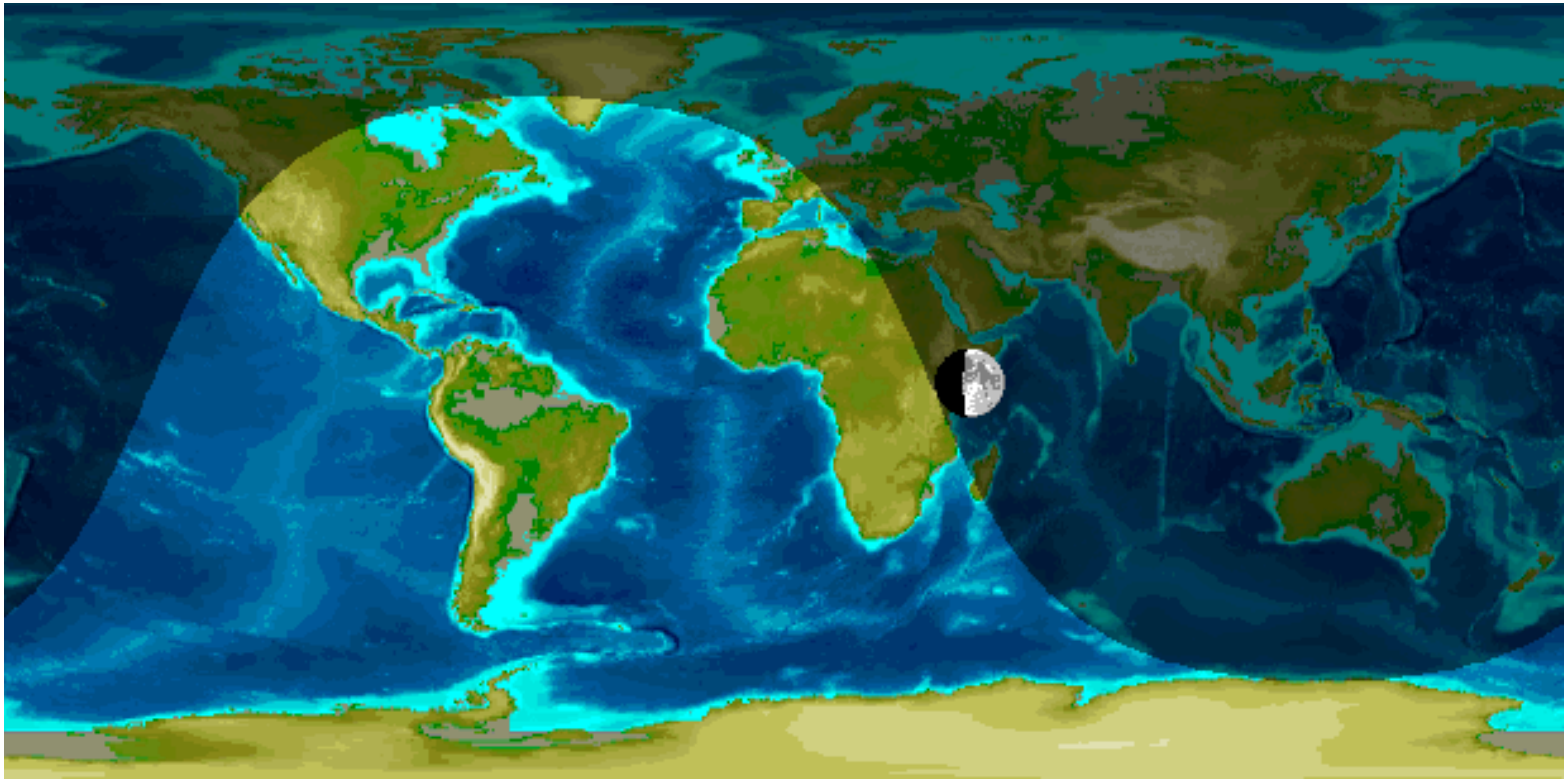
Yearly change of solar radiation



A major cause of changing day length is the rotational angle



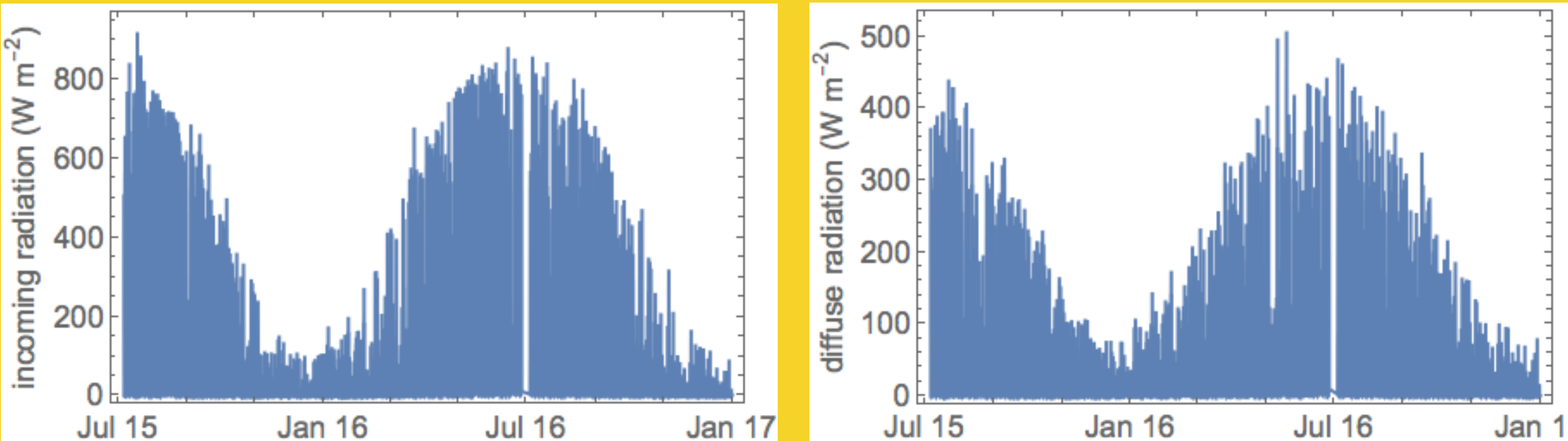
Day-night overview

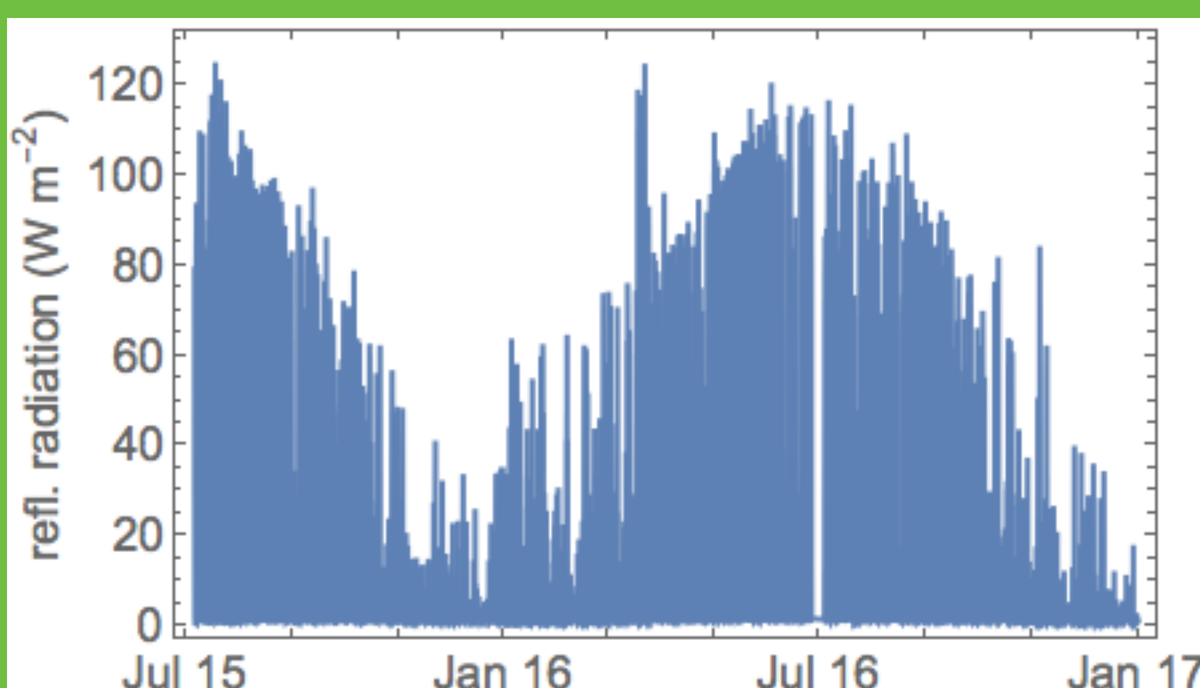


Implications of seasonal behaviour of ecosystems

Radiation measurements at SMEAR Estonia since summer 2015

incoming radiation





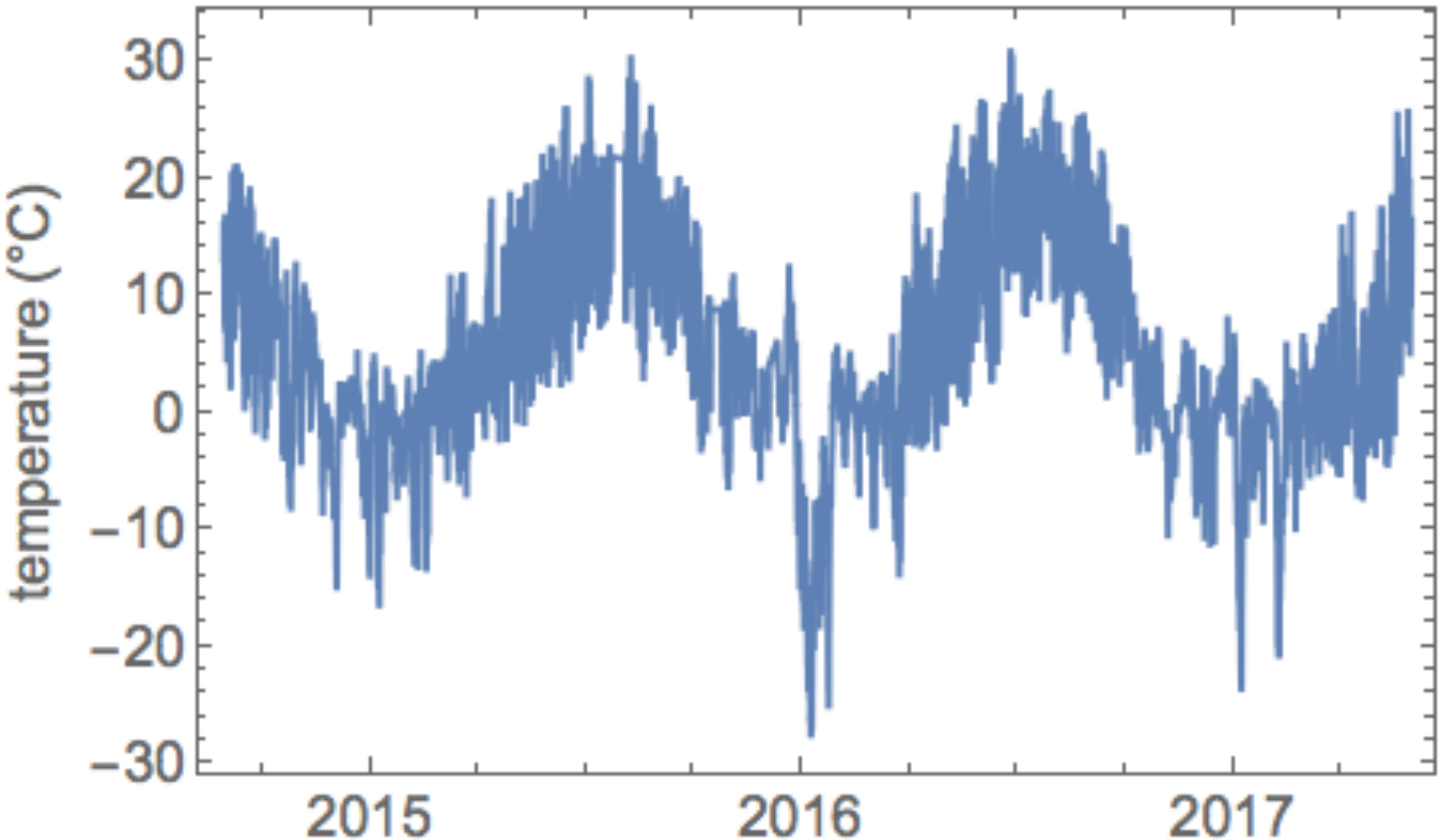
reflected radiation

Summer to Winter changes radiation by a factor of ~10!

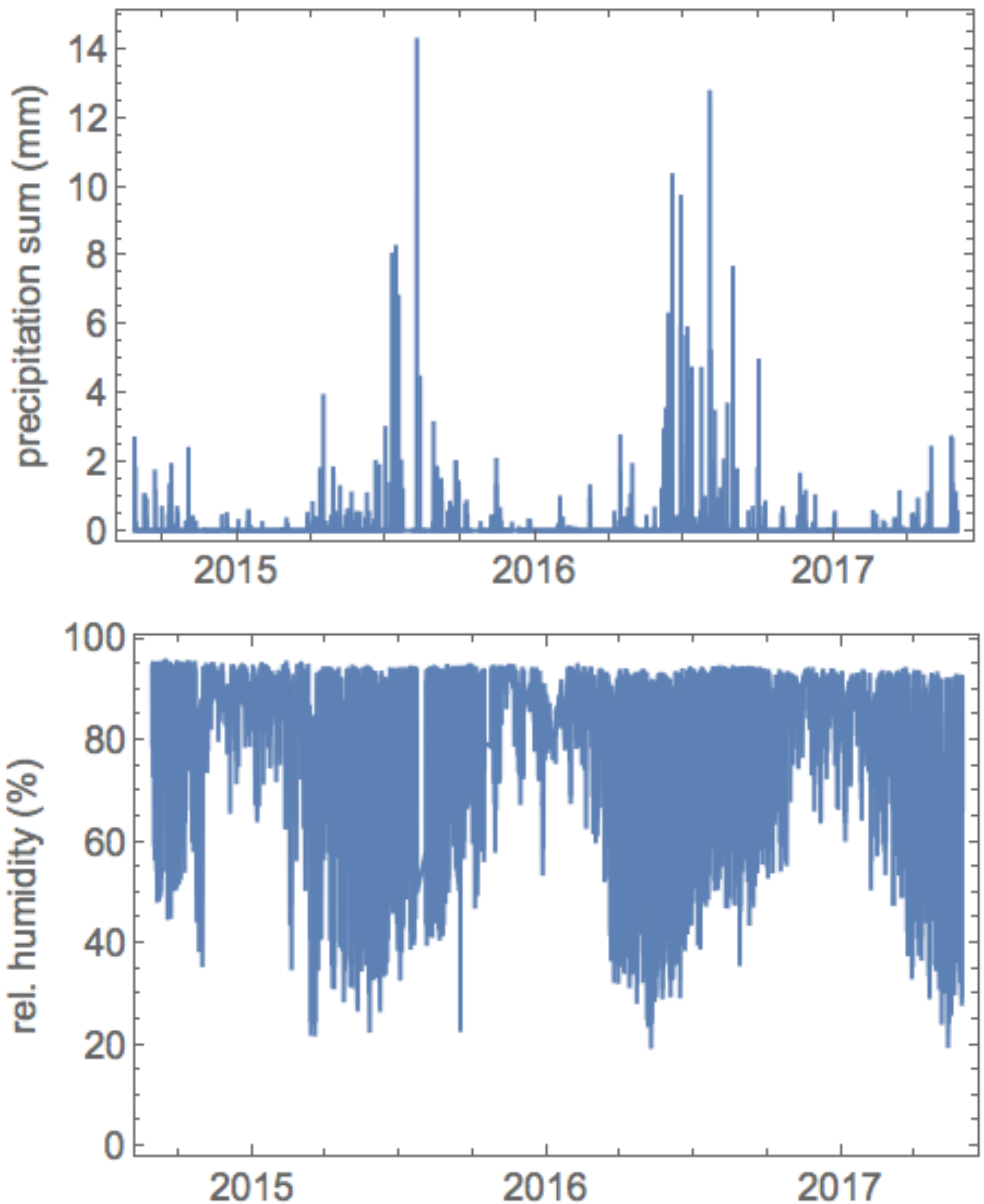
Incoming diffuse radiation is ~50% of direct radiation

Surface reflected radiation is about 1/10 of the possible incoming radiation

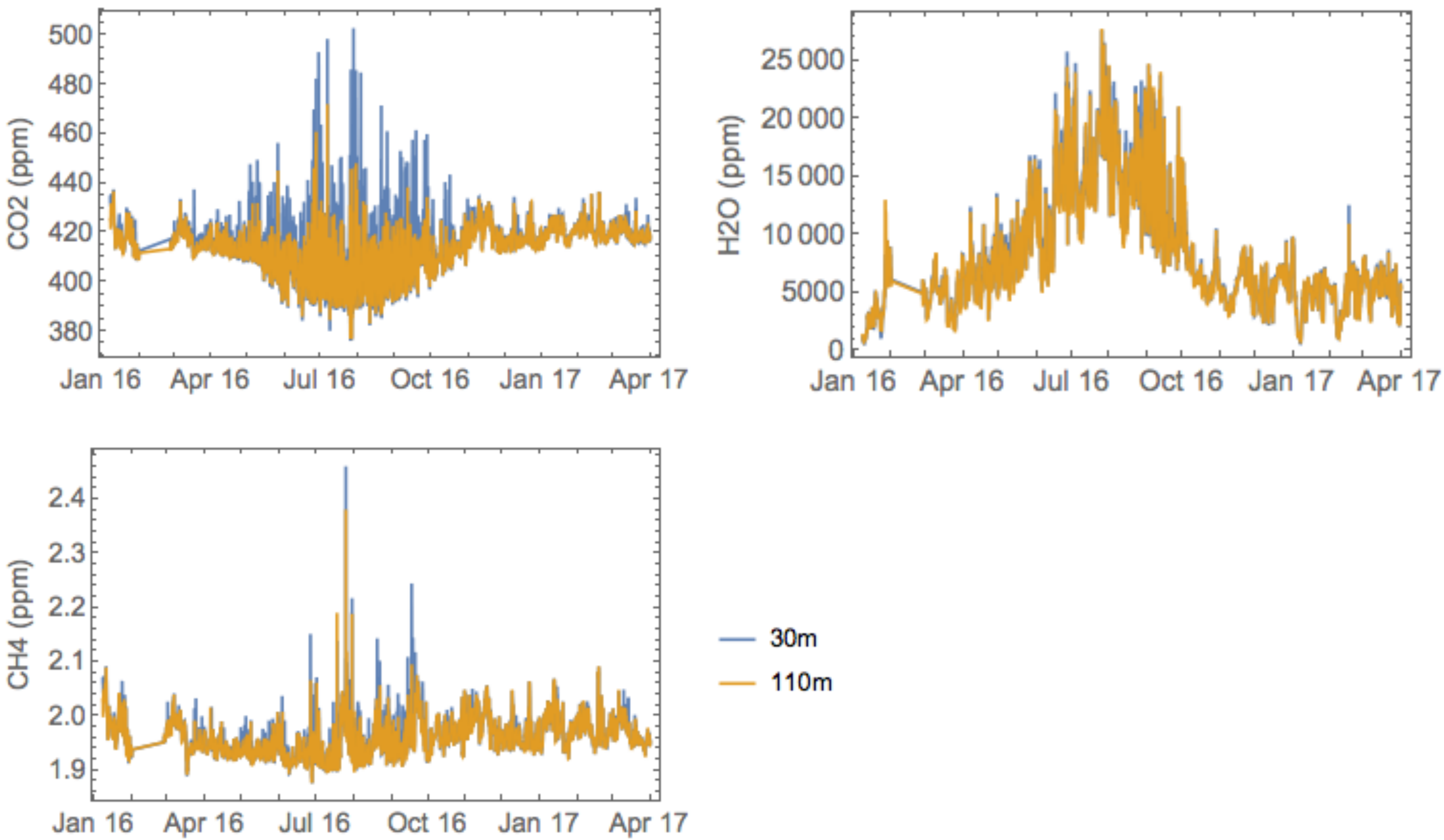
Temperature follows the seasonal and daily sunlight cycle



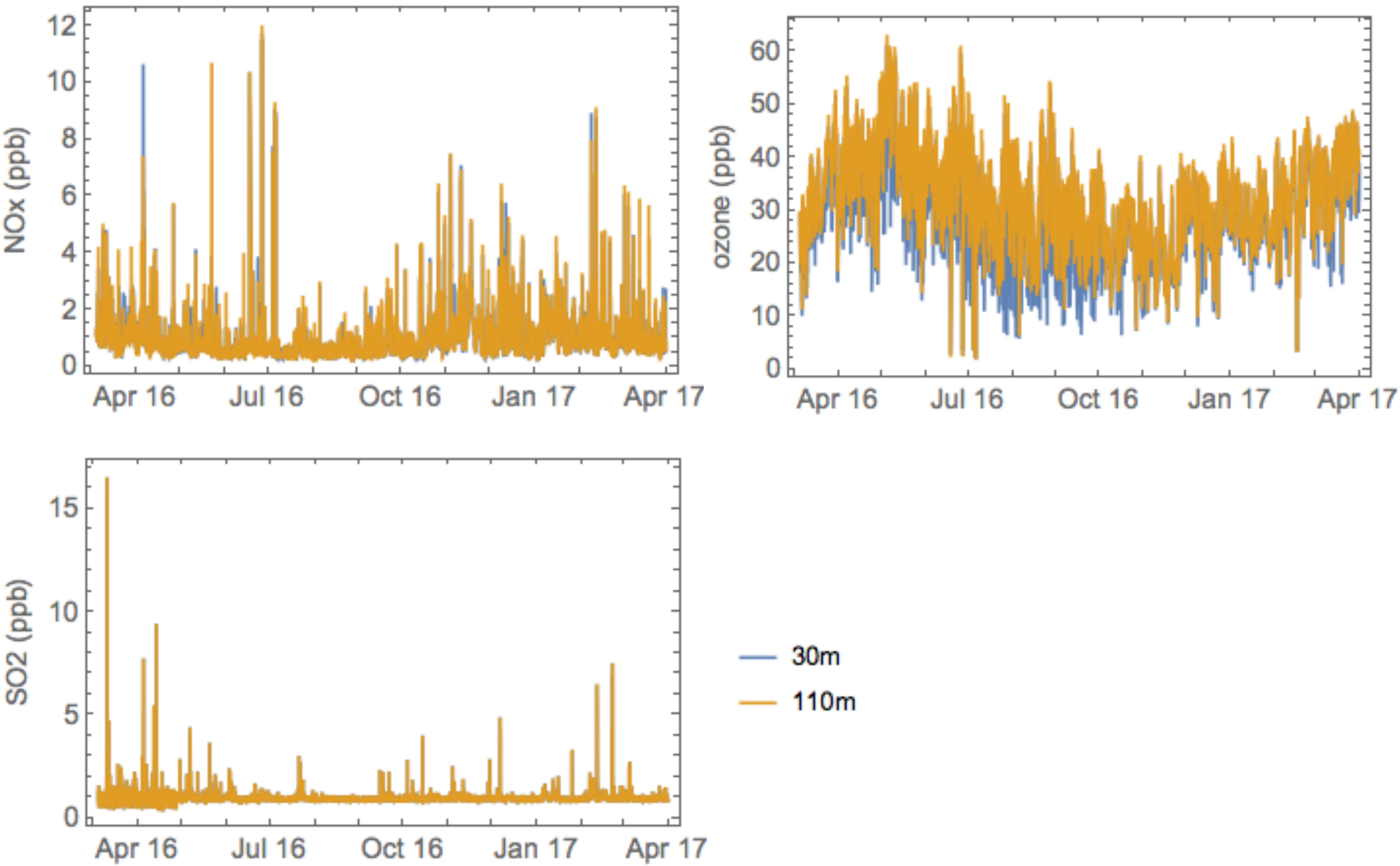
Water vapour and rel. humidity follow the temperature and by that the solar cycle



Action of seasonal cycle driven processes change the state of the atmosphere



Ozone is driven by solar cycle, NOx and SO2 are driven by human activities



Theory of the seasonal behaviour

Atmos. Chem. Phys., 17, 15045–15053, 2017
https://doi.org/10.5194/acp-17-15045-2017

Atmospheric Chemistry and Physics
Open Access

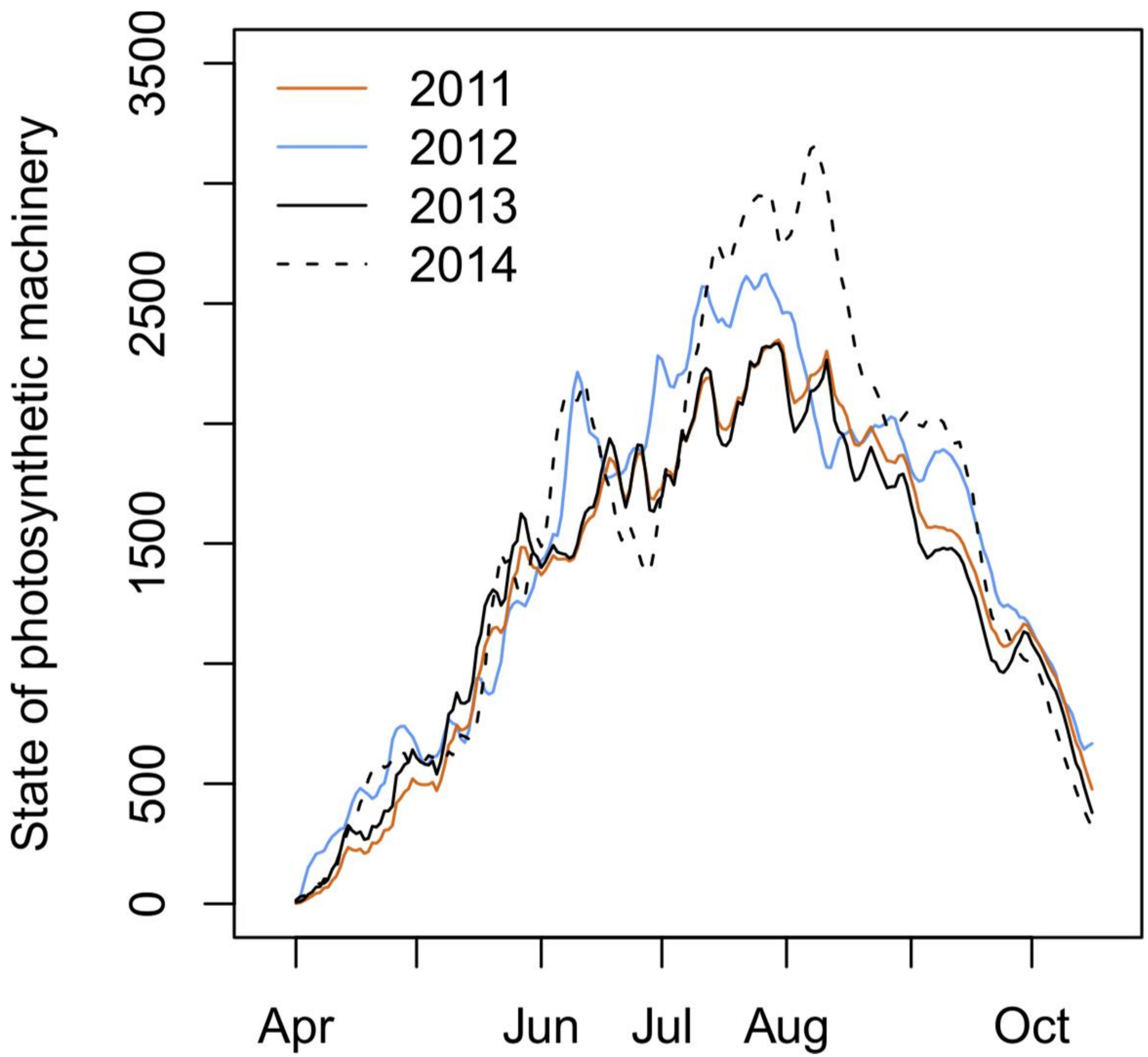
Annual cycle of Scots pine photosynthesis

Pertti Hari[1], Veli-Matti Kerminen[2], Liisa Kulmala[1], Markku Kulmala[2], Steffen Noe[3], Tuukka Petäjä[2], Anni Vanhatalo[1], and Jaana Bäck[1]

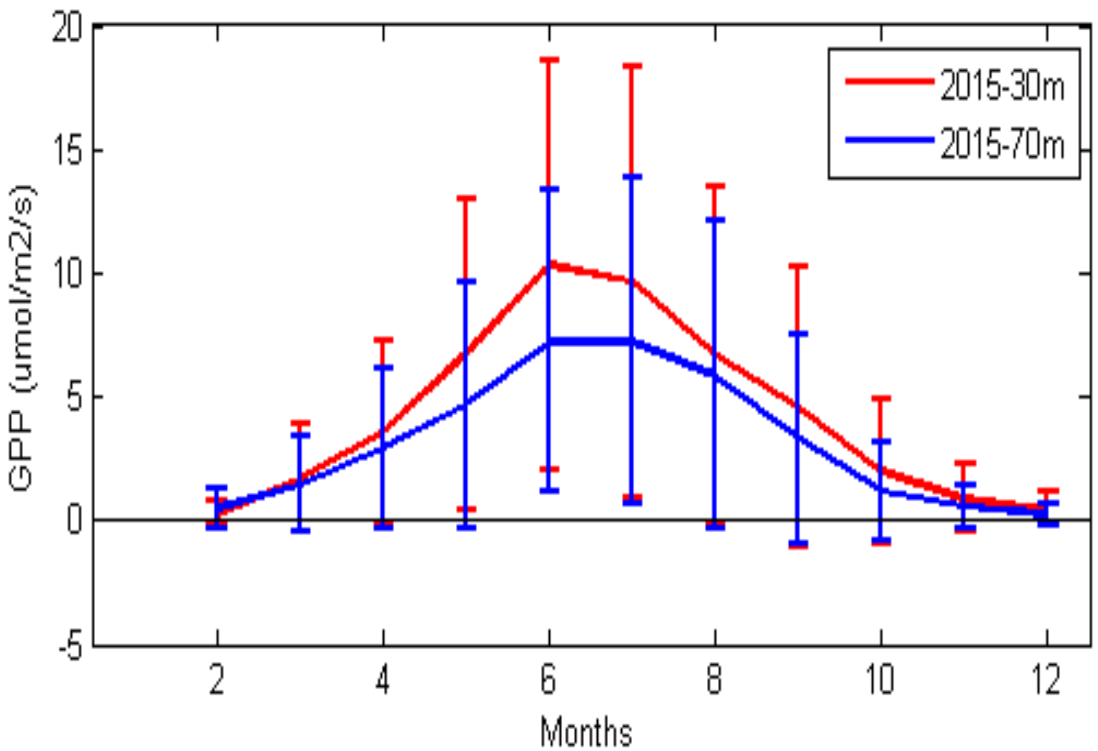
$$\frac{\mathrm{d}S}{\mathrm{d}t} = \mathrm{Max}\left\{0, a_1\left(T + T_f\right)\right\} - a_2 S - a_3 \mathrm{Max}\left(T_f - T\right) I. \quad (5)$$

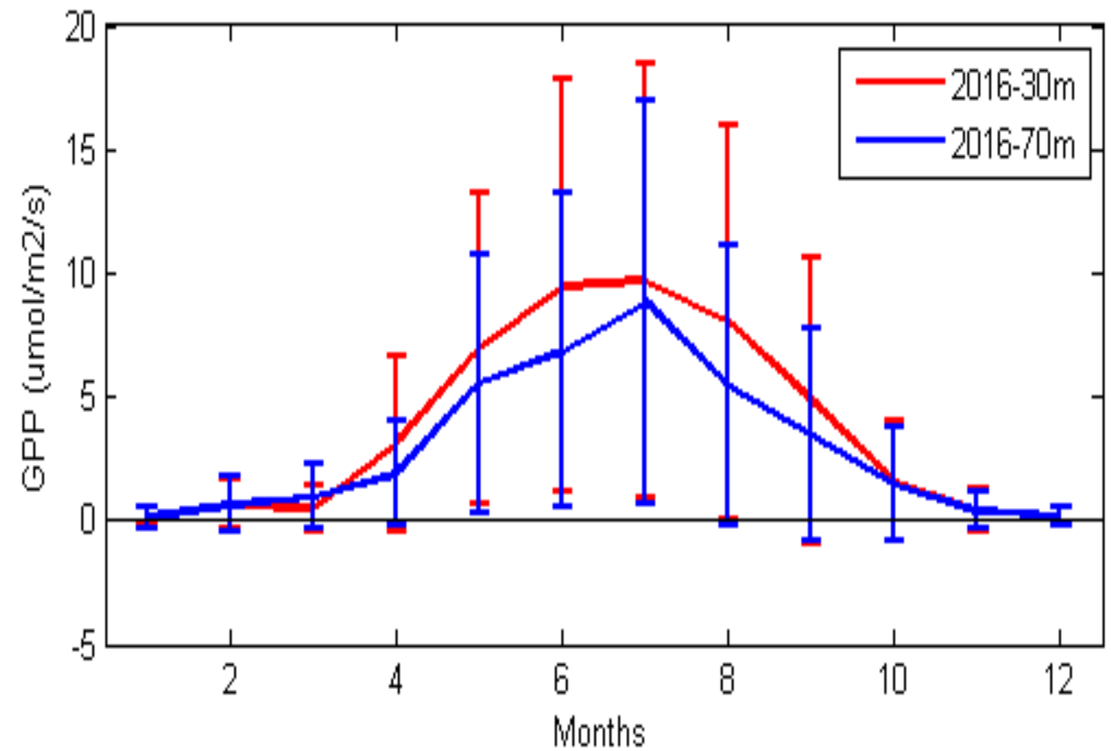
Equation (5) defines the state of the photosynthetic machinery at any moment t when temperature and solar radiation records are available.

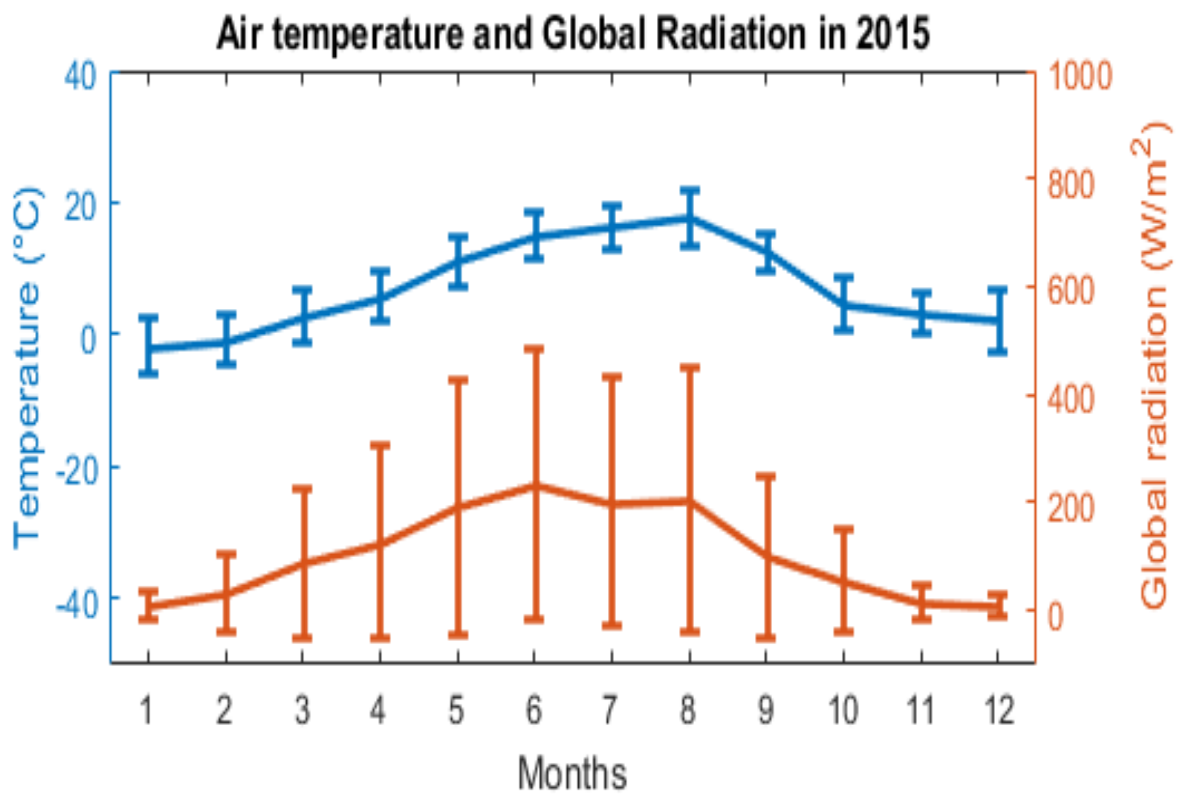
Seasonal behaviour of the photosynthesis process

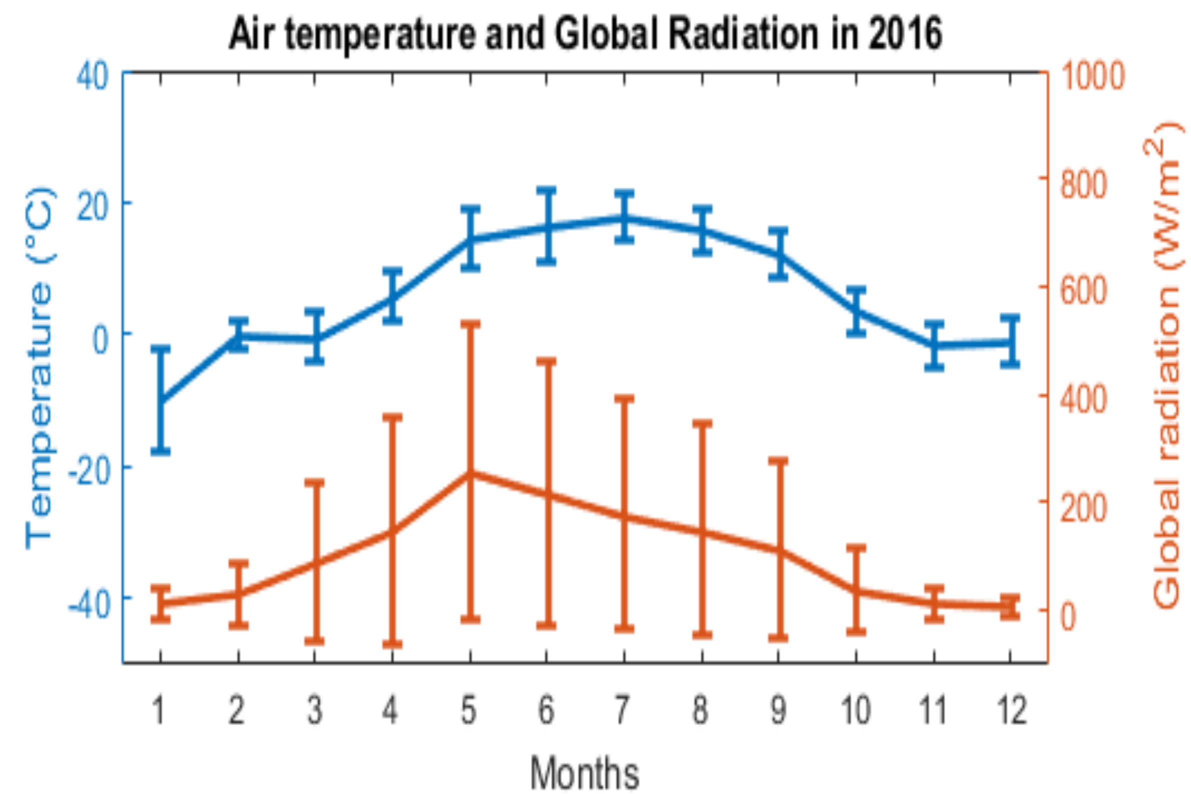


Primary production dynamics measured at SMEAR Estonia



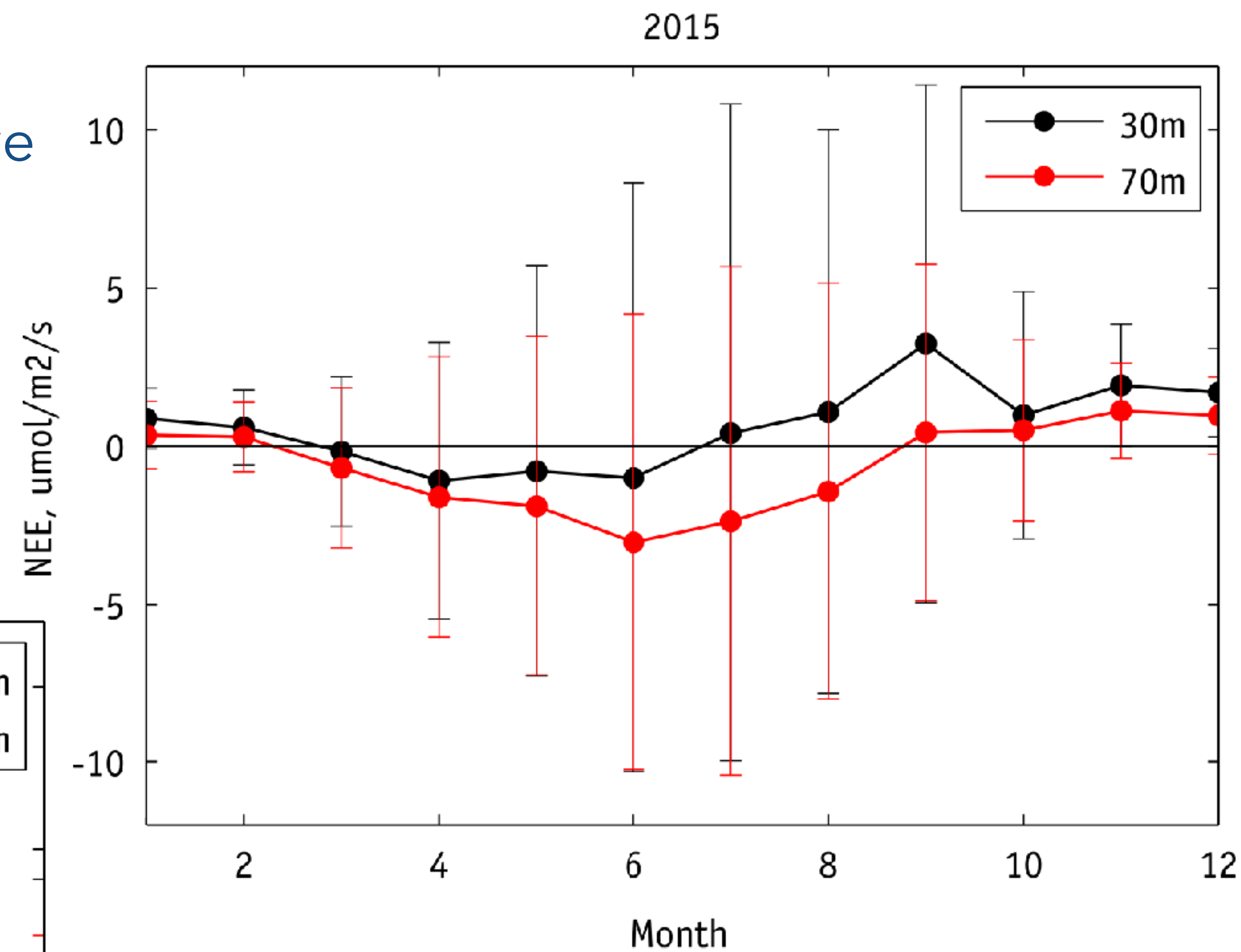


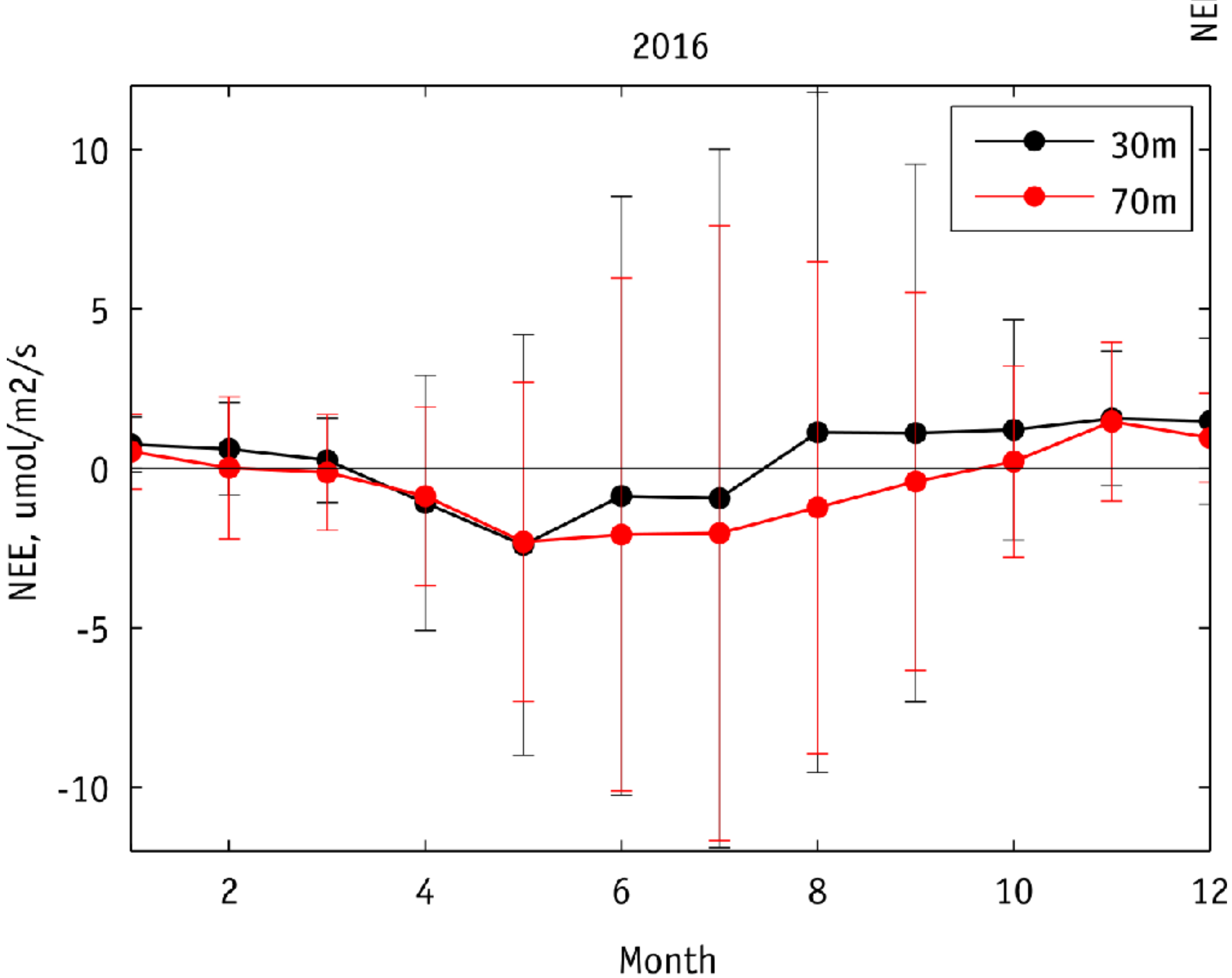




Seasonal cycle determines times when forests are sinks or sources for CO_2

30m flux measurements are more sensitive to spatial stand heterogeneity (clear cut areas, different age structure, species composition).

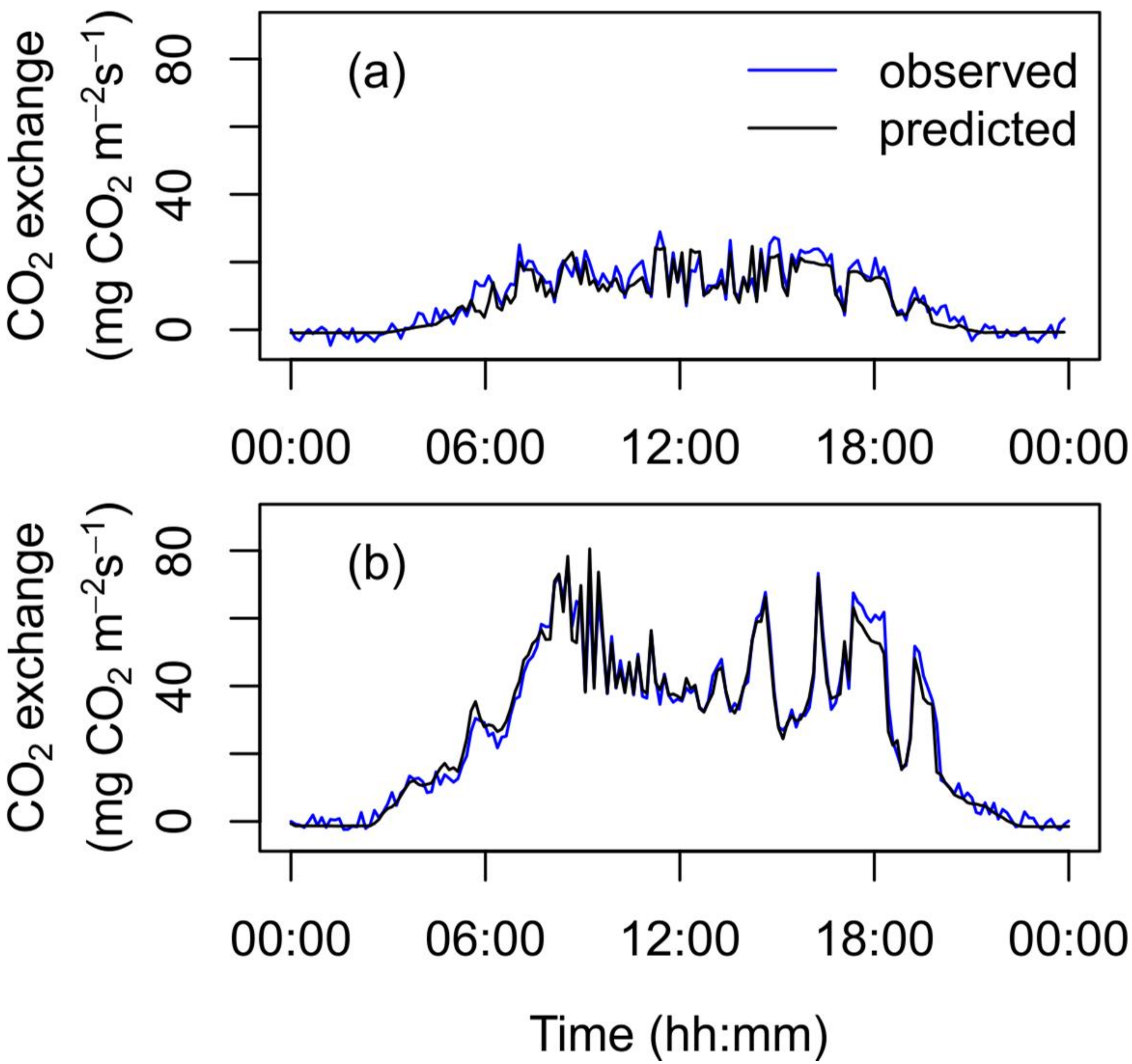




NEE = GPP - RE

Day-night overview

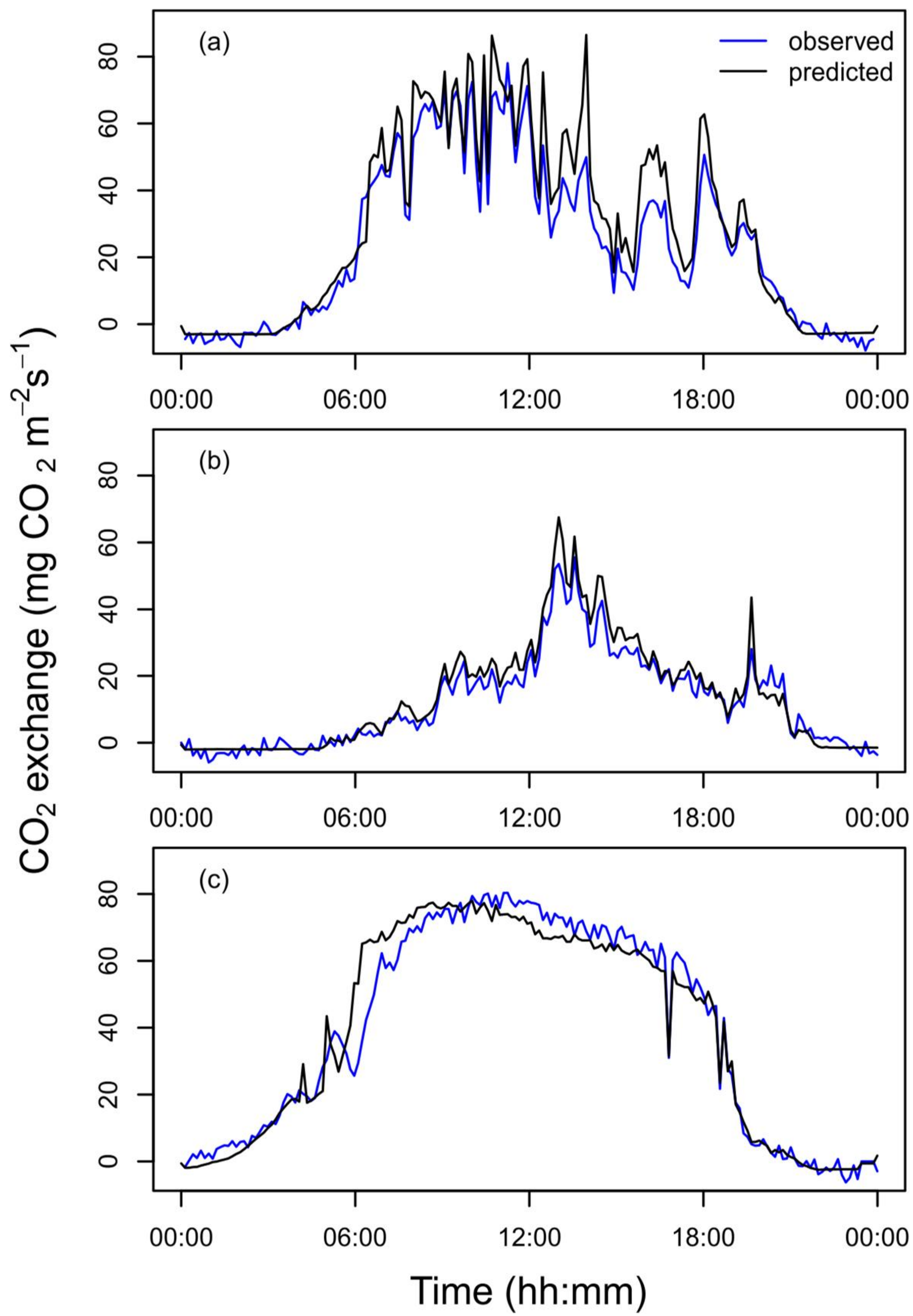
Daily courses of ecosystem processes are directed by the sunlight



Measured and predicted CO_2 exchange during two days.

A. early in the spring (May 8) and B in midsummer (July 18) as function of time

Changes in radiation by cloud cover modulate the daily incoming radiation



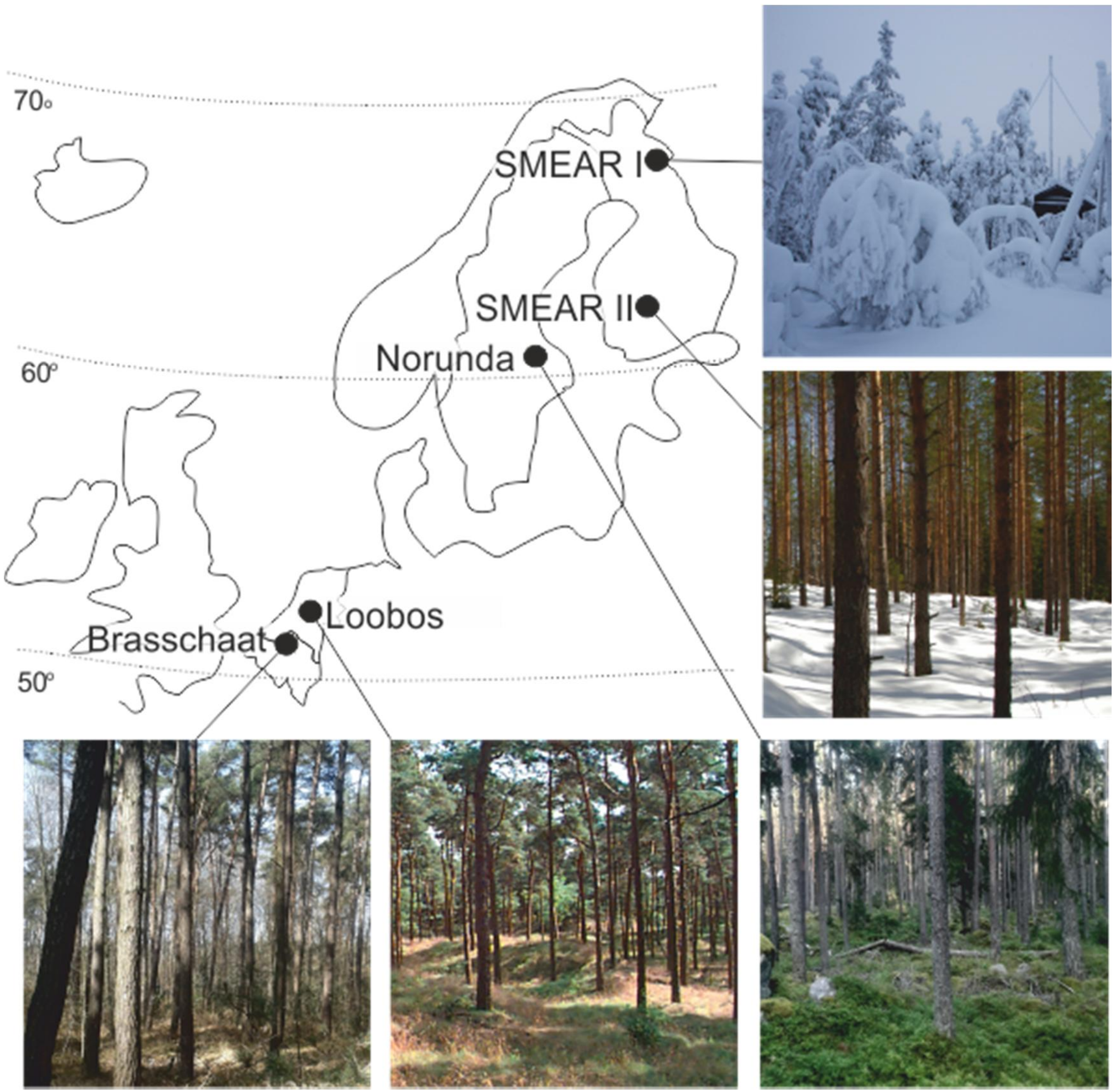
Measured and predicted leaf CO2 exchange

(a) during a day of intermittent cloudiness (August 5),

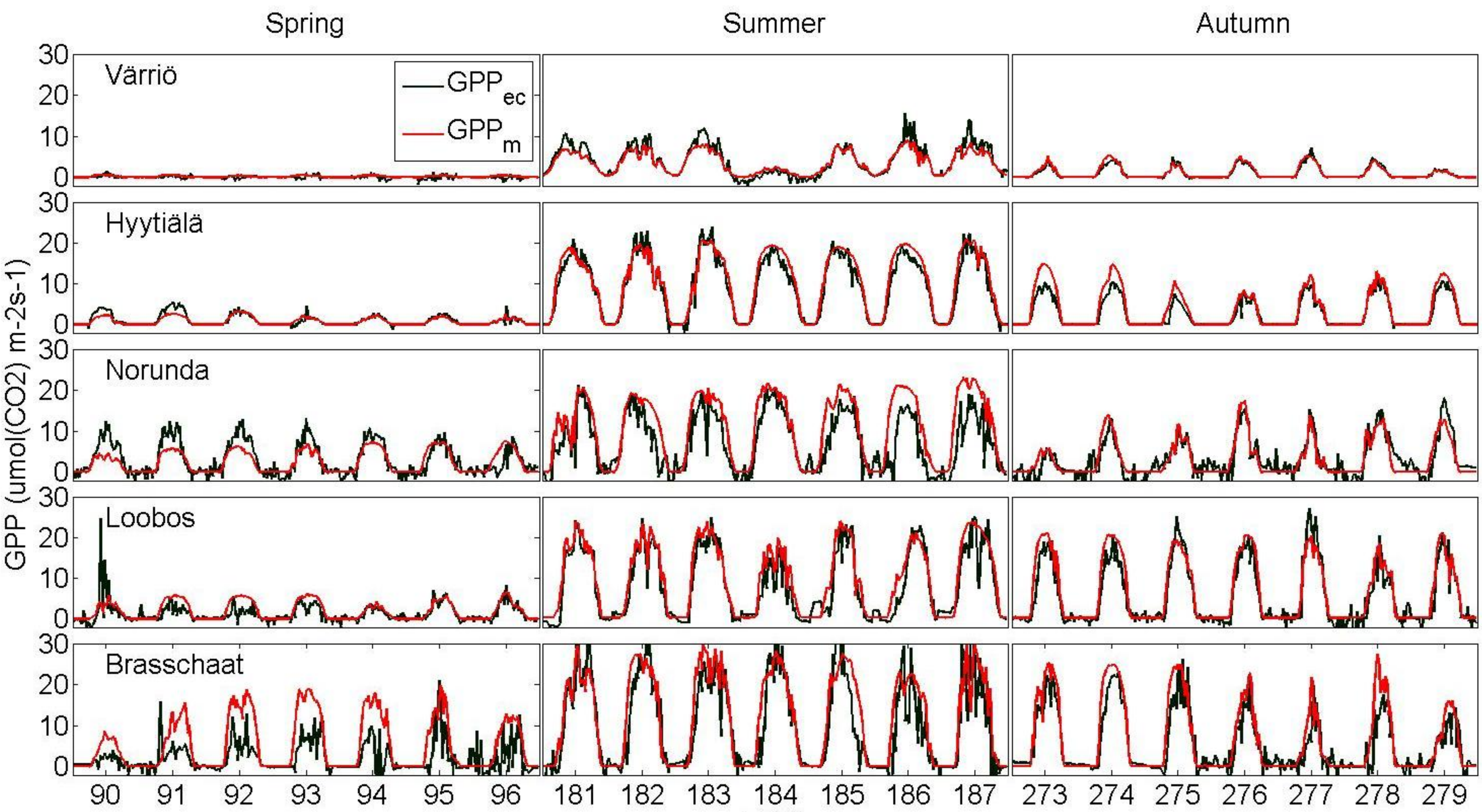
(b) during a cloudy day (July 22), and

(c) during a sunny day when the stomata close partially (July 7) in Finnish Lapland, 68N.

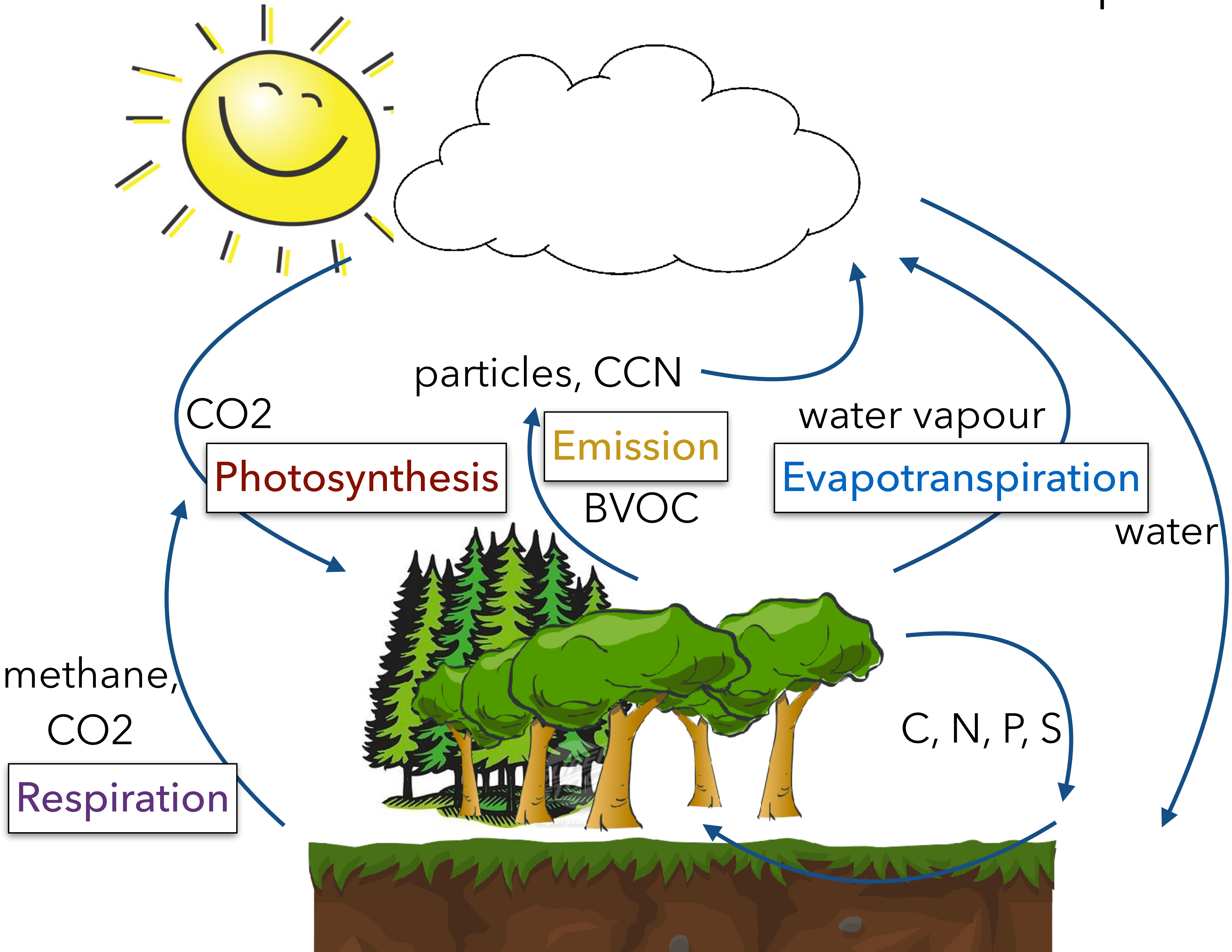
Different solar angles due to geological location



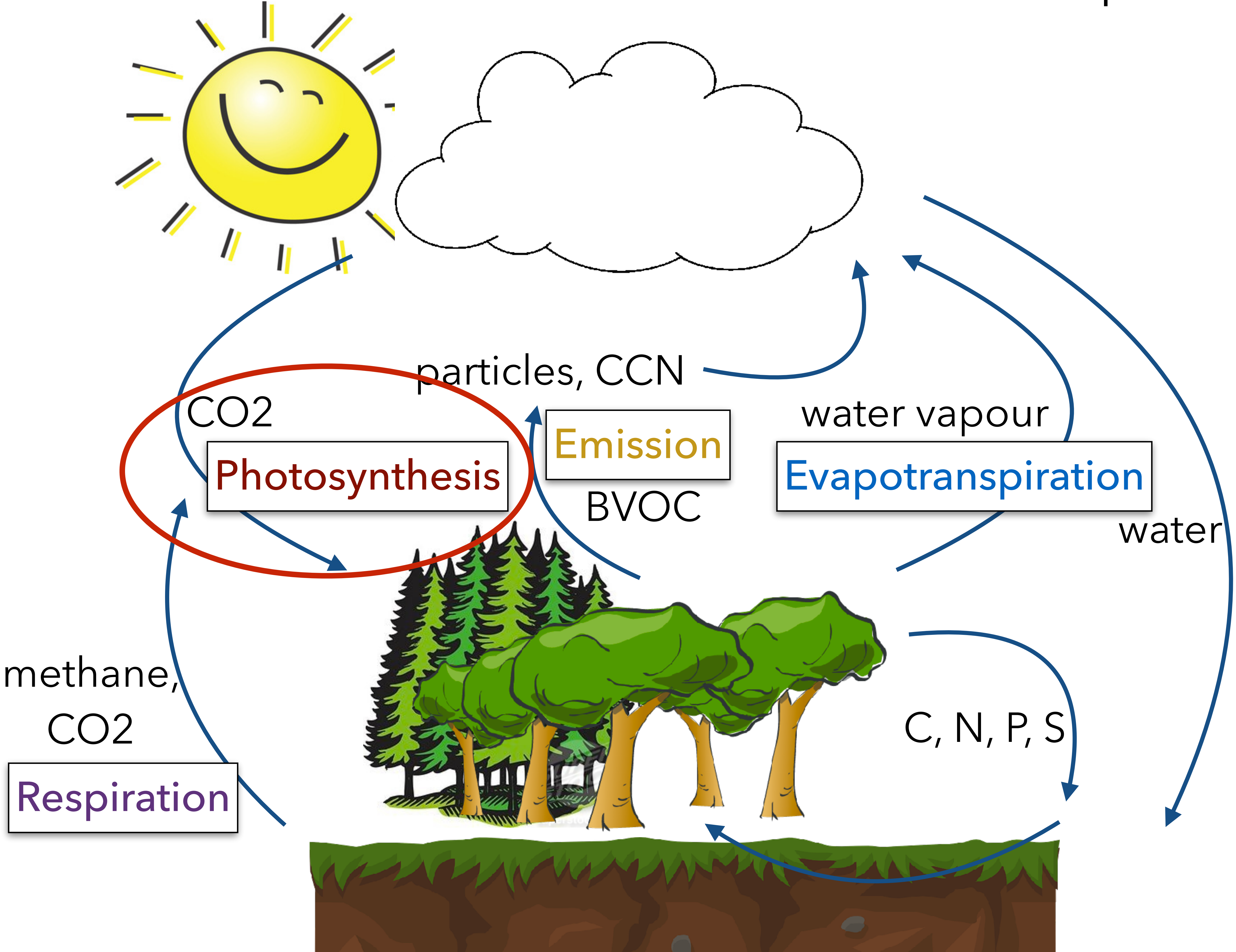
Interplay of daily and seasonal cycle on GPP at different ecosystems



Processes between the forest and the atmosphere



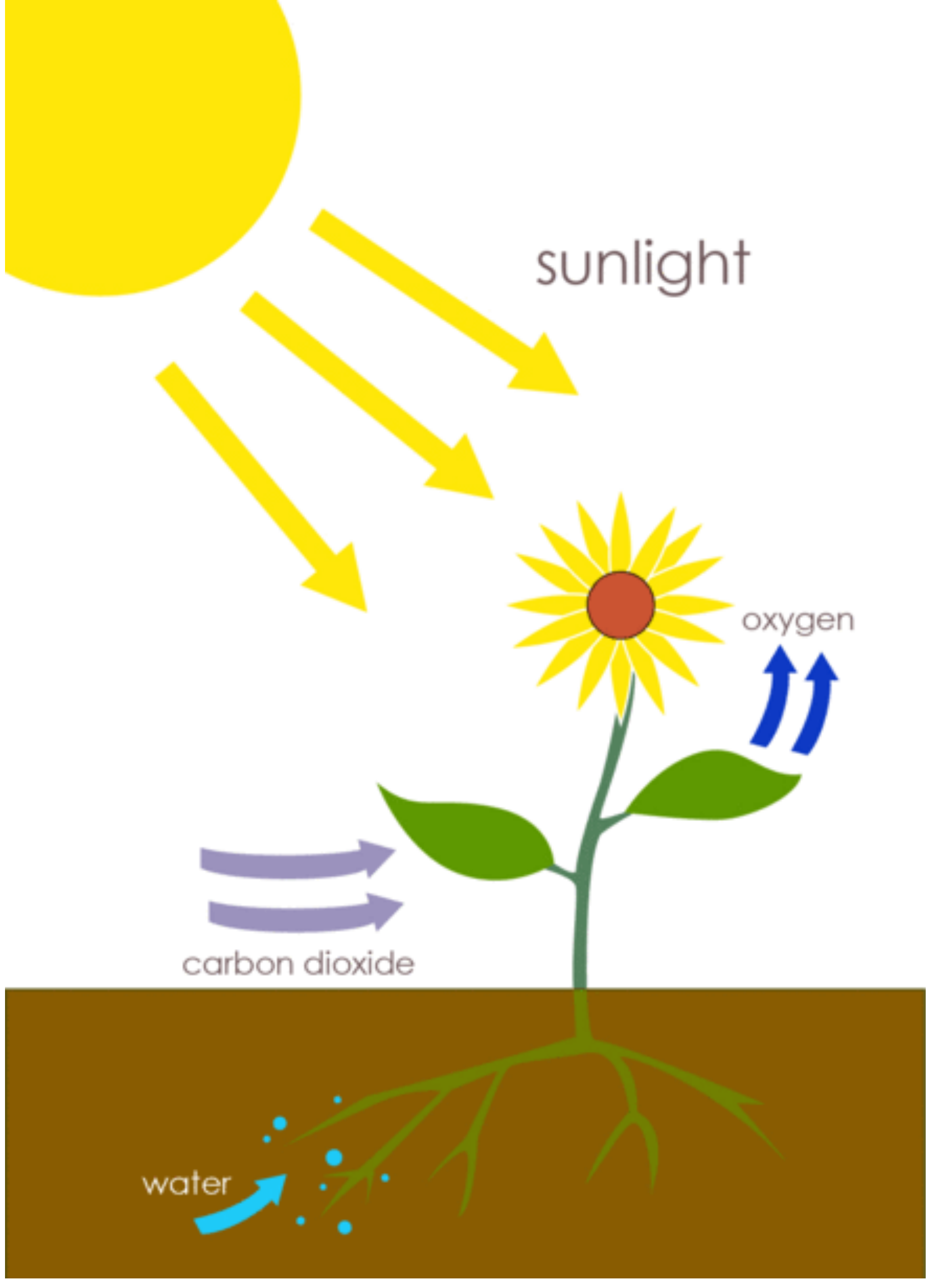
Processes between the forest and the atmosphere



Photosynthesis

General: Takes up carbon (CO_2) from the atmosphere and releases oxygen (O_2) to the atmosphere.

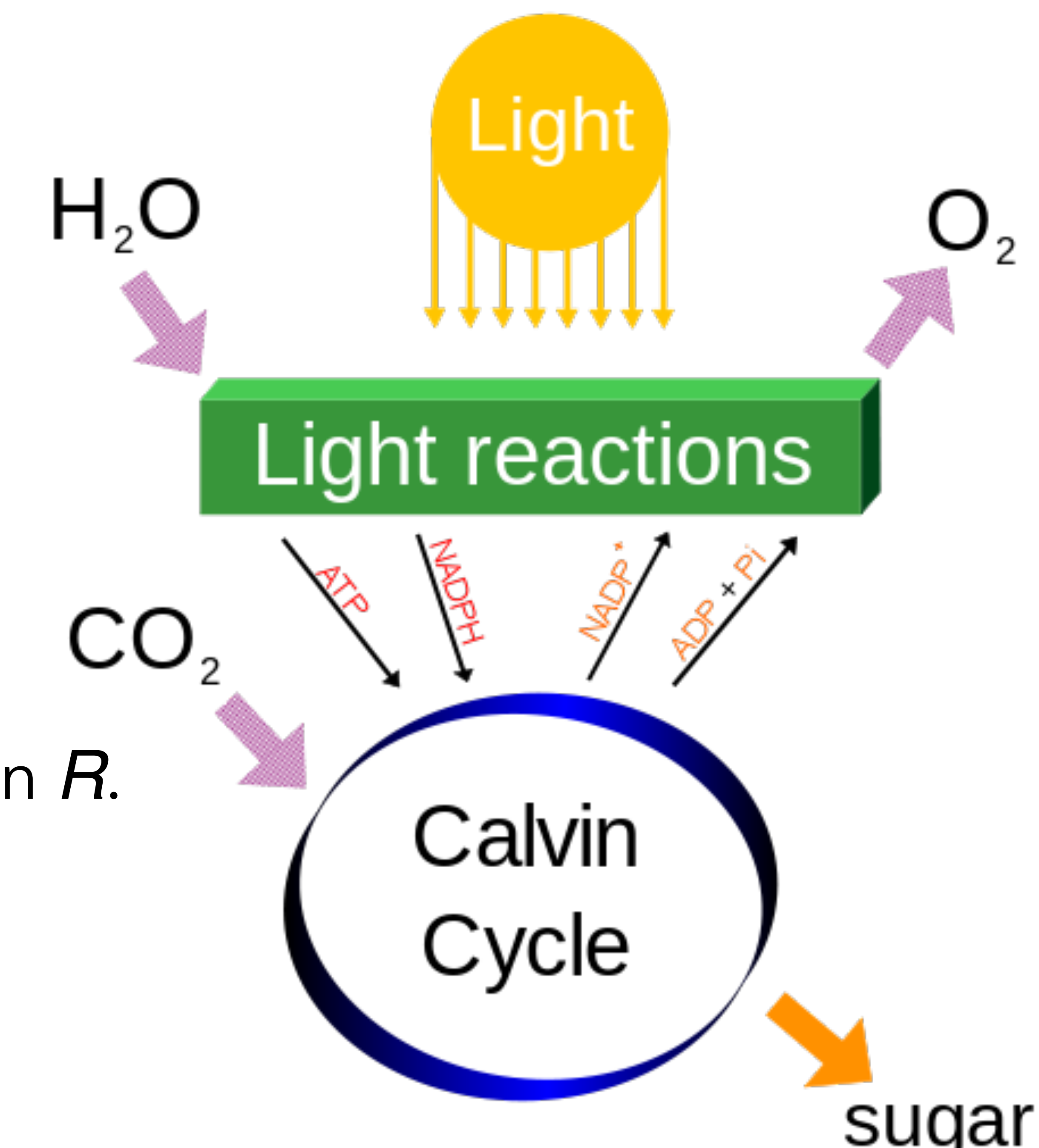
Basic needs:
Sunlight for energy.
Water for oxidation.



Photosynthesis

It is split into light and dark reactions!

It produces sugars that are subsequently used in cellular respiration.

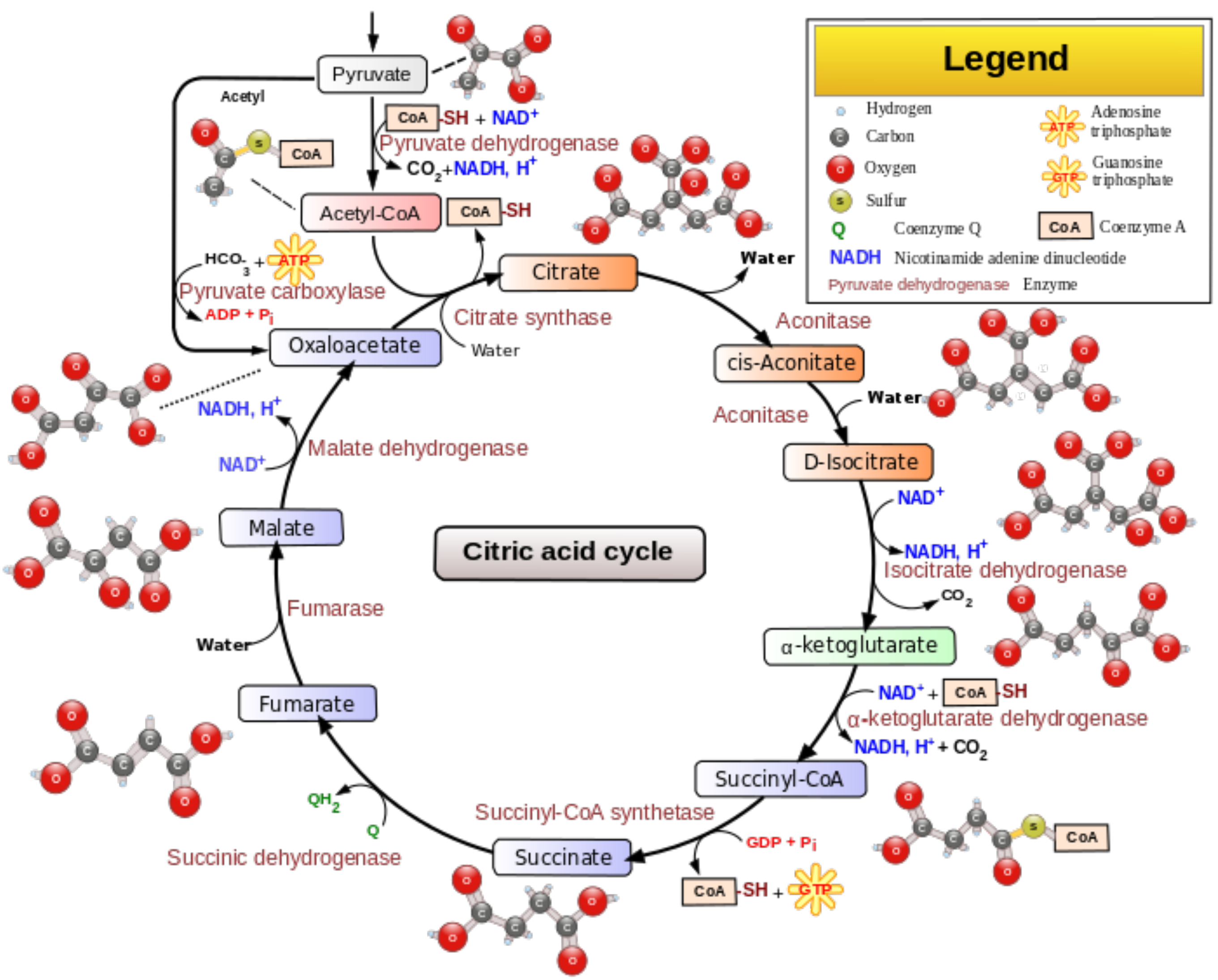


We can see on a leaf/needle scale the “net photosynthesis” *A*, is the difference between gross photosynthesis *P* and the respiration *R*.

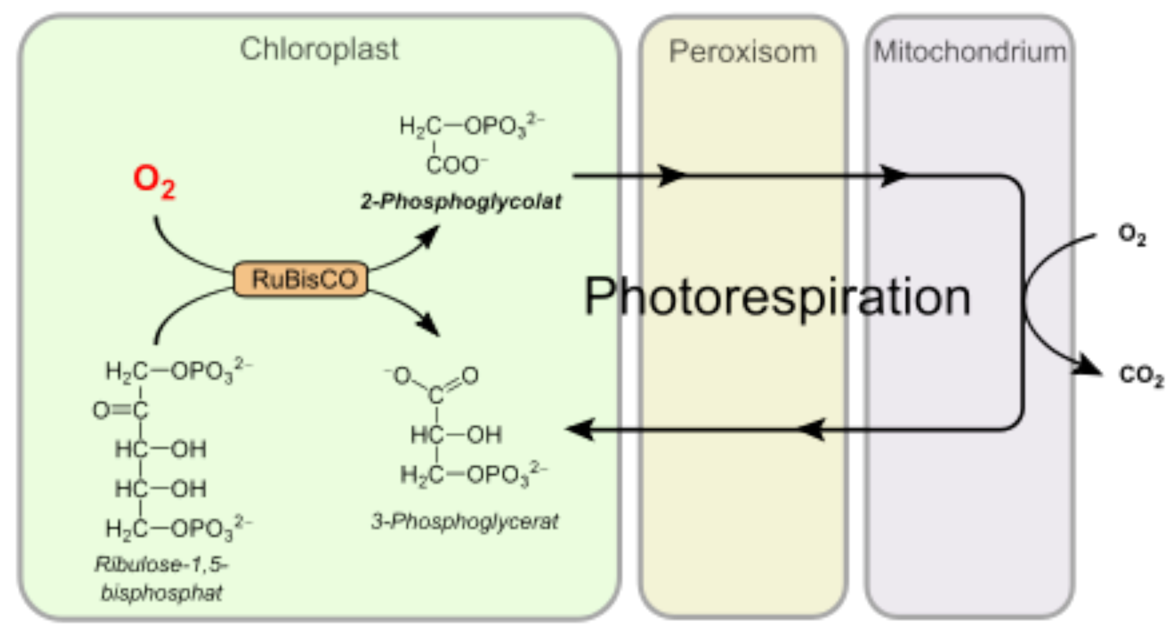
$A = P - R$

Photosynthesis

Respiration is also split into the photorespiration and the dark (cellular aerobic) respiration.



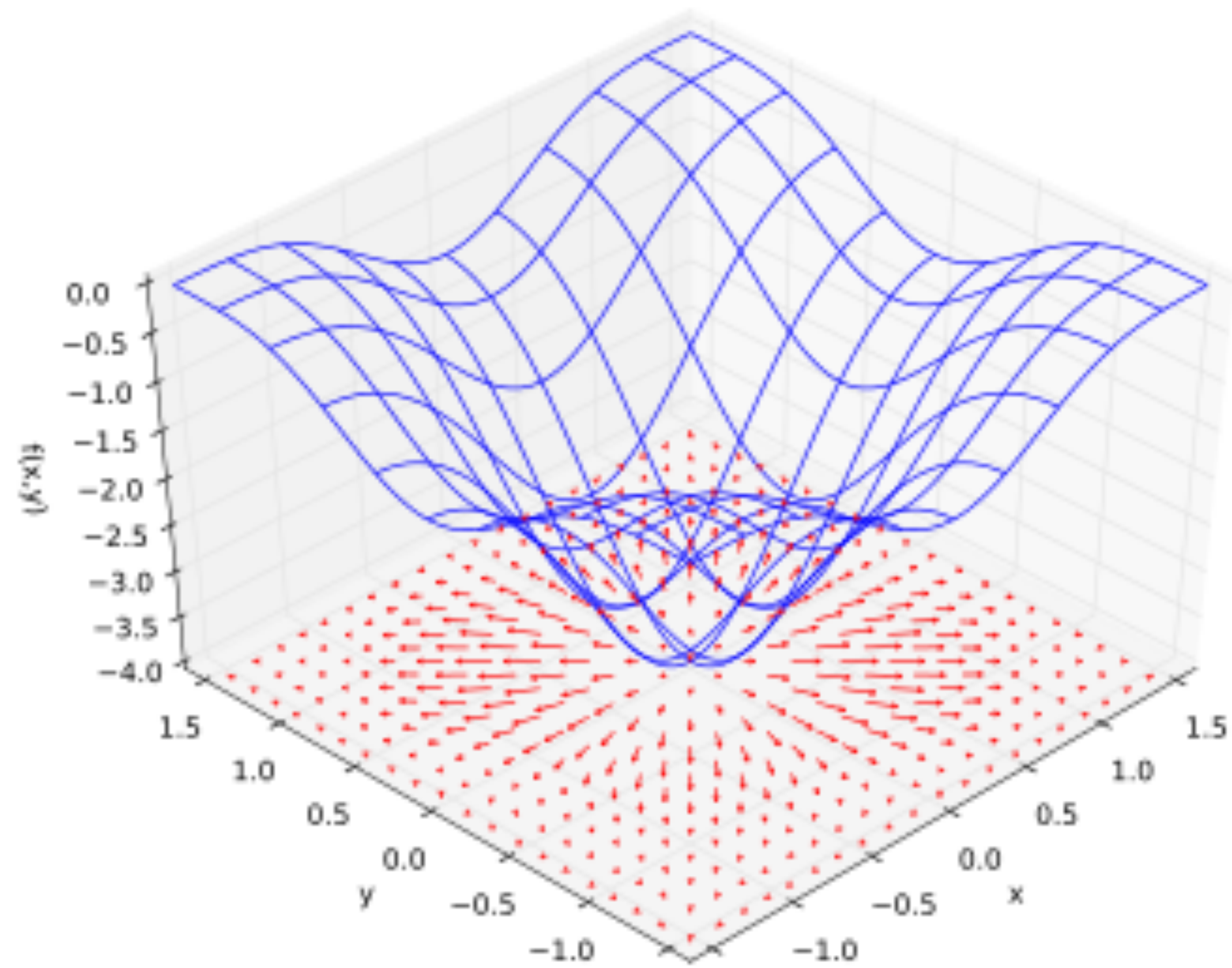
Use of sugar to produce energy and release CO_2.



Uses energy but does not form sugars.

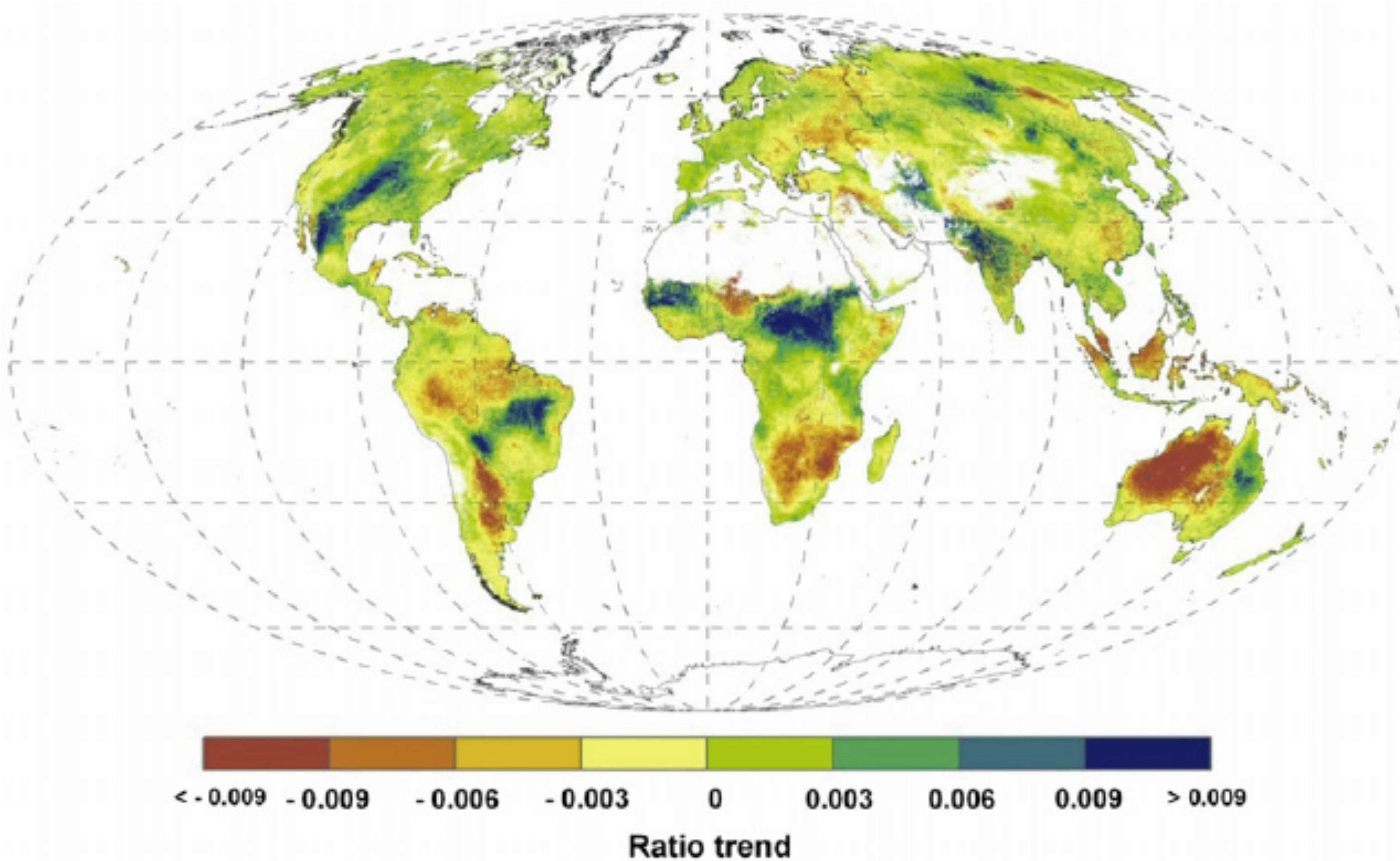
Photosynthesis

We need gradients in water vapour, oxygen and carbon dioxide to maintain transport of the molecules needed for the process and exchange with the environment.



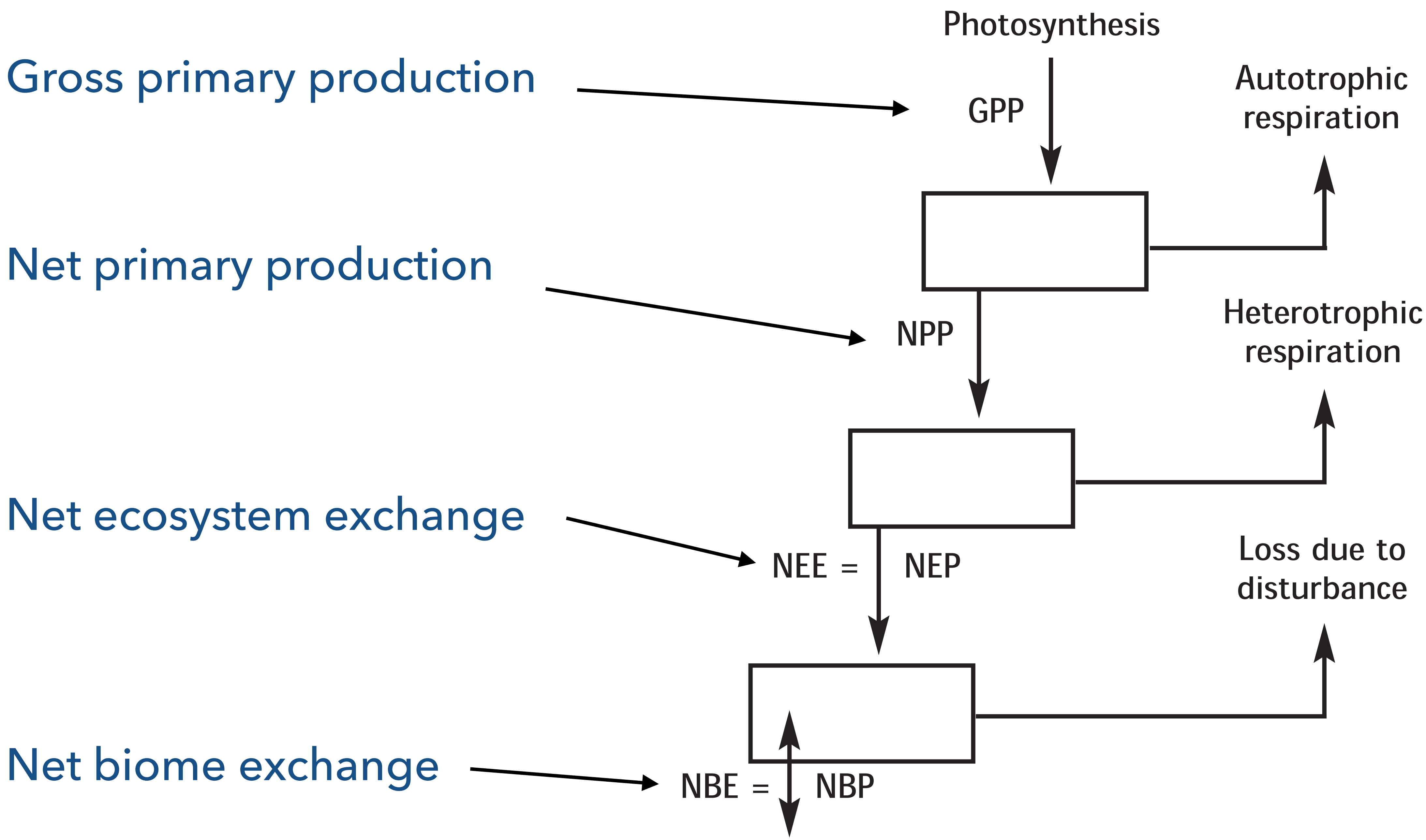
Another important gradient:
The light energy is also used to build up a proton gradient over the thylakoid membrane inside the chloroplasts.

Photosynthesis on larger scales

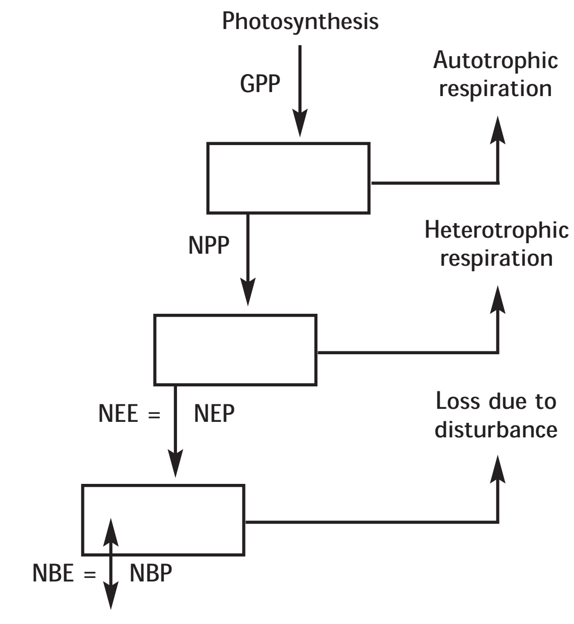


Projected net primary production changes on global scale.

Photosynthesis on larger scales



Photosynthesis on larger scales



Gross primary production GPP:
The total amount of carbon fixed in the process of photosynthesis.

Autotrophic respiration Ra:
Carbon used in plant internal metabolism. It's about half the carbon fixed.

Net primary production NPP:
Net production of organic carbon by plants. NPP = GPP - Ra

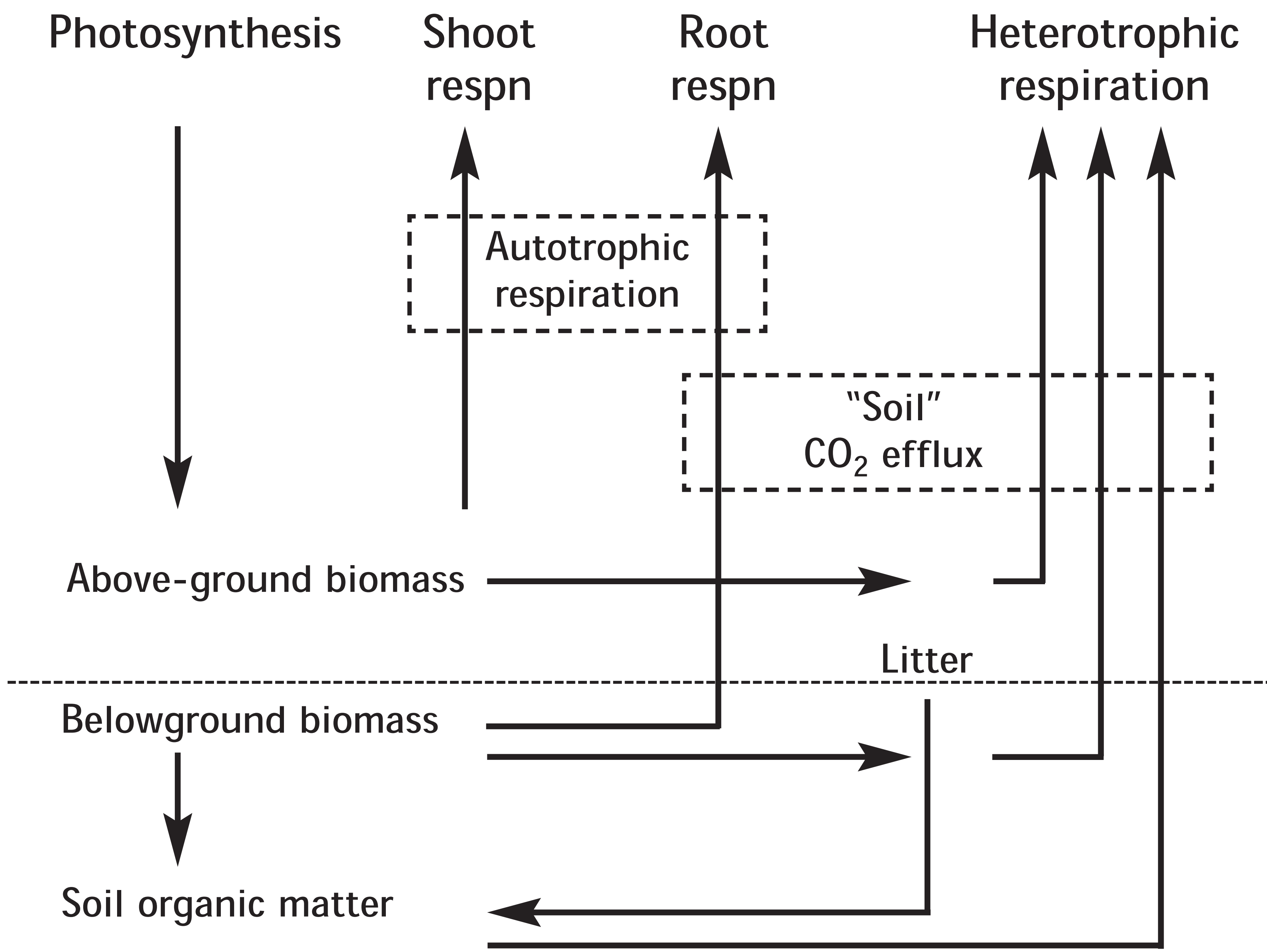
Net ecosystem exchange NEE or net ecosystem production NPP:
Net primary production minus the heterotrophic respiration. NEE = NEP = NPP - Rh

Heterotrophic respiration Rh:
Heterotrophic respiration refers to carbon lost by organisms other than plants in ecosystem.

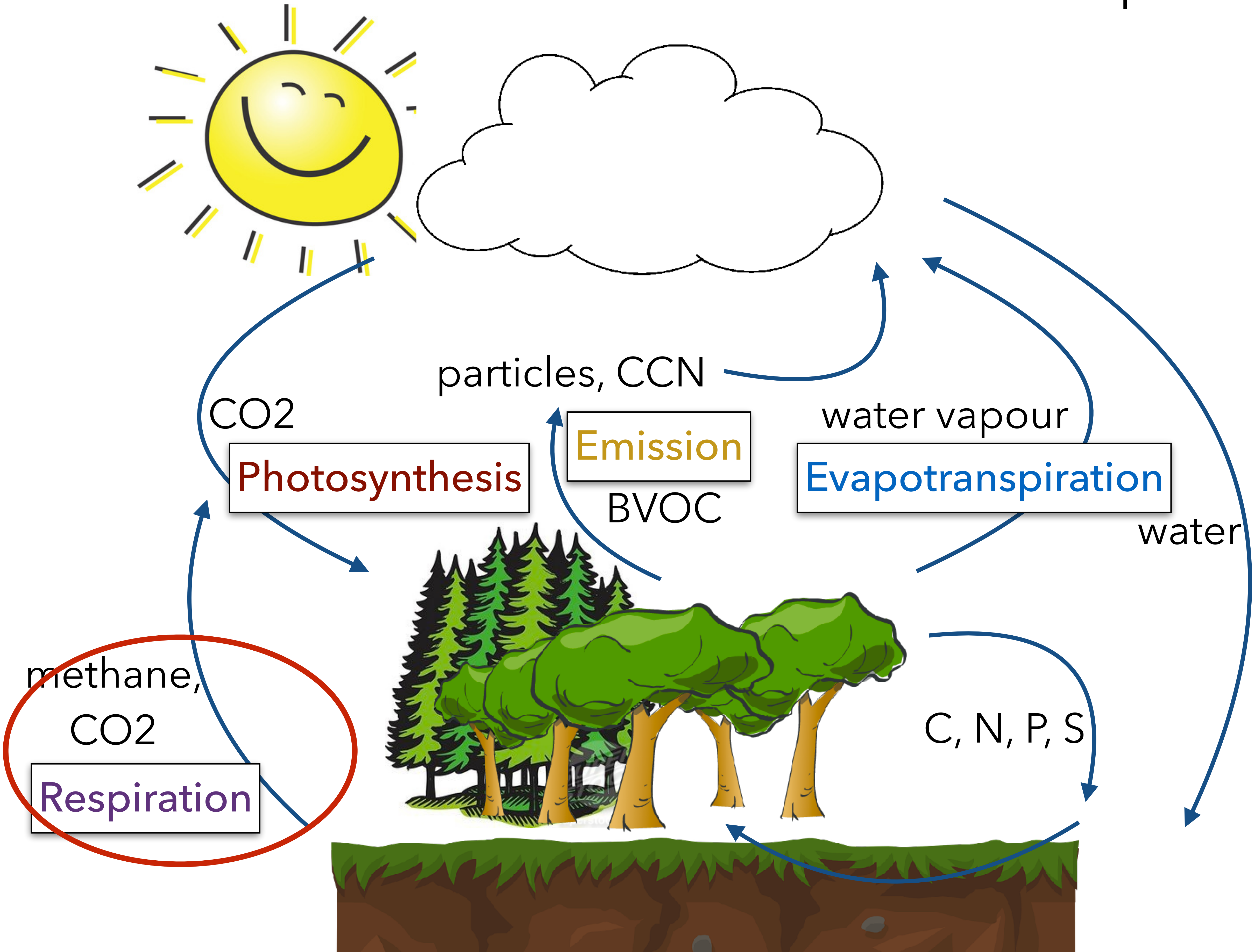
Net biome exchange NBE or net biome production NBP:
Change in carbon stocks including carbon losses by episodic natural or anthropogenic disturbances. NBE = NEE -Ld

Disturbance loss Ld:
Episodic loss of carbon by disturbances (storms, timber production,…)

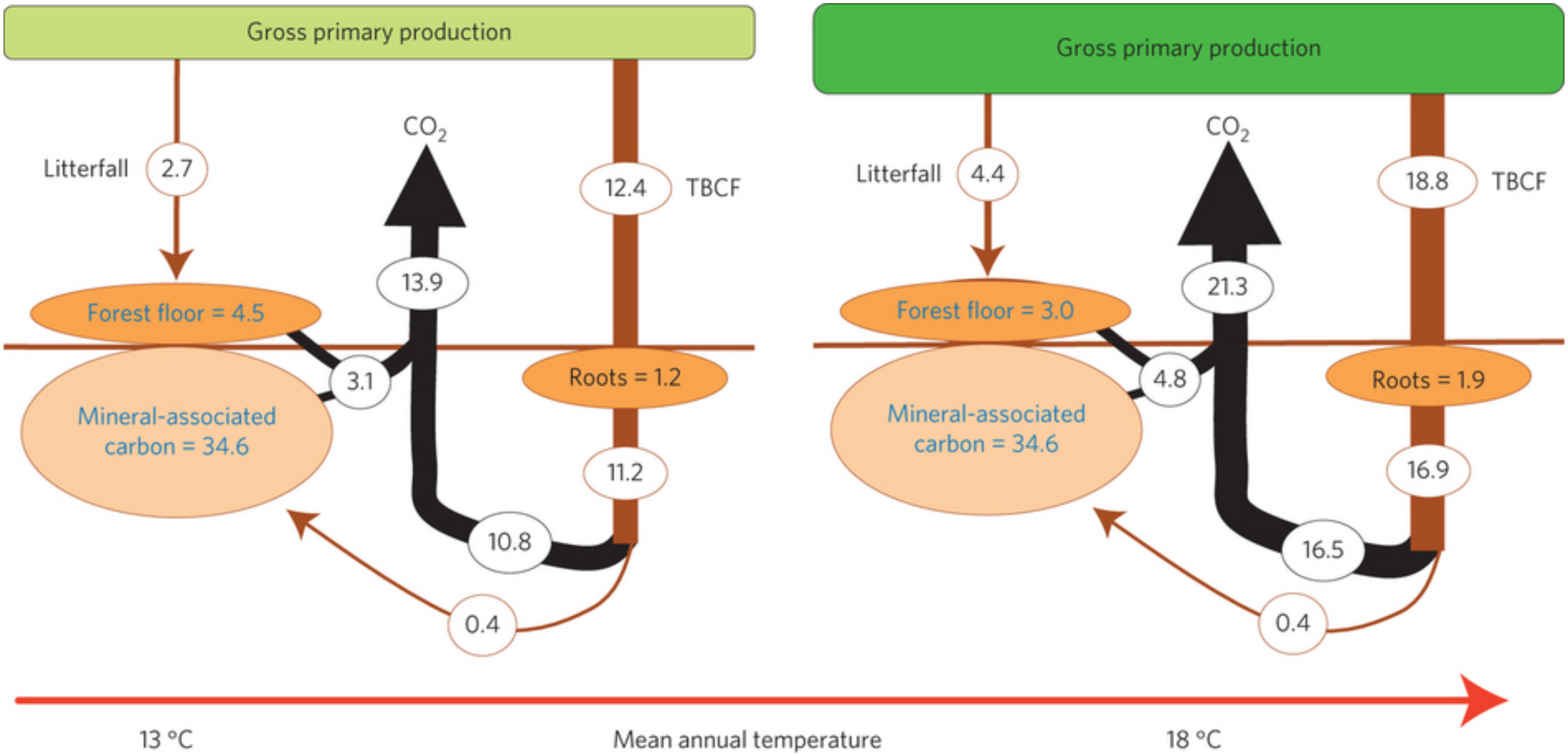
Carbon balance and fluxes



Processes between the forest and the atmosphere



Soil efflux process



Nature Climate Change **4**, 822–827 (2014) doi:10.1038/nclimate2322

Soil respiration and rainfall / soil humidity

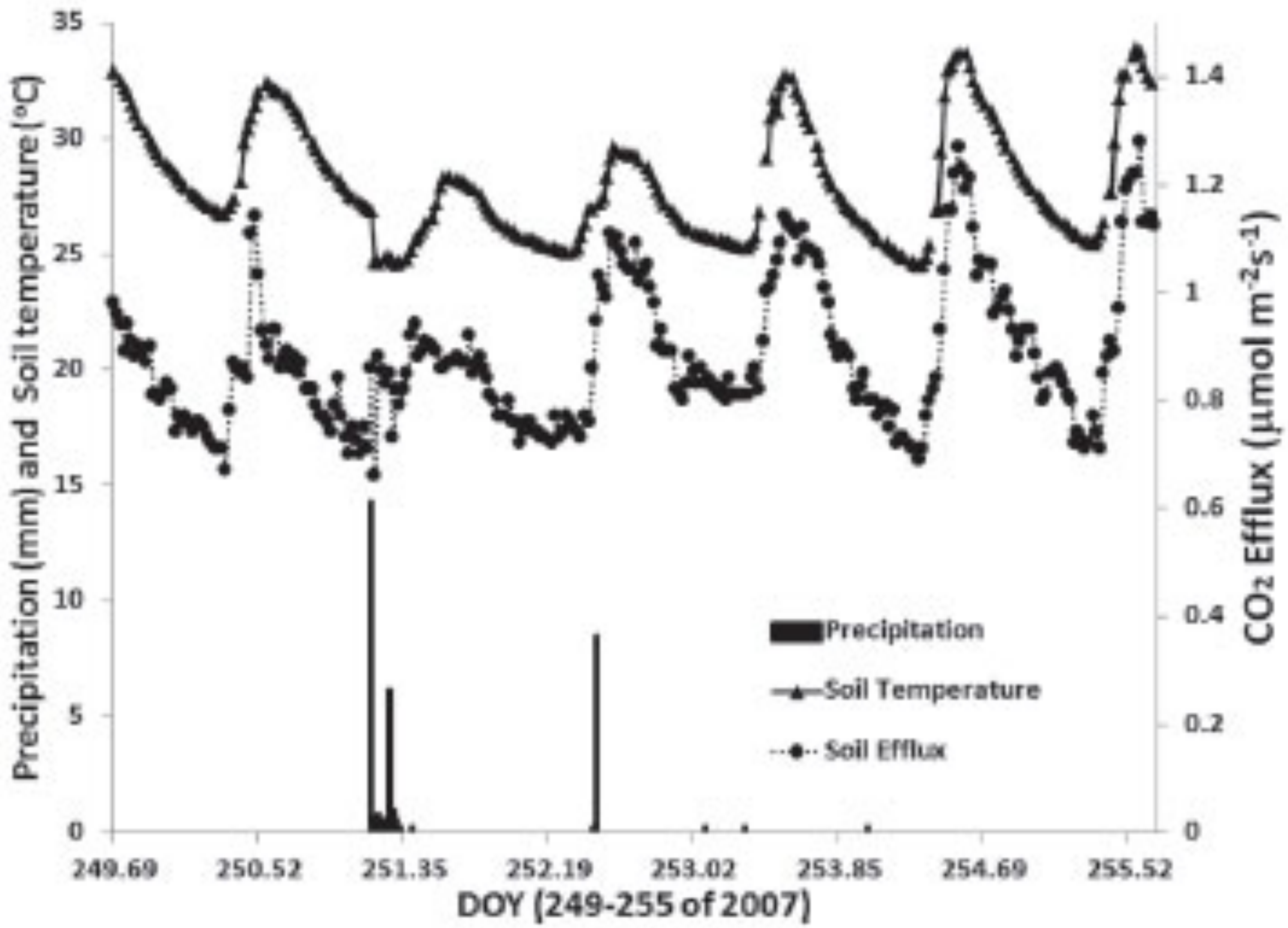
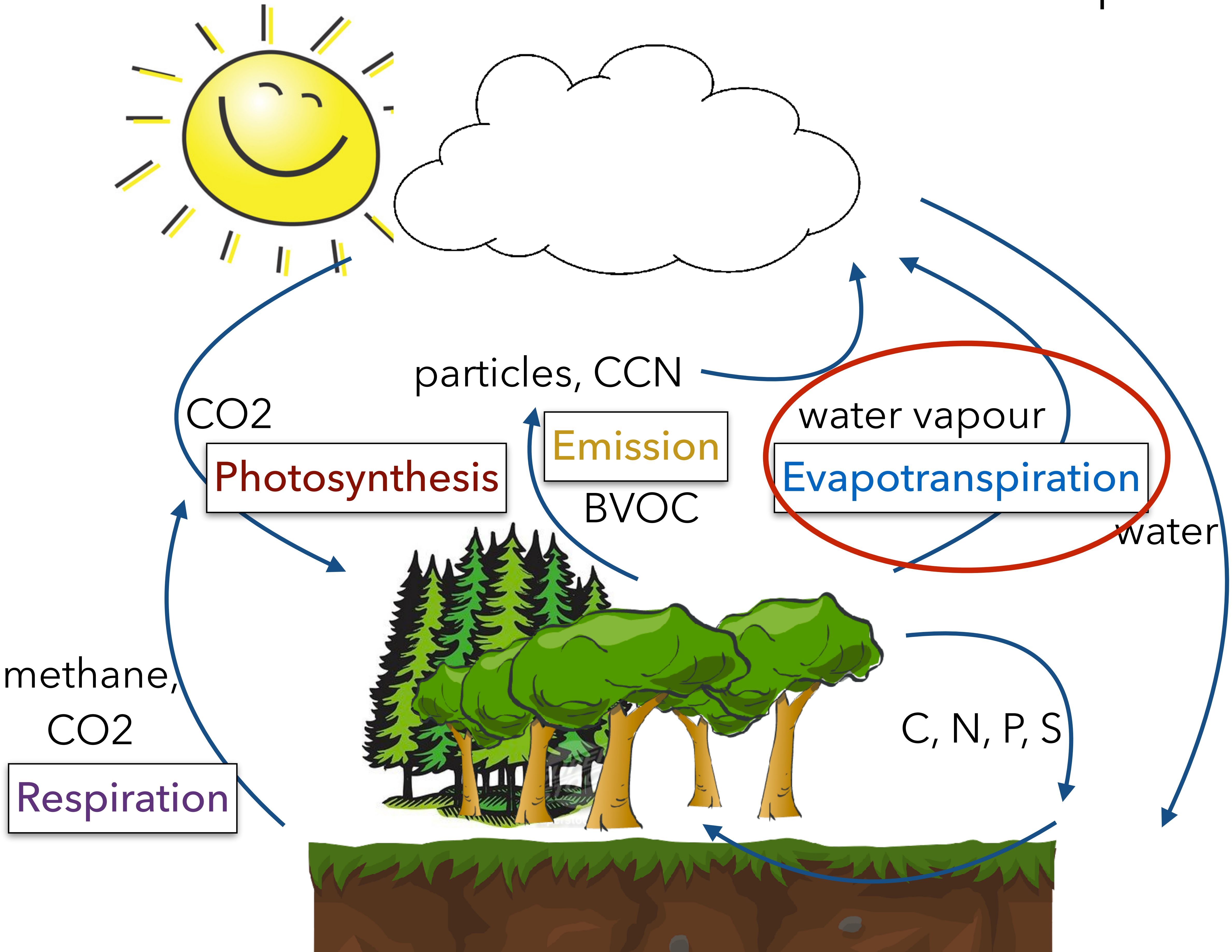
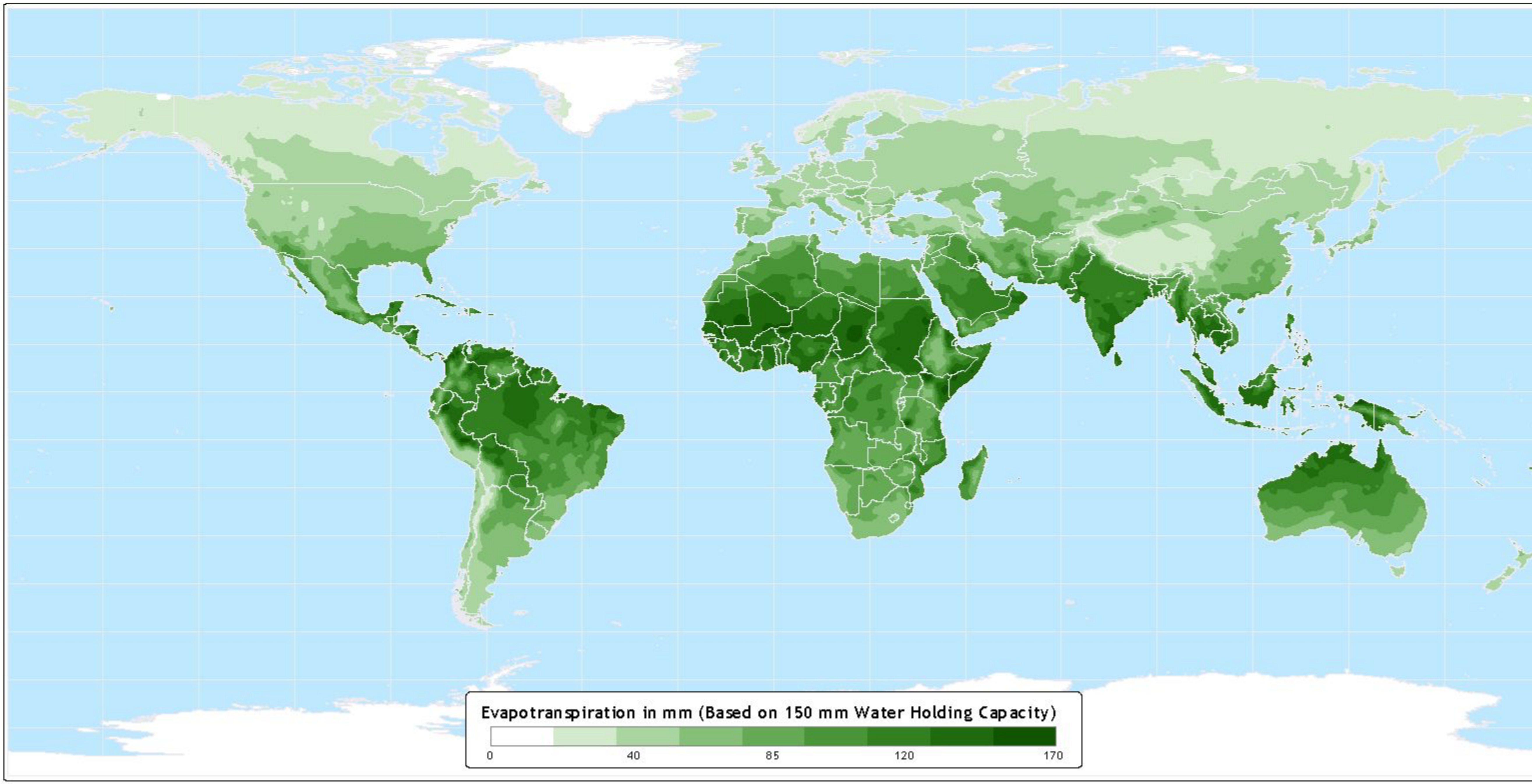


Figure 6 - Effect of rainfall events on the soil CO_2 efflux emission. The precipitation did not change the mean CO_2 emission, but the emission had a slight effect on the soil respiration, followed by soil temperature decrease for the SHF forest from Campina Reserve. In days of year (DOY) from 249-255 of 2007.

Processes between the forest and the atmosphere



Potential Evapotranspiration



Data taken from: Willmott and Matsuura (2001)

Atlas of the Biosphere

Center for Sustainability and the Global Environment
University of Wisconsin - Madison

Some more numbers…

Most of the evaporation of moisture comes from the oceans, lakes and rivers! ~60%

Few is directly sublimated from ice caps, snow and glaciers.

Plant's evapotranspiration makes about 40% annual (summer only 50%, global land cover 30%!)

Forests evapotranspiration is double than that of crops or water bodies!

Soils contain only a tiny fraction of the global water resource (~0.01%)

Water cycle

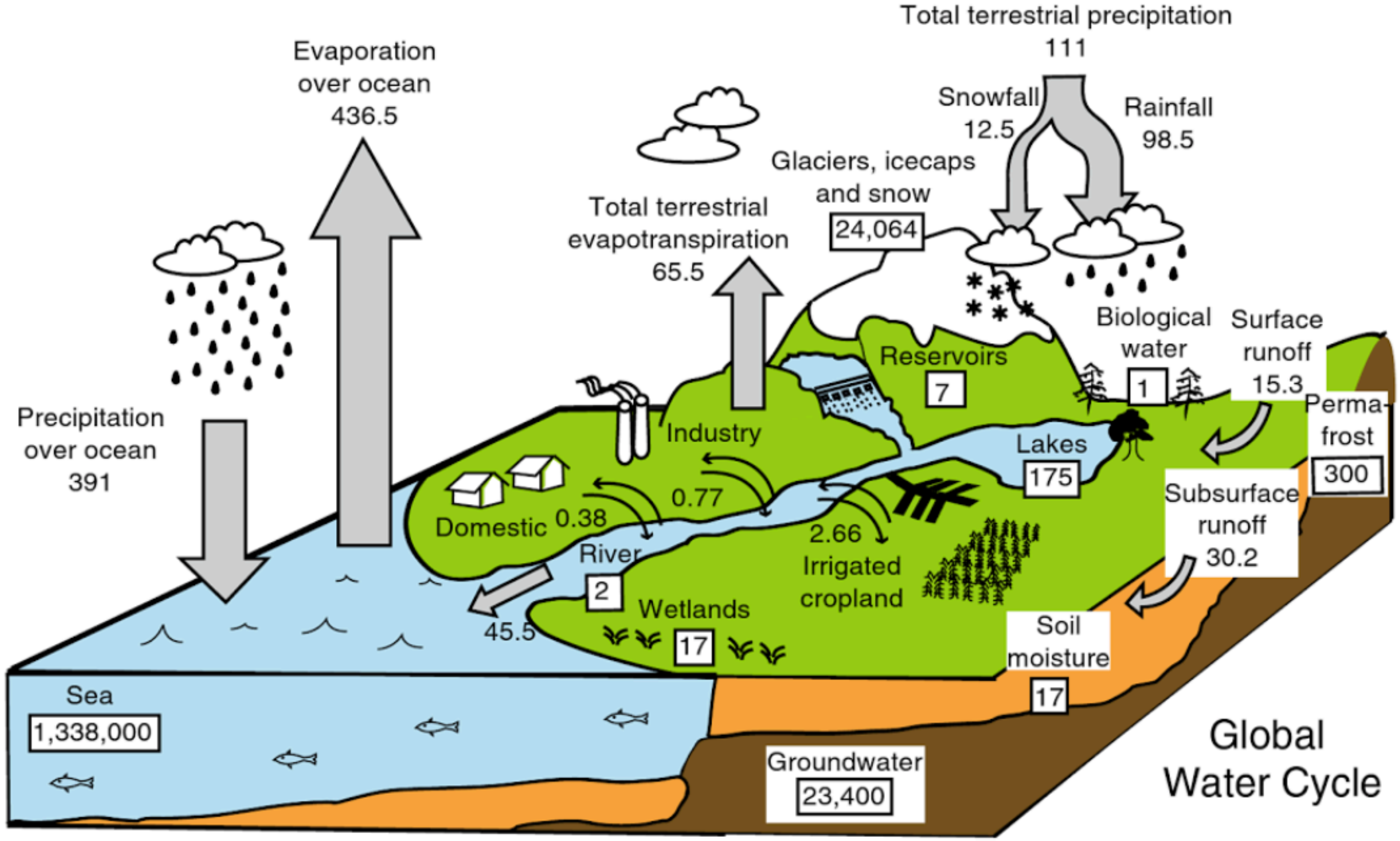


Fig. 14.3 The global water cycle, showing approximate magnitudes of the major pools (1,000 km^3; *boxes*) and fluxes (1,000 km^3 year^{-1}; *arrows*). Most water is in the ocean, ice, and groundwater, where it is not directly accessible to terrestrial organisms. The major water fluxes are precipitation, evapotranspiration, and runoff. Modified from Carpenter and Biggs (2009)

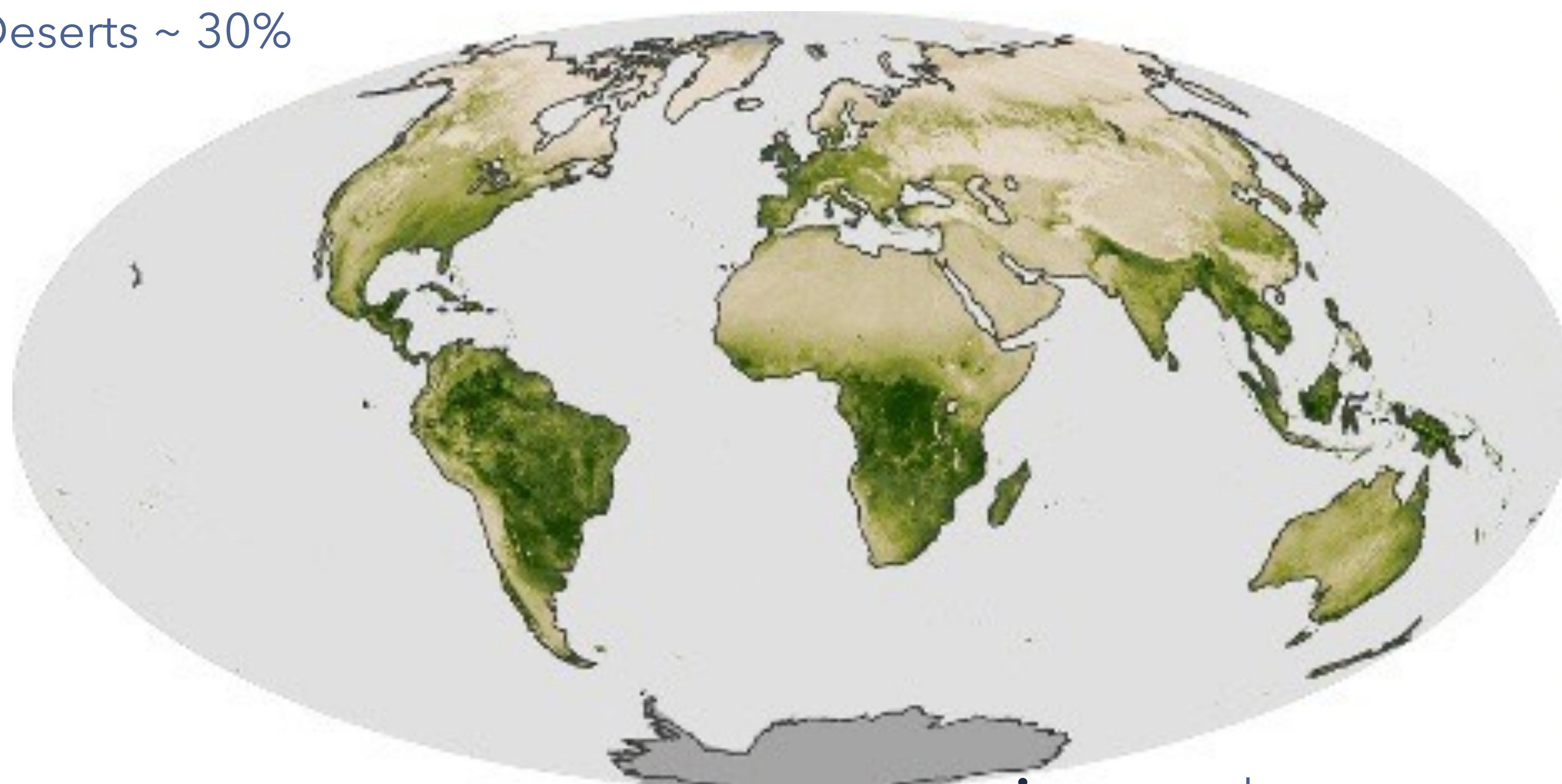
Principles of Terrestrial Ecosystem Ecology
By F Stuart Chapin III, Pamela A. Matson, Peter Vitousek

Active and passive processes

Land surface ~ 30%

- Rain/temp. forest ~ 14%
- Boreal forest (Taiga) ~ 17%
- Agricultural land ~39%
- Deserts ~ 30%

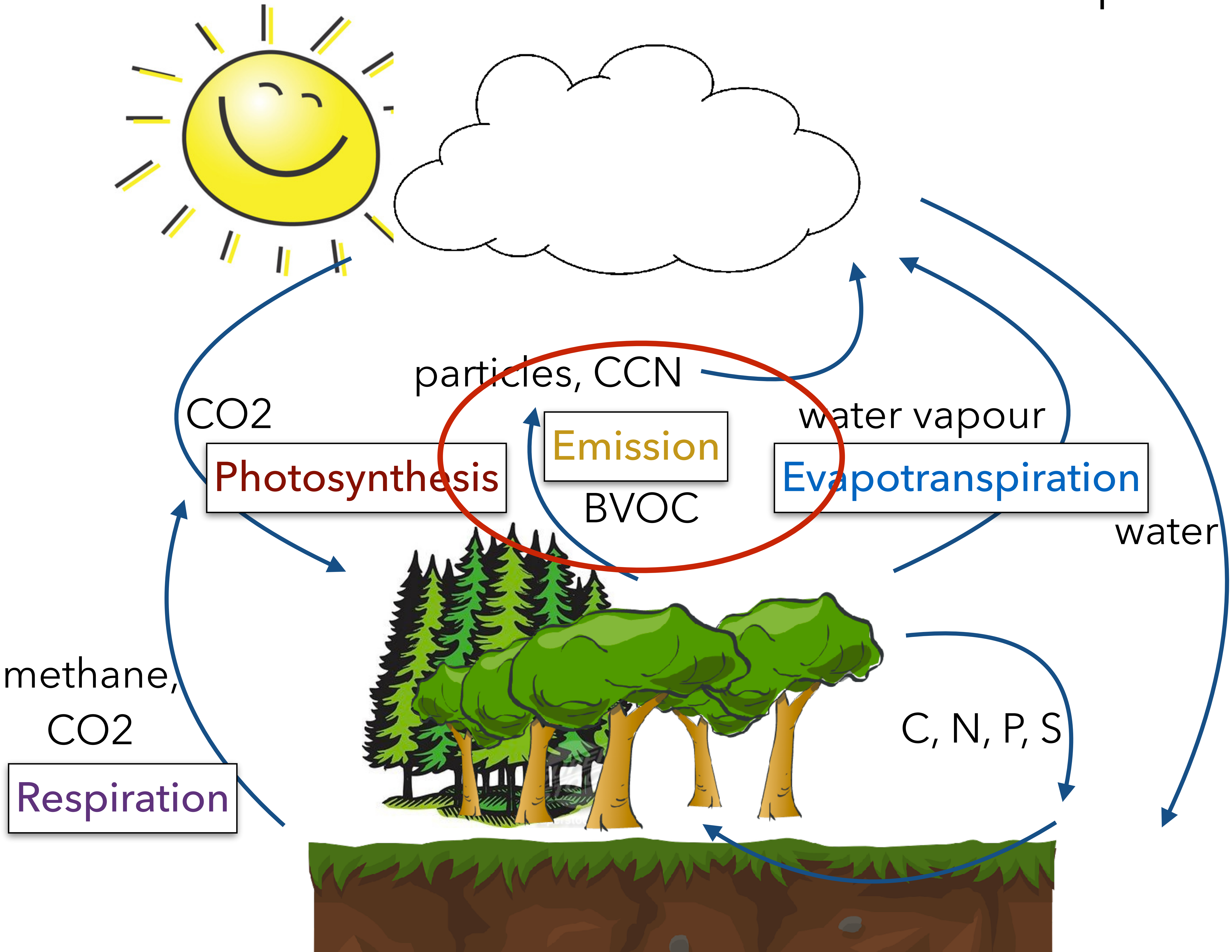
active control on water vapour and carbon by plants --> **FORCING**



Ocean surface ~ 70%

passive control on water vapour and carbon --> **FEEDBACK**

Processes between the forest and the atmosphere



Hydrocarbons and volatile organic compounds

Fossil fuels

Hydrocarbon = ‘hydro(gen)’ (H) + ‘carbon’ (C)

Alcohol (ethanol)

formaldehyde

β-carotine

pesticides

terpenes

methane

Peroxy Acetyl Nitrate (PAN)

pinic acid

Vitamin A

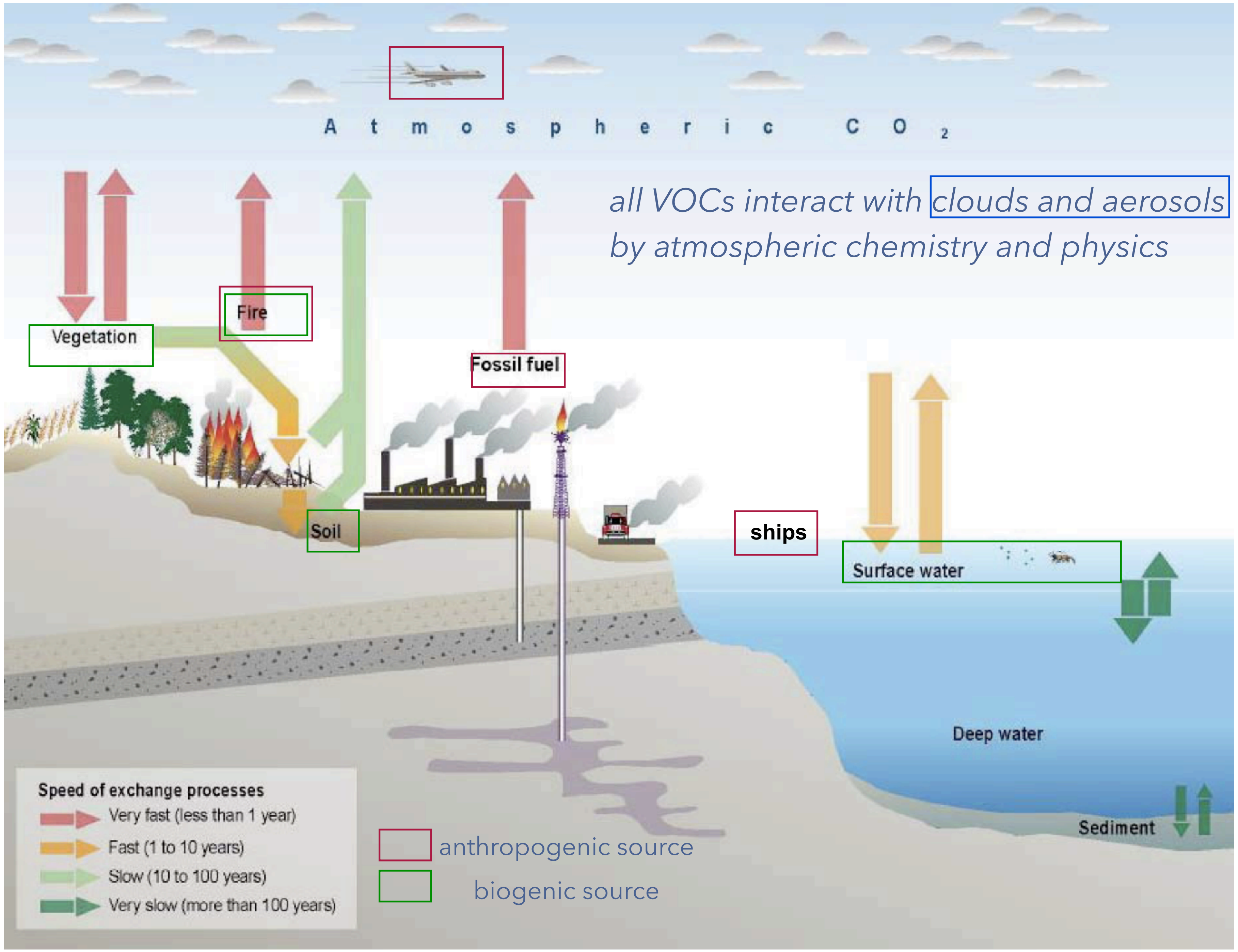
α-pinene

benzene

Organic compound = hydrocarbon (+ further species: nitrogen (N), oxygen (O), sulphur (S) etc).

Occurrence: in living matter and the exchanged gases

Sources of VOC

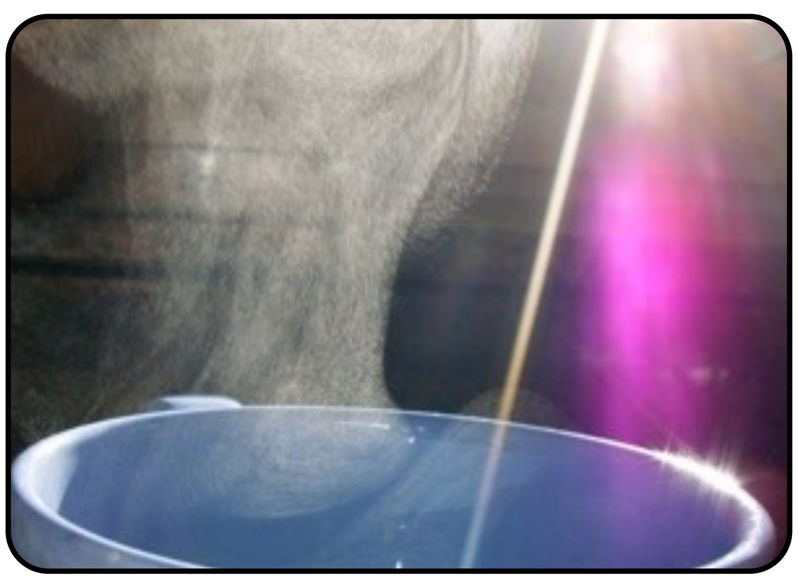


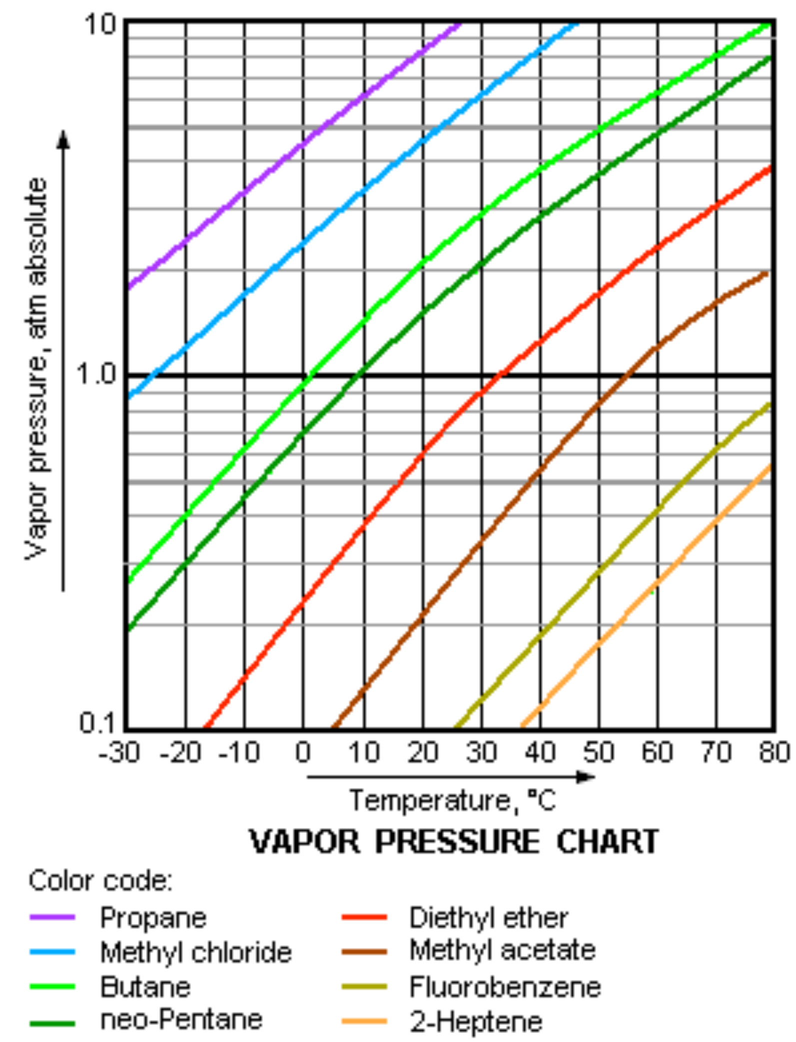
Source: modified http://www.defra.gov.uk/environment/airquality/publications/airqual-climatechange/pdf/chapter02.pdf

What is volatility?

From thermodynamics:

volatility is a measure of the tendency to vaporize!





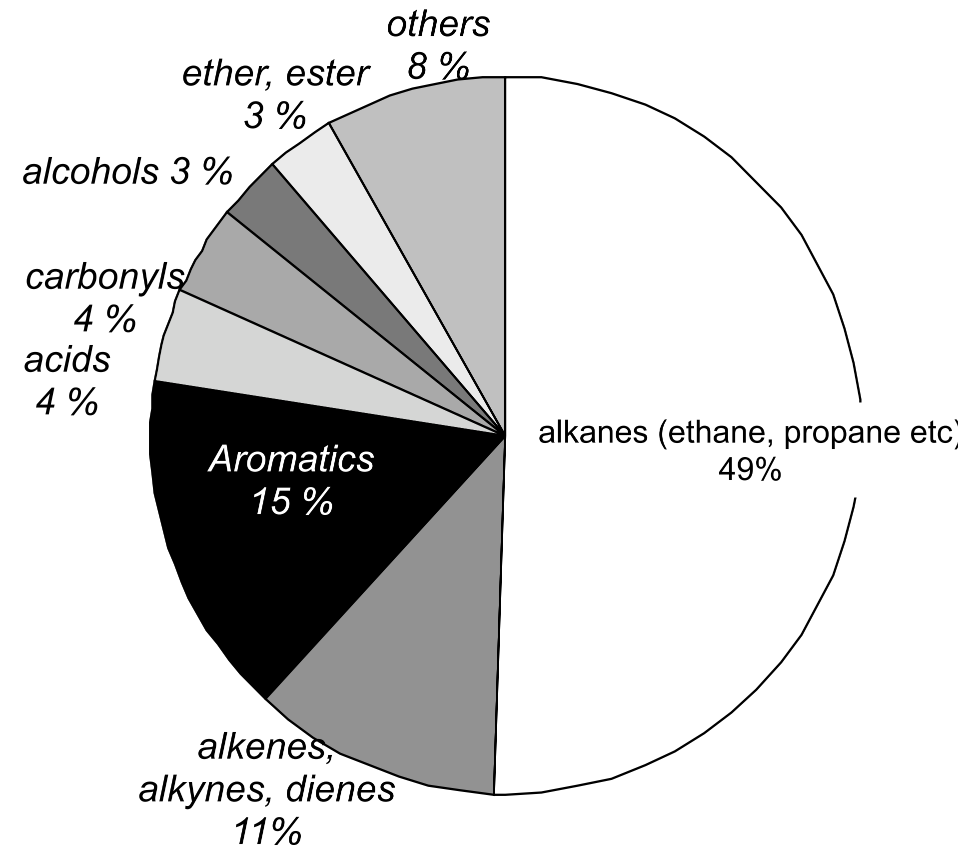
Anthropogenic VOC

Total sum

100-200 Tg Carbon yr^{-1}

Aromatics only

20 Tg Carbon yr^{-1}

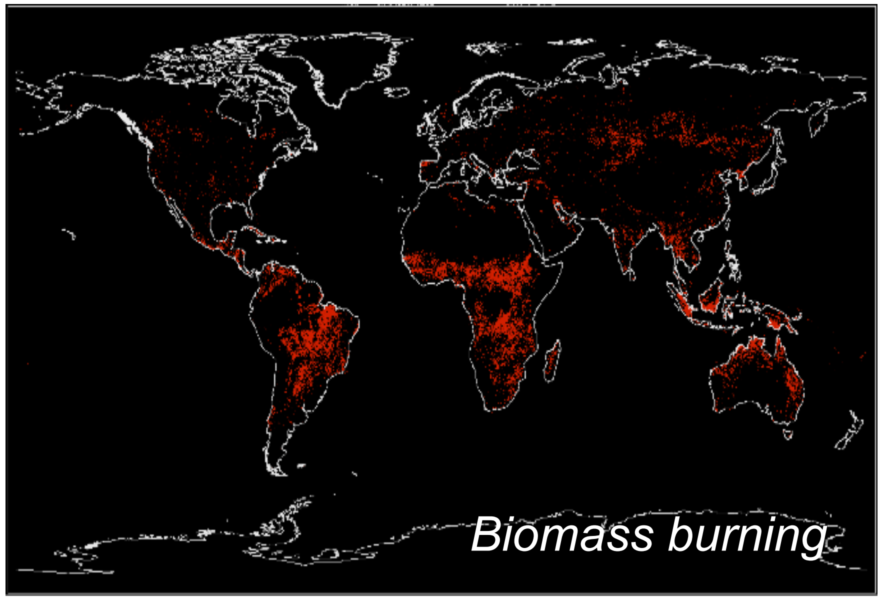


IPCC (2001)

Sources of anthropogenic VOC

traffic

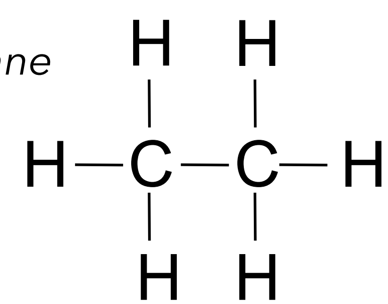
Solvents e.g. in: nail polish, parfumes, printer cart-ridges, tapes, advertisement prod.

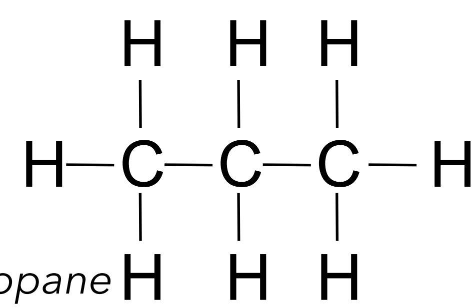


Anthropogenic alkanes

Saturated hydrocarbons (C_xH_y) excluding methane, emitted from all sources shown.

ethane





propane

…

Atmospheric fate

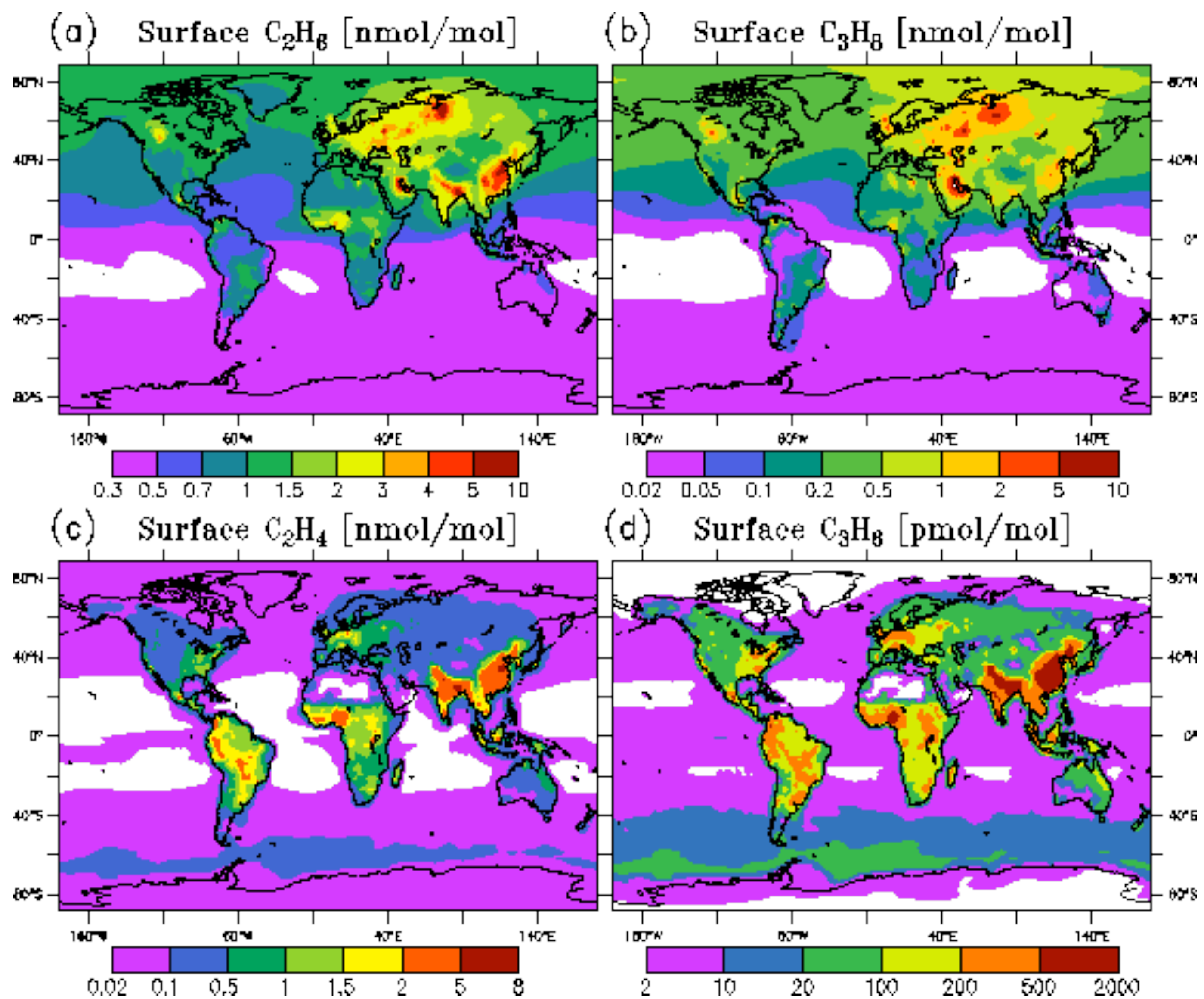
reacts only with OH, but slow (k_{OH}(198K)=2.55 x 10^{-13} cm^3 $molecule^{-1}$ s^{-1}

Long lived (days - months) ethane = 2.7 months, propane = 28 days

Global distribution of surface ethane and propane

Summer

Winter



von Kuhlmann, 2002

The simulation clearly shows the hot spots at metropolitan areas, industries, harbours, oil refineries and the transportation pattern of the long lived gases

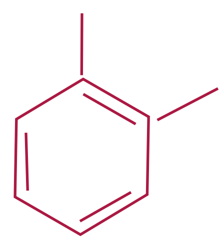
More anthropogenic VOC

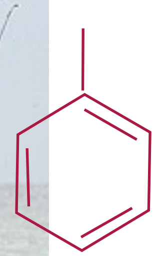
The gases you inhale in cities behind a vehicle.

Emitted by fossil fuel combustion and biomass burning

Benzene

Xylene

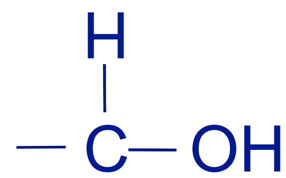




Toluene

- *reaction with OH (and O_3 for styrene)*
- *short live times (1h-2d)*
- *local air pollution*
- *aerosol formation*

Anthropogenic water soluble VOC



formic acid
ethanol (wine, beer etc)
formaldehyde (HCHO)
acetone

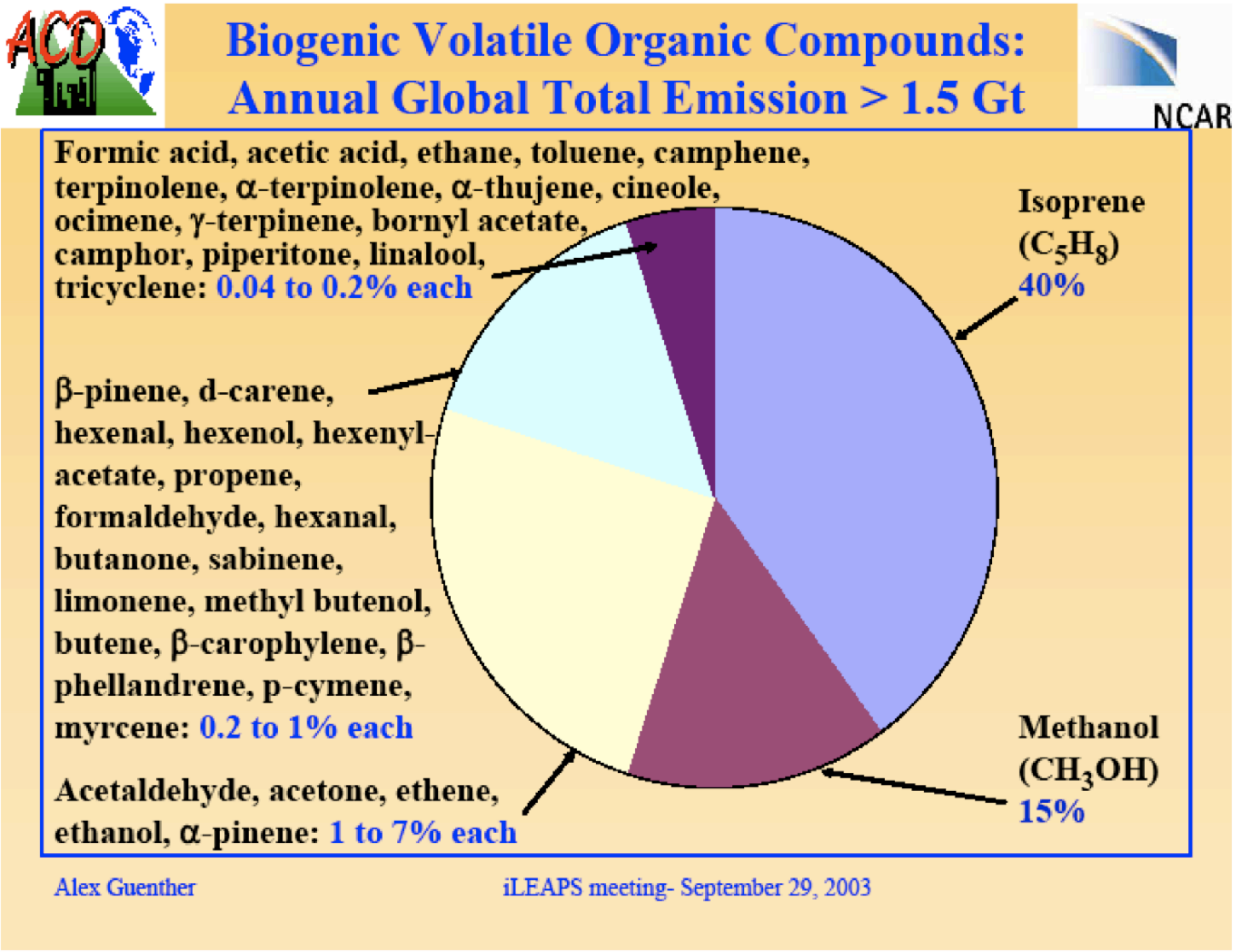
Atmospheric chemical lifetime

long, more than 3 days up to months!
(Exception Aldehydes, some hours)

Main sink are clouds and wash out!

Long range transport!

Global biogenic VOC = BVOC



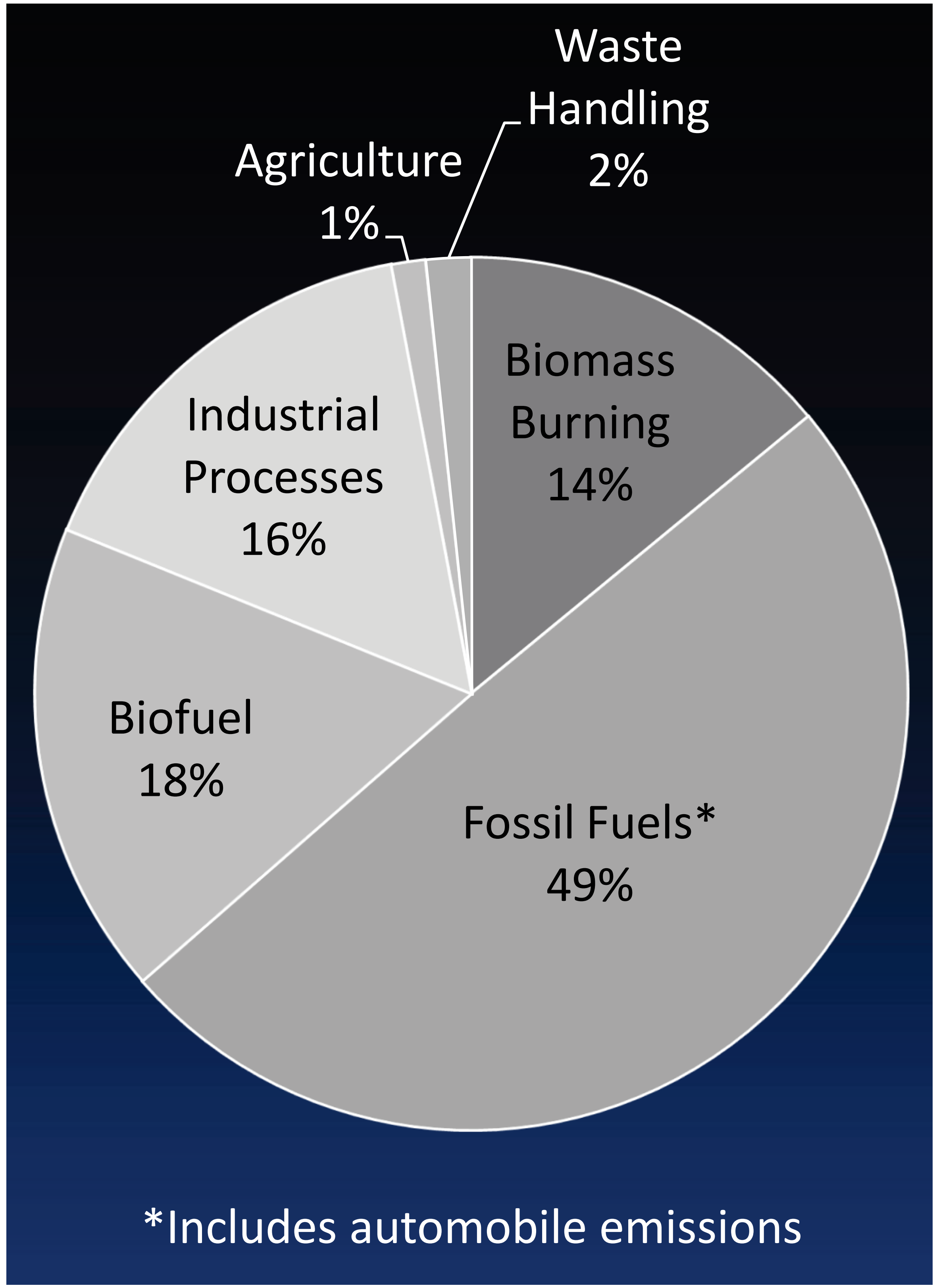
BVOC vs anthropogenic VOC

90 Tg year^{-1}

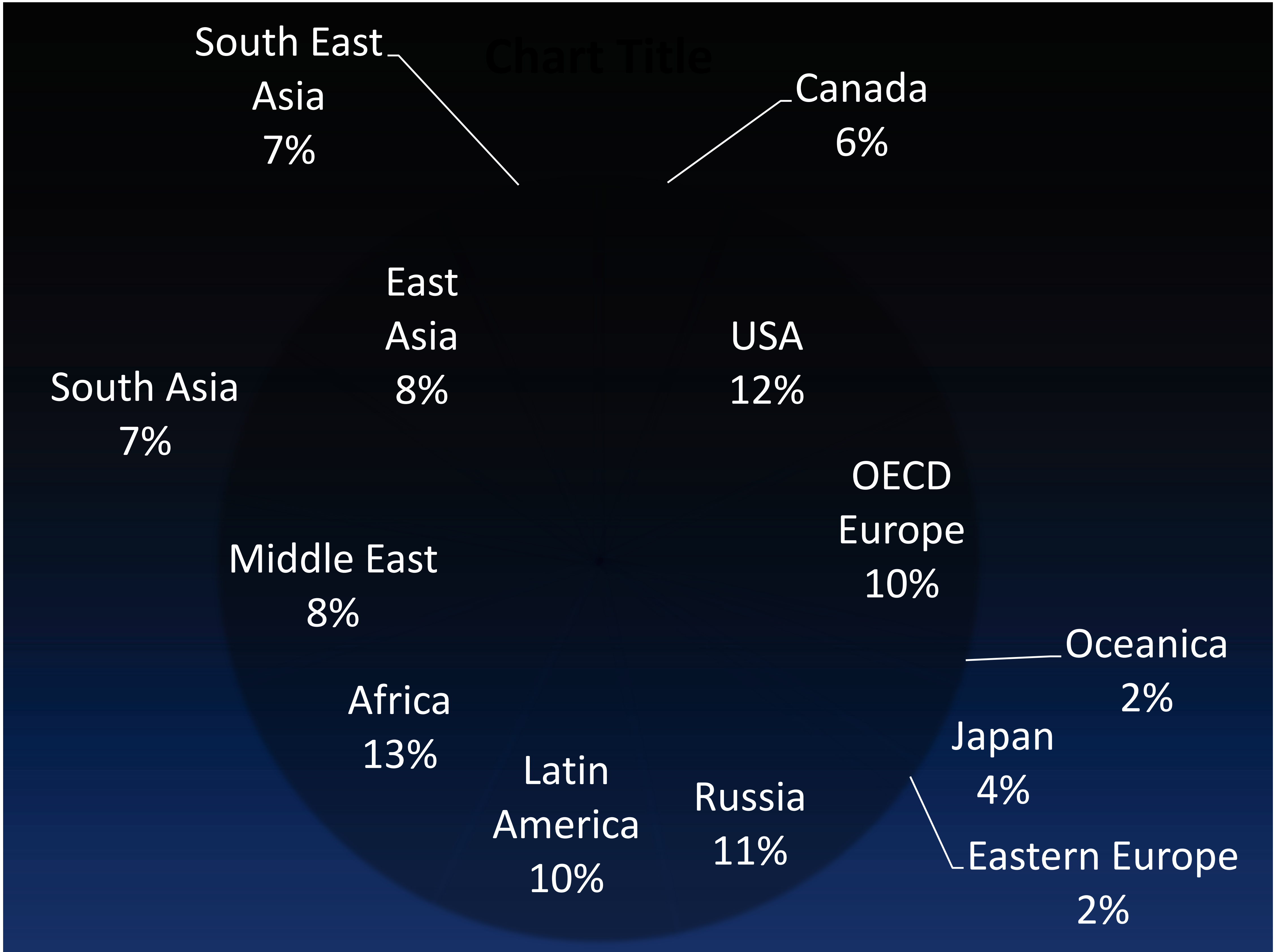
760 Tg year^{-1}

These numbers come from 2014!

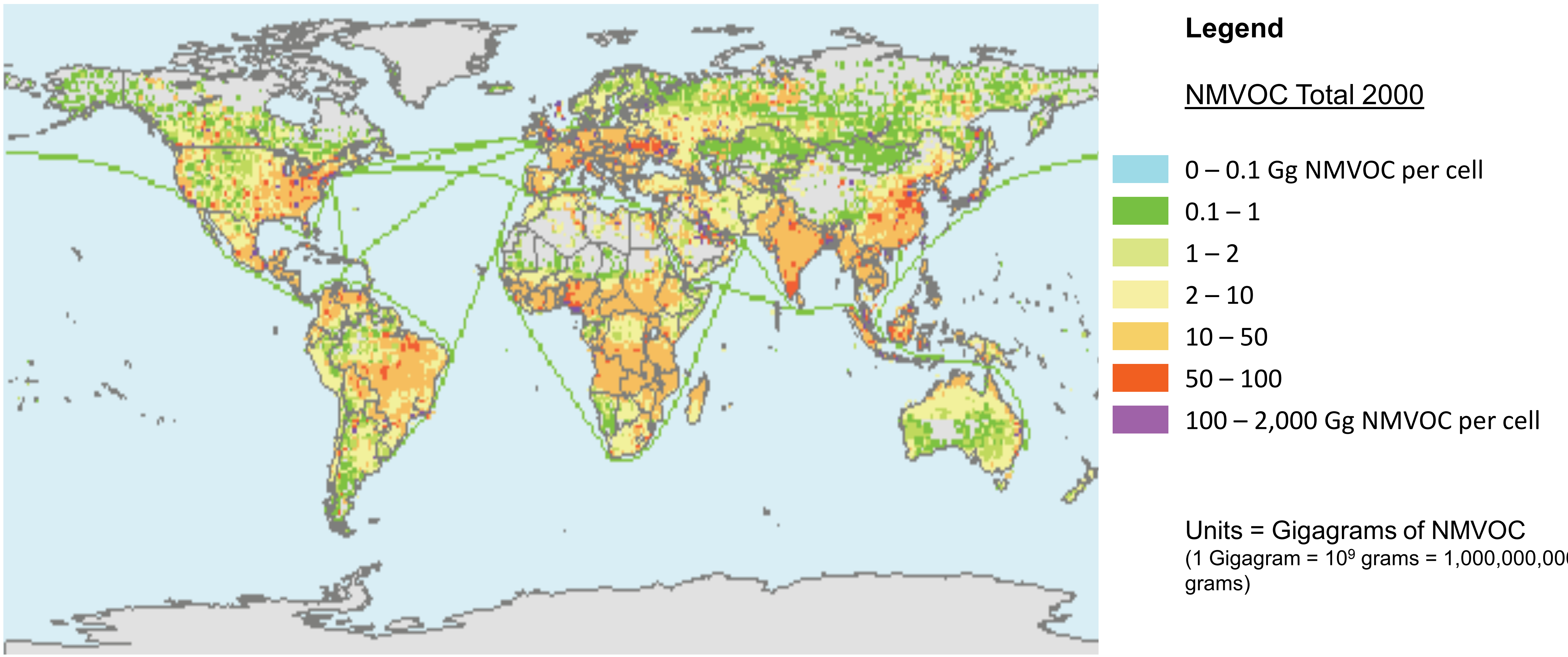
Breakdown of global anthropogenic sources



Anthropogenic VOC emission per region

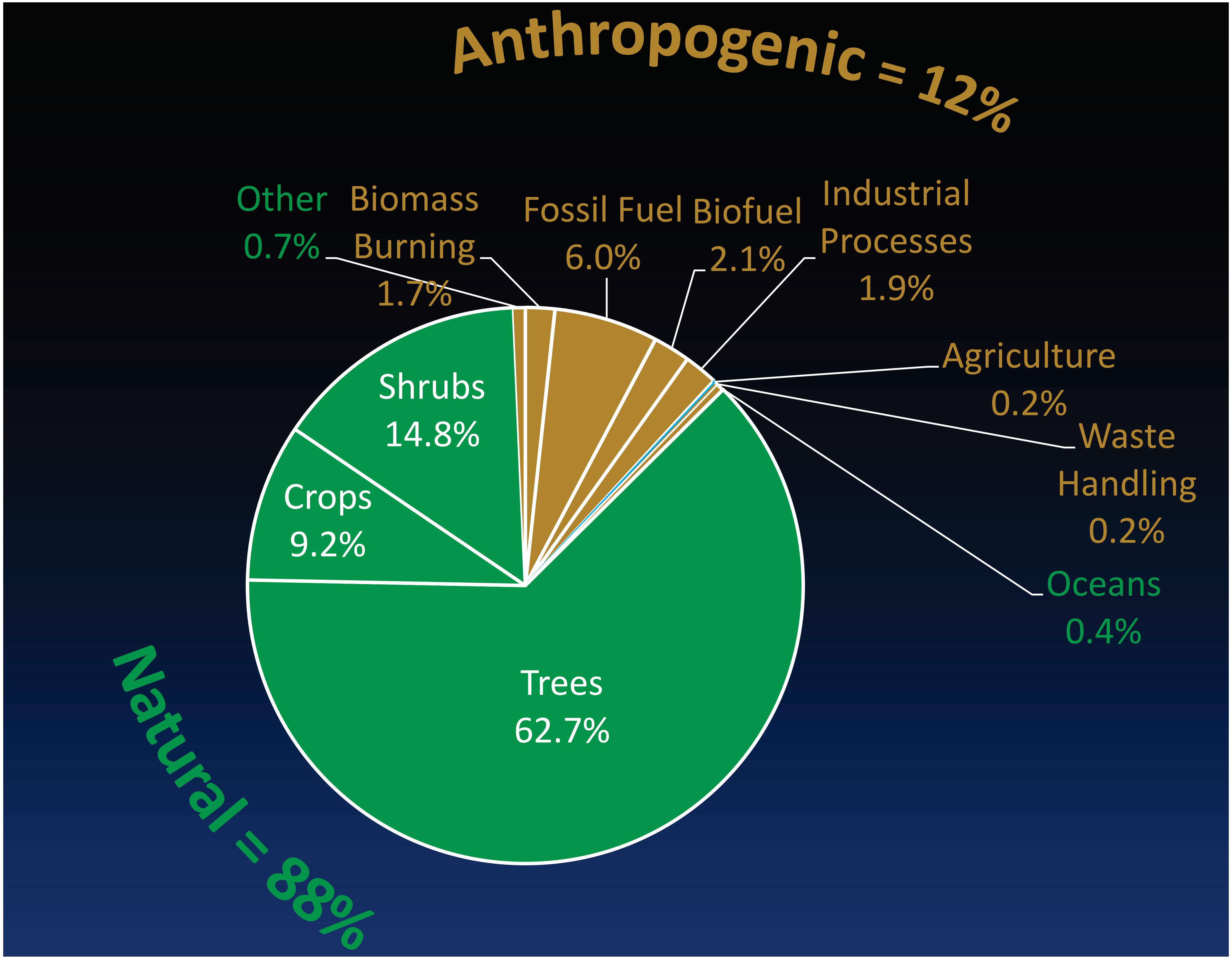


Non-methane VOC emission density

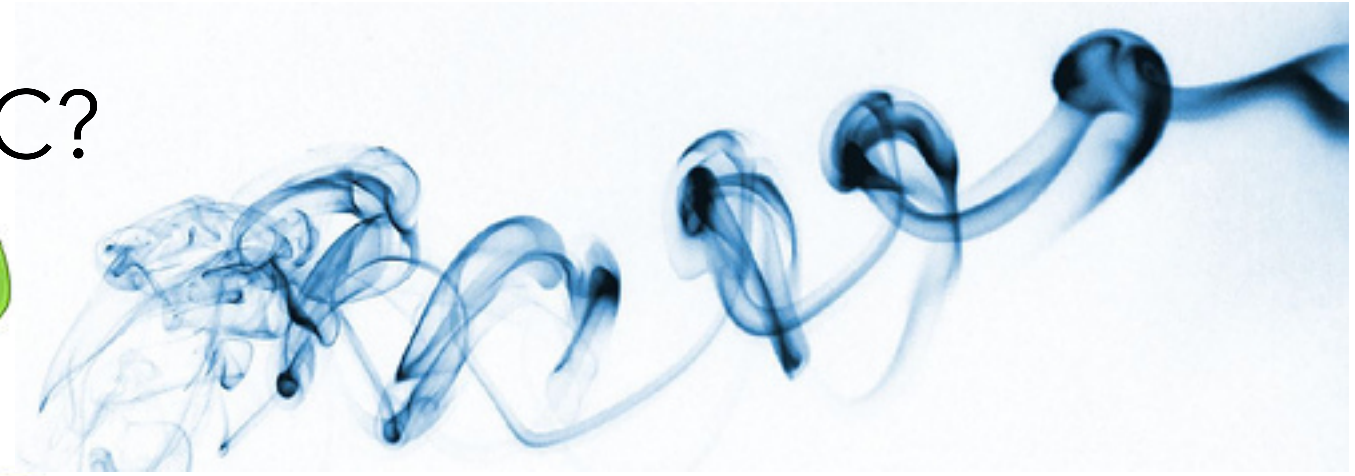


Methane (~572 Tg/yr) is a source that needs to be handled separately!

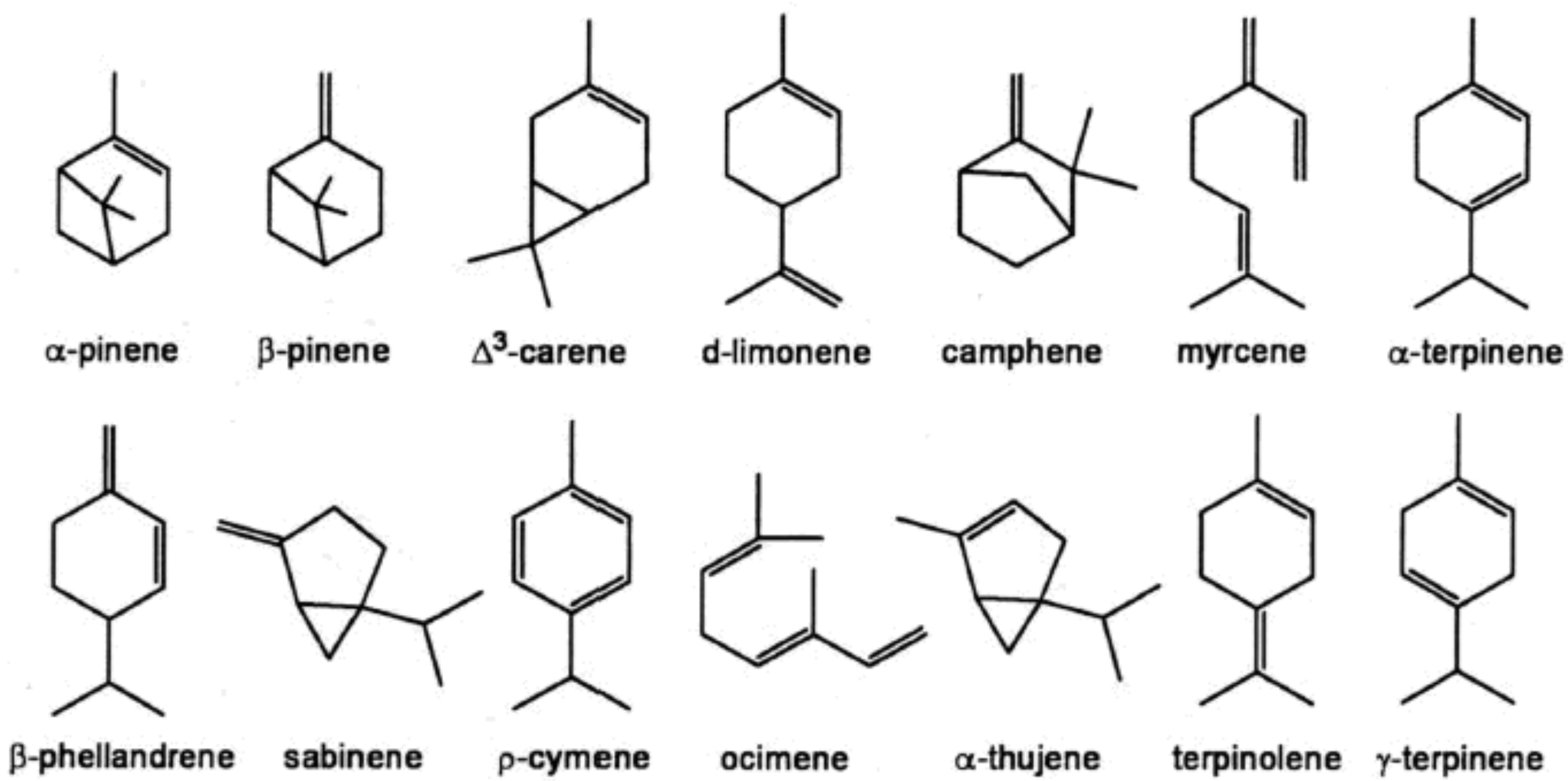
Emission sources



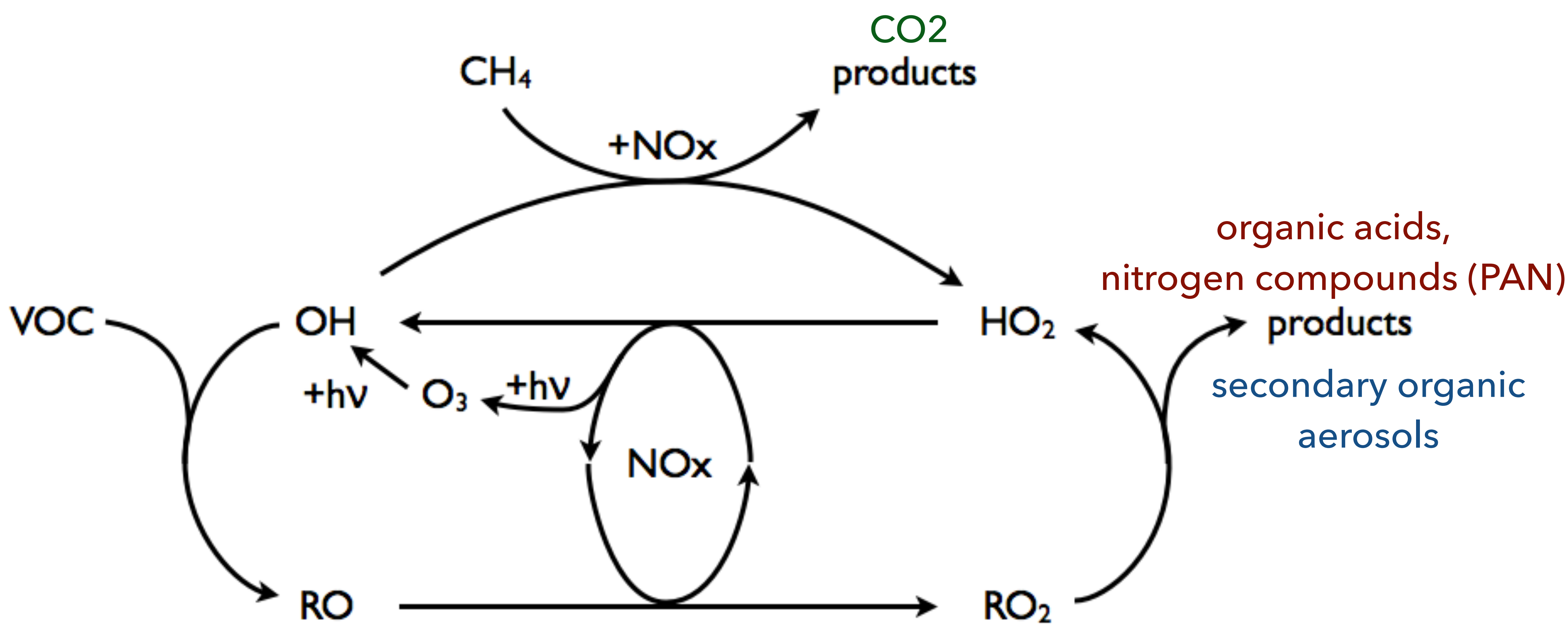
What is a BVOC?



Different plants emit so called
Volatile organic compounds = VOC
as they are originated from biological organism
they are called
Biogenic volatile organic compound = BVOC



The role of BVOC in atmospheric processes



-volatiles are originated mostly from natural sources (~650 GT/yr vs ~50 GT/yr man made, 2000)

-tropospheric ozone and hydroxyl radicals formed by sunlight and the processes above

-nitrogen oxides are mostly originated from burning processes, large fraction man-made

BVOC fate after emission

+hν

B) Oxidation

C) Cloud interactions (uptake, reactions)

+OH

+Ozone

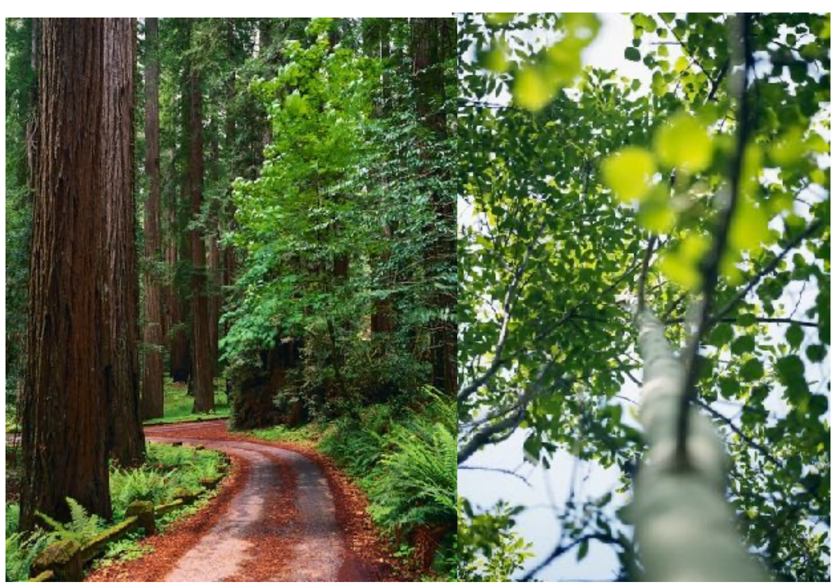
VOC

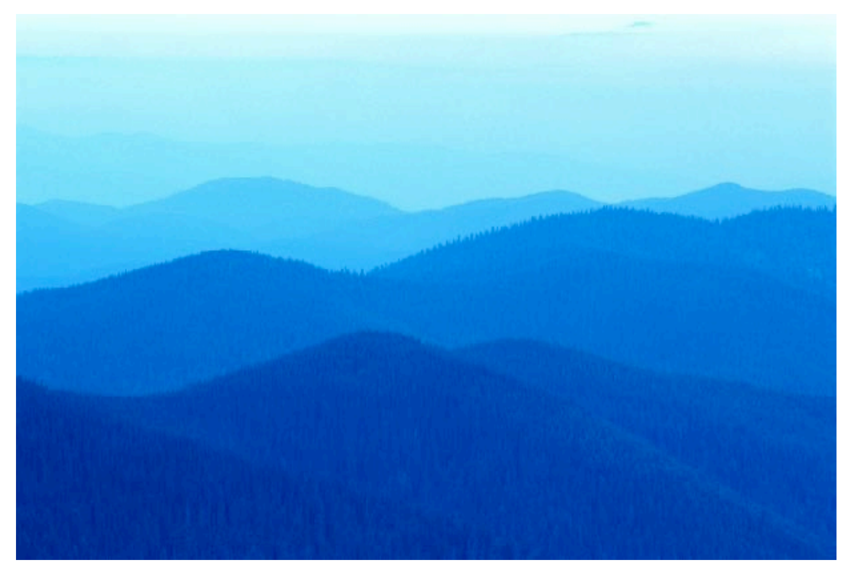
$+NO_3$

Transport

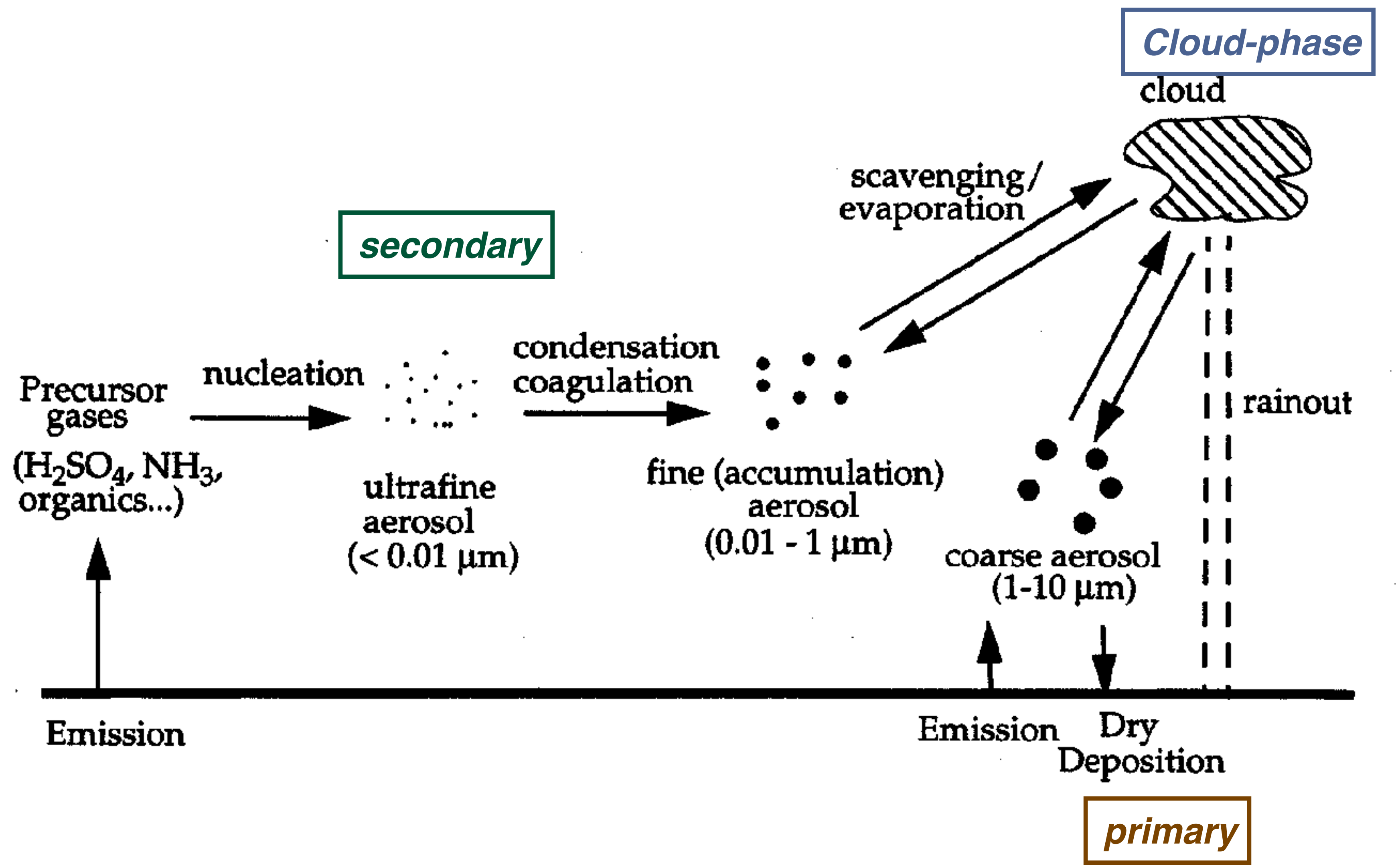
A) Emission

D) Aerosol formation





Short overview on aerosol effects



Environmental importance: health (respiration), visibility, radiative balance, cloud formation, heterogeneous reactions, delivery of nutrients…

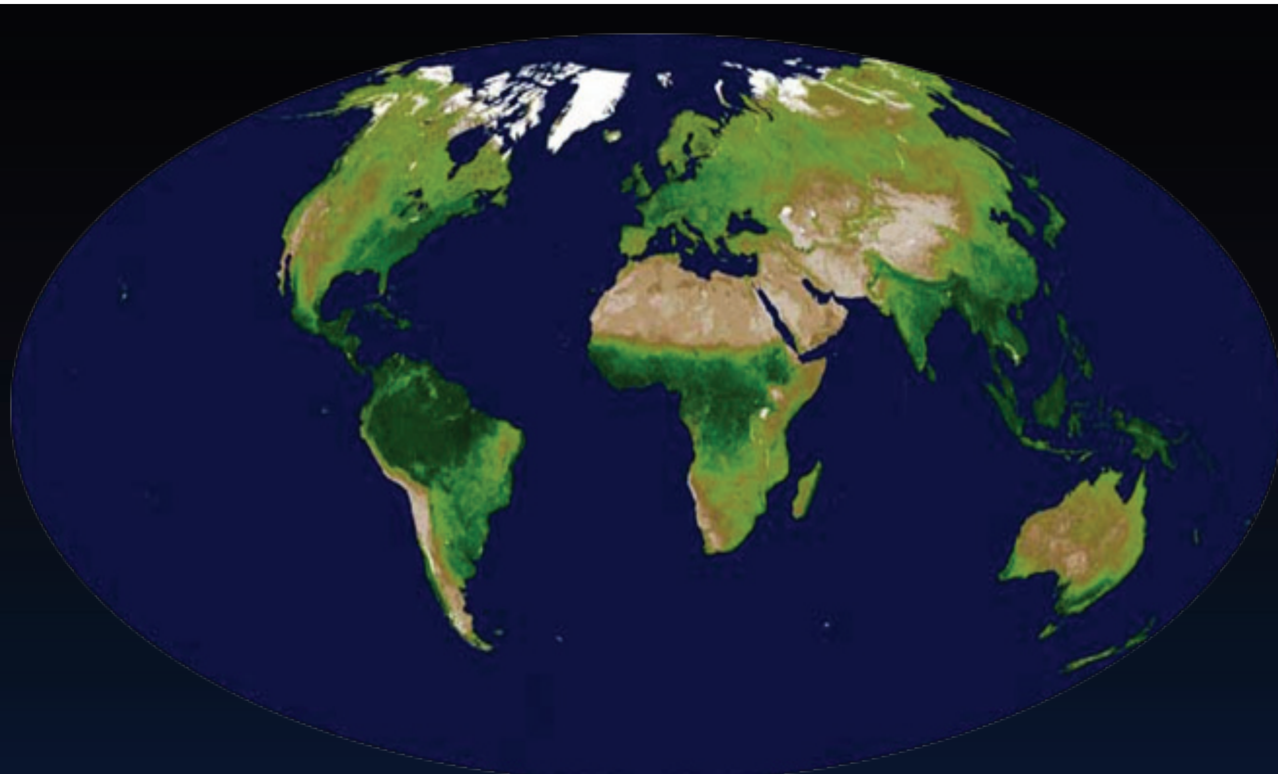
D.J. Jacob

Impact of plant originated BVOC emissions on visibility

(c) U.S. forest service (http://webcam.srs.fs.fed.us/tools/winhaze/)

If 88% are emitted from natural sources…

Why should we be concerned on that 12% fraction we emit ?



Natural vs. Anthropogenic

Natural sources are spread over the whole planet as the global forest cover indicates.

Anthropogenic sources are “concentrated” in areas where humans live. They form together with other pollutants unhealthy conditions.

Lecture