Principles of Radiative Transfer; Biosphere and Land surface Processes

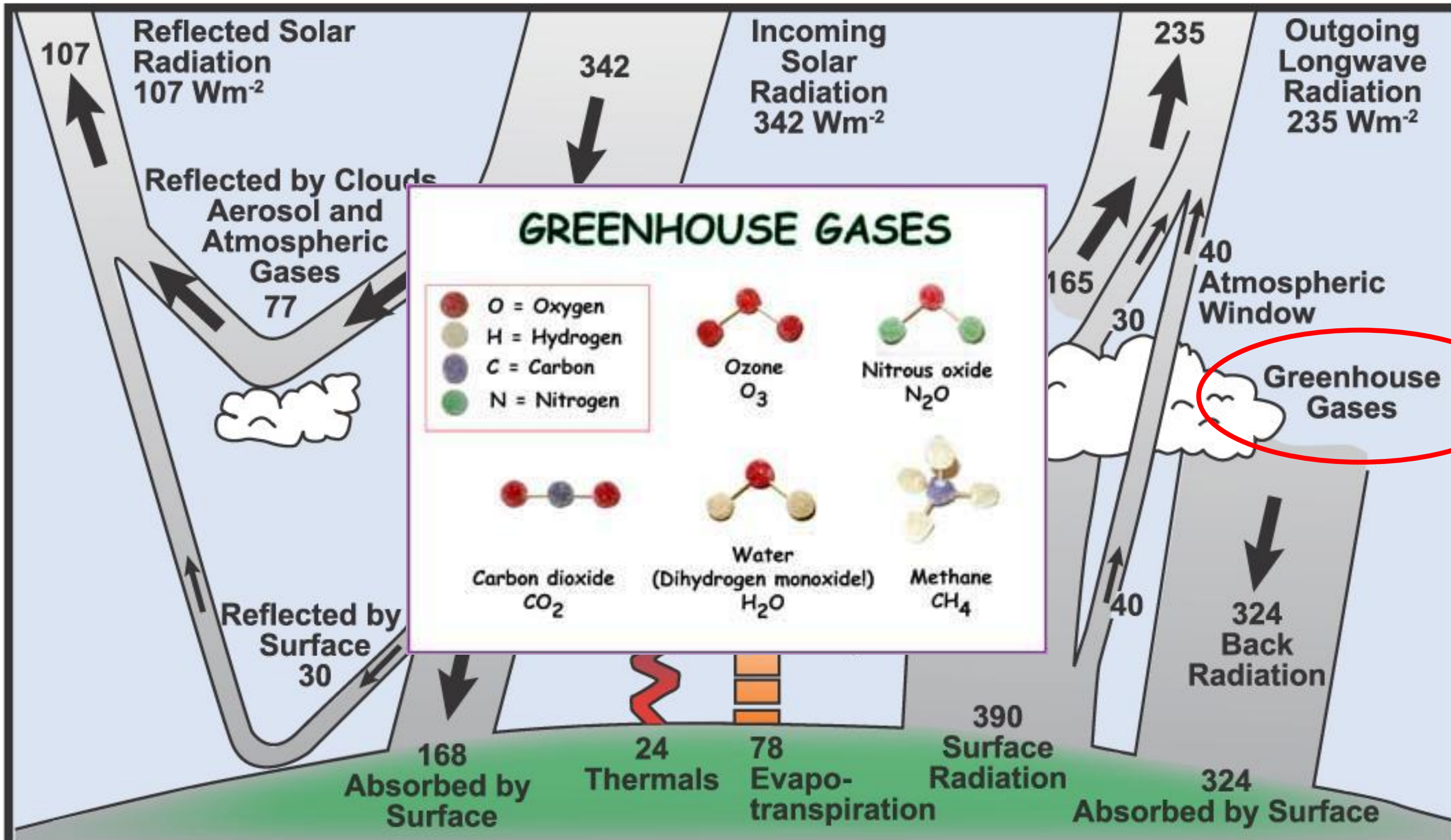
Joint IMD-WMO Group Fellowship Training on Numerical Weather Prediction

Pramit Kumar Deb Burman

Scientist C
pramit.cat@tropmet.res.in
Centre for Climate Change Research
Indian Institute of Tropical Meteorology Pune
Ministry of Earth Sciences,
Government of India
&
Department of Atmospheric and Space Sciences
Savitribai Phule Pune University
India

Earth’s energy

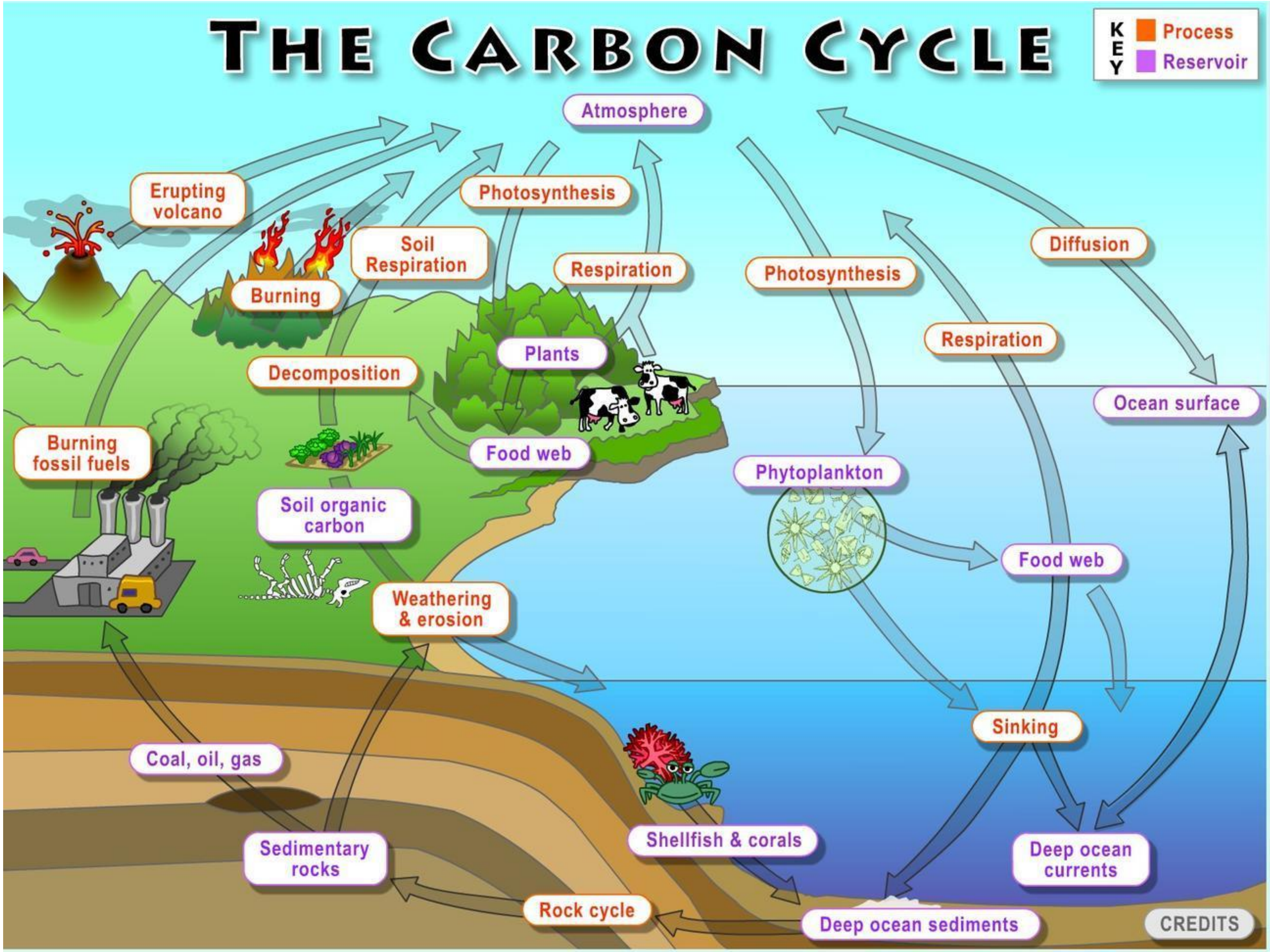
Source: IPCC



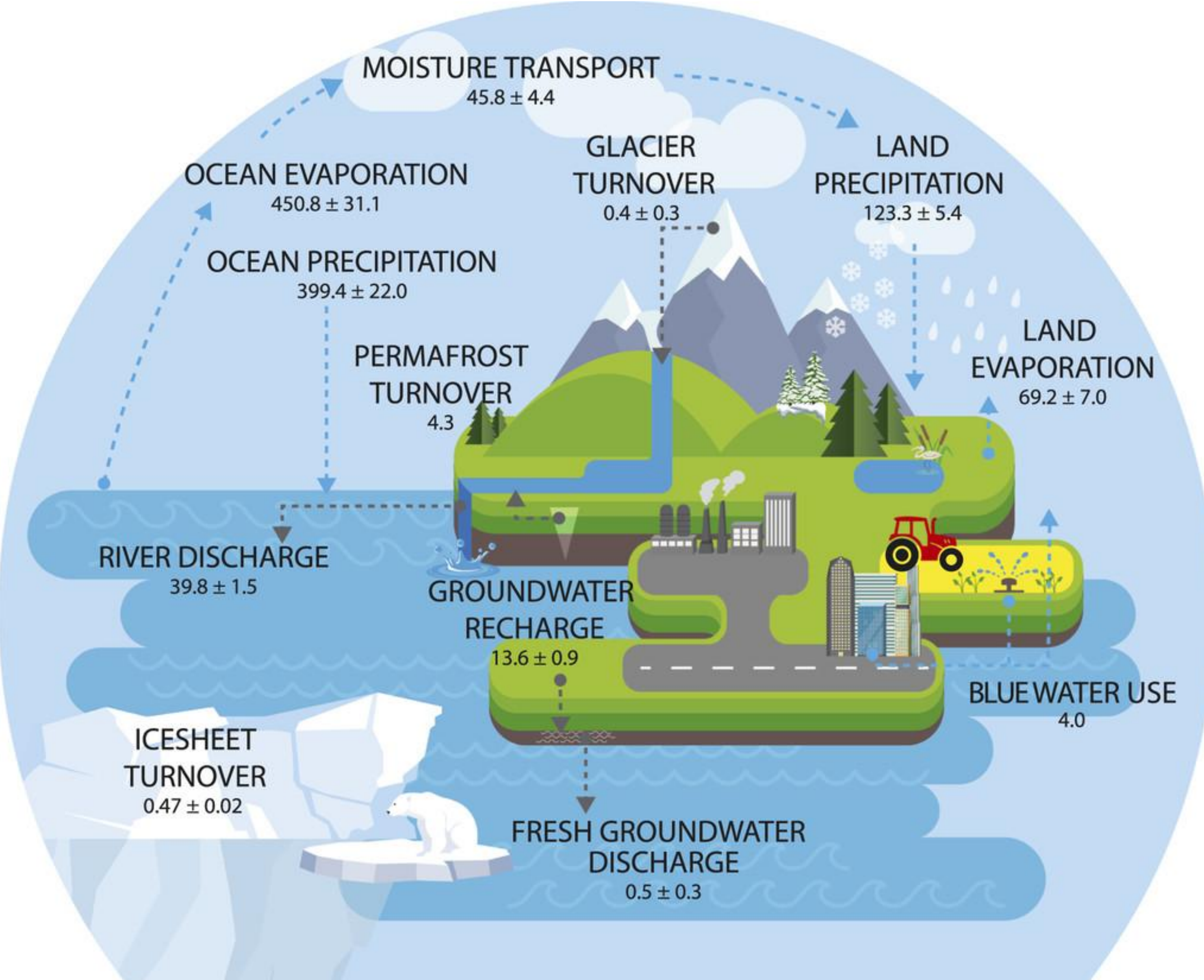
at surface the energy budget is,

$$R_n = R_{SW}(\text{in}) + R_{LW}(\text{in}) - R_{SW}(\text{out}) - R_{LW}(\text{out}),$$

$$R_n = H + LE + G.$$



Picture courtesy: www.cleanet.org

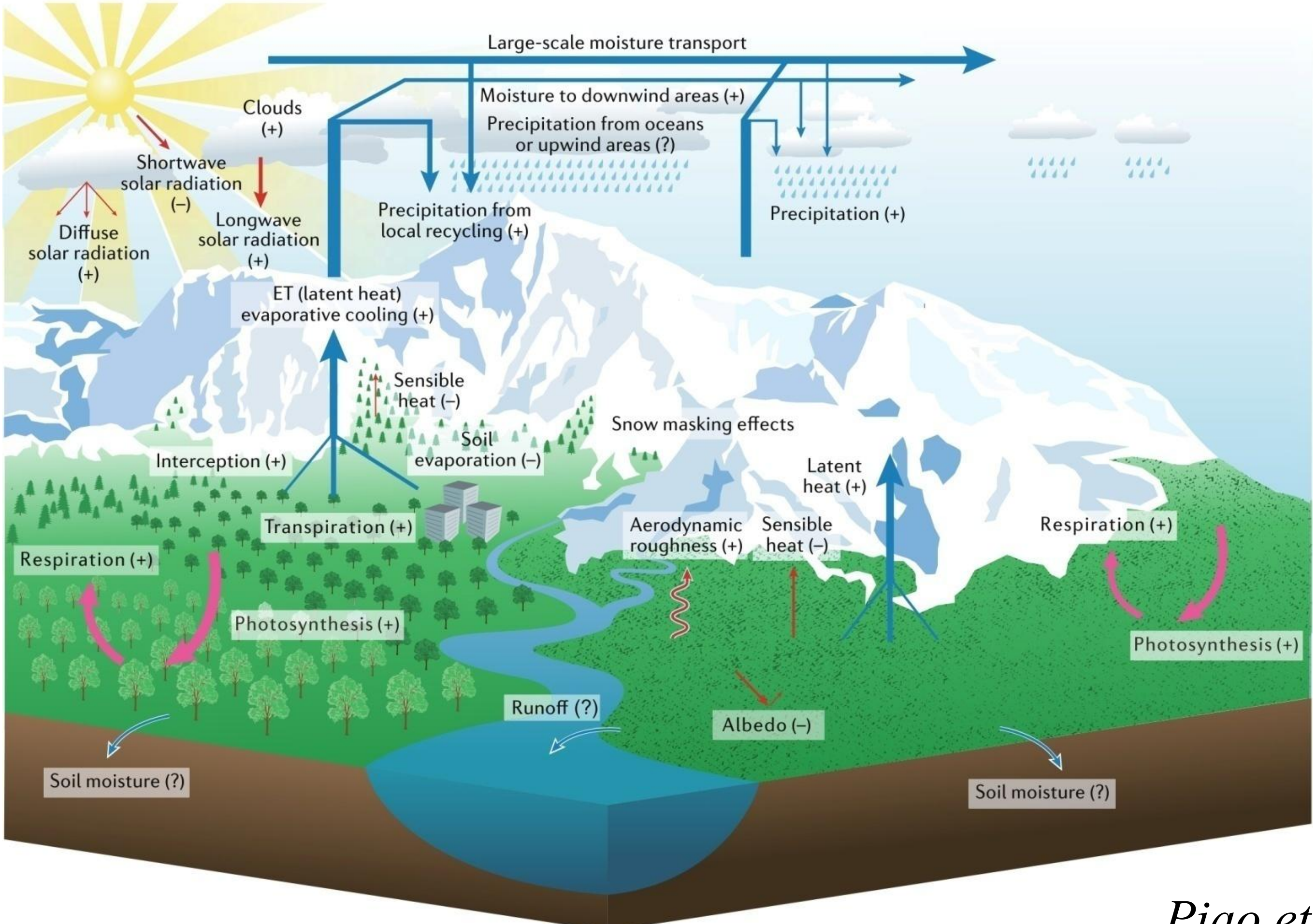


GLOBAL WATER CYCLE FLUXES

Dorigo et al., 2021, BAMS, 102, 10; 10.1175/BAMS-D-19-0316.1

vegetation-atmosphere feedback

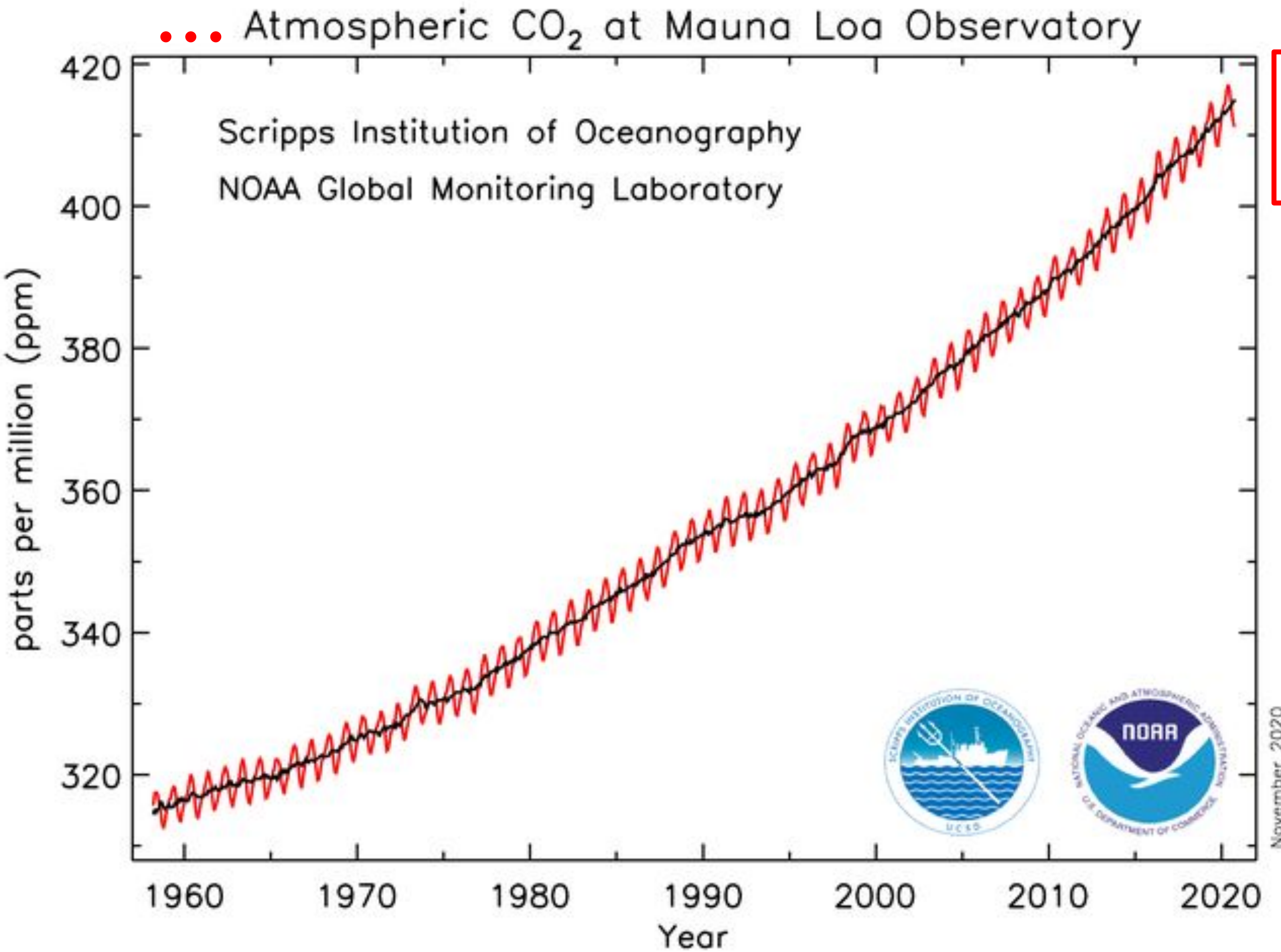
Schematic diagram showing how vegetation greening affects climate via land-atmosphere exchange of carbon, water and energy. For each process or flux, the symbols '–', '+' and '?' in brackets represent a decreasing, increasing and unknown trend, respectively, in response to vegetation greening. Vegetation greening cools global climate mainly through enhancing land carbon sink and evapotranspiration.



Piao et al., 2020

Increasing CO2 in the atmosphere

...

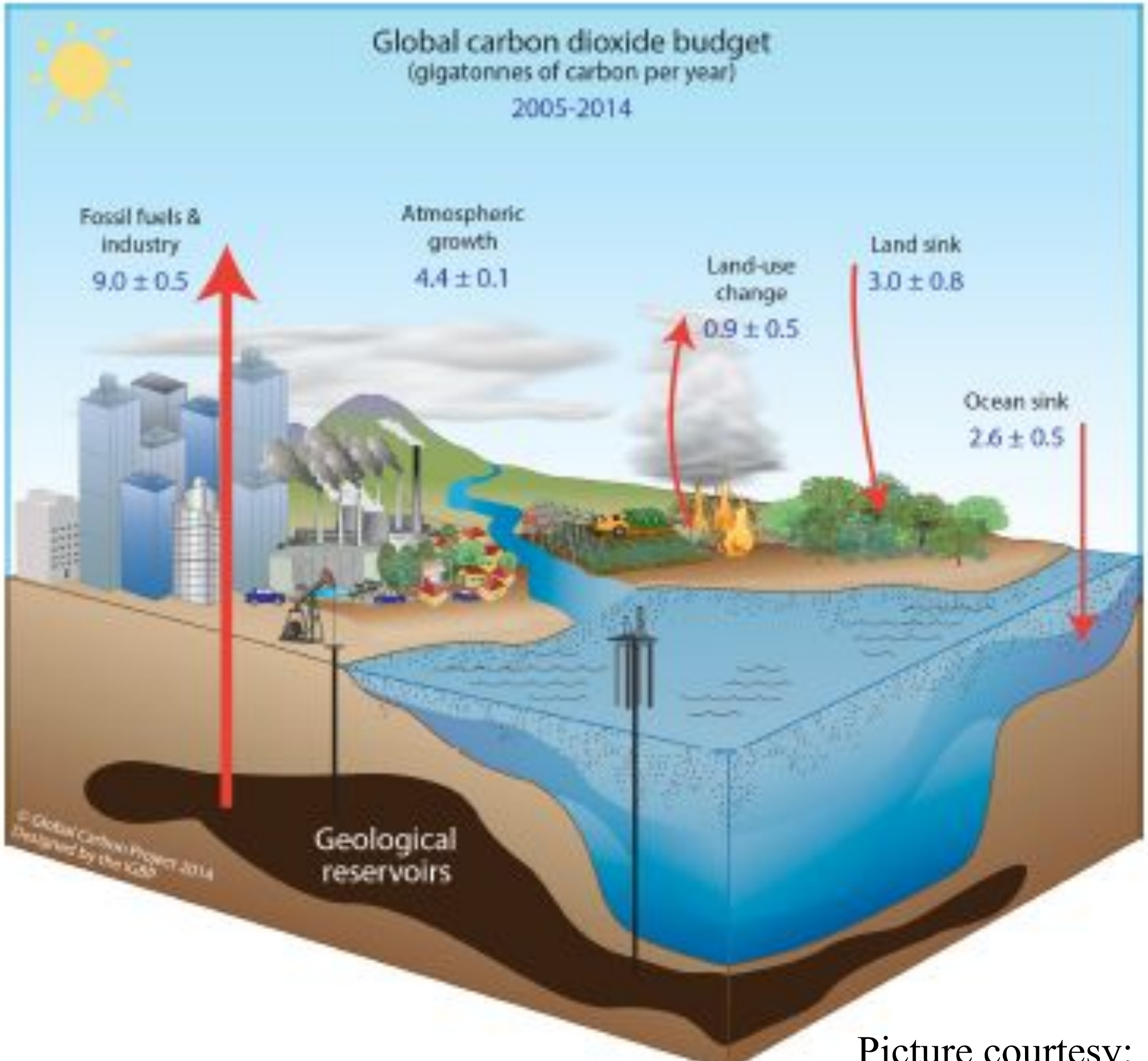


present day
~ 414 ppm

Source: [Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases (noaa.gov)]

pre-industrial
~ 280 ppm

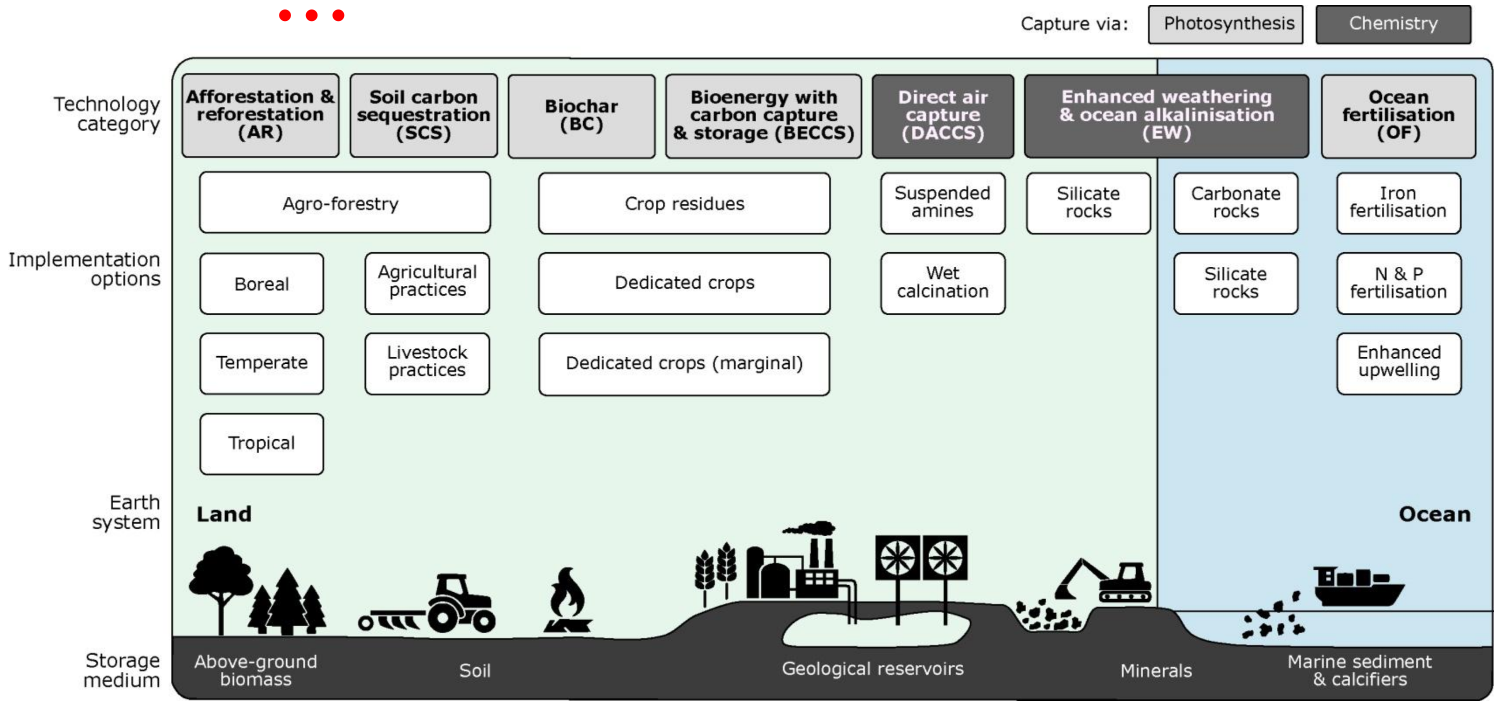
Why is it important to study ?



- ❖ Terrestrial Ecosystems are a major sink of atmospheric CO_2
- ❖ During 2009-2018, $S_{land} = 3.2 \pm 0.6$ GtC $yr^{-1} > S_{ocean} = 2.5 \pm 0.6$ GtC yr^{-1} (Friedlingstein et al., (2019))
- ❖ Paris climate accord: limit global warming to 2 ºC in the present century (Source: UNFCC)
- ❖ Proper accounting of carbon budgets are required to estimate the *intended nationally determined contribution* (INDC) and devise mitigation strategies

Picture courtesy: Le Quéré et al., (2015)

In the context of climate change …

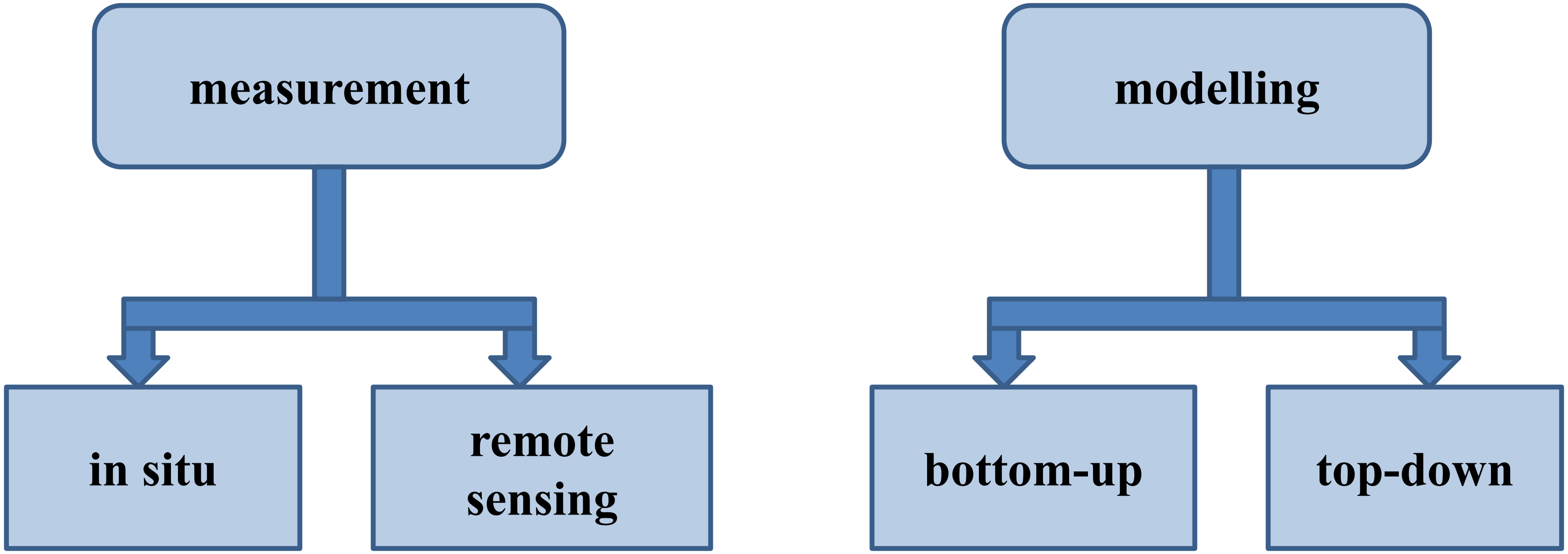


Several mitigation strategies are based on land

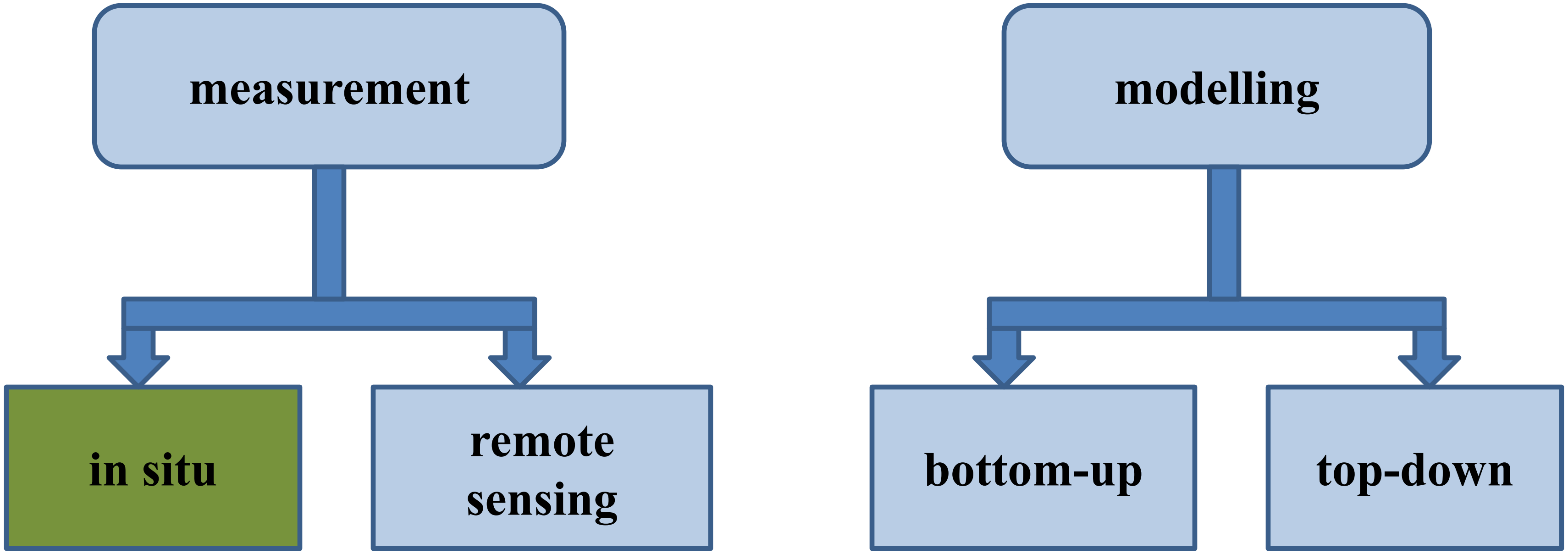
Picture courtesy : Minx et al., (2018)

- ❖ However, large-scale implementation can result in loss of biodiversity in terrestrial ecosystems, including coastal and wetland (IPBES report; Bongaarts, (2019)
- ❖ Climate change puts additional burden on terrestrial ecosystems, including food and fibre production to cater a growing population etc. in all SSPs (Shared Socio-economic Pathway) (IPCC Special Report on Climate Change and Land).
- ❖ Climate Change or Food Security?
- ❖ Fresh potable water resources are also heavily burdened.

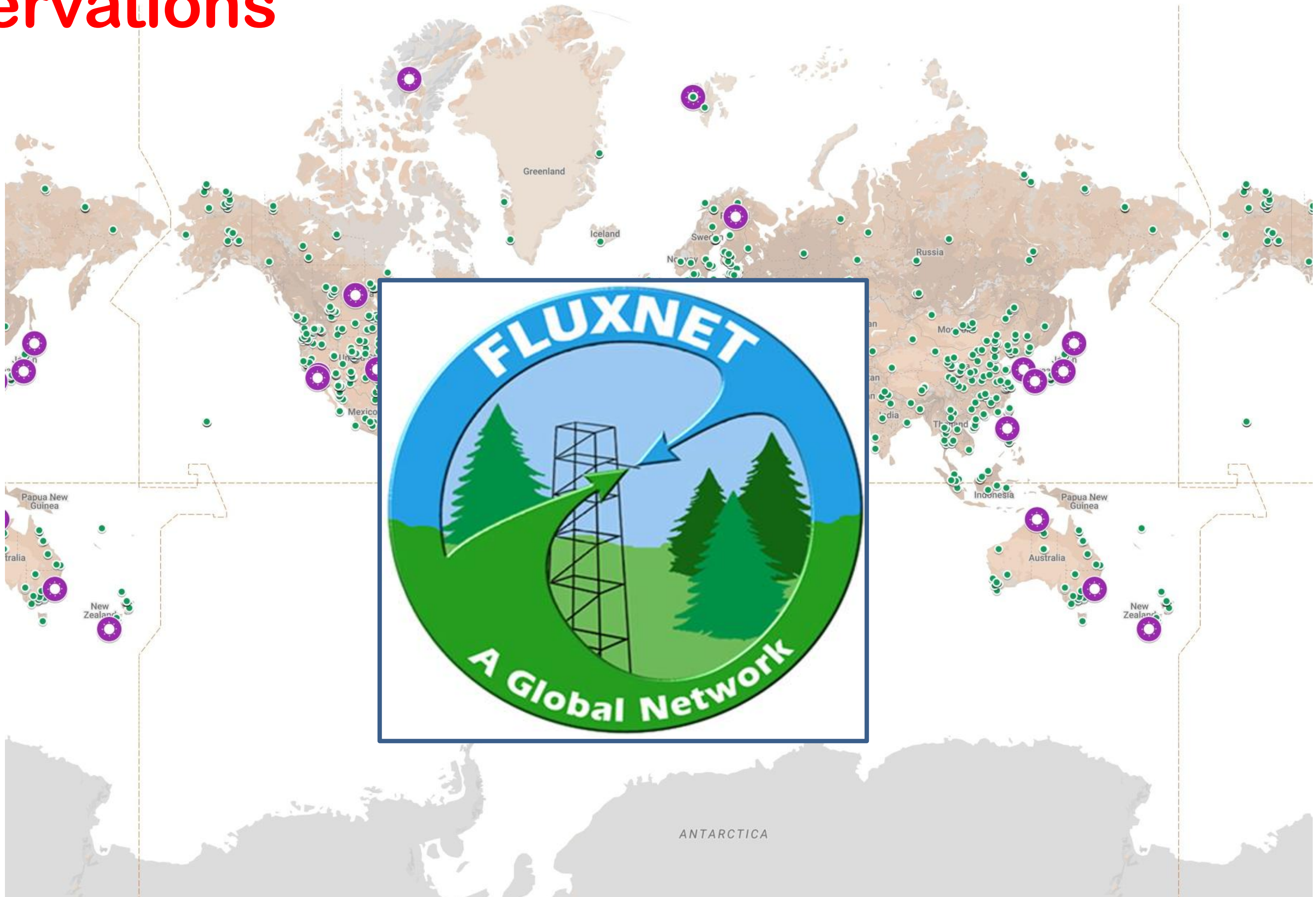
How to estimate the biosphere-atmosphere flux exchanges?



How to estimate the biosphere-atmosphere flux exchanges?



Global ecosystem-atmosphere flux observations

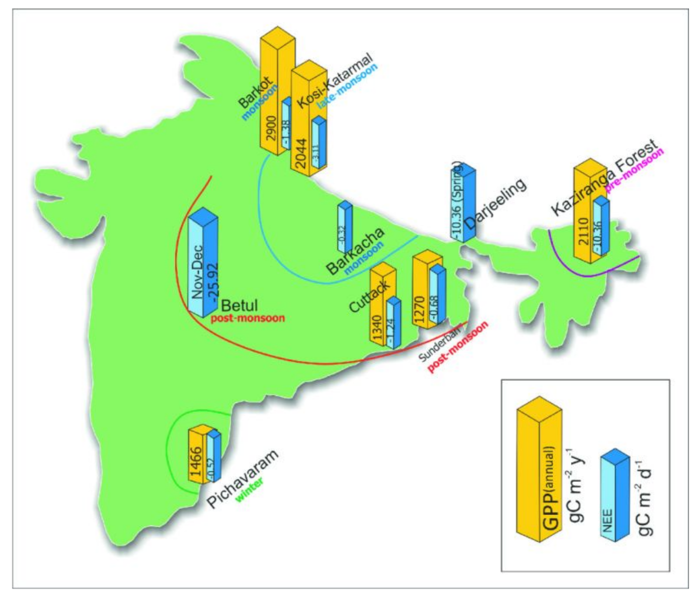


Burba G., 2019. *Illustrative Maps of Past and Present Eddy Covariance Measurement Locations: II. High-Resolution Images*. Retrieved August 6, 2019, from https://www.researchgate.net. 9 pp. DOI: 10.13140/RG.2.2.33191.70561

In the Indian context …

Source: India State of Forest Report 2019, Ministry of Environment, Forest & Climate Change, Government of India.

1. Wide diversity of plant, forest types and climatic regimes
2. Poorly represented in terrestrial ecosystem, Earth system, and climate models
3. Integrated data-model framework required

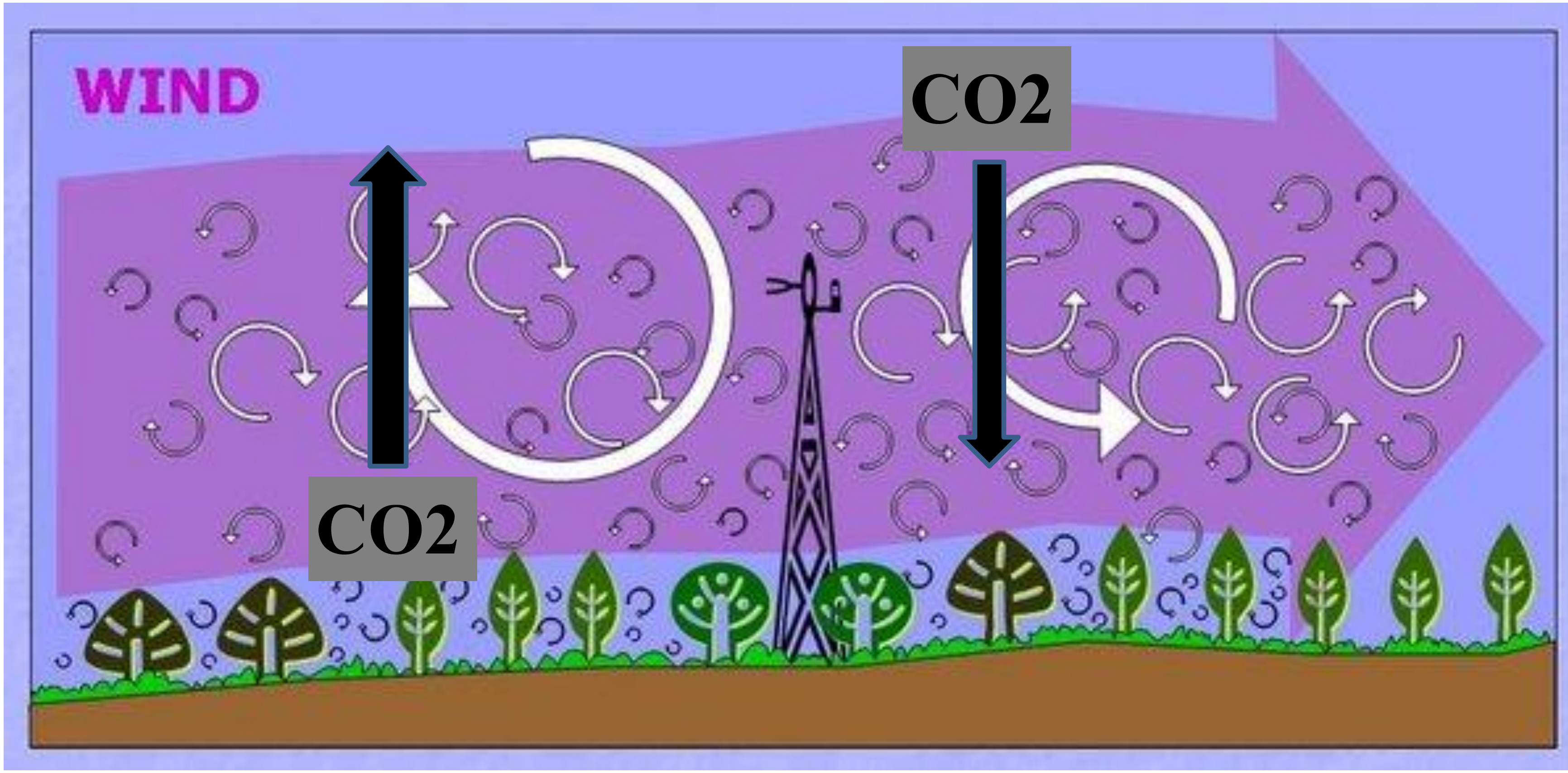


Picture courtesy: Assessment of Climate Change over the Indian Region 2020, Ministry of Earth Sciences, Government of India.

Canopy Crane, Wind River, Washington, USA
Picture Courtesy: Wikipedia

wind parameters
gas (CO_2, water vapour, CH_4 etc.) concentrations
weather parameters (air temperature, pressure, humidity, precipitation etc.)
radiation (incoming and outgoing shortwave and longwave)
photosynthetically active radiation (visible, 40-700 nm)
soil parameters (temperature, moisture, heat flux etc.)
plant physiology, leaf area index (LAI) etc.

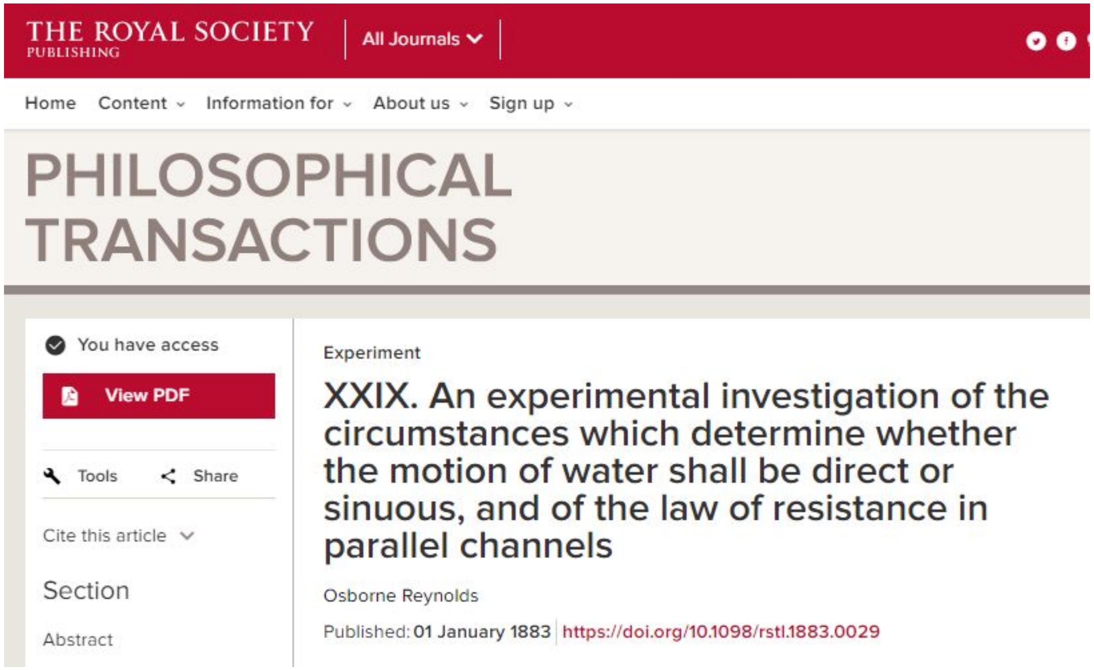
MetFlux India flux tower at the Pichavaram mangroves, Tamil Nadu, India
Picture courtesy: Deb Burman, (2020b)



Eddies are random turbulent motions of wind;
these result in the spatial movement of air parcels
and in the process, the gas molecules.

Picture courtesy: Dr. George Burba, Li-COR Biosciences, USA

Let’s do some mathematics ….


THE ROYAL SOCIETY PUBLISHING | All Journals

Home | Content | Information for | About us | Sign up

PHILOSOPHICAL TRANSACTIONS

You have access

View PDF

Tools | Share

Cite this article

Section

Abstract

Experiment

XXIX. An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels

Osborne Reynolds

Published: 01 January 1883 | https://doi.org/10.1098/rstl.1883.0029

Reynolds averaging:

$x = \bar{x} + x'$

$\bar{x}$ = time mean; usually taken for half and hour

x' = instantaneous fluctuations around the mean

- Need to sample the eddies of all size
- Cumulative contribution to the net exchange
- Flux = mass (or energy) transferred per unit area per unit time
- more eddies sampled, better accurate is the measurement. ho, high-frequency measurements are required, usually 5, 10 or 20 Hz

In vertical dimension ….

- in a turbulent flow (such as in atmosphere),
- the vertical flux of any species c, $F_c = \rho_a \overline{ws}$
- where $s = \rho_c/\rho_a$
- ρ_c = density of species c (CO_2, in our case)
- ρ_a = density of dry air
- using Reynolds averaging,

$$\rho_c = \overline{\rho_c} + \rho_c'$$
$$w = \overline{w} + w'$$
$$\rho_a = \overline{\rho_a} + \rho_a'$$

- Replacing and simplifying,

- $F_c = \overline{(\bar{\rho}_c + \rho_c')(\bar{w} + w')(\bar{\rho}_a + \rho_a')}$

- expand the terms in parentheses
- simplify the expression…

- $F_c = \bar{\rho}_a \overline{w's'}$

- $F_c = \overline{(\overline{\rho_c} + \rho_c')(\overline{w} + w')(\overline{\rho_a} + \rho_a')}$

- expand the terms in parentheses
- simplify the expression…

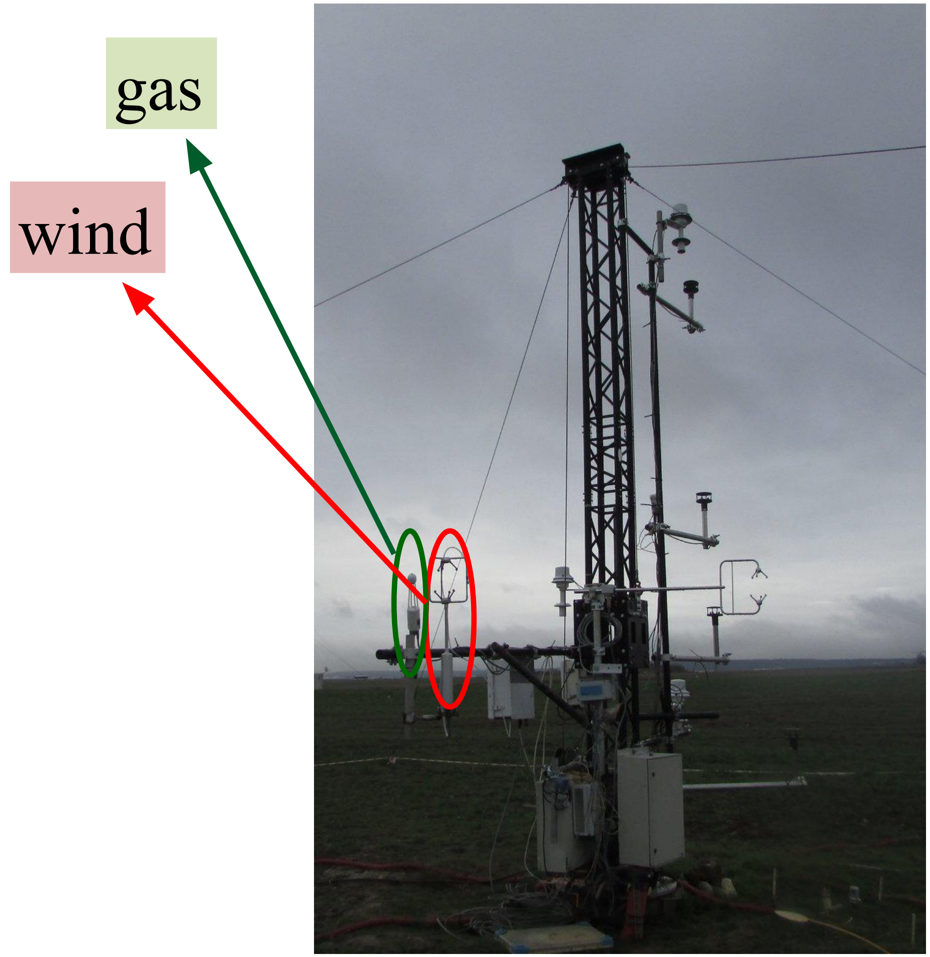
- $F_c = \overline{\rho_a}\,\overline{w's'}$

mind the gap (and the primes) !

- <u>actually, not so simply (Aubinet et al., (2012))</u>

Quality Control

1. despiking to remove erroneous spikes (Vickers & Mahrt, 1997)
2. detrending to remove any long-term trend or ramp in the measurement (Kaimal & Finnigan, 1994)
3. coordinate rotation to ensure proper measurement geometry (Kaimal & Finnigan, 1994)
4. WPL or density correction to account for the atmospheric moisture (Webb et al., 1980)
5. time-lag corrections to ensure the measurements of wind and gas concentrations are synchronous (Moncrieff et al., 1997, 2004)
6. and many more … read Aubinet et al., (2012)



Eddy Covariance flux tower, France

- Why do we need moisture correction?

- Why do we need moisture correction?

moist air is lighter that dry air. If not corrected for the moisture, the measured gas densities will be higher than actual.

We learnt about the Eddy Covariance method;

There are other methods as well

1. Flux-Gradient (Lee, 2018)

   mass flows from high density to low density

   K_c is the eddy diffusivity factor for CO_2

$$F_c = -K_c \frac{\partial \overline{c}}{\partial z}$$

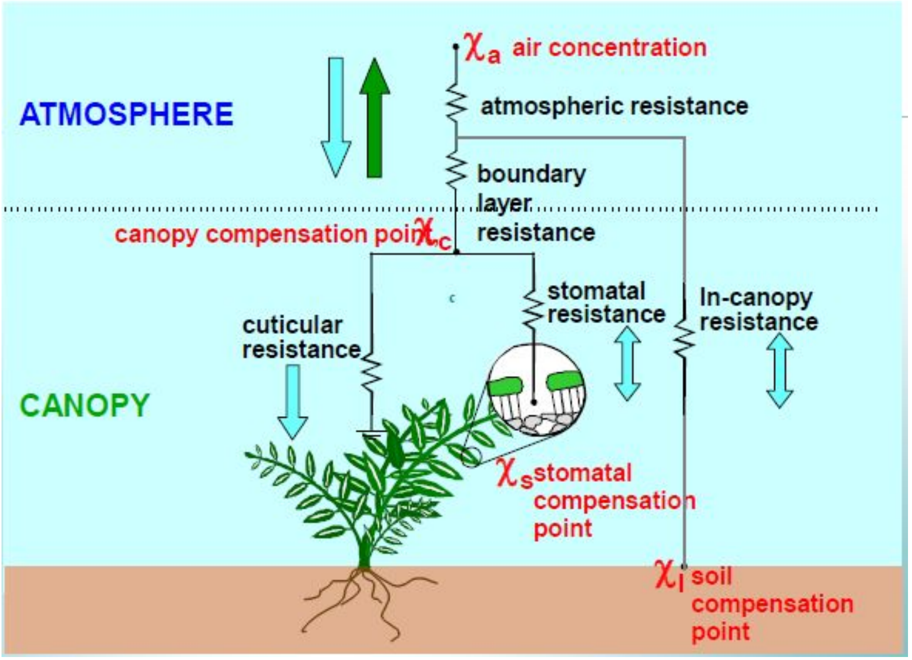
$$= -K_c \frac{\overline{c(2)} - \overline{c(1)}}{z(2) - z(1)}$$

We learnt about the Eddy Covariance method;

There are other methods as well

2. Resistance formulation (analogous to the concept of flow of electricity or fluid)

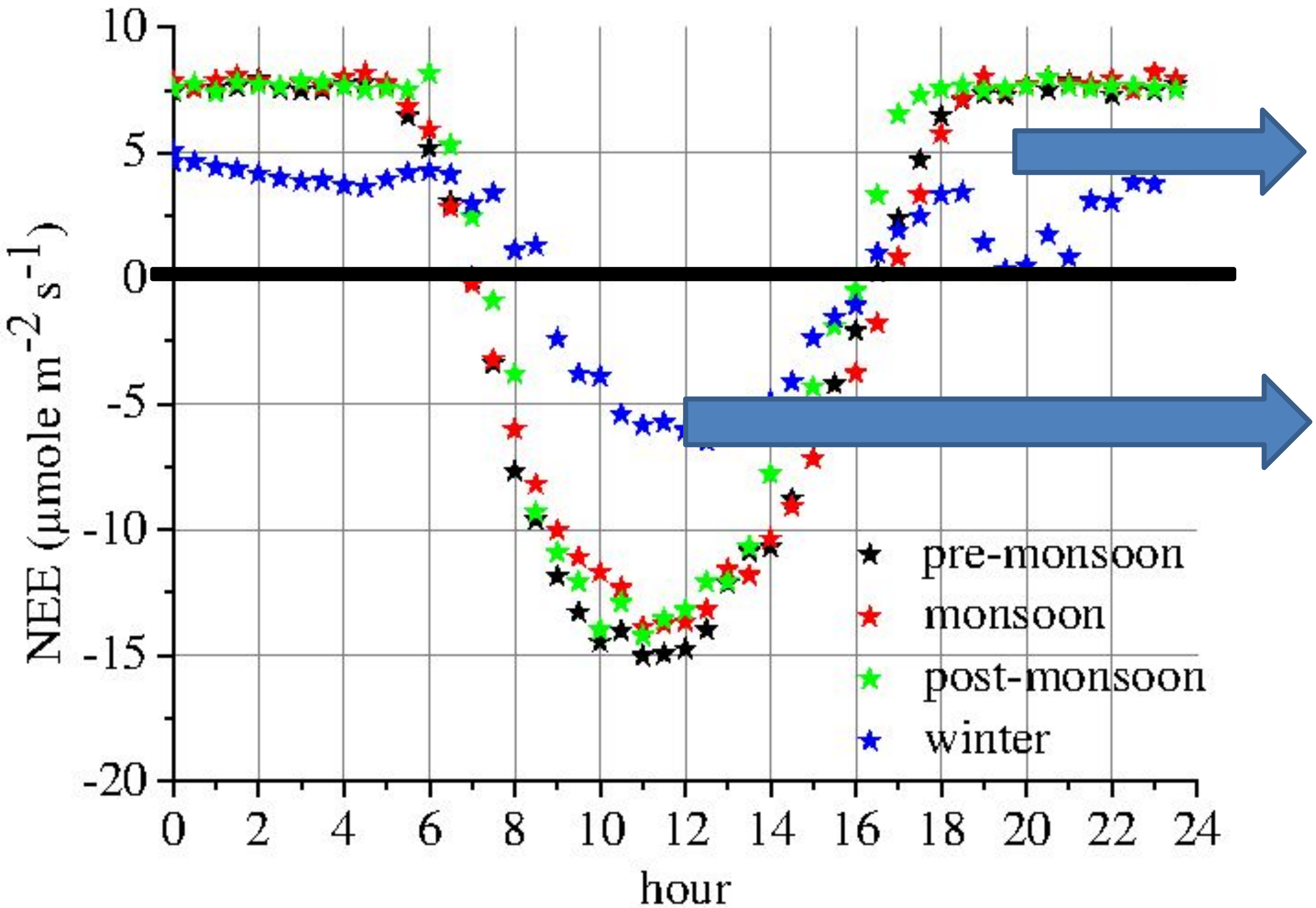
Nemitz et al. (2000)



Bigleaf assumption: entire canopy is considered to behave as a big leaf (Sellers et al., 1992)

Stomatal Resistance $$r_s = \frac{1}{m\frac{A_n \cdot h_s}{cs} + b}$$

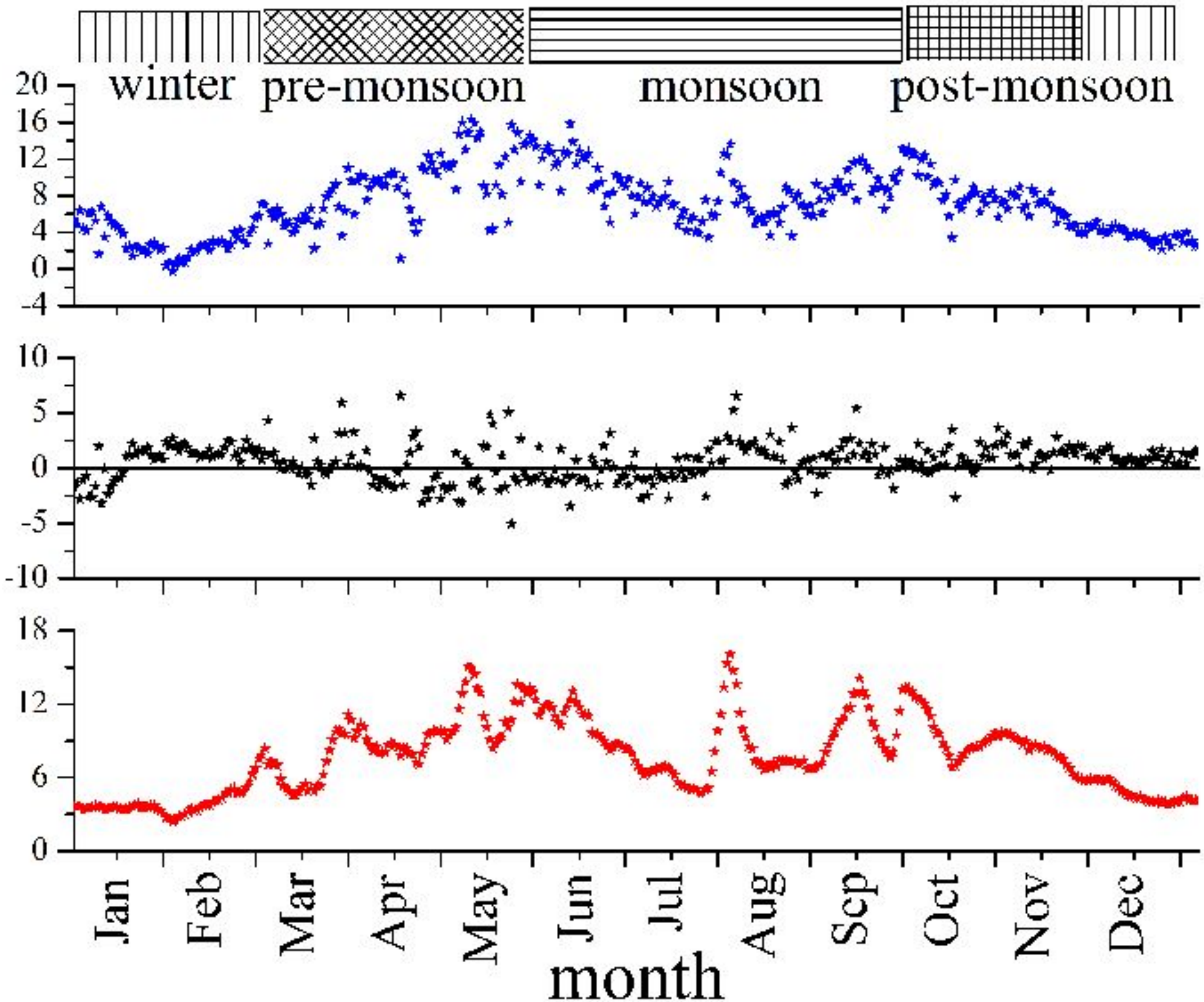
Picture Courtesy: Dr. Eiko Nemitz, Centre for Ecology and Hydrology, UK



nighttime c release

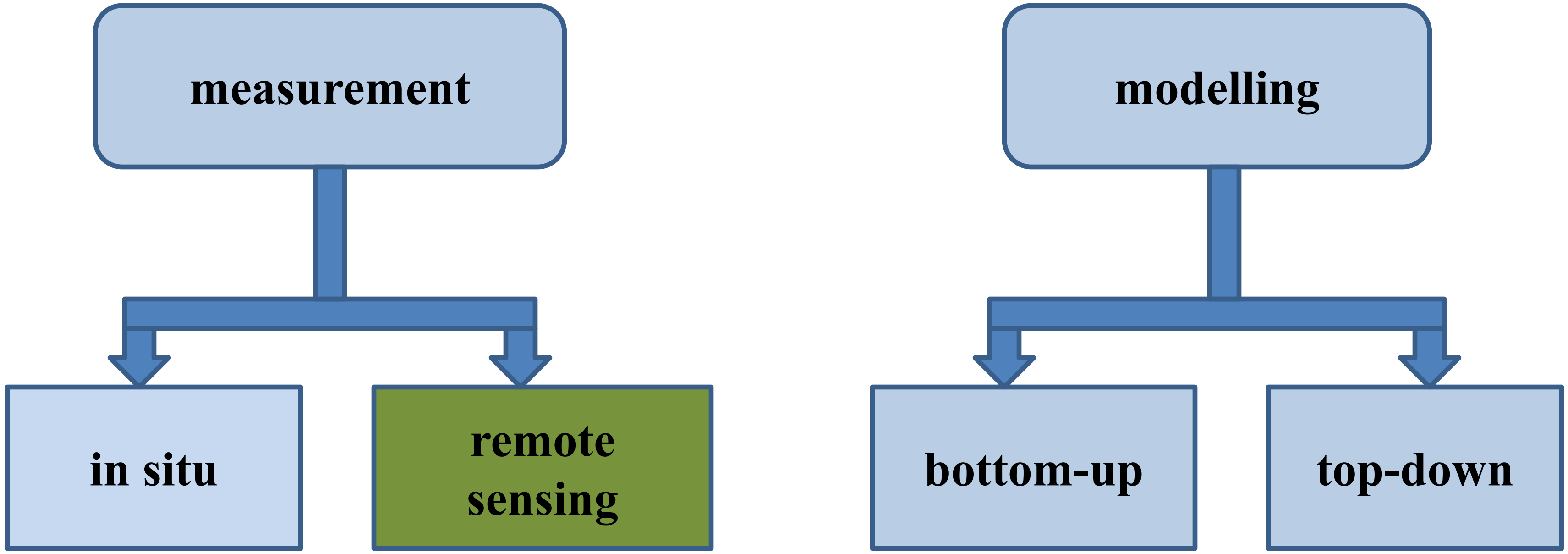
daytime photosynthetic uptake

Deb Burman et al., 2020a



Deb Burman et al., 2020a

How to estimate the biosphere-atmosphere flux exchanges?



Vegetation Indices (VI):

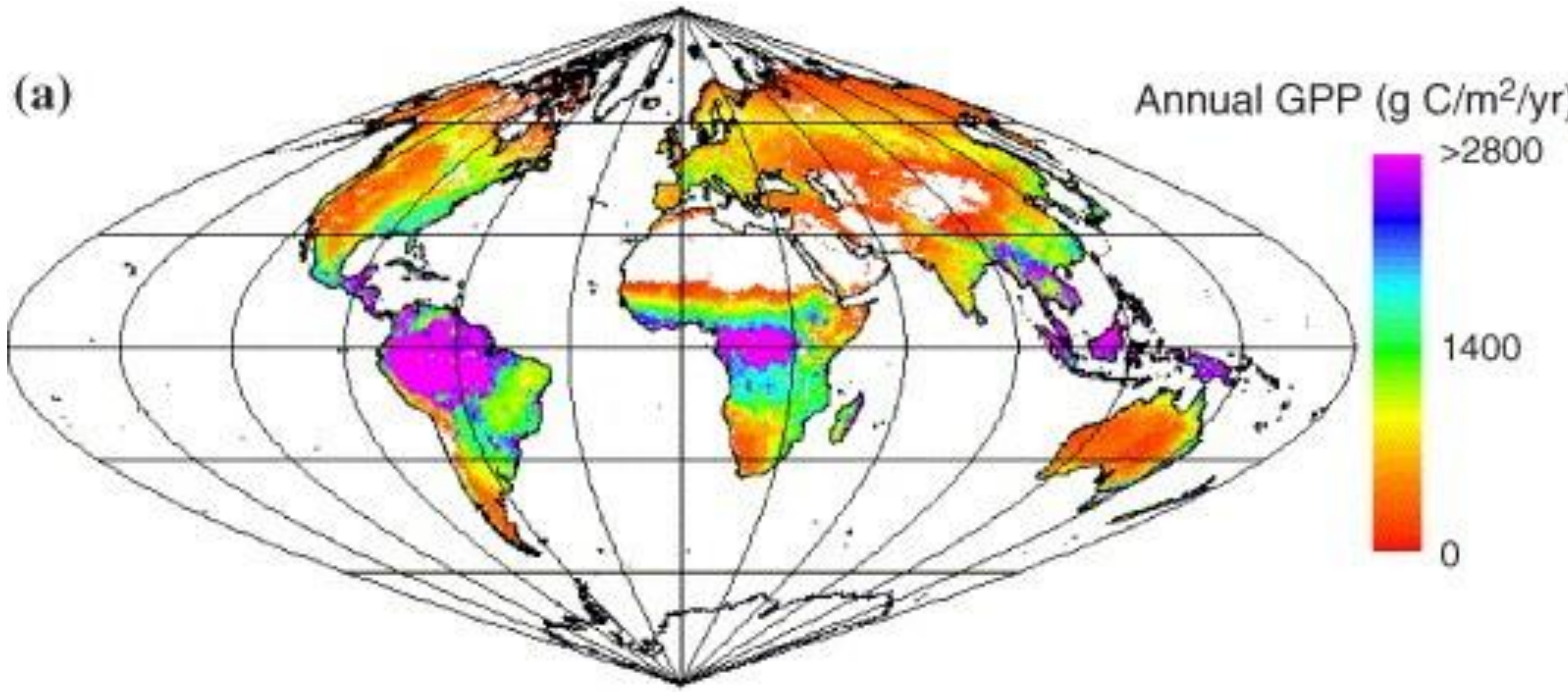
1. ratio of reflectances in different band (Huete et al., 2002)

2. Normalised difference vegetation index (NDVI),

$$NDVI = \frac{\alpha_{nir} - \alpha_{vis}}{\alpha_{nir} + \alpha_{vis}}$$

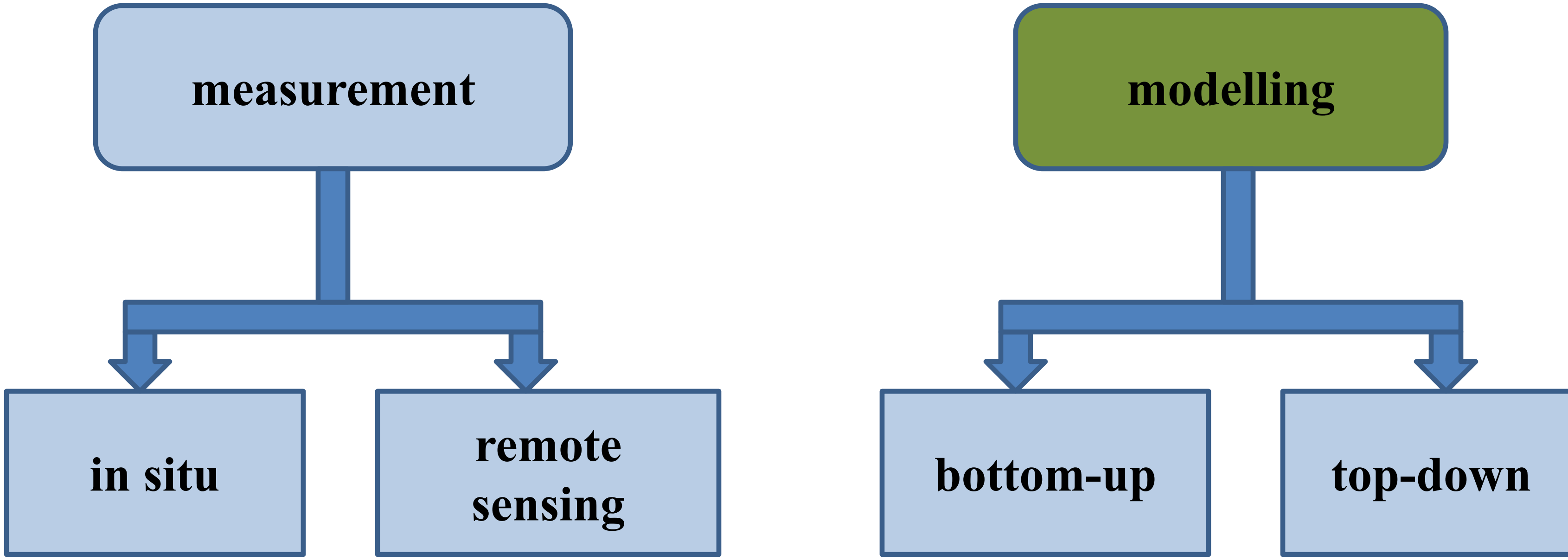
3. Leaf-Area Index (LAI): total one-sided leaf area per unit ground area (Watson, 1947)

4. Enhanced Vegetation Index (EVI), Land-surface Water Index (LSWI) etc.



mean global GPP(gC m^{-2} y^{-1}) distribution, estimated from MODIS (Zhao et al., (2005))

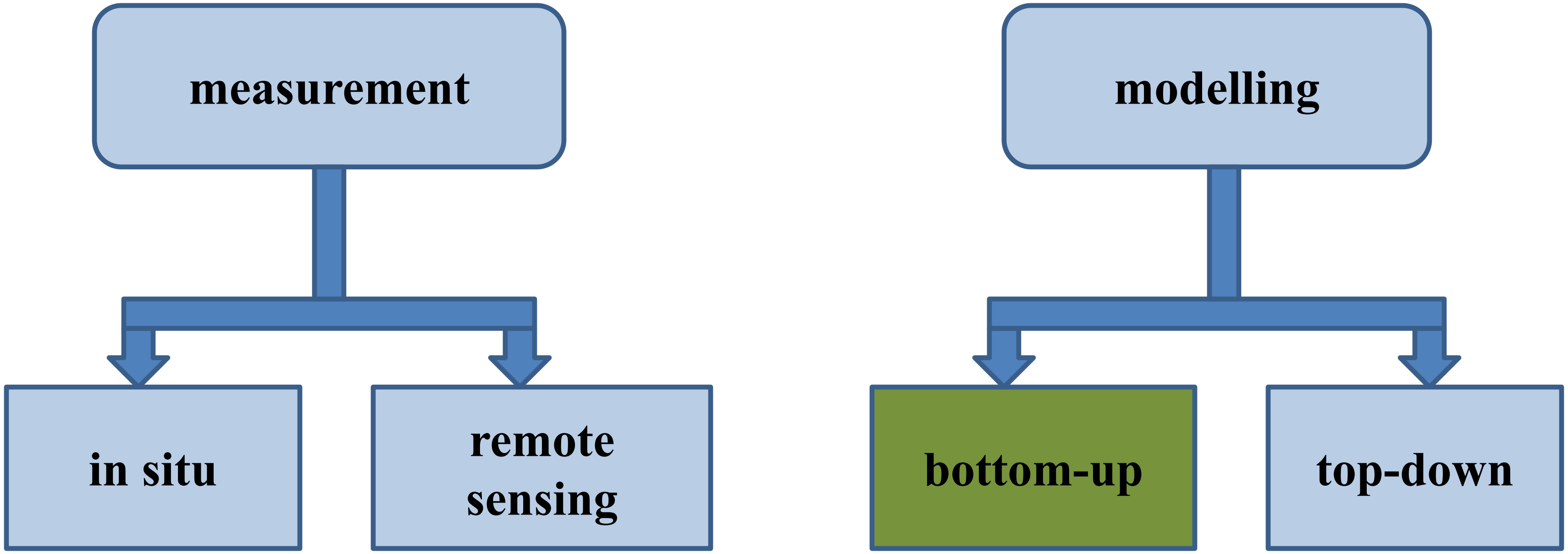
How to estimate the biosphere-atmosphere flux exchanges?



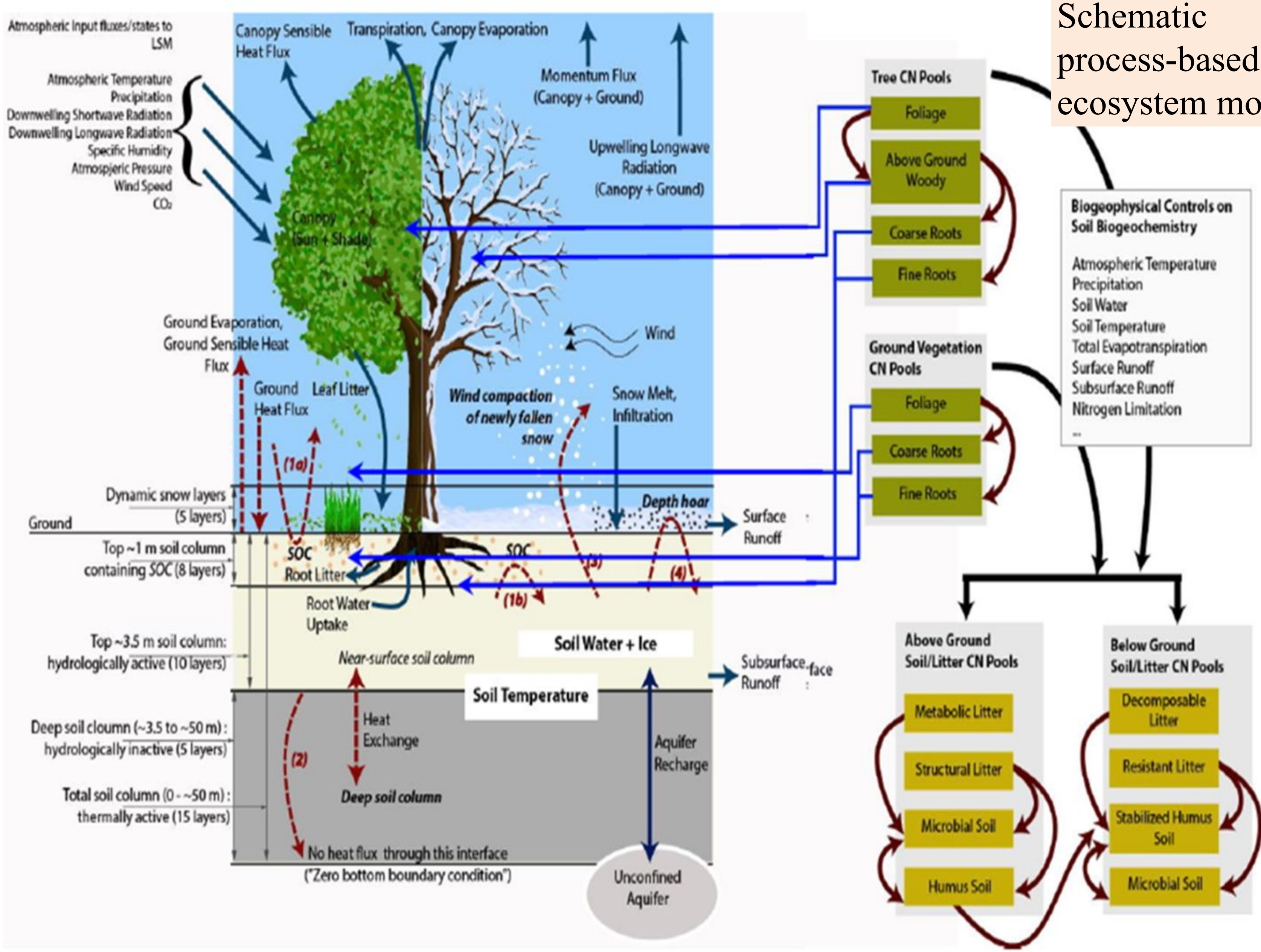
What is a model?

1. a set of mathematical (differential, integral, algebraic etc.) equations
   equations of motion
   continuity equation
   mass conservation
   thermodynamic equations
2. solved at single (point model) or multiple grid points (regional and/or global)
3. the governing equations are derived from our knowledge of physics, chemistry, biology, hydrology etc.
4. if that does not work, we parameterize in phenomenological way, i.e. based on the knowledge gained from observations.
5. in short, we recreate the complex coupled interplay among meteorology, physiology, hydrology etc. to study the evolution of the system and predict its response

How to estimate the biosphere-atmosphere flux exchanges?



Schematic of a process-based, bottom-up ecosystem model



NOAH LSM (Land Surface Model), JULES (Joint UK Land-Environment Simulator), CESM (Community Earth System Model) etc.

Picture Courtesy: Prof. Atul K. Jain, Department of Atmospheric Science, University of Illinois at Urbana-Champaign USA

Table A2
ISAM equations for the carbon modules.

Function	Equations	
Plant autotrophic respiration	$R_{leaf} = k_{leaf} \times \frac{C_{leaf}}{cn_{leaf}} \times \varnothing \times gt$	(S1)
	$R_{stem} = k_{stem} \times \frac{C_{stem}}{cn_{stem}} \times gt$	(S2)
	$R_{root} = k_{root} \times \frac{C_{root}}{cn_{root}} \times \varnothing \times gt$	(S3)
	$Q_{10} = 3.22 - 0.046 \times T_{veg}$ for leaves and stems	(S4)
	$Q_{10} = 3.22 - 0.046 \times T_{soil}$ for roots	(S5)
	$gt = Q_{10}^{(T_{veg}-20)/10}$ for leaves and stems	(S6)

Photosynthetic pathways:

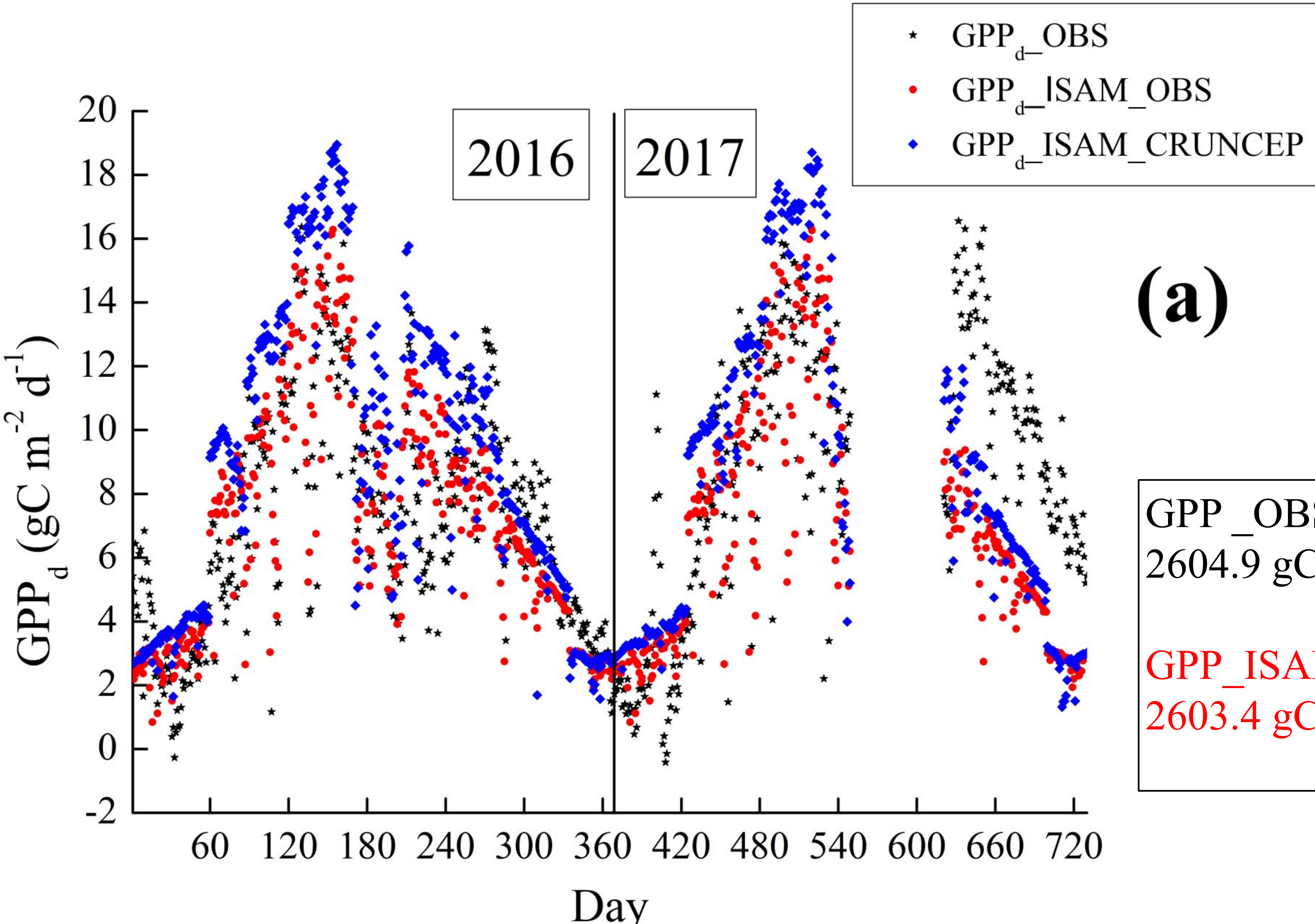
1. C3 (Farquhar et al., 1980; Collatz et al., 1991); Maximum carboxylation capacity (Vcmax), Bulk canopy maximum electron transport rate (Jmax)
2. C4 (Collatz et al.,1992)
3. CAM (Cortázar & Nobel, (1990); Kluge & Ting, (2012))

El-Masri et al., 2013

Respiration:

1. autotrophic respiration (plants) + heterotrophic respiration (animals, microbes)
2. maintenance + growth; usually taken as a percentage of photosynthetic uptake

calibrating and validating a process-based ecosystem model

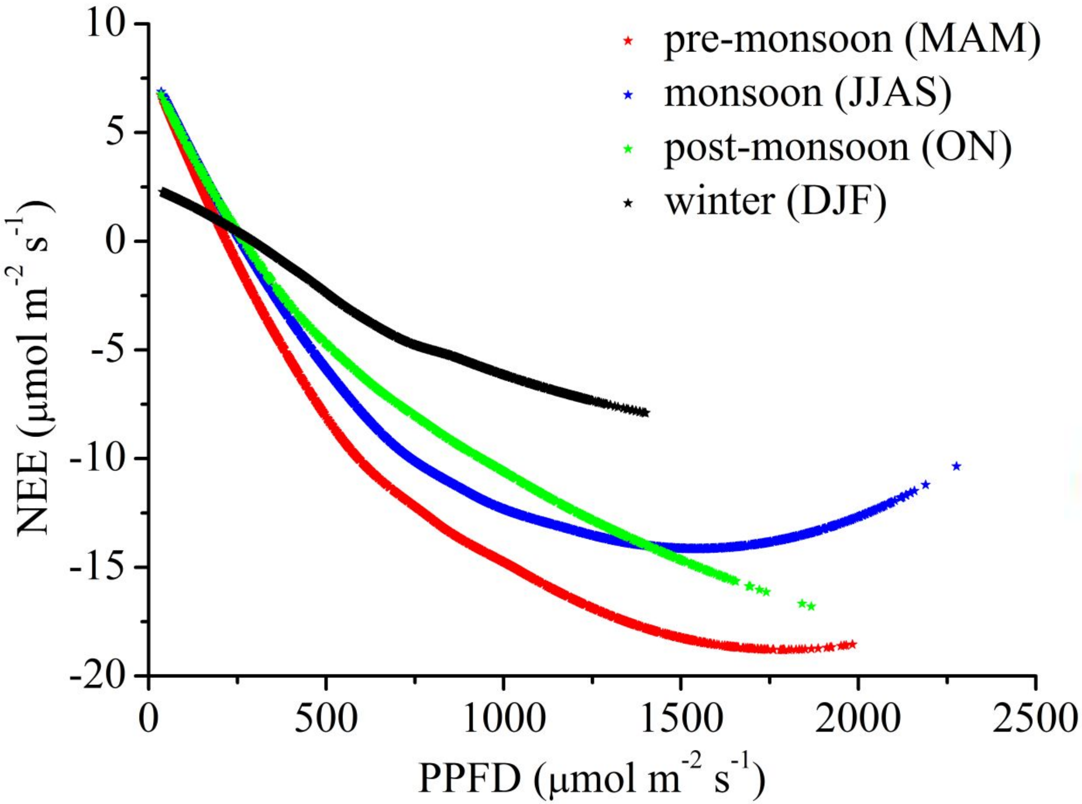


GPP _OBS :
2604.9 gC m^{-2} y^{-1}

GPP_ISAM_OBS:
2603.4 gC m^{-2} y^{-1}

Deb Burman et al., under preparation

functional relationships derived from observations are represented in models



Michaelis-Menten relation:

$$NEE = \frac{\alpha \cdot PPFD \cdot NEE_{sat}}{\alpha \cdot PPFD + NEE_{sat}} + TER.$$

Deb Burman et al., 2020

Season	α (μmol CO_2 μmol^{-1} photons)	NEEsat (μmol m^{-2} s^{-1})	F_m (μmol m^{-2} s^{-1})	LCP (μmol m^{-2} s^{-1})	R_d (μmol m^{-2} s^{-1})
pre-monsoon	- 0.05	- 47.48	- 20	250	7.5
monsoon	- 0.05	- 35.33	- 15	250	10
post-monsoon	- 0.04	- 41.31	- 20	250	10
winter	- 0.02	- 41.23	- 10	250	2.5

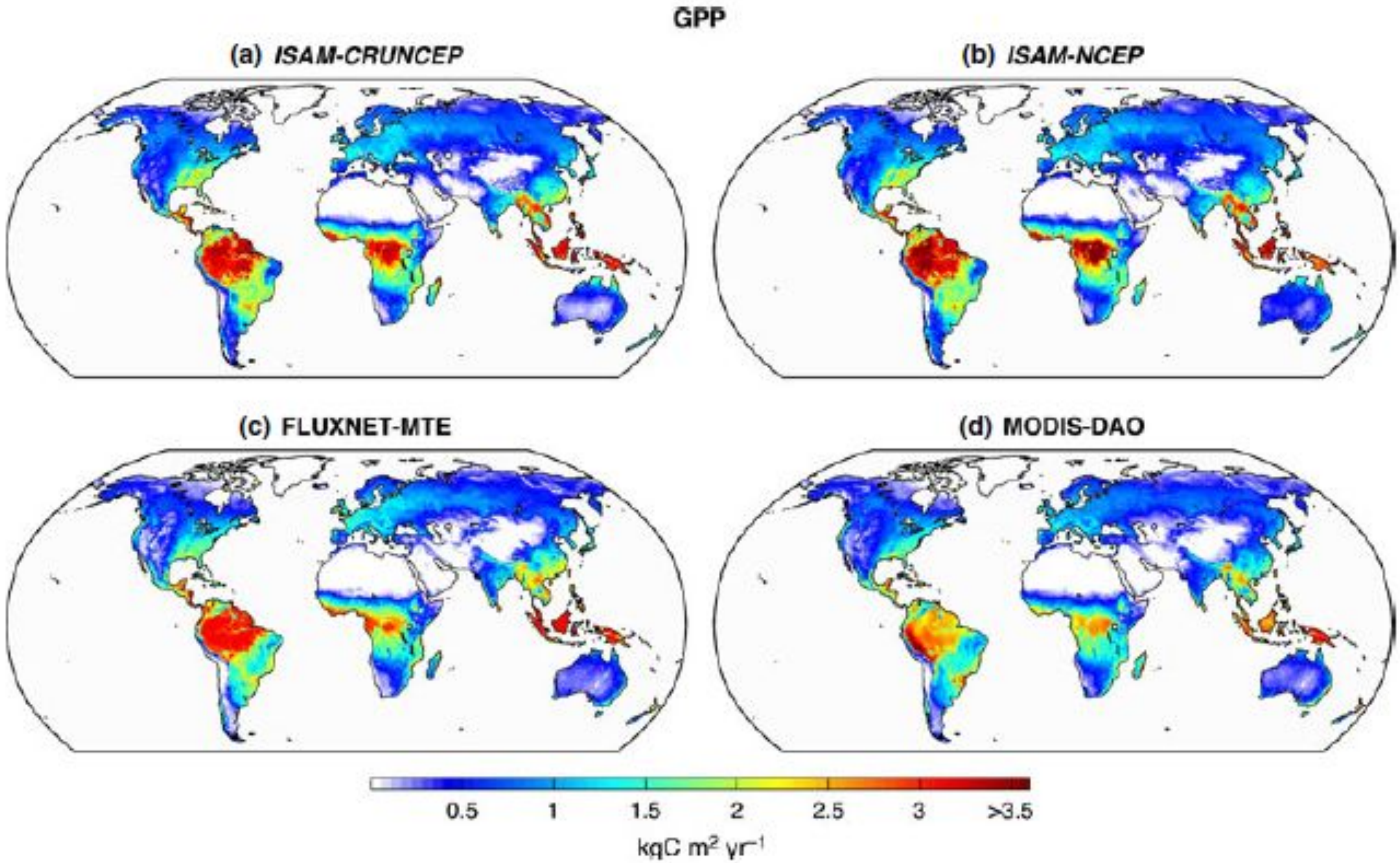
Light Use Efficiency (LUE) approach

- Proposed first by Monteith, 1972
- Carbon uptake by a canopy is directly proportional to the absorbed photosynthetically active (visible band, 400-700 nm) radiation (PAR)
- Proportionality constant (ε) is the light use efficiency. It depends on the canopy type, vegetation health, moisture and nutrient stress etc.

$$APAR = fAPAR * PAR$$

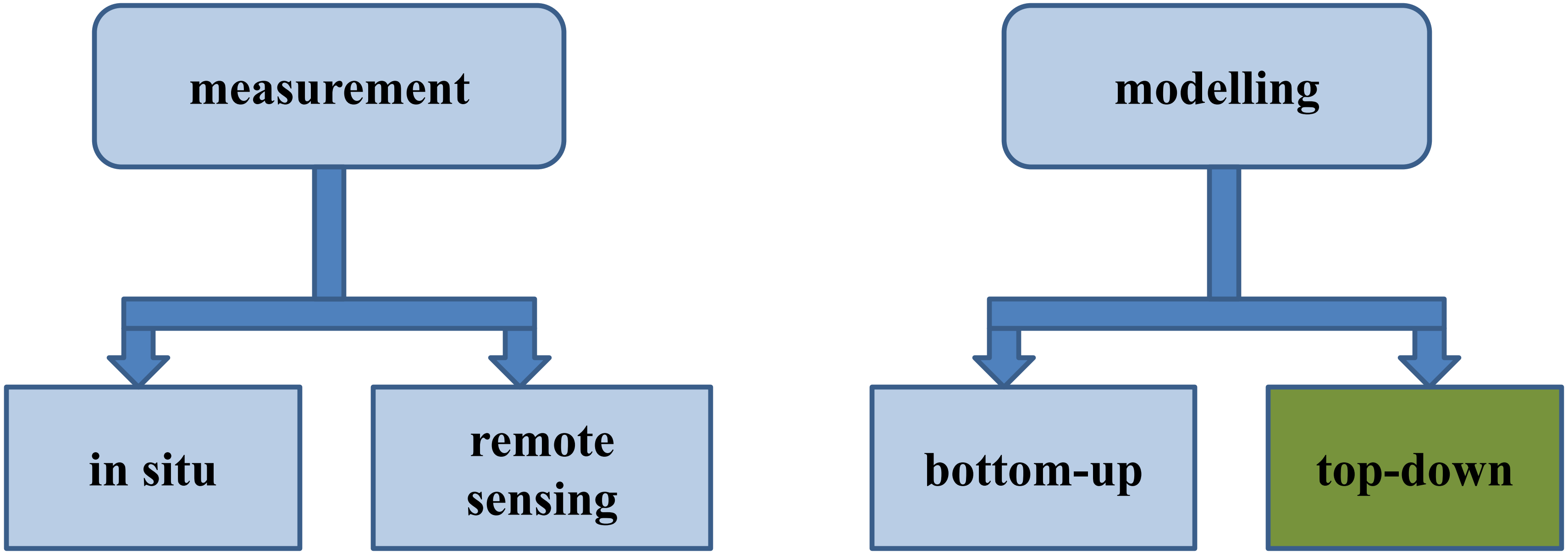
$$NPP = fAPAR * PAR * \varepsilon$$

global scale GPP estimate



Barman et al., (2014)

How to estimate the biosphere-atmosphere flux exchanges?



Inverse Models

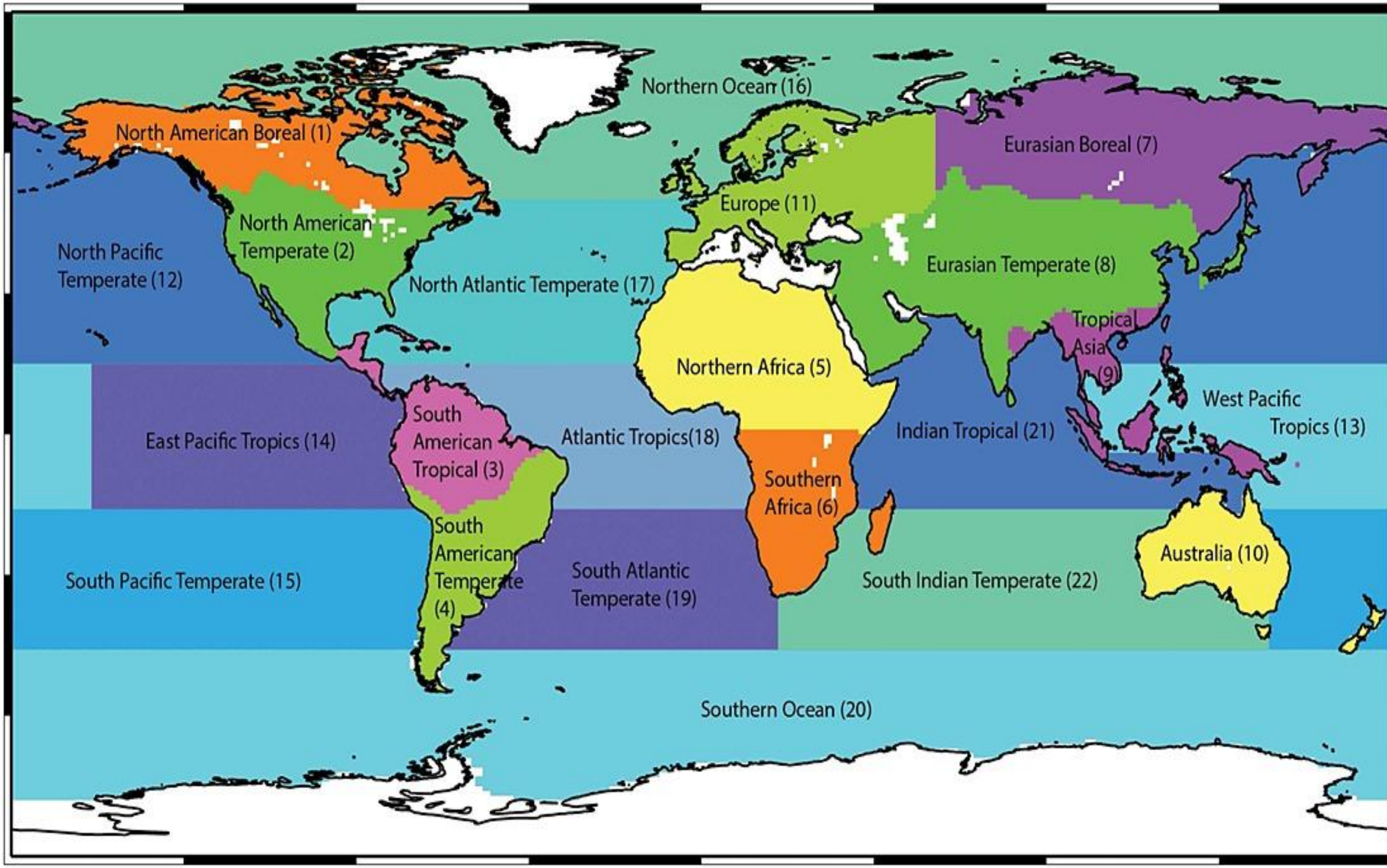
- the atmospheric CO_2 concentrations are observed at multiple spatial and temporal scales and the sources and sinks responsible for these distributions are computed by a backward modelling approach(Gurney et al., (2004); Rayner et al., (2005)).

- variables (ψ) and observations (χ) matrices are connected by the following relation,

$$G.\psi = \chi$$

- G is the coefficient matrix. The inverse of G is mostly calculated by Bayesian inversion (Heimann & Kaminski, (1999)).

- Observed spatio-temporal distribution of trace gases are partitioned into potential sources and sinks using atmospheric transport models (Kaminski et al., (1999)); Lagrangian(Pisso et al., (2019)), Eularian(Pillai et al., (2012)) or hybrid schemes (Siqueira et al., (2000))



The different land (and ocean) zones used in the TRANSCOM inversion (Houweling et al., (2015)

OPEN ACCESS
IOP PUBLISHING
ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. 7 (2012) 044008 (9pp)
doi: 10.1088/1748-9326/7/4/044008

Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections

A Ahlström[1], G Schurgers[1], A Arneth[2] and B Smith[1]

[1] Department of Physica
SE-223 62 Lund, Swede
[2] Institute for Meteorolo
Institute for Technology,

nature geoscience
REVIEW ARTICLE
PUBLISHED ONLINE: 25 JULY 2010 | DOI: 10.1038/NGEO905

Terrestrial biogeochemical feedbacks in the climate system

A. Arneth[1,2*], S. P. Harrison[3,4], S. Zaehle[5], K. Tsigaridis[6,7], S. Menon[8], P. J. Bartlein[9], J. Feichter[10], A. Korhola[11], M. Kulmala[2], D. O'Donnell[10], G. Schurgers[1], S. Sorvari[2] and T. Vesala[2]

References

- Arora, V. K., Boer, G. J., Friedlingstein, P., Eby, M., Jones, C. D., Christian, J. R., … Wu, T. (2013). Carbon-concentration and carbon-climate feedbacks in CMIP5 earth system models. *Journal of Climate*, *26*, 5289–5311. https://doi.org/10.1175/JCLI-D-12-00494.1
- Arora, V. K., Katavouta, A., Williams, R. G., Jones, C. D., Brovkin, V., Friedlingstein, P., … Ziehn, T. (2020). Carbon-concentration and carbon-climate feedbacks in CMIP6 models and their comparison to CMIP5 models. *Biogeosciences*, *17*, 4173–4222. https://doi.org/10.5194/bg-17-4173-2020
- Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D., & Houghton, R. A. (2017). Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science (New York, N.Y.)*, *358*(6360), 230–234. https://doi.org/10.1126/science.aam5962
- Baldocchi, D. D. (2020). How eddy covariance flux measurements have contributed to our understanding of Global Change Biology. *Global Change Biology*, *26*, 242–260. https://doi.org/10.1111/gcb.14807
- Bongaarts, J. (2019). IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science‐Policy Platform on Biodiversity and Ecosystem Services. *Population and Development Review*. https://doi.org/10.1111/padr.12283
- Deb Burman, P. K., Sarma, D., Chakraborty, S., Karipot, A., & Jain, A. K. (2020). The effect of Indian summer monsoon on the seasonal variation of carbon sequestration by a forest ecosystem over North-East India. *SN Applied Sciences*, *2*(2), 154. https://doi.org/10.1007/s42452-019-1934-x
- Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., … Zaehle, S. (2019). Global Carbon Budget 2019. *Earth System Science Data*, *11*(4), 1783–1838. https://doi.org/10.5194/essd-11-1783-2019
- Gu, L., Baldocchi, D., Verma, S. B., Black, T. A., Vesala, T., Falge, E. M., & Dowty, P. R. (2002). Advantages of diffuse radiation for terrestrial ecosystem productivity. *Journal of Geophysical Research Atmospheres*, *107*, 4050. https://doi.org/10.1029/2001jd001242
- IPCC. (2019). IPCC SR: Climate Change and Land. *An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*.
- Kanniah, K. D., Beringer, J., & Hutley, L. (2013). Exploring the link between clouds, radiation, and canopy productivity of tropical savannas. *Agricultural and Forest Meteorology*, *182–183*, 304–313. https://doi.org/10.1016/j.agrformet.2013.06.010
- Keenan, T. F., & Williams, C. A. (2018). The terrestrial carbon sink. *Annual Review of Environment and Resources*, *43*, 219–243. https://doi.org/10.1146/annurev-environ-102017-030204
- Knohl, A., & Baldocchi, D. D. (2008). Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem. *Journal of Geophysical Research: Biogeosciences*, *113*, G02023. https://doi.org/10.1029/2007JG000663
- Kwon, H., Hong, J., & Lim, J. (2009). Seasonality of net ecosystem carbon exchange in two major plant functional types in Korea. *Asia-Pacific Journal of Atmospheric Sciences*, *45*(2), 149–163.

- Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., … Del Mar Zamora Dominguez, M. (2018). Negative emissions - Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*, 063001. https://doi.org/10.1088/1748-9326/aabf9b
- Malhi, Y., & Grace, J. (2000). Tropical forests and atmospheric carbon dioxide. *Trends in Ecology & Evolution*, *15*(8), 332–337. https://doi.org/10.1016/S0169-5347(00)01906-6
- Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., & Cox, P. M. (2009). Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, *458*, 1014–1018. https://doi.org/10.1038/nature07949
- Mitchard, E. T. A. (2018). Review The tropical forest carbon cycle and climate change. *Nature*, *559*(26th July), 2–9. https://doi.org/10.1038/s41586-018-0300-2
- Myers, T. A., & Norris, J. R. (2015). On the relationships between subtropical clouds and meteorology in observations and CMIP3 and CMIP5 models. *Journal of Climate*, *26*(1), 242–260. https://doi.org/10.1175/JCLI-D-14-00475.1
- Pan, Y., Birdsey, R., Fang, J., Houghton, R., Kauppi, P., Kurz, W., … Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science*, *334*(6045), 988–993. https://doi.org/10.1126/science.1201609
- Patra, P. K., Canadell, J. G., Houghton, R. A., Piao, S. L., Oh, N. H., Ciais, P., … Lasco, R. (2013). The carbon budget of South Asia. *Biogeosciences*, *10*(1), 513–527. https://doi.org/10.5194/bg-10-513-2013
- Rojas-Robles, N. E., Garatuza-Payán, J., Álvarez-Yépiz, J. C., Sánchez-Mejía, Z. M., Vargas, R., & Yépez, E. A. (2020). Environmental Controls on Carbon and Water Fluxes in an Old-Growth Tropical Dry Forest. *Journal of Geophysical Research: Biogeosciences*, *125*(8), e2020JG005666. https://doi.org/10.1029/2020JG005666
- Sindhu, K. D., & Sahany, S. (2019). Long-term cloud fraction biases in CMIP5 GCMs over India during monsoon season. *Theoretical and Applied Climatology*, *137*, 2559–2571. https://doi.org/10.1007/s00704-018-02760-1
- Souza, L. S. B. de, Moura, M. S. B. de, Sediyama, G. C., & Silva, T. G. F. da. (2018). Carbon exchange in a caatinga area during an unusually drought year. *Agrometeoros*, *25*, 37–45. https://doi.org/10.31062/agrom.v25i1.26265
- Stanfield, R. E., Dong, X., Xi, B., Kennedy, A., Del Genio, A. D., Minnis, P., & Jiang, J. H. (2014). Assessment of NASA GISS CMIP5 and Post-CMIP5 Simulated Clouds and TOA Radiation Budgets Using Satellite Observations. Part I: Cloud Fraction and Properties. *Journal of Climate*, *27*, 4189–4208. https://doi.org/10.1175/jcli-d-13-00558.1
- Stephens, G. L. (2005). Cloud feedbacks in the climate system: A critical review. *Journal of Climate*, *18*(2), 238–273. https://doi.org/10.1175/JCLI-3243.1
- Tagesson, T., Schurgers, G., Horion, S., Ciais, P., Tian, F., Brandt, M., … Fensholt, R. (2020). Recent divergence in the contributions of tropical and boreal forests to the terrestrial carbon sink. *Nature Ecology and Evolution*, *4*, 202–209. https://doi.org/10.1038/s41559-019-1090-0
- Verduzco, V. S., Garatuza-Payán, J., Yépez, E. A., Watts, C. J., Rodríguez, J. C., Robles-Morua, A., & Vivoni, E. R. (2015). Variations of net ecosystem production due to seasonal precipitation differences in a tropical dry forest of northwest Mexico. *Journal of Geophysical Research: Biogeosciences*, *120*, 2081–2094. https://doi.org/10.1002/2015JG003119
- Vignesh, P. P., Jiang, J. H., Kishore, P., Su, H., Smay, T., Brighton, N., & Velicogna, I. (2020). Assessment of CMIP6 Cloud Fraction and Comparison with Satellite Observations. *Earth and Space Science*, *7*, e2019EA000975. https://doi.org/10.1029/2019EA000975
- Zhang, M., Yu, G. R., Zhuang, J., Gentry, R., Fu, Y. L., Sun, X. M., … Li, Y. N. (2011). Effects of cloudiness change on net ecosystem exchange, light use efficiency, and water use efficiency in typical ecosystems of China. *Agricultural and Forest Meteorology*, *151*, 803–816. https://doi.org/10.1016/j.agrformet.2011.01.011


thank you
danke
謝謝
ngiyabonga
teşekkür ederim
gracias
merci
obrigado
bedankt
спасибо
dziękuję
sukriya
go raibh maith agat
mochchakkeram
tapadh leat
kop khun krap
terima kasih
dakujem
arigatô
grazie
takk
감사합니다
мерси
sagolun
hvala
dank je
maururu
ευχαριστώ
rahmat
paldies
mahalo
хвала
asante
obrigada
tack
ありがとう

some interesting resources to explore

1. warning stripes :

https://www.warningstripes.com/

1. Eddy Covariance from NEON Science :

https://www.youtube.com/watch?v=CR4Anc8Mkas

2. UN REDD+ :

https://www.un-redd.org/

3. Intergovernmental Panel on Climate Change :

https://www.ipcc.ch/