The role of mature forests in sustaining large-scale hydrological cycle :

physical modeling and historical cases

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1. BIOTIC PUMP : the CONTROVERSY

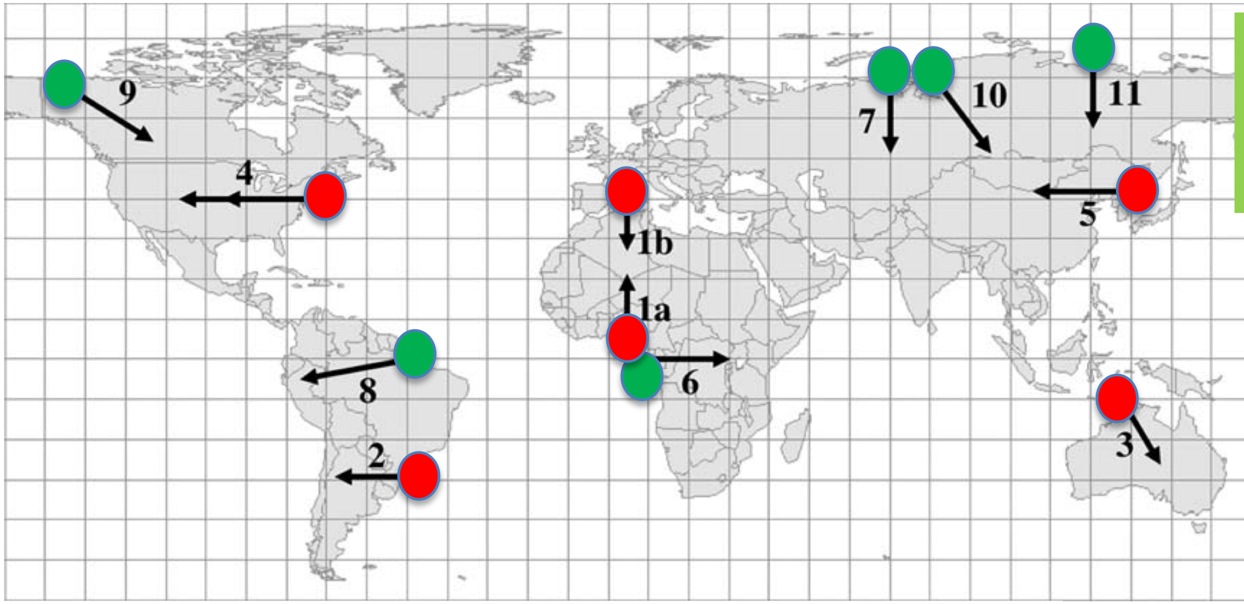
Makarieva, A. M., & Gorshkov, V. G. (2007).
Biotic pump of atmospheric moisture as driver of the hydrological cycle on land.
Hydrology and earth system sciences, *11*(2), 1013-1033.

Forests make rain

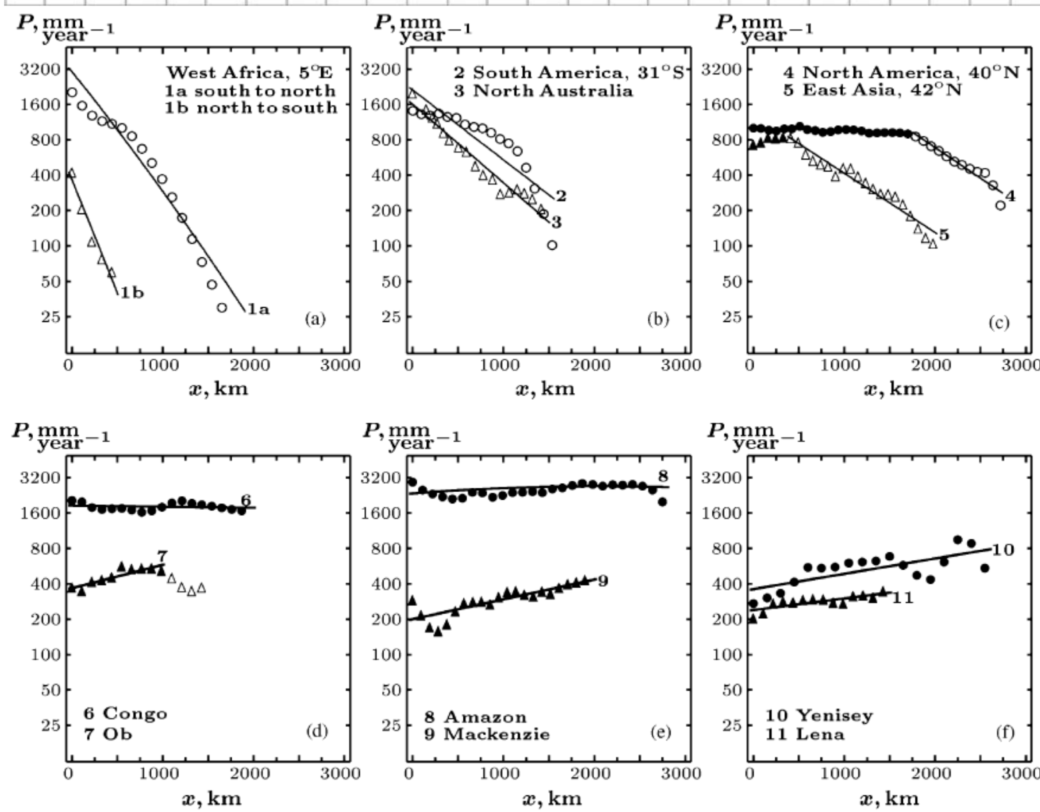
rather than

Rain makes forests

ANNUAL RAINFALL PROFILES



Makarieva, Gorshkov et Li (2009).



NON FORESTED :

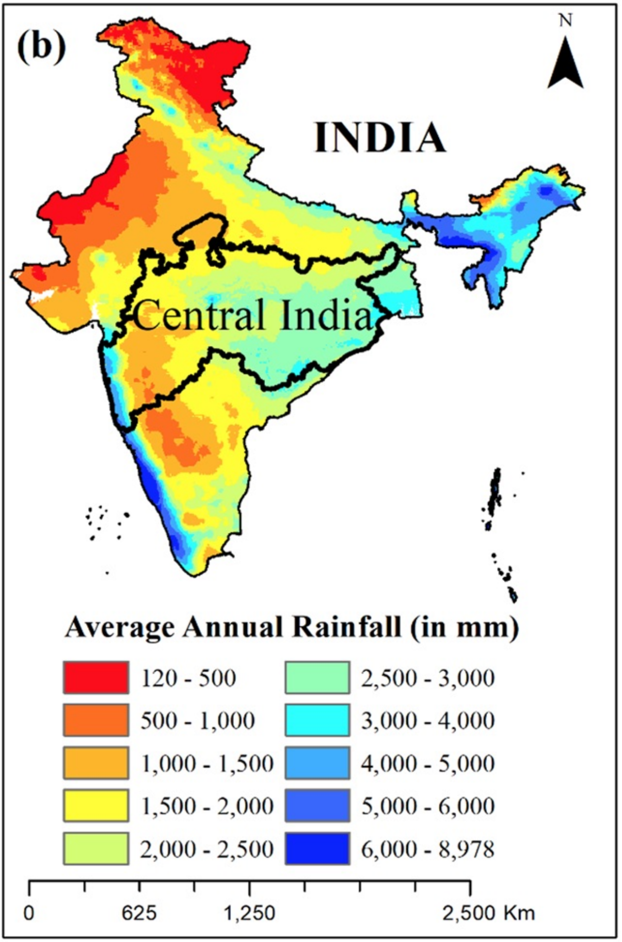
Exponential decay

$P_0 e^{-x/x0}$

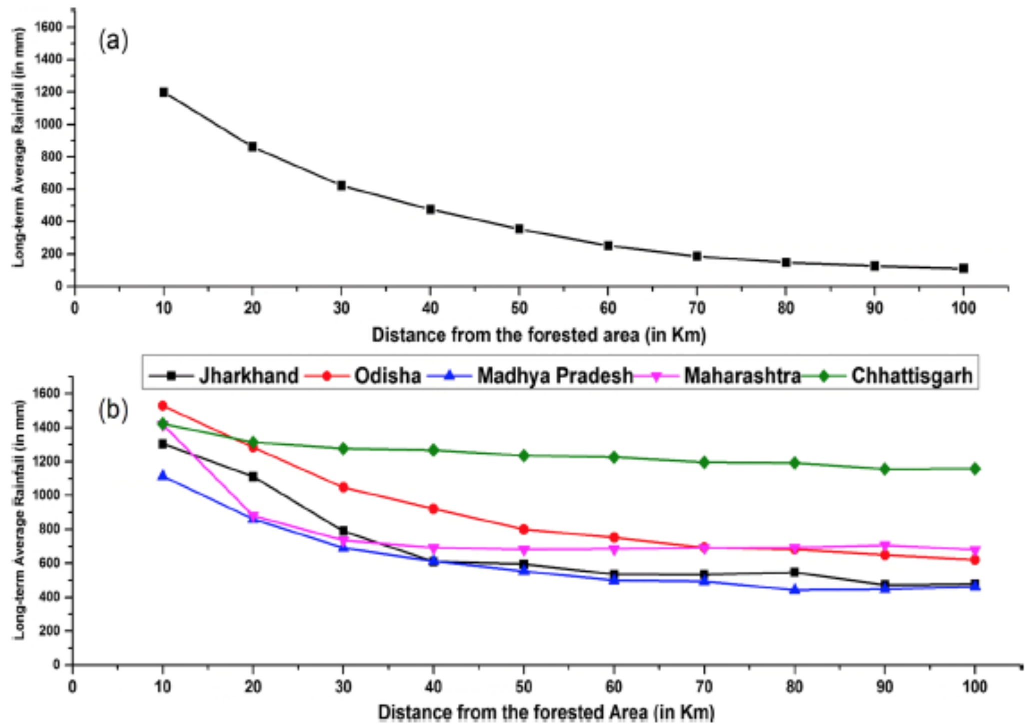
FORESTED :

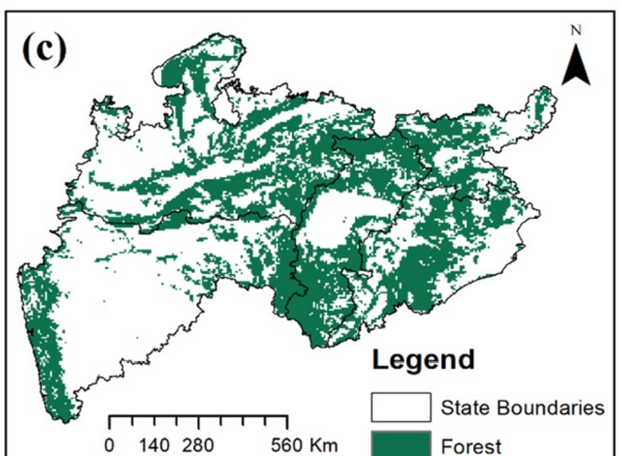
Constant or linear

$P_0 + A x$



Other evidence of spatial correlation between forest distance and rainfall



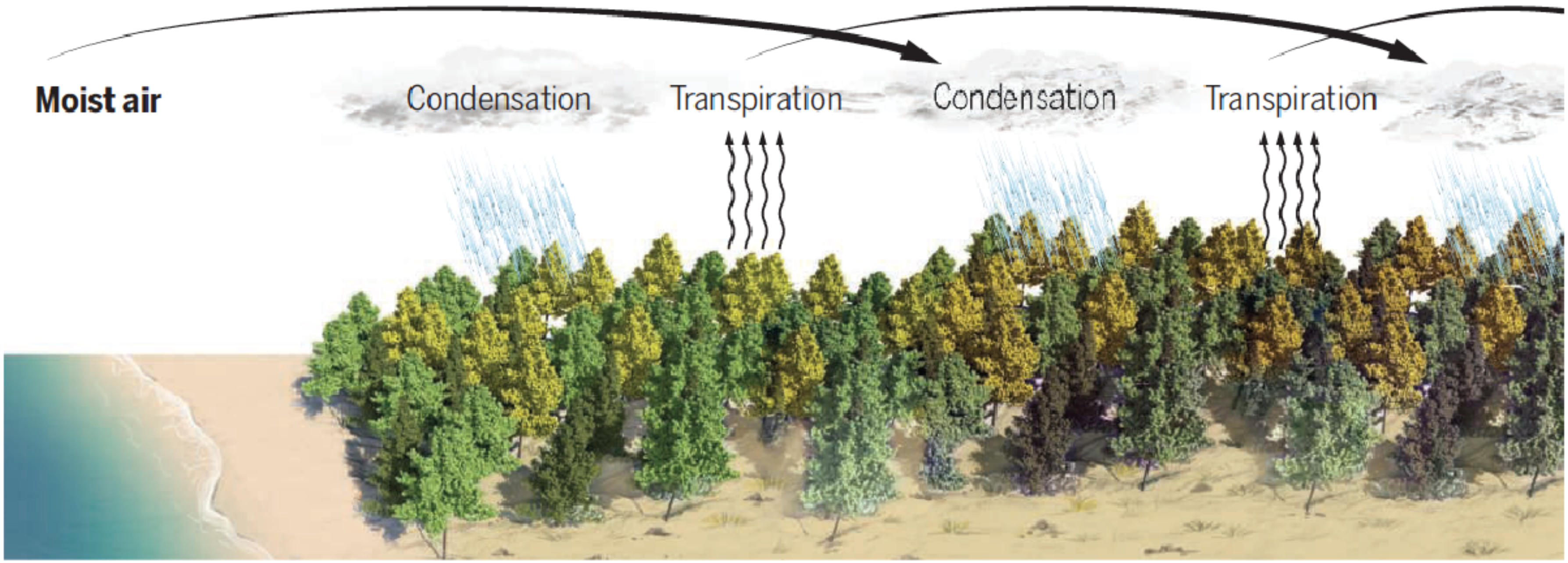


Singh, B. et al. (2024). The relationship between central Indian terrestrial vegetation and monsoon rainfall distributions in different hydroclimatic extreme years using time-series satellite data. *Theoretical and Applied Climatology*, *155*(1), 45-69.

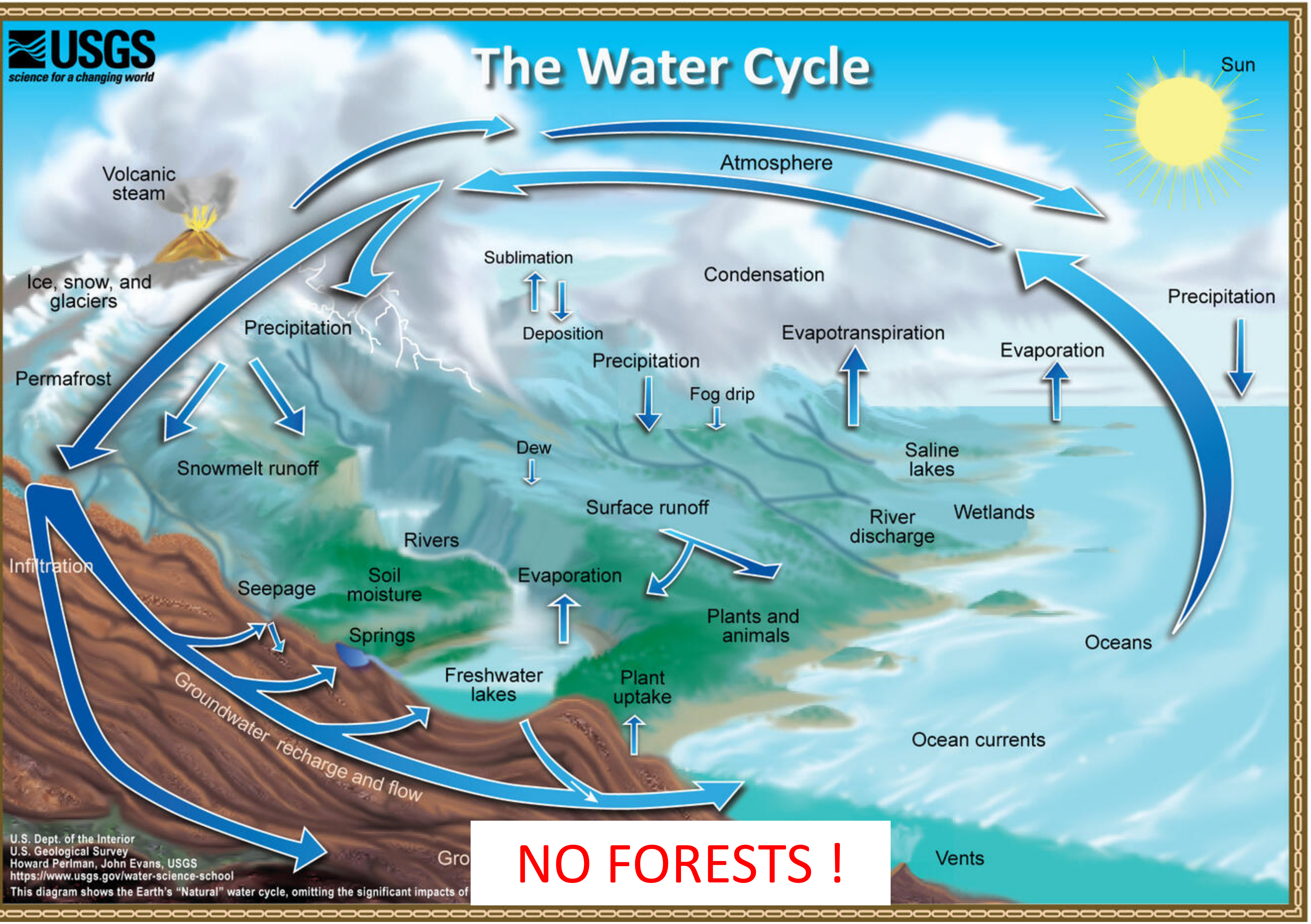
Biotic pump theory

Sowing the wind

The biotic pump theory suggests forests not only make rain, but also wind. When water vapor over coastal forests condenses, it lowers air pressures, creating winds that draw in moist ocean air. Cycles of transpiration and condensation can set up winds that deliver rains thousands of kilometers inland.



Most of meteorologists don’t believe in such **teleconnection**



USGS
science for a changing world
The Water Cycle
Sun
Atmosphere
Volcanic steam
Ice, snow, and glaciers
Sublimation
Deposition
Condensation
Precipitation
Evapotranspiration
Evaporation
Permafrost
Precipitation
Fog drip
Dew
Snowmelt runoff
Saline lakes
Surface runoff
River discharge
Wetlands
Rivers
Infiltration
Seepage
Soil moisture
Evaporation
Plants and animals
Springs
Oceans
Freshwater lakes
Plant uptake
Groundwater recharge and flow
Ocean currents
Gro
Vents
U.S. Dept. of the Interior
U.S. Geological Survey
Howard Perlman, John Evans, USGS
https://www.usgs.gov/water-science-school
This diagram shows the Earth's "Natural" water cycle, omitting the significant impacts of
NO FORESTS !

Computational meteorology : a complex field

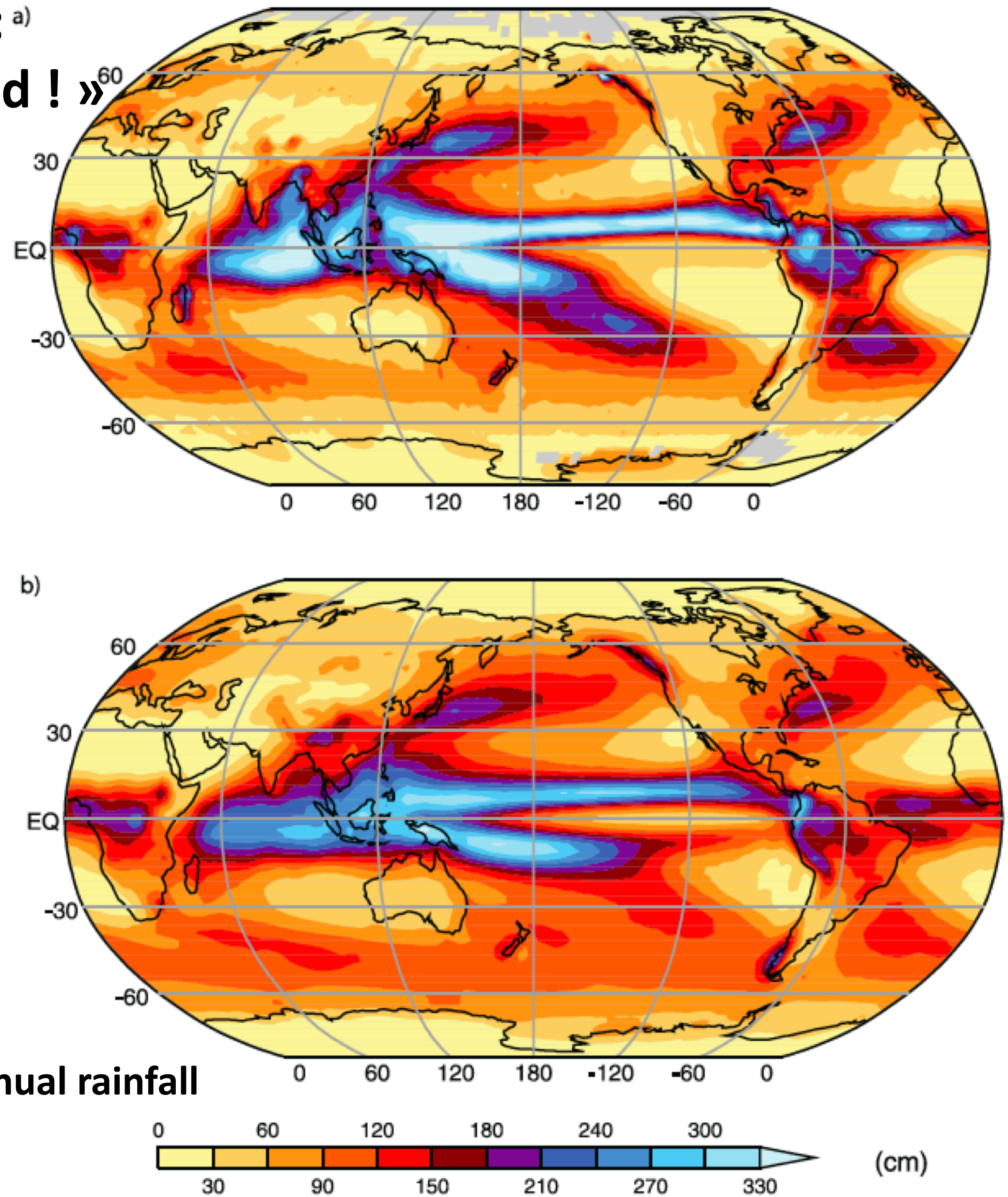
- 3 conservation equations
- Multiple physical processes (including vegetation, hydrology, H_2O phase changes)
- Intensive numerical computing

FORCES → Pressure, winds
ENERGY → Temperature
MASS → C_{H2O} (liquid/gas)

} Water vapor, rain



Meteorological modelers :
« all processes are included ! »



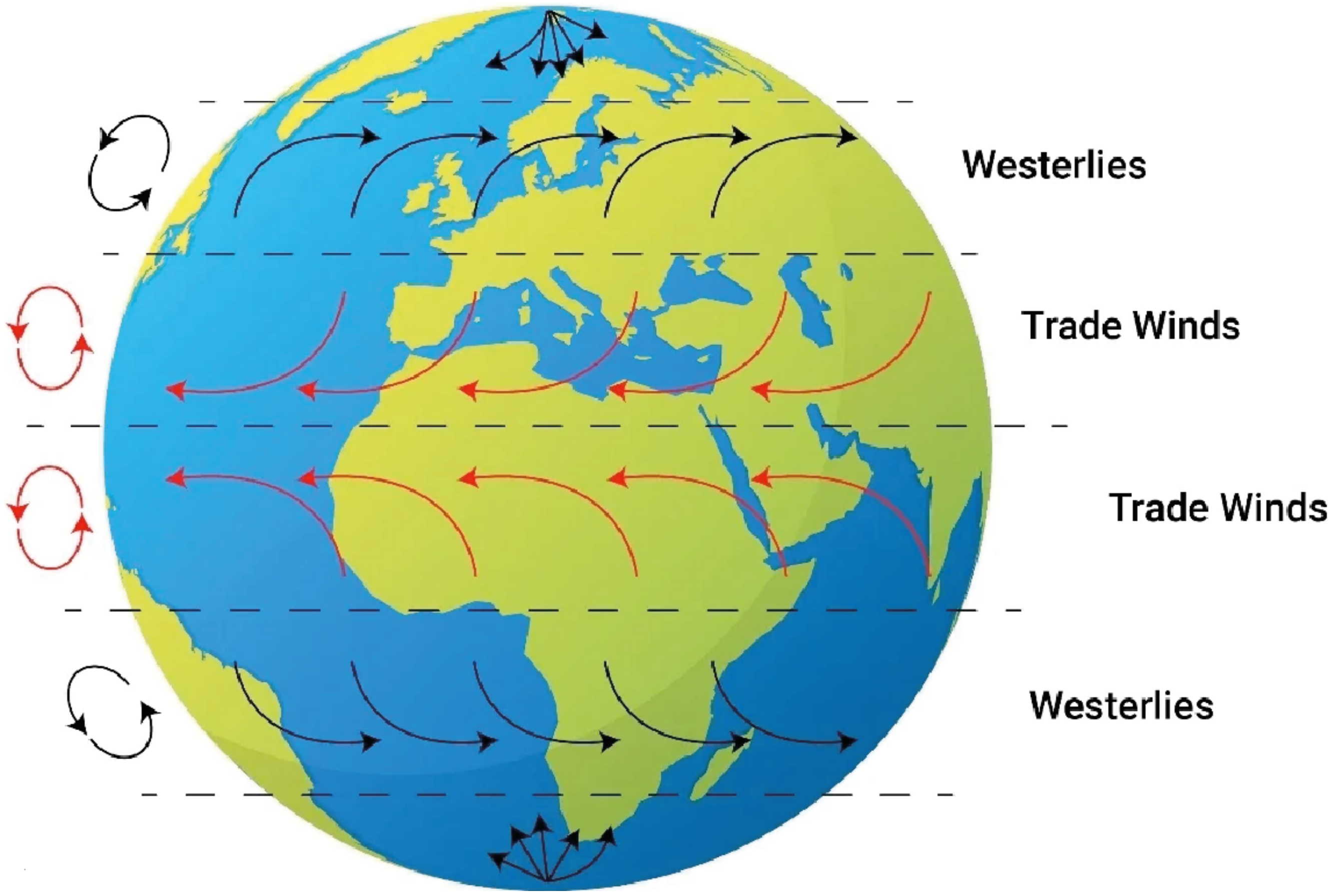
Rainfall (DATA)

Rainfall (MODEL)

Annual rainfall

Yamanaka et al. (2018).

Winds driven meteorology : Coriolis forces, etc

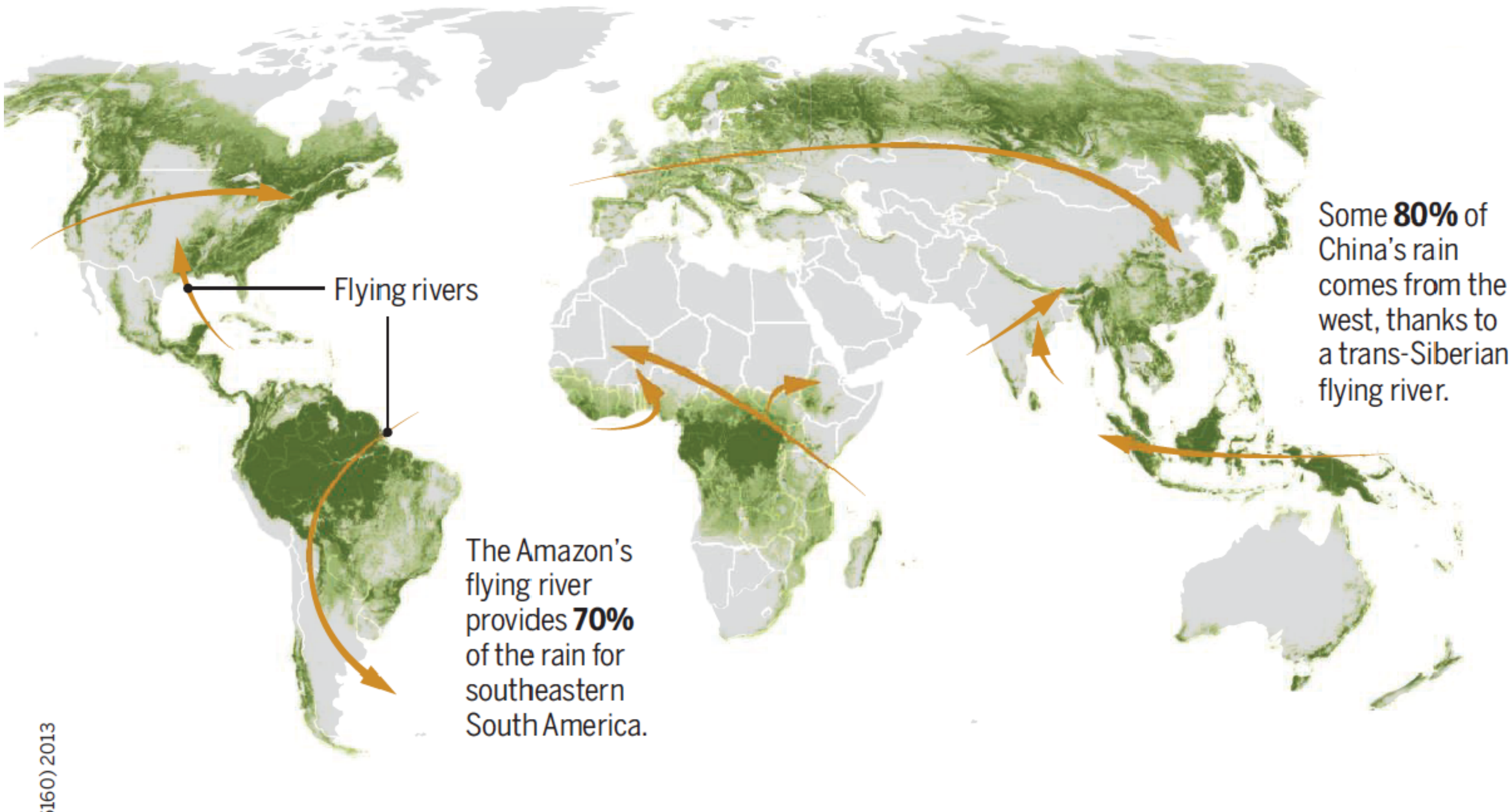


WINDS CARRY WATER VAPOR (ADVECTION)

Tropospheric rivers

Rain parades

So-called flying rivers are prevailing winds that pick up water vapor exhaled by forests and deliver rains to distant water basins. A controversial theory suggests forests themselves drive the winds (bottom).



WINDS CARRY WATER VAPOR

Biotic pump theory

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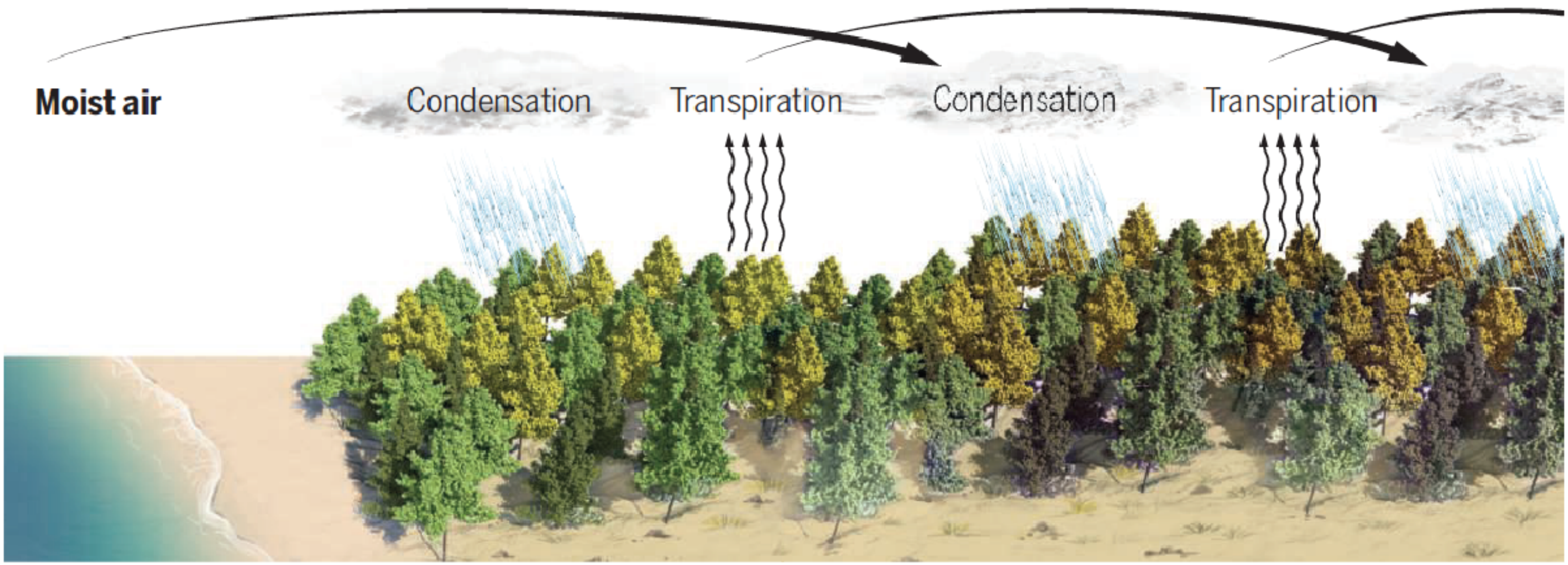
The biotic pump theory suggests forests not only make rain, but also wind. When water vapor over coastal forests condenses, it lowers air pressures, creating winds that draw in moist ocean air. Cycles of transpiration and condensation can set up winds that deliver rains thousands of kilometers inland.



WINDS CARRY WATER VAPOR

Questions :

1. Is water vapor (WV) only transported by winds ?

2. How forests could carry WV ?

3. Does forests removal lead to rain shortage ?

Deforestation effect of land cover change: annual rainfall decay

Perugini, et al. (2017). Biophysical effects on temperature and precipitation due to land cover change. *Environmental Research Letters*, *12*(5), 053002.

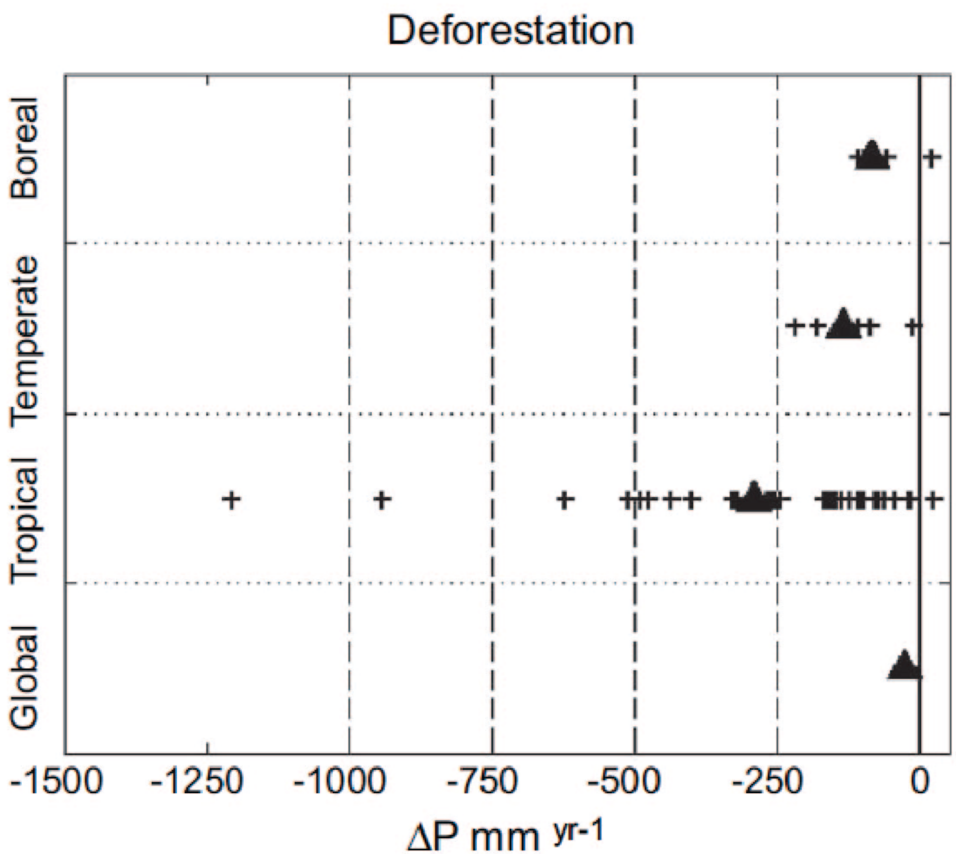


Figure 3. Biophysical effects of regional/global deforestation on regional/global changes of average annual precipitation. Black crosses represent each study data point, filled triangles the average.

AGREEMENT

- ✓ **Two kinds of rainfall profiles: constant over forests and exponential decay elsewhere**
- ✓ **Forest evapotranspiration plays a role for local rainfall (saturation/adiabatic cooling)**
- ✓ Role of forest as global **rainmaker** is not well understood

2. REVISED « BIOTIC PUMP » THEORY

Philosophy of modeling :

« Simplicity is the ultimate sophistication »

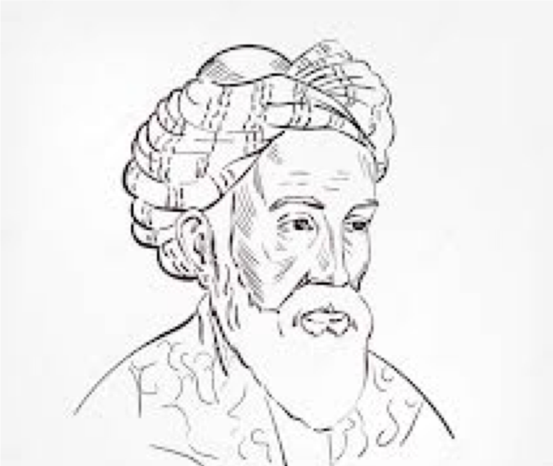
Holistic approach :

water evaporates from ocean to troposphere, rains to continent, re-evaporates and returns to ocean through hydrosystems

Parsimony principle :

Provide a simple and **data**-based physical frame to reveal key **parameters** of forest/climate interactions

→ Better understanding, educational benefits, sharable among scientists, aid for political decision



SOME REMARKS

- ✓ Transport of gas/light particles in the troposphere occurs by **winds** but also with **dispersion** associated to turbulence and convection

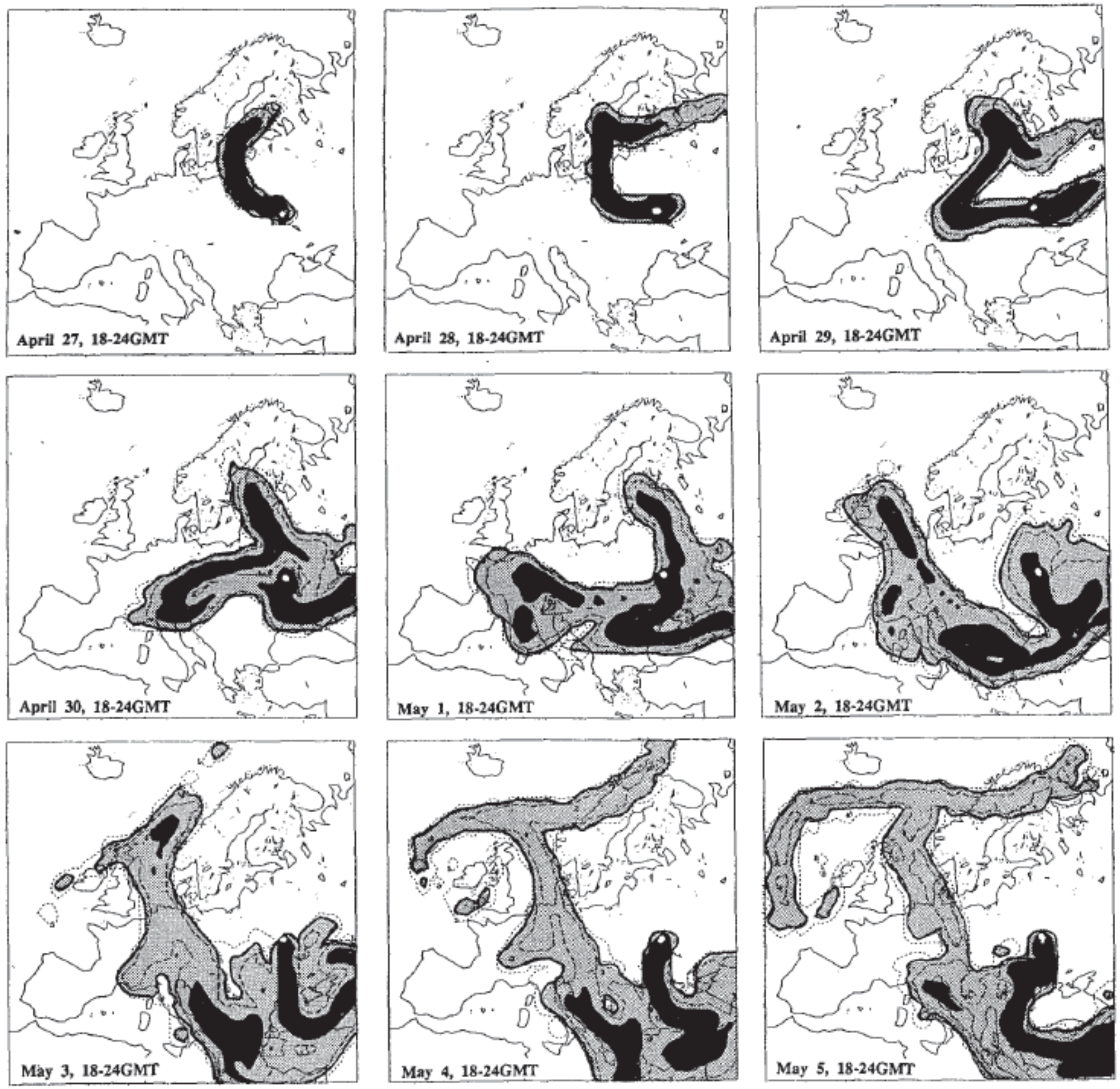
- ✓ Dispersion studies started with models of pollutants transport : CFC, CO, SO_2, Radioactivity

- ✓ Large values of horizontal troposphere diffusivity: **$D_h = 10^3 – 10^5$ m2/s**

1986, Chernobyl pollutant dispersion

April 27th – March 5th

Ishikawa, 1995



2002, Mount Etna eruption: wind + dispersion

clouds composed mostly of water vapour

Tiesi et al. 2006

October 29th

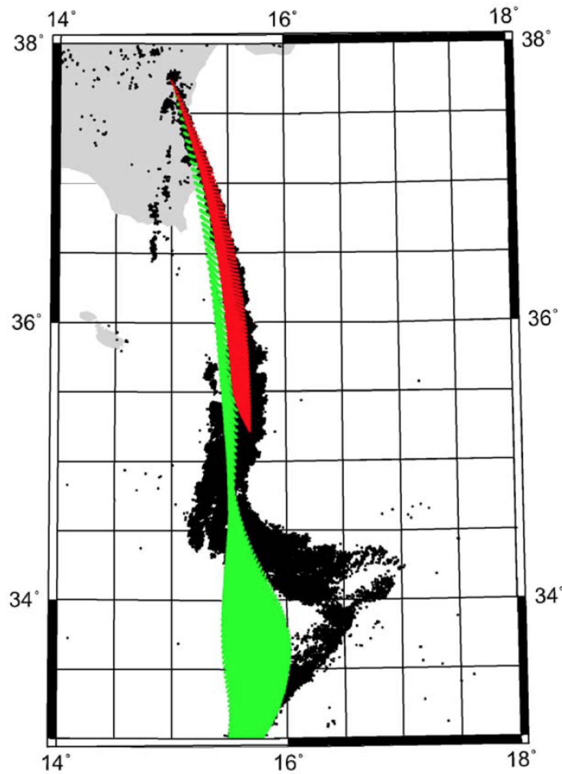


Fig. 5. Superposition of deterministic simulated data with satellite data. Black points: satellite data; dark grey points: deterministic simulation starting on 29 October 2002 at 06:00 UTC (S1); and light grey points: deterministic simulation starting at 00:00 UTC (S2) of the same day.

October 31th

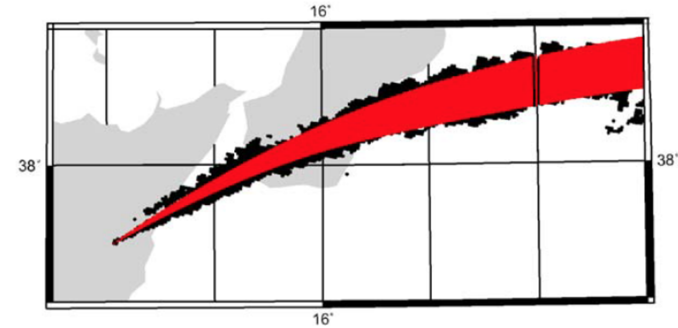
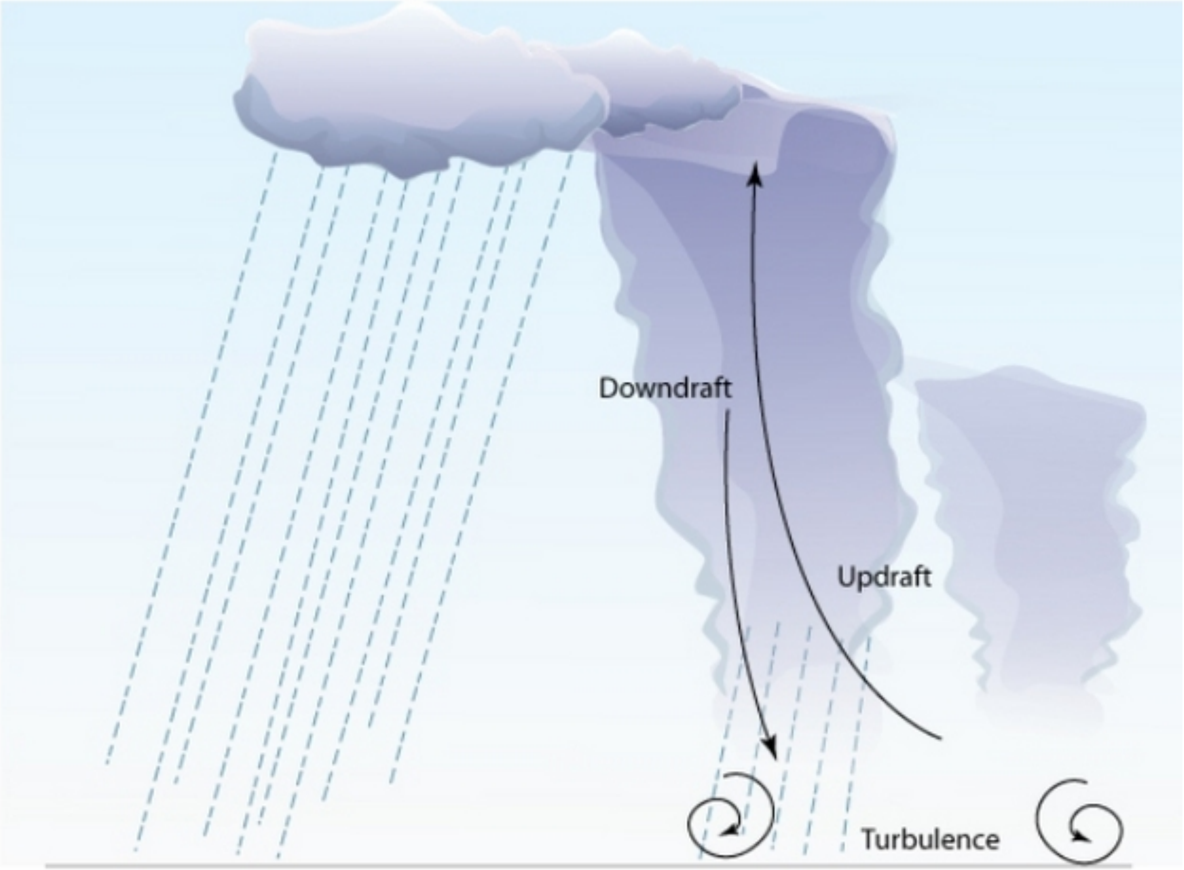


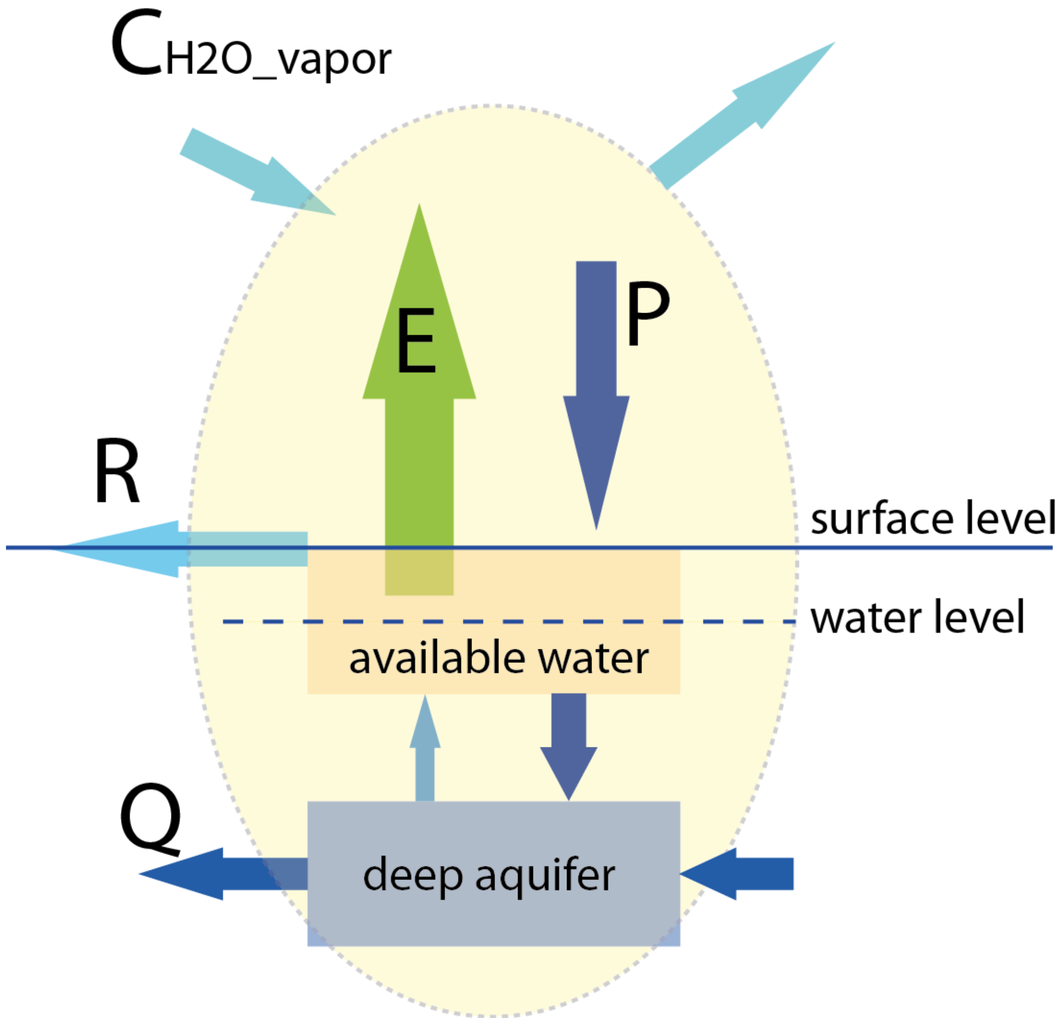
Fig. 6. Superposition of deterministic simulated data with satellite data. Black points: satellite data; dark grey points: deterministic simulation starting on 31 October 2002 at 18:00 UTC.

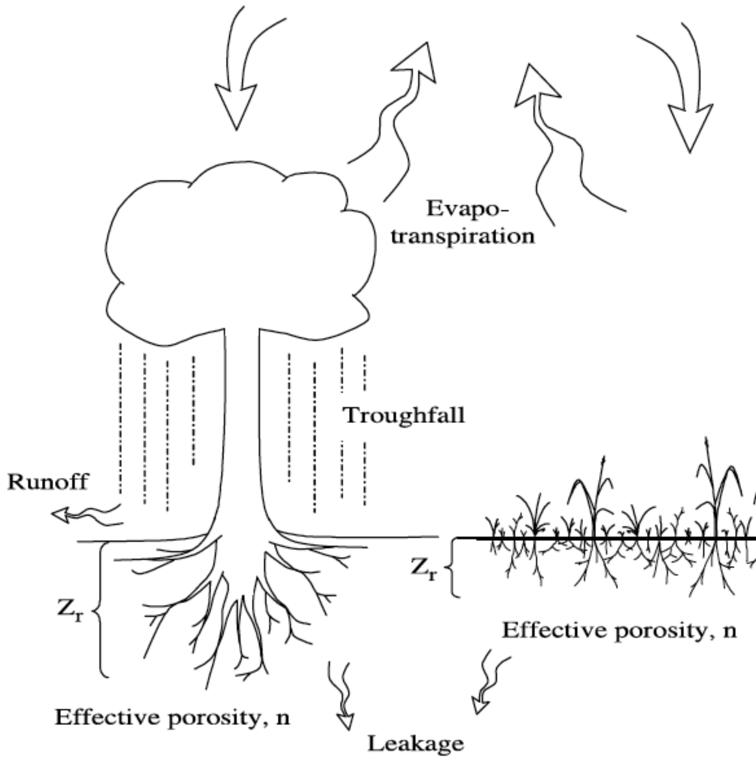
HYPOTHESIS : zero-net horizontal wind

Water vapor is transported only by dispersion (D_h = 10^3 – 10^5 m2/s)



Local water cycle : vertical transfer





Laio et al, 2001

$\Delta H2O = \Delta H_2O\_vapor \quad + \quad (P\text{-}E) \quad - \quad (Q+R)$

Moisture convergence + Infiltration - Outflow

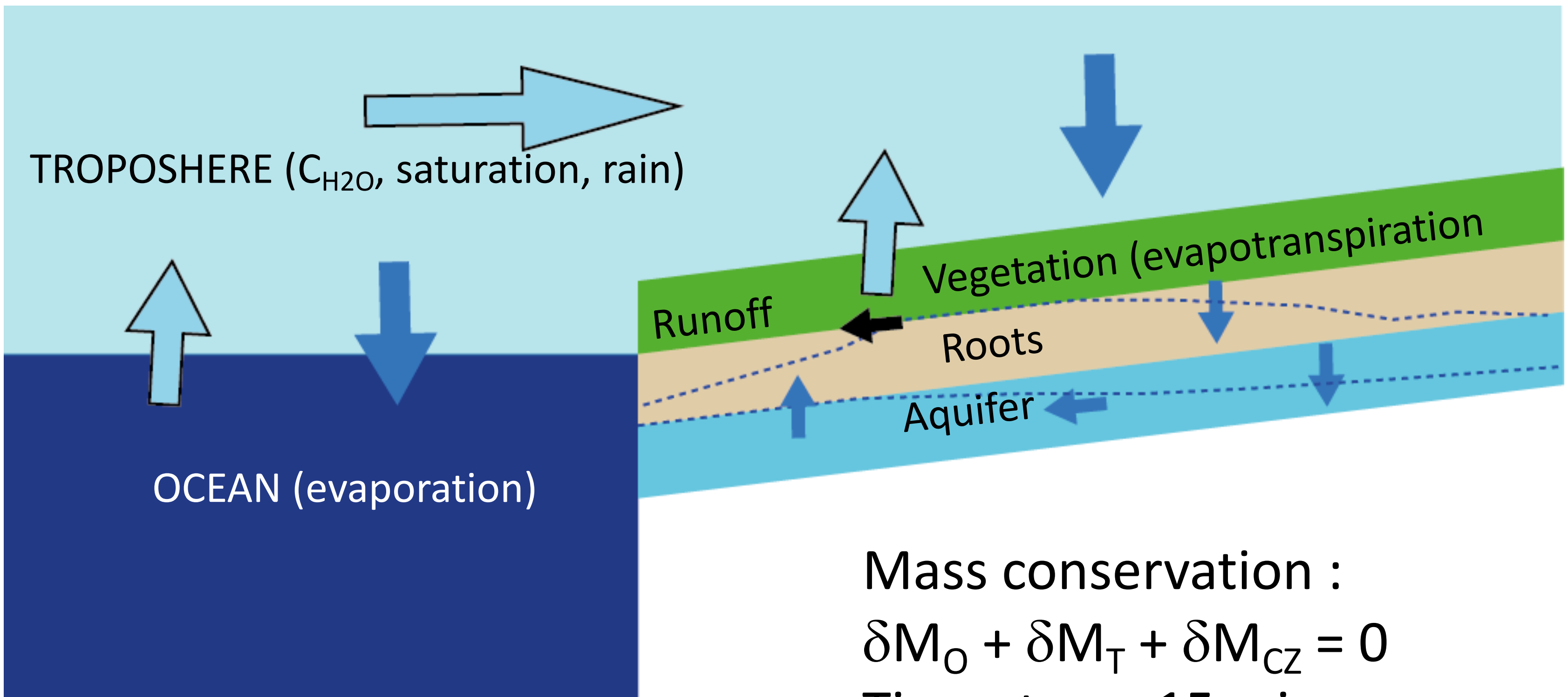
>0 : feeding

<0 : leaking

Global water cycle : horizontal transfer

Numerical model forced by temperature

(daily and annual sinusoidal variation)



Mass conservation :

$\delta M_O + \delta M_T + \delta M_{CZ} = 0$

Time step = 15 min

Runs : 50 years

Computation of pluviometry after 50 years

- ✓ Initially empty aquifers
- ✓ Admissible values of

diffusivity, plant evapotranspiration, roots depth, slope, temperatures

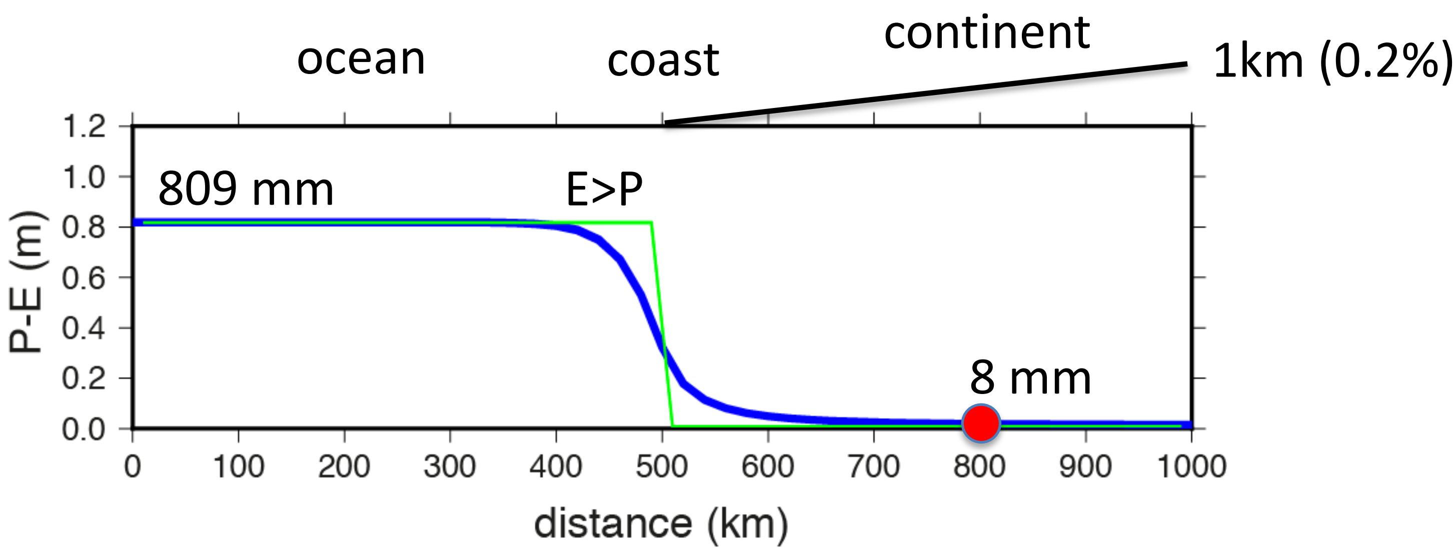
Experiment #	Troposphere diffusivity Dh (m2/s)	EVT_0 (mm/j/°C)	Topographic Slope (%)	ΔT (°C)	P_{300km} (mm/yr)
1 (bare soil)	**10^3**	0	0.2	5	**?**
2 (bare soil)	**10^4**	**0**	0.2	5	**?**
3	10^4	**0.1**	0.2	5	**?**
4	10^4	**0.2**	0.2	5	**?**
5	10^4	**0.3**	**0.2**	5	**?**
6	10^4	0.3	**0.02**	**5**	**?**
7	10^4	0.3	0.02	**10**	**?**

What is the pluviometry 300 km away from the coast ?

Experiment 1

EVT = 0 (bare soil)

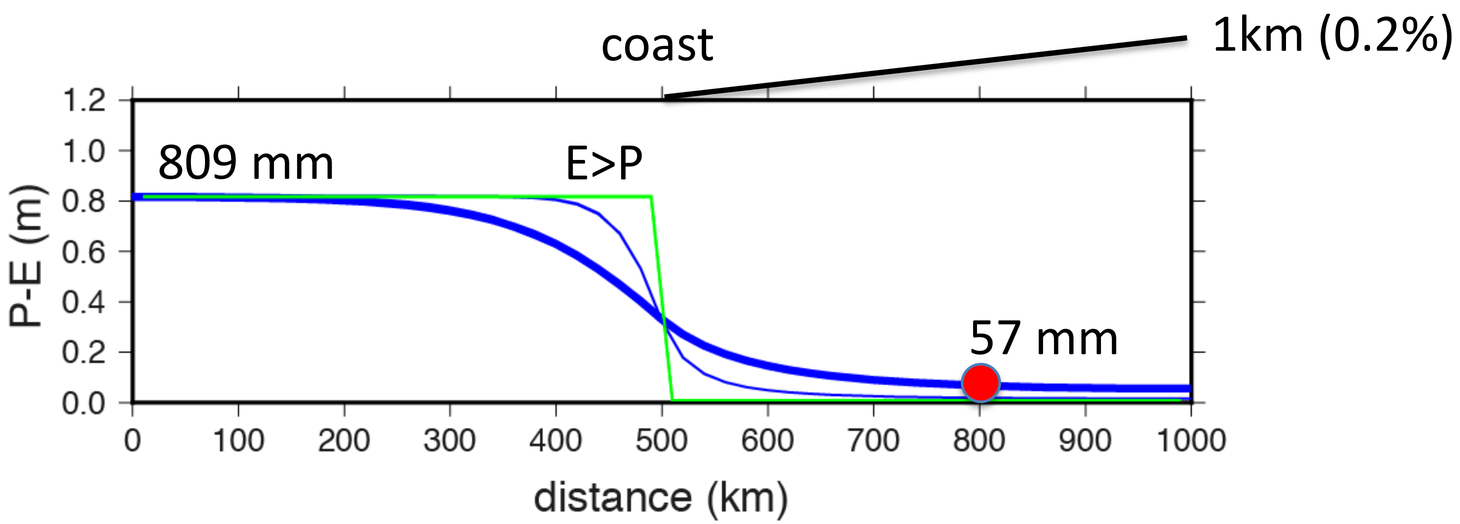
Troposphere diffusivity 10^3 m2/s



Experiment 2

EVT = 0 (bare soil)

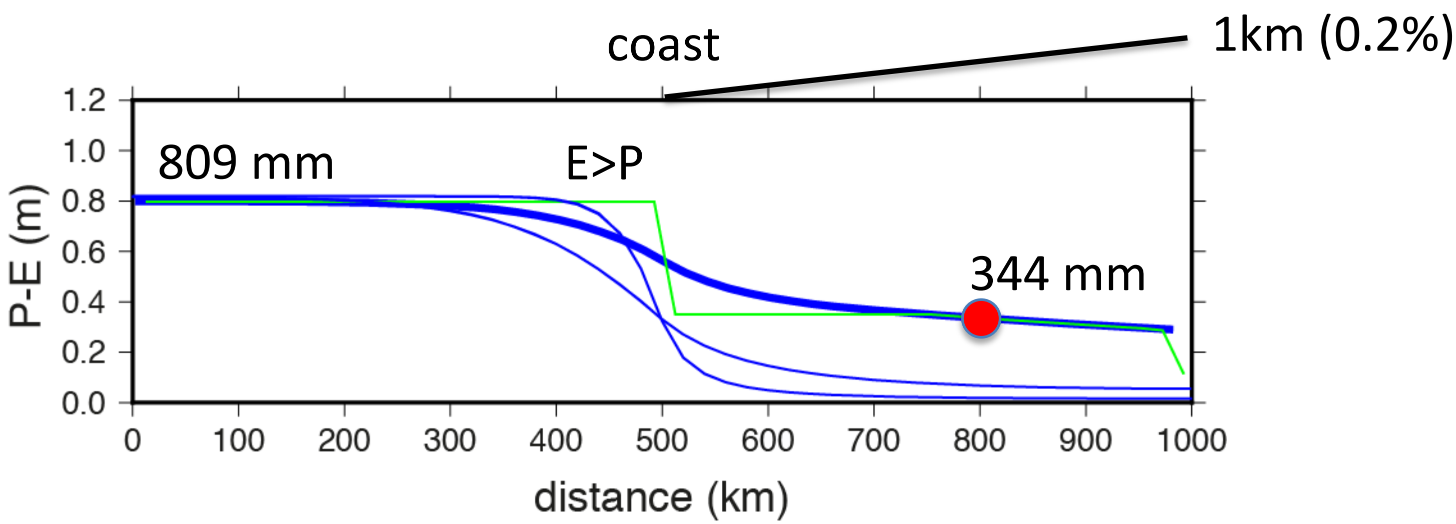
Troposphere diffusivity $10^3 \rightarrow$ **10^4 m2/s**



Experiment 3

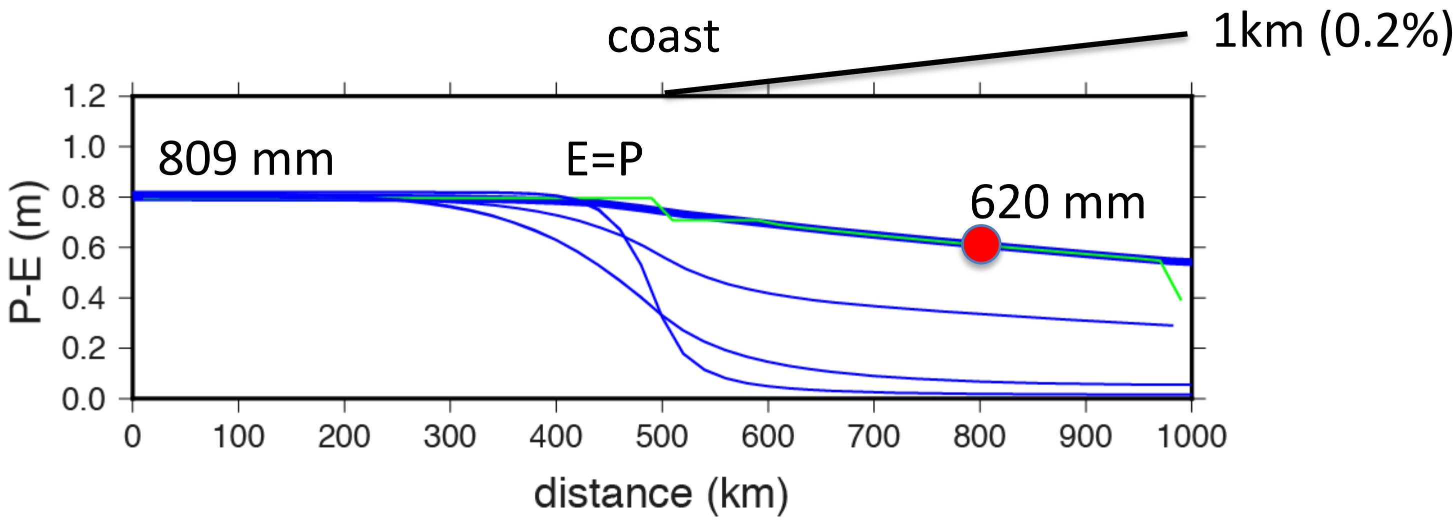
EVT = 0.1mm/d/°C (some plants)

Troposphere diffusivity 10^3 → **10^4 m2/s**



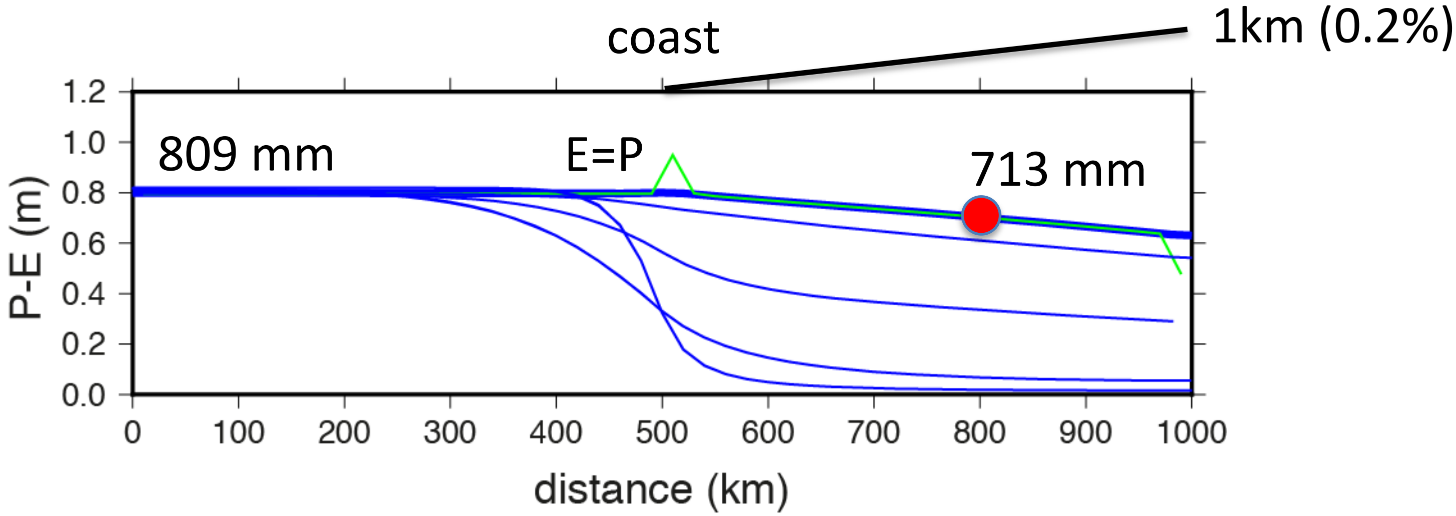
Experiment 4

EVT = 0.2 mm/d/°C (more plants)



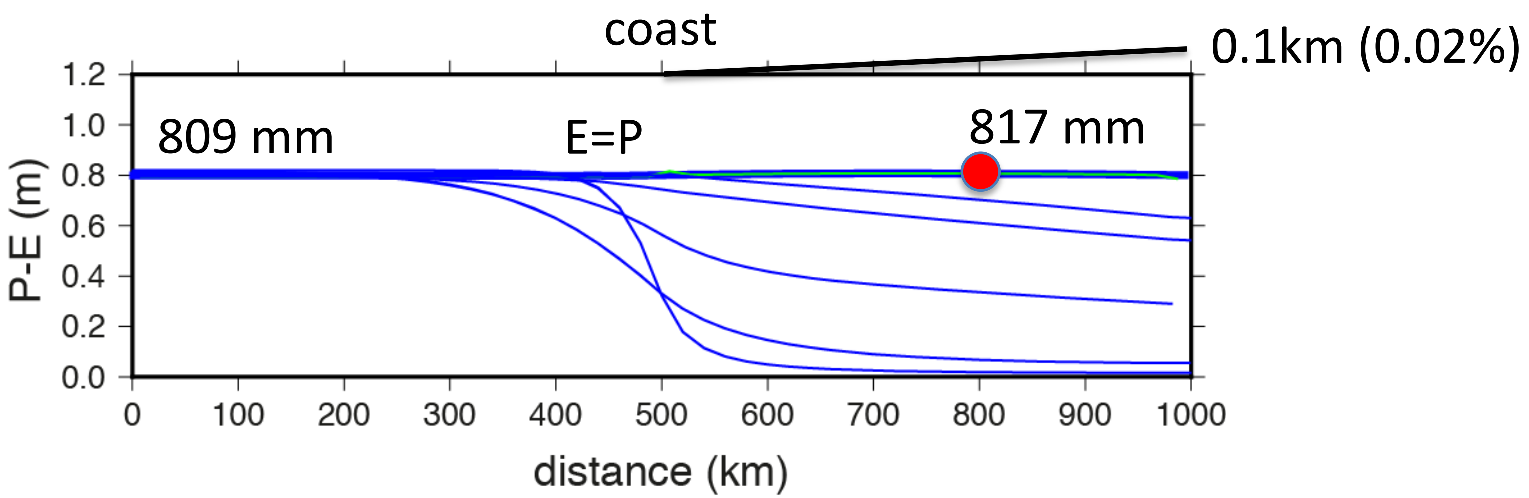
Experiment 5

EVT = 0.3 mm/d/°C (only forests)



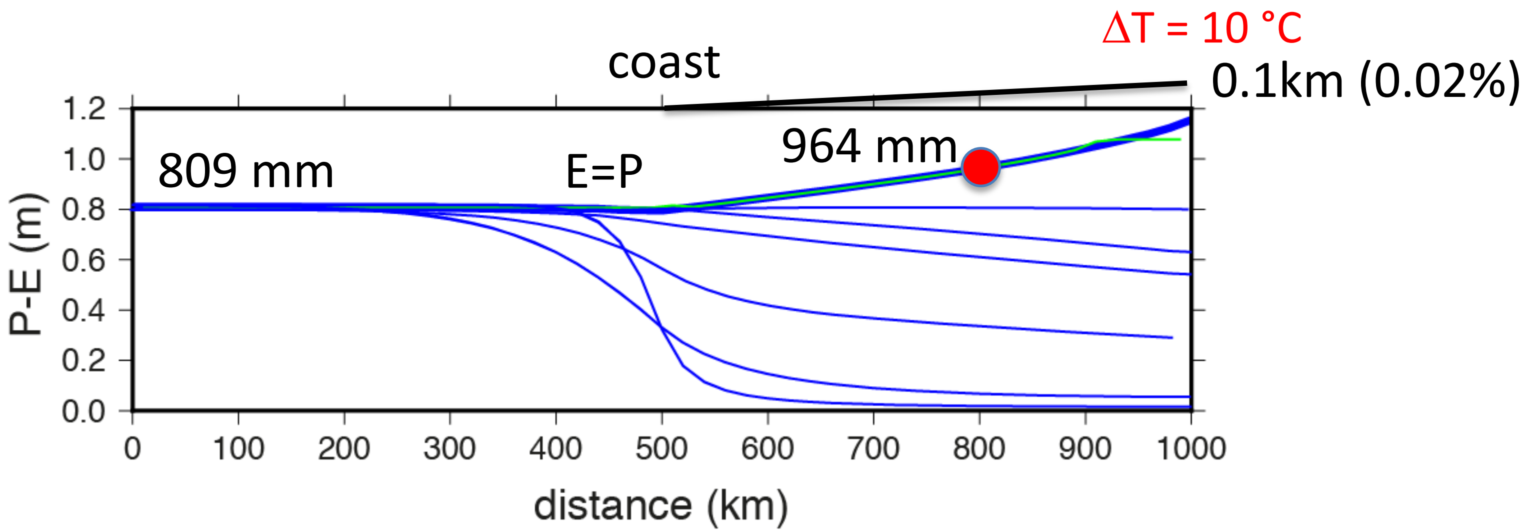
Experiment 6

Slope 0.2 % → 0.02 % (flatter topography)

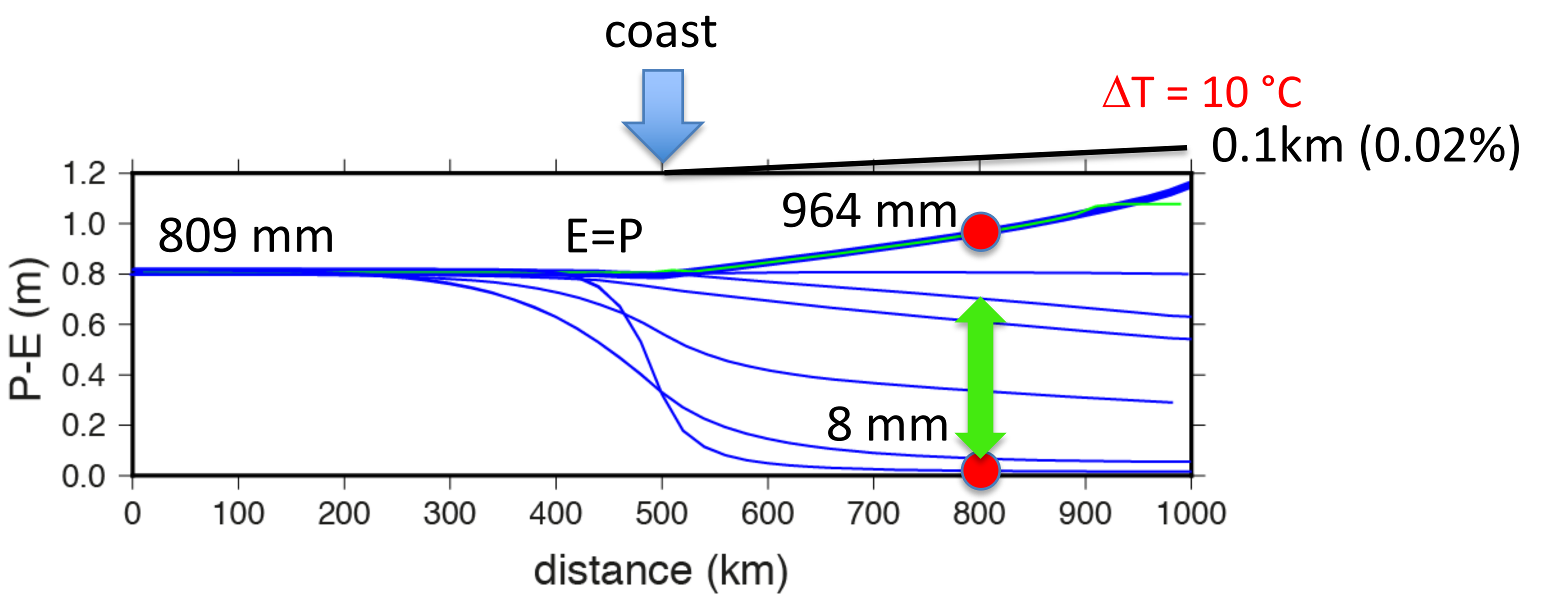


Experiment 7

ΔT continent 5 °C → 10 °C (constrasted temperatures)



Experiments 1 to 7



X 100 amplification

60 % due to water vapor dispersion + high evapotranspiration

Other : aquifer leakage, temperature variation

Summary of pluviometry after 50 years (steady state)

Experiment #	Troposphere diffusivity Kh (m2/s)	EVT_0 (mm/j/°C)	Topographic Slope (%)	ΔT (°C)	P_{300km} (mm/yr)
1	10^3	0	0.2	5	8
2	10^4	0	0.2	5	57
3	10^4	0.1	0.2	5	344
4	10^4	0.2	0.2	5	620
5	10^4	**0.3**	**0.2**	5	**713**
6	10^4	0.3	0.02	5	817
7	10^4	0.3	0.02	10	964

Experiment 5

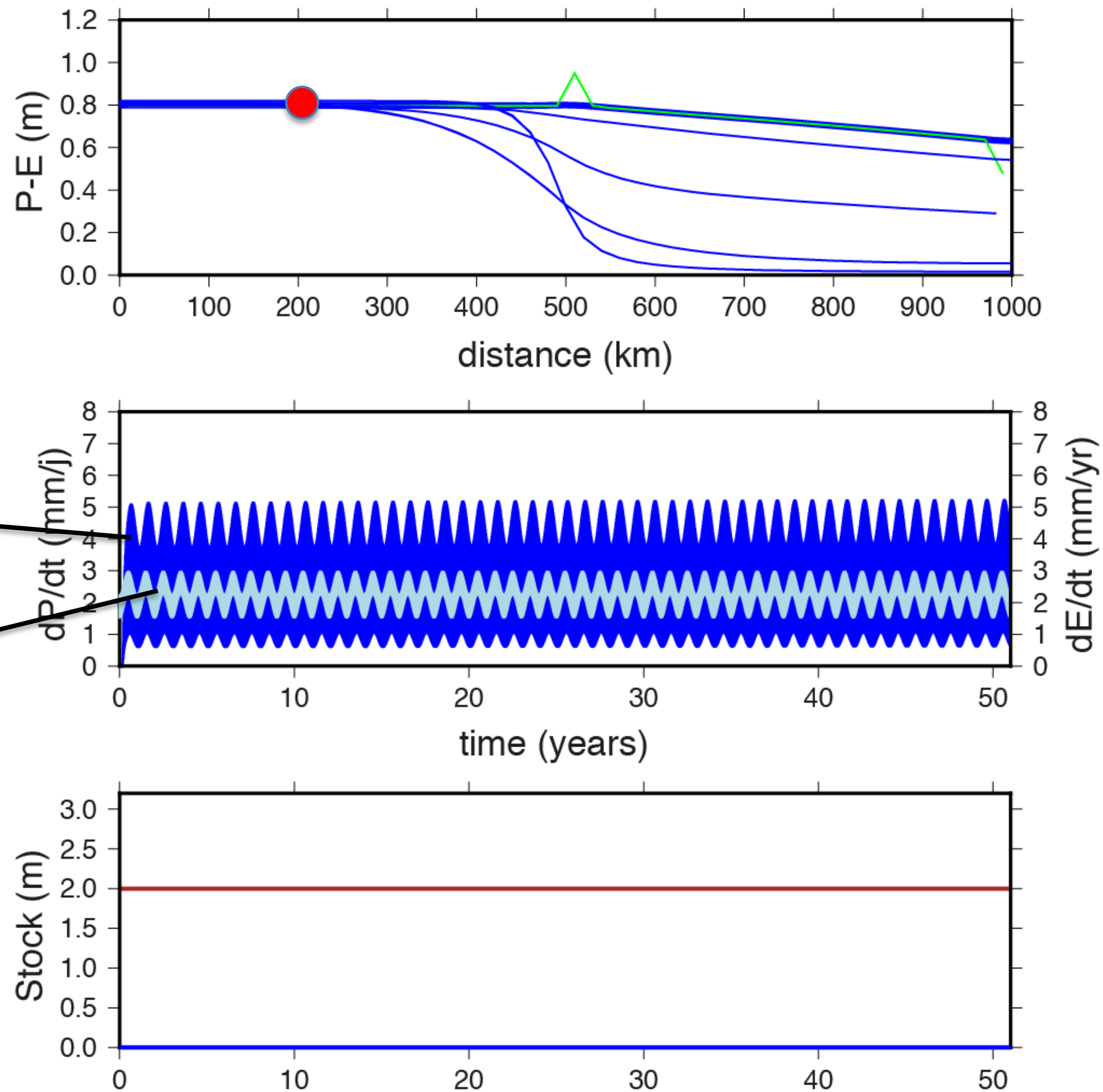
Ocean:

Time evolution over 50 years

Rain rate

Evaporation rate

Infinite stock



Coast:

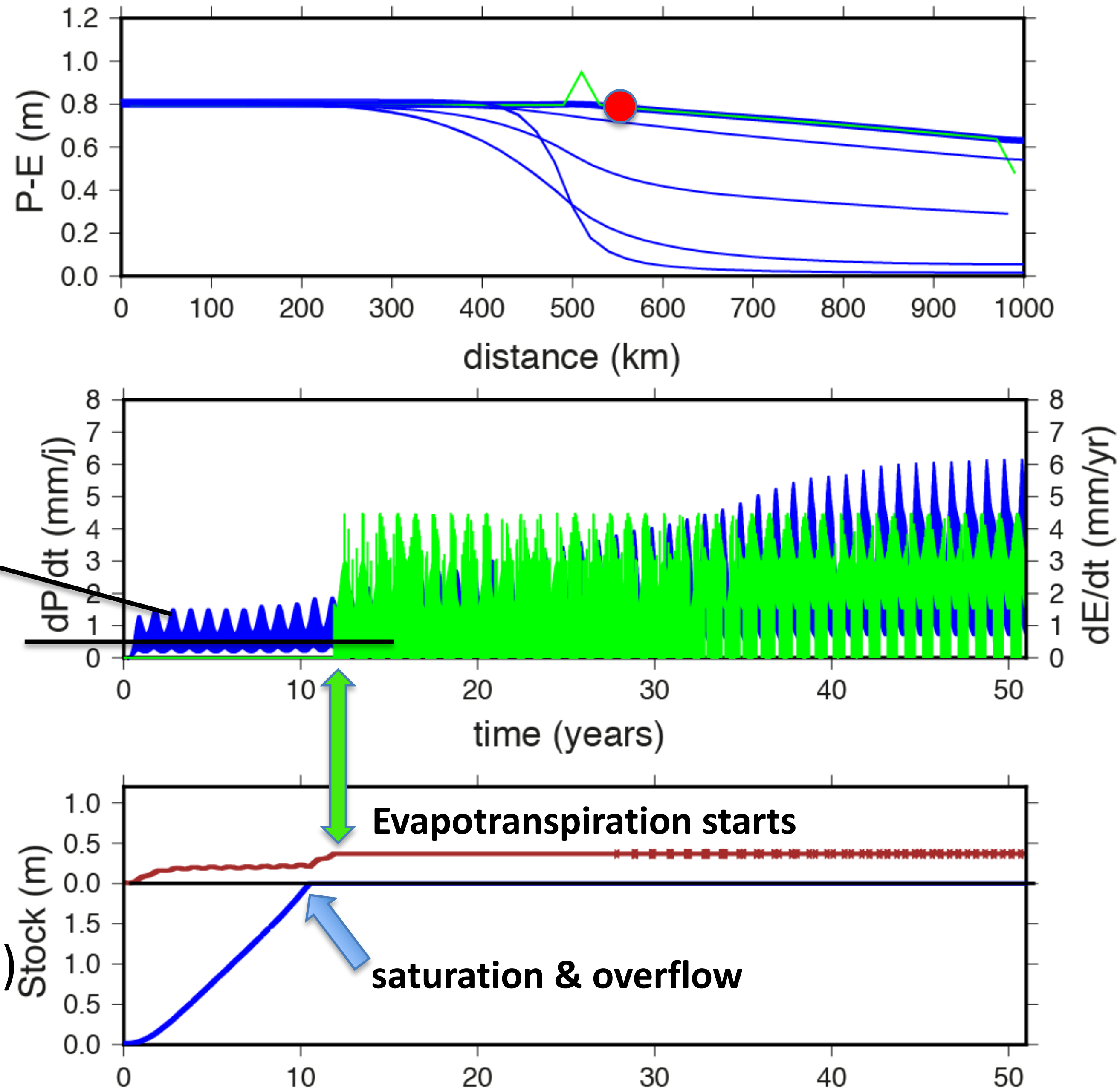
Time evolution over 50 years

Rain rate

Evapotranspiration rate

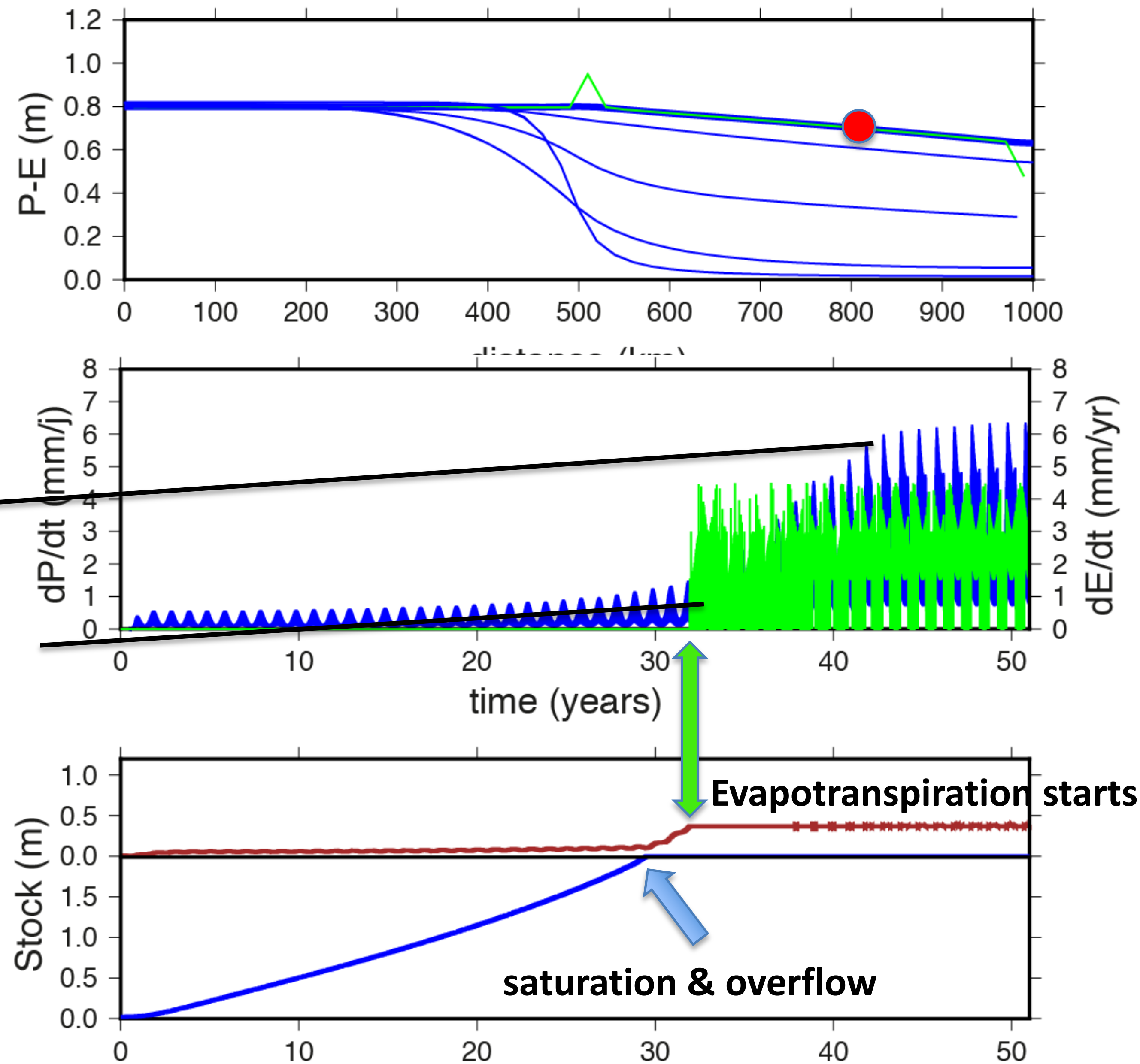
Aquifer filling

(**11 yrs**, starts empty)



Continent:

Time evolution over 50 years



Rain rate

Evapotranspiration rate

Aquifer filling
29 yrs

Preliminary summary of experiments

Due to long range water vapor **dispersion**,

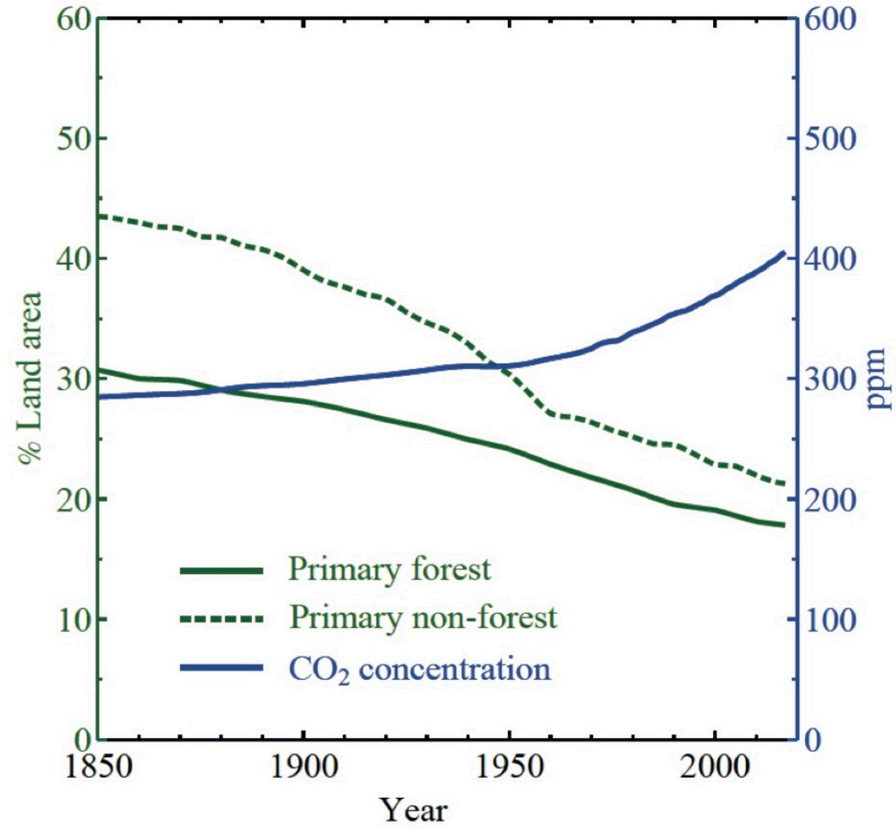
High annual rainfall is occuring inside continent under 3 conditions:

1. High potential evaporation (EVT_0)
2. Deep roots for real evaporation
3. Low aquifer leakage

1. + 2. are only met for natural mature forests

This theory explains the relation between deforestation and water shortage

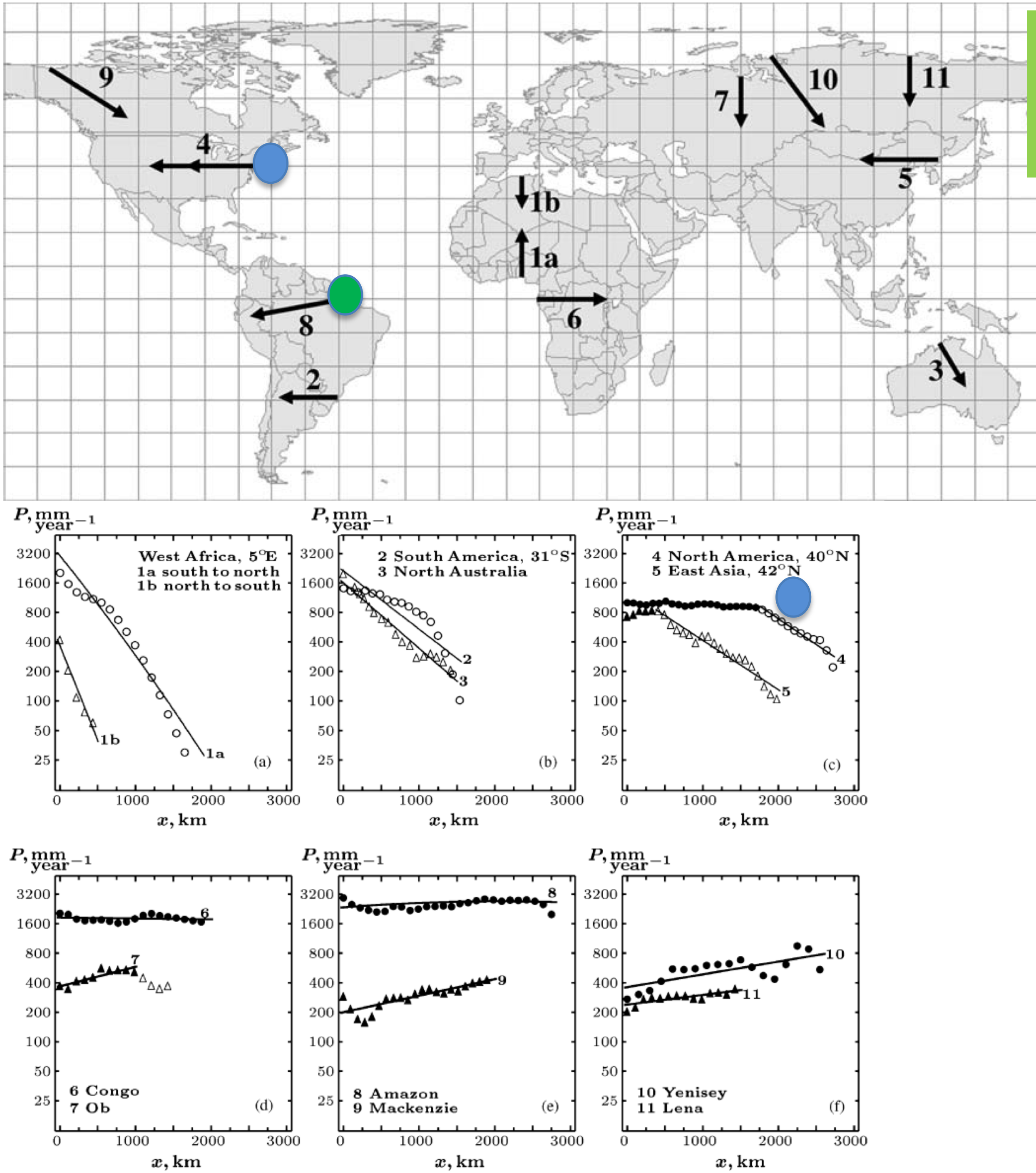
Might be a more important societal topic than CO_2 increase and global warming



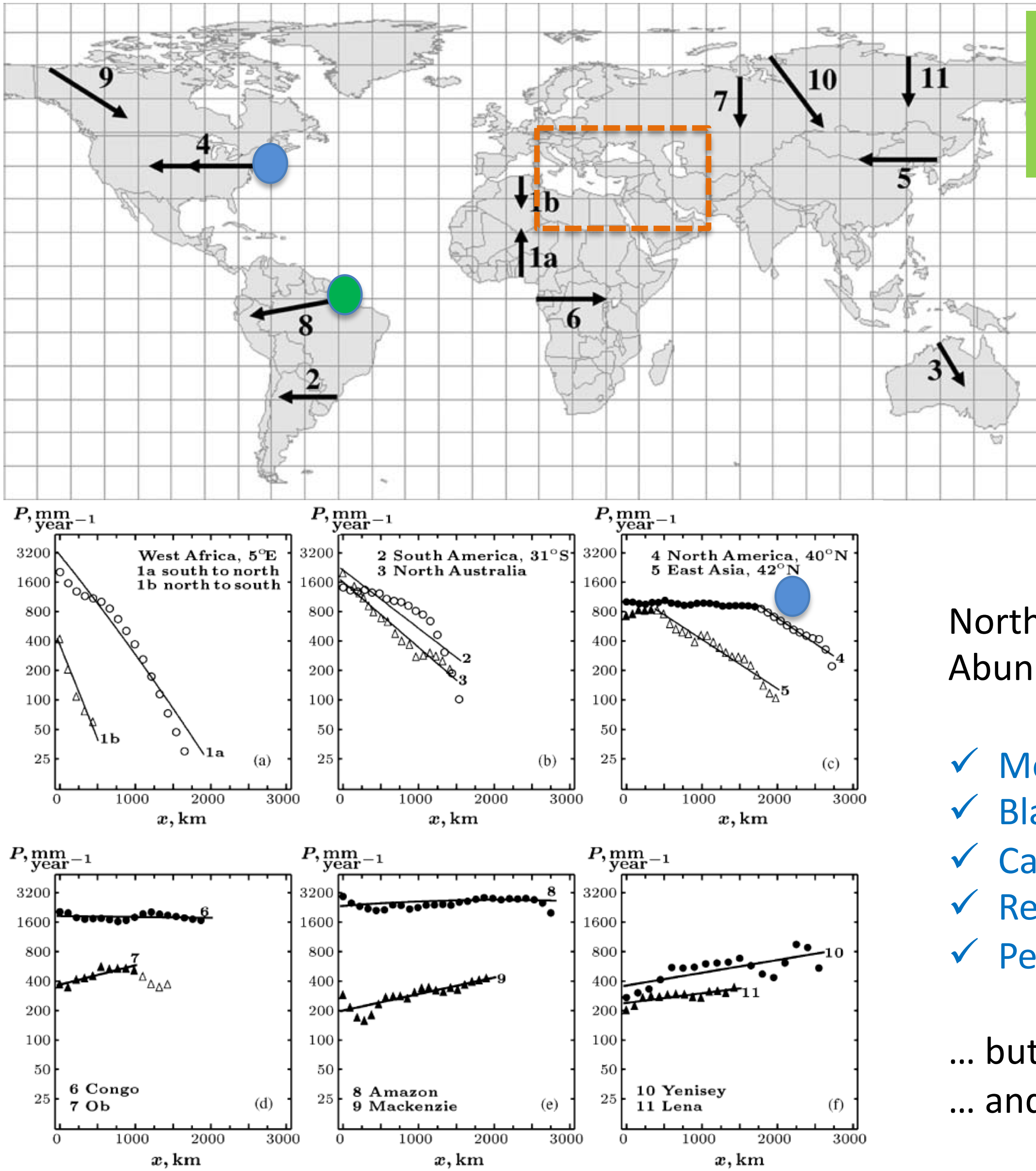
Makarieva, A. M., Nefiodov, A. V., Rammig, A., & Nobre, A. D. (2023). Re-appraisal of the global climatic role of natural forests for improved climate projections and policies. *arXiv preprint arXiv:2301.09998*.

3. LESSONS for the PAST

ANNUAL RAINFALL PROFILES



ANNUAL RAINFALL PROFILES



North africa and Middle East:
Abundant oceanic water vapor:

- ✓ Mediterranean sea
- ✓ Black sea
- ✓ Caspian sea
- ✓ Red sea
- ✓ Persian gulf

… but limited rain
… and limited forested

Forests, civilization and climate

NORTHERN AFRICA:

Wright (2017). Humans as agents in the termination of the African Humid Period. *Frontiers in Earth Science*, *5*, 237134.

MEDITERRANEAN:

Cline (2014). 1177 BC: The Year Civilization Collapsed. Princeton University Press.

IRAN :

Vidale et al. (2017). The late prehistory of the northern Iranian Central Plateau (c. 6000-3000 BC): growth and collapse of decentralised networks. Surplus without the state, political forms in prehistory. In *10th archaeological conference of Central Germany*.

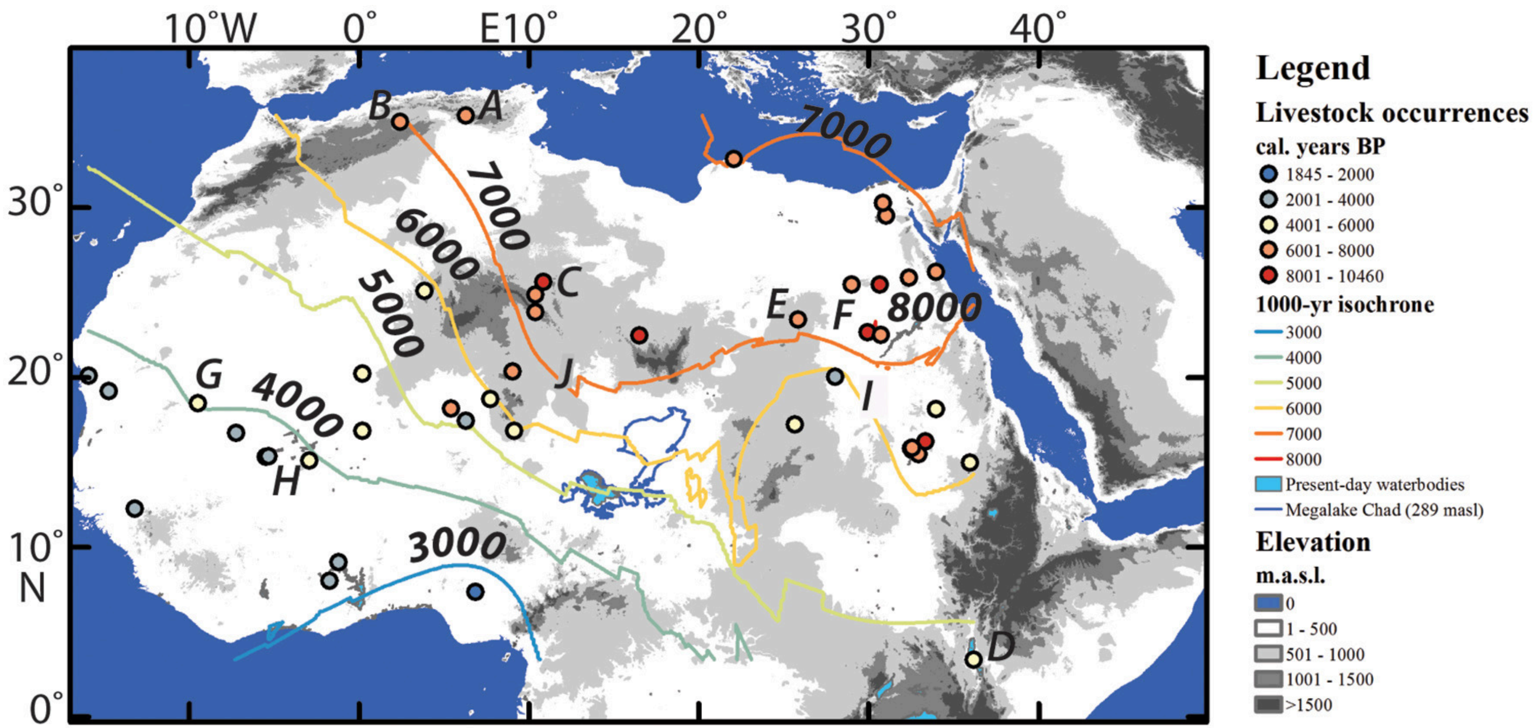
Vaezi et al. (2022). New multi-proxy record shows potential impacts of precipitation on the rise and ebb of Bronze Age and imperial Persian societies in southeastern Iran. *Quaternary Science Reviews*, *298*, 107855.

Shoaee et al. (2023). Defining paleoclimatic routes and opportunities for hominin dispersals across Iran. *Plos one*, *18*(3), e0281872.

Nazari et al. (2024) The myth of Lake Saveh, Central Iranian Plateau: a new synthesis of geological, archaeological and historical data

Africa : Holocene livestock sites

Wright (2017)



« Because humans have been documented as exerting significant pressures on the Net Primary Productivity of prehistoric and historic landscapes elsewhere in the world, it is conceivable that they were also catalysts in accelerating the pace of devegetation in the Sahara at the end of the African Humid Period »

Mid-Holocene drought events in Iran

Vidale et al. (2017).

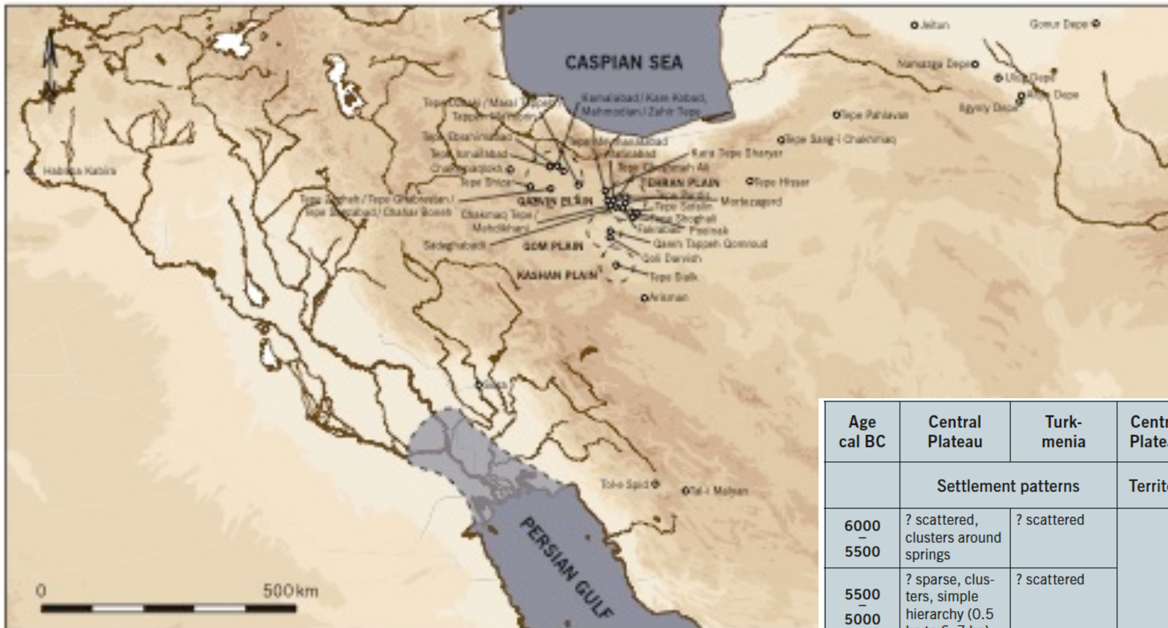


Fig. 1 Map of the Iranian Plateau showing the late prehistoric sites discussed in the text.

Wet

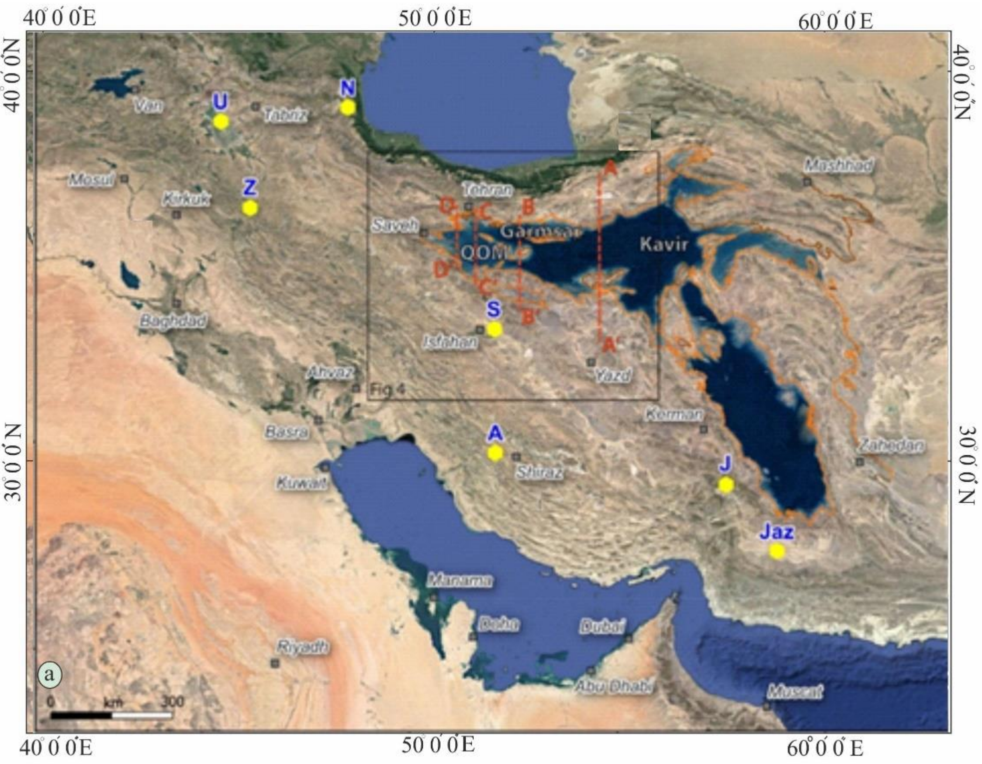
to

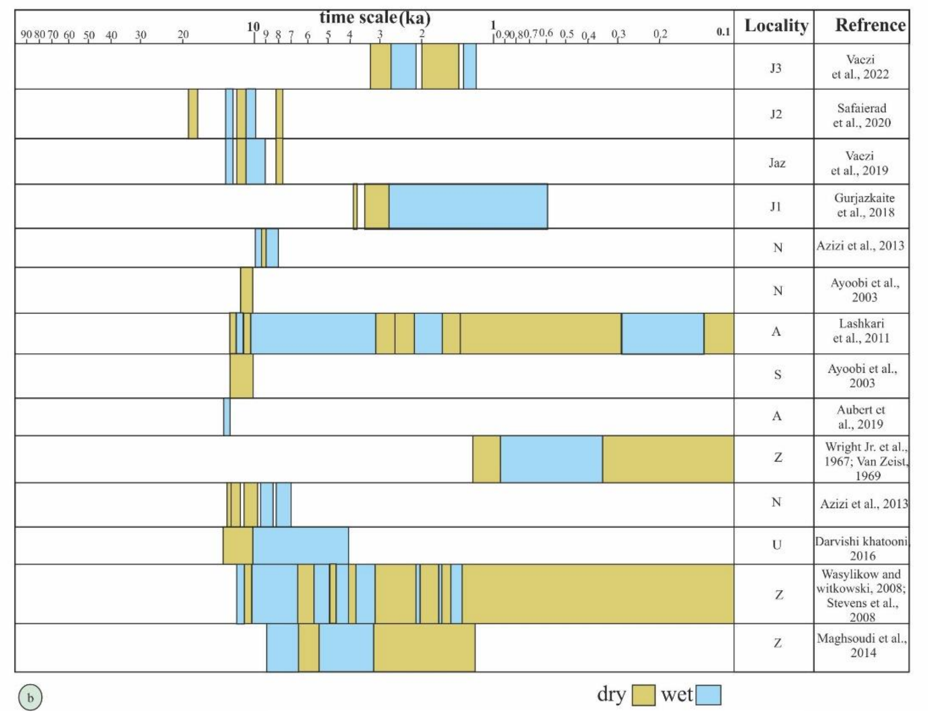
Dry

Age cal BC	Central Plateau	Turk-menia	Central Plateau	Turk-menia	Central Plateau	Turk-menia	Central Plateau	Turk-menia	Central Plateau	Turk-menia
	Settlement patterns		Territorial potential		Precipitation		Artificial irrigation		Administration	
6000–5500	? scattered, clusters around springs	? scattered	Permeable to outer valleys	Limited (horizontal shift)	Limited but higher than present in mid Holocene	Limited (but higher than present in mid Holocene) and greater than in Central Plateau	–?	Incipient	–?	Tokens
5500–5000	? sparse, clus-ters, simple hierarchy (0.5 ha to 6–7 ha)	? scattered					Incipient ?	Simple canal networks	Tokens	Tokens
5000–4500	? sparse, clus-ters, simple hierarchy (0.5 ha to 6–7 ha)	? scattered					Simple canal networks	Simple canal networks	Tokens	Tokens expanding use
4500–4000	? sparse, clus-ters, simple hierarchy (0.5 ha to 6–7 ha)	? scattered, but growing in number					Simple canal networks	Simple canal networks	Tokens	Tokens expanded use, animal forms
4000–3500	? sparse, clus-ters, simple hierarchy (0.5 ha to 6–7 ha)	Two-tiered hierarchy (< 1 ha vs. 10–20 ha)					Simple canal networks	Canal networks and basins	Tokens	Seals with eccentric (off-centre/ off-centred) holes
3500–3000	Deformed hier-archy: 0.5 ha to specialised industrial areas measuring 30–50 ha	Probably three-tiered hierarchy (capitals > 30 ha)					Simple canal networks	Canal networks and basins	Sporadic use of seals (?) »Proto-elamite« tablets	General use of seals with central holes
3000–2500	Collapse, abandonment	Urbanism peak (capitals > 30–50 ha)		**Strongly cir-cumscri-bed (Murghab)**	**Drought event**	**Drought event**	–	Canal networks and basins	–	General use of seals, no writing
2500–1700	Desert	Former cities abandoned, palatial urba-nism in the Murghab delta		Strongly cir-cumscri-bed (Murghab)	Increased aridity	Increased aridity	–	Canal networks and basins urban artifi-cal basins	–	Seals and no writing

Archeology of the Central Iranian plateau during Holocene

Nazari et al. (2024).





Wet Dry

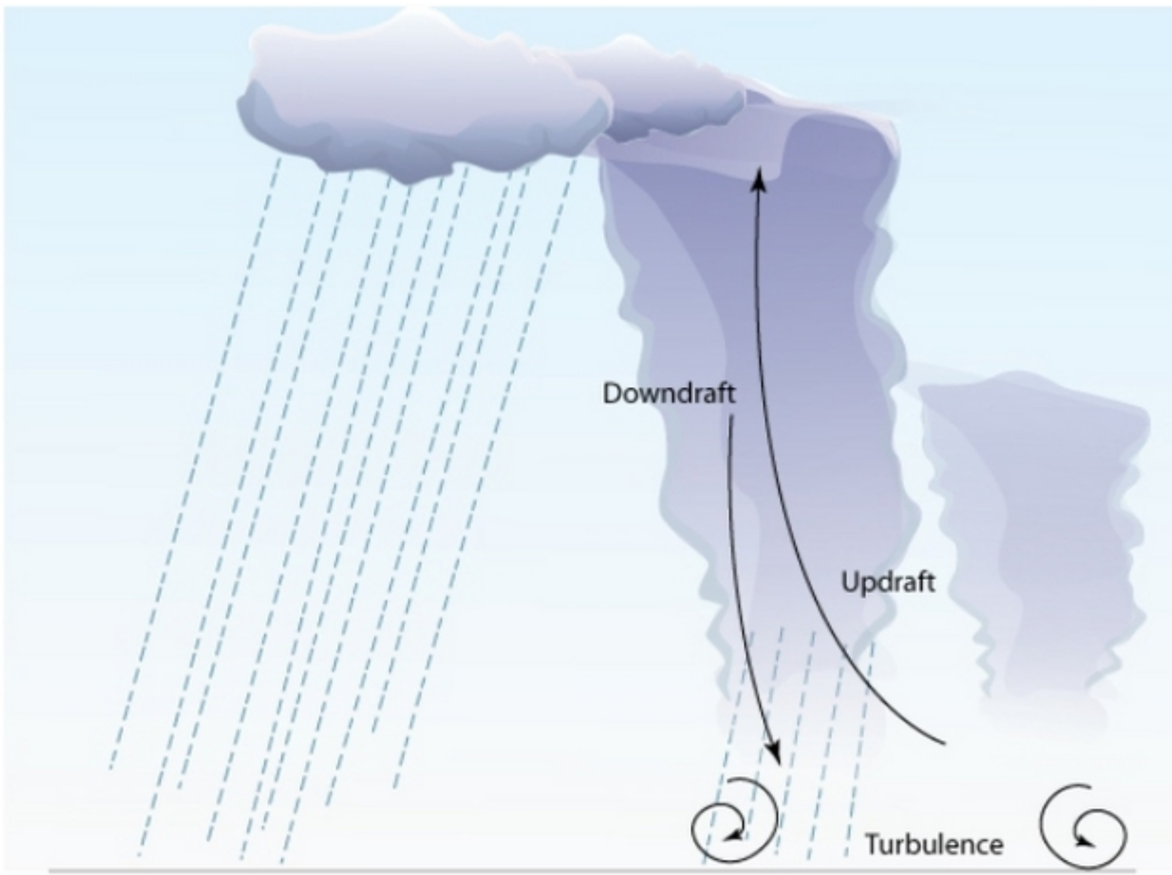
Conclusion

The revised **biotic pump model** could be used to test a scenario for naturally forested zones :

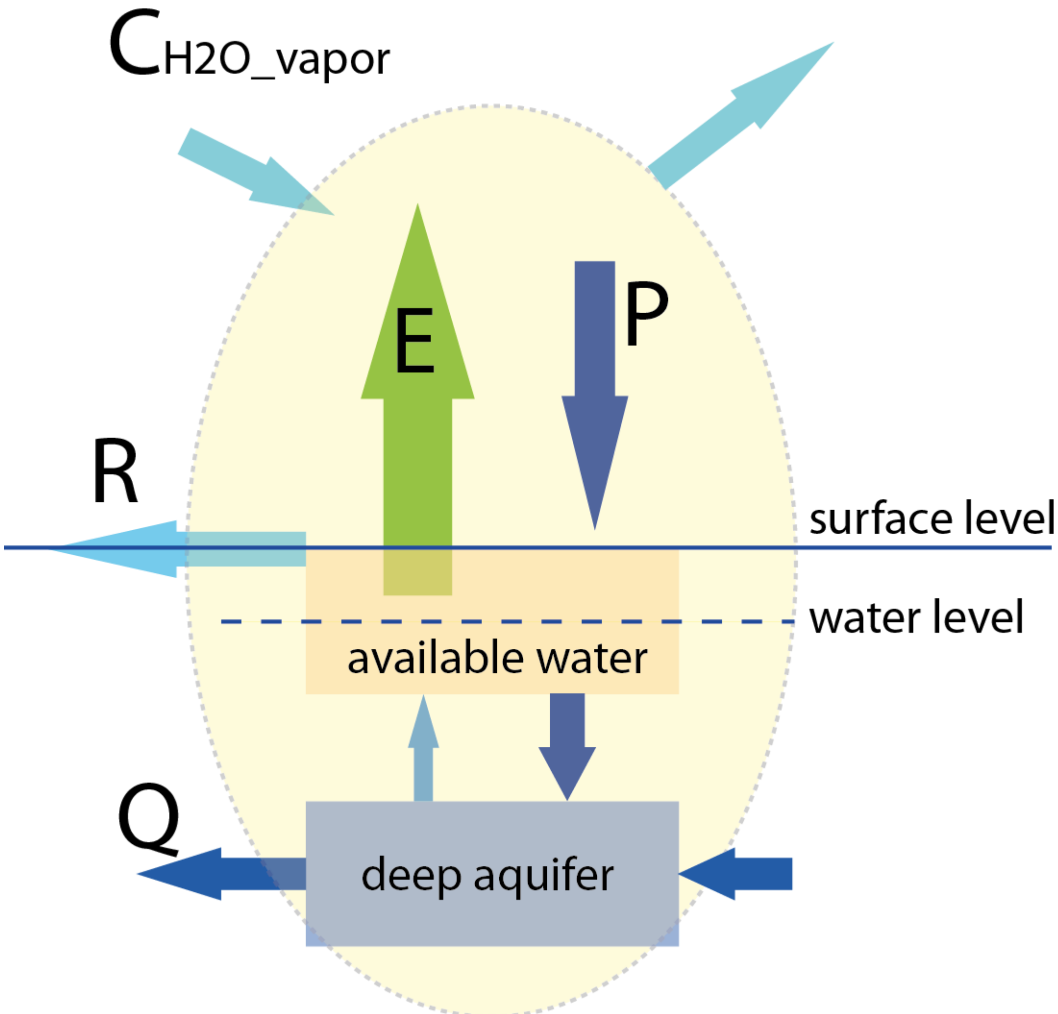
1. Climatic system has a long term equilibrium (invariant global climate)
2. Extension of pastoralism and cultivation leads to deforestation
3. Lack of evapotranspiration stops atmospheric connections to large water bodies
4. Average rainfall decreases and aquifers become depleted
5. Societies must adapt or leave because of persistent drought

Could be one of the path to civilization collapse

Thank you for your attention


Downdraft
Updraft
Turbulence

Physical model and constitutive equations



$\Delta H2O = (C^{+}-C^{-}) \quad + \quad (P-E) \quad - \quad (Q+R)$

Moisture convergence / Infiltration / Outflow

TROPOSPHERE :

C : Dispersion equation of water vapor (Fick's law, parameter Dh ($10^3 – 10^5$ m2/s). Cf Pisso et al. 2009

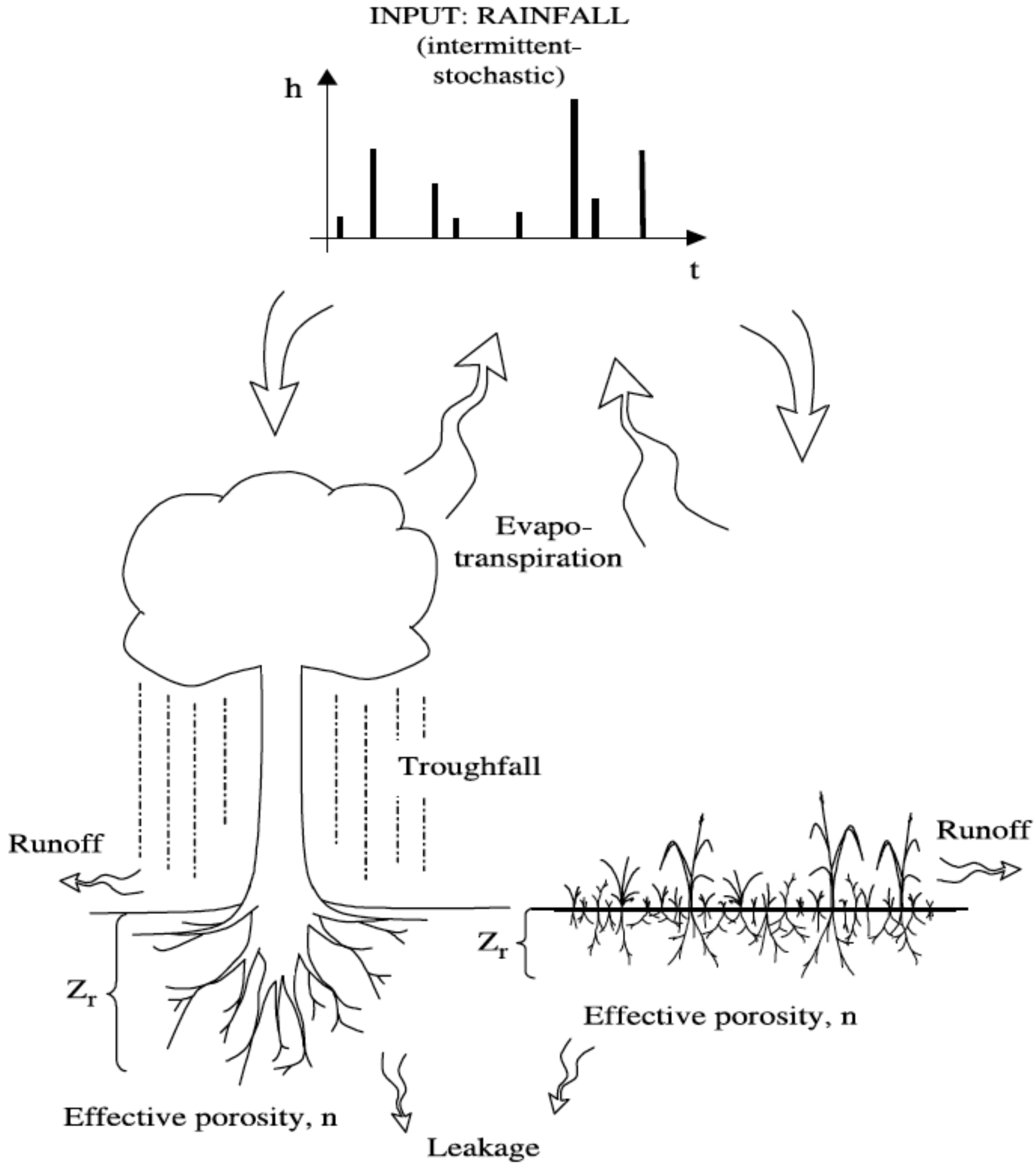
P : Rain rate is function of vapor saturation and max precipitable water

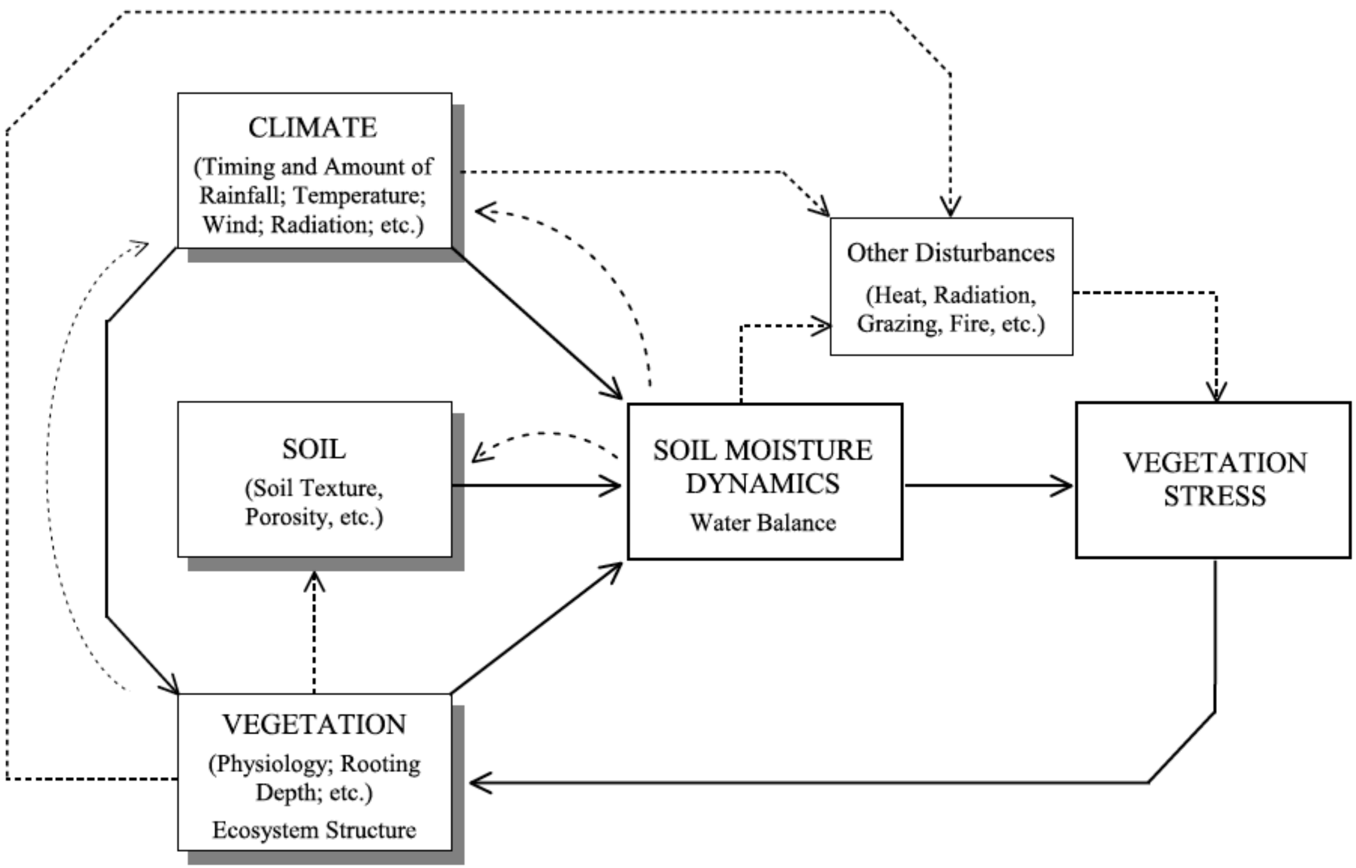
CRITICAL ZONE :

E : Forest evapotranspiration increases with temperature: **roots pump** into a reservoir (withdrawal by vertical flow);

I : P-E

Q+R : Horizontal flow follows topographic slope (Darcy's law)


INPUT: RAINFALL
(intermittent-
stochastic)
h
t
Evapo-
transpiration
Troughfall
Runoff
Runoff
Z_r
Z_r
Effective porosity, n
Effective porosity, n
Leakage


CLIMATE
(Timing and Amount of Rainfall; Temperature; Wind; Radiation; etc.)
Other Disturbances
(Heat, Radiation, Grazing, Fire, etc.)
SOIL
(Soil Texture, Porosity, etc.)
SOIL MOISTURE DYNAMICS
Water Balance
VEGETATION STRESS
VEGETATION
(Physiology; Rooting Depth; etc.)
Ecosystem Structure