The relevance of atmospheric models to climate change predictions: the case of the South-American monsoon system

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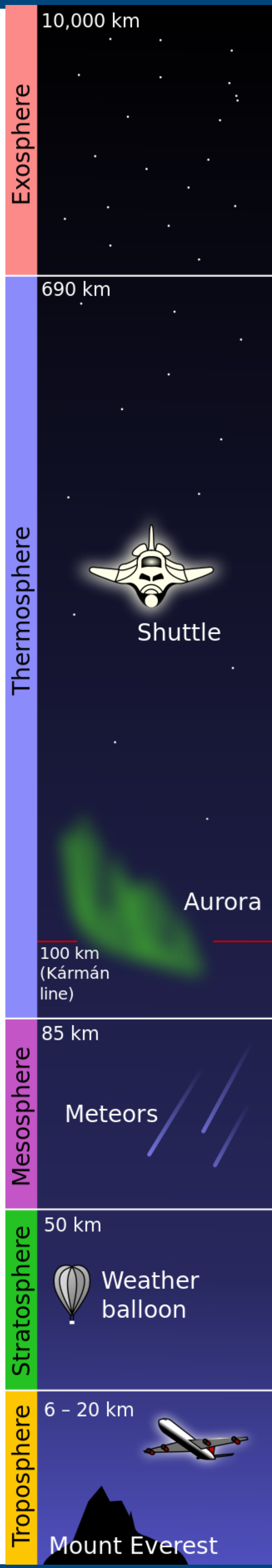
Summary

1. **Introduction**
   - definitions and terminology of atmospheric science
   - fundamentals of atmospheric models
2. **Climate model of the South-American monsoon system**
   - introduction to the South-American monsoon system
   - description of a state-of-art model
   - results and discussions
3. **Conclusions**

Basic definitions

atmosphere: layer of gases surrounding a planet and held in place by the gravity of that planet



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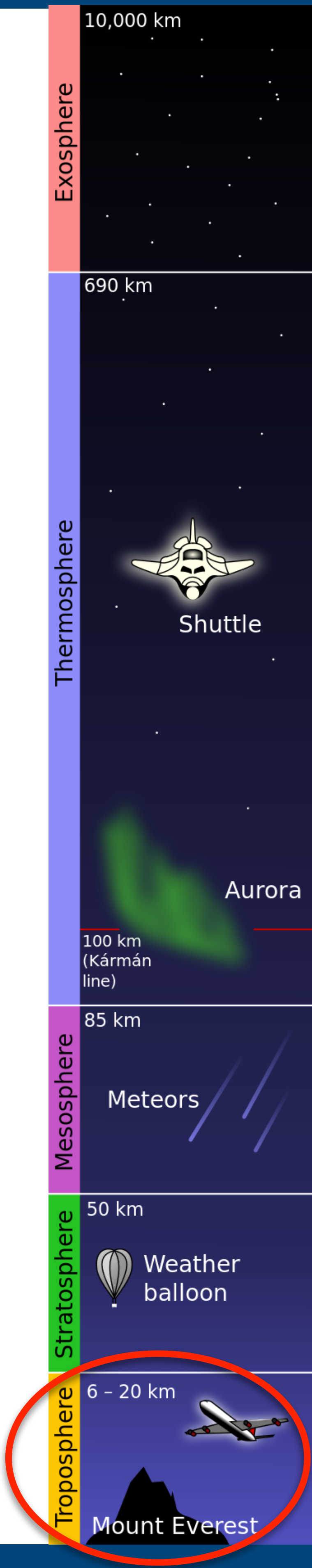
weather: the temporary (day-to-day) state of the atmosphere defined majorly by temperature and precipitation activity
Weather phenomena mostly occur in the Troposphere



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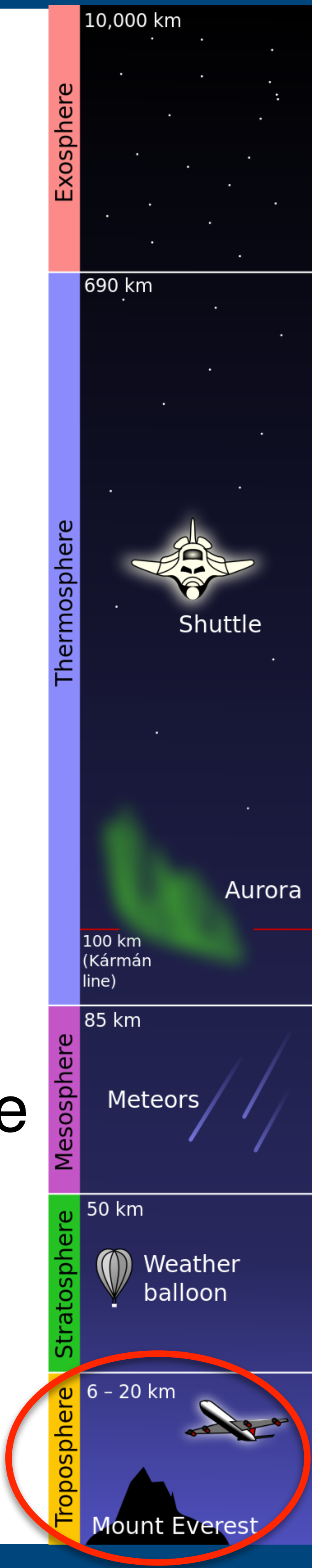
climate: statistical description of weather ("average weather") over a 30-years interval, defined by the mean and variability of:
temperature, humidity, atmospheric pressure, wind, precipitation
A climate system has 5 components:
atmosphere, hydrosphere, cryosphere, lithosphere and biosphere



What is an atmospheric model?

essential tool for atmospheric science

A model is used to:

- make physical sense to experimental data
- explain physical mechanisms of atmospheric phenomena
- making predictions about systems for which measurements are impracticable ("experimental approach")

Always characterized by a
mathematical representation

requirement: consistency with all achievable measurements

experimental data as a feedback for models and viceversa

Important scales

Atmospheric processes encompass a wide range of scales

Spatial and Temporal Scales	Example Process/Model
– **Molecular** (<< 2 mm, >min)	Diffusion/Diffusion equation
– **Microscale** (2 mm - 2 km, hours)	In cloud processes/thermodynamics and microphysics
– **Mesoscale** (2 - 2000 km, hours to days)	Tornadoes to Thunderstorms/ weather forecasts
– **Synoptic** (500 - 10,000 km, days to weeks)	Climate System: anticyclones cyclones, Fronts / regional to hemispheric model
– **Planetary** (> 10,000 km, > weeks)	atmosphere circulation / Global circulation model

Atmospheric predictability

model that predicts the deterministic evolution of the atmosphere:

"forecast model"

weather prediction (mesoscale)

BUT

The deterministic predictability of the atmosphere is limited by initial conditions (Lorentz, 1969)

(two weeks, mesoscale)

↓

study of the **statistics** of the atmosphere

beyond the deterministic limit

↙ ↘

seasonal weather forecasts **climate change forecasts**

Climate change

change of the statistical distribution of weather patterns which lasts for an extended period of time

Synoptic/planetary scale

time evolution of the statistics driven by

"external forcing"

natural

(biotic processes,
variations in solar radiation,
plate tectonics, volcanics eruptions,
Earth's revolution)

anthropogenic

(greenhouse gas emissions,
deforestation)

Physics of climate models

The physics of each atmospheric model starts from primitive equations:

1. **Continuity equation:** the conservation of (dry and water) mass.

2. **Conservation of momentum:** hydrodynamical atmospheric flow on the Earth surface (Navier–Stokes equations)

3. **Thermal energy equation:** conservation of energy, it relates the overall temperature of the system to heat sources and sinks

all partial differential equations

Need of numerical simulations

Impossibility to solve the physical equations at any time and spatial point

- **Simplification**: focus on only the relevant processes
- **Parametrization**: expressing a process as a parameter, which is function of at least two parameters
- **Approximation**: either physical and mathematical approximations

(**finite-difference method**, **finite-element method**, etc)

partial derivatives are substituted with *finite-difference quotients*

PDE are reduced to a system of algebraic equations

Solutions of the models are *numbers* rather than *formulas*:

Numerical model

Climate model of the South-American monsoon system

"A deforestation-induced tipping point
for
the South-American monsoon system"

N. Boers *et al.*,
Scientific Reports **7**, Article number: 41489 (**2017**)

Monsoon system

monsoon system: reversal in the low-level wind direction between summer (wet) and winter (dry) seasons

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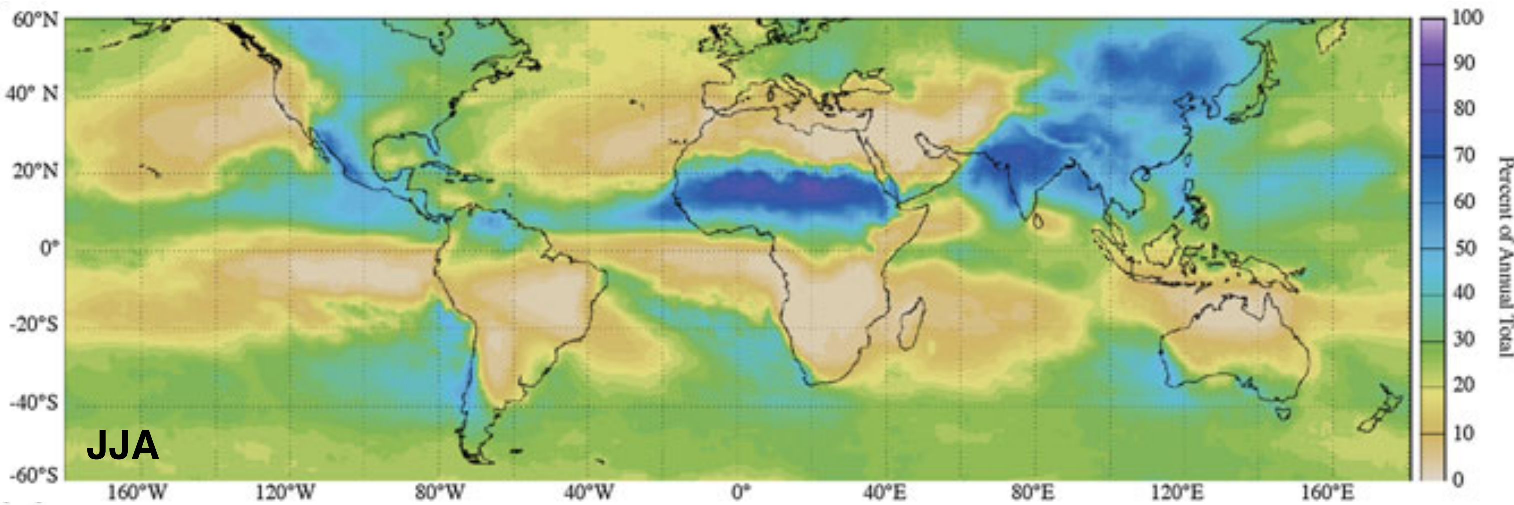
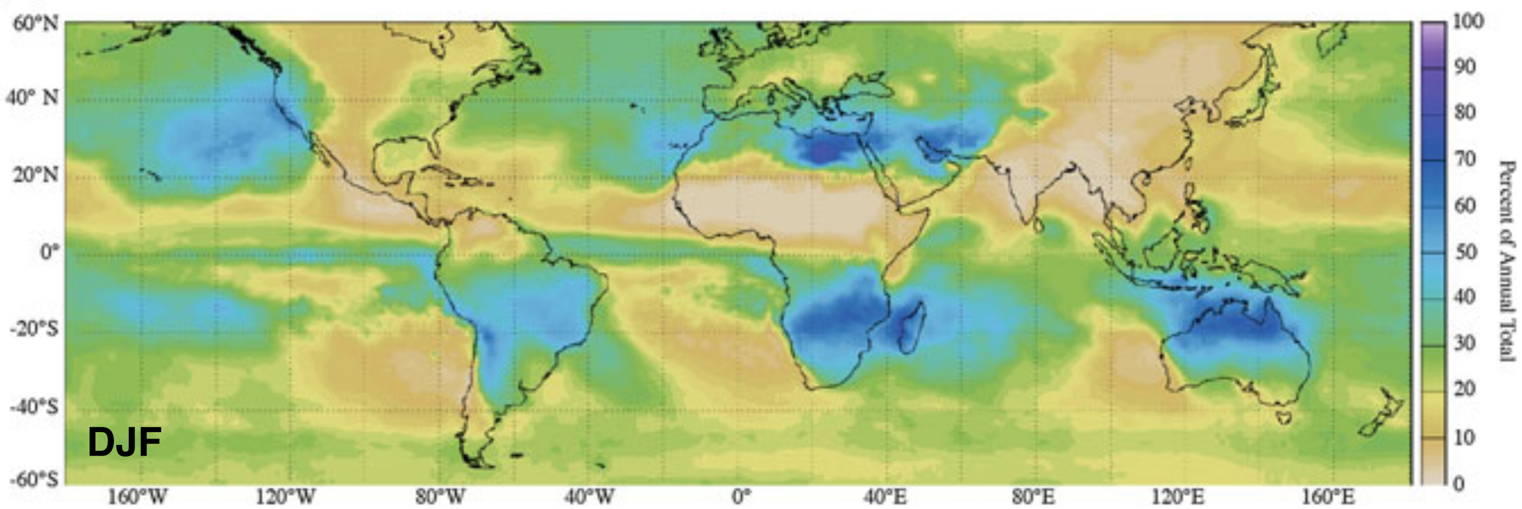
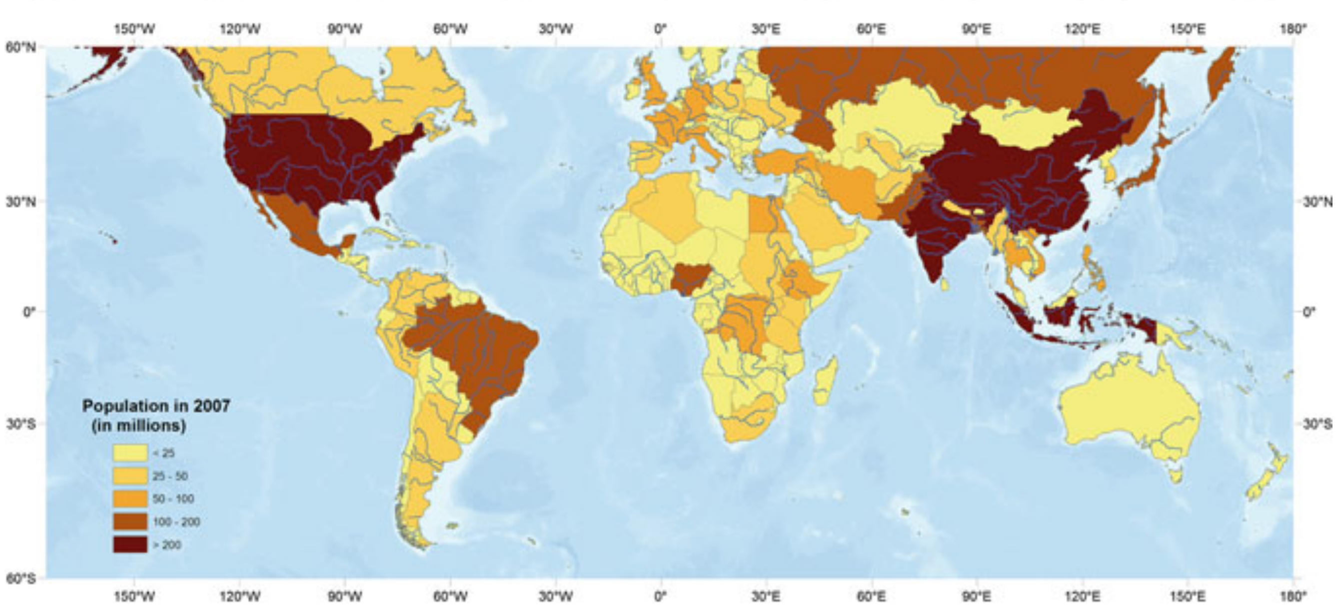


- more than **43%** of Earth's population (7,5 billion people, 2017) lives in monsoon regions



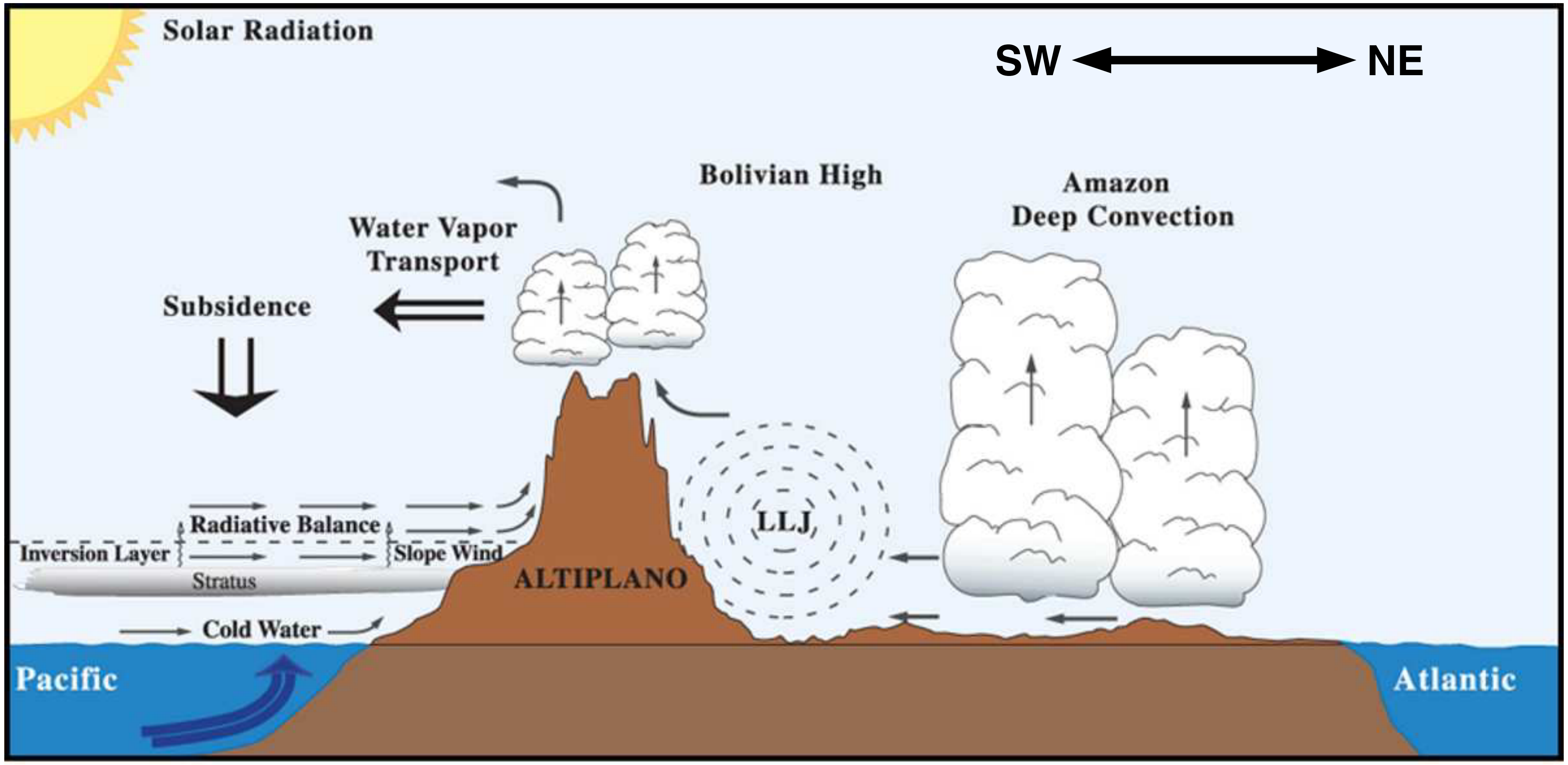
- at the end of 21st century it will be **50%** of a population of 10 billion people



Climate change in these regions are crucial for food and health security

L. M. V. de Carvalho, I. F. A. Cavalcanti, *"The South American Monsoon System"*

The South-American monsoon system (SAMS)



thermal gradient
between ocean and continent

↓

pressure gradient

↓

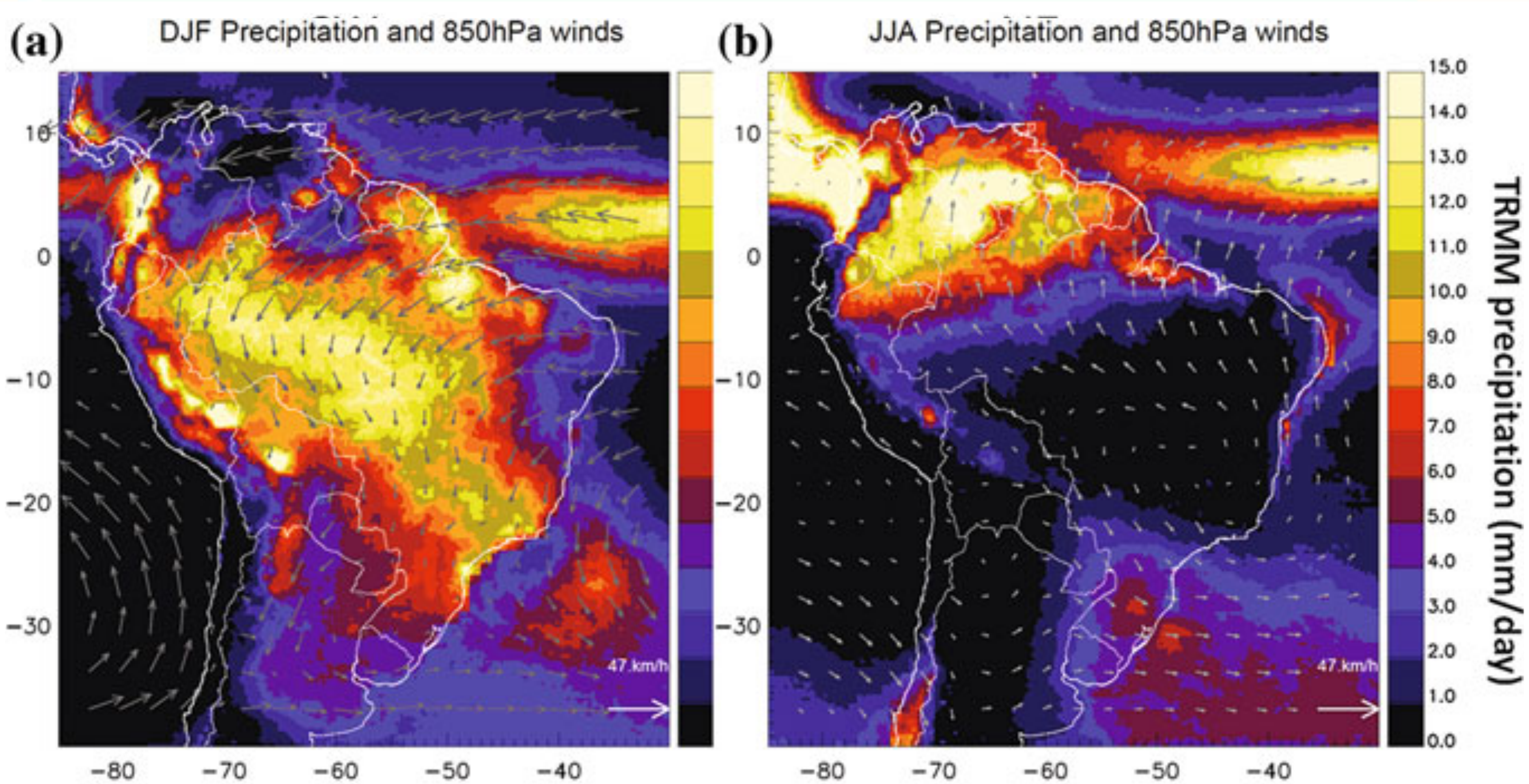
low-level moist air inflow
from the ocean
(South Atlantic convergence zone)

↓

moist winds
cross the Amazon basin
and are blocked by the Andes
(Bolivian High)

↓

a **Low-Level Jet** transports
moisture to the subtropics



L. M. V. de Carvalho, I. F. A. Cavalcanti,
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Current situation in the Amazon basin

Amazon basin:
40% (7,500,000 km^2) of the South-American continent
Amazon rainforest:
world largest rainforest (5,500,000 km^2)
Amazon river:
world largest and longest (6,992 km) river

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Fires and **deforestation** in the state of Rondônia
for agriculture land or urban environment

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Fires and **deforestation** in the state of Rondônia
for agriculture land or urban environment

about **20%** of the rainforest surface (before 1970) has been **deforested**

(Butler, Rhett A., *Calculating deformation figures for the Amazon*)

impacts in carbon, energy and water fluxes

Modeling deforestation effects on SAMS

how the SAMS will be affected by deforestation?

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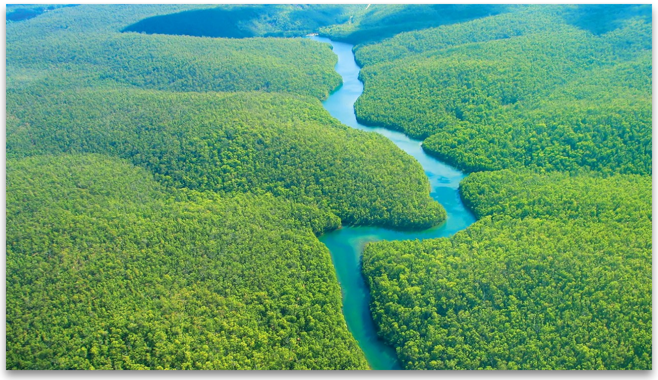
study of the South America-Atlantic ocean coupling

Amazon rainforest

Atlantic moisture reservoir



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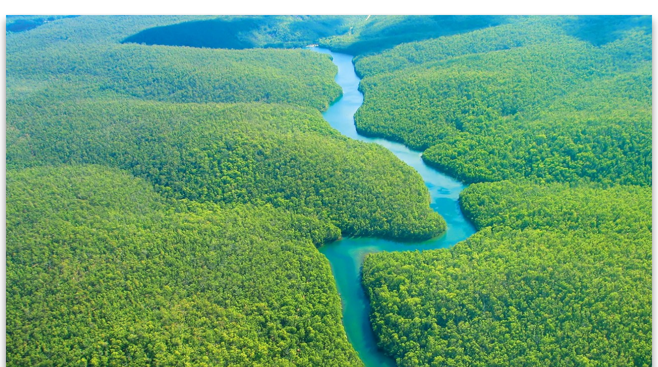

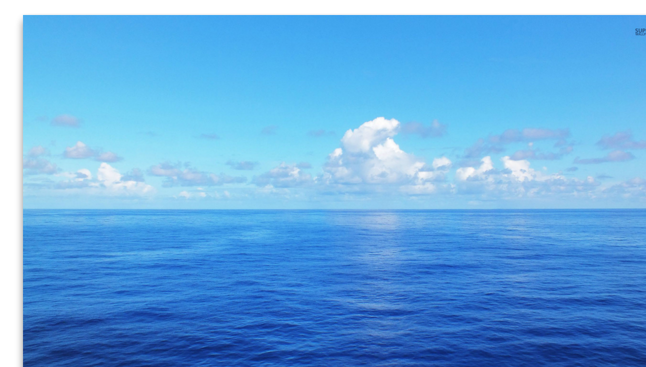

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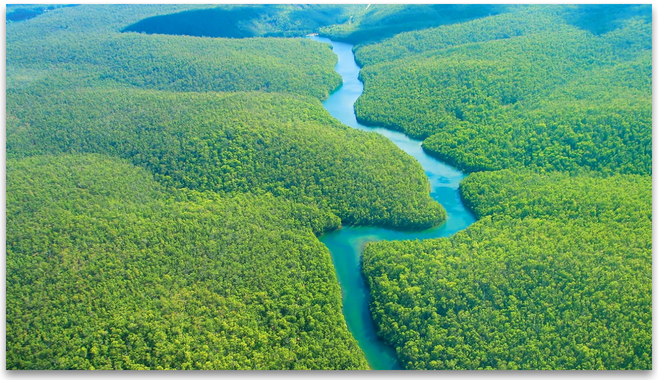

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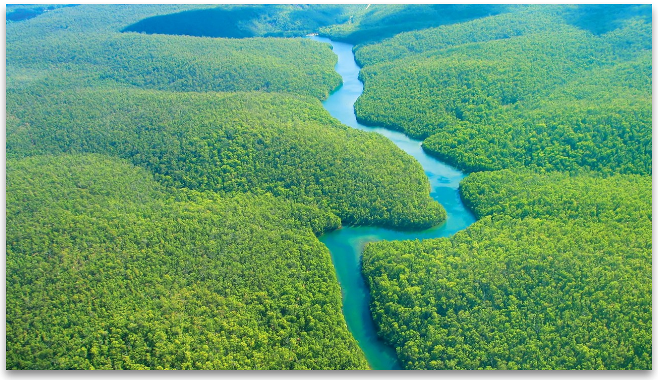
condensational latent heat release (LH)

Amazon rainforest
evapotranspiration

ocean-land atmospheric heating gradient

Atlantic moisture reservoir
precipitation



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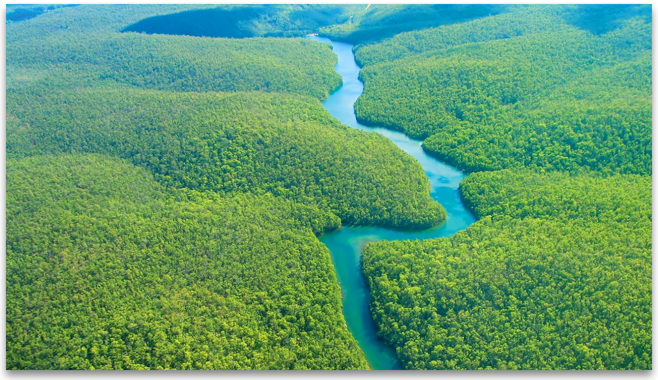

ocean-land atmospheric heating gradient

amplification of moisture transport

Atlantic moisture reservoir

precipitation

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Modeling deforestation effects on SAMS

how the SAMS will be affected by deforestation?

study of the South America- Atlantic ocean coupling

breakdown
of the feedback

~~presence of positive feedback mechanism~~

~~**condensational latent heat release (LH)**~~

Amazon rainforest

evapotranspiration

external forcing:
deforestation

ocean-land atmospheric heating gradient

⟷

amplification
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Atlantic moisture reservoir

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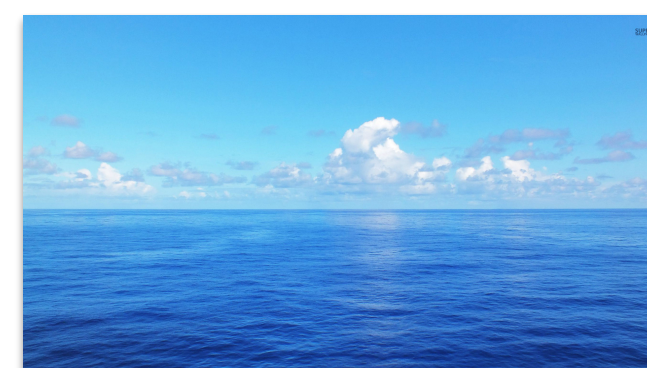

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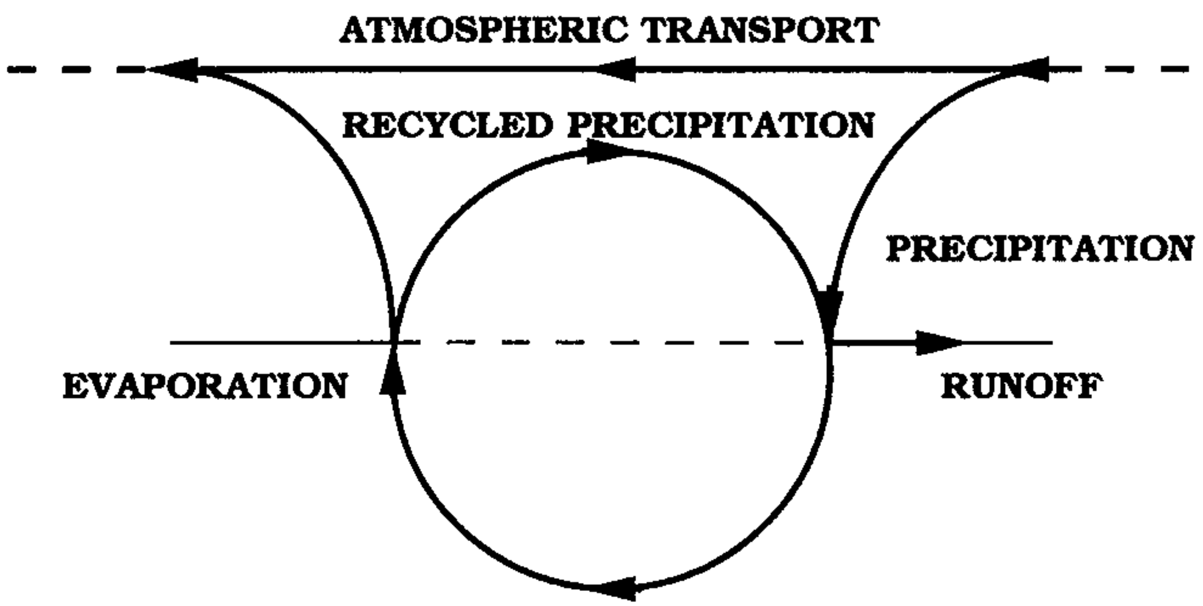
Physics of the SAMS model

Parametrization

Six observables:

- atmospheric moisture content, A
- soil moisture content, S
- evapotranspiration, E(S)
- precipitation, P(A)
- river run-off, R(S)
- wind velocity, **W**

water cycle



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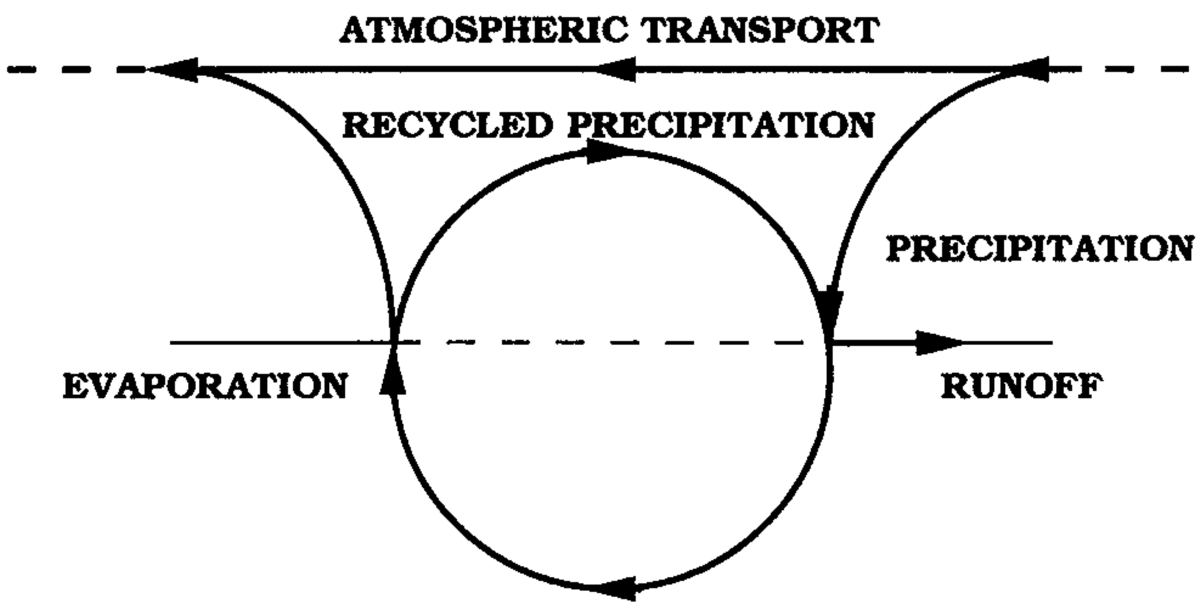

water conservation

Physics of the SAMS model

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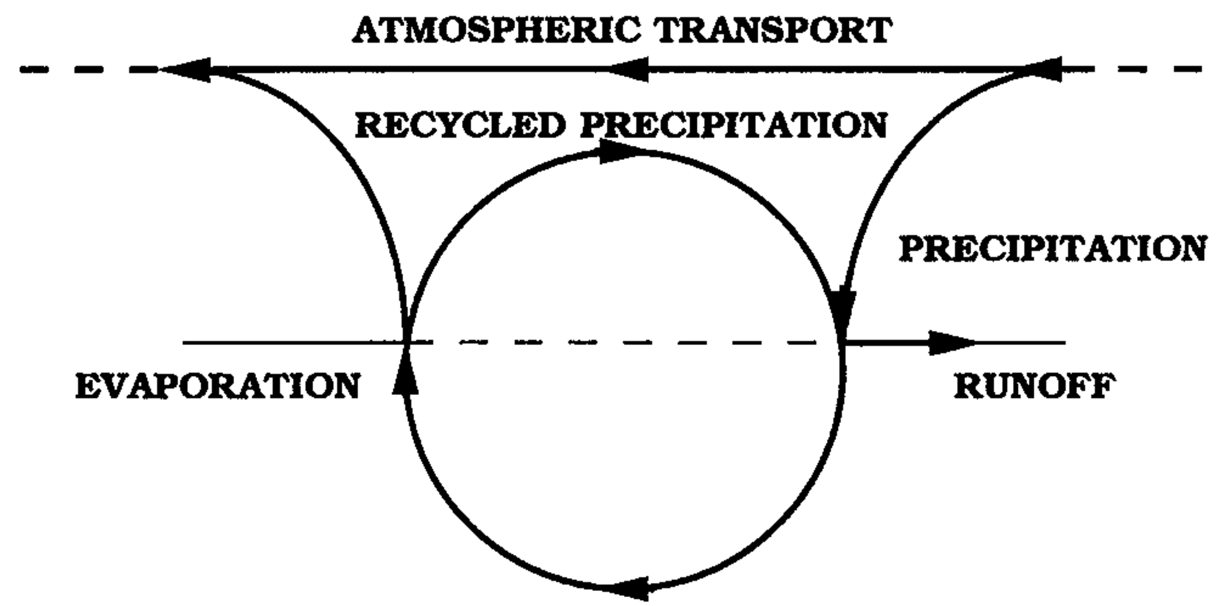


coupled non-linear partial differential equations:

water conservation →

$$\begin{cases} \partial_t A = E - P - \vec{\nabla} \cdot \vec{M} \\ \partial_t S = P - E - R \end{cases}$$

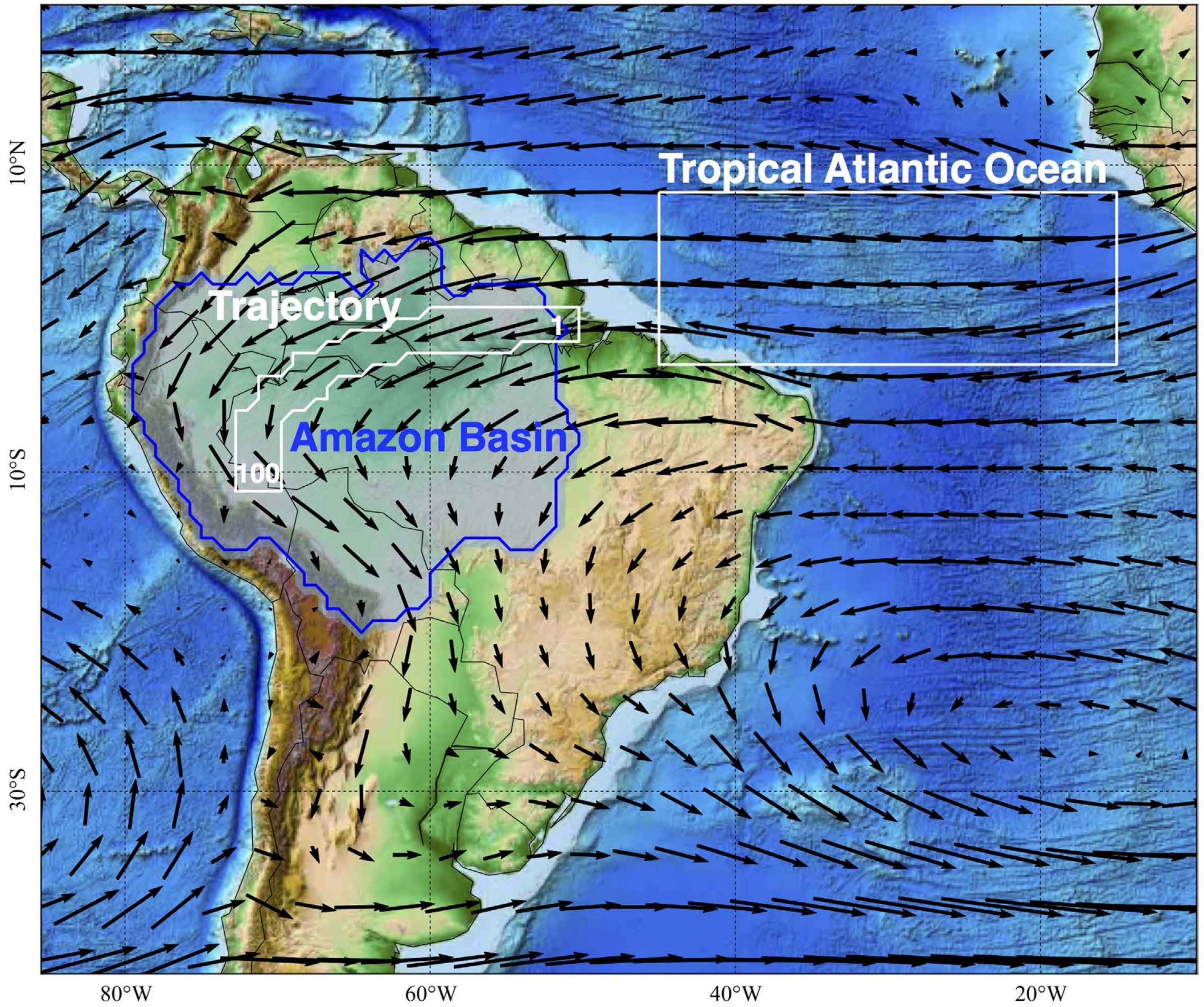
where $\vec{M} = A\vec{W}$ (moisture flow) and $\vec{W} = \vec{W}^{\mathrm{trade}} + \vec{W}^{\mathrm{H}}$(A, E)

$\vec{W}^{\mathrm{trade}}$: due to trade wind (constant)

$\vec{W}^{\mathrm{H}}$: due to heating gradient (dynamic)

Physics of the SAMS model

Discretization



laminar atmospheric flow:
one-dimensional model
trajectory made of 100 boxes

conservative regime (wet season)

Physics of the SAMS model

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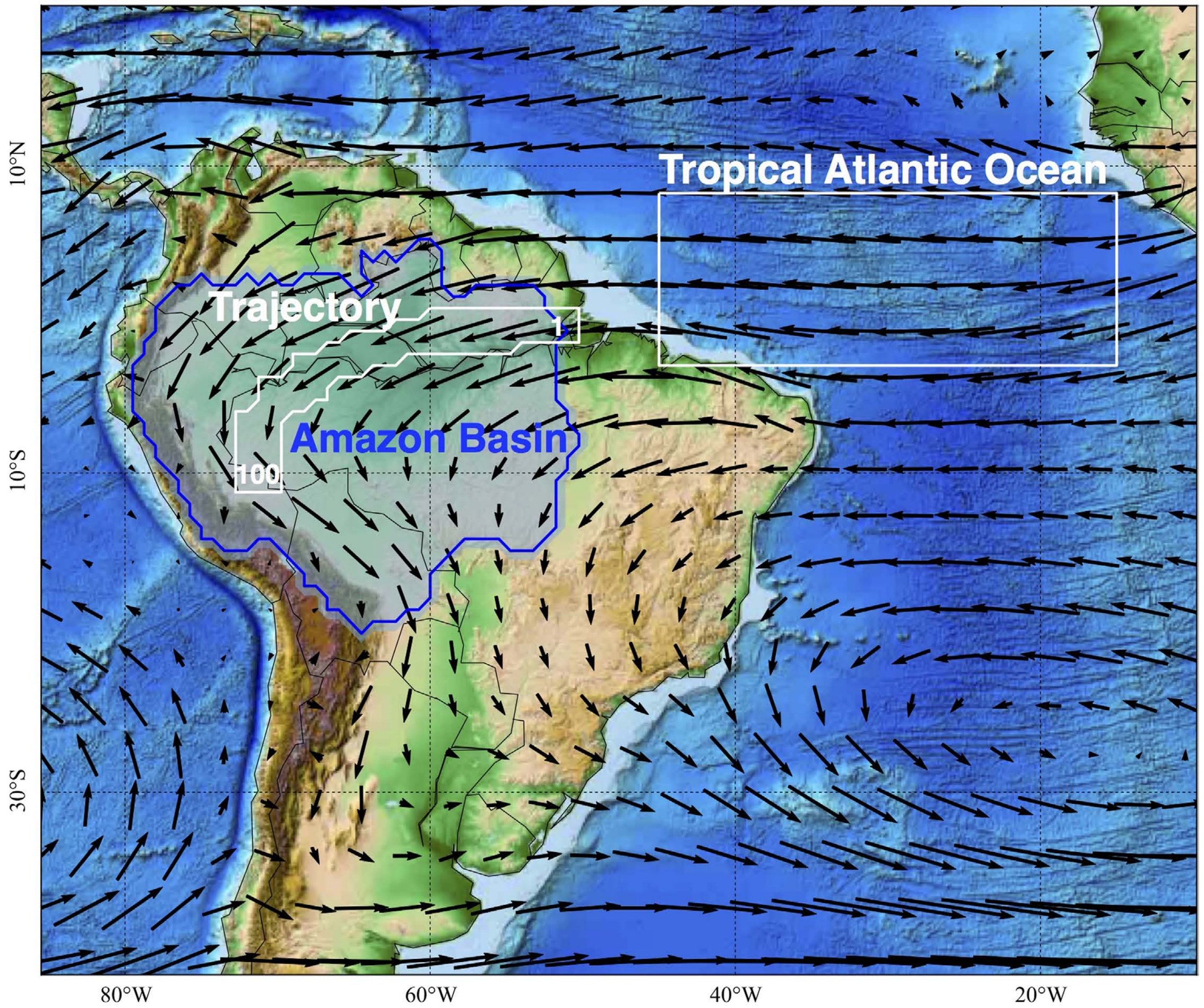

laminar atmospheric flow:
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conservative regime (wet season, **DJF**)

Approximation

$$A_i(t+1) = A_i(t) + E_i(t) - P_i(t) - \frac{W_i(t)A_i(t) - W_{i-1}(t)A_{i-1}(t)}{l}$$

$$S_i(t+1) = S_i(t) + P_i(t) - E_i(t) - R_i(t)$$

i = box index

deforestation is simulated by reducing evapotranspiration **E**

↓

reduction of latent heat release

↓

decrease of heating gradient between ocean and land

$$\pi(t) = \langle \mathrm{H} \rangle^{\mathrm{T}} - \langle \mathrm{H} \rangle^{\mathrm{AO}}$$

↓

moisture inflow reduction

$$\mathbf{W}^{\mathrm{H}} \propto \pi(t)$$

when $\pi(t) = 0$ ⟶ breakdown of the feedback

Results of the model

Amplification Factor (**AF**): amplification of moisture inflow due to LH release

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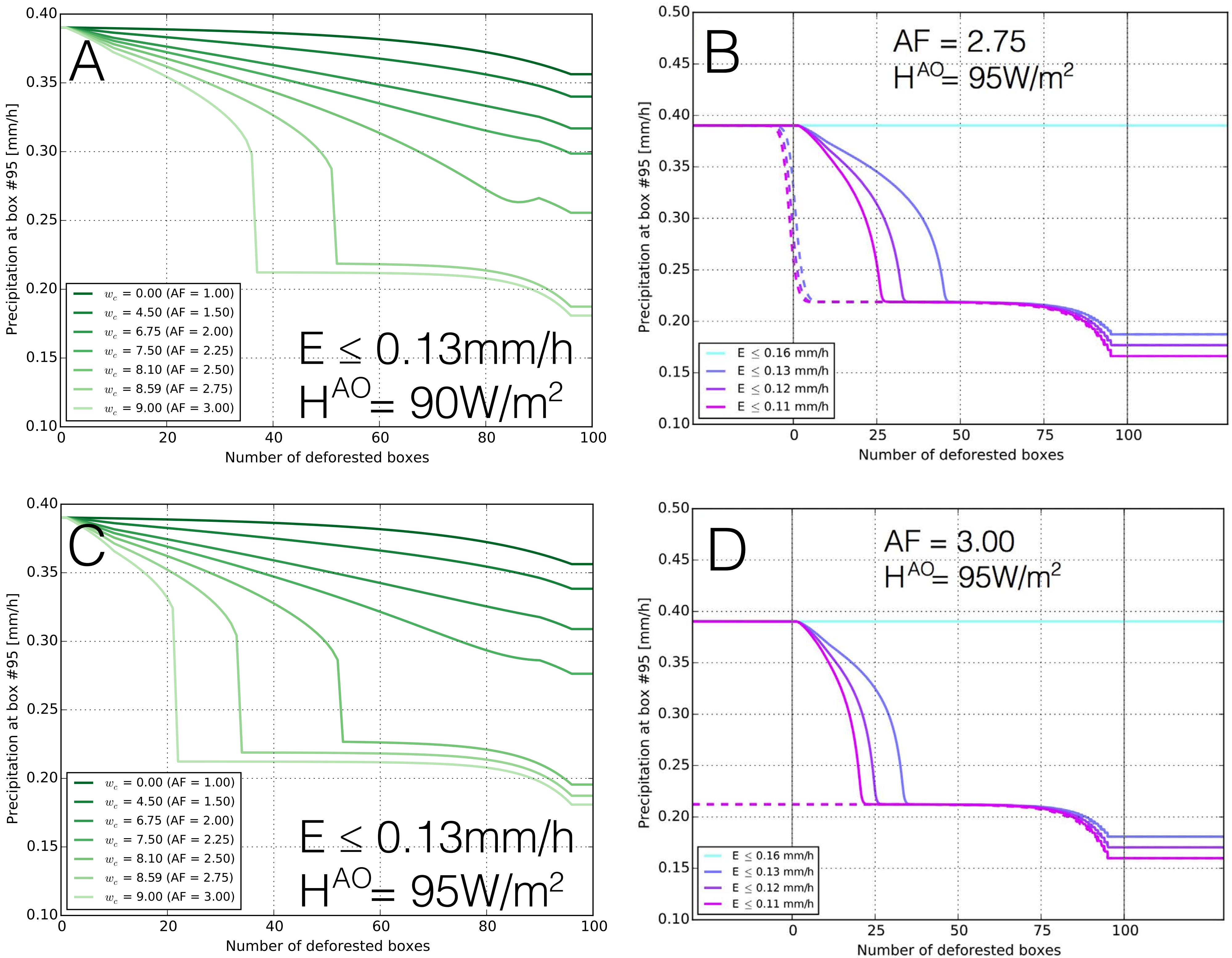


Observations:

- strong dependence of **P** on **AF, E** and Atlantic heating
- for some values of **AF**, existence of a **threshold for deforestation** beyond which **P** rapidly decreases to **less than 60%** of P before deforestation
- Presence of a hysteresis in the deforestation-reforestation cycle

solid lines:
deforestation process

dashed lines:
reforestation process

Conclusions

- Atmospheric models are crucial for climate change predictions, they can work as "numerical experiments"

- A state-of-art atmospheric model of the effect of Amazon deforestation on SAMS is presented.
  The existence of a deforestation-induced tipping point for the SAMS is indicated.

- Crossing a threshold level of deforestation, precipitation reductions up to 40% in non-deforested parts are predicted.

- The responsible physical mechanism is identified in the breakdown of a positive feedback (i.e. latent heat release) to maintain sufficient level of moisture inflow from ocean to land.

- Despite the precise values at which these transitions occur are model-dependent, this study provides a conceptual basis for further investigations.

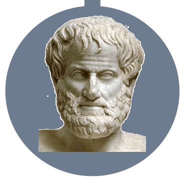
Thanks for the attention!

History of atmospheric science

De Windstoot, Willem van de Velde II, 1707

History of atmospheric science

650 BC
Babylonians predict weather from cloud patterns

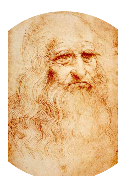


about 350 BC
Aristotele describes weather patterns in *Meteorologica*

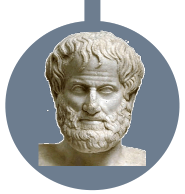
History of atmospheric science

650 BC
Babylonians predict weather from cloud patterns

1404-1472
Swinging-plate anemometer
L. B. Alberti



1481
L. Da Vinci
drew hygrometer
in *Codex Atlanticus*



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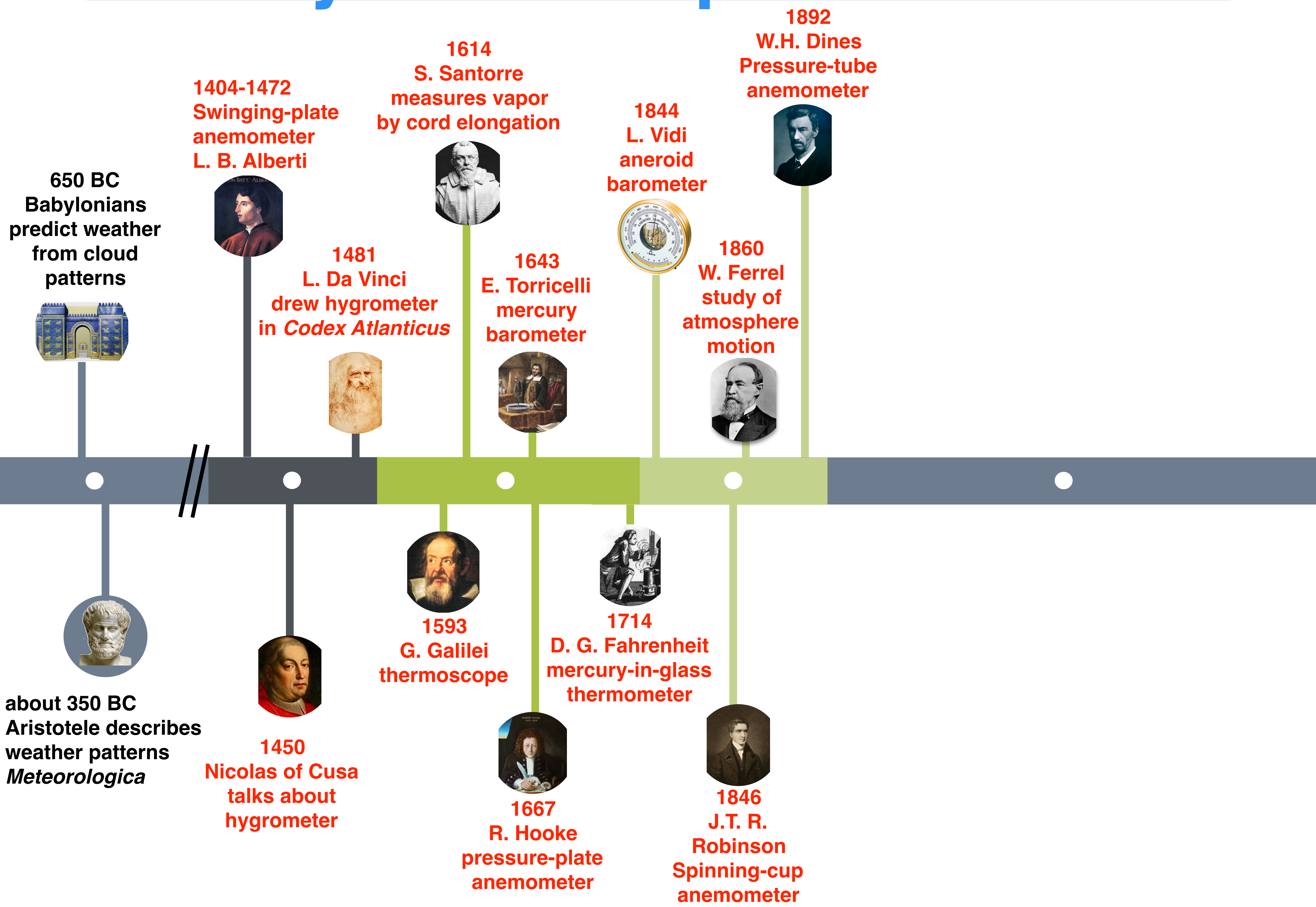
1450
Nicolas of Cusa talks about hygrometer

History of atmospheric science



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