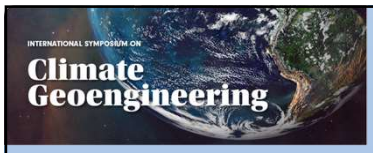


ACADEMIA BRASILEIRA DE CIÊNCIAS
MCMXVI

# *Climate modelling uncertainties: implication for geoengineering studies*

***Pedro L. da Silva Dias***

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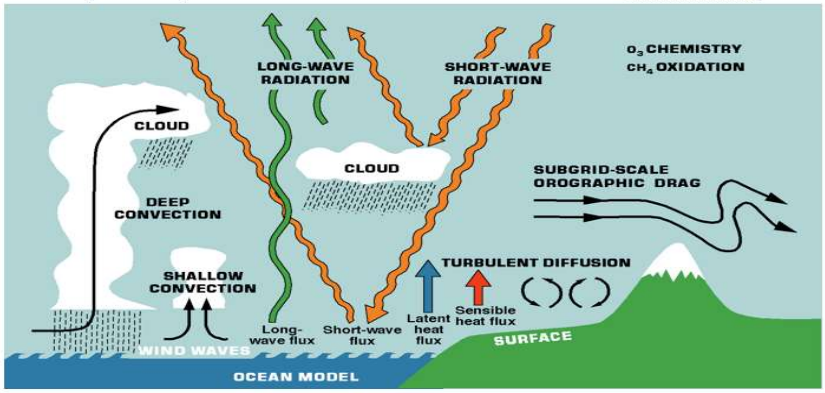
Instituto de Astronomia, Geofísica e Ciências Atmosféricas

1

## Physical processes in weather/climate modeling



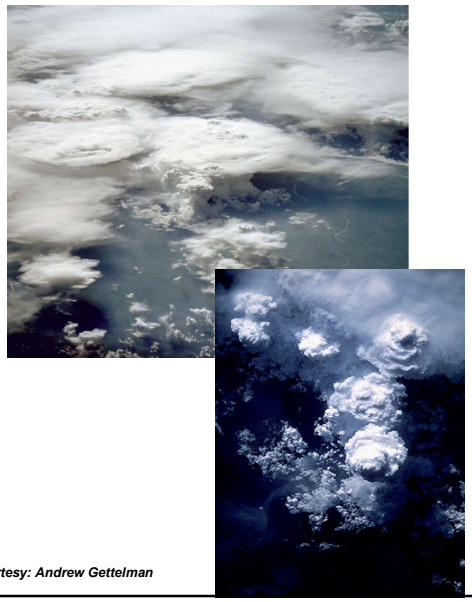

Momentum conservation: 3D

Mass conservation: air, water ,trace gases,aerosols …

Energy Conservation: 1st Law of Thermodynamics

2

# Sub-Grid Processes: Clouds



*Courtesy: Andrew Gettelman*

Need to represent:

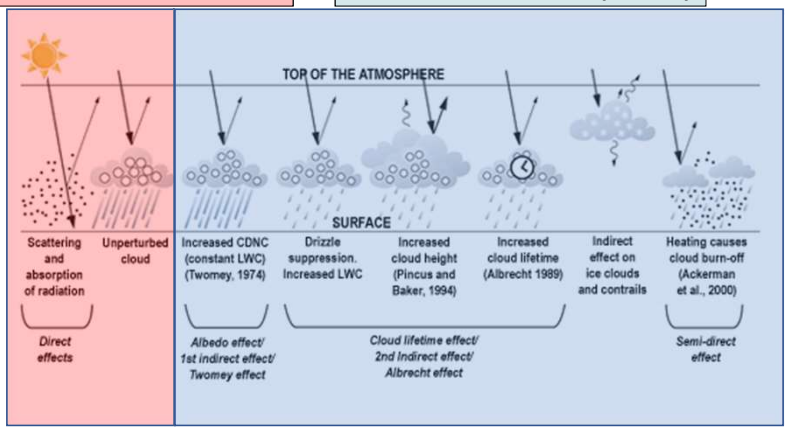
- Cloud formation and dissipation
- Different types of clouds
- Overlap of clouds
- Convection in clouds
- Precipitation
- Cloud – Radiation interaction
- Cloud Microphysics – interaction with aerosols

…

3

# Aerosol Effects

**Previous Generation Model** | **Present Generation (CESM)**

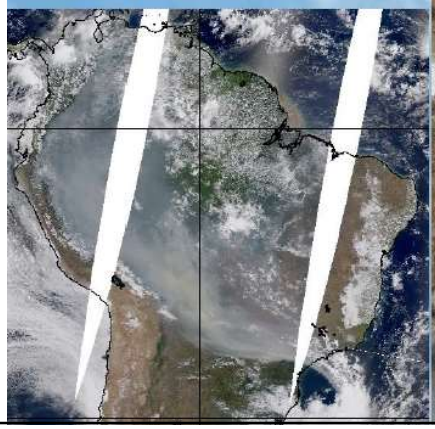


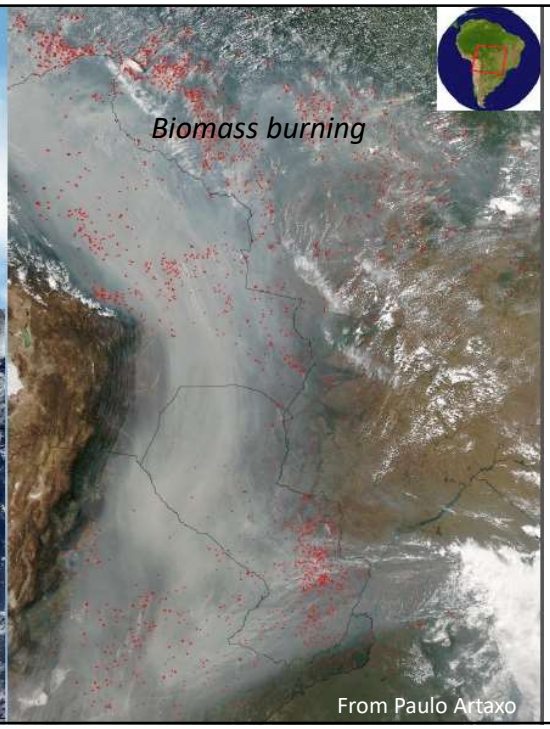

New cloud microphysics and aerosol treatment permit the study of Aerosol Indirect Effects

4

**Large scale aerosol distribution in Amazonia**

- Severe health effects on the Amazonian population (about 20 million people)
- Climatic effects, with strong effects on cloud physics and radiation balance.
- Changes in carbon uptake and ecosystem functioning



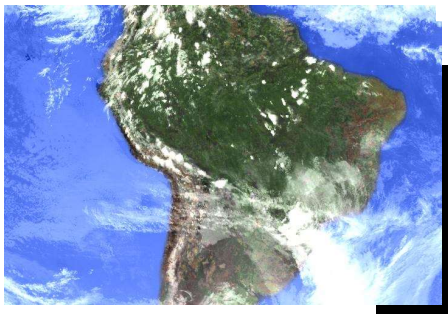


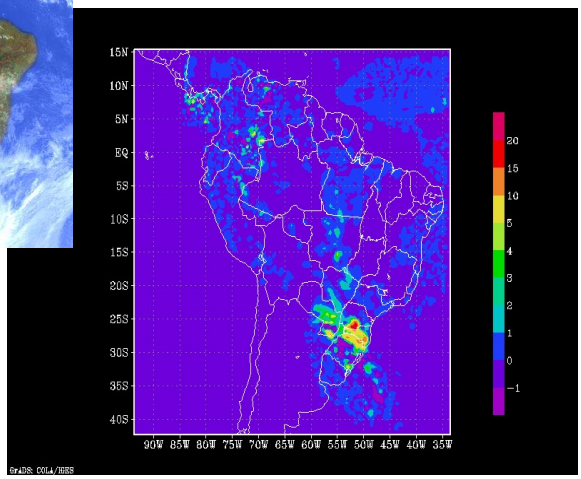

5

Reduction on the Convective precipitation (mm)

$\Delta P = (P - P_{aer})$

GOES-8 IR – 20020919 20:45Z



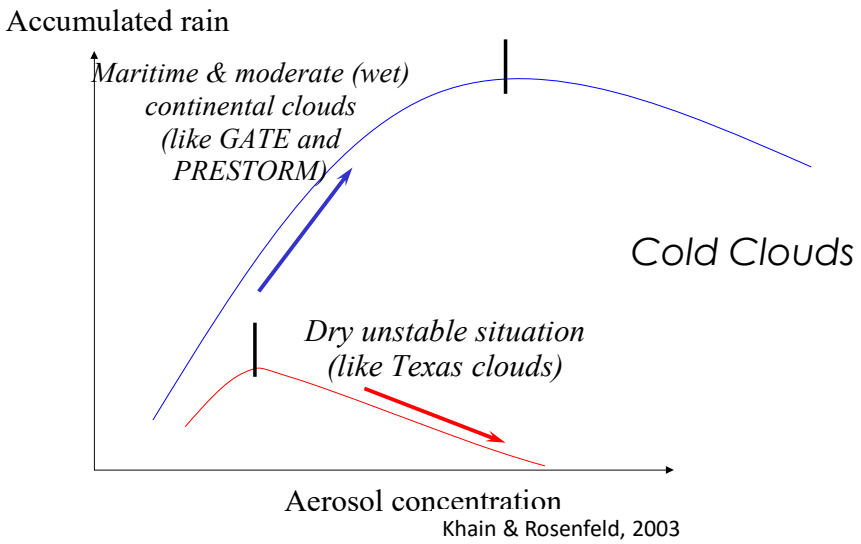



**Role of radiative forcing of aerosols (modelling results)**

Freitas et al. 2005

6

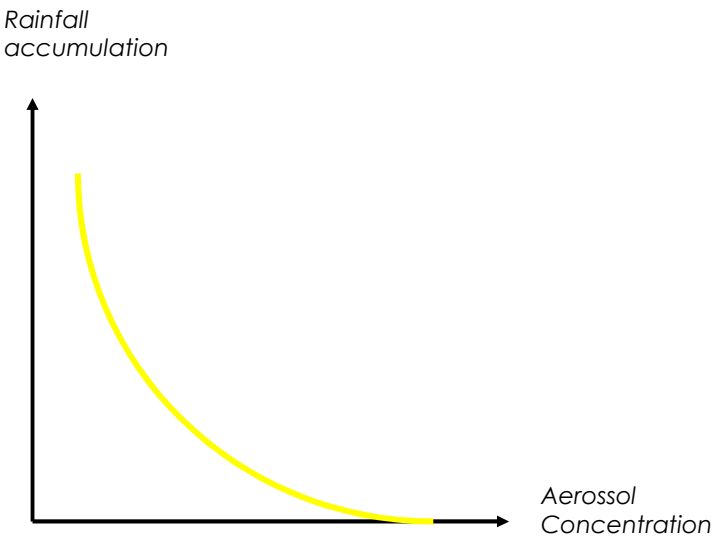
**Scheme of aerosol effects on precipitation**




Khain & Rosenfeld, 2003

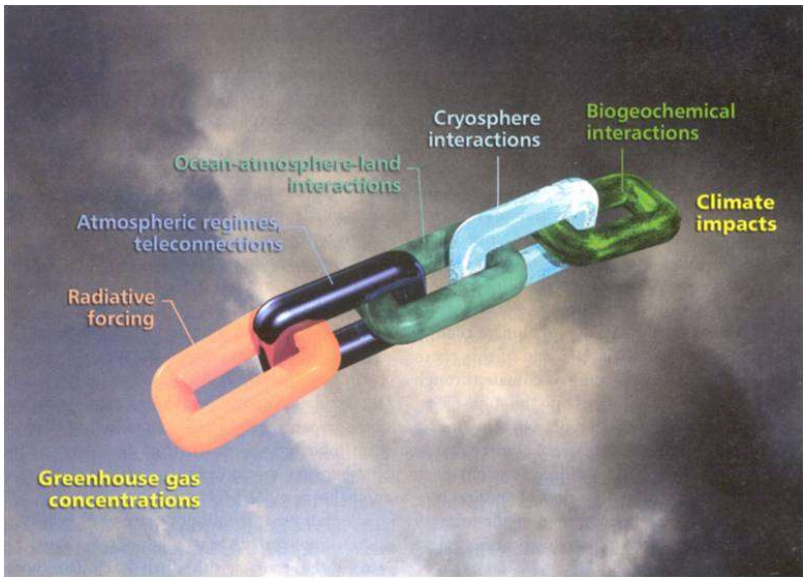
7

*Warm Clouds*




8

***Climate is a complex system: interaction among several components***




Bull. American Met. Soc. - 2008

9

## *Modeling the Earth Atmosphere System*

$$\frac{\partial X_a}{\partial t} + L_a X_a = N_a(X_a, X_o, X_v, X_c, X_s) + F_a(X_a, X_o, X_v, X_c, X_s)$$ *atmosphere*

$$\frac{\partial X_o}{\partial t} + L_o X_o = N_o(X_a, X_o, X_v, X_c, X_s) + F_o(X_a, X_o, X_v, X_c, X_s)$$ *ocean+hydrology + ice*

$$\frac{\partial X_s}{\partial t} + L_s X_s = N_s(X_a, X_o, X_v, X_c, X_s) + F_s(X_a, X_o, X_v, X_c, X_s)$$ *soil*

$$\frac{\partial X_v}{\partial t} + L_v X_v = N_v(X_a, X_o, X_v, X_c, X_s) + F_v(X_a, X_o, X_v, X_c, X_s)$$ *vegetation*

$$\frac{\partial X_c}{\partial t} + L_c X_c = N_c(X_a, X_o, X_v, X_c, X_s) + F_c(X_a, X_o, X_v, X_c, X_s)$$ *chemical species*

$X_a = (u, v, w, T, q_v, q_l, q_r, q_i, \ldots)$

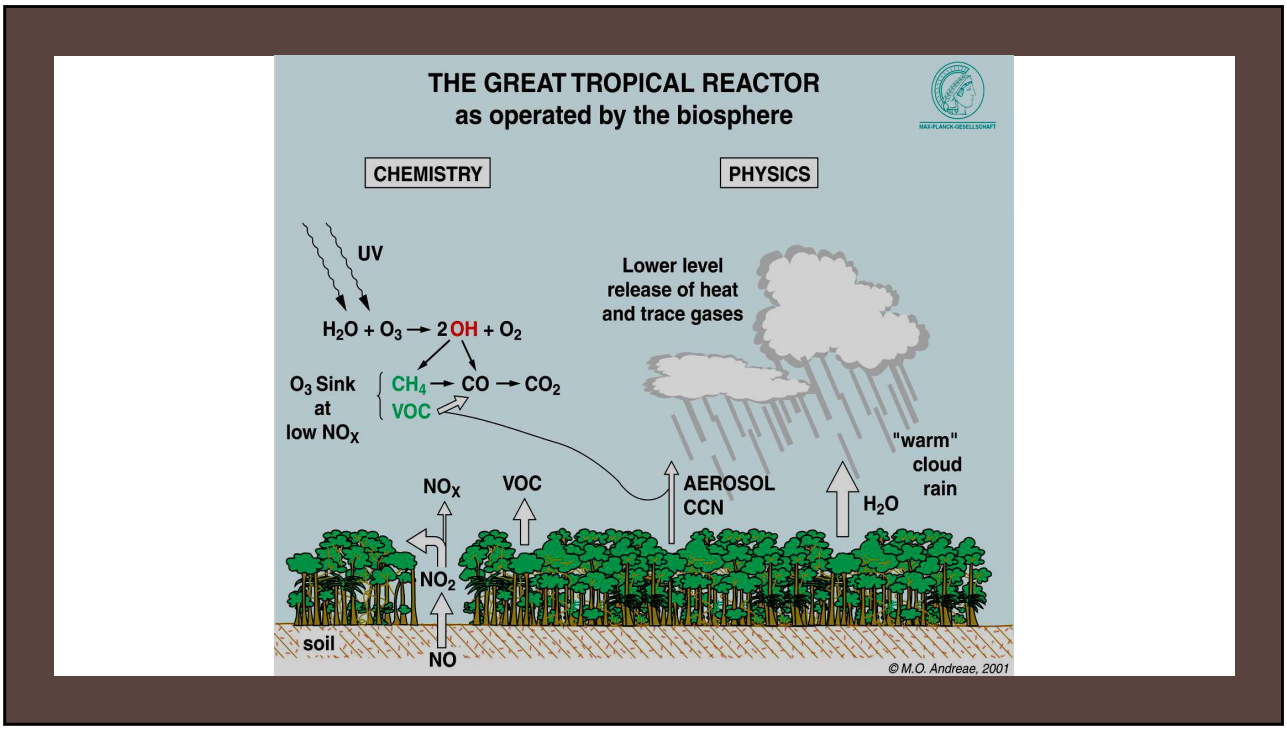
$X_o = (u, v, w, T, s_v, \ldots)$

$X_s = (T^i{}_s, W^j{}_s, N^i{}_n, \ldots)$

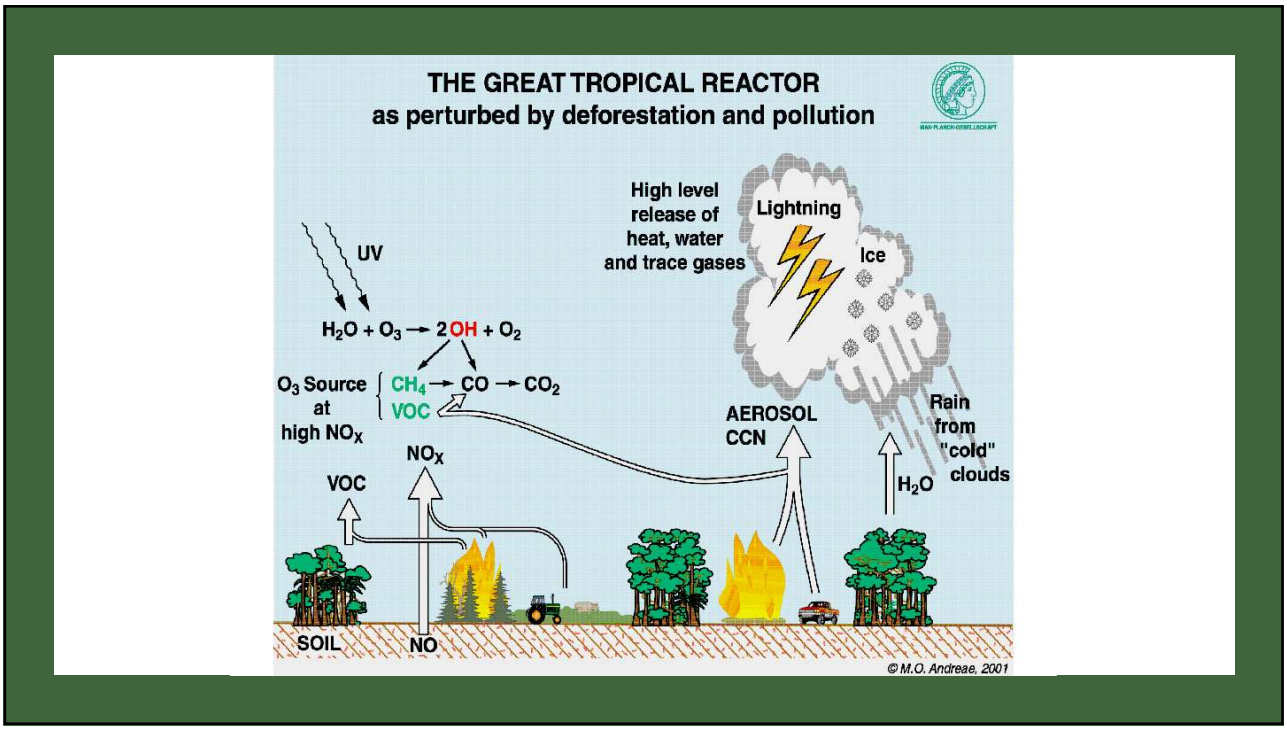
$X_v = (lai^i, sig^j{}_v, root^i{}_d, stom^j{}_c, VOC^i, C^i, N_i, \ldots)$

$X_c = (CO_2, CH_4, O_3, NO_x, VOC's, SO_2, \ldots)$

10

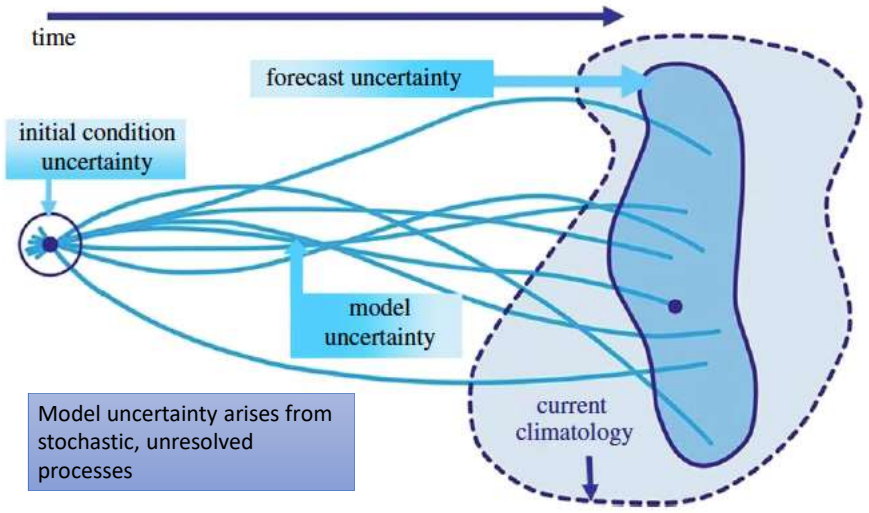

THE GREAT TROPICAL REACTOR
as operated by the biosphere
CHEMISTRY
PHYSICS
UV
$H_2O + O_3 \rightarrow 2OH + O_2$
$O_3$ Sink at low $NO_X$
$CH_4 \rightarrow CO \rightarrow CO_2$
VOC
Lower level release of heat and trace gases
"warm" cloud rain
$NO_X$
VOC
AEROSOL CCN
$H_2O$
$NO_2$
soil
NO
© M.O. Andreae, 2001

11


THE GREAT TROPICAL REACTOR
as perturbed by deforestation and pollution
High level release of heat, water and trace gases
Lightning
Ice
UV
$H_2O + O_3 \rightarrow 2OH + O_2$
$O_3$ Source at high $NO_X$
$CH_4 \rightarrow CO \rightarrow CO_2$
VOC
AEROSOL CCN
Rain from "cold" clouds
$NO_X$
VOC
$H_2O$
SOIL
NO
© M.O. Andreae, 2001

12

## Incertezas na previsão de tempo e clima




Slingo & Palmer (Phil. Trans. R. Soc. A **(2011)**

13

## *Dealing with uncertainties -2*

*2. Forecast model f (X,t) -> DX/Dt = f(X,t)*

*f(X,t) is not perfectly known:*

- *Formulation of physical processes (radiation, turbulence, phase change of water – vapour, liquid, ice);*
- *Spatial resolution of the models (100km, 10km, 1km ….): how do we deal with upscaling?*
- *Numerical Methods: discretization*
- *F(X,t) is a multivariate function: physical interactions among components not completely understood – uncertainties in parameters.*

14

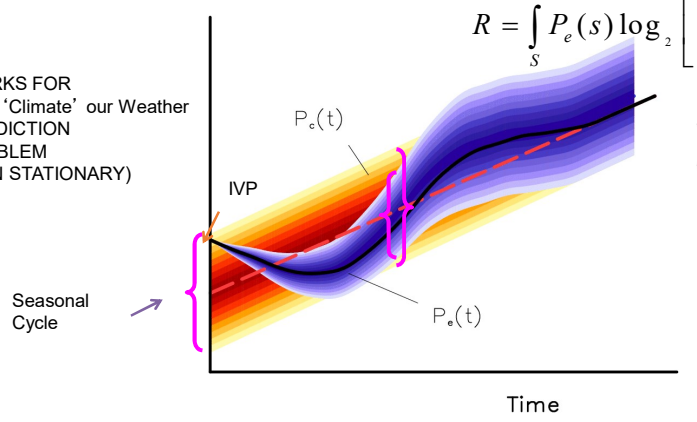
A HARD PROBLEM

Schematic Prediction (absent climate drift):

Initial value, Climate change & Total Predictability

$$R = \int_S P_e(s) \log_2 \left[ \frac{P_e(s)}{P_C(s)} \right] ds \frac{1}{n}$$

WORKS FOR
ANY 'Climate' our Weather
PREDICTION
PROBLEM
(NON STATIONARY)




Add information from initial state distribution (uncertain) + model uncertainty

How long is this information retained? (dynamics of the problem)

Predictability question

*"Mean" and "Spread" contributions*

*to predictive 'information'*

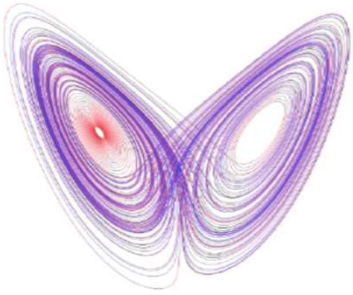
G. Branstator
Haiyan Teng

15

How can we predict weather beyond 10 days?
- effect of slow forcing in Lorenz's model

'Predictability in the midst of chaos'

*If we can't predict the weather beyond the next week or so, why is it possible to make seasonal forecasts?*

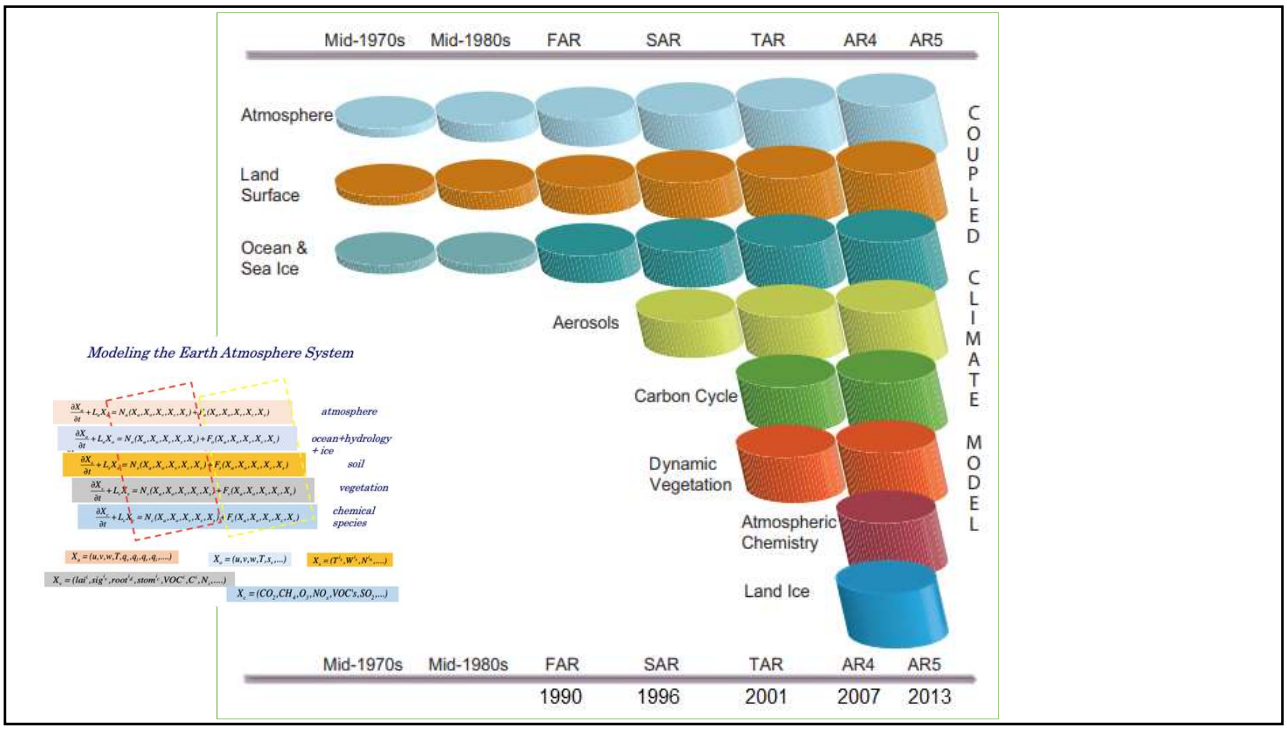


What is the impact of boundary forcing, *f*, on Lorenz Attractor?

$$\dot{X} = -\sigma X + \sigma Y + f$$
$$\dot{Y} = -XZ + rX - Y + f$$
$$\dot{Z} = XY - bZ$$

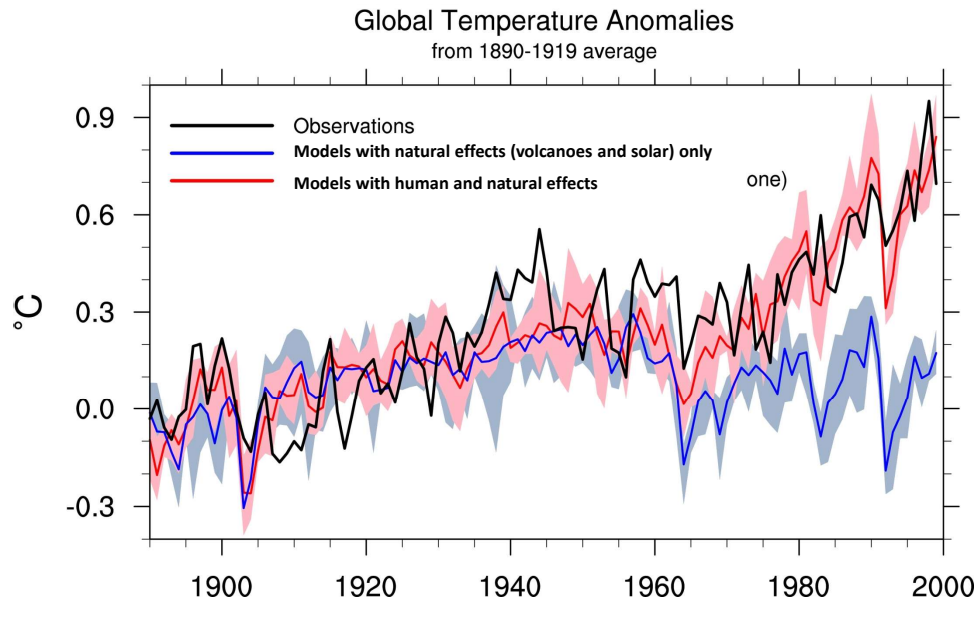
Birth of Seasonal Forecasting
'Predictability of Monsoons'
J. G. Charney and J. Shukla, 1981

16

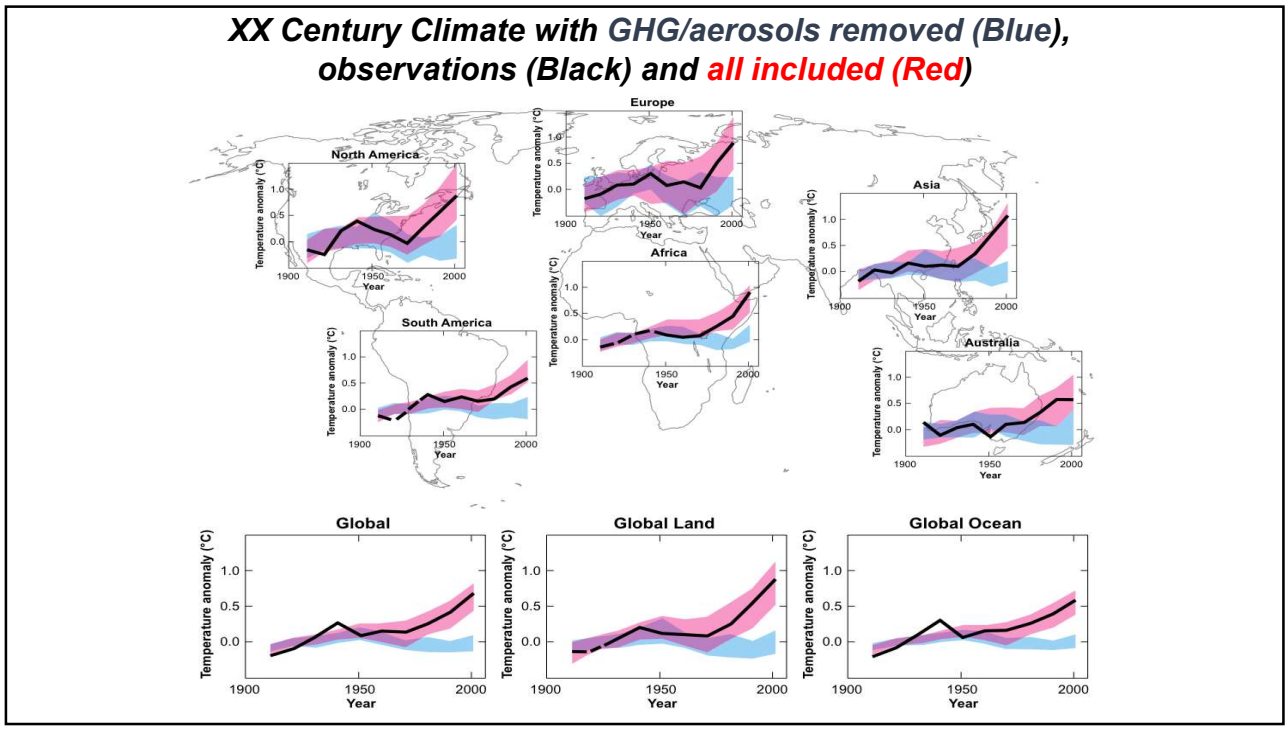



17

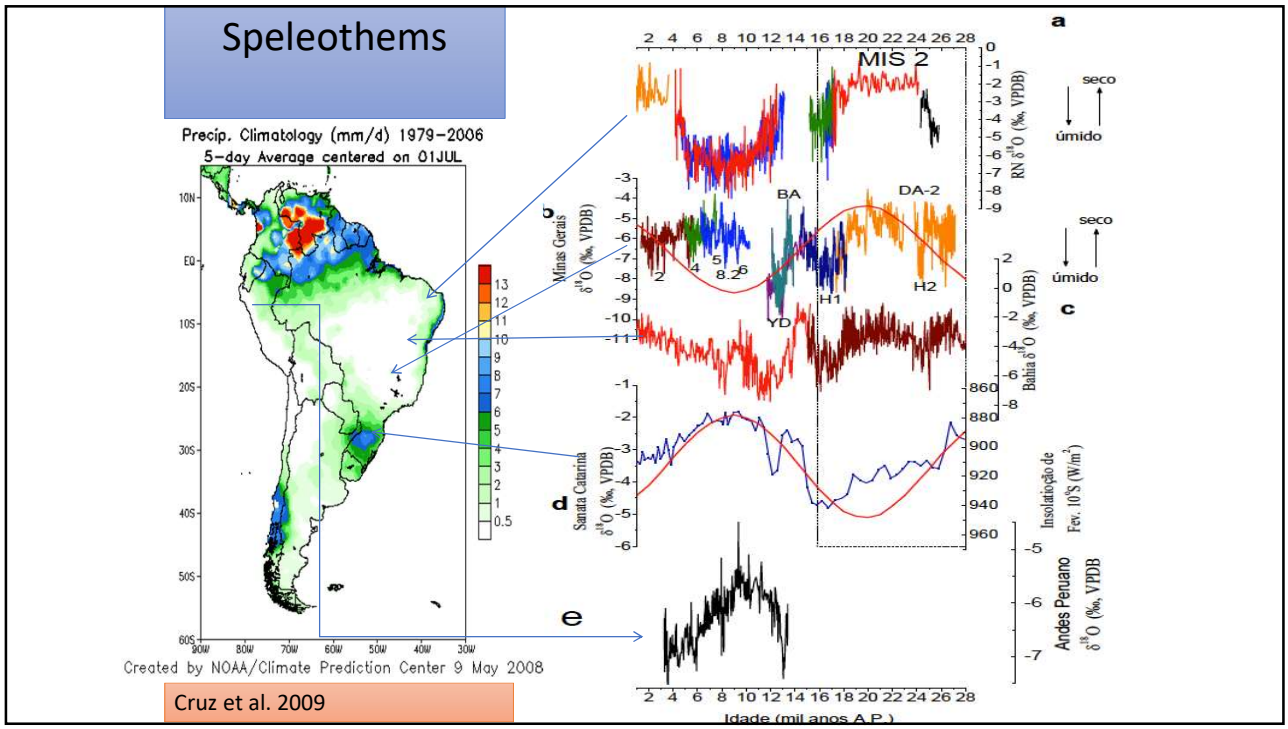
## Climate Models: natural processes do not explain warming after 1965..



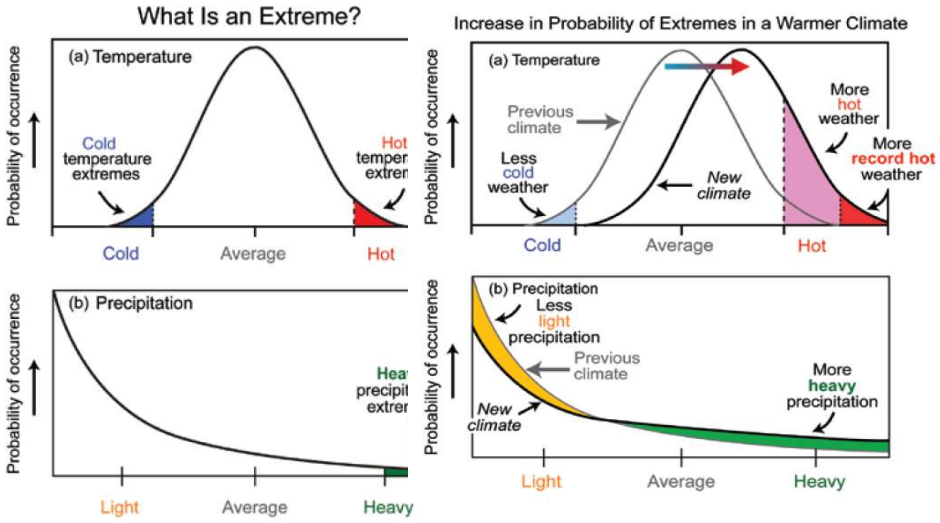

18


XX Century Climate with GHG/aerosols removed (Blue), observations (Black) and all included (Red)
Europe
North America
Asia
Africa
South America
Australia
Global
Global Land
Global Ocean
Temperature anomaly (°C)
Year

19


Speleothems
Precip. Climatology (mm/d) 1979-2006
5-day Average centered on 01JUL
Created by NOAA/Climate Prediction Center 9 May 2008
Cruz et al. 2009
MIS 2
BA
DA-2
H1
H2
YD
seco
úmido
Idade (mil anos A.P.)

20




21

1. Solar Radiation reaching the Earth: orbital and solar output

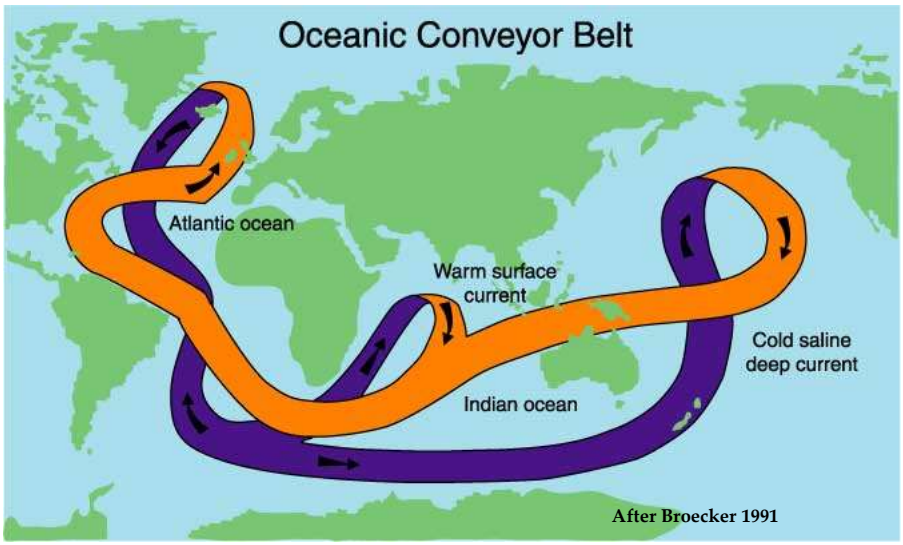
2. Changes in the Atmospheric Composition - Short Wave and Long Wave

3. Changes in the Earth's surface (tectonics, vegetation/climate interactions)

22

But there are other mechanisms for explaining climate variability – internal mechanisms

23




24

## Other mechanisms for climatic variability:

- **Nonlinearities: Interaction among different time scales ….**

25

## *Nonlinearity => energy transfer among scales*

***Dynamics of resonant interaction through advection terms***

*•Examples:*

*•Interaction between slow ( O(5-7days) ) and fast modes ( O(1 day or less) ) => intraseasonal scales (20-60 days) Raupp and Silva Dias. (2004,2005,2006, 2008)*

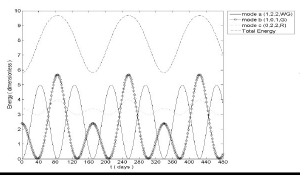
*•Importance of diurnal variation leading to energy in intraseasonal time scales (Raupp and Silva Dias, 2009,2010)*

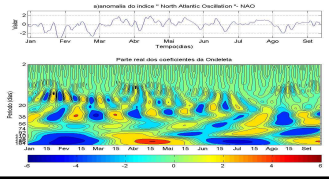
*•Coupled ocean/atmosphere simplified models: interaction between intraseasonal scale ( O(20-60d) ) with interannual (El Nino/La Nina) - O (2-3 yr) => decadal/multidecadal time scales (Ramirez et al. 2009,2011, 2017)*

$$c_a^{\,2}\frac{dA_a}{d\tau} = A_b A_c \eta_a^{bc} + q_a \delta\left(\frac{\varpi_a \pm \nu_f}{\varepsilon}\right)$$

$$c_b^{\,2}\frac{dA_b}{d\tau} = A_a A_c^{*} \eta_b^{ac} + q_b \delta\left(\frac{\varpi_b \pm \nu_f}{\varepsilon}\right)$$

$$c_c^{\,2}\frac{dA_c}{d\tau} = A_a A_b^{*} \eta_c^{ab} + q_c \delta\left(\frac{\varpi_a \pm \nu_f}{\varepsilon}\right)$$





26

Journal of Atmospheric Sciences - DOI: 10.1175/JAS-D-15-0325.1

**Multiscale Atmosphere–Ocean Interactions and the Low-Frequency Variability in the Equatorial Region**

ENVER RAMIREZ

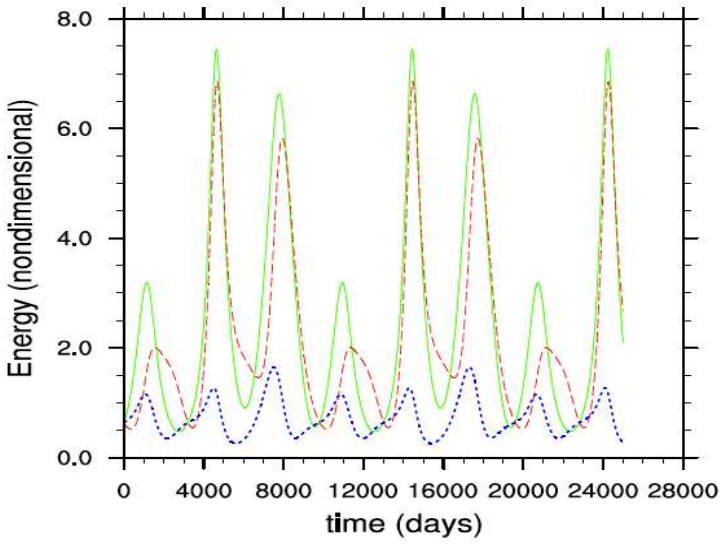
*Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, São Paulo, Brazil*

PEDRO L. DA SILVA DIAS AND CARLOS F. M. RAUPP

*Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, Brazil*

MULTITIME SCALINGS: $\partial_t \rightarrow \varepsilon^{-1}\partial_{\bar{\tau}} + \partial_t + \varepsilon\partial_\tau .$

27




Simplified coupled model resonant interaction: atmospheric Kelvin (moist)(green), Rossby atmosphere (dry – green) and ocean Kelvin (blue)

28

Normal Mode Decomposition of the Quasi Biennial Oscillation: hints on the 2016 disruption

Raphaldini, B., Teruya, A, S. W., Silva Dias, P. L., Mayta, V. R. C.

[1]Instituto de Astronomia, Geofisica e Ciencias Atmosfericas, Universidade de Sao Paulo

Multiscaling problem: QBO – 2yr and MJO – 20-60 days

- Some background on multiscaling processes involving MJO
  - Nonlinear resonance: interaction among normal modes of the linearized operator of the governing equations assuming basic state at rest
    - Vertical modes and Horizontal Modes
    - Rossby, gravity-inertia, mixed Rossby-gravity, Kelvin waves for each vertical mode. => complete set => expansion of observed atmospheric fields
    - Possible non-linear resonance involving triads of normal modes, interaction between triads with one member in common etc….
  - Going from the diurnal to intraseasonal with atmospheric models

29

*Changes in extreme daily rainfall for São Paulo, Brazil*

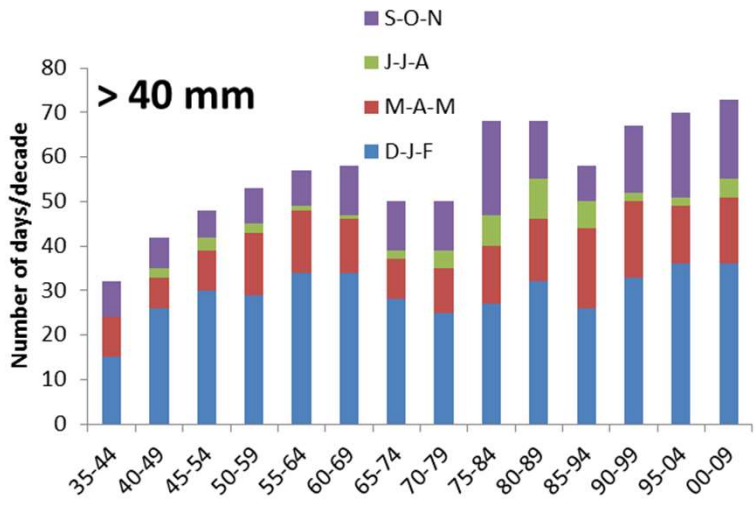
**Maria A. F. Silva Dias, Juliana Dias, Leila M. V. Carvalho, Edmilson D. Freitas & Pedro L. Silva Dias**

**Climatic Change**
An Interdisciplinary, International Journal Devoted to the Description, Causes and Implications of Climatic Change

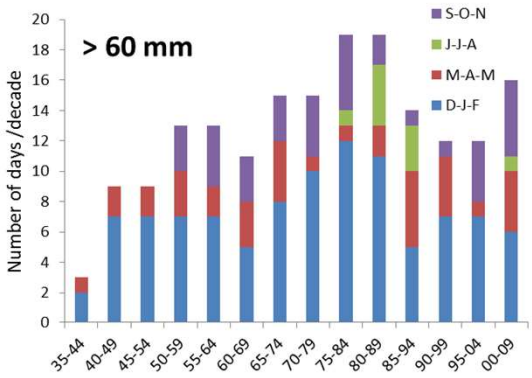
Climatic Change

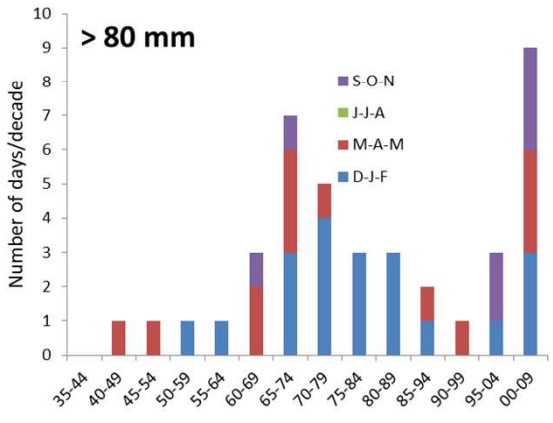
30

# Number of days per decade of rainfall over 40 mm for each season




31



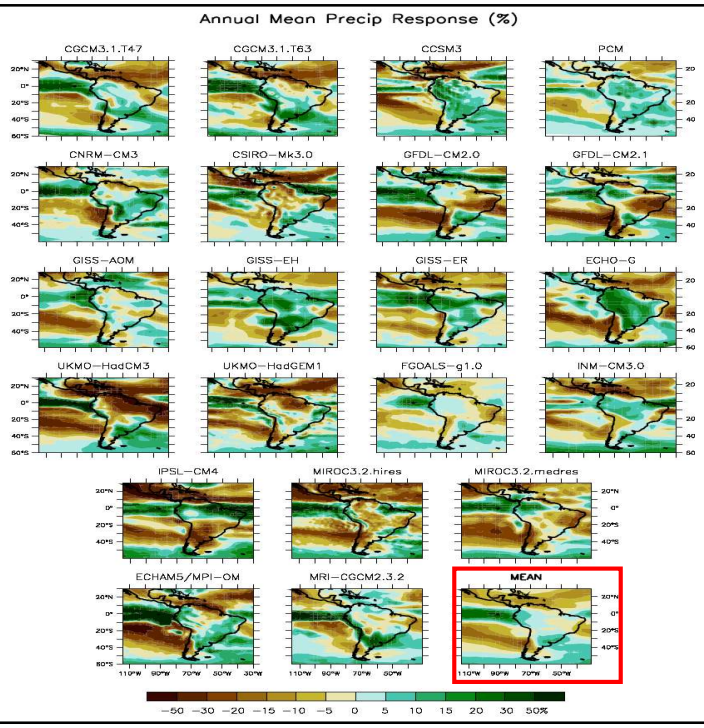




32

# Conclusions on the causes of observed tendencies in rainfall extremes

- Global climate – account for ~ 50% of observed variability in the wet season
- Local features – remaining observed variability in the wet season
  - Growth of urban área
  - Air pollution
- During the dry season global climate accounts for > 80% of observed variability in rainfall extremes

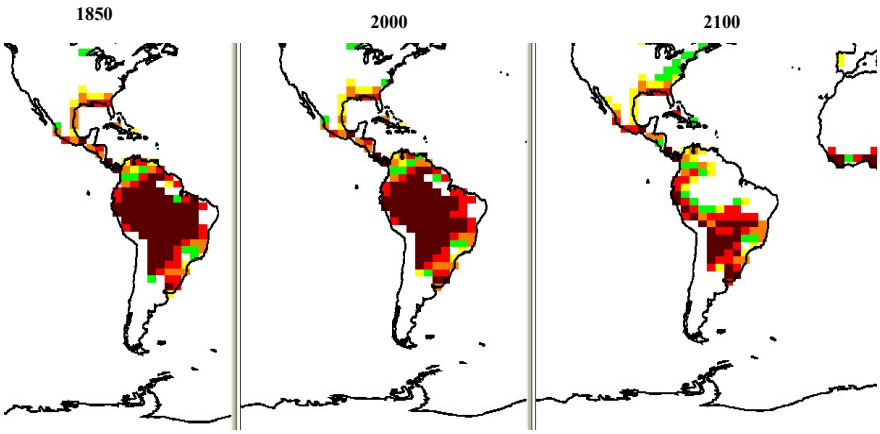
33




***Percent change in precipitation from the years 1980-1999 to 2080-2099 under the A1B scenario. Brown indicates a reduction in precipitation and green an increase. The per cent change in the precipitation averaged over all models is shown in the lower right hand corner.***

34

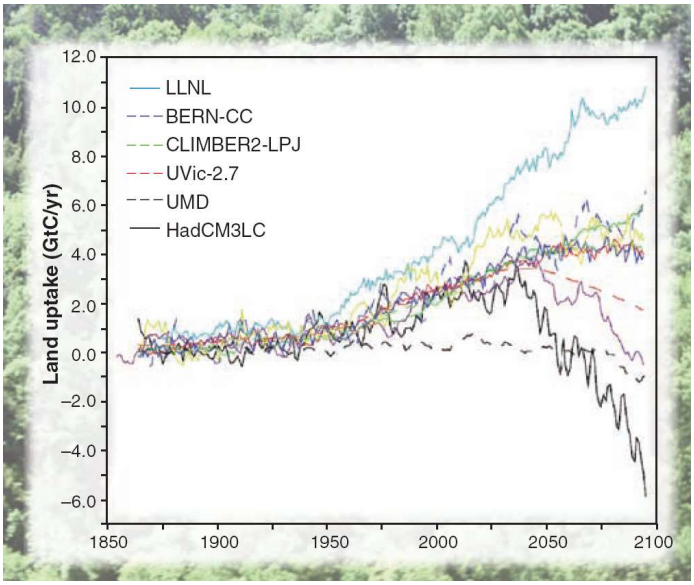
## *Example of extreme climate trajectories in IPCC models: the Hadley Center model and Amazon Forest*



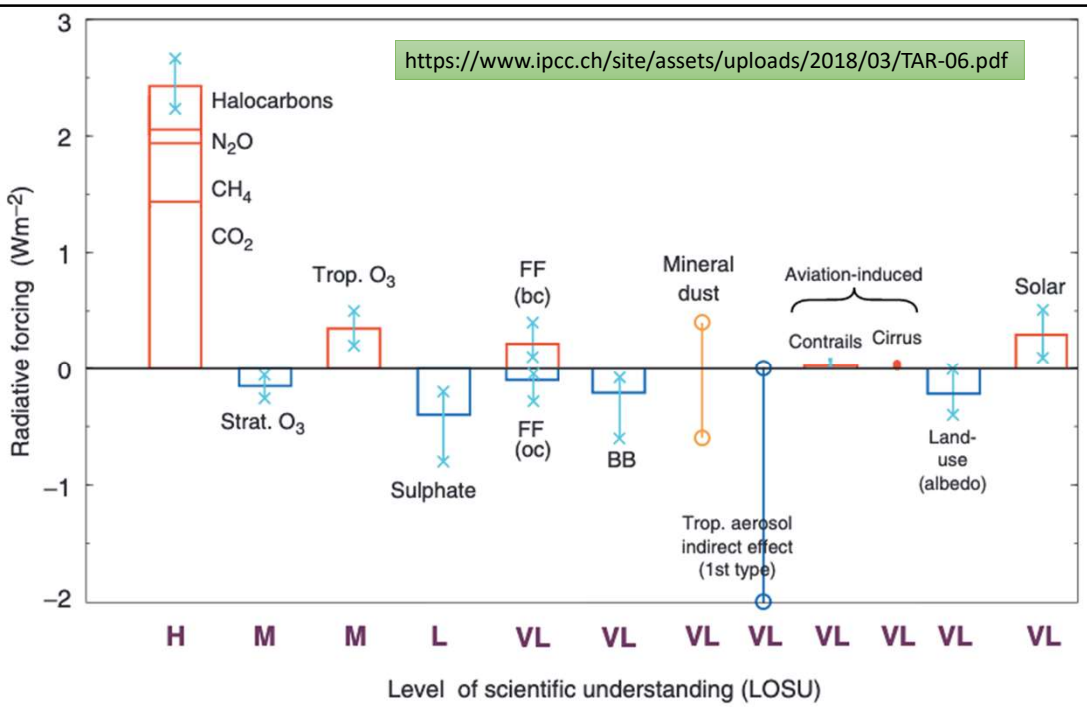

*Retrocesso da floresta amazônica por mudança climática*

35

## *However, considerable discrepancies among IPCC models due to dynamical vegetation models..*




36




37

## *Conclusion*

- Relevance of climate model uncertainties for Geoengineering Modeling and Climate:
  - **Carbon storage**: uncertainties in modeling biogeochemical cycles
    - Dynamical vegetation – complexity
    - Ocean biogeochemistry!
  - **Solar Geoengineering**
    - Radiative Forcing associated to Aerosols
      - Aerosols and warm & cold clouds – complex cloud microphysics interactions
      - Stratospheric effects!
        - Stratosphere/Troposphere interactions : need higher vertical resolution and more accurate ozone chemistry
  - Role of internal nonlinear dynamics in controlling slow climate variability

38

***Thanks!!!***

***pedro.dias@iag.usp.br***

39