A simple model of multiple climate regimes

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Overview

1. Introduction

2. Essential Climate Feedback Processes

Ocean's Thermohaline Circulation, Large-Scale Circulation of the Atmosphere, Atmospheric CO_2

3. A Simple Climate Model

Structure of the underlying model and explanations on physical concepts involved

4. Results and Discussion

Results given by simulations of this model and its relation to phenomenas on earth

1. Introduction

We build up a simple climate model including both atmospheric and oceanic heat circulation (between the tropics and the poles) to show the existence of a limited number of stable climate regimes producing multiple equilibrium states. We want to use this latter idea to explain the Earth's climate sensibility and stability to smaller and bigger external variation (e.g. variation of the orbit or the solar insolation).

2. Essential Climate Feedback Processes

a. Driving of the Ocean's Thermohaline Circulation

- Critical role in setting the global temperature distribution (1/3 of the equator to pole heat flux)
- Turbulences mix relative warm water into colder water at depth (otherwise no thermodynamic efficiency as there are (almost) no heat sources in the ocean)
- Source of mixing is the global tropical cyclone activity: Changes in it imply changes in the poleward heat flux by the oceans. This affects climate.
- Lateral heat flux induced by a source of mixing in the tropical oceans scales as

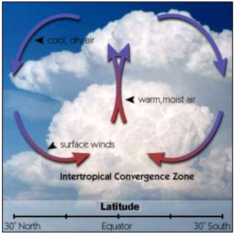
$$F \sim P^{\frac{2}{3}} B^{\frac{2}{3}},$$

F - lateral heat flux, P - Power in vertical mixing,
B - total buoyancy gradient at sea surface

2. Essential Climate Feedback Processes

b. Greenhouse Trapping and Large-Scale Circulation of the Atmosphere

- Large-scale atmospheric circulation system (e.g. Hadley cells)



(http://whyfiles.org/174earth_observe/images/hadley.jpg)

- Circulation below critical threshold → deep convection in descent region which gets more humid (similarly ascent region becomes drier, but relative intensity less than in descent one) ⇒ net greenhouse trapping by the atmosphere increases
- heat transport of ocean ↗
  ⇒ large scale circulation ↘ ⇒ greenhouse trapping ↗

2. Essential Climate Feedback Processes

c. Atmospheric CO_2

- Atmospheric CO_2 varies with temperature and ice volume
- CO_2 is more soluble in cold, fresh than in warm, salty water
- deepening of tropical thermocline → increase of “warm” water in ocean → increase in CO_2. We have

$$h \sim P^{\frac{1}{3}} B^{-\frac{2}{3}},$$

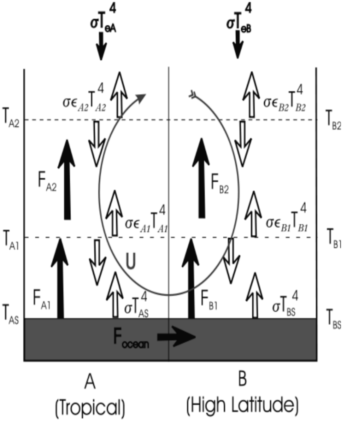
  h - thermocline depth, P - Power in vertical mixing,
  B - total buoyancy gradient at sea surface

- Atmospheric CO_2 varies with volume-weighted mean temperature of ocean (but it depends on more factors this)

3. A Simple Climate Model

a. Overview of the model

- $T_{i,j}$ - temperature at certain atmospheric layers
- T_{eA}, T_{eB} - effective blackbody emission temperatures
- $F_{i,j}$ - turbulent fluxes (carrying enthalpy)
- U - intensity of large-scale atmospheric circulation
- $\epsilon_{i,j}$ - longwave emissivity (depend on water vapor and CO_2)
- σ - StefanBoltzmann constant ($\sim 5.6704 \times 10^{-8} \frac{W}{m^2 K^4}$)
- White arrows - infrared fluxes

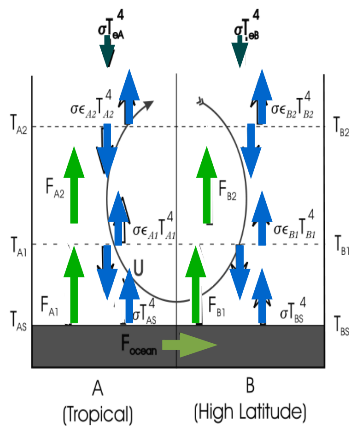


3. A Simple Climate Model

b. Physical conditions

Turbulent fluxes in relation with temperature

- $T_{i,j}$ - temperature at certain atmospheric layers
- T_{eA}, T_{eB} - effective blackbody emission temperatures
- $F_{i,j}$ - turbulent fluxes (carrying enthalpy)
- F_{ocean} - lateral heat flux



Turbulent fluxes in relation with temperature

- Turbulent fluxes, carrying enthalpy, are determined to enforce that the temperature lapse rate is not bigger than moist adiabatic lapse rates, i.e.

  $$T_{i,j} \leq T_{i,j+1} + \Delta T_{i,j},$$

  where $\Delta T_{i,j}$ determined by saturated adiabats corresponding to $T_{i,j}$. There are no turbulent fluxes in the corresponding box if solution without fluxes satisfies this equation.
- If this equation is violated, there are turbulent fluxes satisfying

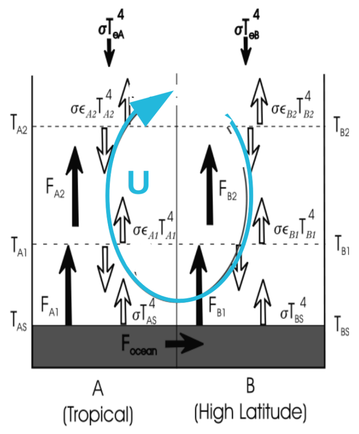
  $$F_{i,j} = \beta(T_{i,j} - T_{i,j+1} - \Delta T_{i,j})$$

  where β is large and $F_{i,j} \geq 0$ is enforced

3. A Simple Climate Model
b. Physical conditions

Large-scale atmospheric circulation

- U - intensity of large-scale atmospheric circulation



Large-scale atmospheric circulation

- Transports heat from A to B: horizontal circulation determined to enforce that horizontal temperature gradient doesn't exceed a critical value (depending on latitude and angular rotation of the earth)
- Magnitude of atmospheric circulation is given by

$$U = \beta(T_{A2} - T_{B2} - \Delta T_c),$$

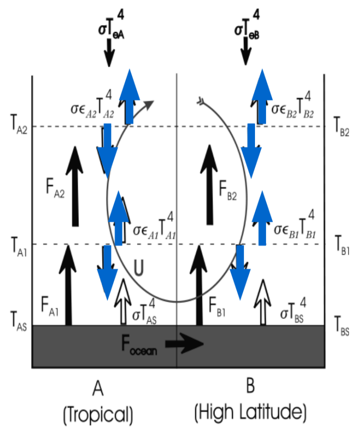
  where β large number, and ΔT_c critical horizontal temperature gradient (if below threshold value, then no atmospheric circulation)
- For simplicity same equation for higher latitudes, even if the heat transport there is dominated by baroclinic eddies

3. A Simple Climate Model

b. Physical conditions

Emissivity and CO_2 content

- $\epsilon_{i,j}$ - longwave emissivity (depend on water vapor and CO_2)



3. A Simple Climate Model

b. Physical conditions

Emissivity and CO_2 content

- Emissivities are based on CO_2 concentration and vapor density

  $$\epsilon_{i,j} = 1 - e^{-\alpha \mathrm{CO}_2 - \gamma q_{i,j}} \qquad \alpha, \gamma \ - \ c^{te},$$

  in the corresponding layers with $q_{i,j}$ specific humidity, except upper right layer where humidity decreases with increasing circulation strength

  $$q_{B2} = \widetilde{H} q^*_{B2}(1 - aU),$$

  $\widetilde{H}$ - prescribed background relative humidity, a - constant, q^*_{B2} - saturation specific humidity

Emissivity and CO_2 content

- Atmospheric CO_2 content depends, in this model, only on weighted ocean temperature (not including many factors)

$$\mathrm{CO}_2 = C + \lambda \left(T_{BS} + \frac{h}{H}(T_{AS} - T_{BS}) \right),$$

C - base value of CO_2, h - thermocline depth, λ - constant, H - mean ocean depth

- Parameters are tuned to give reasonable CO_2 fluctuations between glacial and interglacial cycles

Oceanic heat flux

- Buoyancy gradient between tropical and high latitude boxes

$$B \sim T_{AS} - T_{BS}$$

Mixing power related to tropical cyclone activity

$$P \sim \sum_i V_i^3,$$

V_i being maximum wind speed in tropical cyclones, summed over the globe and some characteristic time and satisfying

$$V_i^2 \sim \epsilon_T (k_0^* - k),$$

latter being the relation between average storm intensity and theoretical upper bound on storm intensity

Oceanic heat flux

- $k_0^* - k$ being the difference of saturation enthalpy of sea surface and enthalpy of boundary layer air, and satisfying the aerodynamic flux formula for the surface flux for enthalpy

$$F_{A1} \sim \mid V_S \mid (k_0^* - k),$$

$\mid V_S \mid = \sqrt{u_*^2 + U^2}$ - magnitude of surface wind speed

-

$$V_i^2 \sim \epsilon_T \frac{F_{A1}}{\sqrt{u_*^2 + U^2}},$$

ϵ_T - thermodynamic efficiency (constant except if deep convective flux $F_{CA} = 0$), U - circulation strength, u_* - accounts for contribution of small scale and fluctuating wind to average wind speed

Overview

- 2 or 3 stable regimes, depending on choice of parameters
- Solutions (as surface temperature, fluxes, CO_2 content, etc.) are shown as a function of the ratio of the effective black body emission temperatures of high and low latitude boxes, i.e $\frac{T_{eB}}{T_{eA}}$
- Sensitivity of parameters: a larger variation in one parameter (affecting the pole-to-equator temperature gradient) might not produce two or three regimes, but only one

4. Results and Discussion

Results

Surface temperature SST

Jumps in the polar surface temperature are greater than those in the tropical surface temperature (partially due to water vapor which affects polar temperatures more)

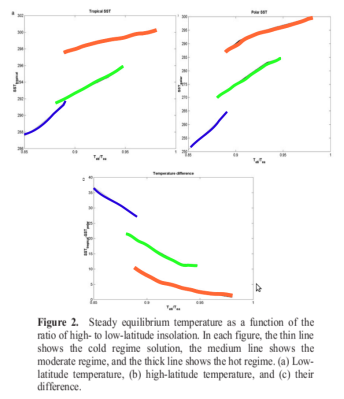


Figure 2. Steady equilibrium temperature as a function of the ratio of high- to low-latitude insolation. In each figure, the thin line shows the cold regime solution, the medium line shows the moderate regime, and the thick line shows the hot regime. (a) Low-latitude temperature, (b) high-latitude temperature, and (c) their difference.

Poleward Enthalpy Transport

- All poleward heat flux is carried by the atmosphere in the cold solution: no convective flux from the first to the second layer of tropical box, so no tropical cyclones
- In moderate regime, the poleward heat flux is carried by both the atmosphere and oceans
- In the hot regime, the ocean's heat transport is so effective that it shuts down the atmospheric circulation

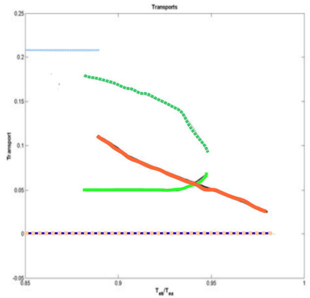


Figure 3. As in Figure 2, but showing nondimensional lateral enthalpy transport. Gray lines show atmospheric transport; black lines show oceanic transport.

Atmospheric transport velocity

- No poleward heat flux by atmosphere in hot regime
- In the cold regime, all the heat is carried by the atmosphere

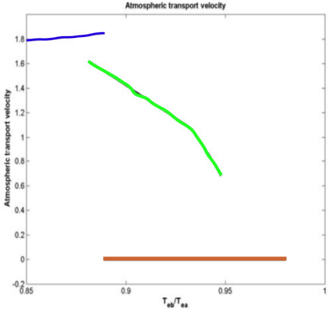


Figure 4. As in Figure 2, but showing nondimensional atmospheric transport velocity.

Vertical Heat Fluxes

Vertical heat fluxes are absolutely absent in the cold regime. Here the atmospheric overturning is so strong that it stabilizes the tropical atmosphere to deep convection

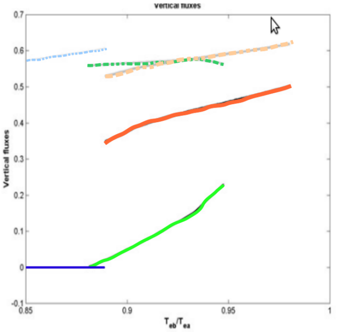


Figure 5. As in 2, but showing turbulent vertical fluxes in the low-latitude box. Gray lines show fluxes from level 1 to level 2; black lines show surface fluxes.

4. Results and Discussion
Results

Wind speed of tropical cyclones

The absence of deep convection prevents tropical cyclone activity in the cold regime (the jump from the moderate to the hot regime is primarily due to a decrease in mean surface winds)

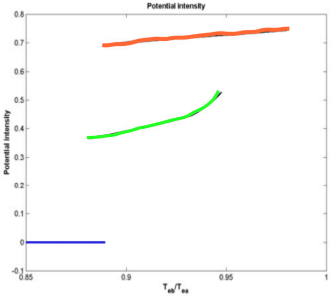


Figure 6. As in Figure 2, but showing the nondimensional potential maximum wind speed of tropical cyclones in the low-latitude box.

4. Results and Discussion

Results

Emissivity of the upper layer of the high latitude box

- Small jump from the cold to the moderate regime is mostly due to the temperature dependence of the water vapor content, but also to CO_2 increase from change in ocean temperature
- Large jump from the moderate to hot regime is dominated by the stop of atmospheric circulation and corresponding subsidence drying

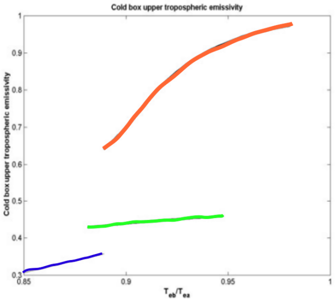


Figure 7. As in Figure 2, but showing the emissivity of layer 2 in the high-latitude box.

Thermocline Depth

- Approaches surface in cold regime due to lack of vertical mixing when tropical cyclones are absent
- Slowly increases in the moderate regime with the increase of tropical cyclone potential and decrease of gradient of ocean temperature
- Increase in the hot regime due to weak gradient of ocean temperature and strong intensity of tropical cyclones

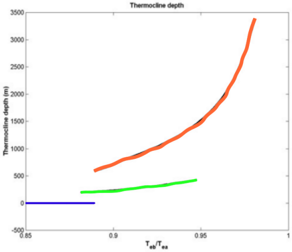


Figure 8. As in Figure 2, but showing the tropical thermocline depth.

4. Results and Discussion

Results

CO_2 Content

- Uncertainty in how atmospheric CO_2 reacts to long-term changes in thermohaline circulation and ocean temperature

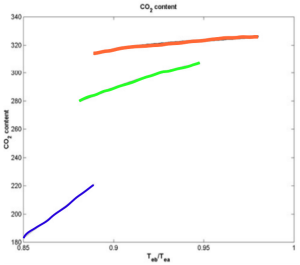


Figure 9. As in Figure 2, but showing the atmospheric CO_2 content.

4. Results and Discussion

Results

Parameter dependence

Depending on the choice of parameters, the model does not always achieve a steady state, in these cases the solution “flip-flops” between two quasi-equilibrium states

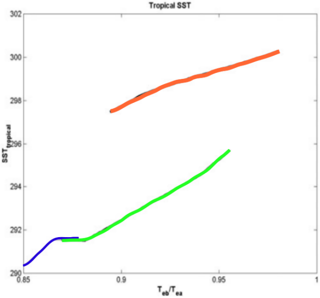


Figure 10. As in Figure 2a, except that atmospheric CO_2 constant.

4. Results and Discussion

Discussion

- Consistency of the model with: any effect cooling the tropics (usually) diminishes tropical cyclone activity → less vertical mixing and oceanic enthalpy flux out of the tropics → tropical temperatures within a relatively narrow range
- Transitions should be accompanied by strong changes in atmospheric circulation and average wind speeds inversely correlated with global temperature: consistent with this model where strong changes of oceanic enthalpy transport are (partially) compensated by changes in atmospheric transport, correlated with surface wind speed

- In this model, periodic forcing (e.g. orbital) can produce a large response provided it induces regime transitions: earth's climate sensitive to small changes in insolation caused by varying orbit while stable over a long periods during which solar output changes by 30%
- A lot of the time-dependent dynamics of this model is missing: there should be strong hysteresis in the timescale of warming vs cooling (the upper ocean warms adjusts quicker when transitioning to higher temperatures than to lower ones)
- Strong dependence of tropical cyclone activity on climate; but very few proxies of past storminess are available (currently available data does not extend as far back as the last ice age)

Thanks