Lecture Notes

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Overview:1

Purpose; Study models of the interaction between the global economy and the climate to

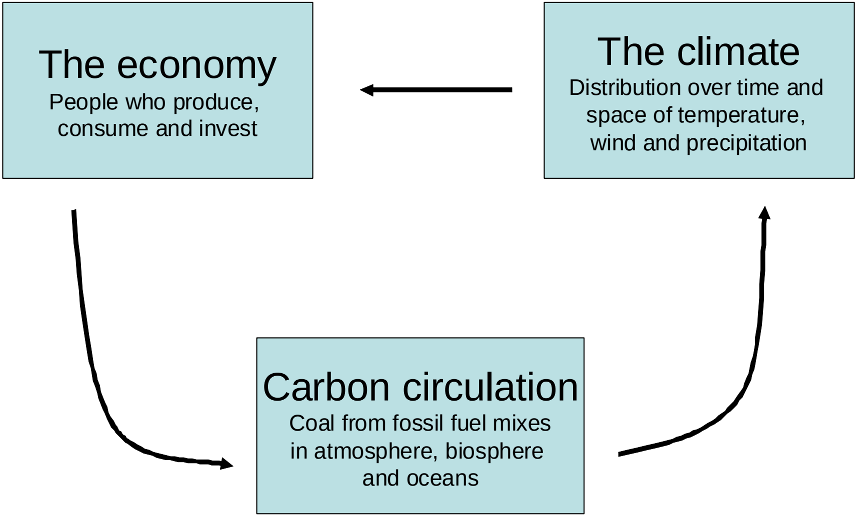
- provide understanding of important mechanisms,
- analyze optimal policy.
- Involves resulta from both social and natural sciences.
- But we are economists – use our comparative advantage to contribute and critically analyze the economic side but take "conventional wisdom" from the natural science as given.
- Economics is key for analyzing effects of policy.

Overview:2

Emissions are caused by decisions taken by billions of people, firms and other agents acting on markets. Cannot be understood without economics. Economics is important for

- analyzing effects of policy,
- understanding endogenous adaptation and technical change,
- making forecasts.

A schematic IAM - interactions

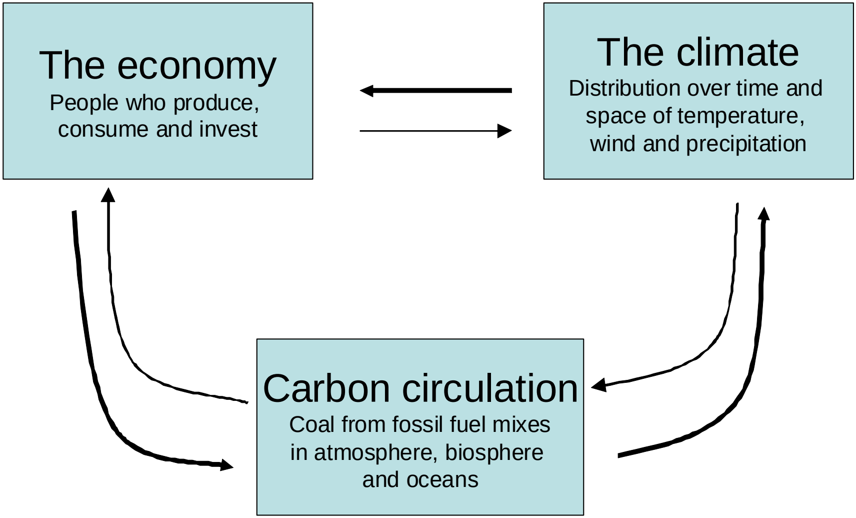


The economy
People who produce, consume and invest

The climate
Distribution over time and space of temperature, wind and precipitation

Carbon circulation
Coal from fossil fuel mixes in atmosphere, biosphere and oceans

A schematic IAM - dynamic and bidirectional



The economy

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Climate models - forcing and the energy budget

- Incoming *energy flow of energy,* (short wave solar radiation) (342 $\text{W/m}^2 = 2400kW$ per football field), in steady state equals;
- Outgoing *energy flow*, consisting of
  - direct reflection (1/3)
  - Long-wave (heat) radiation (2/3).
  - The latter is a function of, in particular temperature and greenhouse gases.
- Without greenhouse gases and atmosphere, ground temperature would be -19°C.

The energy budget

- Consider a system (e.g., the earth) in a situation of net energy flow = incoming-outgoing flow=0.
- In such a case, the *energy budget is balanced* and no heat is accumulated or lost.
- Suppose now that the energy budget is perturbed by a positive amount F (inflow increased and/or outflow decreased)
- Now budget is now longer balanced but in surplus.
- Leads to an accumulation of heat in the system, temperature rises, quicker the larger is the energy budget surplus.
- Speed of temperature increase also depends on heat capacity of the system (mass and material). Compare a balloon with air and a balloon with water.
- As the temperature goes up, outgoing energy flow increases when temperature rises. Called *Planck feedback*.

A new balance is achieved

- Suppose there is an initial surplus in energy budget of F (forcing).
- As long as there is a surplus in the budget, temperature increases.
- Outflow is an *increasing* function of temperature $(O(T))$ (thermal radiation). So a higher temperature *reduces* surplus.
- Approximate the increased outflow as proportional to temperature increase. $O(T) \approx O(\bar{T}) + (T - \bar{T})\, O'(\bar{T})$
- Denote $\kappa \equiv O'(\bar{T})$, let $\bar{T}$ be pre-industrial temperature and re-name T_t as temperature over $\bar{T}$.
  - Energy budget is then $F - \kappa T_t$.
- Approximate rate of change in temperature is proportional (with constant σ) to surplus in budget: $\frac{dT_t}{dt} = \sigma (F - \kappa T_t)$.
- What determines σ? Will there be a new equilibrium? Yes, when $T_t = \frac{F}{\kappa}$
- If earth were a blackbody without atmosphere with a temperature of 15°C, $\kappa \approx 3.3 \frac{W/m^2}{K}$. Due to feedbacks, likely to be smaller.

Forcing

- Most of long-wave surface radiation is absorbed by clouds and greenhouse gases and re-emitted back.
- Strength depends on greenhouse gas concentration.
- Most important is water vapor. Second is CO_2.
- Human activities has increased concentration of CO_2 and other greenhouse gases, e.g., methane.
- Increase is equivalent to increased incoming radiation (forcing) of 1.7 and 1 W/m^2, respectively.

Forcing in 2011 relative to 1750

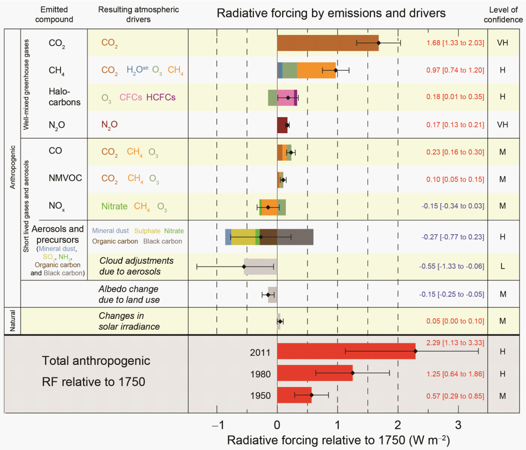
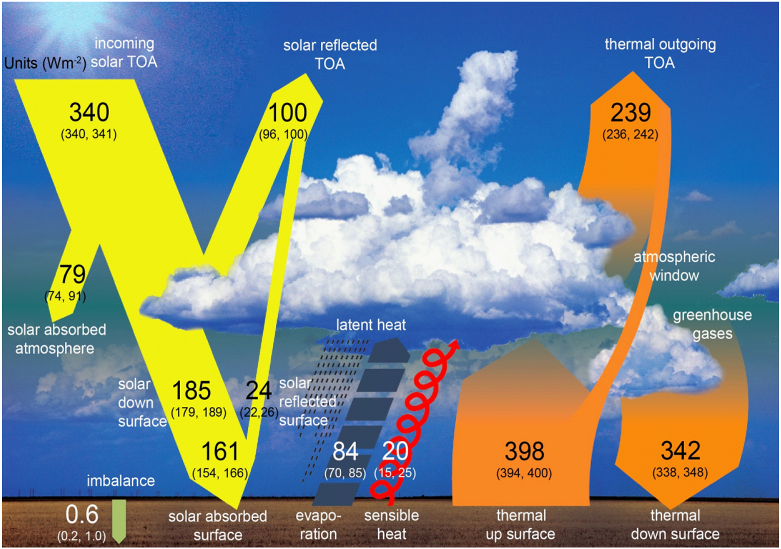


Figure: Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Source: IPCC, Assessment report 5, Summary for policy makers fig 5.

Energy Flows



Feedback effects

- Gross flows as very large relative to direct greenhouse effect.
- Creates feedback effects. Example, more CO_2 increase forcing, leads to
    - higher concentration of water vapor, increase greenhouse effect.
    - melting of icecaps, decrease direct surface reflection (albedo).
    - changed cloud formation, change back radiation and reflection.
- Feedback mechanisms are very important and have been so historically.
- Direct effect of CO_2 emission, quite certain. Not the case for feedback.

Feedbacks in the energy budget

- Let us formalize feedback as follows: Increased temperature increases *effective forcing,* adding a term xT_t to the energy budget, becoming:

$$\frac{dT_t}{dt} = \sigma \left(F + xT_t - \kappa T_t \right) = \sigma \left(F - \left(\kappa - x \right) T_t \right).$$

- The steady state for a given forcing F now becomes

$$T\left(F\right) = \frac{1}{\kappa - x} F$$

- A realistic value of $\frac{1}{\kappa - x}$ is around 0.8, but with large uncertainty.

Greenhouse effect and climate sensitivity

- Higher concentration of CO_2in atmosphere reduces outgoing energy flow (long-wave (heat) radiation).
- Well approximated by a logarithmic function (Arrhenius greenhouse law, 1896). For a given concentration S of CO_2 in the atmosphere and the pre-industrial level S_0, forcing is

$$F(S) = \frac{\eta}{\ln 2} \ln\left(\frac{S}{S_0}\right)$$

- An often used approximation of η is 3.7.
- Combine with $T(F) = \frac{F}{\kappa - x}$ gives

$$T(F(S)) = \frac{\eta}{\kappa - x} \frac{1}{\ln 2} \ln\left(\frac{S}{S_0}\right).$$

- The ratio $\eta/(\kappa - x)$ has a very important interpretation and is often labelled the *Equilibrium Climate Sensitivity (ECS).*
- IPCC AR5: ECS is "likely in the range 1.5 to 4.5°C", "extremely unlikely less than 1°C", and "very unlikely greater than 6°C".

Heating of oceans

- Equation $\frac{dT_t}{dt} = \sigma \left(F - (\kappa - x) \, T_t \right)$ does not take into account heating of oceans/atmosphere separately.
- Two other terms in energy budget for atmosphere, capturing energy flow from atmosphere to ocean and *vice versa.*
- These new terms *do not balance* if temperature is different (in an average sense).
- New law-of-motion for atmospehere

$$\frac{dT_t}{dt} = \sigma_1 \left(F_t - (\kappa - x) \, T_t - \sigma_2 \left(T_t - T_t^L \right) \right)$$

  where T_t and T_t^L, respectively, denote the atmospheric and ocean temperature in period t.
- Complete by setting

$$\frac{dT_t^L}{dt} = \sigma_3 \left(T_t - T_t^L \right)$$

- Implies a drag on heating, but no difference with respect to long-run effect of forcing.

Simulation

- Make a discrete time approximation. Yields a system of difference equations;

$$\begin{aligned} T_t &= T_{t-1} + \sigma_1 \left(F_{t-1} - (\kappa - x)\, T_{t-1} - \sigma_2 \left(T_{t-1} - T_{t-1}^L \right) \right) \\ T_t^L &= T_{t-1}^L + \sigma_3 \left(T_{t-1} - T_{t-1}^L \right) \end{aligned}$$

instead of

$$\begin{aligned} \frac{dT_t}{dt} &= \sigma_1 \left(F_t - (\kappa - x)\, T_t - \sigma_2 \left(T_t - T_t^L \right) \right) \\ \frac{dT_t^L}{dt} &= \sigma_3 \left(T_t - T_t^L \right) \end{aligned}$$

- Can easily be simulated in a spead-sheet program.

Simulation

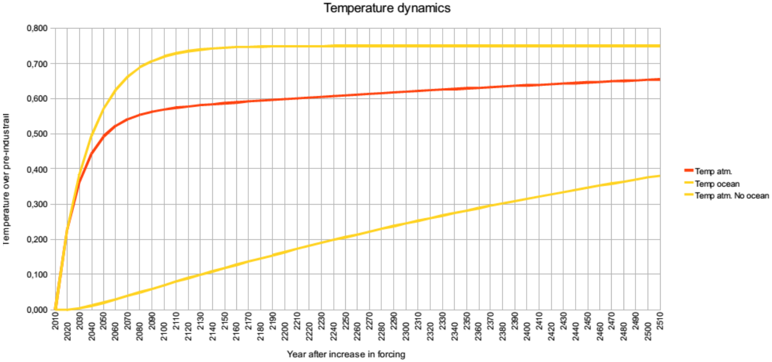
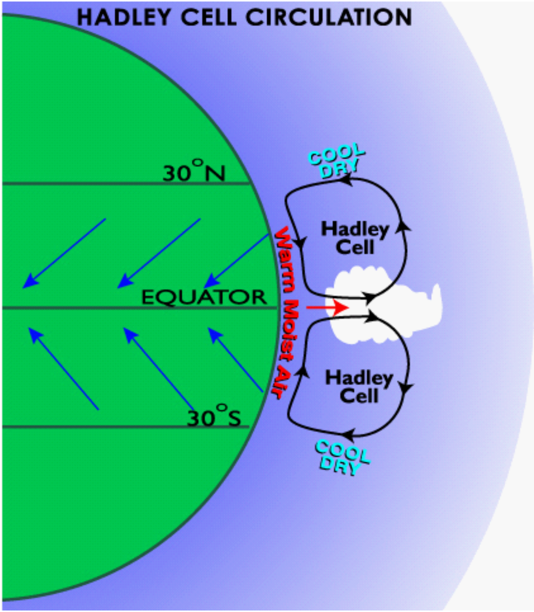


Figure: Increase in atmospheric and ocean temperature after a permanent forcing of $1W/m^2$.

Climate models:1

- Circulation models.
- Energy is not evenly radiated to the earth. Highest around equator.
- Creates systematic flows of air and water.
- Used to forecast weather – but also climate.

Climate models:Circulation cells

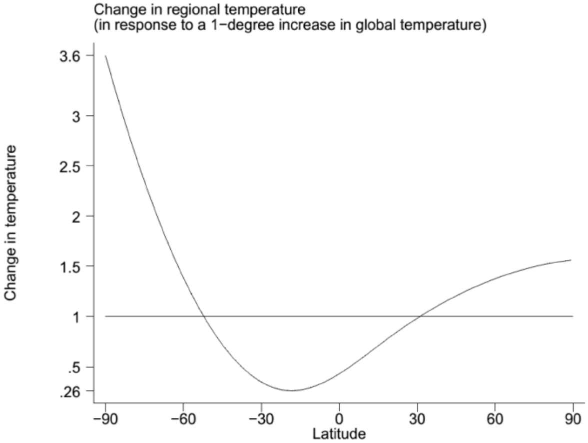


Climate models: key points

- Ocean currents also transport heat from equator towards poles.
- More accurate descriptions need to model landmasses and mountains.
- Climate models build on deterministic laws of physics but are chaotic in nature. This implies:
  - A "butterfly effect" – small variation in initial state e.g., distribution of energy, leads to unsystematic large differences in weather a few weeks later.
  - Unconditional distribution stable, e.g., mean and variance of temperature and wind speeds.
  - Best forecast is unconditional distribution for forecasts beyond a few weeks.
- State-of-the art climate models build on same principles.

Downscaling

- Circulation models (very) large and (very) time consuming to run.
- Simplification: use a statistical representation of how a change in global mean temperature affects different locations.
- Simplest case – use latitude. Estimate a different sensitivity β_i for each latitude.
- $T_{i,t} = \bar{T}_i + \beta_i * T_t + z_{i,t}$



Change in regional temperature
(in response to a 1−degree increase in global temperature)

Historic climate

- Use various proxy data, tree rings, corals, plankton and pollen...
- Also data on greenhouse gas concentrations. Postive correlation suggests positive feedback.

Ice ages

- Small change in solar influx or variation in earth's orbit gets amplified by feed-back.
- A key mechanism may be ice-albedo feedback (Arrhenius).
- A small negative F leads to buildup of the icecap.
- Increase albedo of earth, amplifies the initial effect.
- Additional effects may come from greenhouse gases.
- See https://youtu.be/gGOzHVUQCw0

Non-linearities

- Recall that the equilibrium climate sensitivity is affected by feedbacks

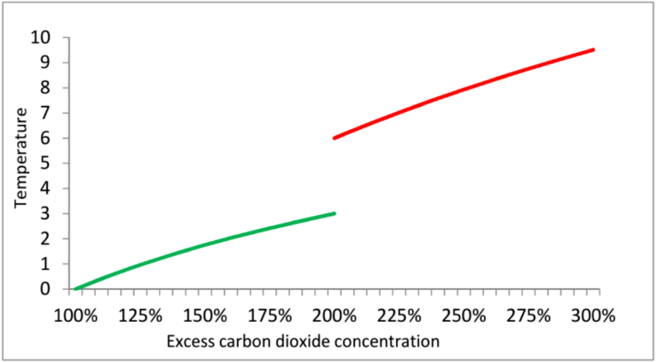
$$T(F) = \frac{\eta}{\kappa - x}\frac{1}{\ln 2}\ln\left(\frac{S}{\bar{S}}\right).$$

- We are quite uncertain about the value of x. One think that could happen is that it suddenly increases at some temperature. For example, suppose

$$x = \begin{cases} 2.1 \text{ if } T < 3^{o}C \\ 2.72 \text{ else} \end{cases}$$

- This produces a jump in the relation between CO_2 and long-run temperature.

Tipping points

- Suppose $\eta = 3.7$ and $\kappa = 3.3.$ and $x = 2.1$ if $T < 3^o C$ and 2.72 else. Then, the relation between CO_2 concentration and long-run temperature looks like follows
- 

Tipping points:2

- Tipping points like then one described are possibilities and many of them are known to exist on local and regional scales.
- If they exist on a global scale and if so at which temperatures is much more debated.

Feedback uncertainty

- Uncertainty in the feedback produces a skewed distribution of the climate sensitivity.
- Since $\lambda \equiv \frac{\eta}{\kappa - x}$ is a non-linear transformation of x, uncertainty about λ becomes very skewed with possibilities of very large values.
- Suppose the uncertainty about x by a symmetric triangular density function with mode 2.1 and endpoints at 1.35 and 2.85. The mean, and most likely, value of x translates into a climate sensitivity of 3.

Feedback uncertainty