Modelling the Climate System

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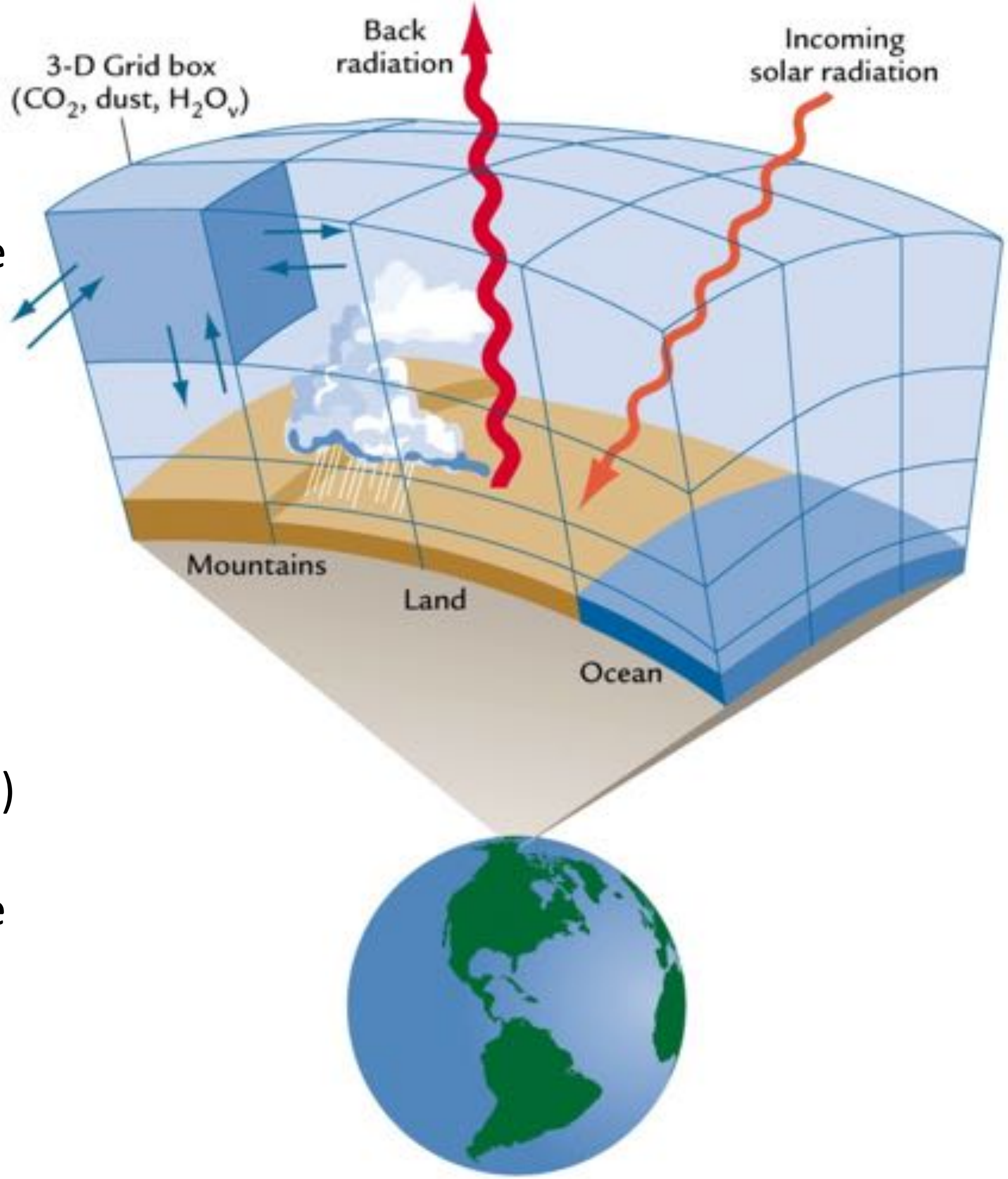
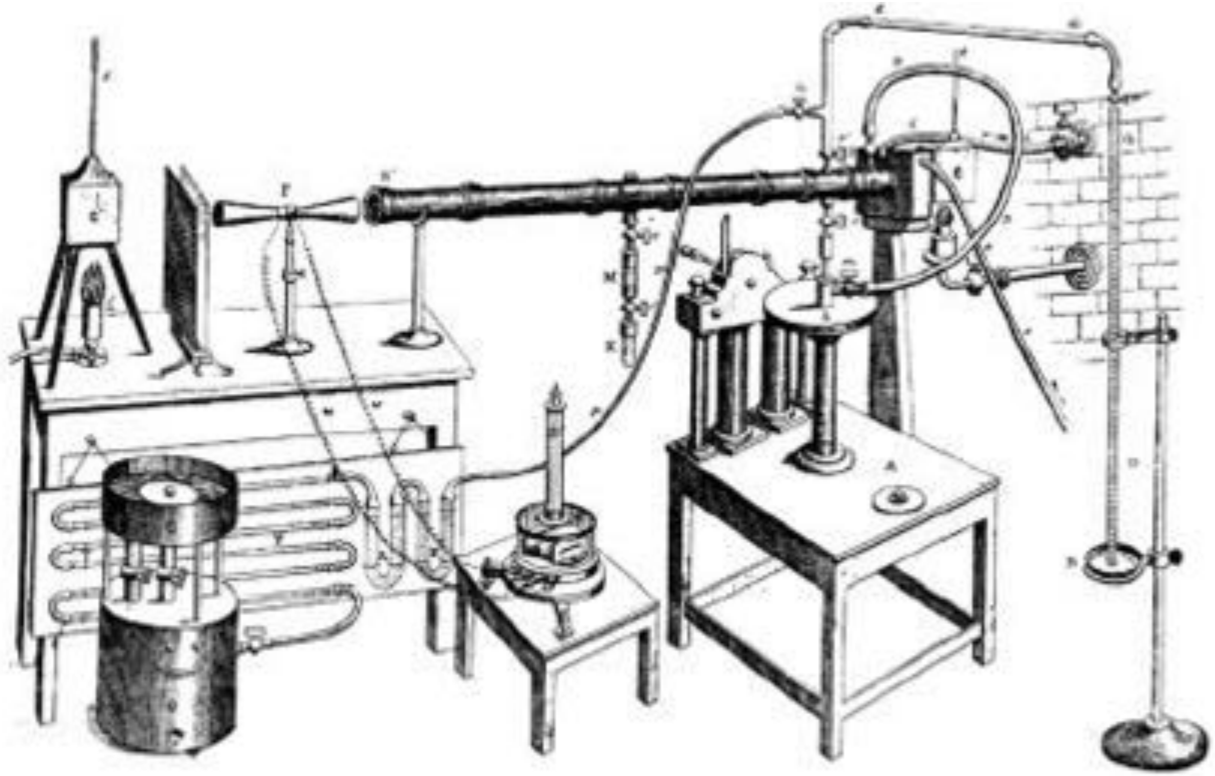
- Anthropogenic Climate Change
- Conceptual model of the Climate System
  - Governing equations
  - Solving the differential equations
  - Example 1- Climate Projections
  - Example 2- Geoengineering
- State-of-the-art climate models
  - Governing equations (ocean)
  - Solving the equations
  - Example: acceleration of the EAC – sending Nemo to Tasmania
- Climate Change research



Fourier concluded that at the distance the earth is from the Sun the earth should be much colder than observed. ***Jean-Baptiste Joseph Fourier (1768-1830)***

"The atmosphere admits of the entrance of the solar heat, but checks its exit; and the result is a tendency to accumulate heat at the surface of the planet". ***John Tyndall (1859)***



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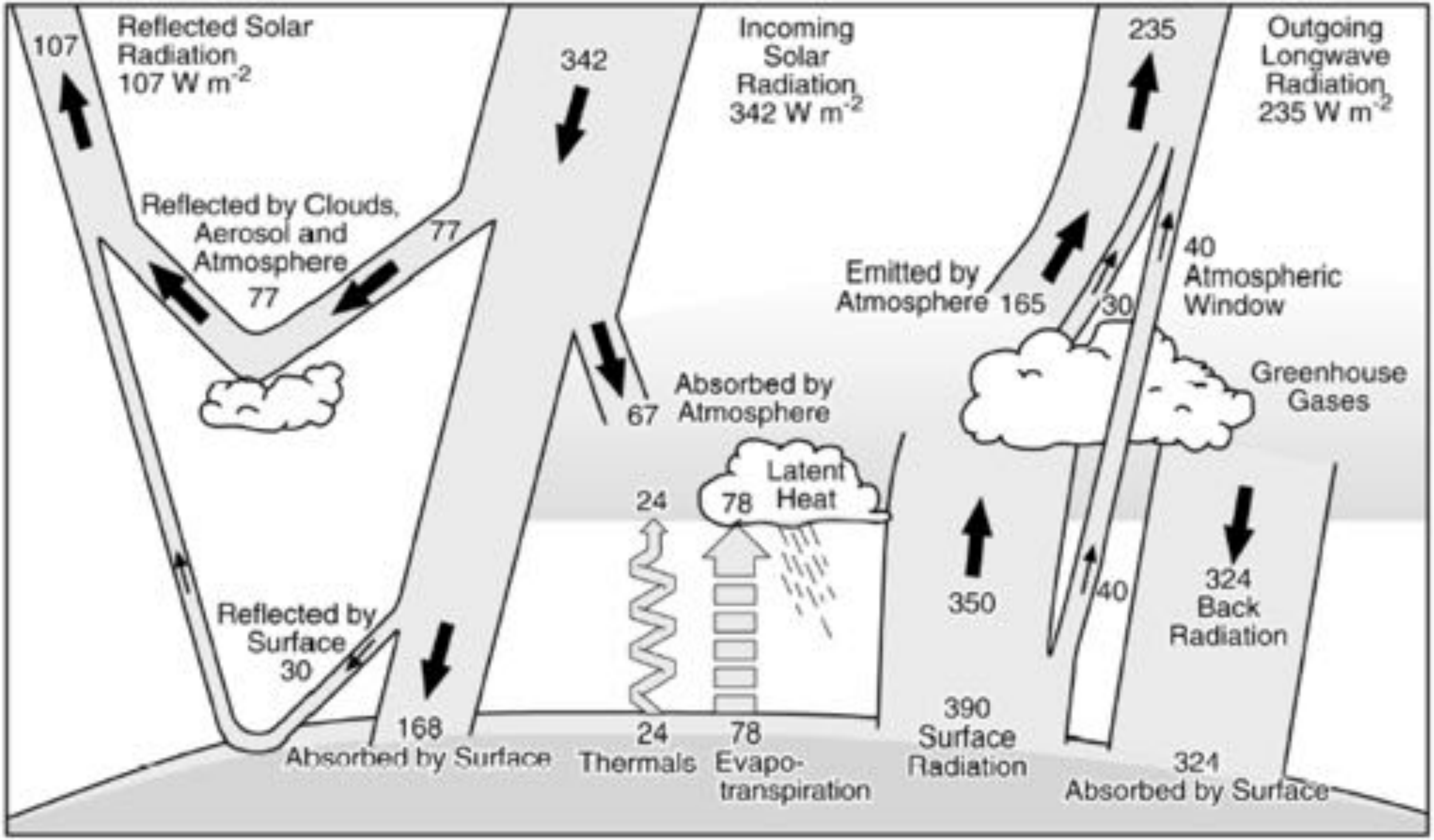
Arrhenius was the first person to predict that emissions of carbon dioxide from the burning of fossil fuels and other combustion processes would cause global warming. **Svante August Arrhenius (1896)**


107
Reflected Solar Radiation 107 W m-2
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77
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30
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67
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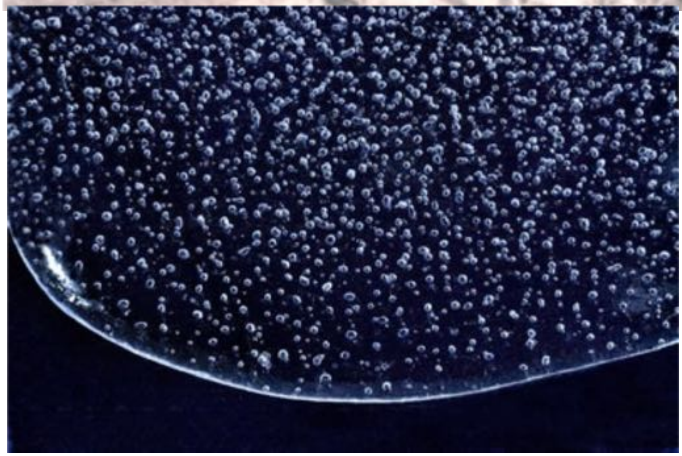
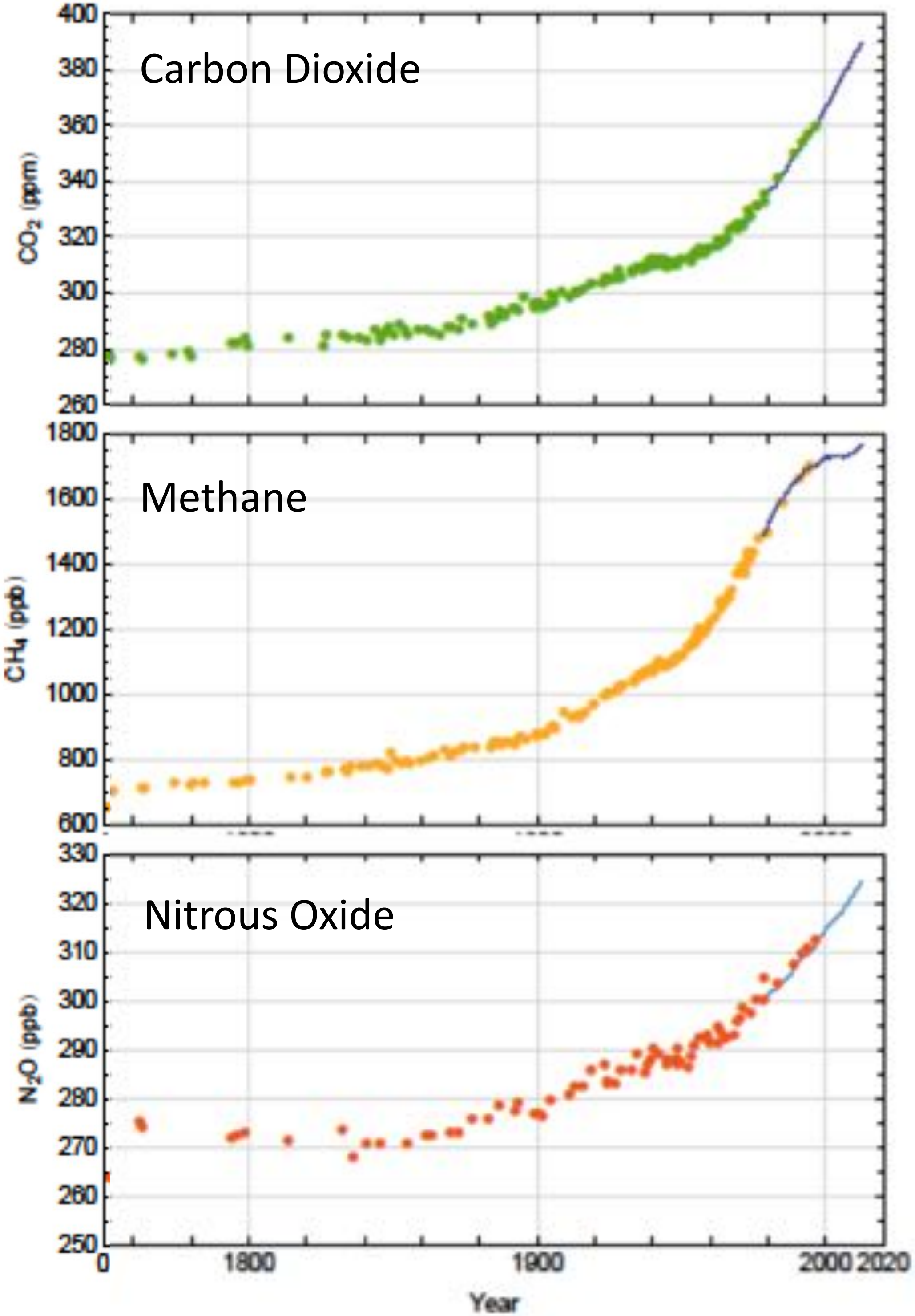
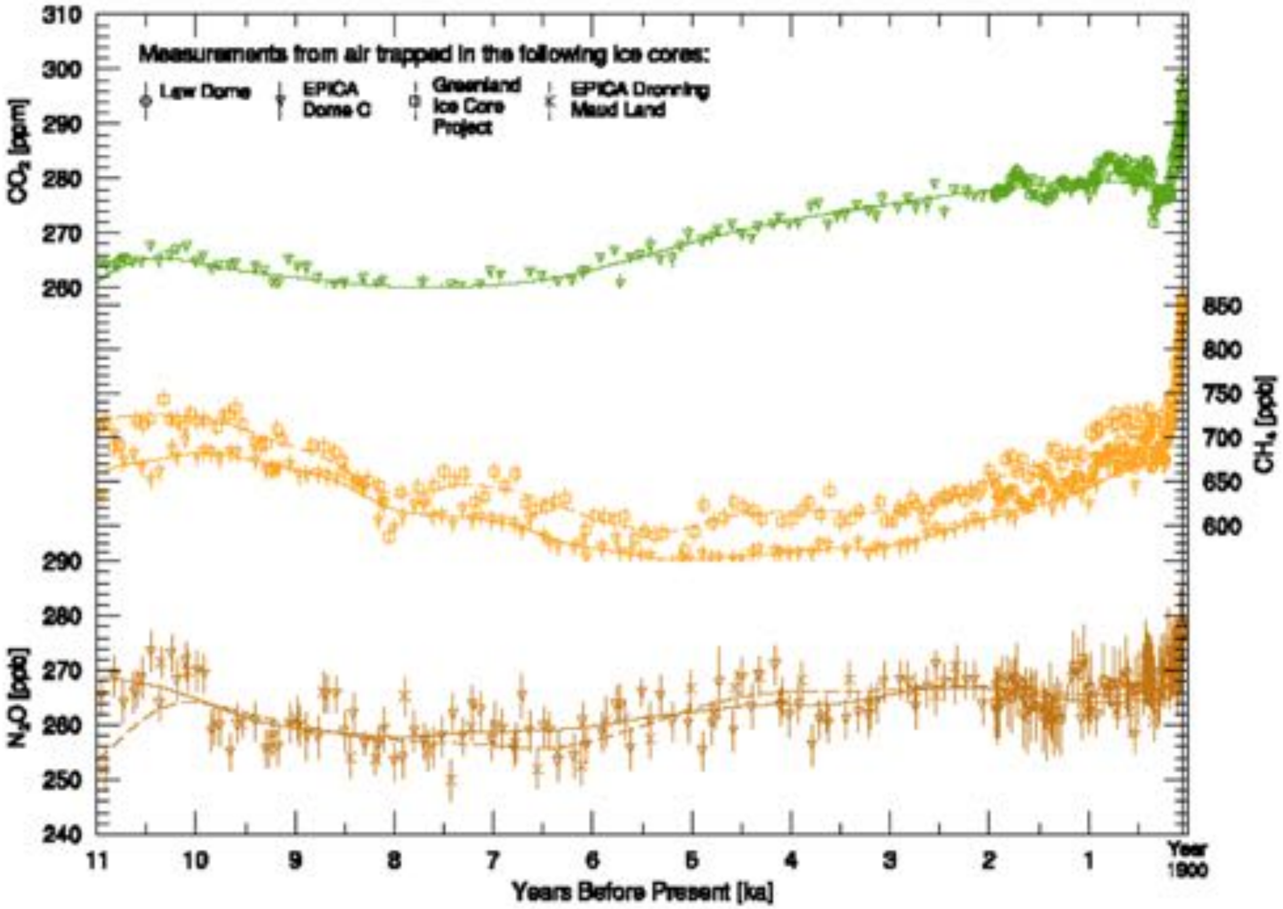
- Changes in greenhouse gas concentrations over the last 200yr can be directly linked to human activity (primarily burning of fossil fuels)

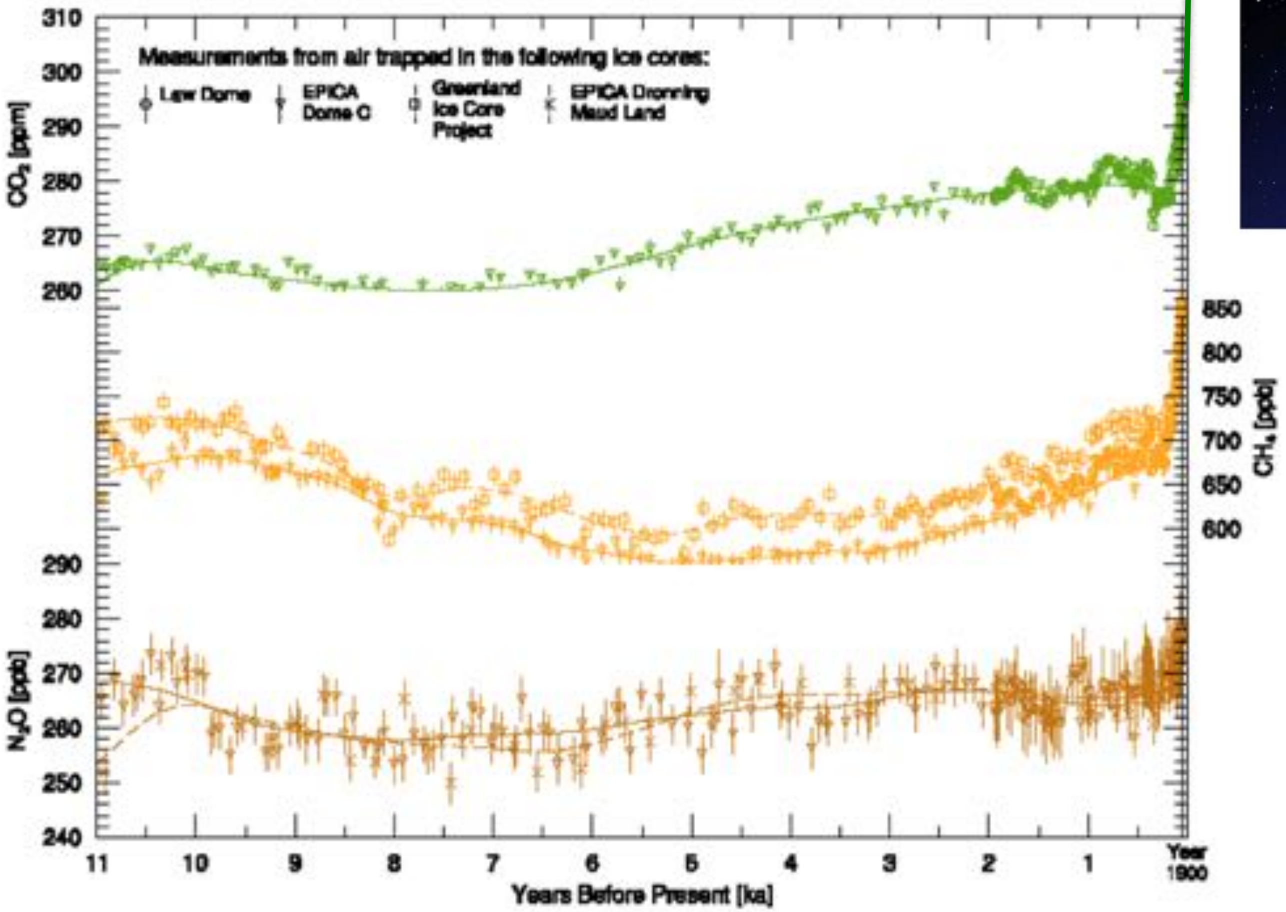


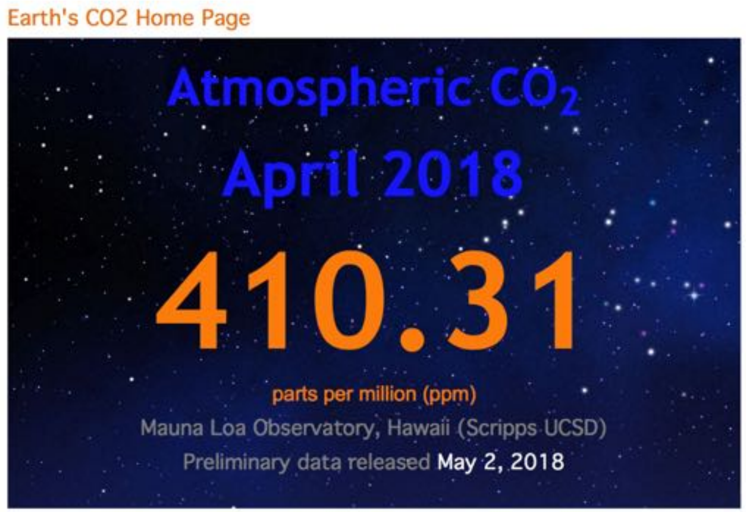


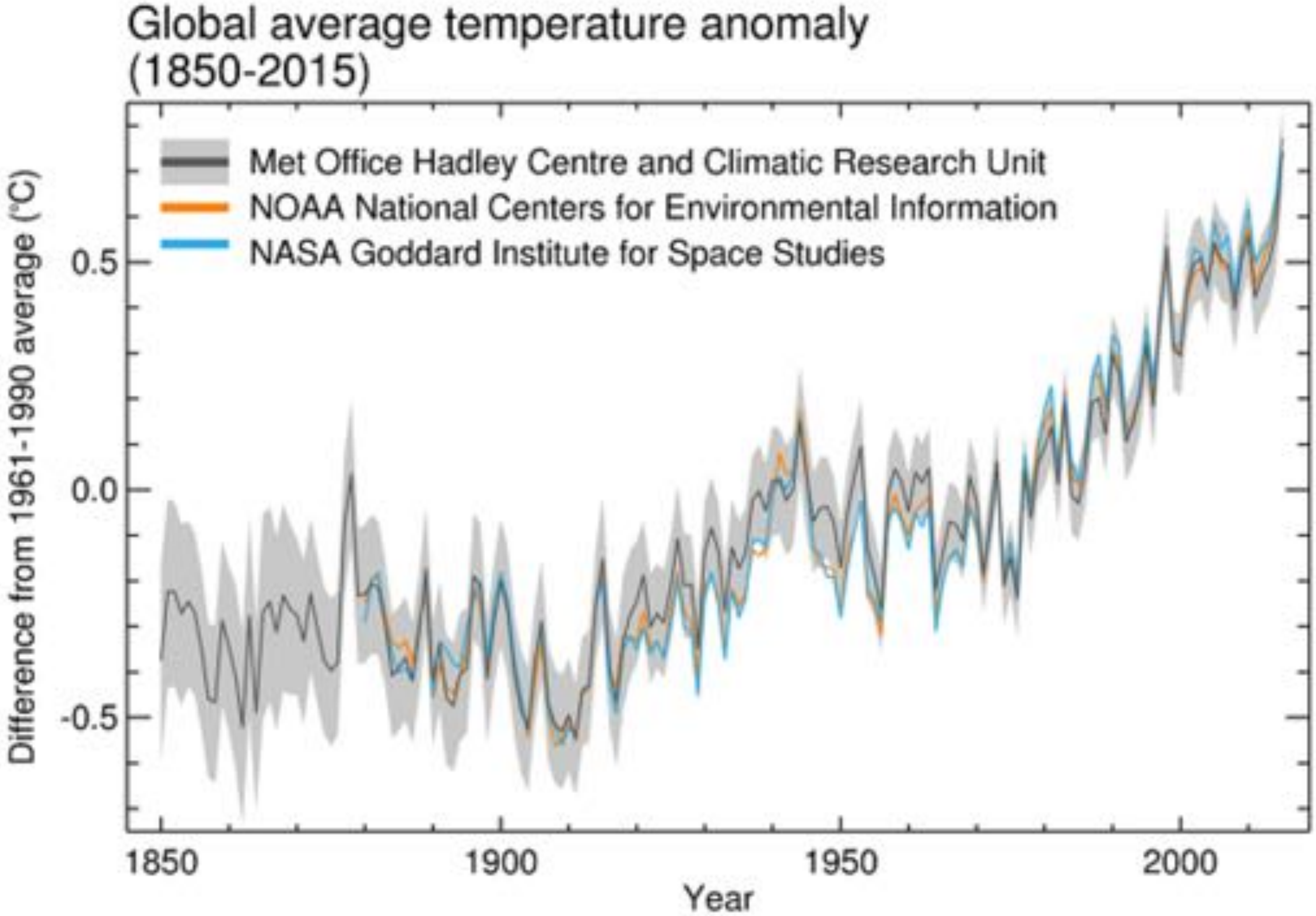


Measurements from air trapped in the following ice cores:
Law Dome
EPICA Dome C
Greenland Ice Core Project
EPICA Dronning Maud Land
CO2 [ppm]
CH4 [ppb]
N2O [ppb]
Years Before Present [ka]
Year 1900

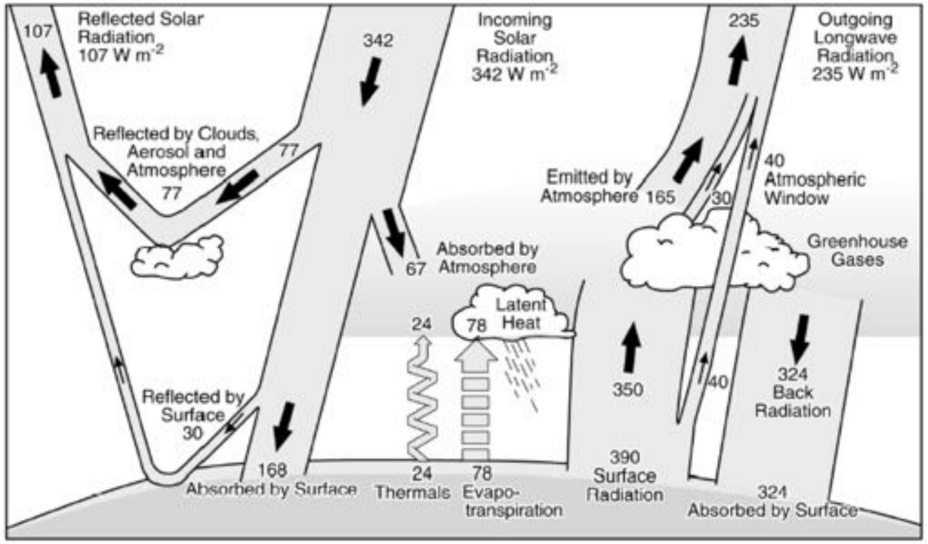
- Levels are unprecedented since the end of the last ice age and are well beyond natural fluctuations







Global average temperature anomaly
(1850-2015)
Met Office Hadley Centre and Climatic Research Unit
NOAA National Centers for Environmental Information
NASA Goddard Institute for Space Studies
Difference from 1961-1990 average (°C)
0.5
0.0
-0.5
1850
1900
1950
2000
Year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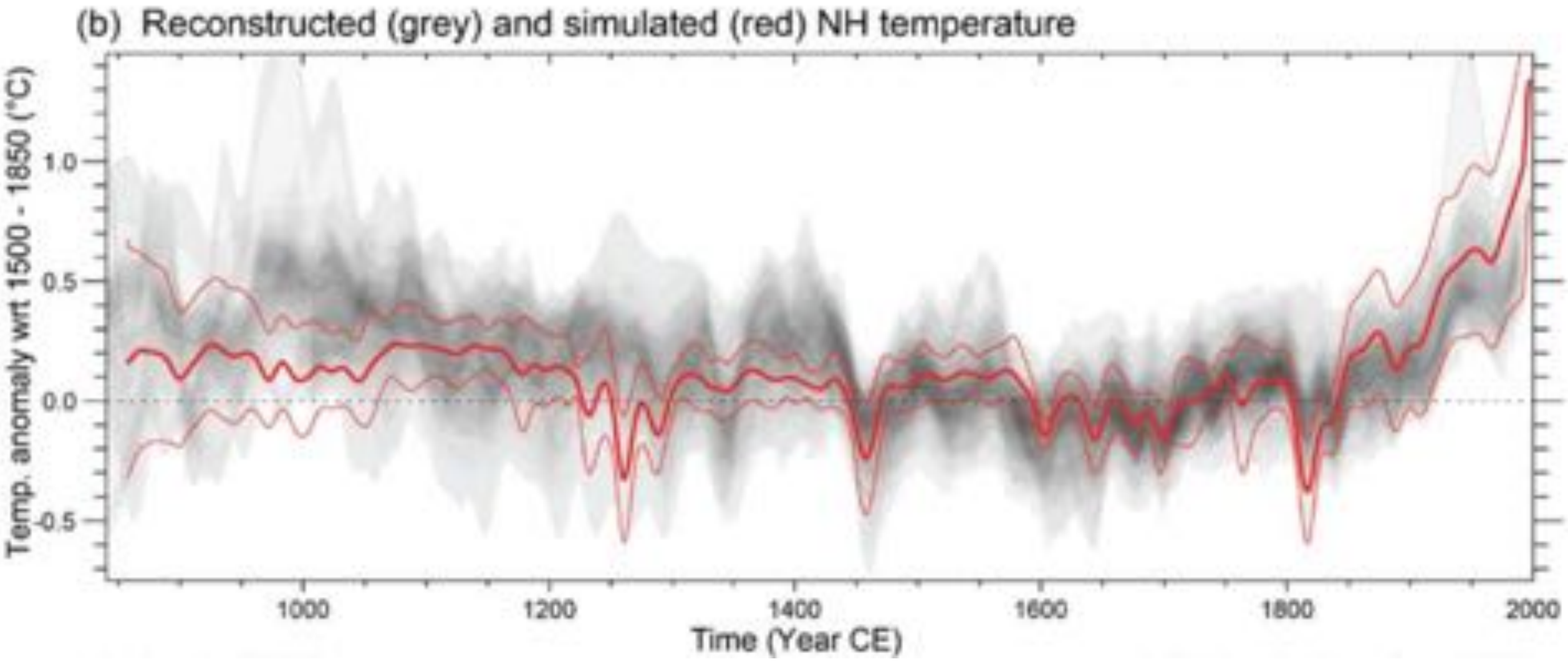
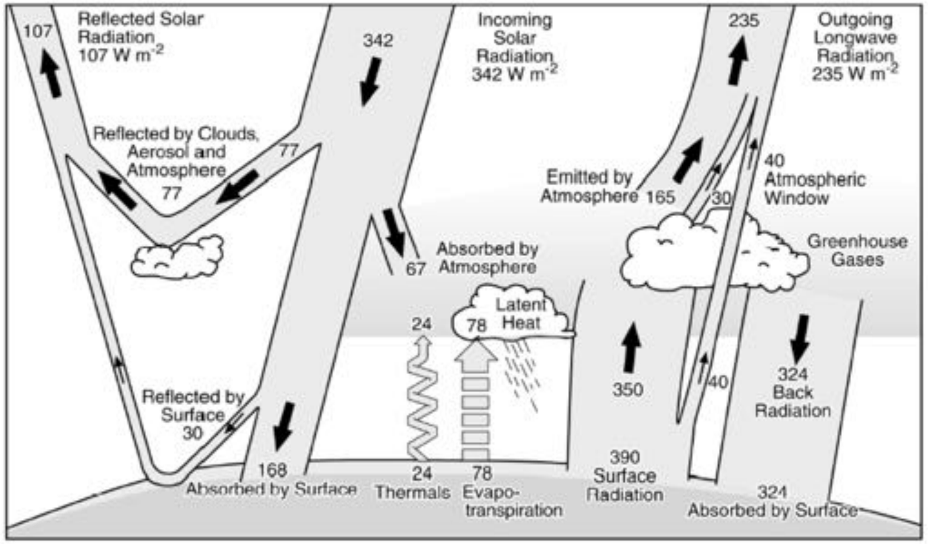

(b) Reconstructed (grey) and simulated (red) NH temperature
Temp. anomaly wrt 1500 - 1850 (°C)
1.0
0.5
0.0
-0.5
1000
1200
1400
1600
1800
2000
Time (Year CE)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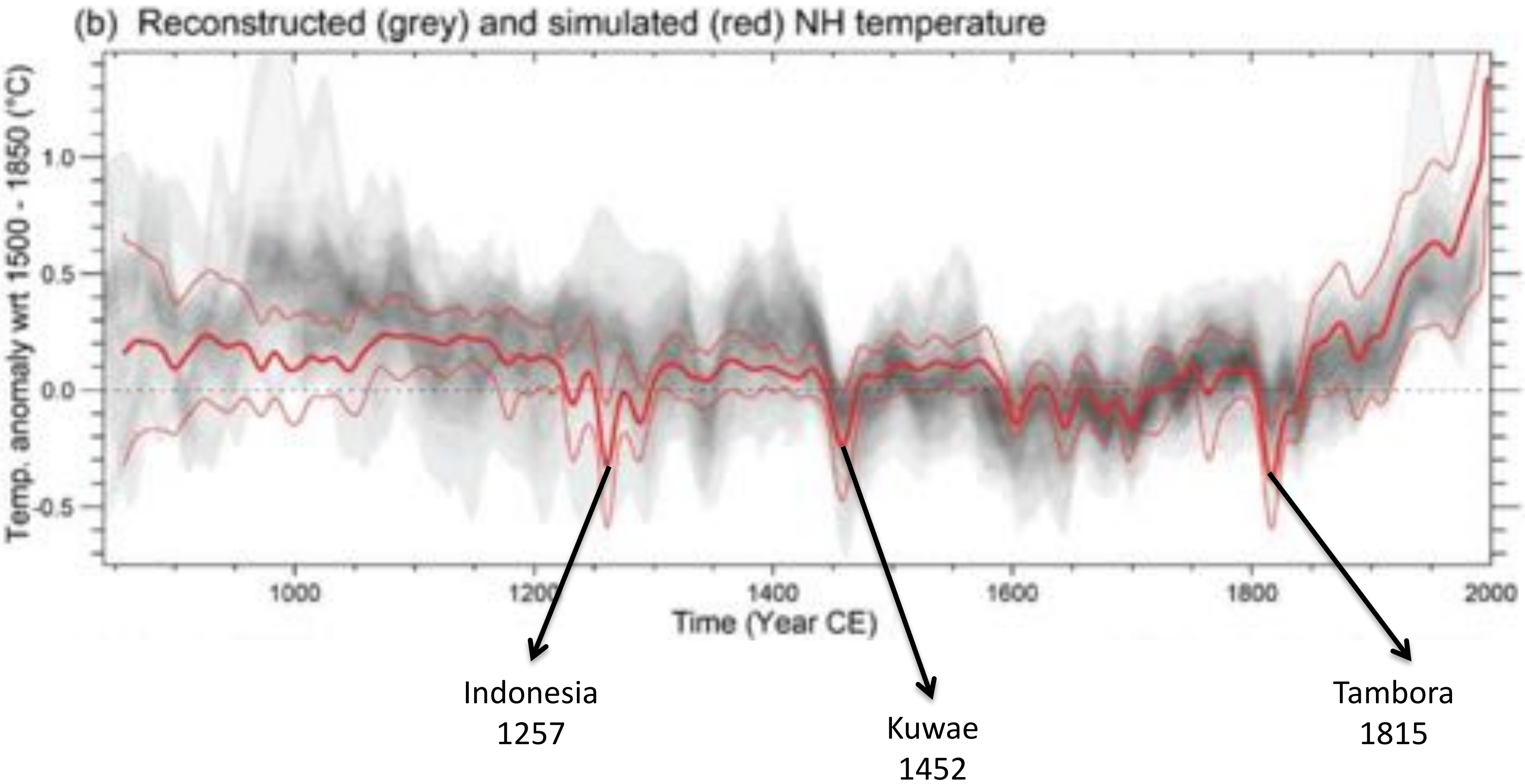
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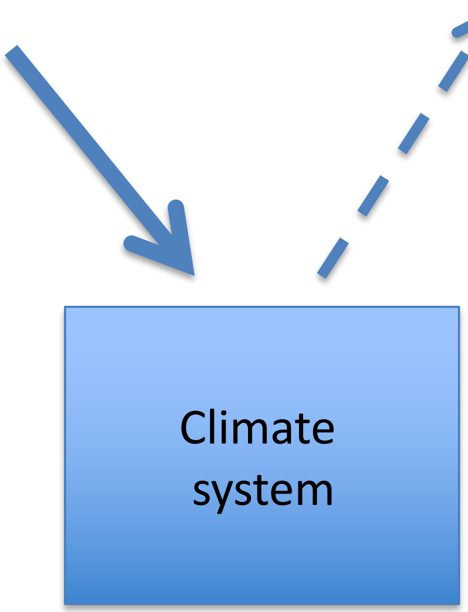
2000
Time (Year CE)
Indonesia
1257
Kuwae
1452
Tambora
1815

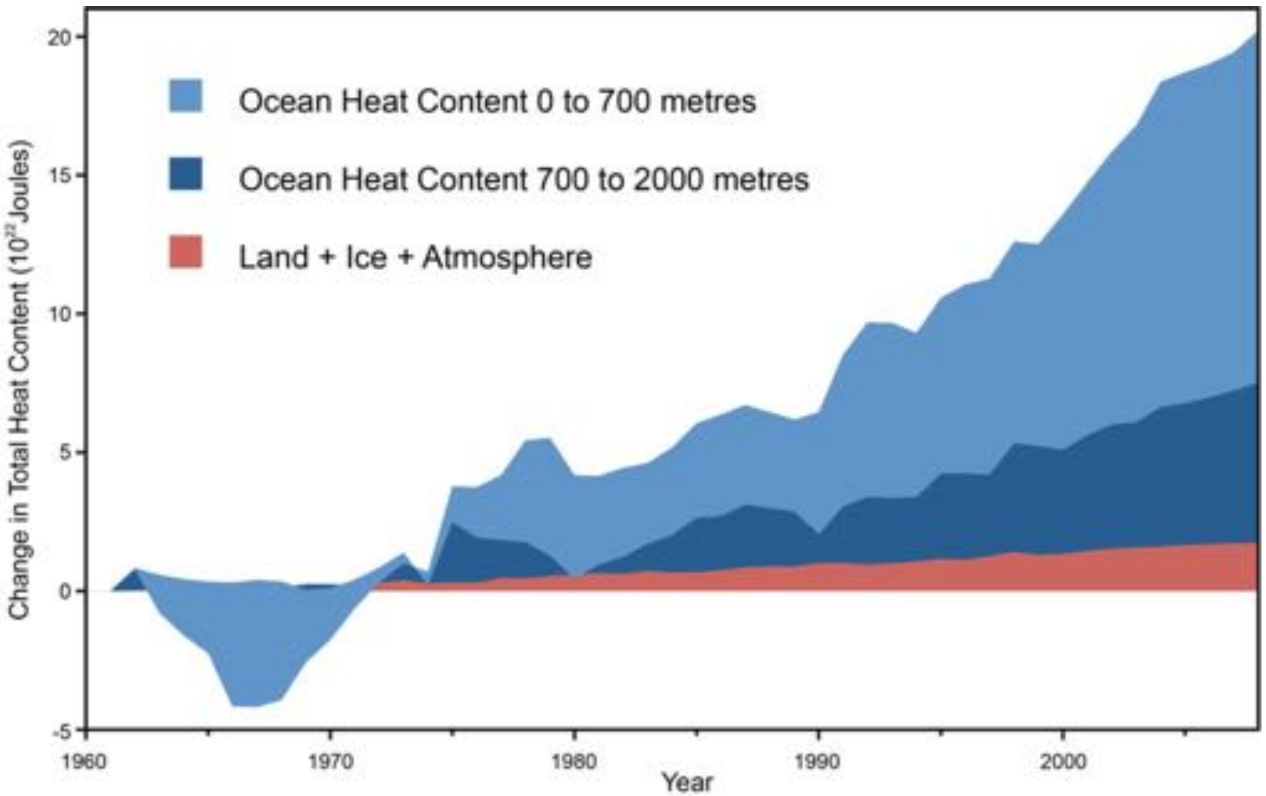
Simplified [Box] model of the climate system

Assumptions:

- Most of the thermal mass of the climate system is in the ocean



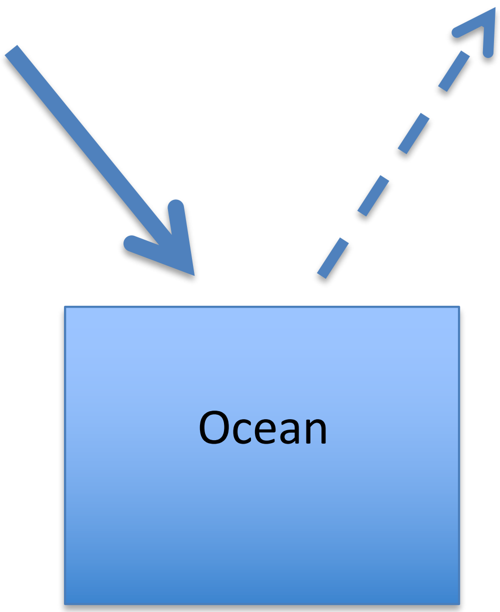
Hiroshima
15 kilotons = 15,000,000 Kg
1Kg of TNT is equivalent to 4 Million Joules

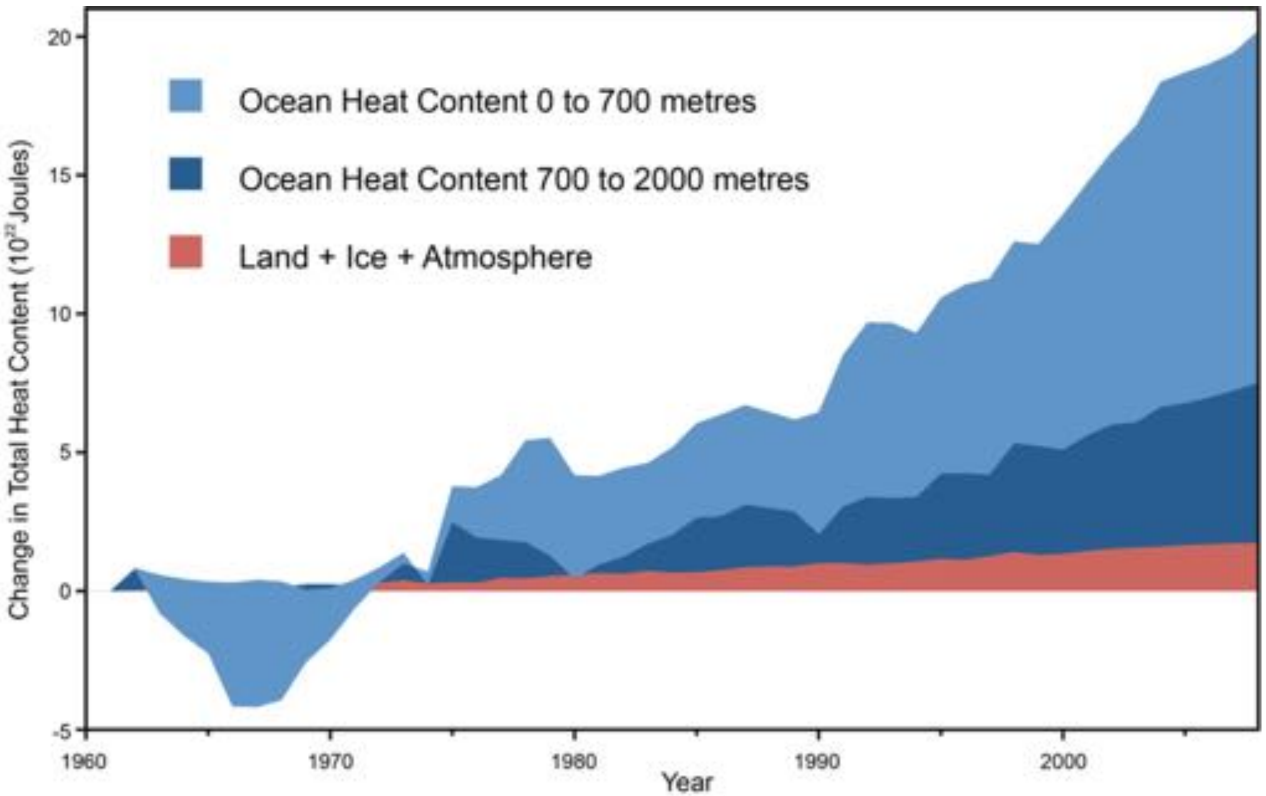


Simplified [Box] model of the climate system

Assumptions:

- Most of the thermal mass of the climate system is in the ocean
- Upper ocean is well mixed and responds quickly to surface energy changes
- Deep ocean interacts more slowly with the upper ocean
- Upper ocean and deep ocean are well mixed





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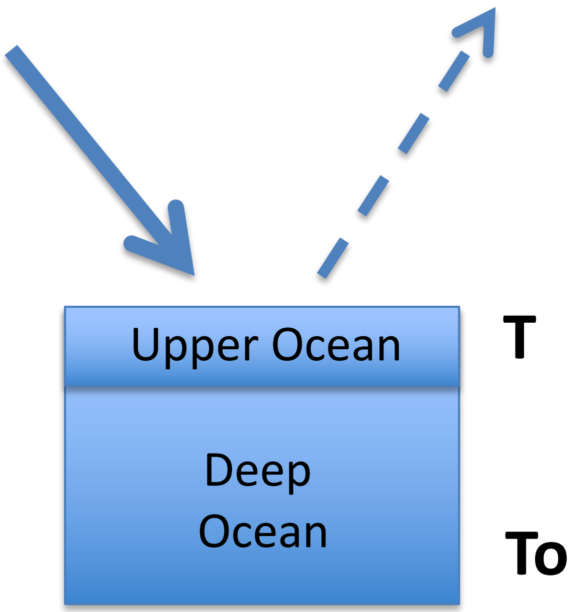
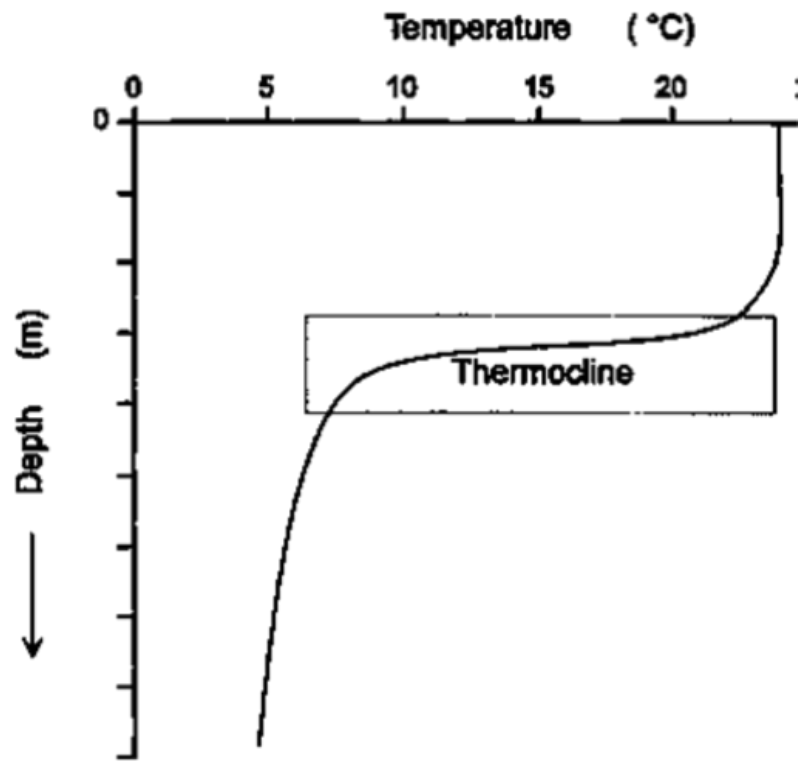
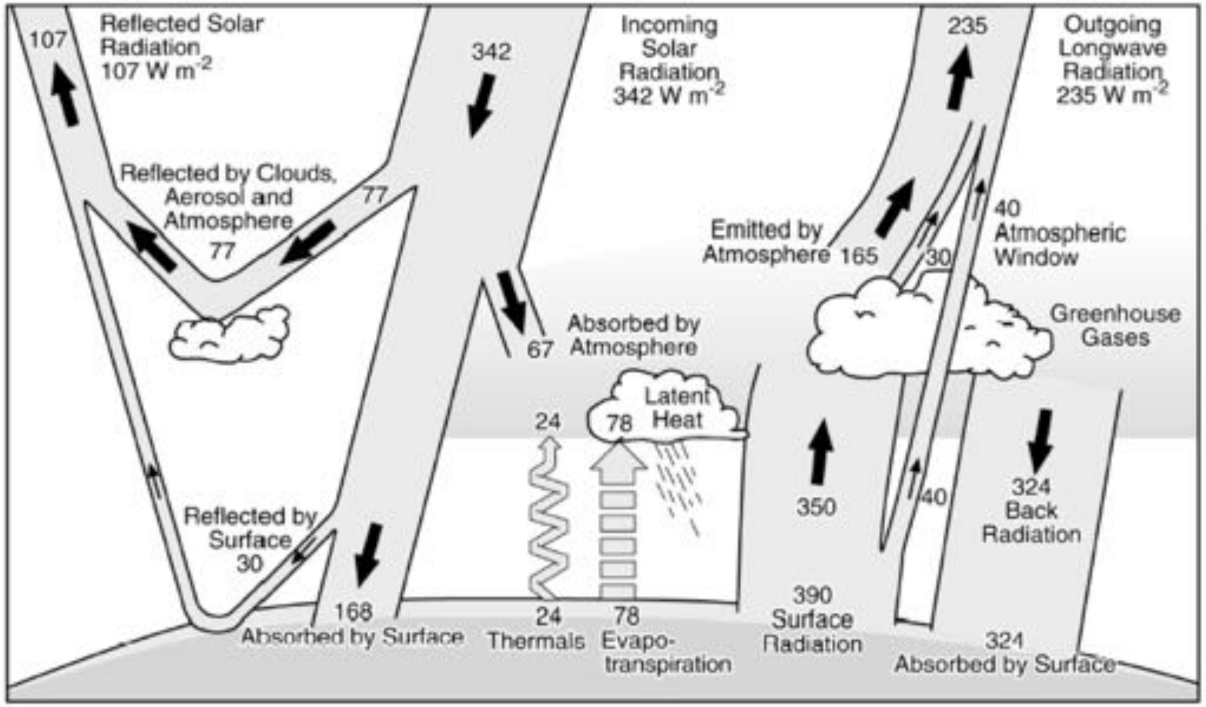
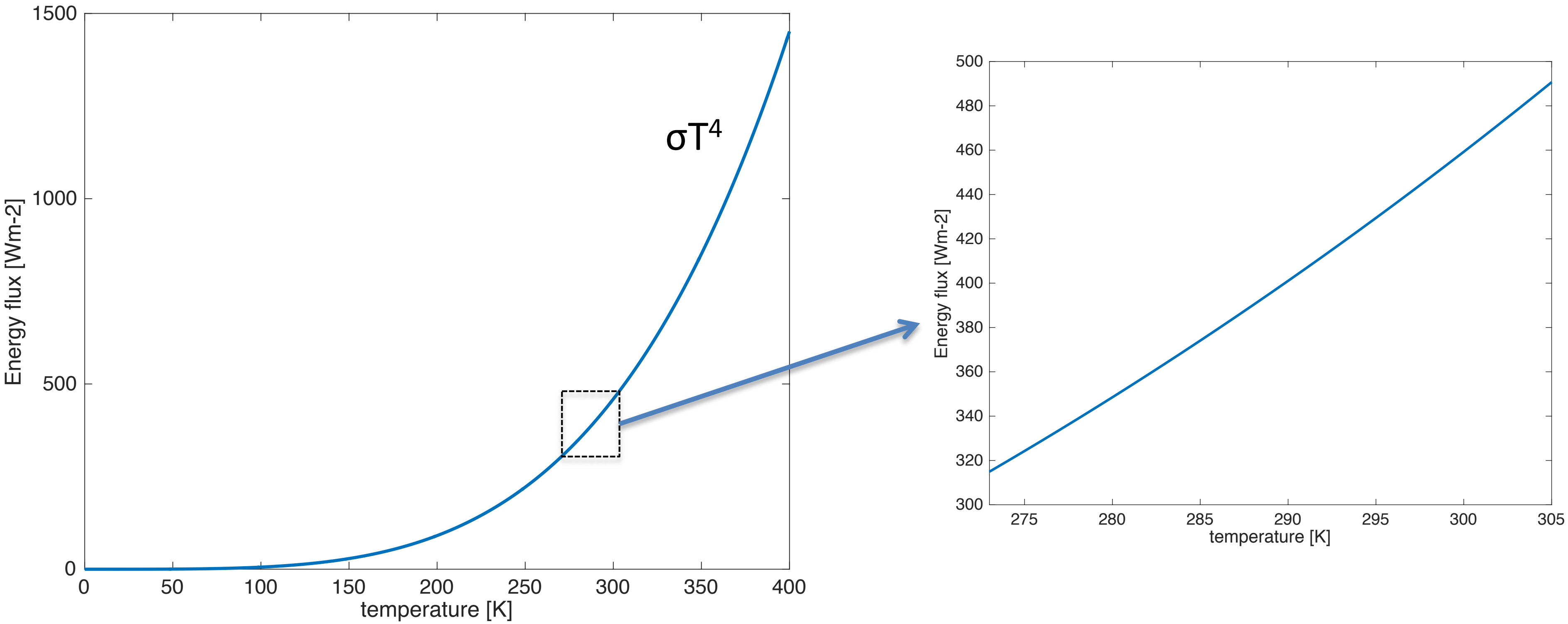




Assumptions:

- Heat loss from the planet surface increases linearly with temperature (includes black body radiation, sensible and latent heat losses)

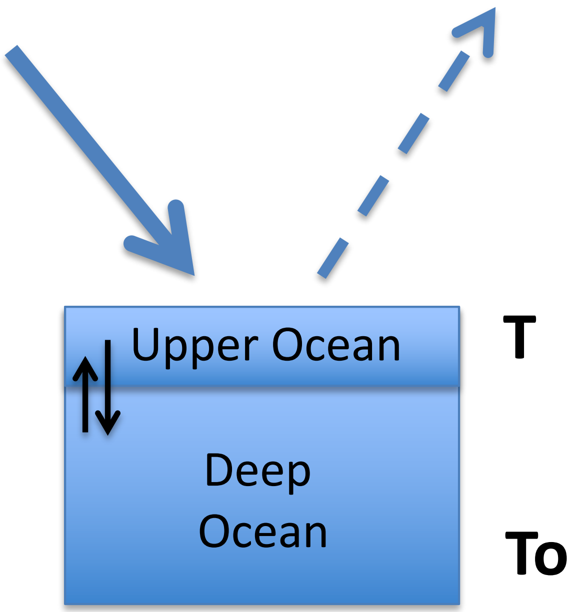




Simplified [Box] model of the climate system

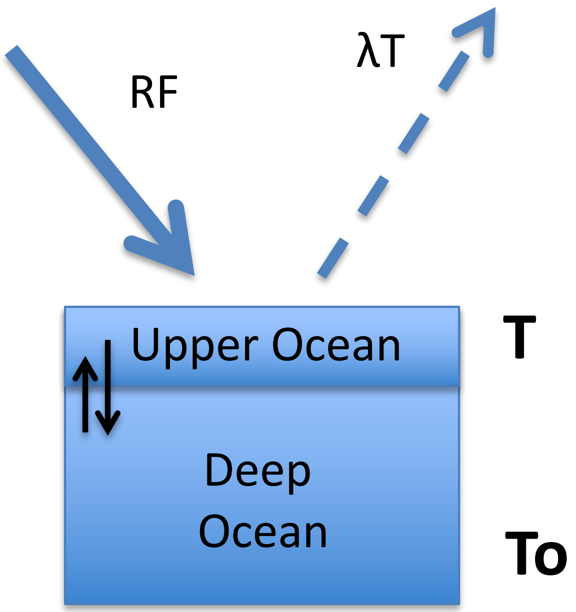
Assumptions:

- Most of the thermal mass of the climate system is in the ocean
- Upper ocean is well mixed and responds quickly to surface energy changes
- Deep ocean interacts more slowly with the upper ocean
- Upper ocean and deep ocean are well mixed
- Heat loss from the planet surface increases linearly with temperature (includes black body radiation, sensible and latent heat losses)
- Transfer of heat from the upper to the deep ocean just depends on the temperature difference



Simplified [Box] model of the climate system

Change in energy content/s	=	Heat capacity	x	Change in temperature/s	=	Energy in/s	-	Energy out/s



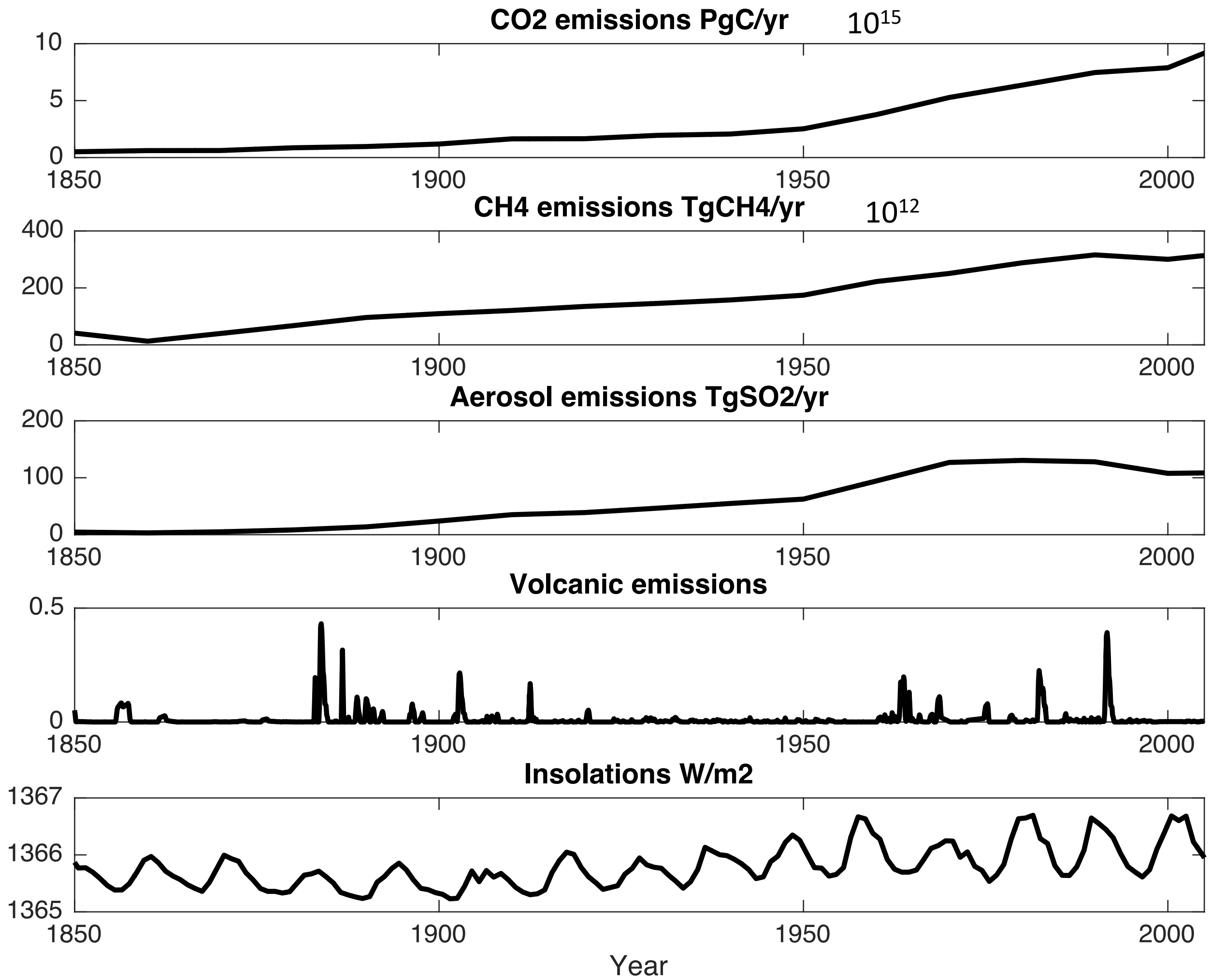
$$C\frac{dT}{dt} = RF - \lambda T - \gamma(T - T_o)$$

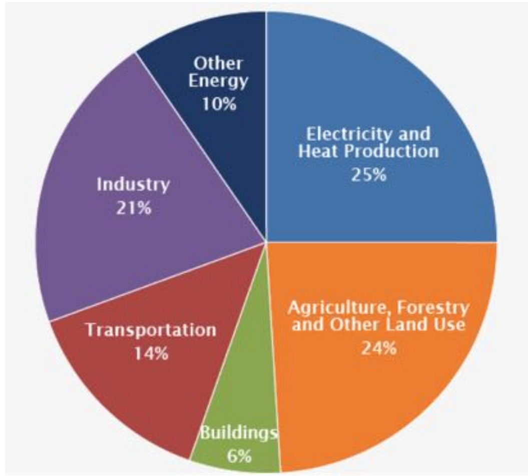
$$C_o\frac{dT_o}{dt} = \gamma(T - T_o)$$

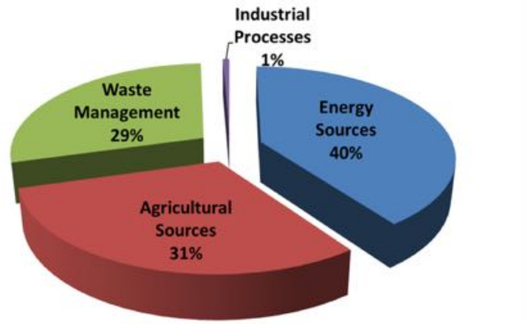
$$RF = R^{CO2} + R^{CH4} + R^{aer} + R^{volc} + R^{sol}$$

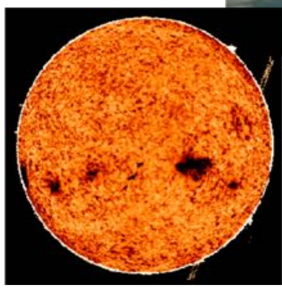
Model inputs

To calculate the radiative forcing we need certain information: model inputs









Model inputs

$$RF = R^{CO2} + R^{CH4} + R^{aer} + R^{volc} + \boxed{R^{sol}}$$

Solar radiation

- S is the radiation flux per square meter at top of atmosphere
- Energy passing through a circle is distributed over a sphere
- A proportion α of the surface energy is reflected back to space

Insolation hitting earth = S x πR^2 [W]
This is distributed over total earth surface $4\pi R^2$ [m^2]
On average, insolation per square meter at surface = S x πR^2 / $4\pi R^2$ = S/4

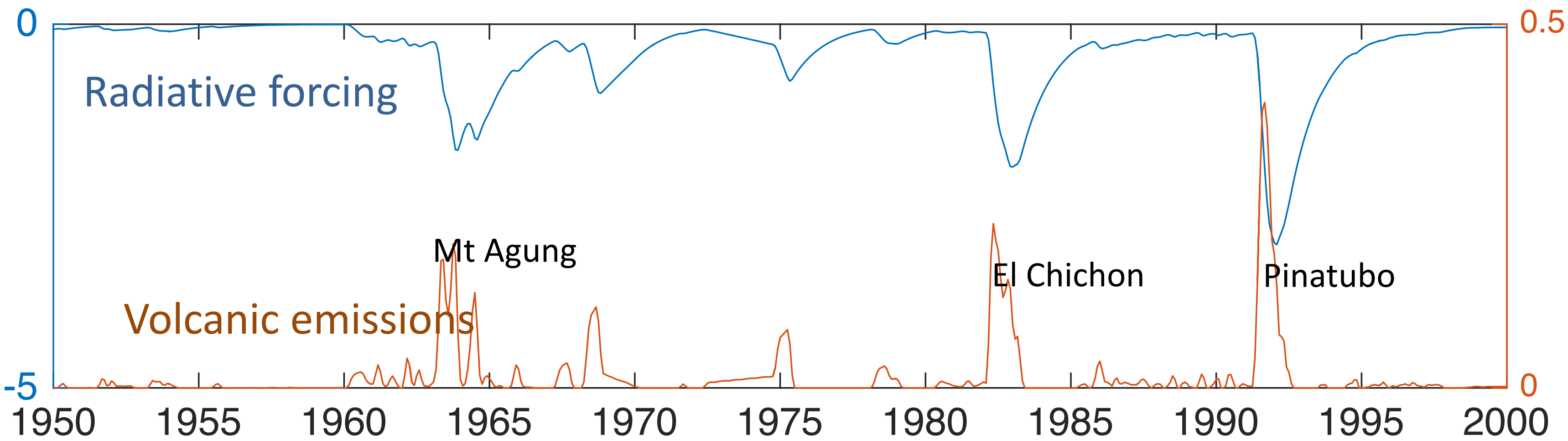
$$R^{sol} = \frac{S(t)}{4}(1-\alpha)$$

Model inputs

$$RF = R^{CO2} + R^{CH4} + R^{aer} + \boxed{R^{volc}} + R^{sol}$$

Volcanic aerosols

- Particles from volcanic eruptions are ejected into the stratosphere
- These reflect away solar radiation (i.e. produce a negative radiative forcing)
- Volcanic aerosols fall out over a timescale of ~ 1-3 years



OT (Optical thickness) increases with emissions of volcanic aerosols and decay with timescale τ^{volc} (2.5 years)
R^{volc} is proportional to OT (constant is negative)

$$\frac{\partial(OT)}{\partial t} = E^{volc} - \frac{1}{\tau^{volc}}(OT)$$

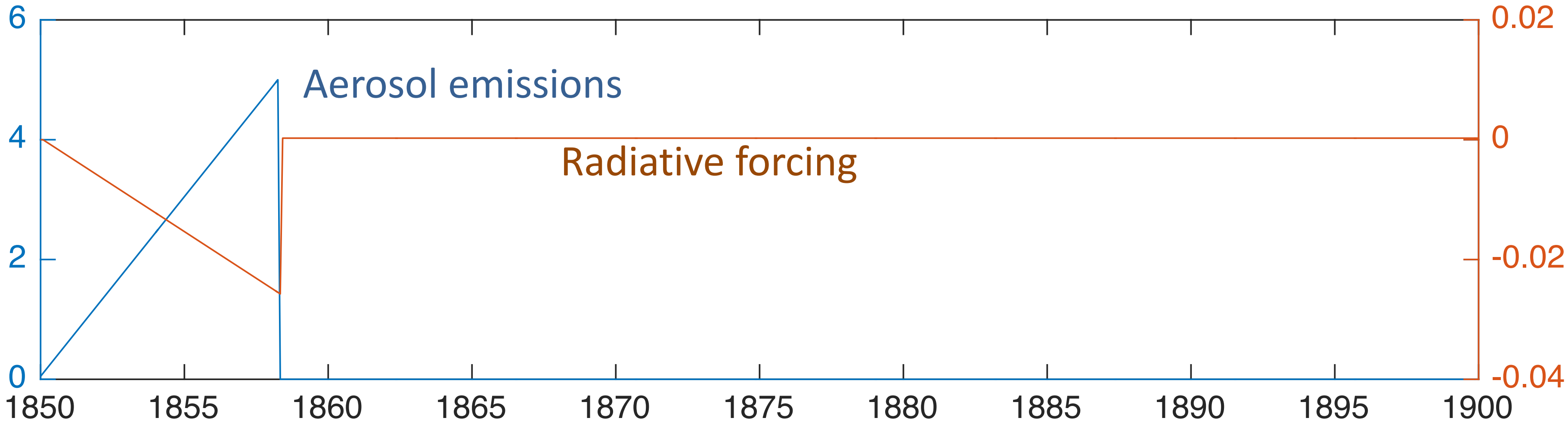
$$R^{volc} = c^{volc}\ OT$$

Model inputs

$$RF = R^{CO2} + R^{CH4} + \boxed{R^{aer}} + R^{volc} + R^{sol}$$

Human aerosols

- Aerosols (mainly SO_4) released into lower atmosphere
- Particles are rained out almost immediately (few days)



R^{volc} is proportional to the rate of emissions (constant is negative)

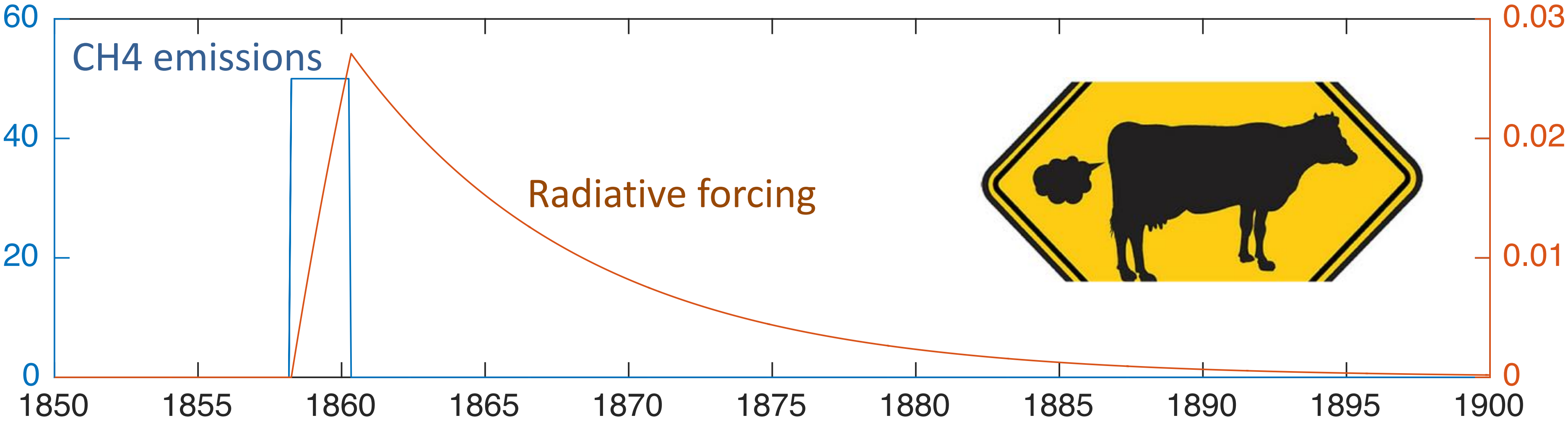
$$R^{aer} = c^{aer} E^{aer}$$

Model inputs

$$RF = R^{CO2} + \boxed{R^{CH4}} + R^{aer} + R^{volc} + R^{sol}$$

Methane emissions

- Methane in the atmosphere is emitted by energy production, agricultural processes and the decay of waste products
- It decays via oxidation in the atmosphere with a half life of ~ 10 years (but the decay rate increases with increased methane concentrations)



$$\frac{\partial C^{CH4}}{\partial t} = c^{CH4} E^{CH4} - \frac{1}{\tau^{CH4}} C^{CH4}$$

$$\tau^{CH4} = \tau_{PI}^{CH4} \left(\frac{C^{CH4}}{C^{CH4} + C_{PI}^{CH4}} \right)^{\alpha}$$

$$R^{CH4} = c^{CH4} \log_e \left(\frac{C^{CH4} + C_{PI}^{CH4}}{C_{PI}^{CH4}} \right)$$

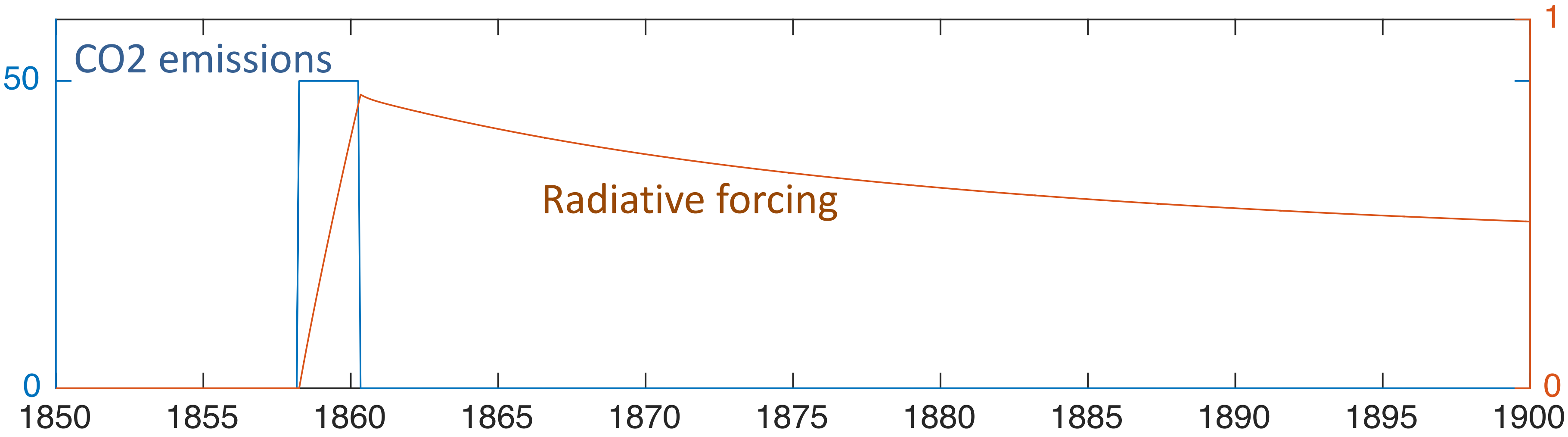
- Radiative forcing increases with the log of CH4 concentration

Model inputs

$$RF = \boxed{R^{CO2}} + R^{CH4} + R^{aer} + R^{volc} + R^{sol}$$

CO2 emissions

- CO2 in the atmosphere is primarily produced through the burning of fossil fuel, with a contribution from deforestation and agriculture
- Carbon cycle is complex and includes uptake and release of CO2 by the terrestrial biosphere and ocean. Half life 100's of years



$$R^{CO2} = c^{CO2}\, log_e\left(\frac{C^{CO2} + C^{CO2}_{PI}}{C^{CO2}_{PI}}\right)$$

- Radiative forcing increases with the log of CO2 concentration

Model inputs

$$RF = \boxed{R^{CO2}} + R^{CH4} + R^{aer} + R^{volc} + R^{sol}$$

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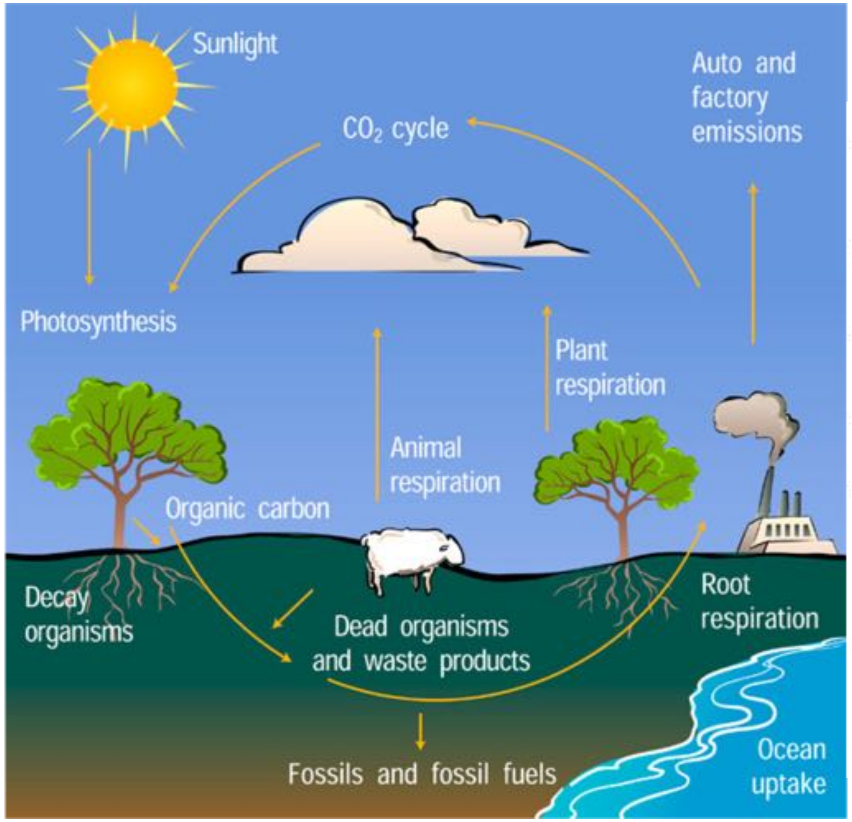


$$\frac{dC^{at}(t)}{dt} = E^{co2} - k_a(C^{at} - A \cdot B \cdot C^{up}) + [(1-\varepsilon)mN(t) + \delta S(t) - P(t, C^{at})] \quad (4)$$

$$\frac{dC^{up}(t)}{dt} = k_a(C^{at}(t) - A \cdot B \cdot C^{up}(t)) - k_d\left(C^{up}(t) - \frac{C^{lo}(t)}{d}\right) \quad (5)$$

$$\frac{dC^{lo}(t)}{dt} = k_d\left(C^{up}(t) - \frac{C^{lo}(t)}{d}\right) \quad (6)$$

$$\frac{dN(t)}{dt} = P(t, C^{at}) - mN(t) \quad (7)$$

$$\frac{dS(t)}{dt} = \varepsilon mN(t) - \delta S(t) \quad (8)$$

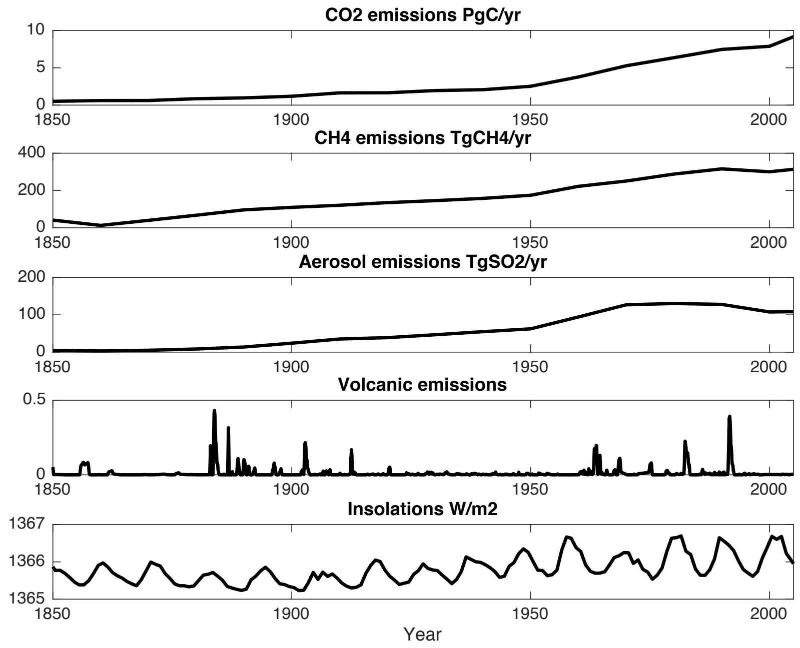
$$P(t) = P_0(1 - a_2(C^{at}(t) - C_0^{at}) \quad (9)$$

where C^{at}, C^{up}, C^{lo}, N and S are the inventories of carbon dioxide (GtC) in the atmosphere, upper ocean and deep ocean, terrestrial vegetation and soil, respectively, P is net primary production by terrestrial plants (GtC/yr) and E is the human emissions of CO2 (GtC/yr) See table for definition of constants.

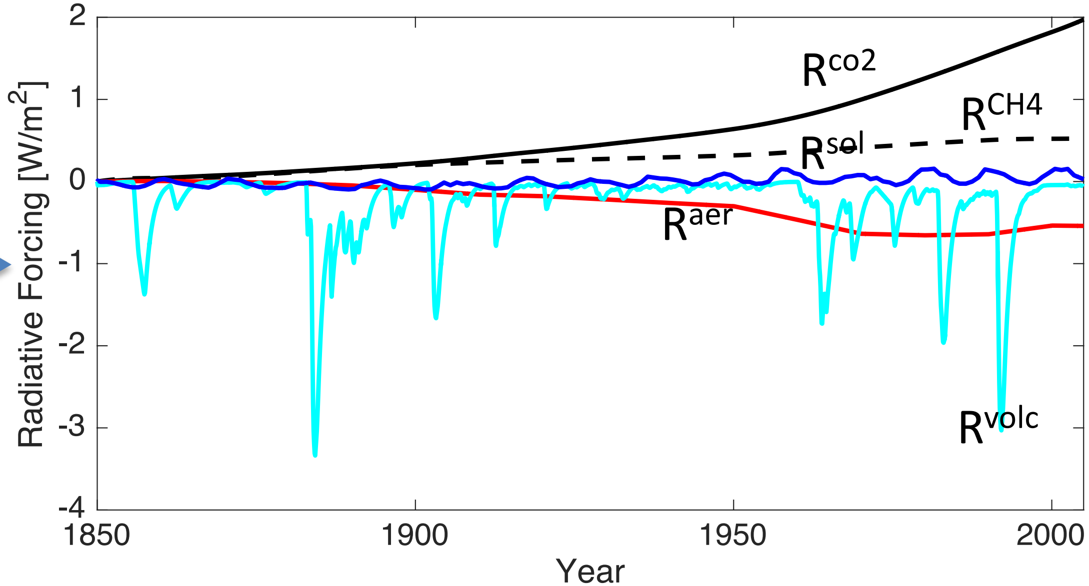
$$R^{CO2} = c^{CO2} \log_e\left(\frac{C^{CO2} + C_{PI}^{CO2}}{C_{PI}^{CO2}}\right)$$

Solving the Model

Model inputs…



Radiative Forcing…



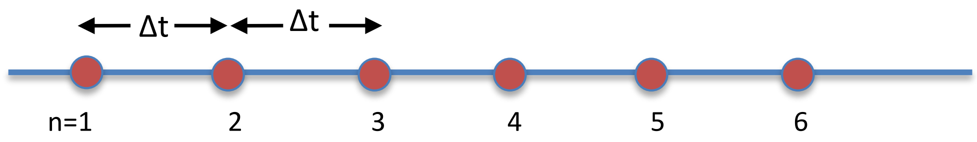
$$RF = R^{CO2} + R^{CH4} + R^{aer} + R^{volc} + R^{sol}$$

Energy balance model

$$C\frac{dT}{dt} = RF - \lambda T - \gamma(T - T_o)$$

$$C_o\frac{dT_o}{dt} = \gamma(T - T_o)$$

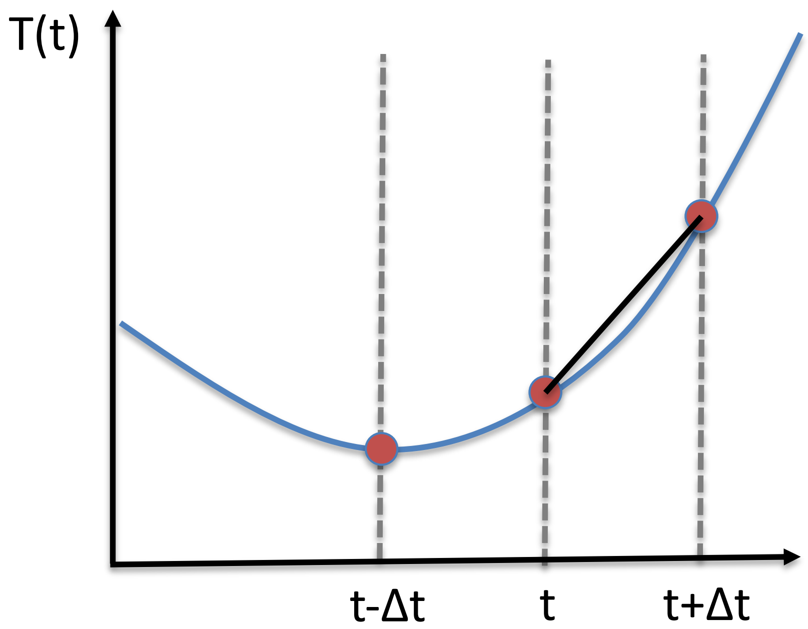
Solving the Model



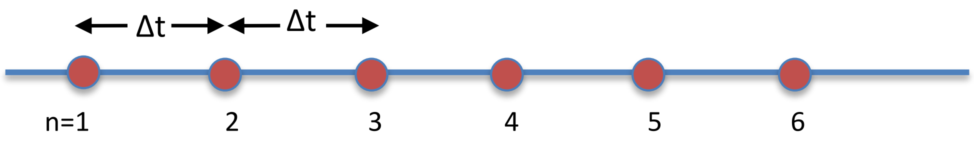
$$\left(\frac{dT}{dt}\right)_t \approx \frac{T_{(t+\Delta t)} - T_{(t)}}{\Delta t}$$

$$C\frac{dT(t)}{dt} = RF(t) - \lambda T(t) - \gamma\big(T(t) - T_o(t)\big)$$

$$T(t+\Delta t) \approx T(t) + \frac{\Delta t}{C}\Big[RF(t) - \lambda T(t) - \gamma\big(T(t) - T_o(t)\big)\Big]$$



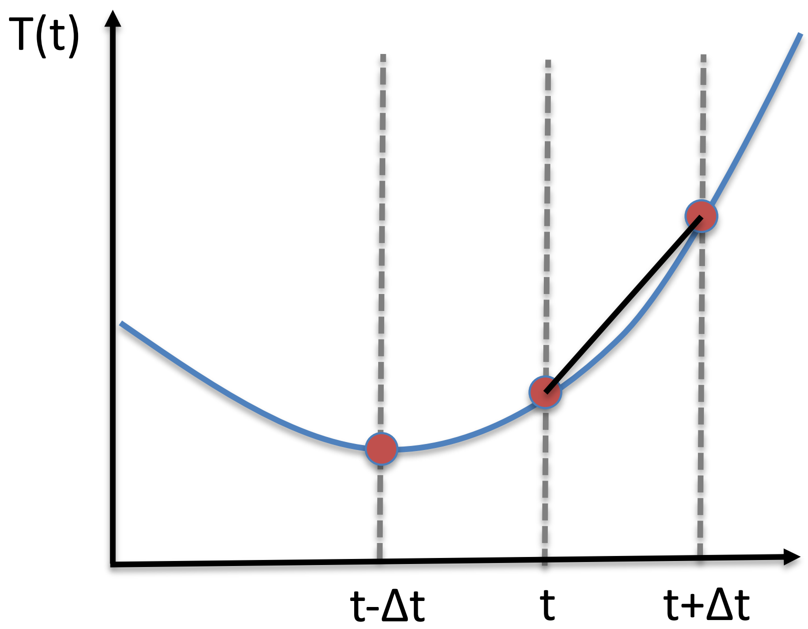
Solving the Model



$$\left(\frac{dT}{dt}\right)_t \approx \frac{T_{(t+\Delta t)} - T_{(t)}}{\Delta t} \qquad C\frac{dT(t)}{dt} = RF(t) - \lambda T(t) - \gamma\big(T(t) - T_o(t)\big)$$

$$T(t+\Delta t) \approx T(t) + \frac{\Delta t}{C}\left[RF(t) - \lambda T(t) - \gamma\big(T(t) - T_o(t)\big)\right]$$

$$T_o(t+\Delta t) \approx T_o(t) + \frac{\Delta t}{C_o}\left[\gamma\big(T(t) - T_o(t)\big)\right]$$



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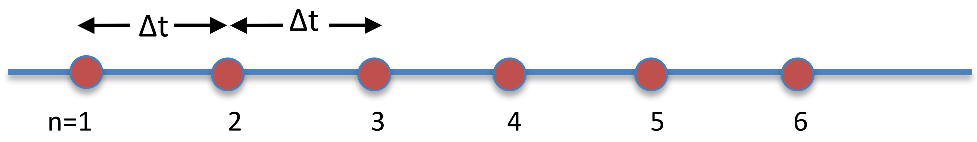
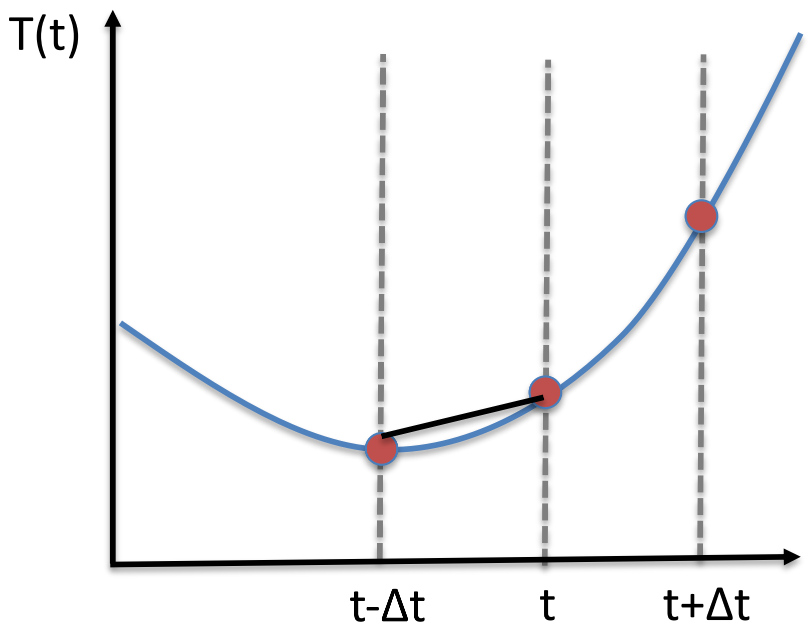


$$\left(\frac{dT}{dt}\right)_t \approx \frac{T_{t+\Delta t} - T_t}{\Delta t}$$

Forward difference

$$\left(\frac{dT}{dt}\right)_t \approx \frac{T_t - T_{t-\Delta t}}{\Delta t}$$

Backward difference



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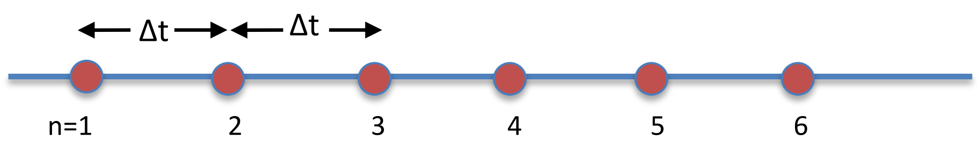

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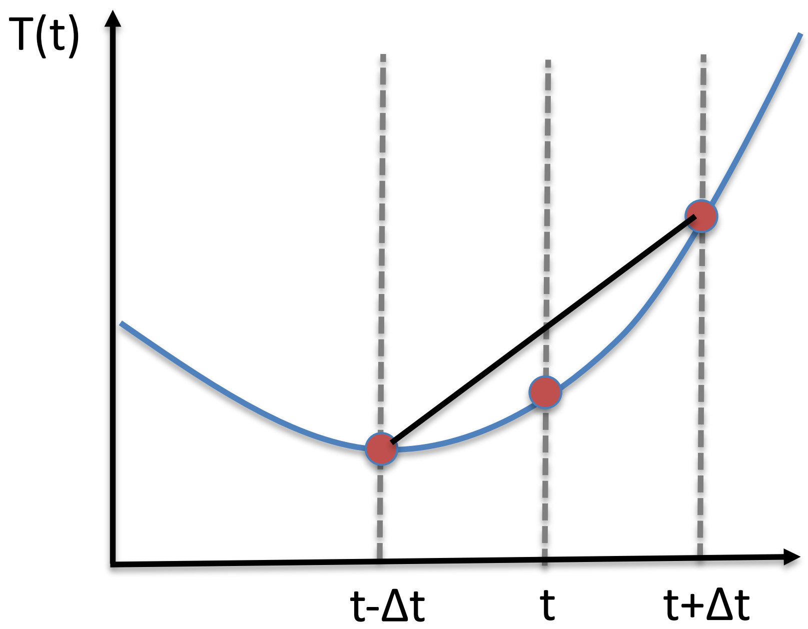
Forward difference

$$\left(\frac{dT}{dt}\right)_t \approx \frac{T_t - T_{t-\Delta t}}{\Delta t}$$

Backward difference

$$\left(\frac{dT}{dt}\right)_t \approx \frac{T_{t+\Delta t} - T_{t-\Delta t}}{2\Delta t}$$

Centred difference



Solving the Model

Taylor expansion of T(t+*Δ* t)

$$T(t+\Delta t) = T(t) + \Delta t\left(\frac{dT}{dt}\right)_t + \frac{(\Delta t)^2}{2}\left(\frac{d^2T}{dt^2}\right)_t + \frac{(\Delta t)^3}{6}\left(\frac{d^3T}{dt^3}\right)_t + \cdots$$

$$T(t-\Delta t) = T(t) - \Delta t\left(\frac{dT}{dt}\right)_t + \frac{(\Delta t)^2}{2}\left(\frac{d^2T}{dt^2}\right)_t - \frac{(\Delta t)^3}{6}\left(\frac{d^3T}{dt^3}\right)_t + \cdots$$

$$\left(\frac{dT}{dt}\right)_t = \frac{T(t+\Delta t) - T(t)}{\Delta t} - \frac{(\Delta t)}{2}\left(\frac{d^2T}{dt^2}\right)_t - \frac{(\Delta t)^2}{6}\left(\frac{d^3T}{dt^3}\right)_t + \cdots$$ Forward difference

$$\left(\frac{dT}{dt}\right)_t = \frac{T(t) - T(t-\Delta t)}{\Delta t} + \frac{(\Delta t)}{2}\left(\frac{d^2T}{dt^2}\right)_t - \frac{(\Delta t)^2}{6}\left(\frac{d^3T}{dt^3}\right)_t + \cdots$$ Backward difference

$$\left(\frac{dT}{dt}\right)_t = \frac{T(t+\Delta t) - T(t-\Delta t)}{2\Delta t} - \frac{(\Delta t)^2}{6}\left(\frac{d^3T}{dt^3}\right)_t + \cdots$$ Centred difference

- The error increases with the time step Δt size
- Error is proportional to Δt for forward and backward approximations
- Error is proportional to Δt^2 for central approximation
- For small Δt central difference error will be smaller

Solving the Model

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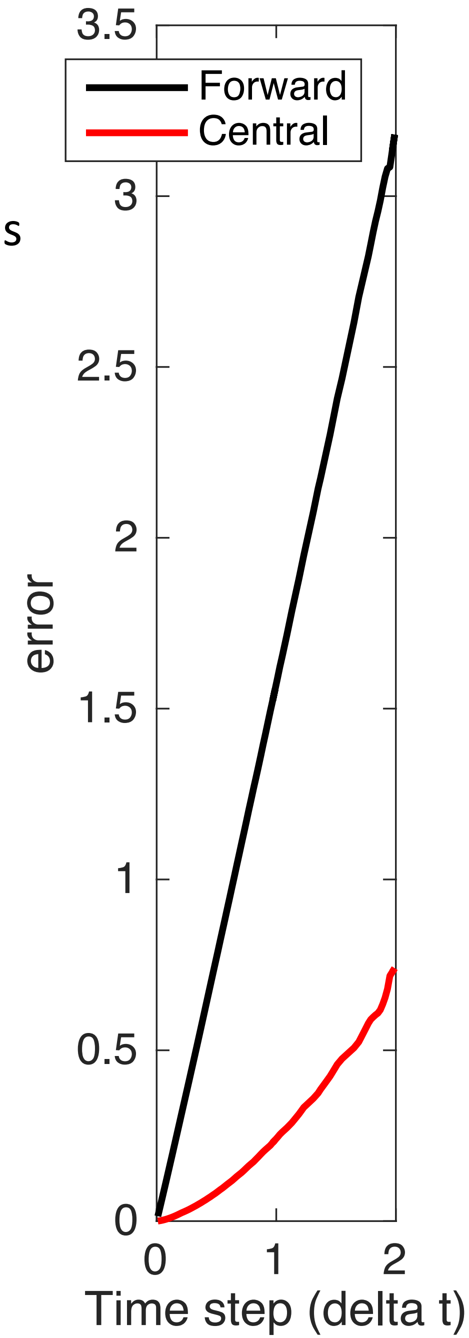


$$\frac{dT}{dt} = \sqrt{t}$$

$$T(t + \Delta t) = T(t) + \Delta t\sqrt{t}$$ Forward difference

$$T(t + \Delta t) = T(t - \Delta t) + 2\Delta t\sqrt{t}$$ Centred difference

Solving the Model

Other more sophisticated schemes provide higher order correction terms
e.g a commonly used scheme is the fourth order Runge Kutta

$$\frac{dT}{dt} = F(T, t)$$

$$k_1 = \Delta t\, F(T(t), t)$$
$$k_2 = \Delta t\, F(T + \frac{k_1}{2}, t + \frac{\Delta t}{2})$$
$$k_3 = \Delta t\, F(T + \frac{k_2}{2}, t + \frac{\Delta t}{2})$$
$$k_4 = \Delta t\, F(T + k_3, t + \Delta t)$$

$$\mathrm{T}(\mathrm{t} + \Delta t) = T(t) + \frac{k_1}{6} + \frac{k_2}{3} + \frac{k_3}{3} + \frac{k_4}{6} + O[\Delta t^5]$$

Solving the Model

$$T(t+\Delta t) = T(t) + \frac{\Delta t(RF - \lambda T - \gamma(T - T_o))}{C}$$

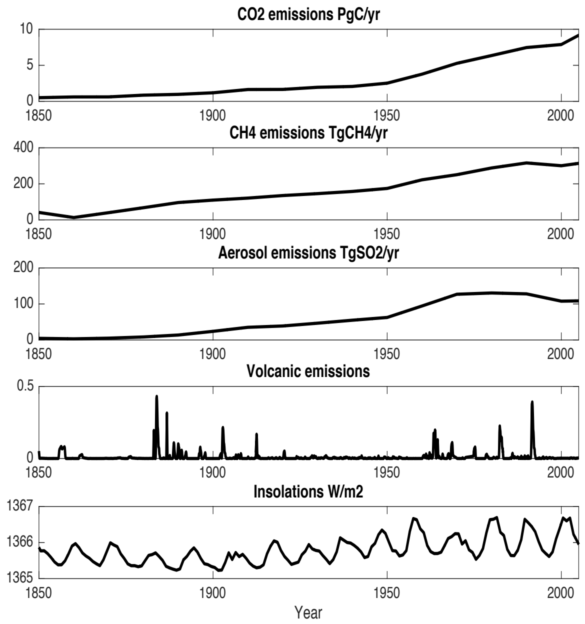
$$T_o(t+\Delta t) = T_o(t) + \frac{\Delta t(\gamma(T - T_o))}{C_o}$$

Forward difference

Code for simplest forward differencing:

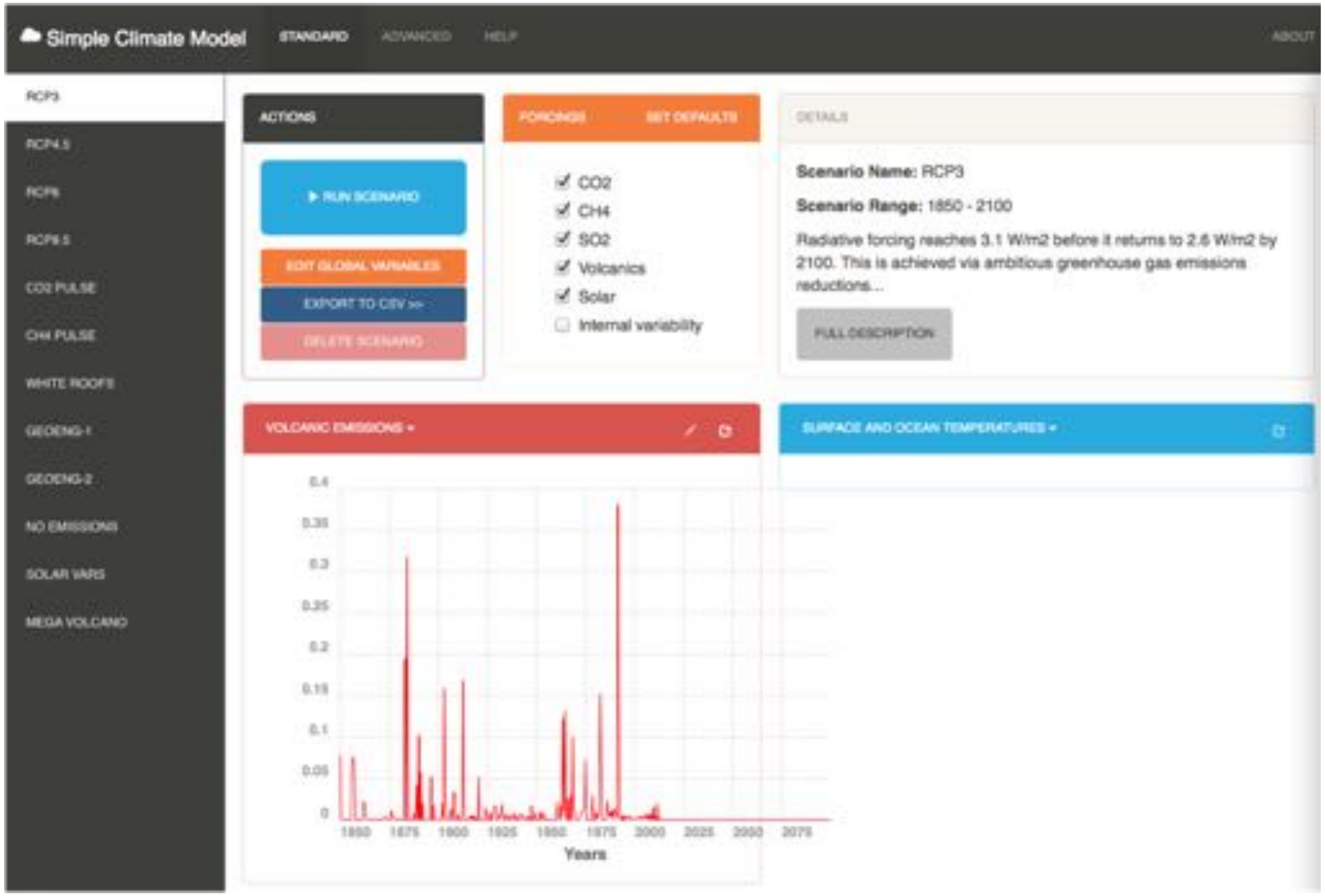
```
T(1)=0; % initialise the upper ocean temperature
To(1)=0; % initialise the lower ocean temperature

for t=1:N-1  % loop over time steps
   RF = R_CO2(t) + R_CH4(t) + R_SO2(t) + R_volc(t) + R_sol(t);
   % Solve for T and To at time t+1 based on T and To at time t
   T(t+1)   = T(t) + DT*( RF - L*T(t) - g*(T(t)-To(t)) )/C ;
   To(t+1) = To(t) + DT*( g*(T(t)-To(t)) )/Co;
end
```



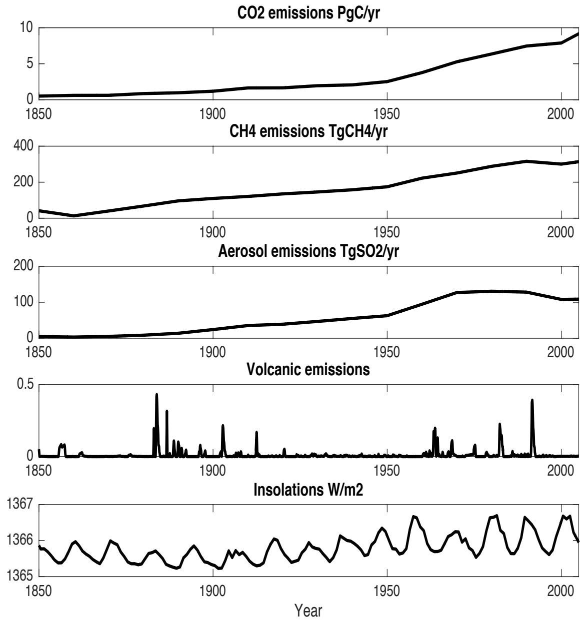
Using the model: Evaluation

http://144.6.234.149:8080/#

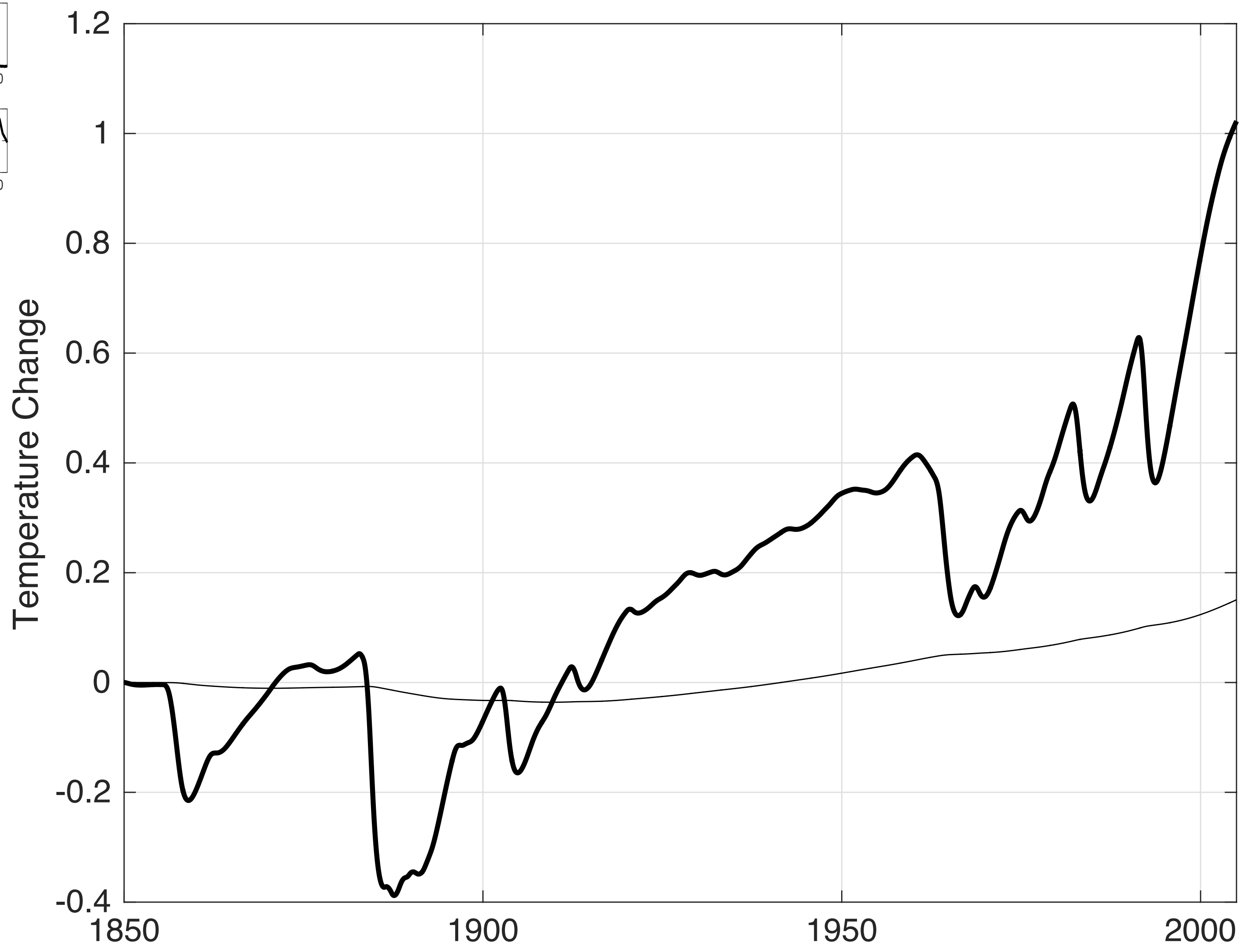


Using the model: Evaluation

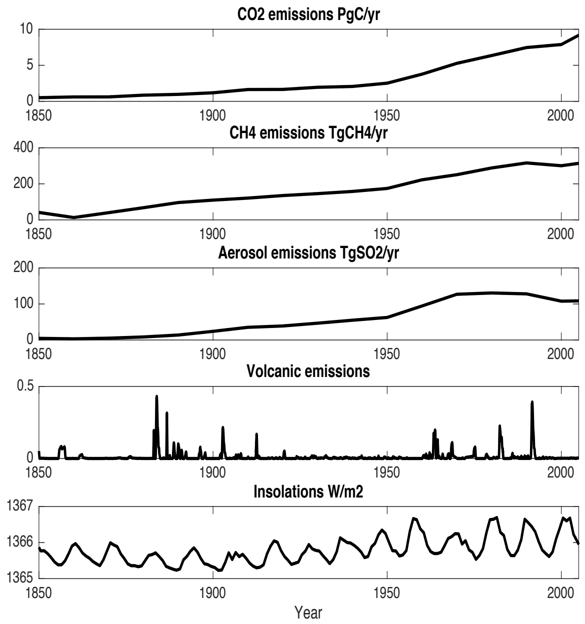
http://45.55.211.78:8080



Black: simple model output

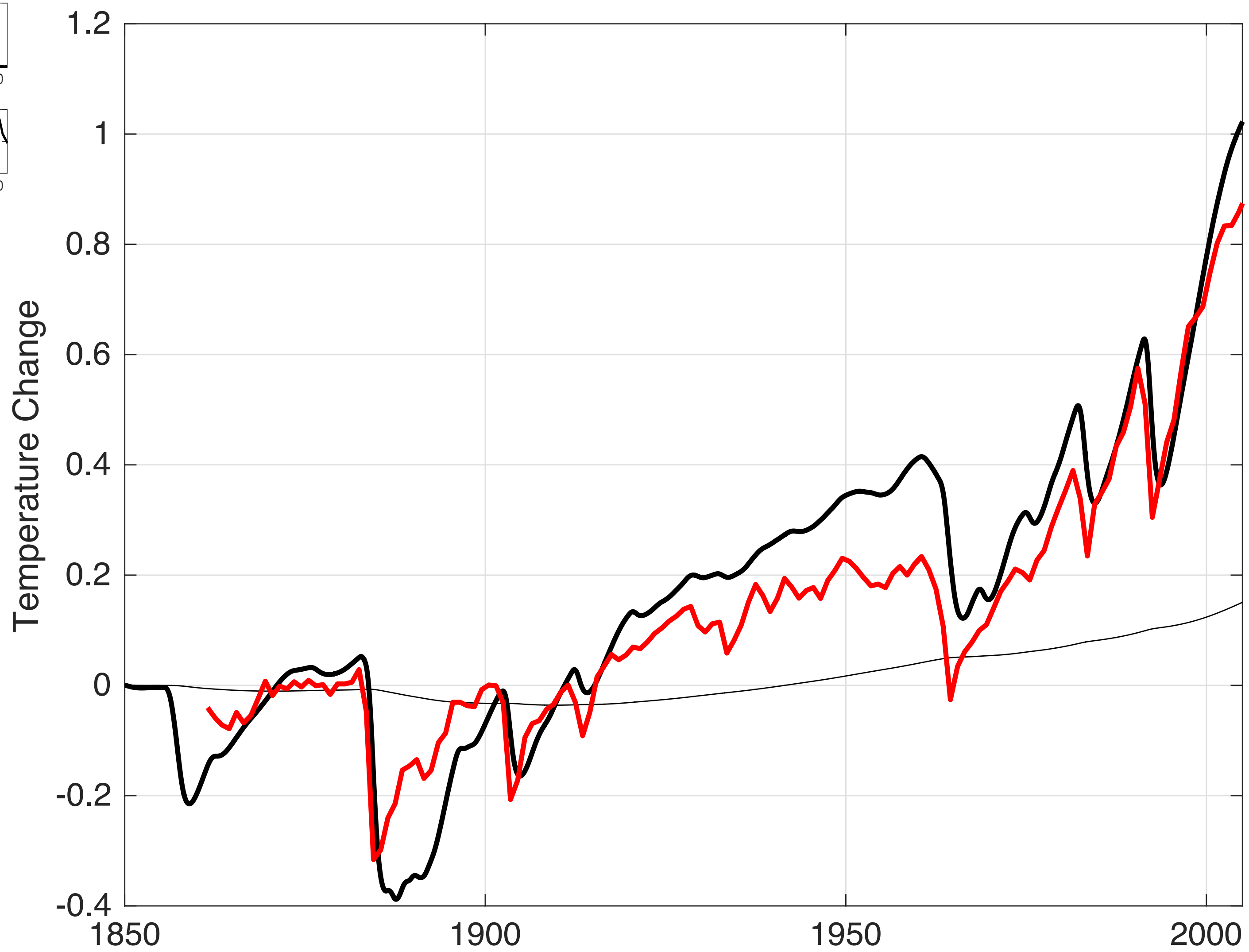


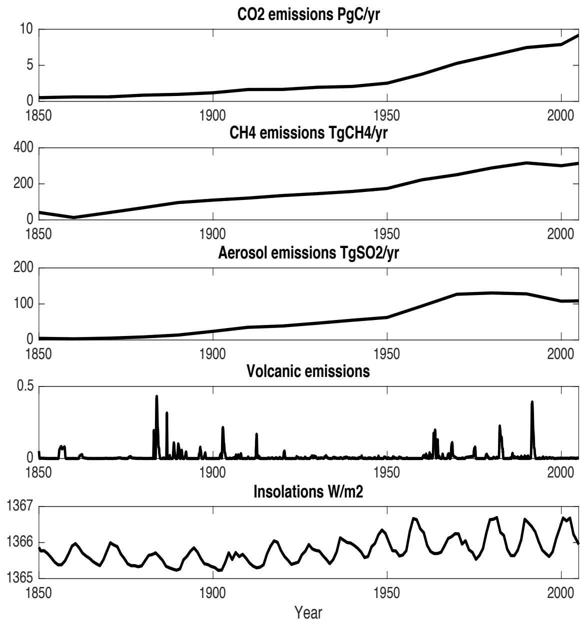
Using the model: Evaluation



Black: simple model output

Red: Average of 20 sophisticated climate models



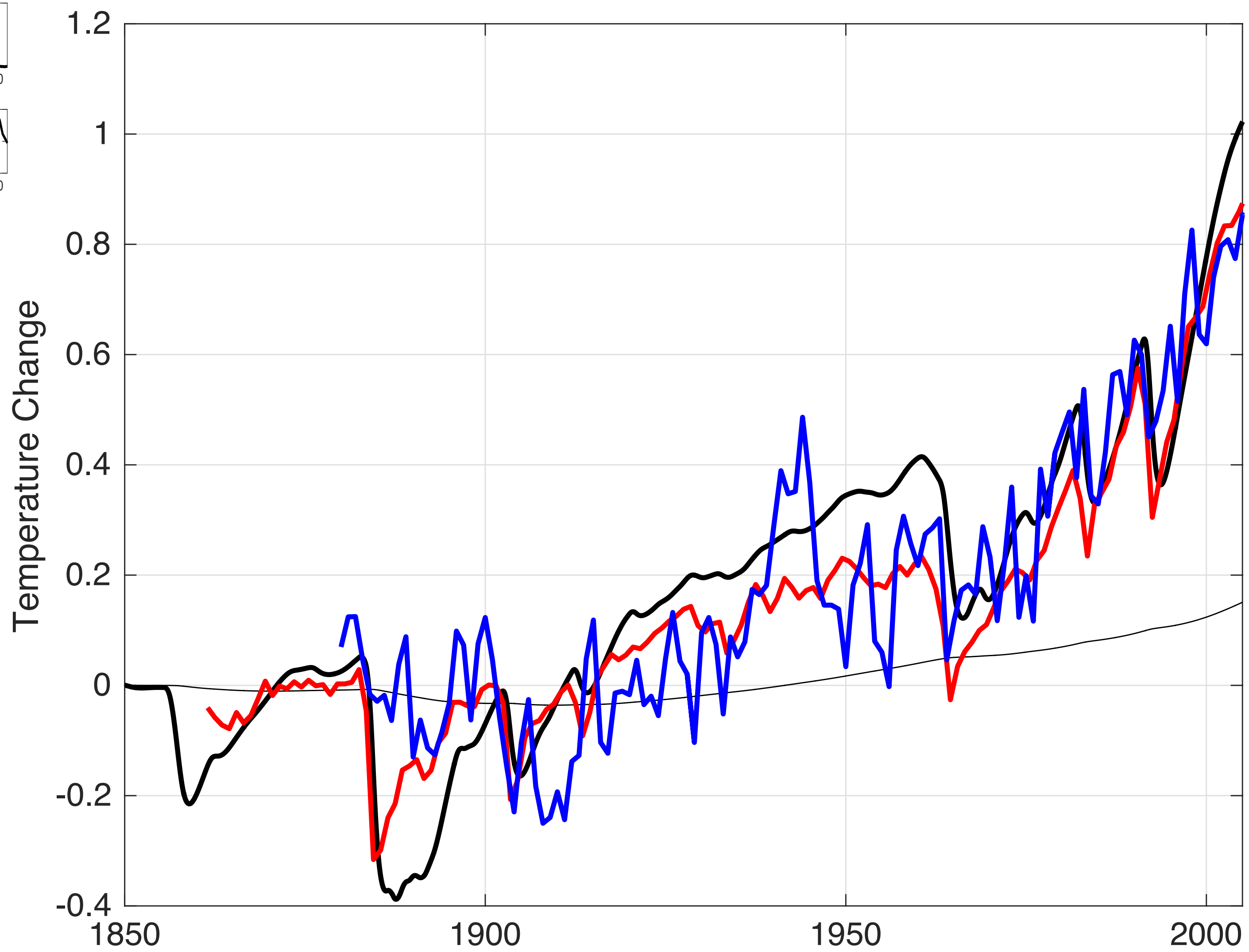


Using the model: Evaluation

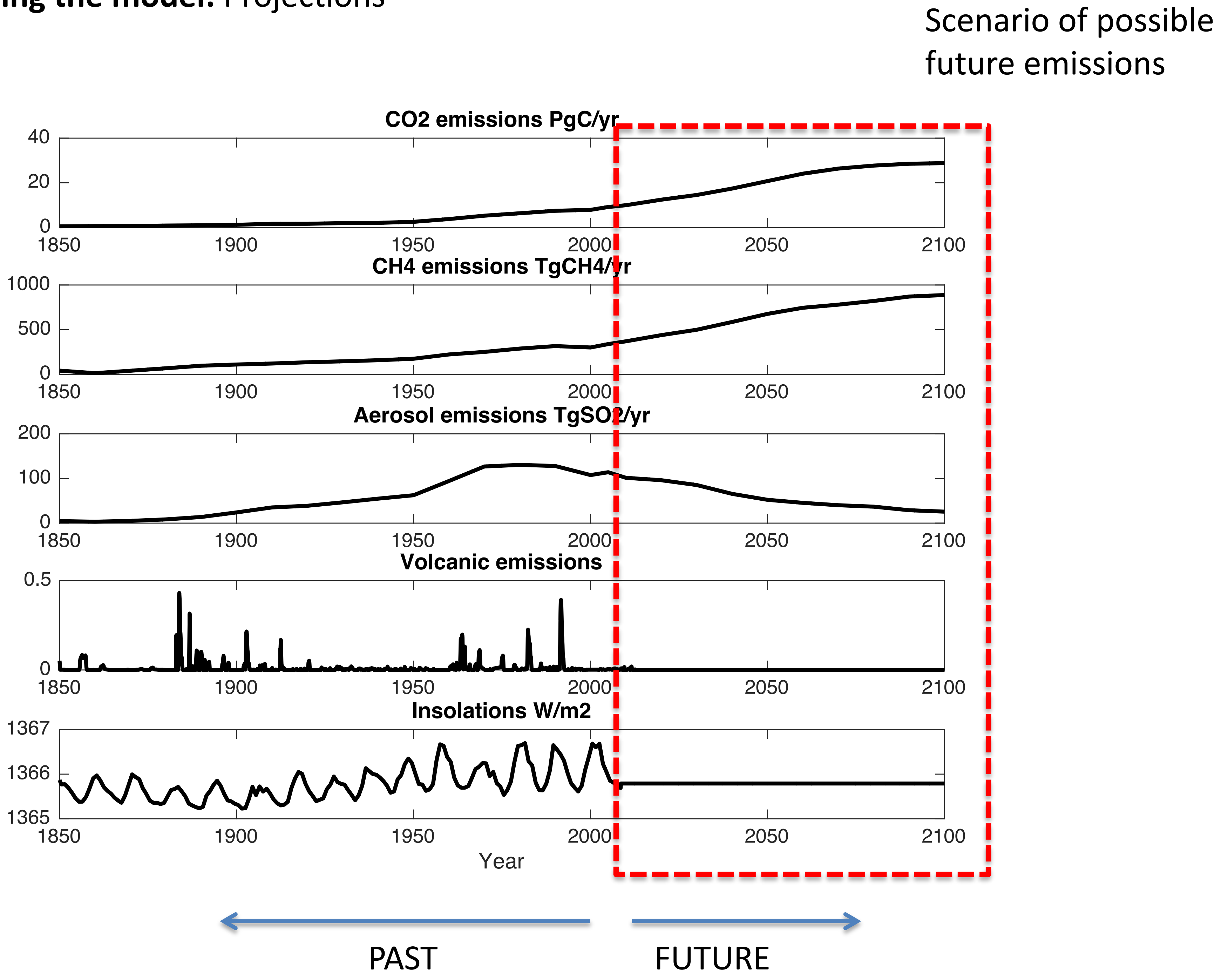
Black: simple model output

Red: Average of 20 sophisticated climate models

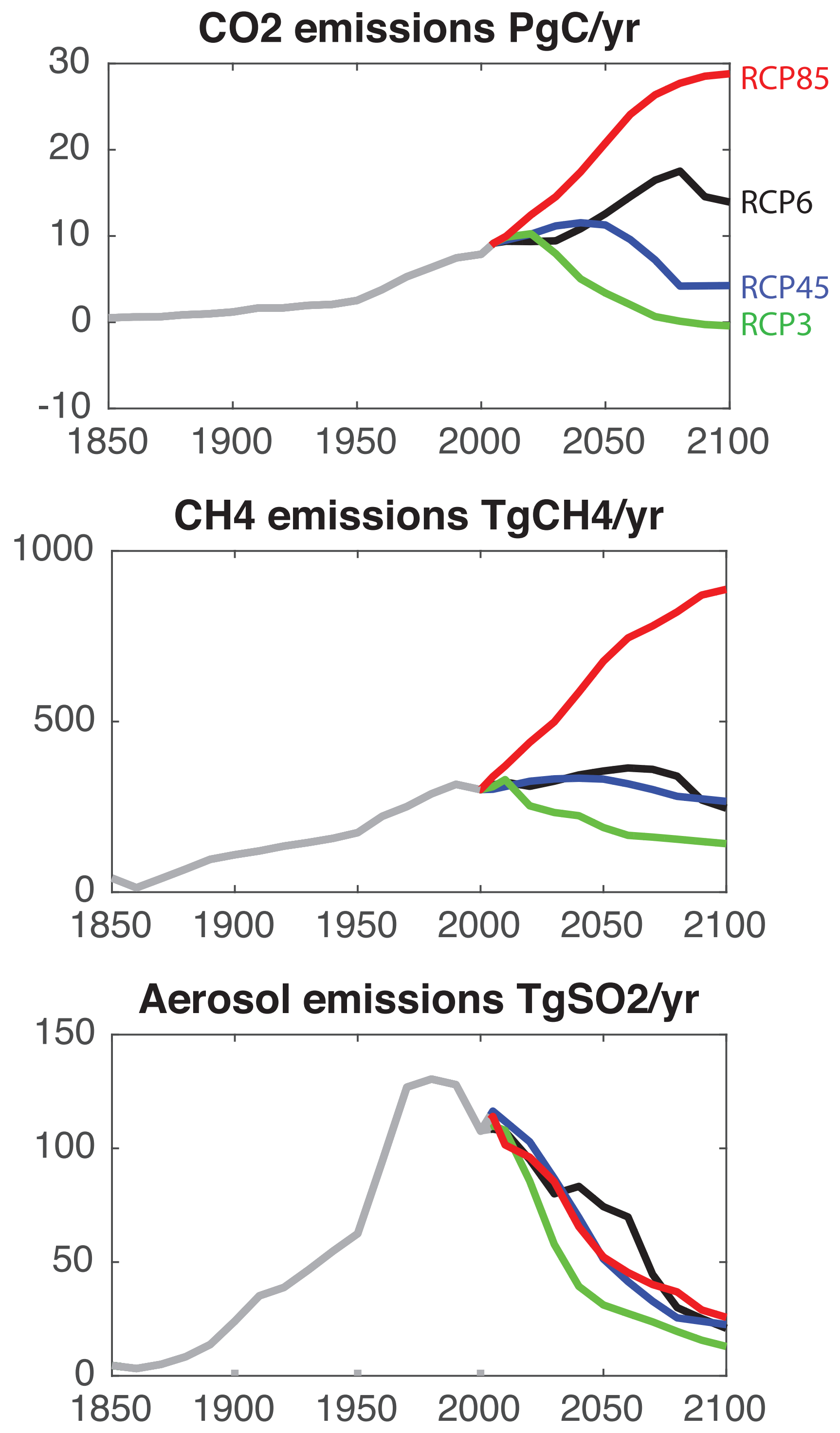
Blue: Observations



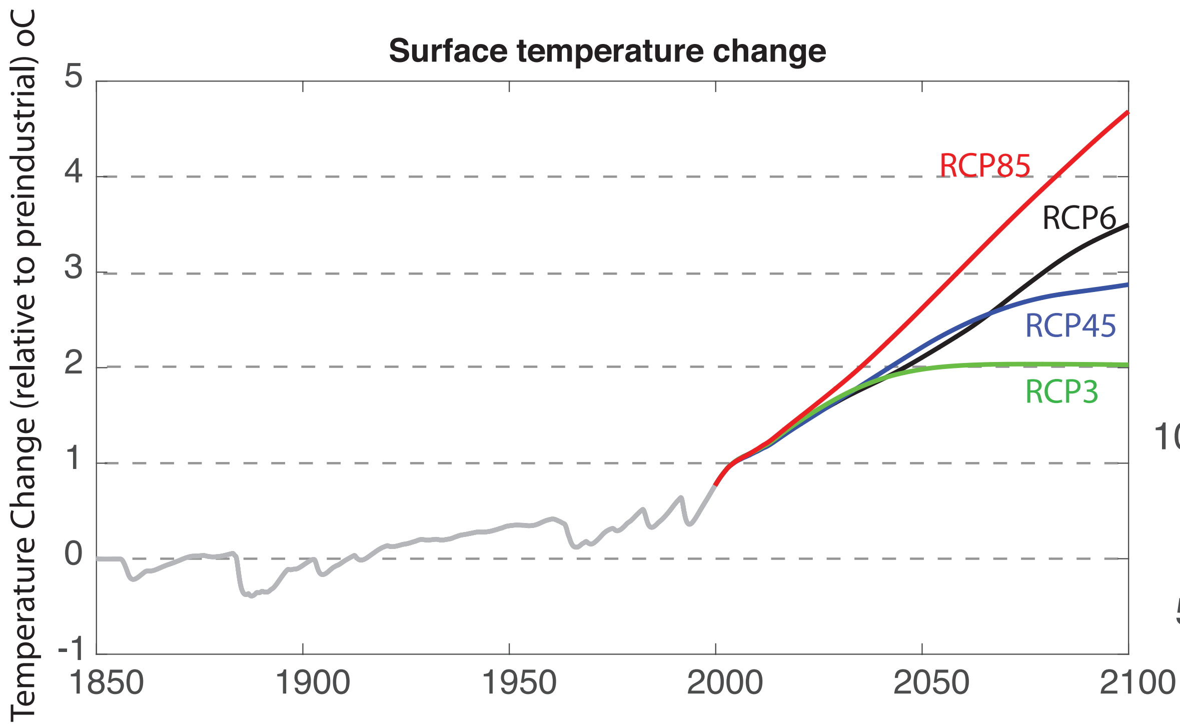
Using the model: Projections

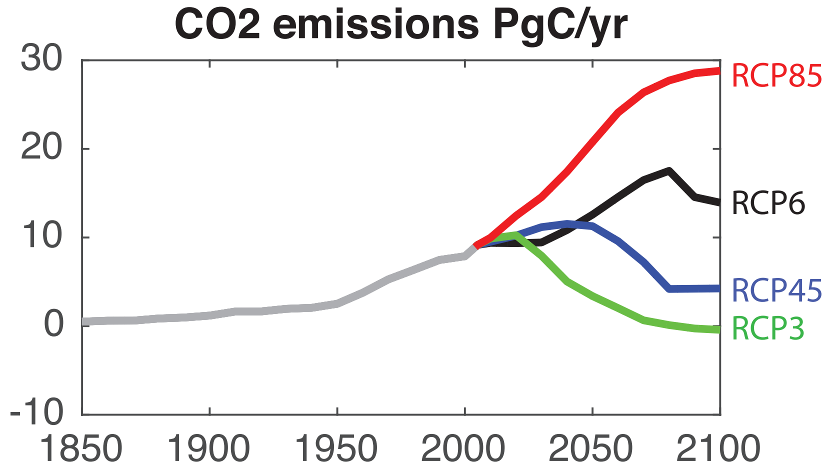


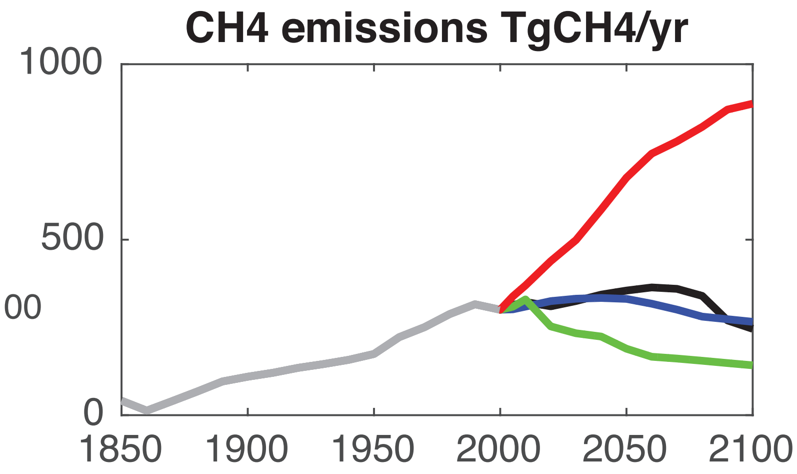
Using the model: Projections

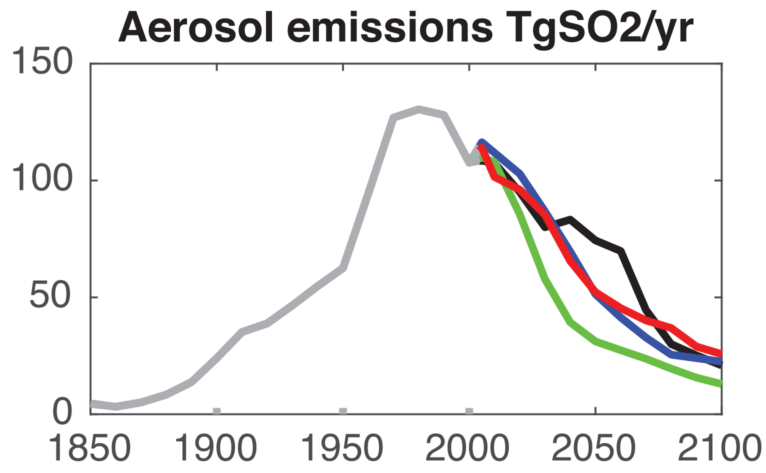


Using the model: Projections

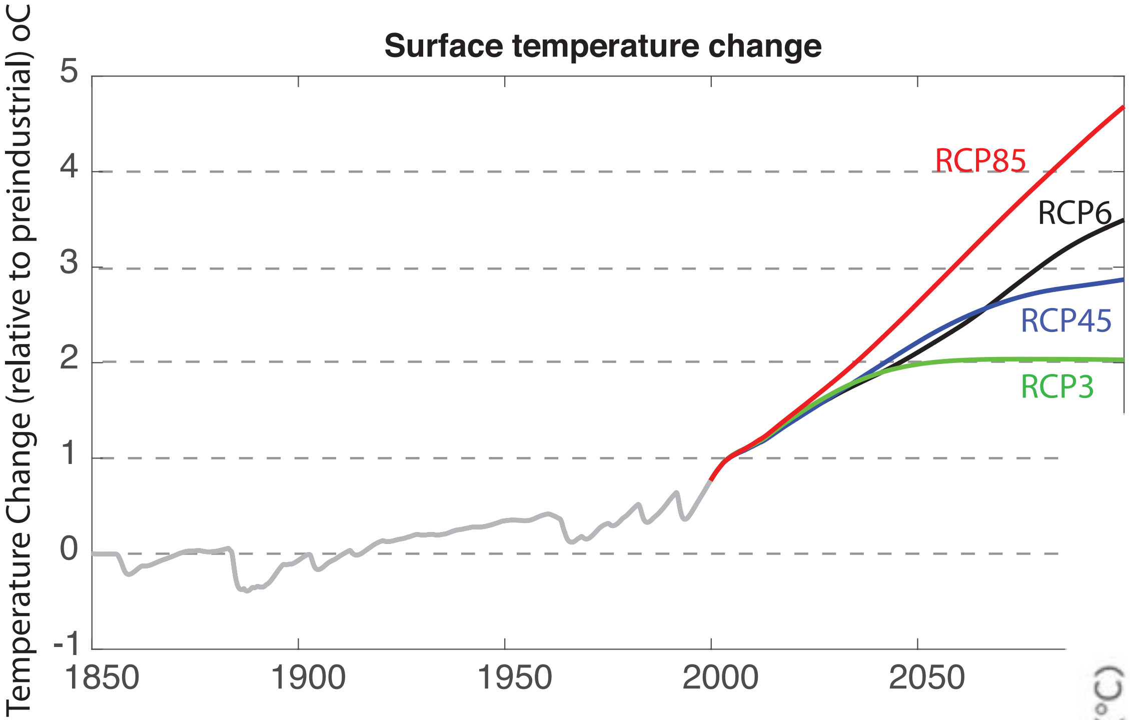


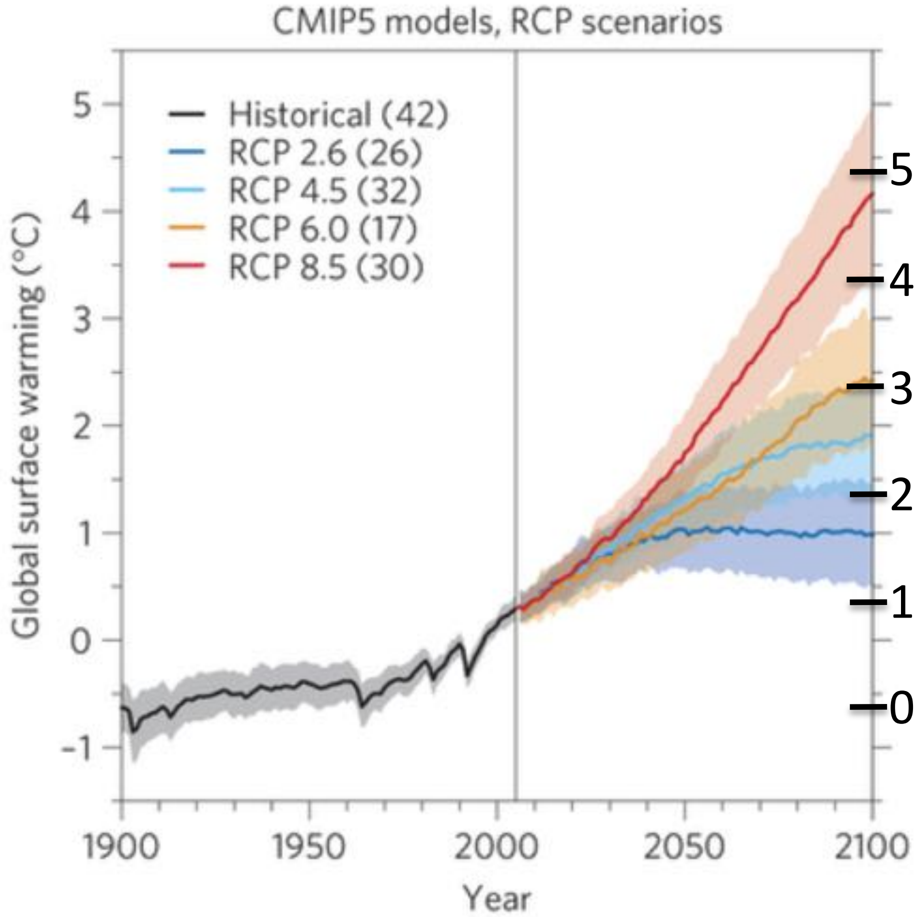




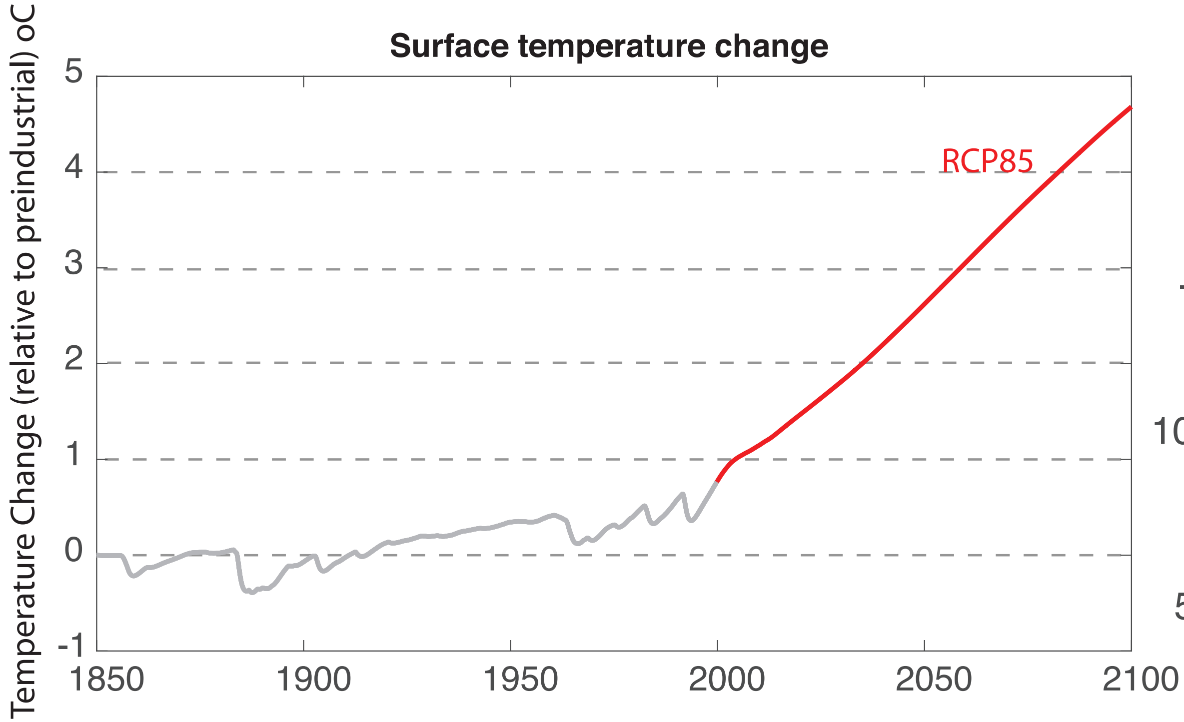


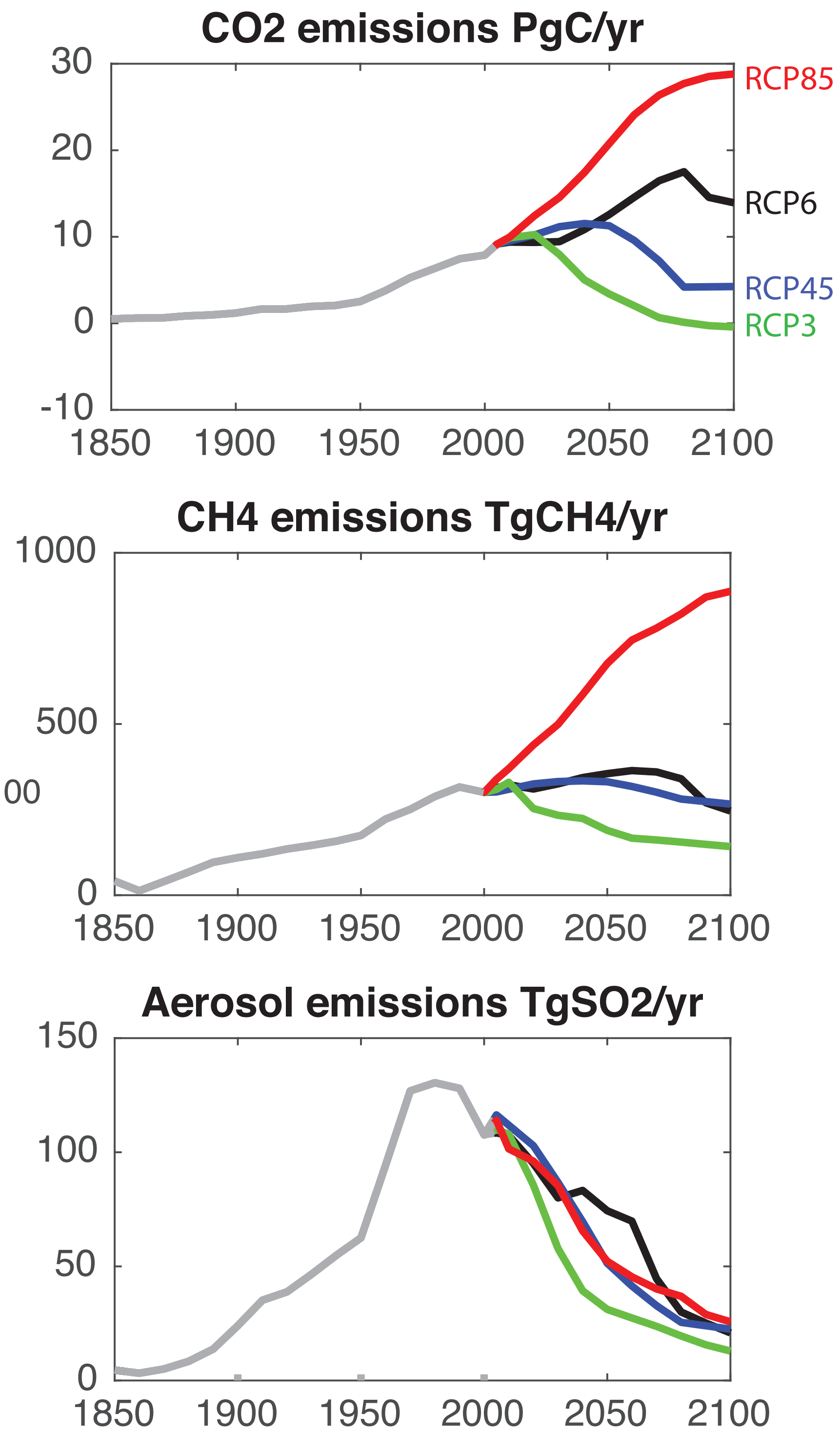
Using the model: Projections



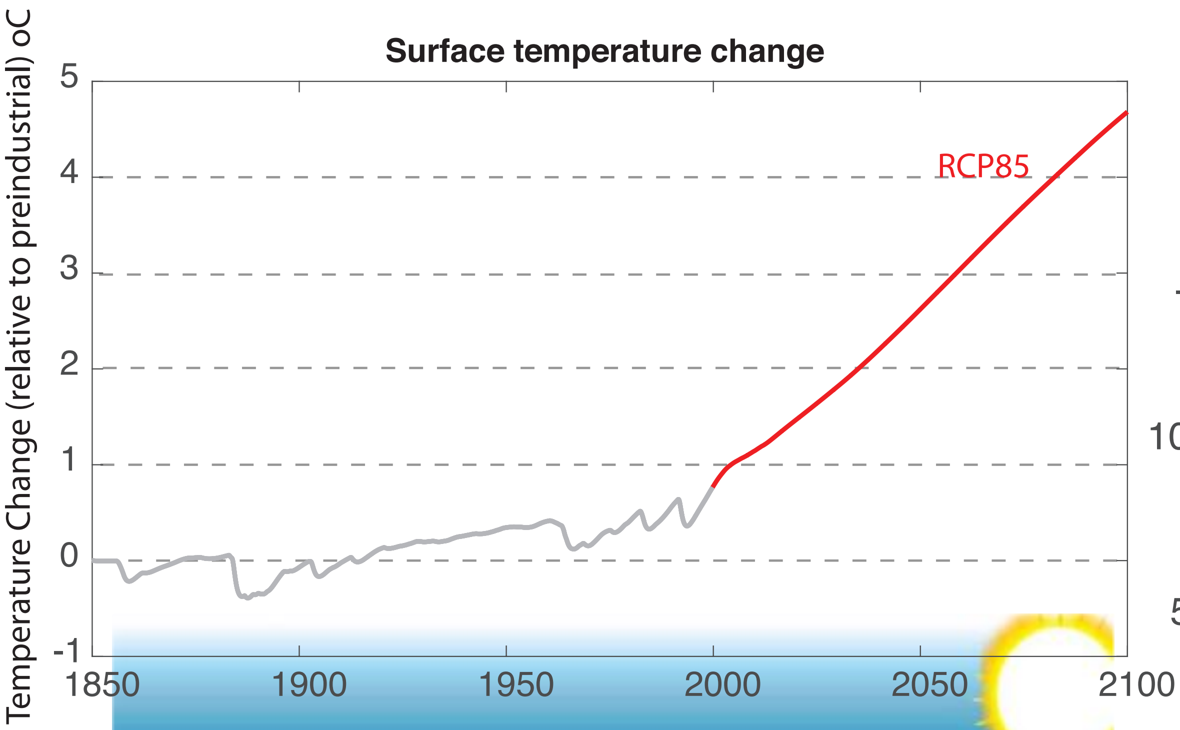


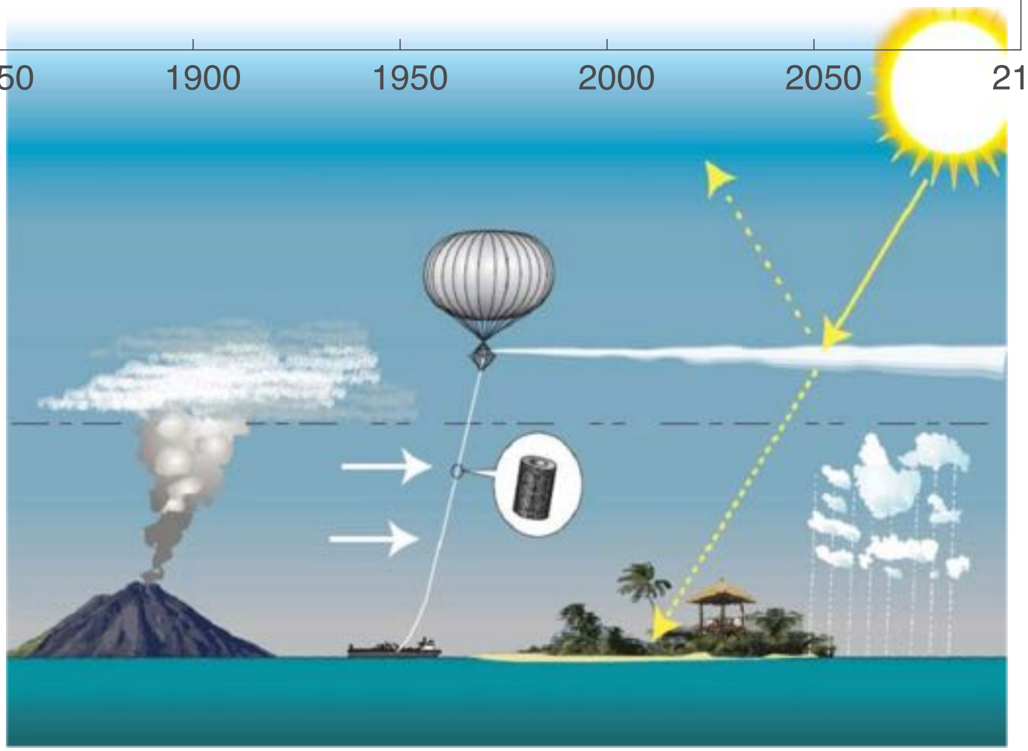
Using the model: Geoengineering

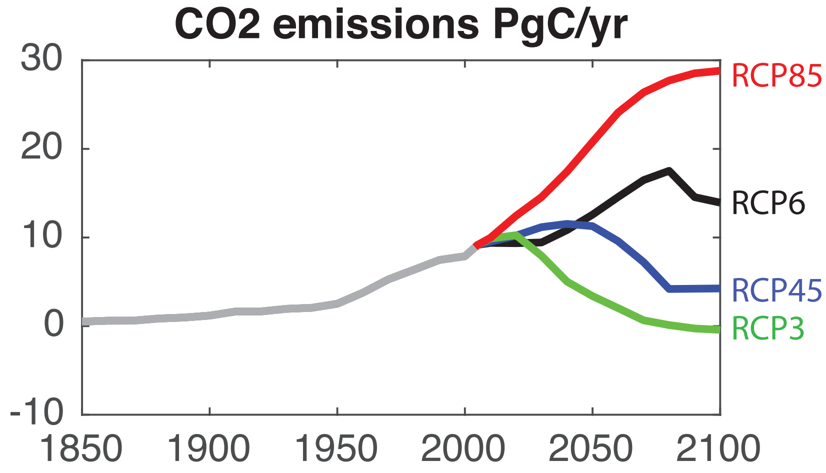


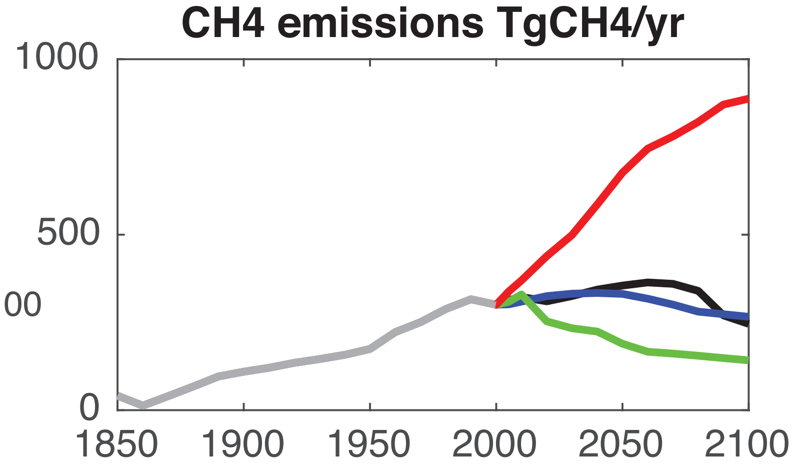


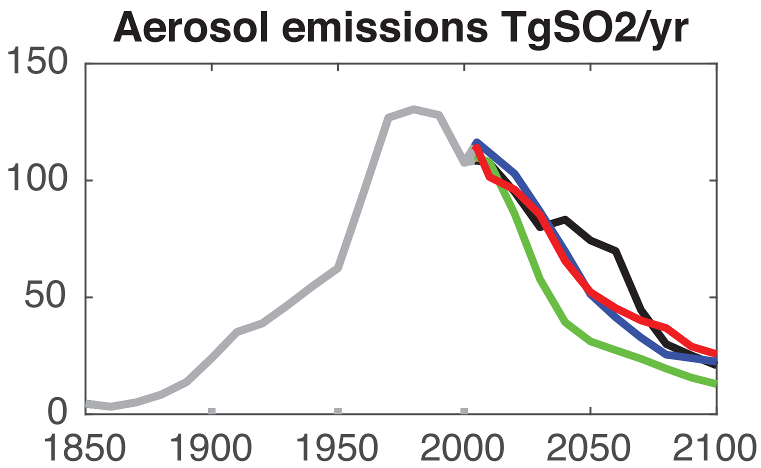
Using the model: Geoengineering











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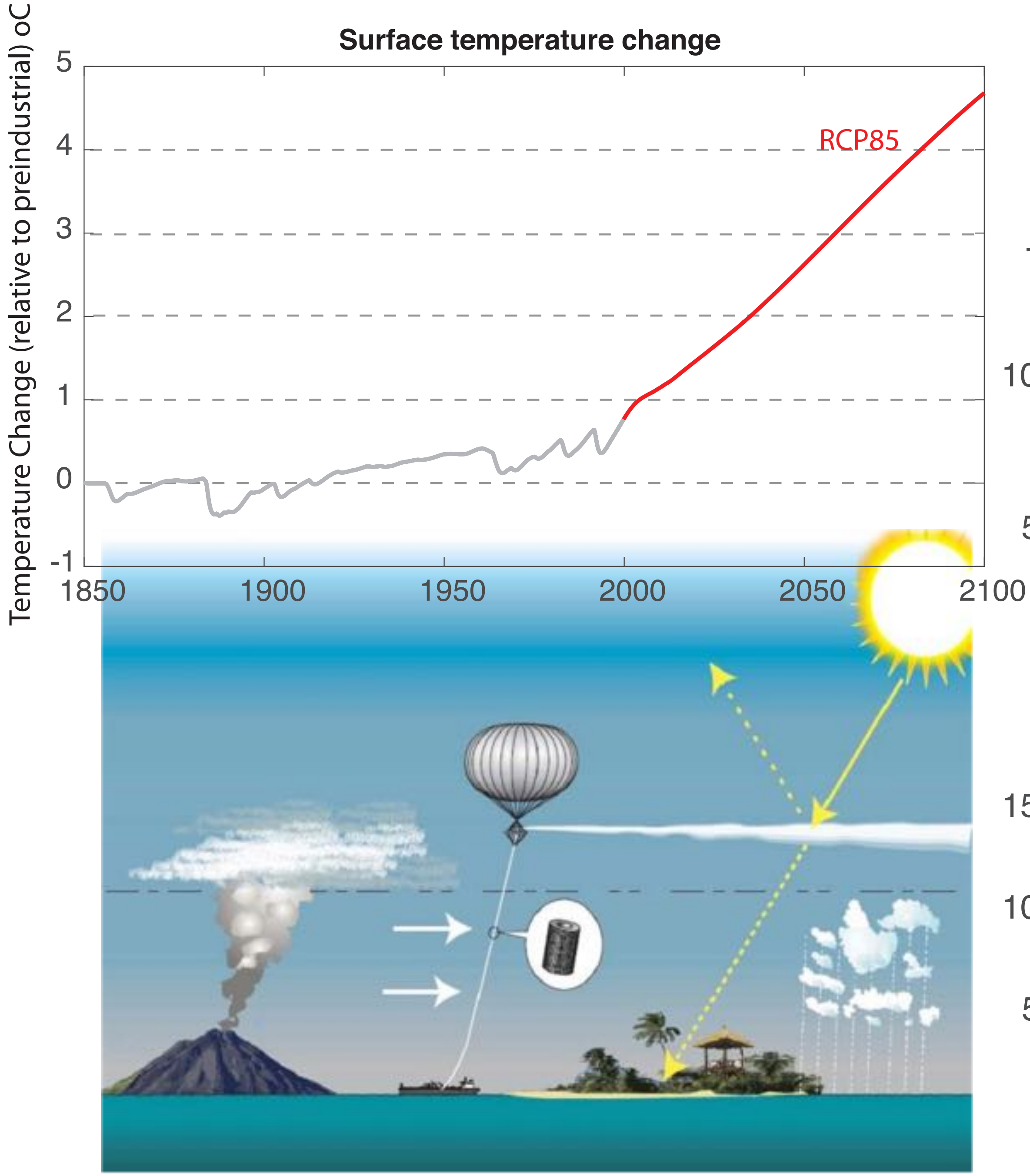

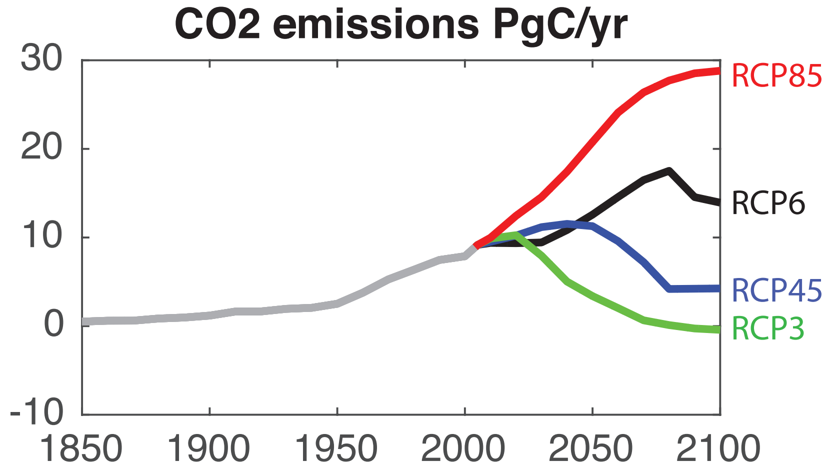

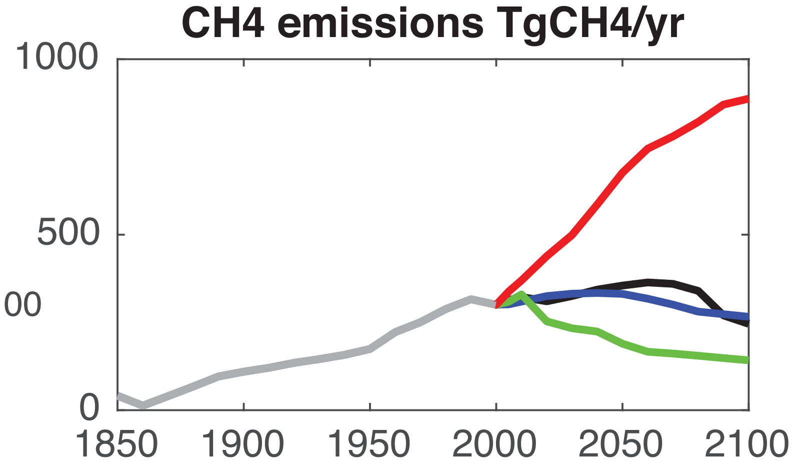

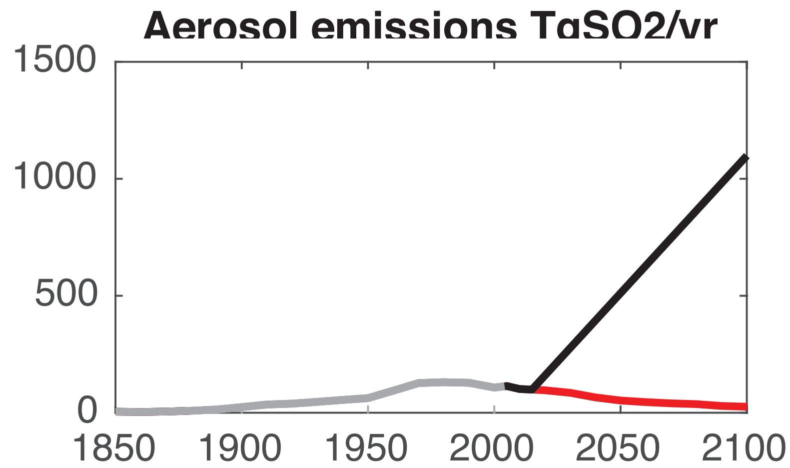

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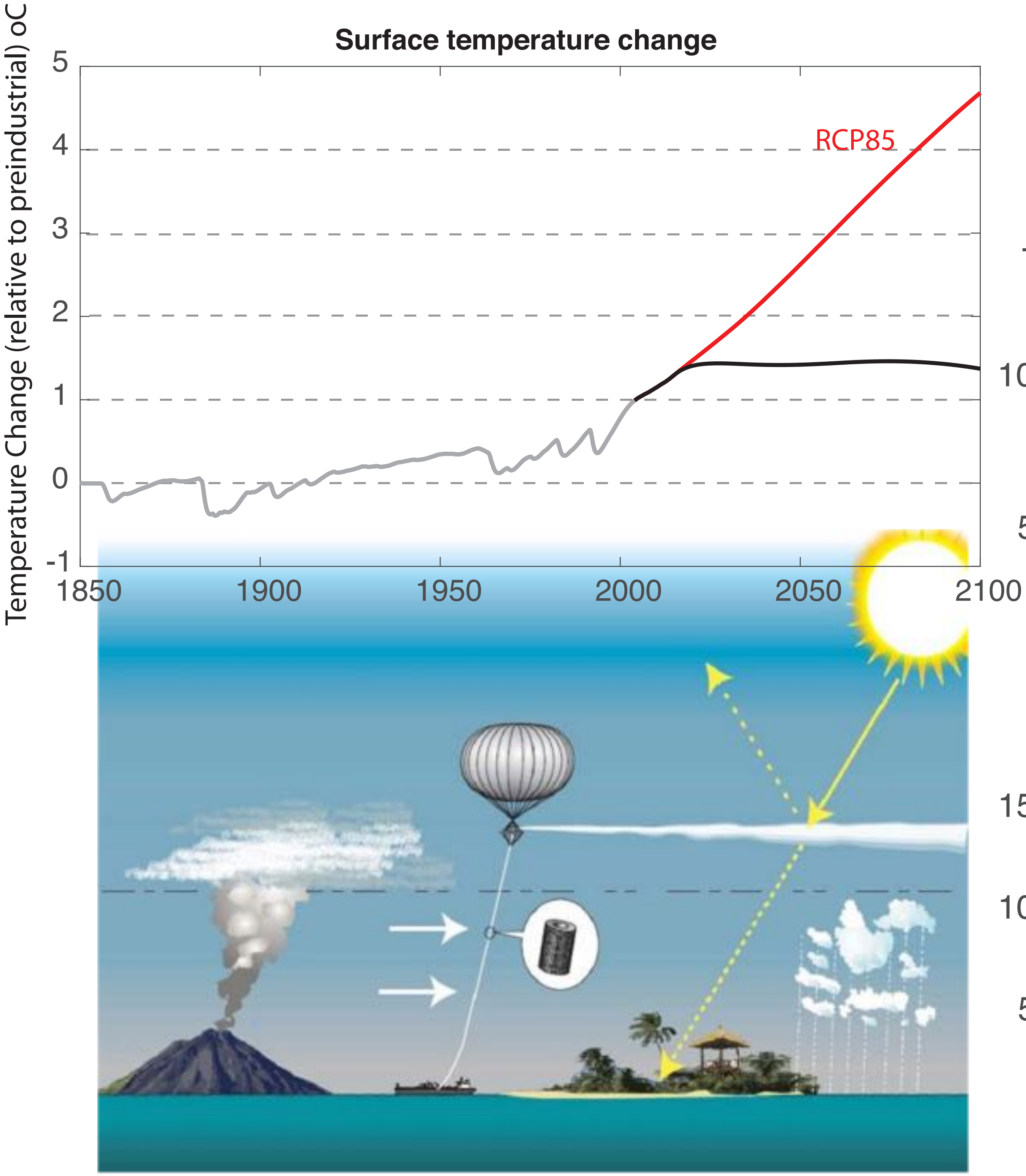
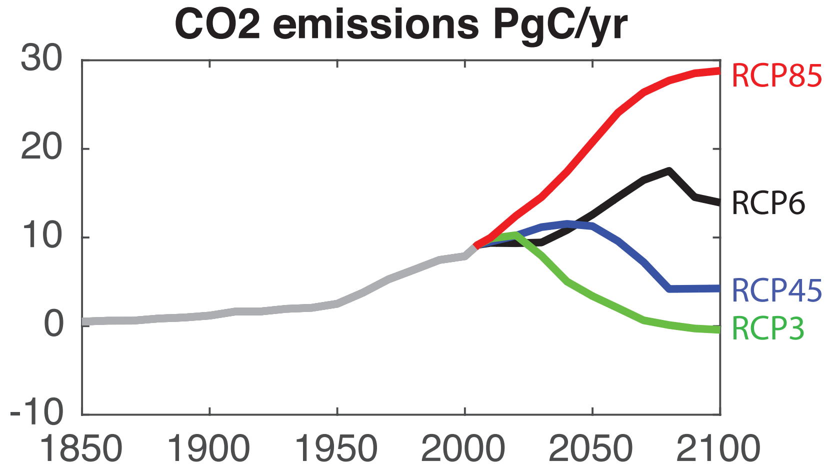
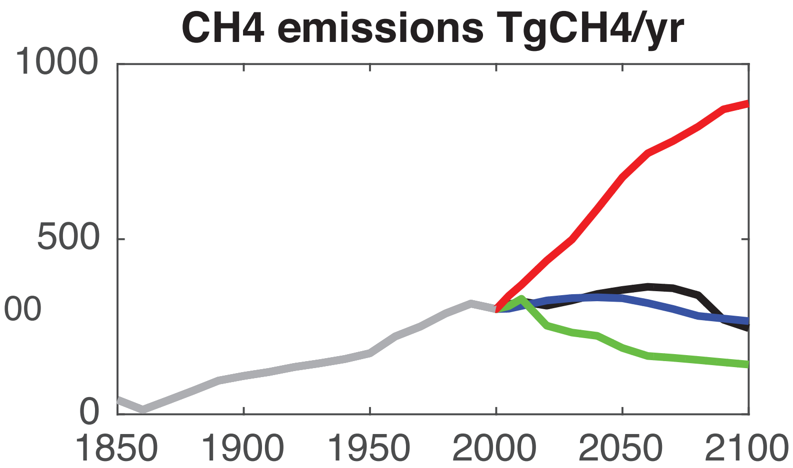
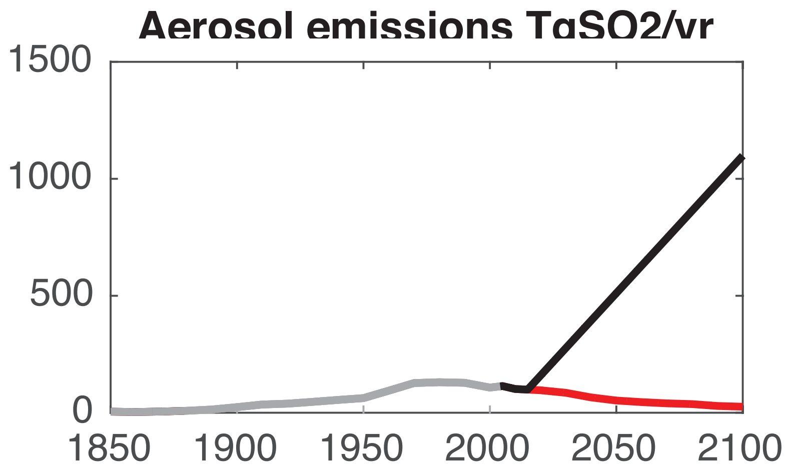
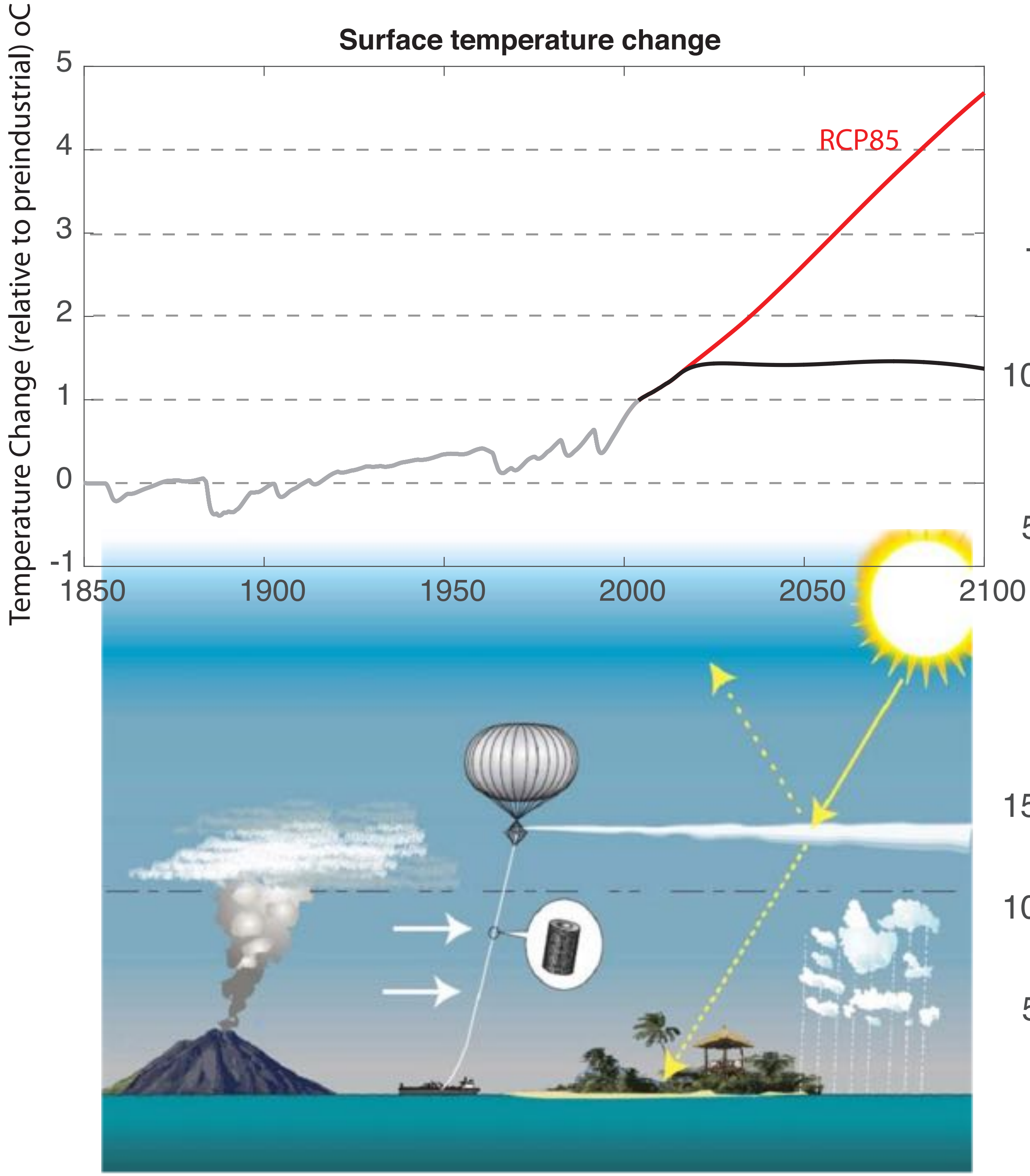


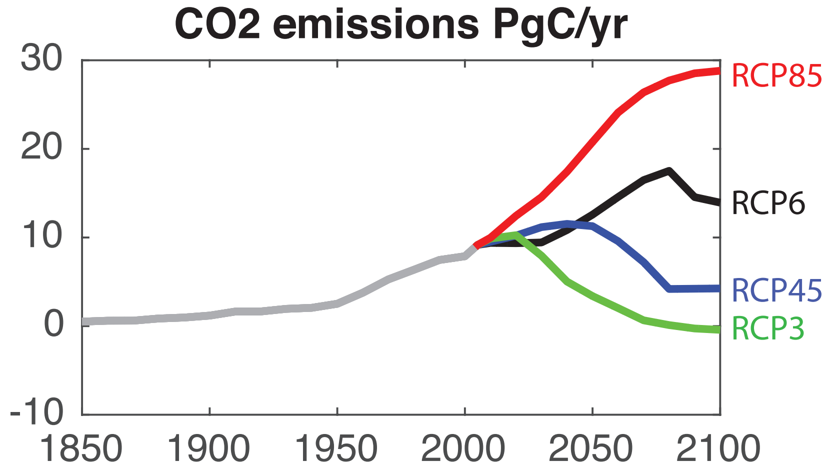


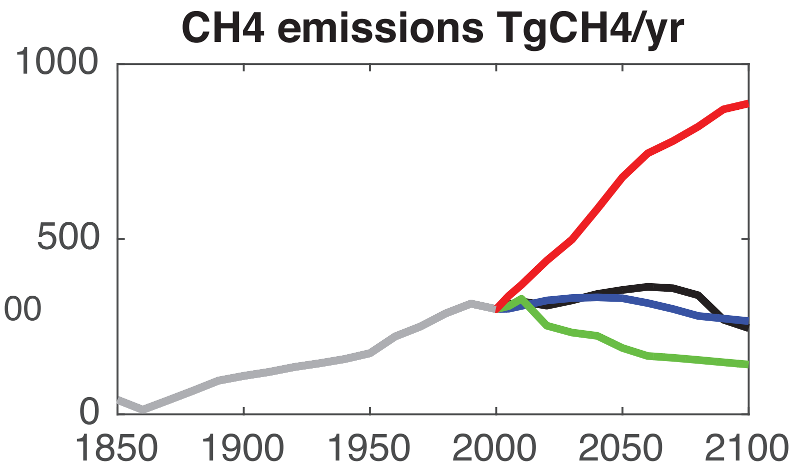


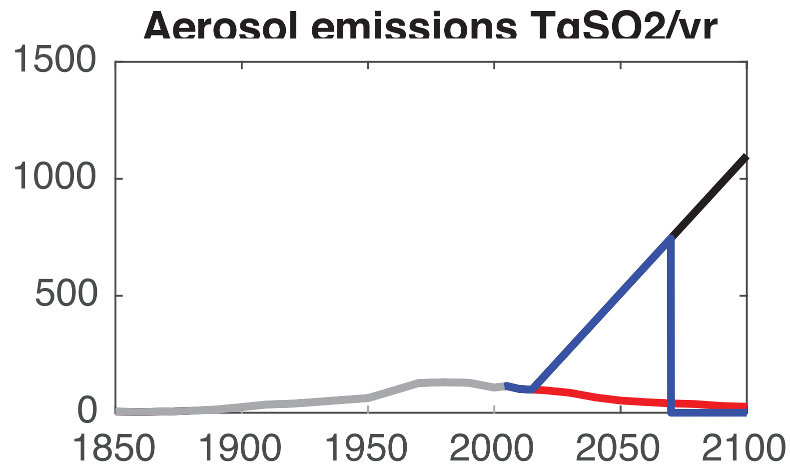


Using the model: Geoengineering

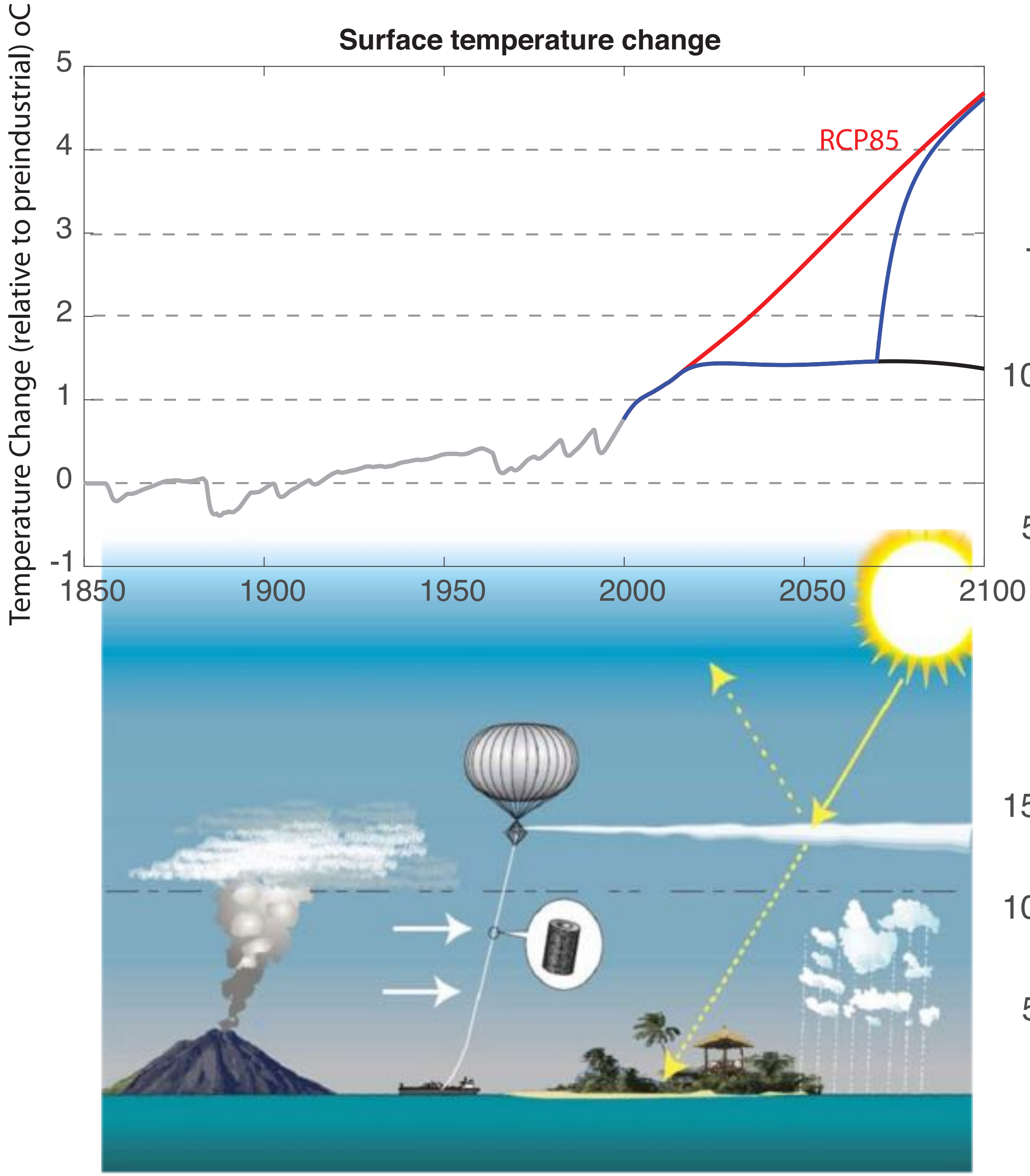


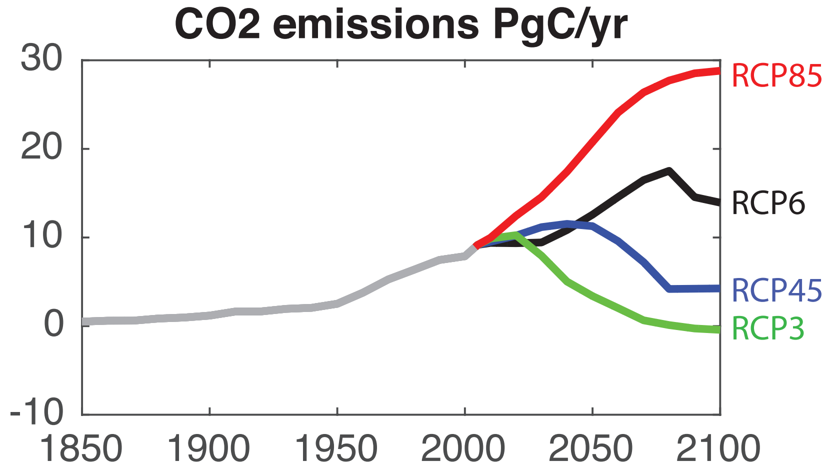


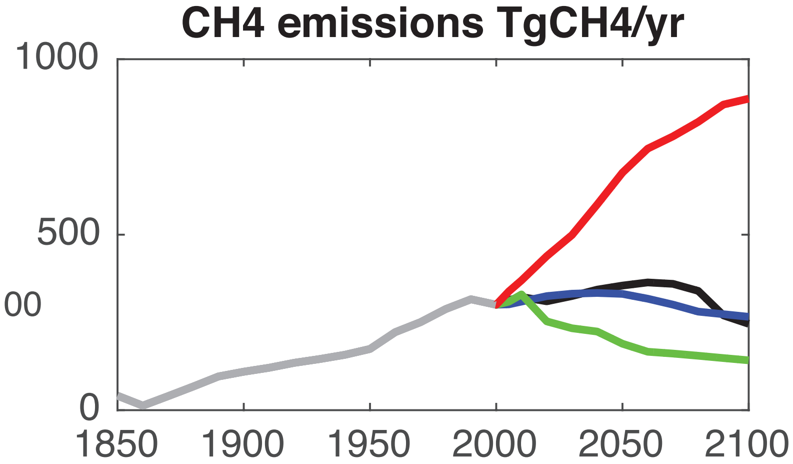


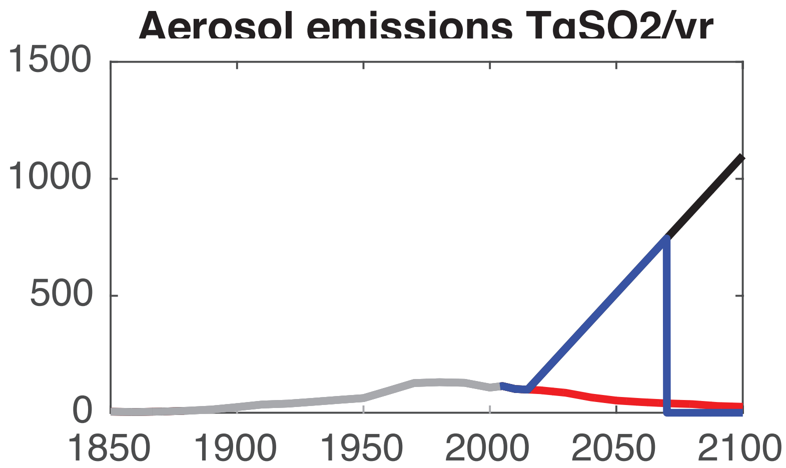


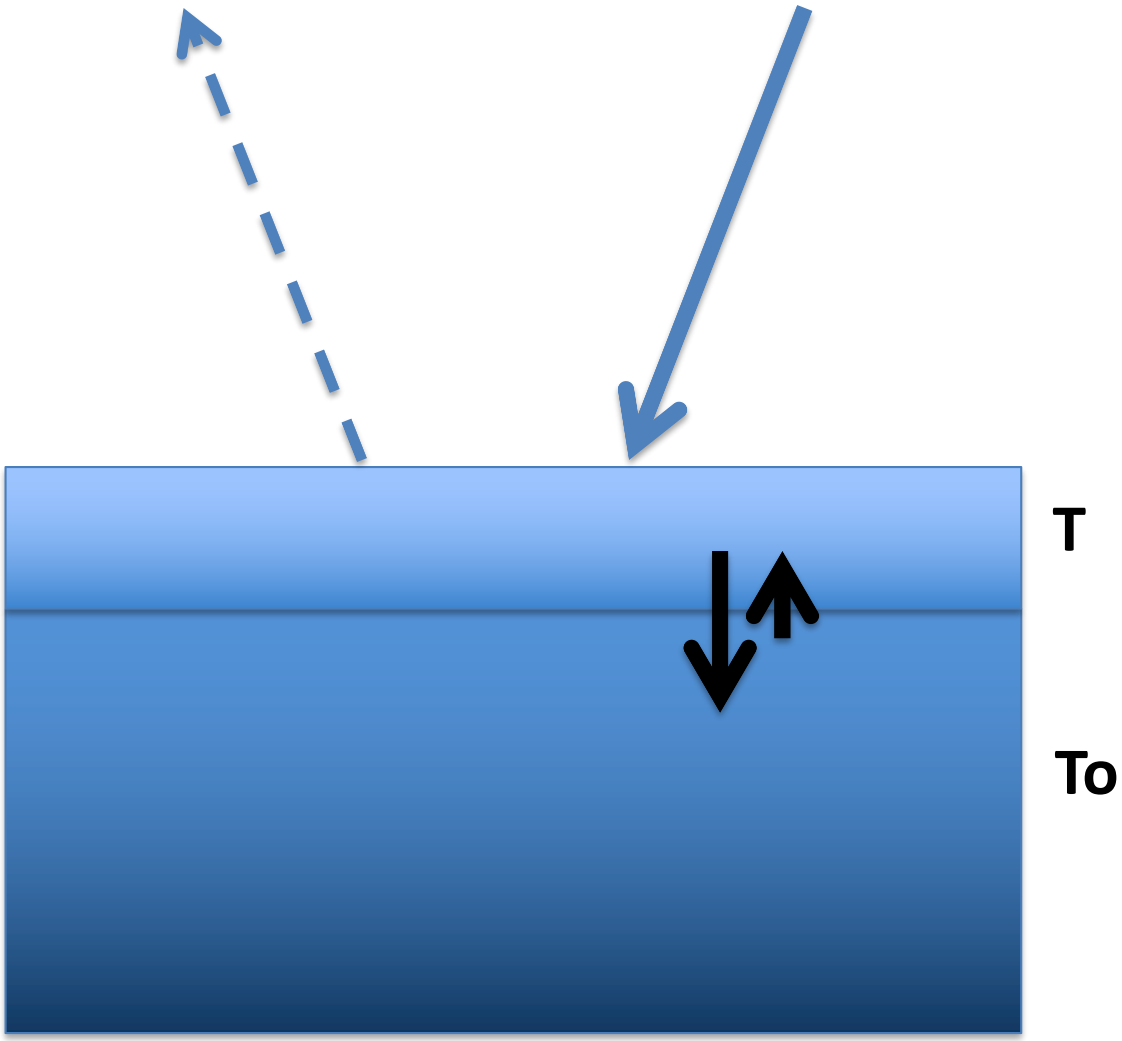
Using the model: Geoengineering











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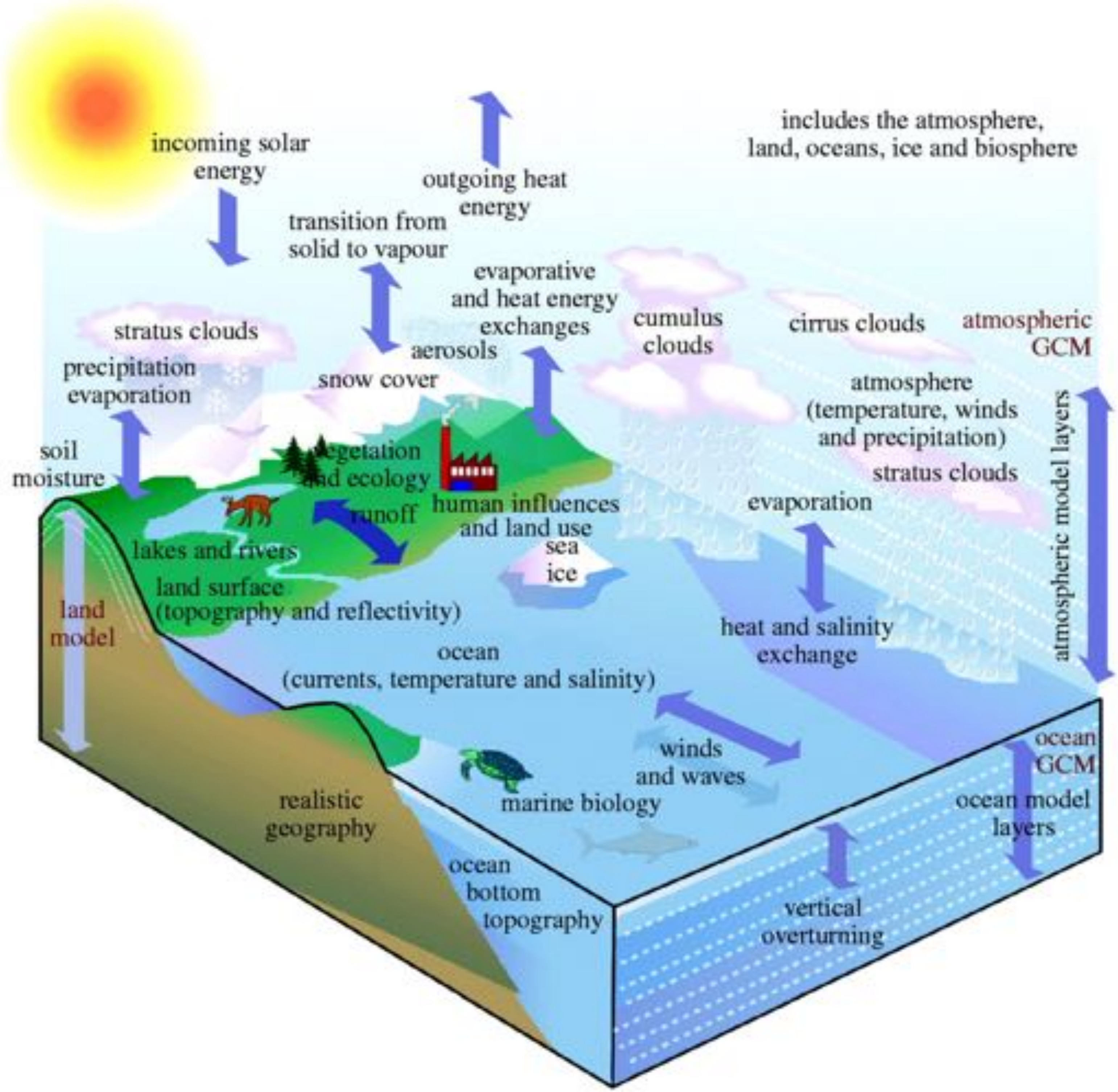

incoming solar energy
outgoing heat energy
includes the atmosphere, land, oceans, ice and biosphere
transition from solid to vapour
evaporative and heat energy exchanges
stratus clouds
precipitation evaporation
aerosols
snow cover
cumulus clouds
cirrus clouds
atmospheric GCM
atmosphere (temperature, winds and precipitation)
soil moisture
vegetation and ecology
human influences and land use
runoff
stratus clouds
evaporation
atmospheric model layers
lakes and rivers
sea ice
land surface (topography and reflectivity)
land model
heat and salinity exchange
ocean (currents, temperature and salinity)
winds and waves
ocean GCM
marine biology
realistic geography
ocean model layers
ocean bottom topography
vertical overturning

Governing equations of the Ocean

$$\frac{D}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + A_H(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) + A_Z(\frac{\partial^2 u}{\partial z^2})$$

$$\frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + A_H(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) + A_Z(\frac{\partial^2 v}{\partial z^2})$$

$$\frac{Dw}{Dt} + hu = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + A_H(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}) + A_Z(\frac{\partial^2 w}{\partial z^2})$$

F=ma

$$f = 2\Omega \sin\theta, \qquad h = 2\Omega \cos\theta$$

$$\frac{DS}{dt} = K_s\left(\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2} + \frac{\partial^2 S}{\partial z^2}\right)$$

Conservation of salt

$$\rho C_p \frac{D\theta}{dt} = K_\theta\left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2}\right) + Q$$

Conservation of energy

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Conservation of mass

$\rho = \rho(T,S,p)$

Equation of state

Governing equations of the Ocean

$$\frac{D}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

Acceleration Coriolis Pressure gradients Horizontal friction Vertical friction

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + A_H(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) + A_Z(\frac{\partial^2 u}{\partial z^2})$$

$$\frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + A_H(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) + A_Z(\frac{\partial^2 v}{\partial z^2})$$

$$\frac{Dw}{Dt} + hu = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + A_H(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}) + A_Z(\frac{\partial^2 w}{\partial z^2})$$

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$$\rho C_p\frac{D\theta}{dt} = K_\theta\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right) + Q$$

Conservation of energy

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

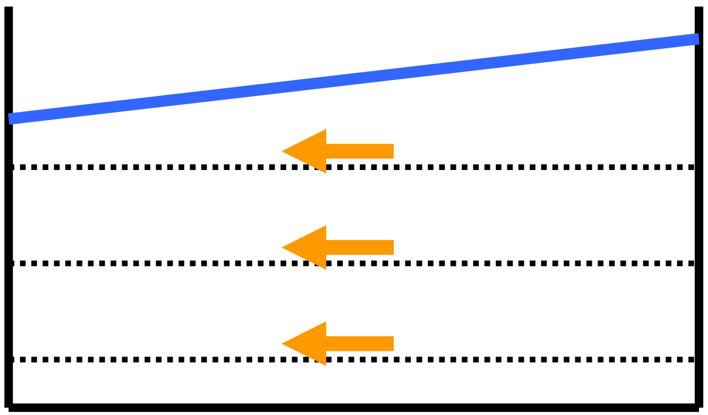
Conservation of mass

Governing equations

$$\frac{Du}{Dt} - \cancel{fv} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + A_H\left(\cancel{\frac{\partial^2 u}{\partial x^2}} + \frac{\partial^2 u}{\partial y^2}\right) + A_Z\left(\cancel{\frac{\partial^2 u}{\partial z^2}}\right)$$

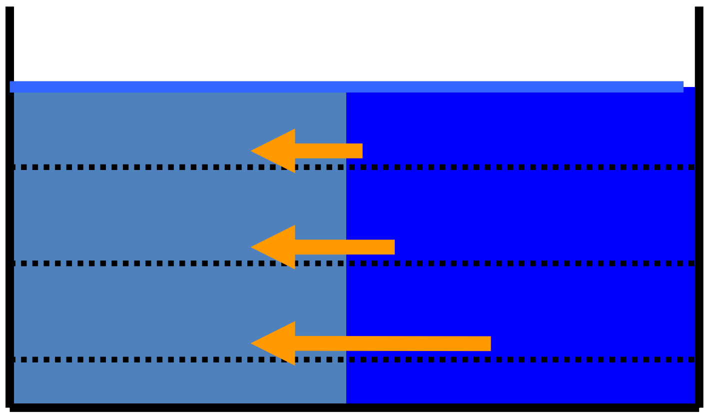
Pressure force:

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$



ρ_0

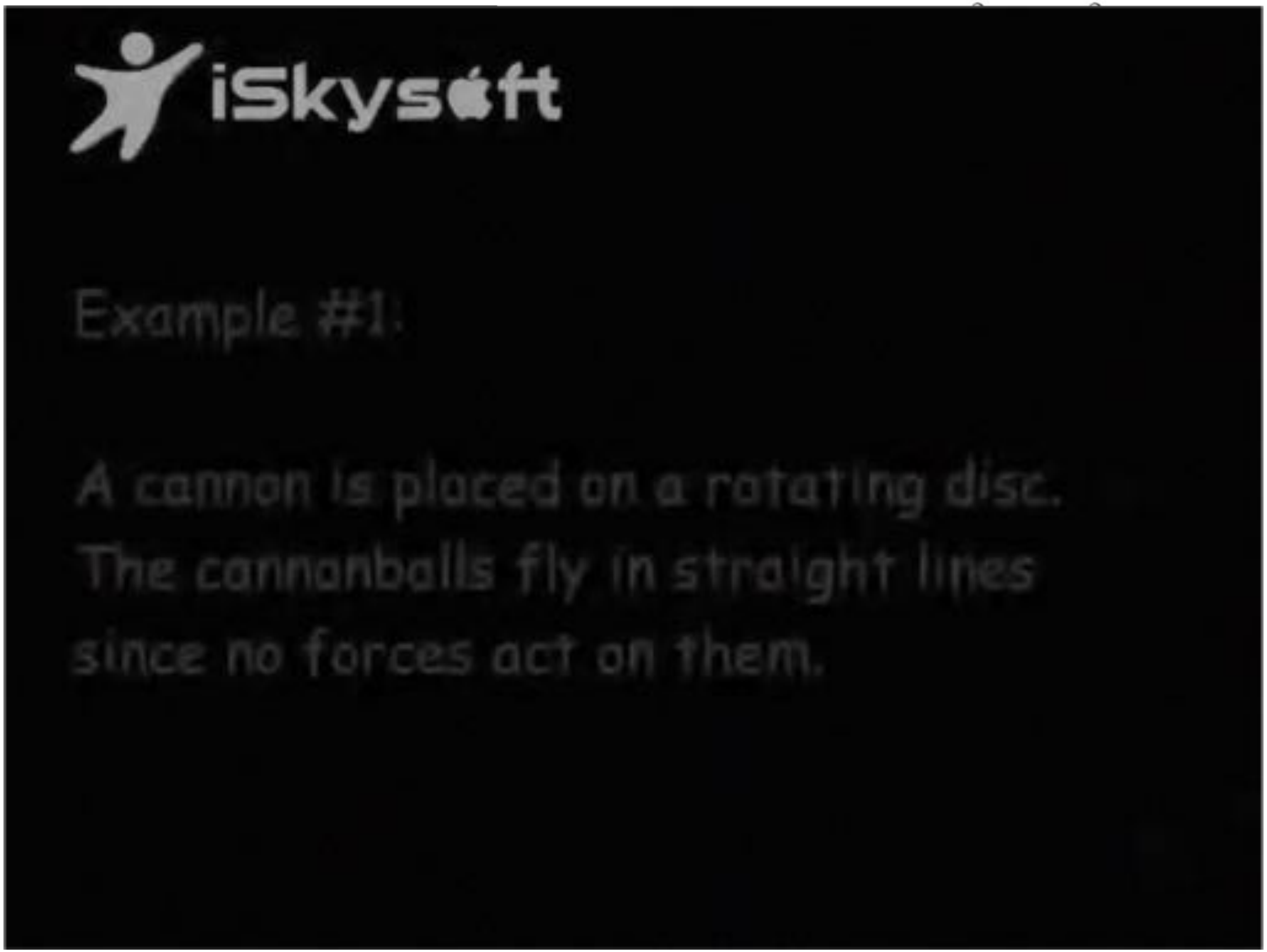
Motion due to surface slopes



$\rho_1 < \rho_2$

Motion due to density differences

$$\frac{Du}{Dt} - fv = -\cancel{\frac{1}{\rho}\frac{\partial p}{\partial x}} + A_H(\cancel{\frac{\partial^2 u}{\partial x^2}} + \frac{\partial^2 u}{\partial y^2}) + A_Z(\cancel{\frac{\partial^2 u}{\partial z^2}})$$



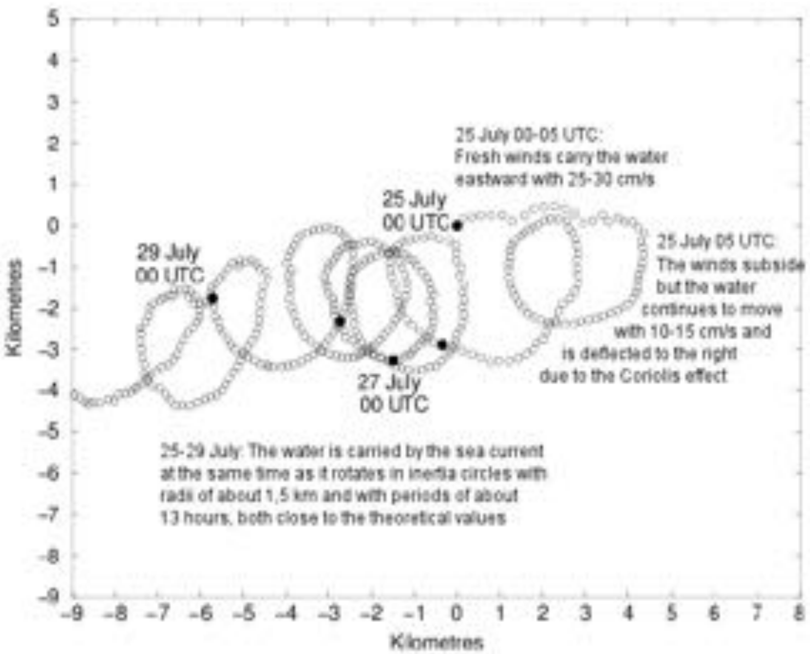
Governing equations

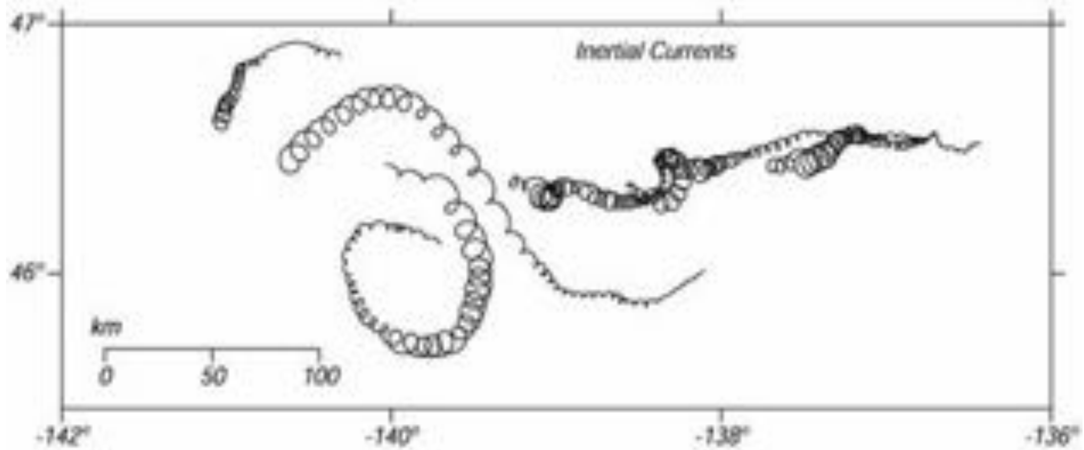
$$\frac{Du}{Dt} - fv = -\cancel{\frac{1}{\rho}\frac{\partial p}{\partial x}} + A_H(\cancel{\frac{\partial^2 u}{\partial x^2}} + \frac{\partial^2 u}{\partial y^2}) + A_Z(\cancel{\frac{\partial^2 u}{\partial z^2}})$$

Inertial Oscillations:

$$\frac{du}{dt} = fv, \qquad \frac{dv}{dt} = -fu, \qquad where\ f = 2\Omega \sin(latitude)$$

$$u = V\sin(ft), \qquad v = V\sin(ft), V^2 = u^2 + v^2$$





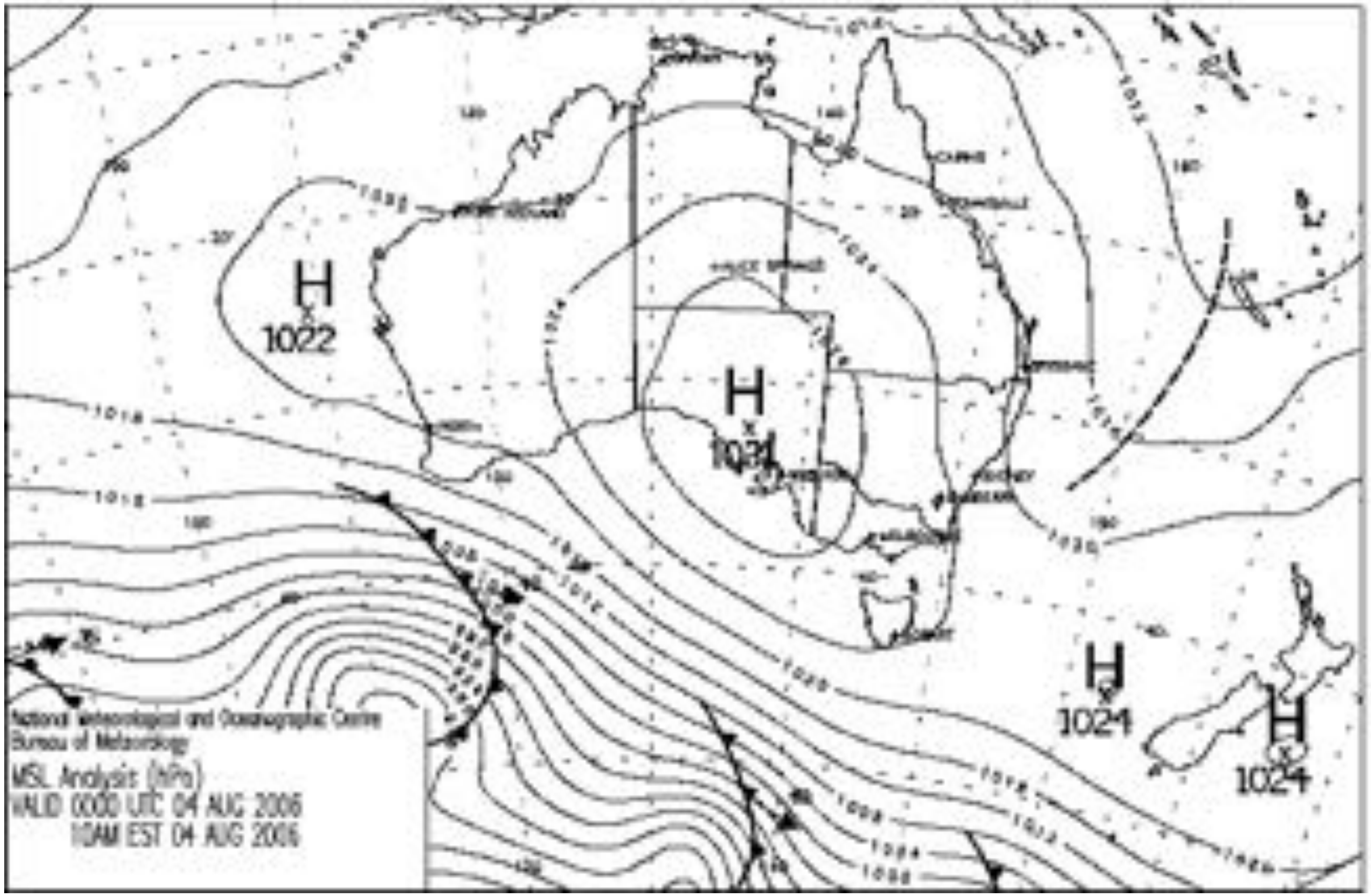
Governing equations

$$\cancel{\frac{Du}{Dt}} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + A_H\left(\cancel{\frac{\partial^2 u}{\partial x^2}} + \frac{\partial^2 u}{\partial y^2}\right) + A_Z\left(\cancel{\frac{\partial^2 u}{\partial z^2}}\right)$$

Geostrophic flow:

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = fv, \quad \frac{1}{\rho}\frac{\partial p}{\partial y} = -fu$$

$where\ f = 2\Omega \sin\,(latitude)$



Governing equations

$$\cancel{\frac{Du}{Dt}} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + A_H\left(\cancel{\frac{\partial^2 u}{\partial x^2}} + \frac{\partial^2 u}{\partial y^2}\right) + A_Z\left(\cancel{\frac{\partial^2 u}{\partial z^2}}\right)$$

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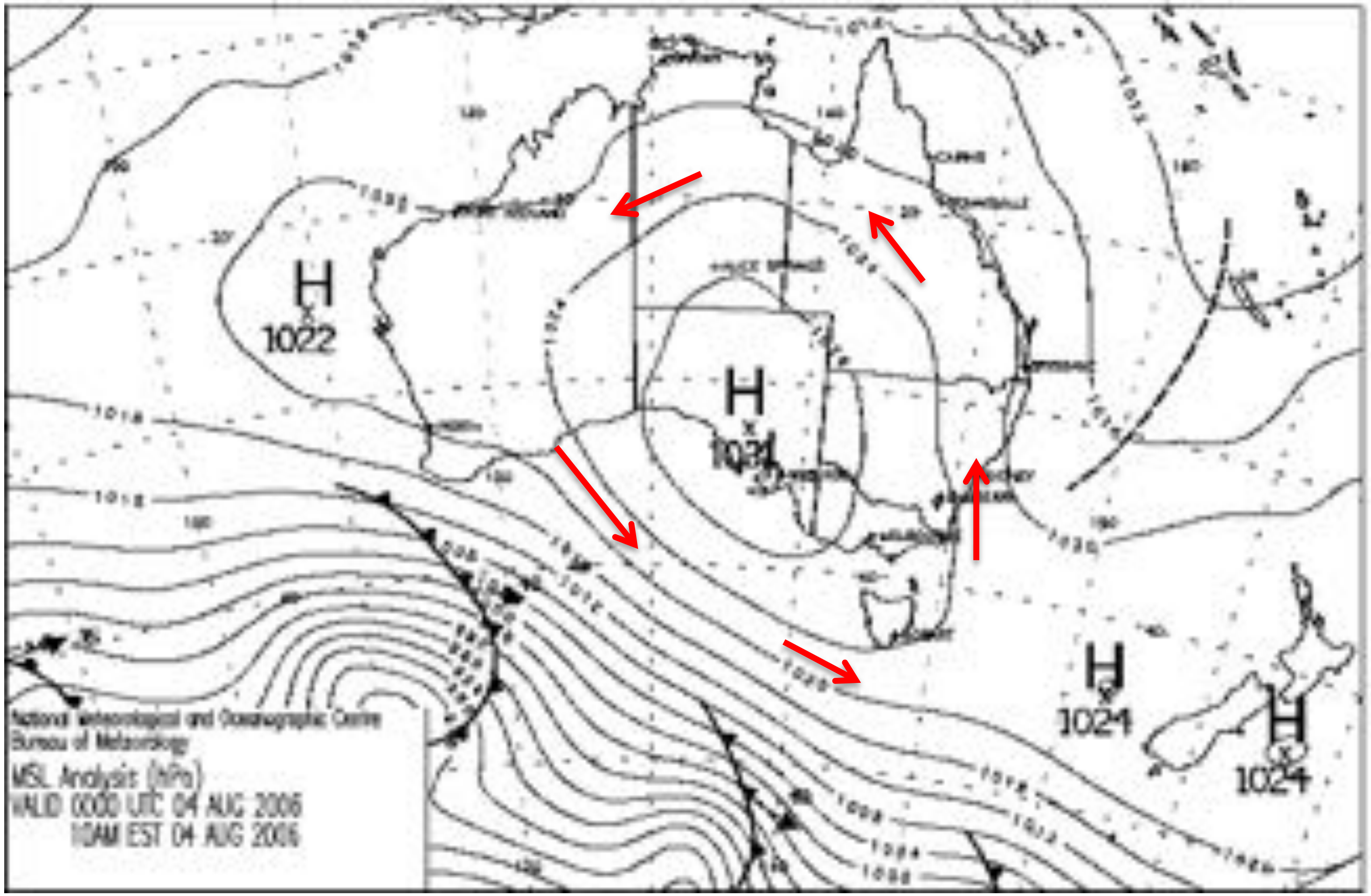


Governing equations of the Ocean

$$\frac{D}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + A_H(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) + A_Z(\frac{\partial^2 u}{\partial z^2})$$

$$\frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + A_H(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) + A_Z(\frac{\partial^2 v}{\partial z^2})$$

$$\frac{Dw}{Dt} + hu = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + A_H(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}) + A_Z(\frac{\partial^2 w}{\partial z^2})$$

F=ma

$$f = 2\Omega\sin\theta, \qquad h = 2\Omega\cos\theta$$

$$\frac{DS}{dt} = K_s\left(\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2} + \frac{\partial^2 S}{\partial z^2}\right)$$

Conservation of salt

$$\rho C_p\frac{D\theta}{dt} = K_\theta\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right) + Q$$

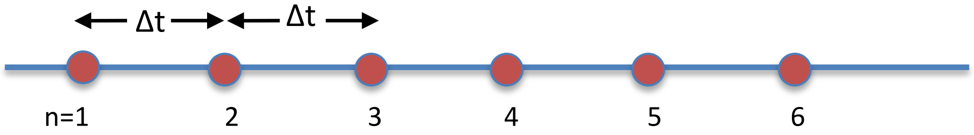
Conservation of energy

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Conservation of mass

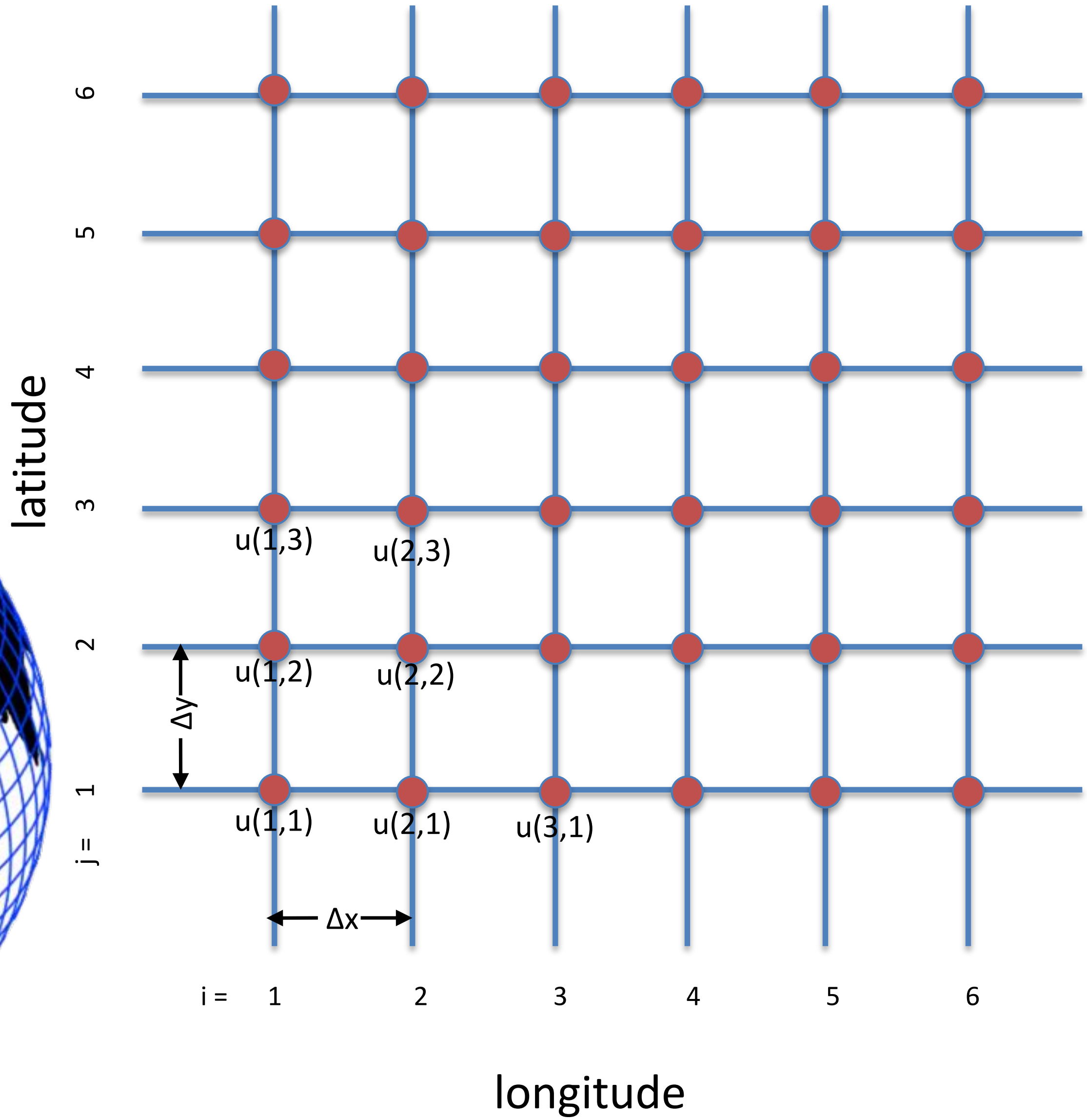
$\rho = \rho(T,S,p)$

Equation of state

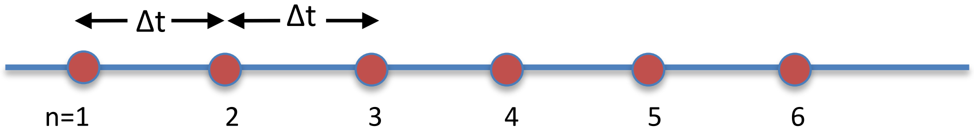


$$\frac{du}{dt}$$

$$\frac{d^2u}{dx^2}, \qquad T\frac{du}{dx}$$

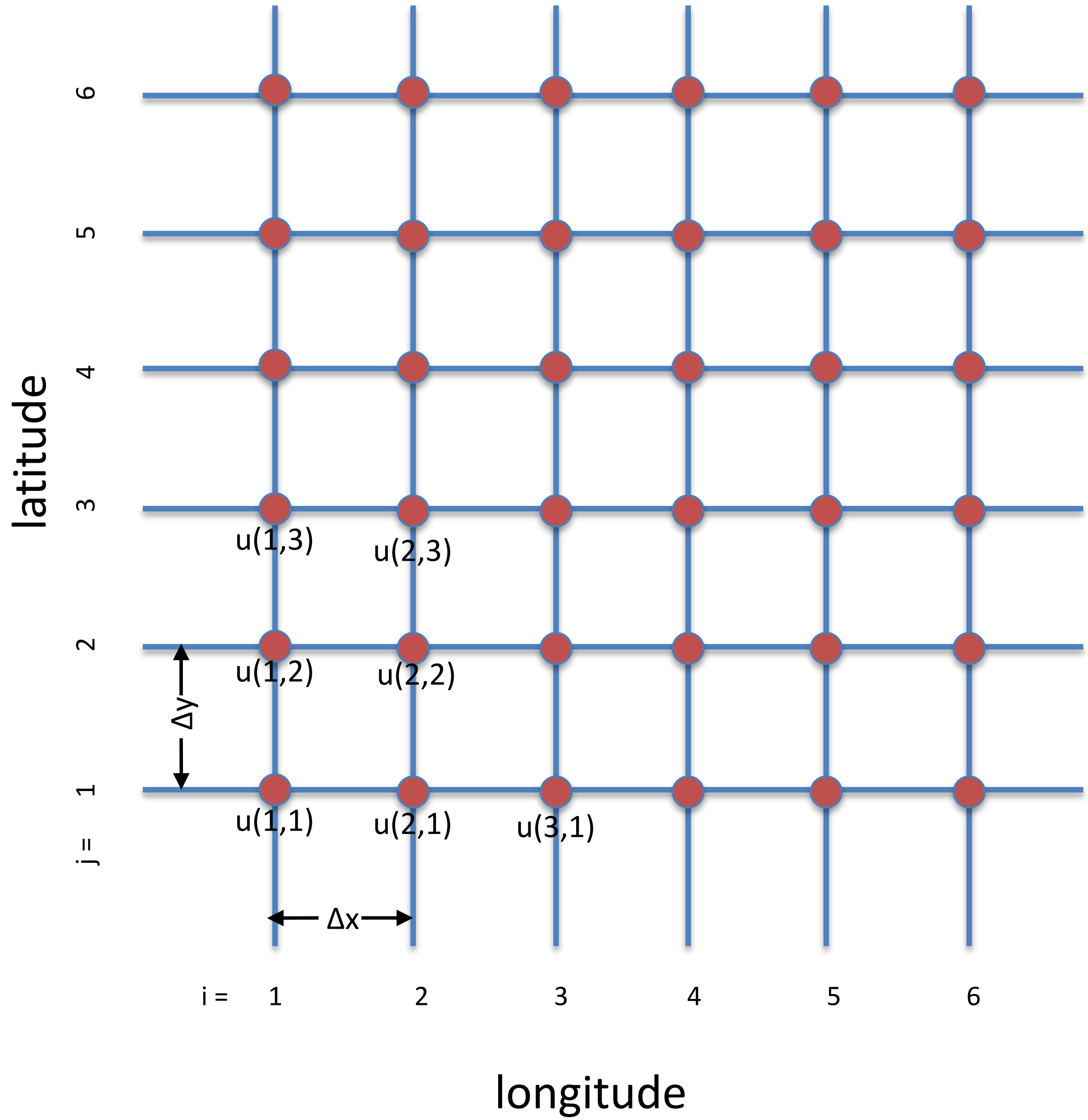


$$\frac{du}{dt}$$

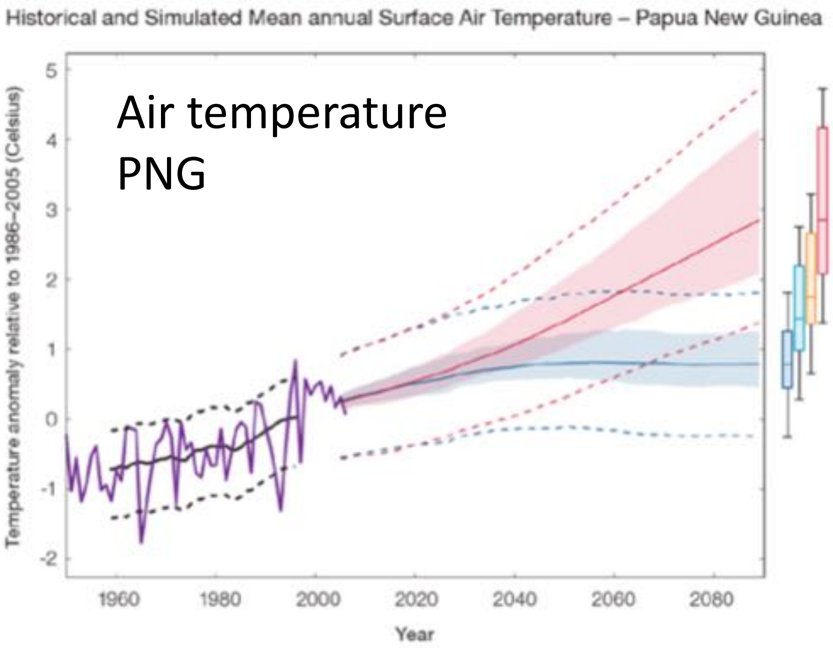


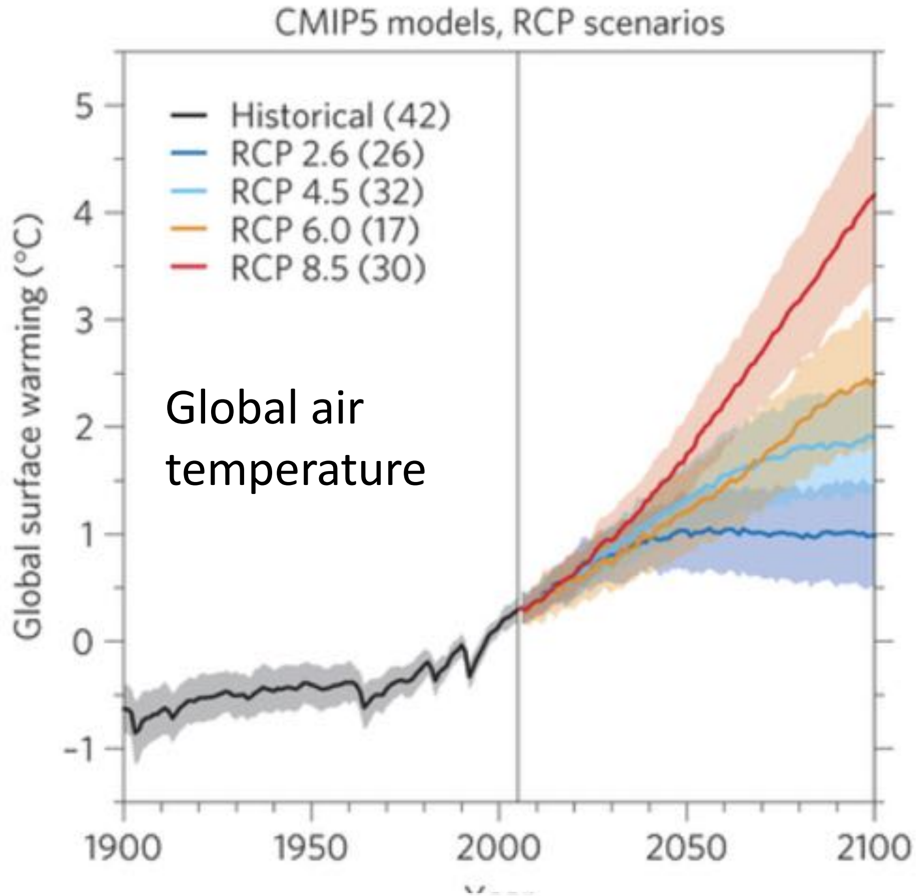
$$\frac{d^2u}{dx^2}, \qquad T\frac{du}{dx}$$

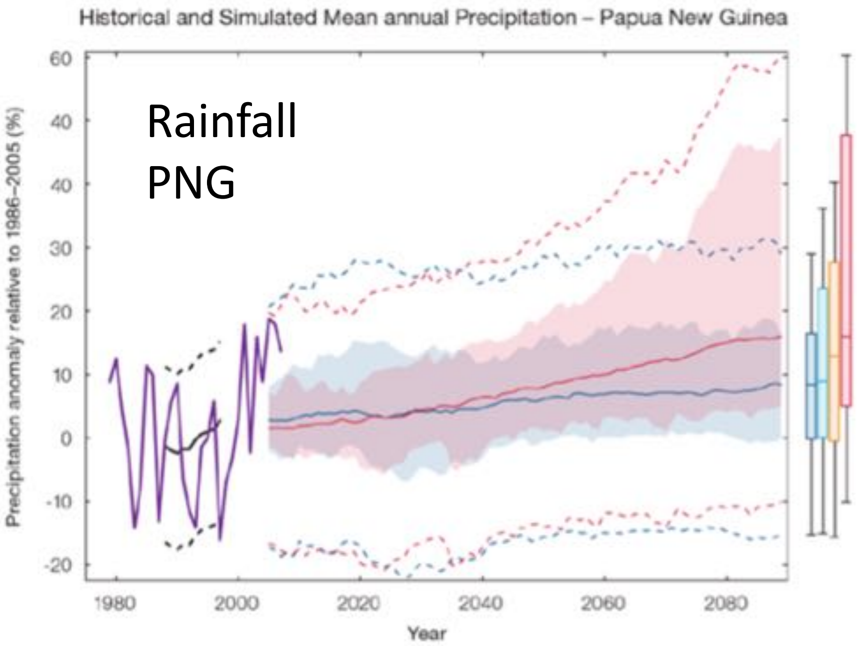
$$\frac{du}{dx} \approx \frac{u(2,1) - u(1,1)}{\Delta x}$$

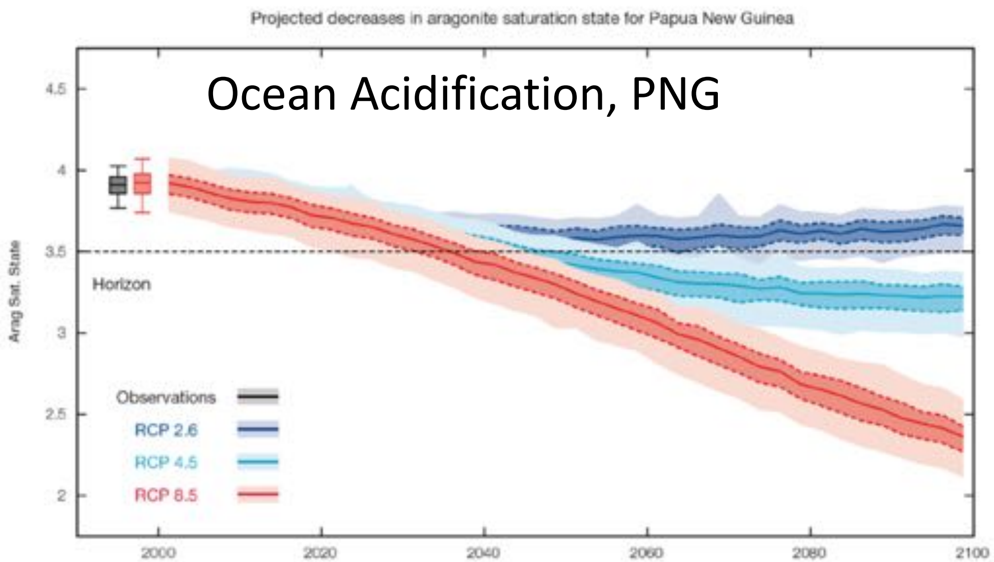


Example: Using an ocean/climate model

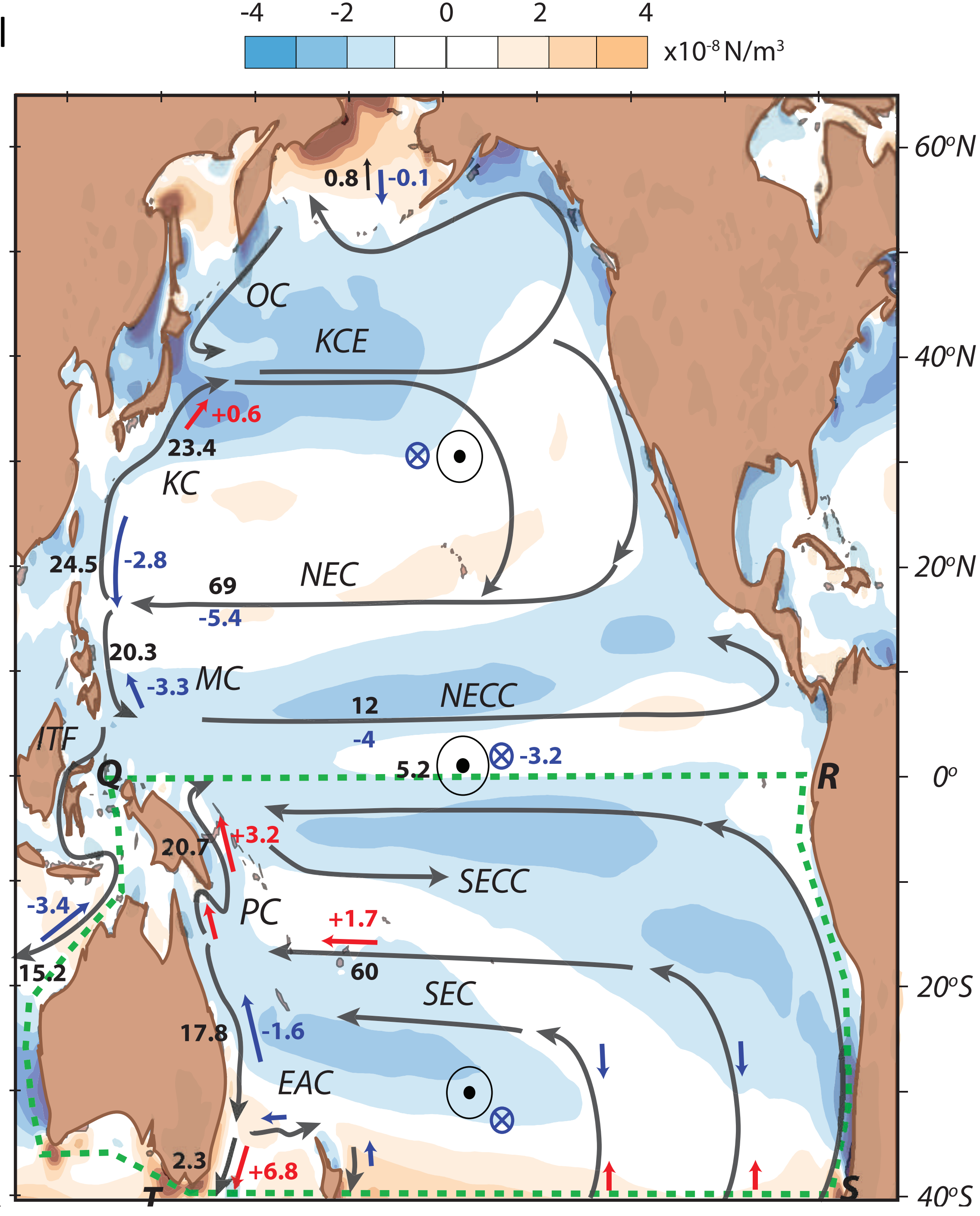








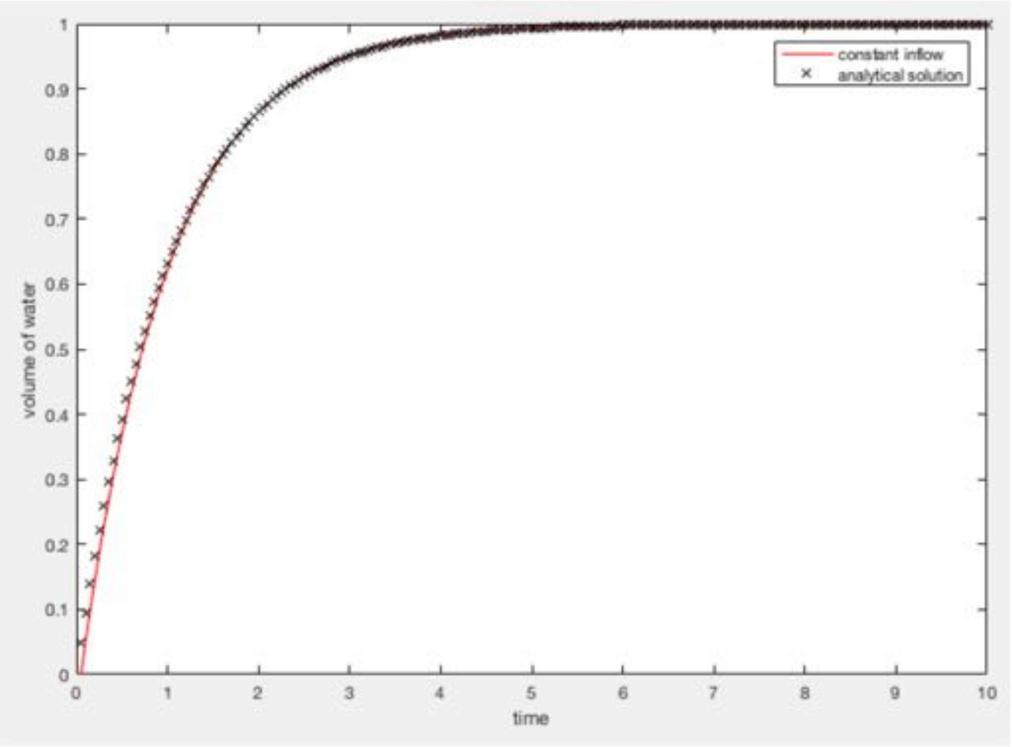
Example: Using an ocean/climate model



- Simple models can capture important features of the climate system
- Can recreate past climate change (global average) and be used to look at future changes.
- More complex models (e.g. based on Navier Stokes) are needed to resolve local features and the dynamics of the climate system
- Equations usually require numerical solution. Finite difference methods discretise space and time
- Interested in modelling the climate system or researching climate change, come talk to us at the CCRC

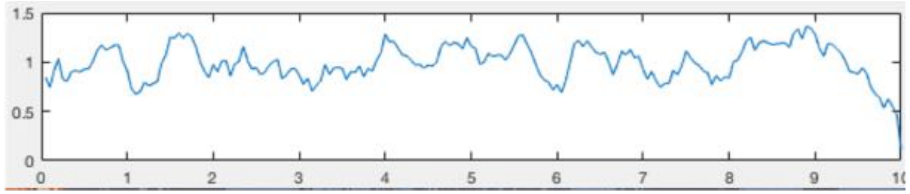
Analogue example to the energy balance model (bathtub with constant inflow and variable outflow of water)

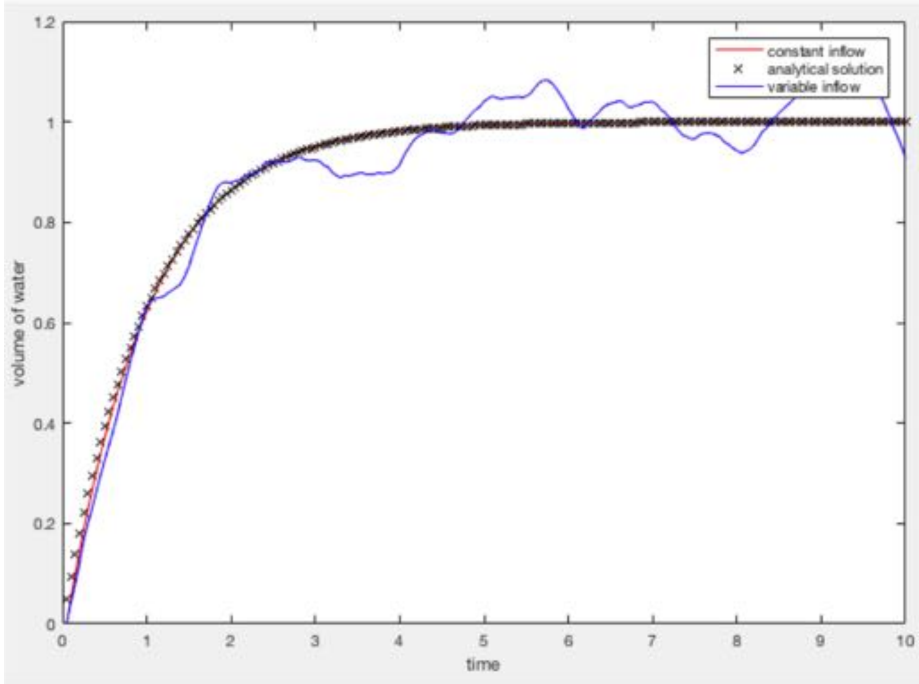
```
clear
% MATLAB code with simple finite difference solution
% consider a bathtuv with a constant inflow and an outflow that
varies
% depending on the depth (or equivalently volume) of water
%dV/dt = input - output
%where output is proportional to the volume (or depth)

inp = 1; %litre/second
N=200; % no. of timesteps
DT=0.05; %time step [seconds]
time=(1:N)*DT; % vector of times [seconds]
const=1; %constant of proportionality

V(1)=0; %initial condition; depth at t=0

% numerical Solution
for t=2:N
V(t) = V(t-1) +DT*( inp - const*V(t-1)  );
end

figure(1);clf
plot(time , V)
hold on

% Analytic solution
Vanalytic = inp - exp(-time);
plot(time,Vanalytic,'kx')
```



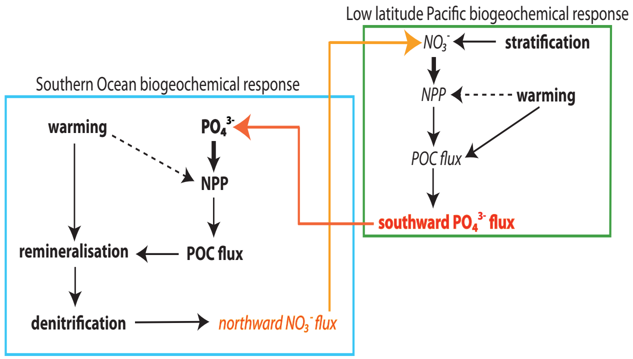
Analogue example to the energy balance model (bathtub with constant inflow and variable outflow of water)

```
%% what about a time varying input
inp2=smooth(rand(1,N),10)*2;%generate random inflow
timesereies

figure(2);clf
plot(time,inp2);

V2(1)=0; %depth at t=0

% numerical Solution
for t=2:N
V2(t) = V2(t-1) +DT*( inp2(t-1) - const*V2(t-1)  );
end
```



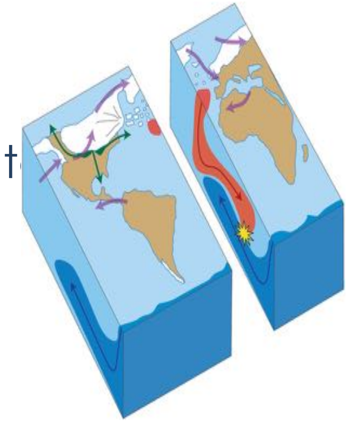


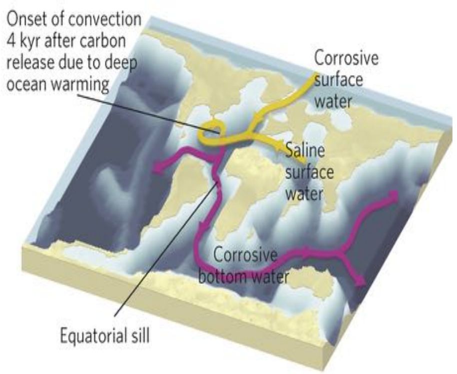
A. Prof Katrin Meissner

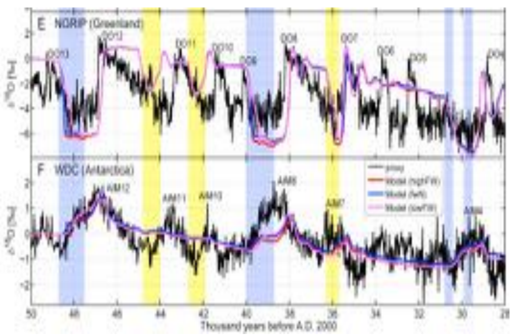


Director Climate Change Research Centre

- Climate change and variability
- Feedbacks between climat components
- Ocean circulation
- Carbon cycle
- Biogeochemical cycles
- Past climate change
- Isotopes







Prof Steven Sherwood

ARC Laureate Fellow
Deputy Director Climate Change Research Centre

Himawari 8 image showing triggering of cloud lines over Gulf of Carpentaria

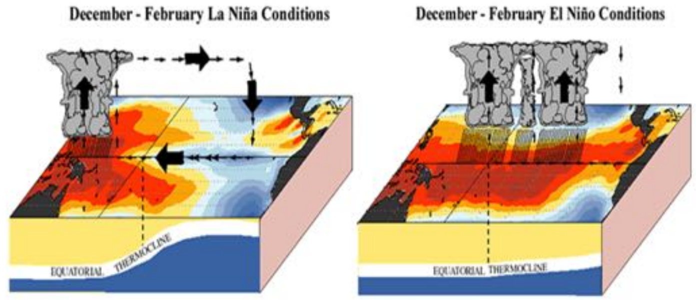
Research profile:

- Atmospheric water, cloud and convective processes
- Atmospheric radiation and thermodynamics
- Climate change and feedbacks
- Climate data analysis and homogenisation
- Heat stress and climate adaptability

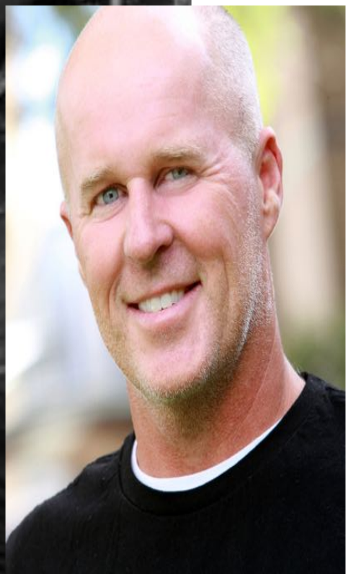
Current group topics:

- Understanding the mid-Holocene "Green Sahara"
- Low-cloud feedbacks on global temperature
- Convective triggering and persistence
- Fluctuation-dissipation approaches to cloud-climate relationships
- Aerosol impacts on precipitating clouds

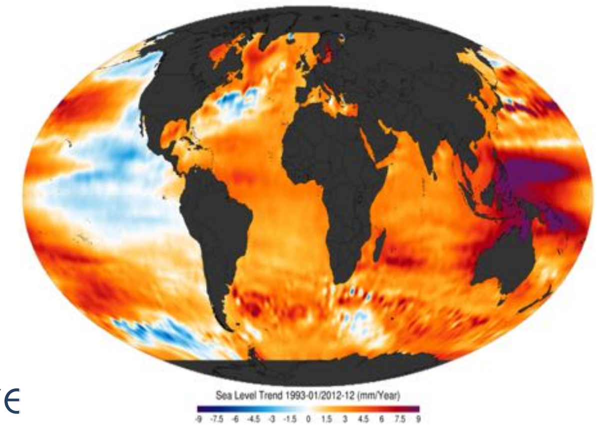
Scientia Prof Matthew England



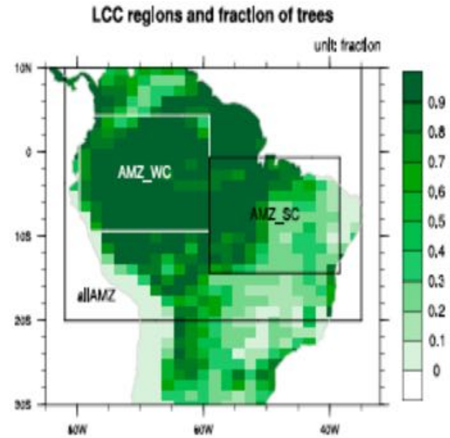
Scientia Professor of Climate Dynamics
CCRC and ARC Centre of Excellence in Climate System Science (ARCCSS)



- Antarctic climate
- The Southern Ocean
- El Niño and tropical modes
- Ocean heat uptake and sea-leve
- Ocean drivers of climate extremes (floods, drought)

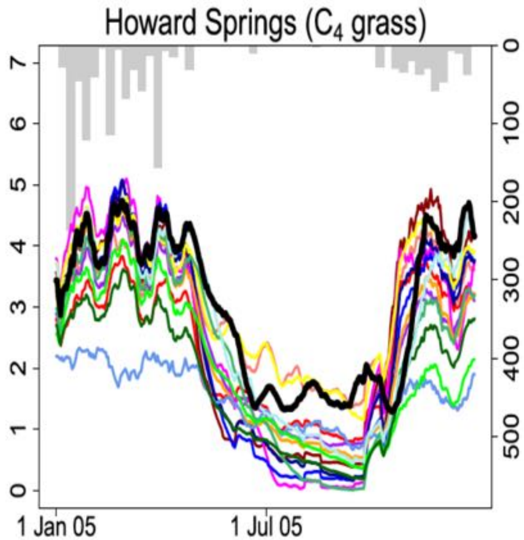


Prof Andy Pitman



Director ARC Centre of Excellence for Climate System Science (ARCCSS)
Director ARC Centre of Excellence for Climate Extremes (ARC CLEX)

- Land Surface Processes
- How the land amplifies climate extremes
- Climate and regional modelling
- Water, energy and carbon processes
- How land use change affects climate
- Use of climate models for risk assessment
- Engagement of business with climate risk

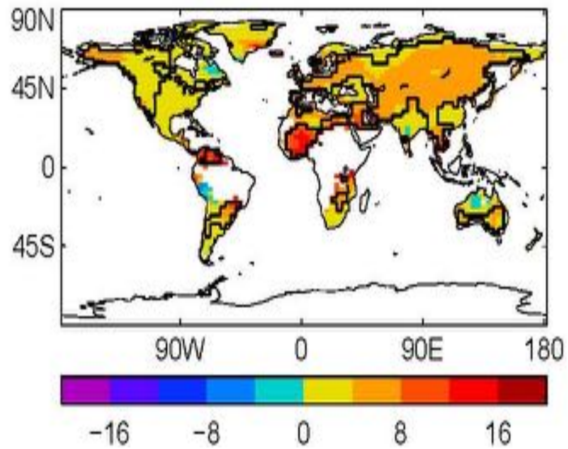


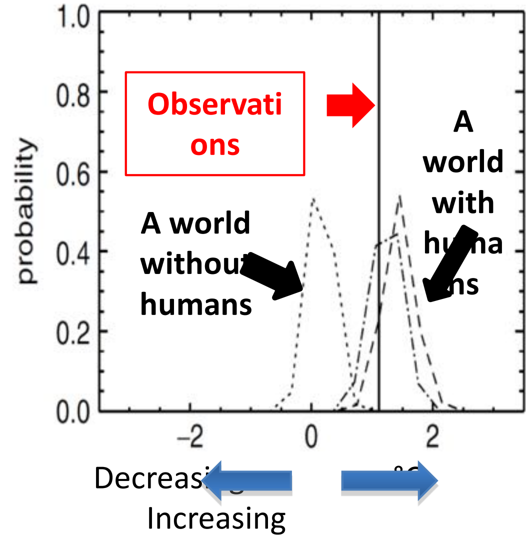
A. Prof Lisa Alexander

- Changes in the frequency and/or severity of extreme climate events have the potential to have profound societal and ecological impacts.

- Lisa's work primarily focuses on improving our understanding of observed changes in these events using multiple research tools ranging from station observations to climate model output.

- Much of her work has been focused on the creation of high quality global datasets and comparison with state of the art climate models.





Increasing trends in the hottest night of the year
– humans are to blame

A. Prof Jason Evans

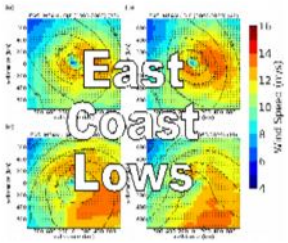
Journal of Climate Editor
Co Chair of GEWEX Hydroclimate Panel
Coordinator of CORDEX Australasia

Expertise:

- Regional Climate Models, Processes & Projections
- Water cycle over land
- Land-atmosphere interactions
- Remote sensing of land degradation

Major collaborations:

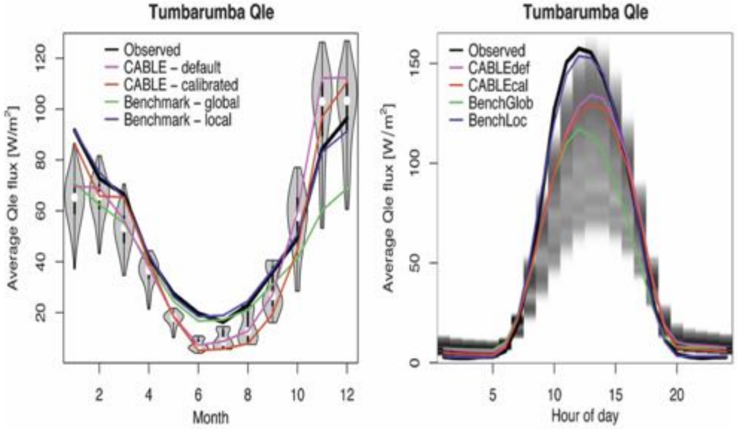
- NSW State Government
- National Environmental Science
- Program Earth System & Climate Change Hub
- ARC Centre of Excellence for Climate Extremes



A. Prof Donna Green

- Climate change and energy policy
- Climate change and human health
- Air pollution and environmental justice
- Climate adaptation for Indigenous Australians

Dr. Gabriel Abramowitz



CCRC Post Graduate Coordinator

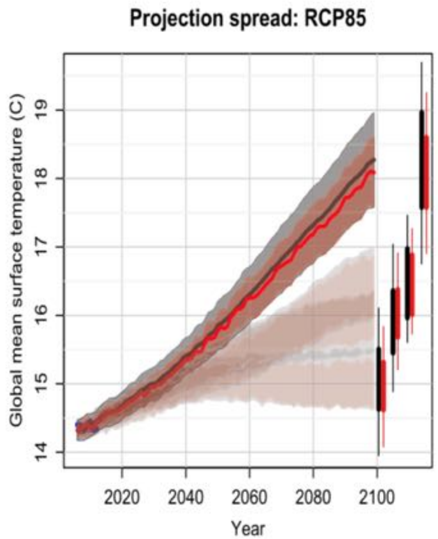
Co-chair of the GEWEX Global Land-Atmosphere System Study (GLASS) panel

Committee member for the Australian community land surface model, CABLE

Chair of the Australian Energy & Water Cycle Experiment Benchmarking Working Group

Research areas:

- Model evaluation and benchmarking (including climate, hydrological, ecological models)
- Model dependence in ensemble prediction
- Machine learning applications in climate
- Land surface model process representation



Dr. Melissa Hart

Graduate Director - ARC Centre of Excellence for Climate System Science

Developed and co-ordinated a national graduate program in climate science across 5 universities -120 PhD students

Urban Climate

- Quantification of the urban heat island magnitude
- Impact of land-use and anthropogenic activities on the climate of cities

Air Pollution Meteorology

- Synoptic and mesoscale controls on air pollution
- Air pollution impacts from prescribed burns and wildfires

Dr. Alex Sen Gupta

Senior Lecturer
BEES Postgraduate Coordinator (Thesis Examination)

Climate variability and change can dramatically effect the ocean, its ecosystems and the industries that rely on these. Related projects include:

- Understanding the effect of anthropogenic warming on the ocean circulation, temperatures and marine critters!
- Processes and drivers of marine heat waves
- Numerical simulation of tropical tuna
- Climate model evaluation and climate projections