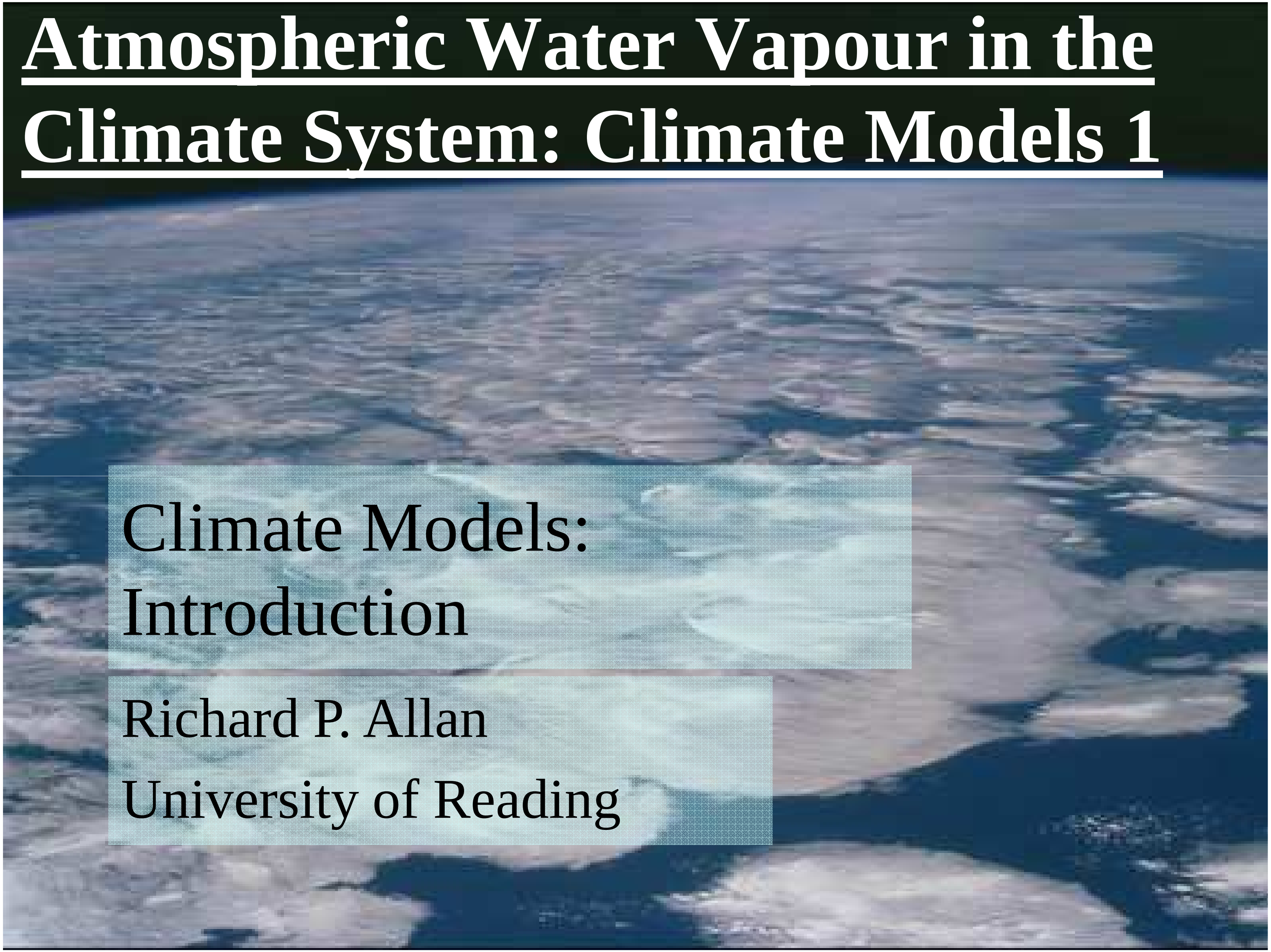
Atmospheric Water Vapour in the Climate System: Climate Models 1



Climate Models: Introduction

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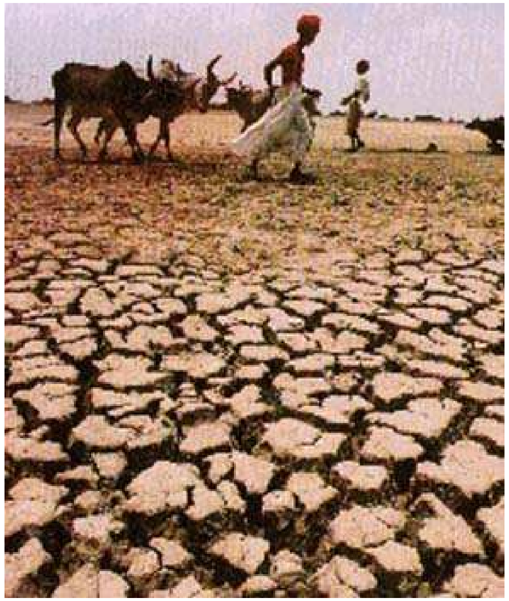
Atmospheric Water Vapour in the Climate System: Climate Models 1

- Introduction and Motivation
- The Climate System and The Global Water Cycle
- Fundamentals: Simple Climate Models
- The beginnings of Numerical Weather Prediction
- …and the end of long term prediction?
- Climate models, grid boxes
- Parametrization
- History and Furture of climate models

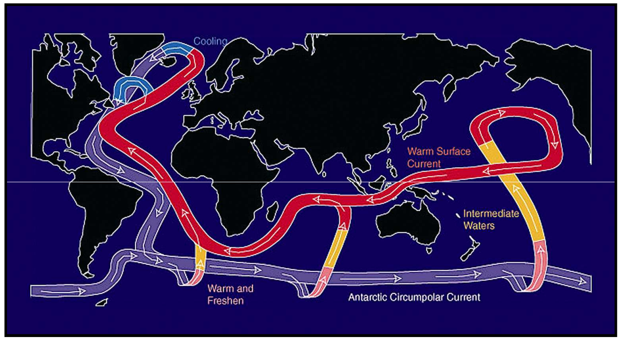
Introduction / Motivations

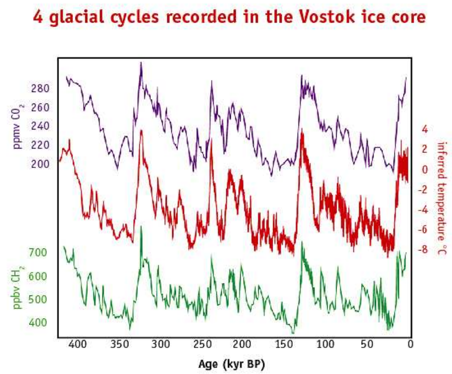


- The importance of climate change on past societies (e.g. Jared Diamond: Collapse)
- Current and future climate change will impact an already stressed world
- The water cycle is crucial in influencing the trajectory of climate change and in determining the likely impacts upon society
- The complexity of the system demands sophisticated representation of the processes likely and even unlikely to influence climate; water vapour is central to some of the most important processes

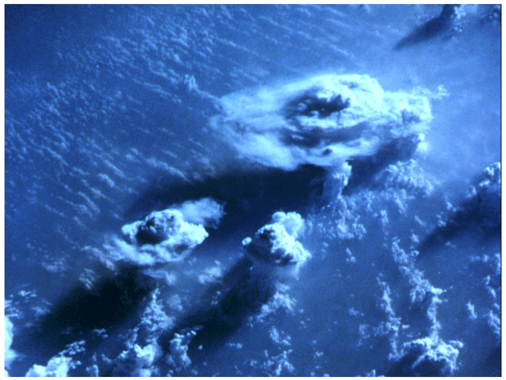
Climate consists of a continuum of time and space scales -

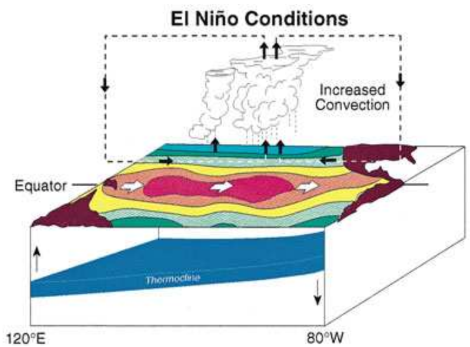
from days to months, years, decades and millennia

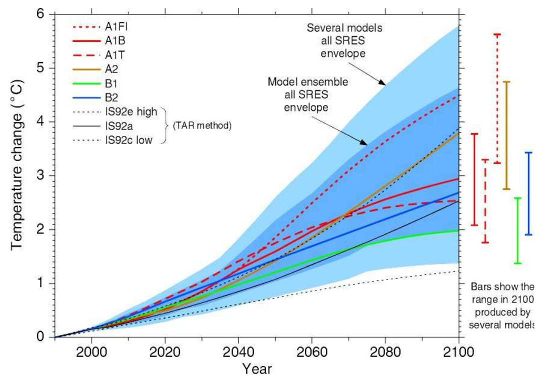




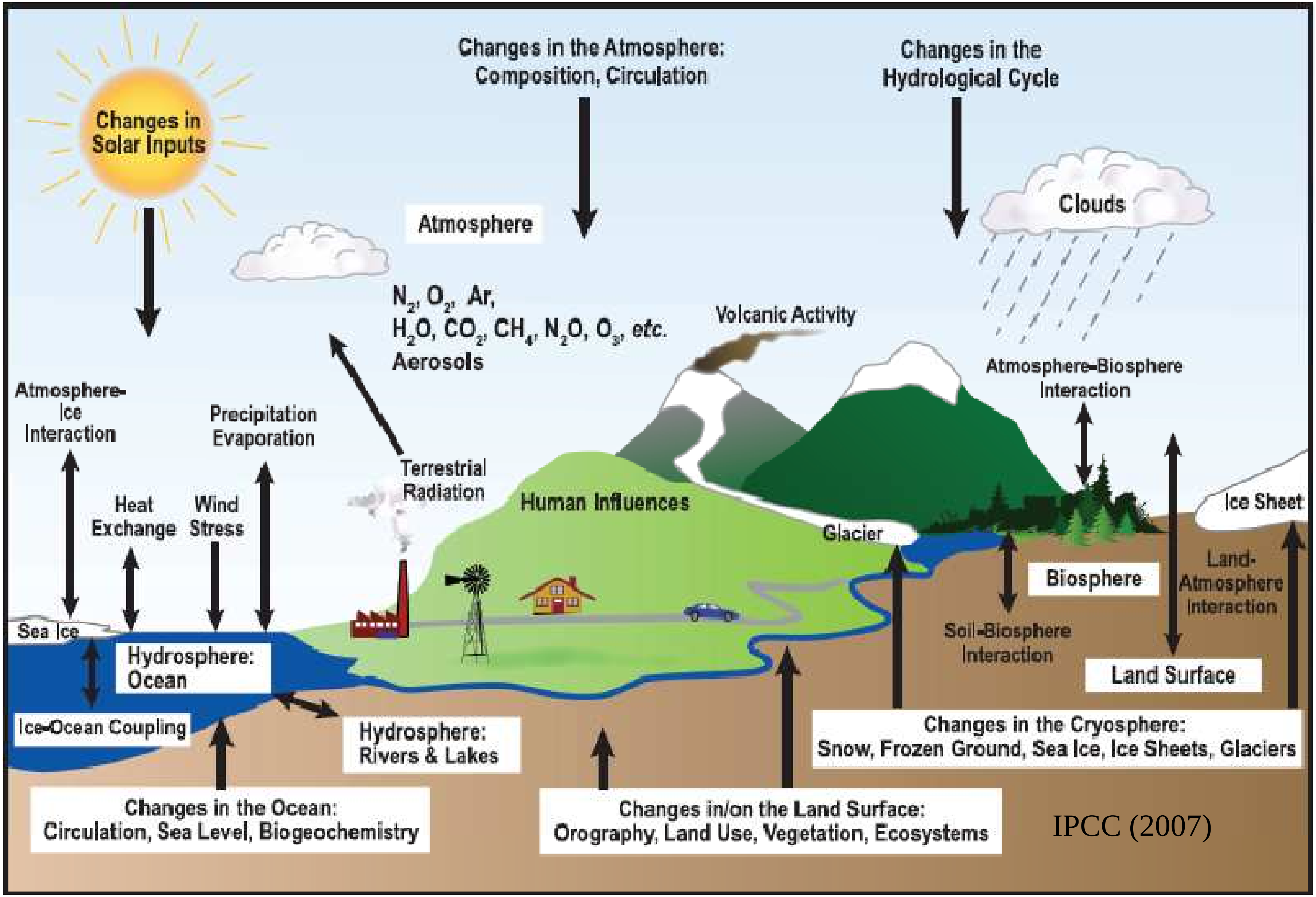
from local to regional, continental and global

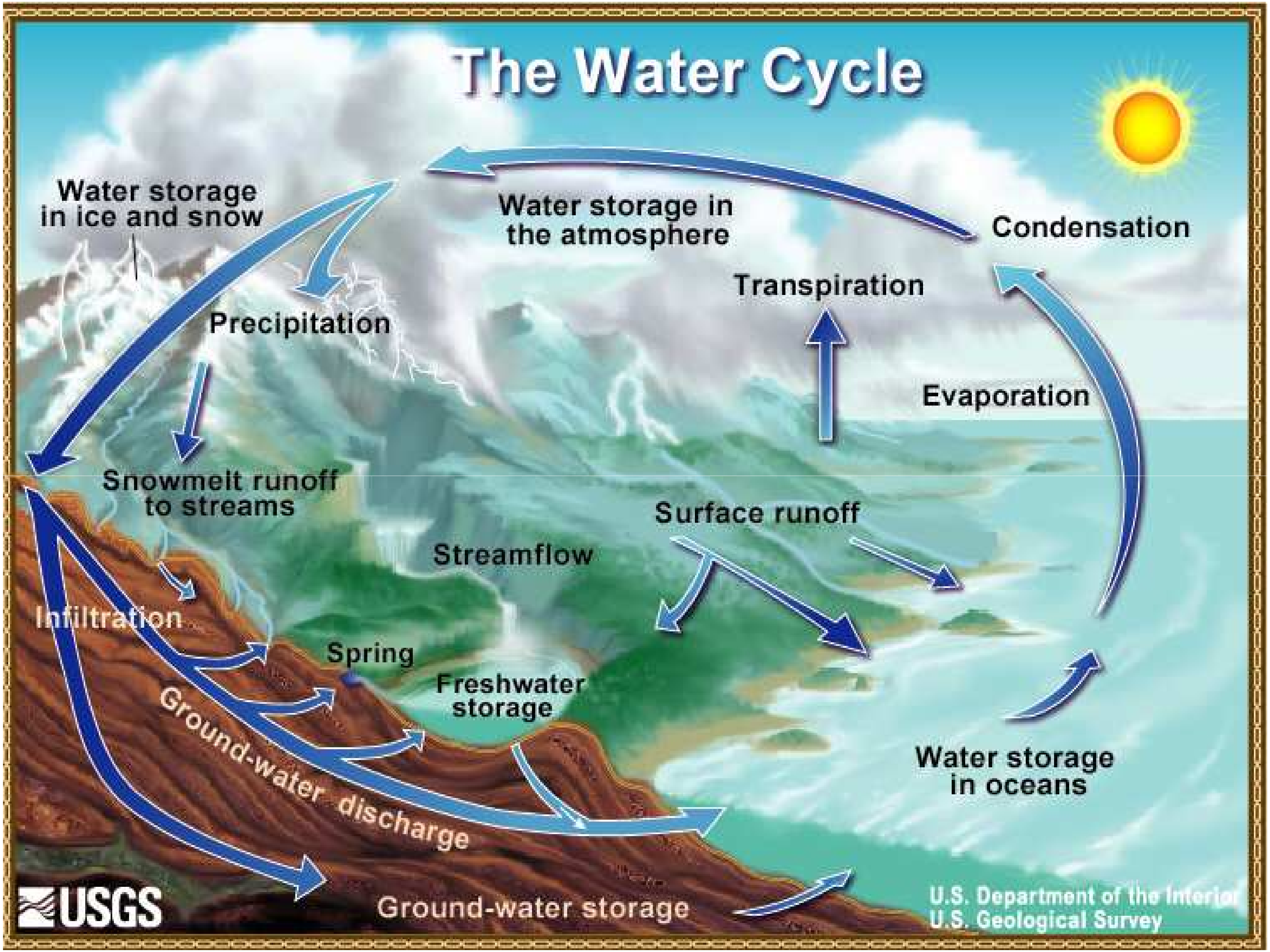






The Climate System





The Water Cycle
Water storage in ice and snow
Water storage in the atmosphere
Condensation
Transpiration
Precipitation
Evaporation
Snowmelt runoff to streams
Surface runoff
Streamflow
Infiltration
Spring
Freshwater storage
Ground-water discharge
Water storage in oceans
USGS
Ground-water storage
U.S. Department of the Interior
U.S. Geological Survey

Climate Models: Terminology

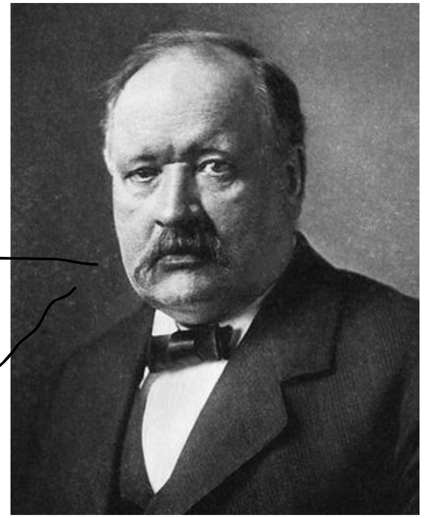
- Climate scientists refer to climate models as “GCMs”
- This originally meant General Circulation Model
- These days it usually means Global Climate Model
- We also have RCMs – Regional Climate Models
- An AGCM is an “Atmospheric GCM”
- An AOGCM is an “Atmosphere-Ocean GCM”
- “Earth System Model” is a recent term for a complex climate model
- An NWP model is Numerical Weather Prediction model
- Reanalyses are NWP models using a fixed model and data assimilation system to estimate the 3D state of the atmosphere
- Climate models: e.g., CCCMA, CNRM_CM3, GFDL_CM2.1, GISS_E_R, IAP_FGOALS, INMCM3, IPSL_CM4, MIROC_hires, MIROC_medres, MRI_CGCM2, NCAR_CCSM3, NCAR_PCM1, HadAM3, HadGEM1
- Model Intercomparison Projects, the MIPs:
  - AMIP, CMIP, CFMIP, SMIP, ENSIP, PMIP…

What is a model?

- – *"A representation of a system that allows for investigation of the properties of the system and prediction of future outcomes."*
- – **"Model**, **models**, or **modelling** may refer to: a pattern, plan, representation, or description designed to show the structure or workings of an object, system, or concept" (Wikipedia).

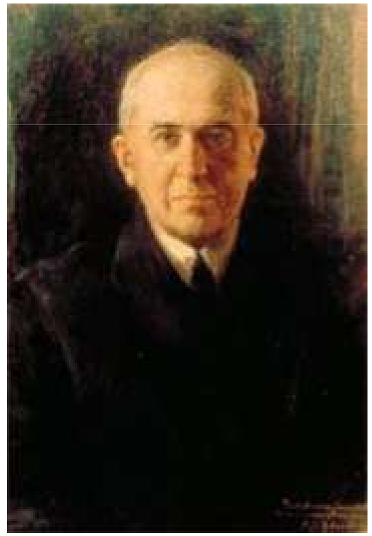
- A simple model might include estimating the temperature of the surface based on the incoming solar energy, heat capacity and many assumptions
  - – Other examples: business model, economic model, engineering, etc

Simple models?



$$\Delta F = \alpha \ln(C/C_0)$$

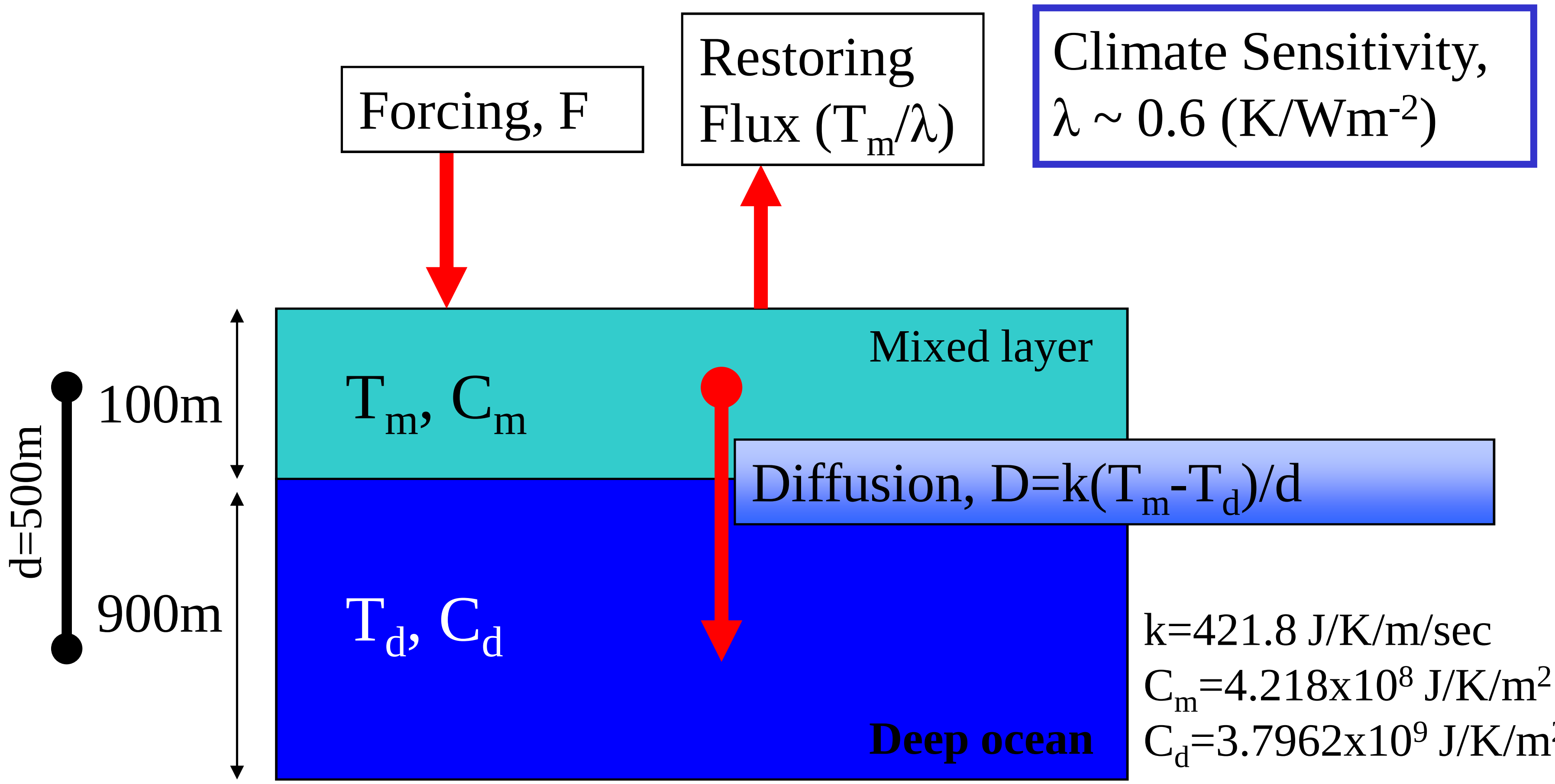
- Svente Arrhenius estimated the effect of changes in "carbonic acid" (CO_2) on the ground temperature
- Milankovitch: estimated surface temperature based on calculated solar radiation changes
- Simple models are good for simple systems; many aspects of the Earth's climate system are not simple….



How do we predict climate change?

- Need to know what processes are important for determining the present day and past climate change
  - FORCINGS (e.g. solar output)
  - FEEDBACKS (e.g. ice-albedo response)
- How will forcings change in the future?
- Will ocean/atmosphere processes amplify or retard this forcing of climate?

A Simple Climate Model



$k=421.8$ J/K/m/sec

$C_m=4.218\text{x}10^8$ J/K/m^2

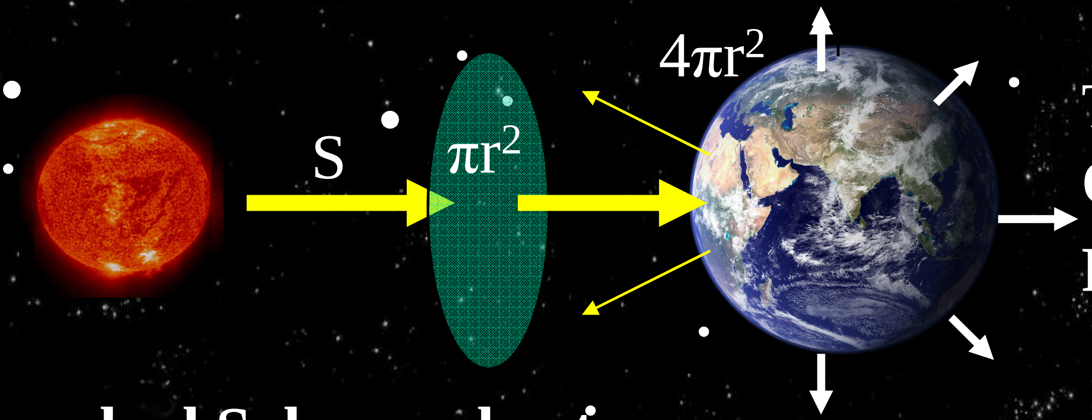
$C_d=3.7962\text{x}10^9$ J/K/m^2

$dT_d/dt=D/C_d$; $dT_m/dt=(F-D-T_m/\lambda)/C_m$

T is temperature anomaly (K)

C is heat capacity J/K/m^2

Earth's Radiation balance

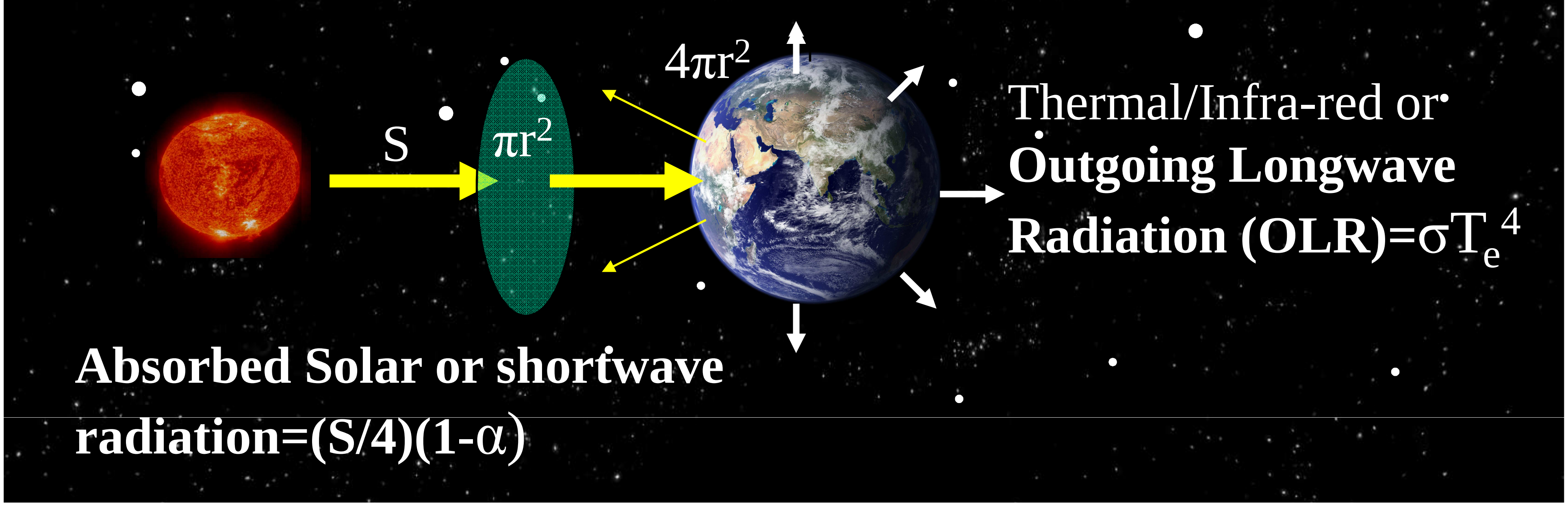


Thermal/Infra-red or **Outgoing Longwave Radiation (OLR)=σT_e^4**

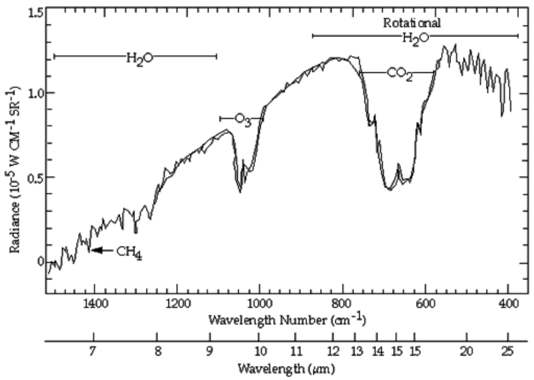
Absorbed Solar or shortwave radiation=(S/4)(1-α)

The Driving Force for Climate

Earth's Radiation balance

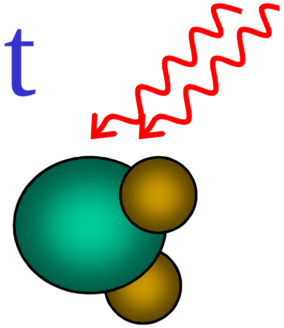


- There is a balance between the absorbed sunlight and the thermal/longwave cooling of the planet
- $(S/4)(1-\alpha)=\sigma T_e^4$, $S \sim 1366\ Wm^{-2}$, $\alpha \sim 0.3$, $OLR \sim 239\ Wm^{-2}$
- How does it balance? Why is the Earth's average temperature ~15^{o}C?



H_2O N_2O CO_2 HCFCs O_3 CH_4

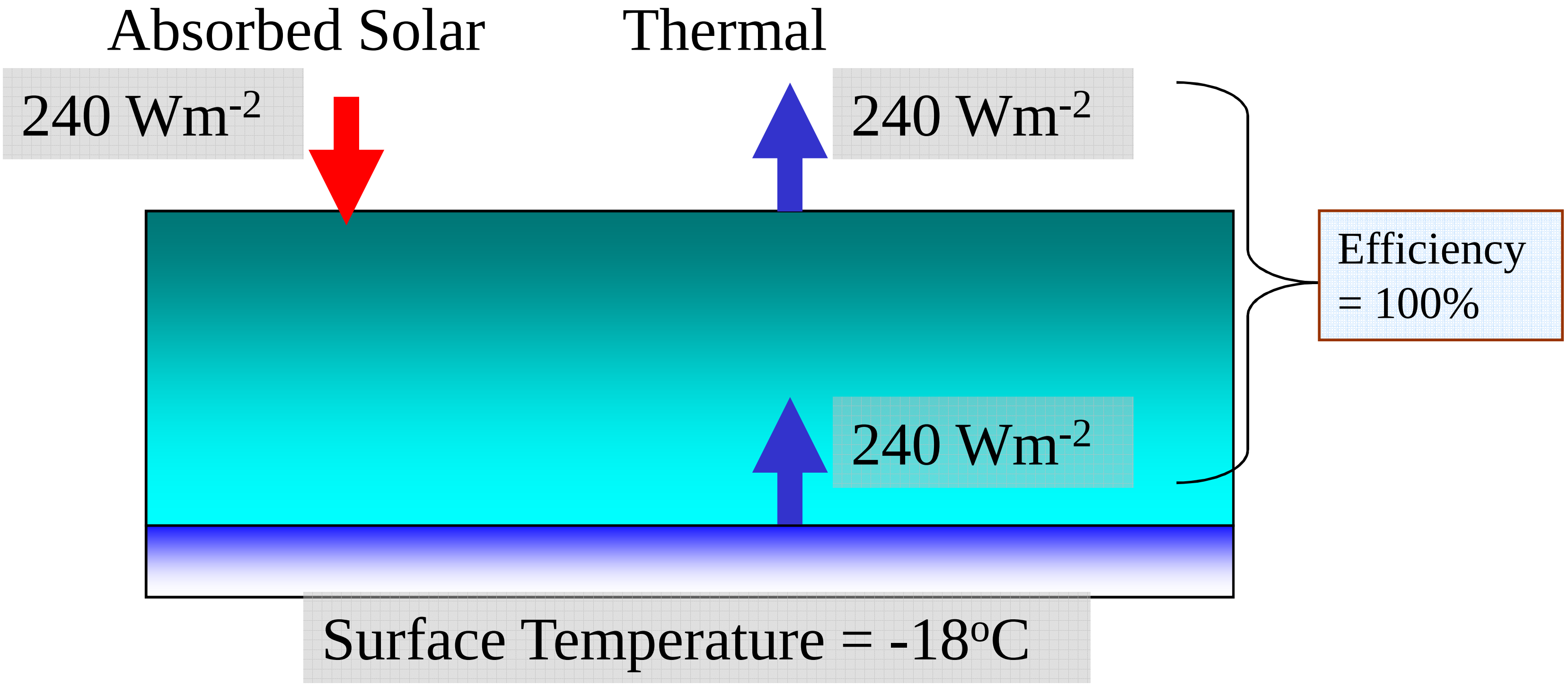
The Greenhouse Effect



- The physical structure of molecules determines which wavelengths of electromagnetic radiation may be absorbed/emitted e.g. through vibration, rotation, spin, electron transitions, etc
- The water molecule is particularly versatile in its absorption/emission properties
- Radiation absorbed by molecules is re-emitted at the local temperature, in all directions
- Greenhouse gases effectively reduce the efficiency of Earth's ability to cool through thermal radiative emission to space
- To balance the absorbed solar radiation, Earth's temperature has to be sufficient to combat this radiating inefficiency to generate the necessary outgoing longwave radiation

What would the Earth be like without a greenhouse effect?

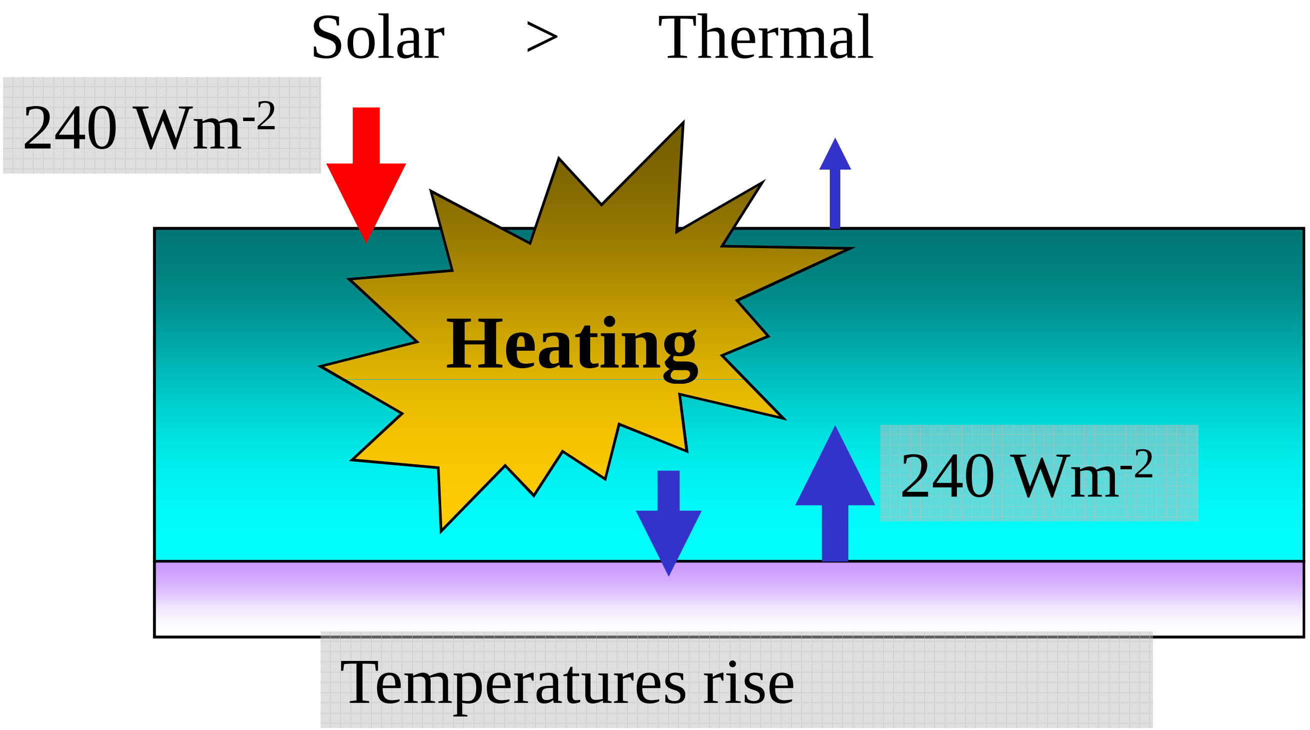
Earth's global average energy balance: no atmosphere



$$(1-\alpha)S_o/4 = \sigma T_S^4$$

$S_o \sim 1366\ Wm^{-2}$, $\alpha \sim 0.3$

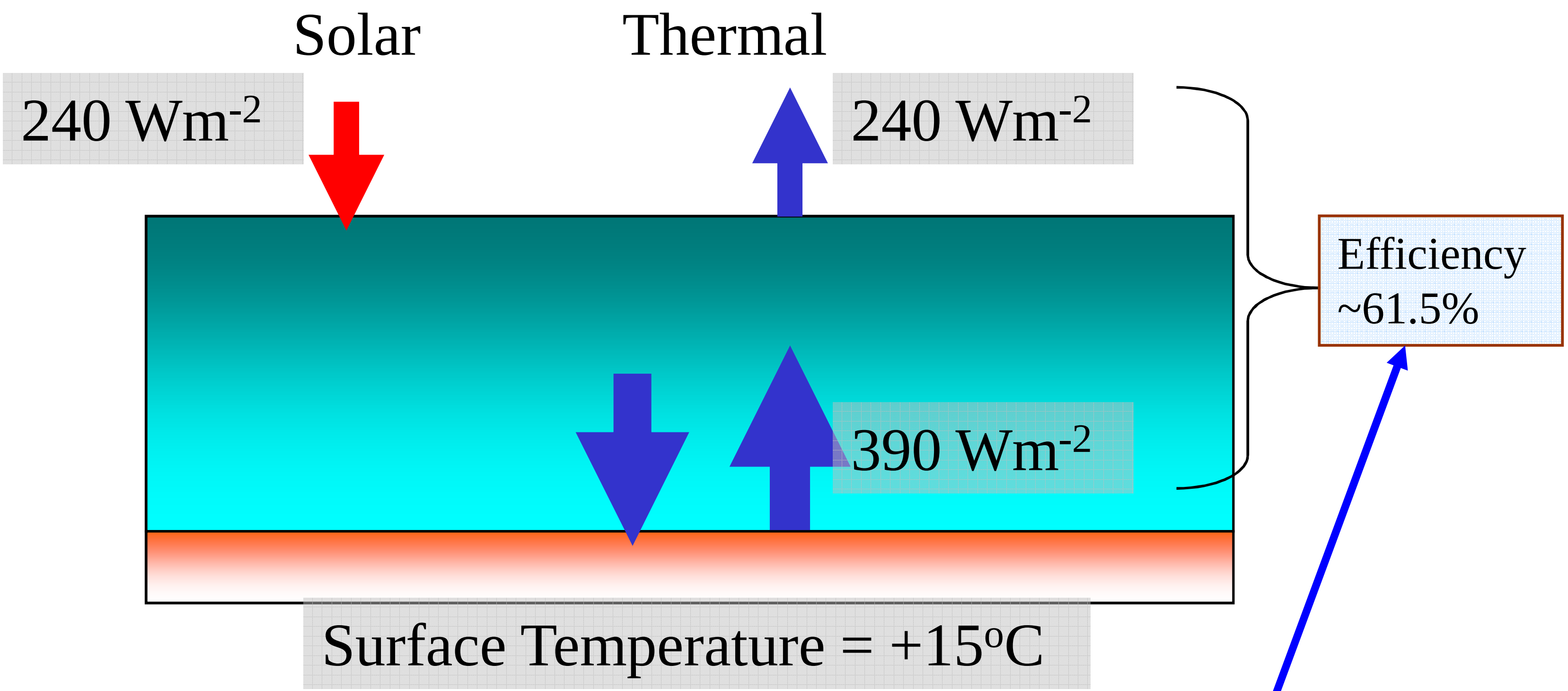
Earth's global average energy balance: add atmosphere



$$(1-\alpha)S_o/4 \neq \sigma T_S^4$$

$S_o \sim 1366\ Wm^{-2}$, $\alpha \sim 0.3$

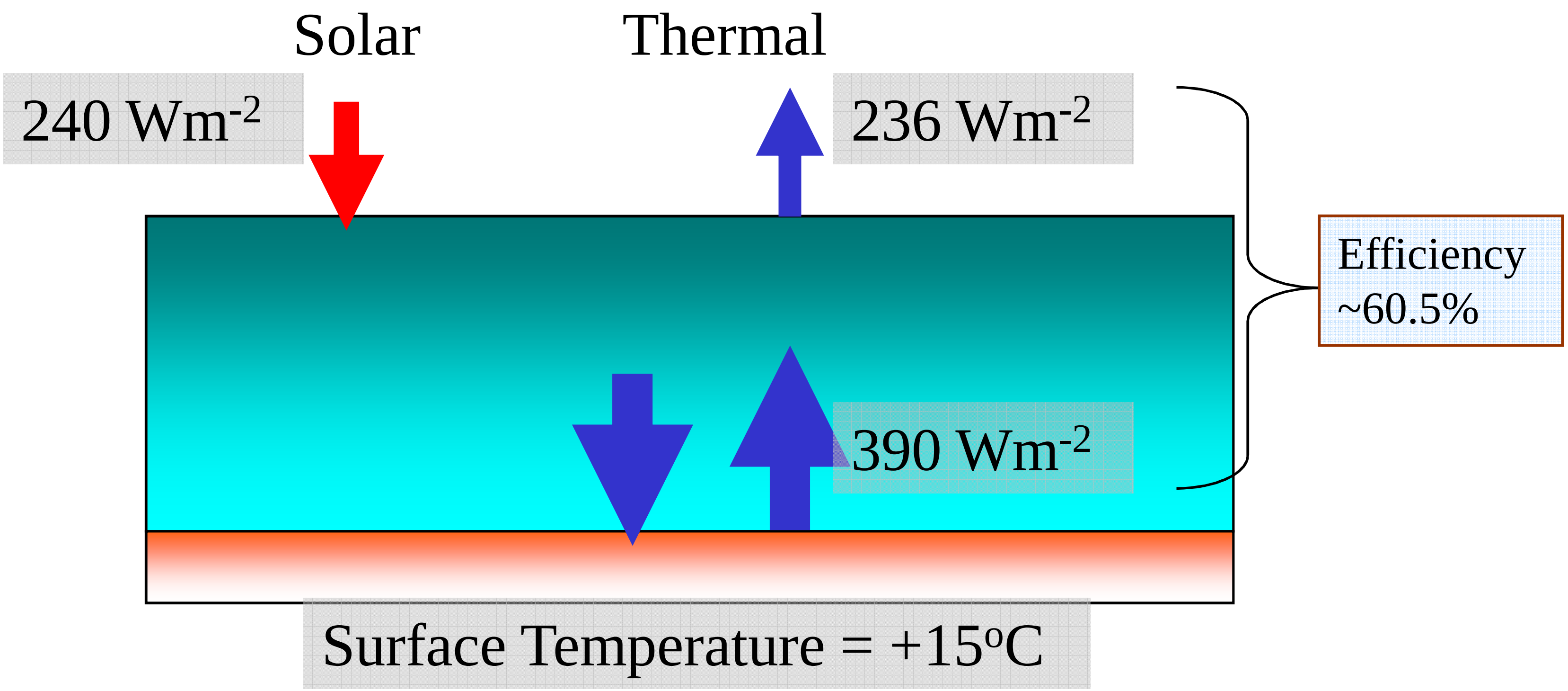
Earth's global average energy balance: present day



$$(1-\alpha)S_o/4 = \sigma T_E^4$$

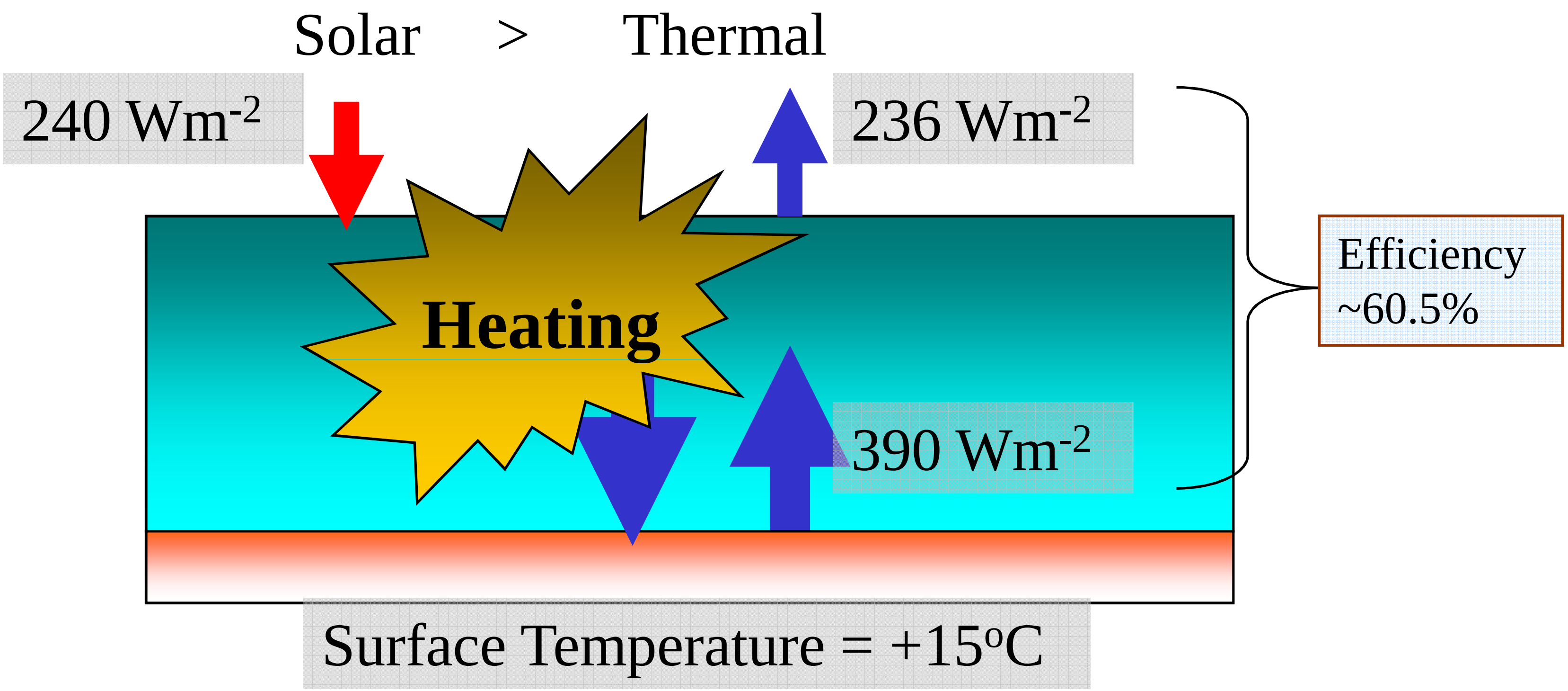
Radiating Efficiency, or the inverse of the Greenhouse Effect, is strongly determined by water vapour absorption across the electromagnetic spectrum

Now introduce a radiative forcing (e.g. $2xCO_2$)



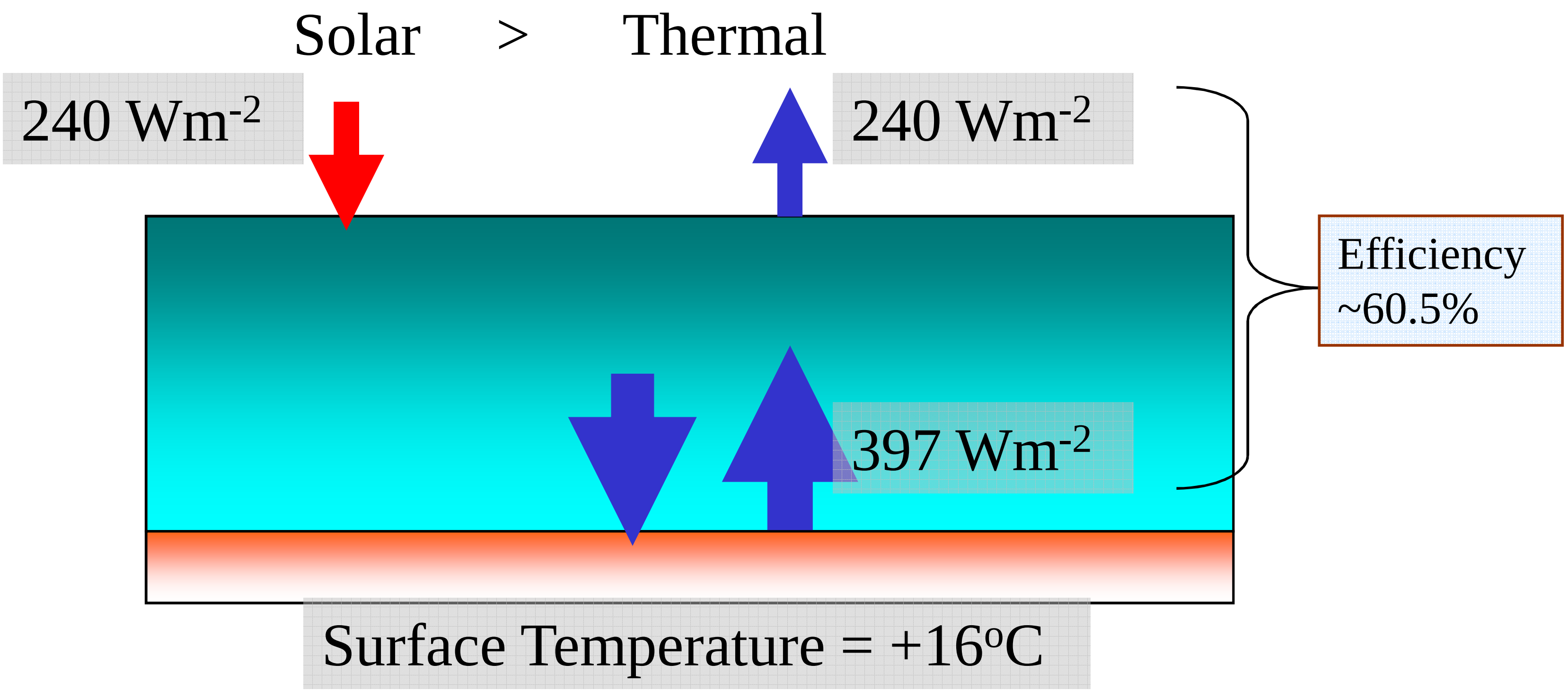
$S_o \sim 1366\ Wm^{-2}$, $\alpha \sim 0.3$

Now introduce a radiative forcing (e.g. $2xCO_2$)



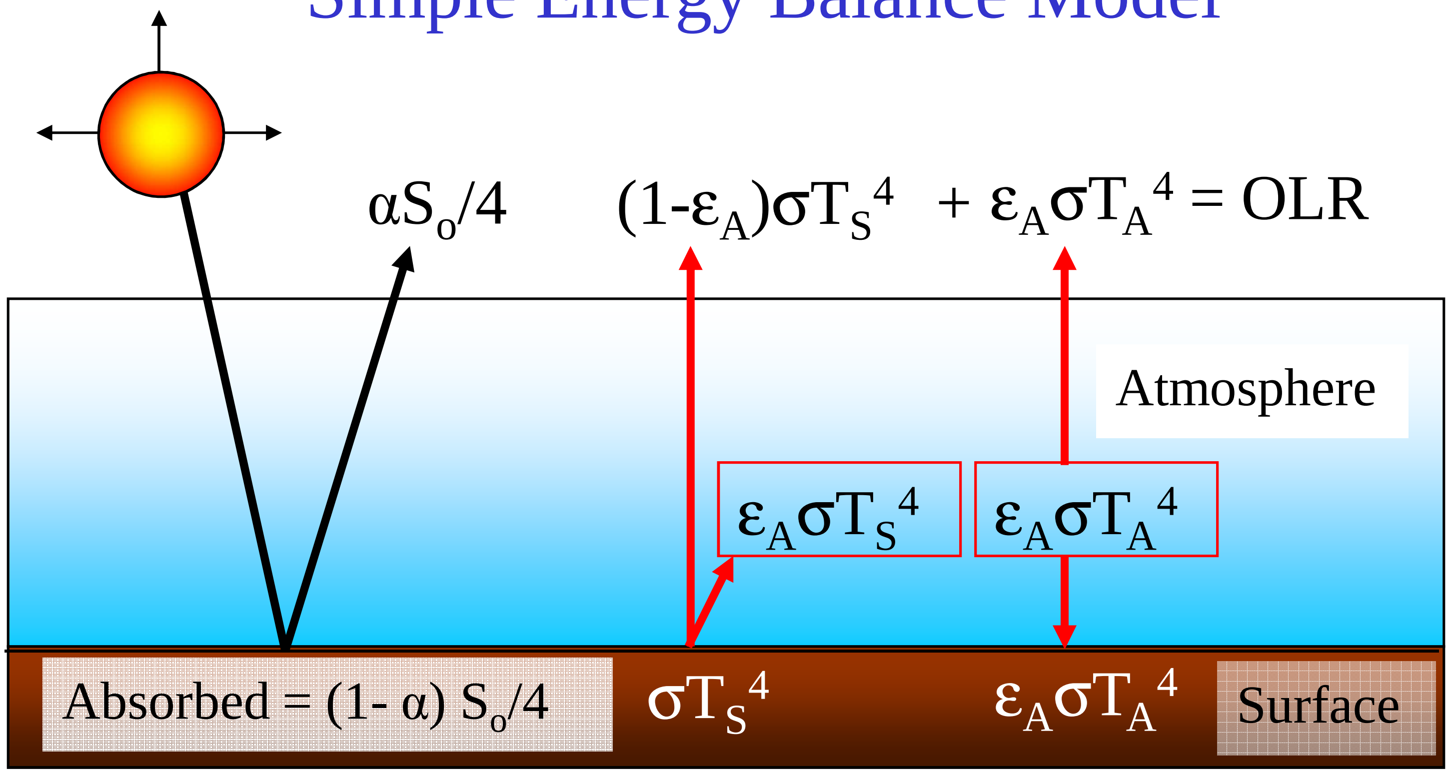
$S_o \sim 1366\ Wm^{-2}$, $\alpha \sim 0.3$

New global temperature



The $2xCO_2$ increased temperature by about 1ºC but this is without considering the response of the system including, crucially, feedbacks involving water vapour.

Simple Energy Balance Model



1) What is the effective emission temperature of the Earth?
2) What is the energy balance at:
   a) The surface?
   b) The atmosphere?
3) What are the effective surface and atmospheric temperatures?

Assume S_o=1366 Wm^{-2}; $\alpha = 0.3$; ε_A=0.8 (σ=5.67x$10^8 Wm^{-2}K^{-4}$)

Radiative-convective equilibrium

If we assume that only radiative processes are operating, the equilibrium surface temperature is very high, tropospheric temperatures very low and the profile is strongly superadiabatic*.

In reality, convection removes heat from the surface, warms the atmosphere and adjusts the lapse-rate towards that observed#.

From the classic paper by Manabe and Wetherald, JAS, 1967

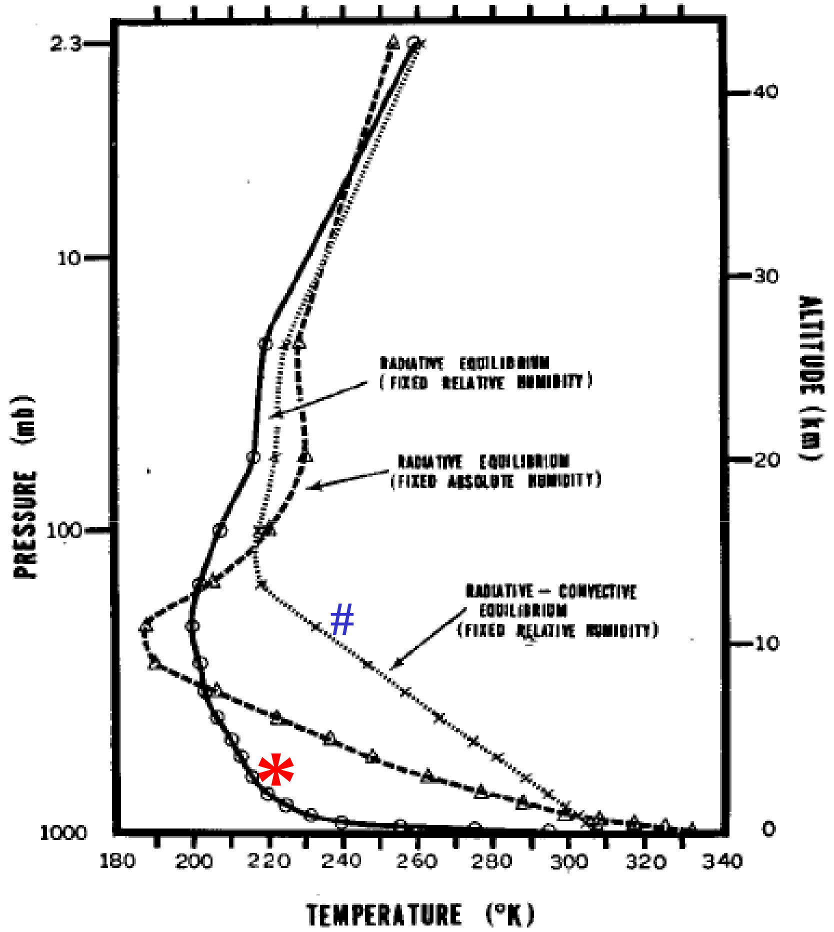
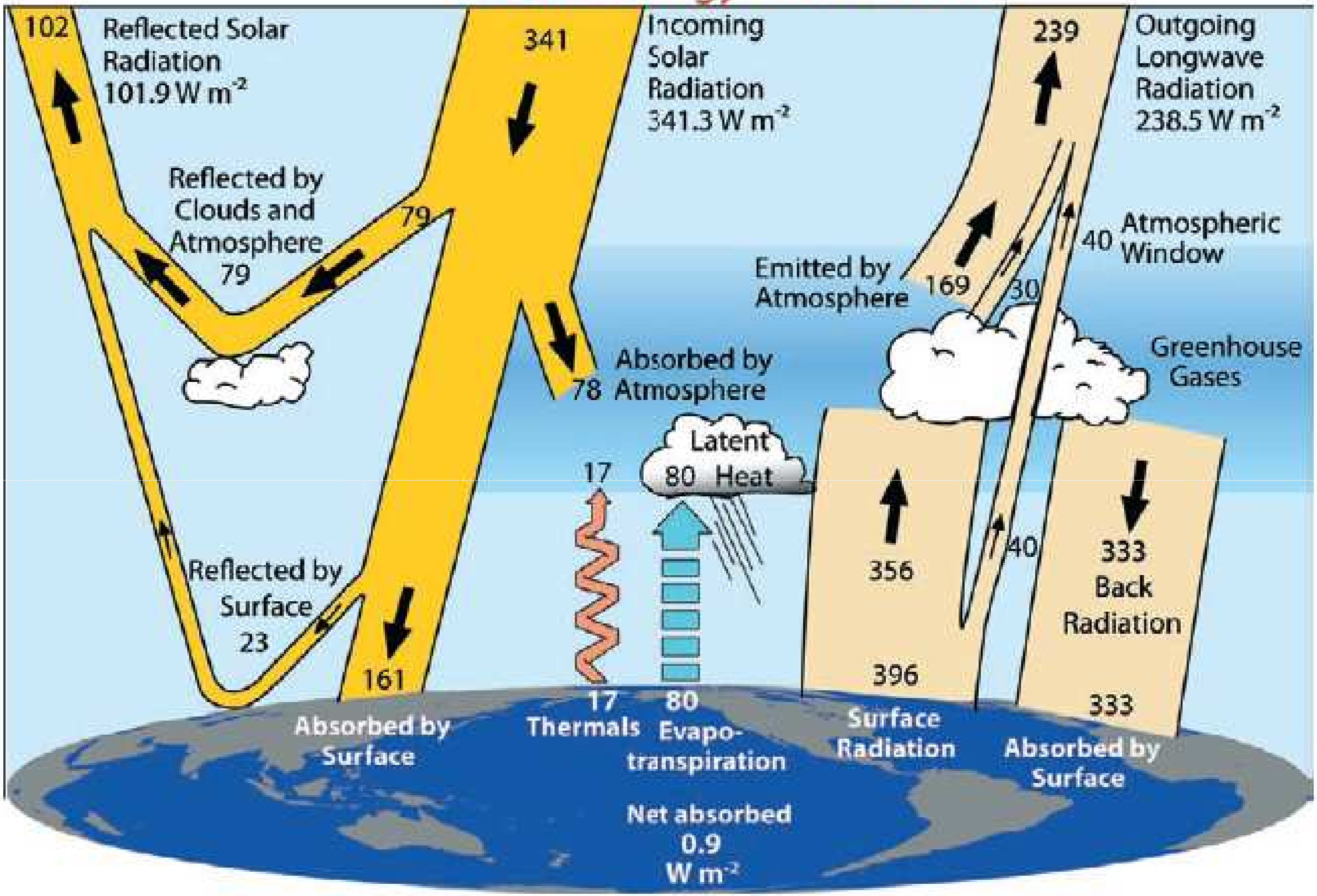


Fig. 5. Solid line, radiative equilibrium of the clear atmosphere with the given distribution of relative humidity; dashed line, radiative equilibrium of the clear atmosphere with the given distribution of absolute humidity; dotted line, radiative convective equilibrium of the atmosphere with the given distribution of relative humidity.

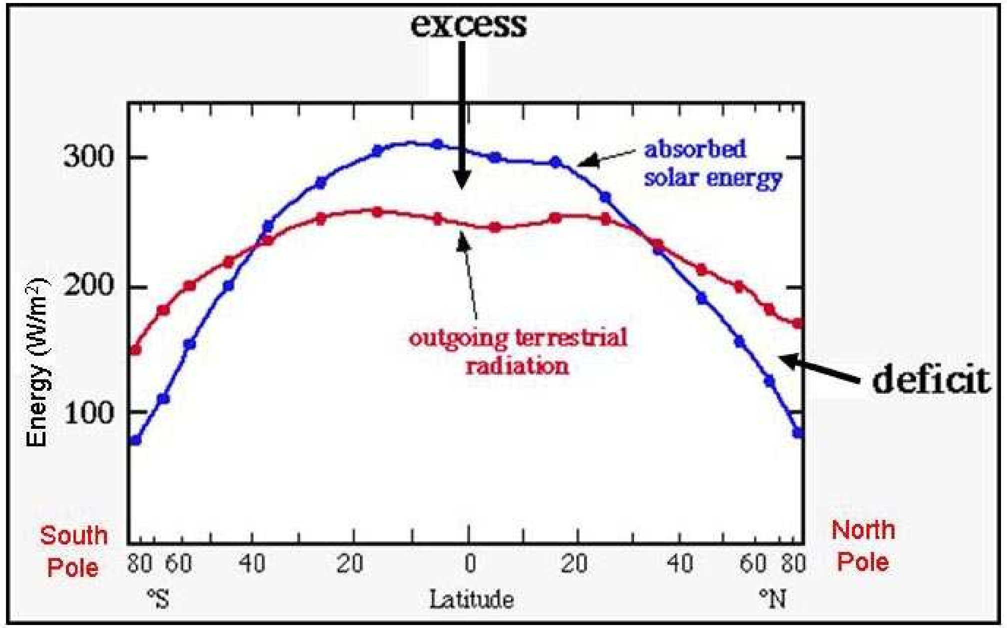
Global Energy Flows W m-2



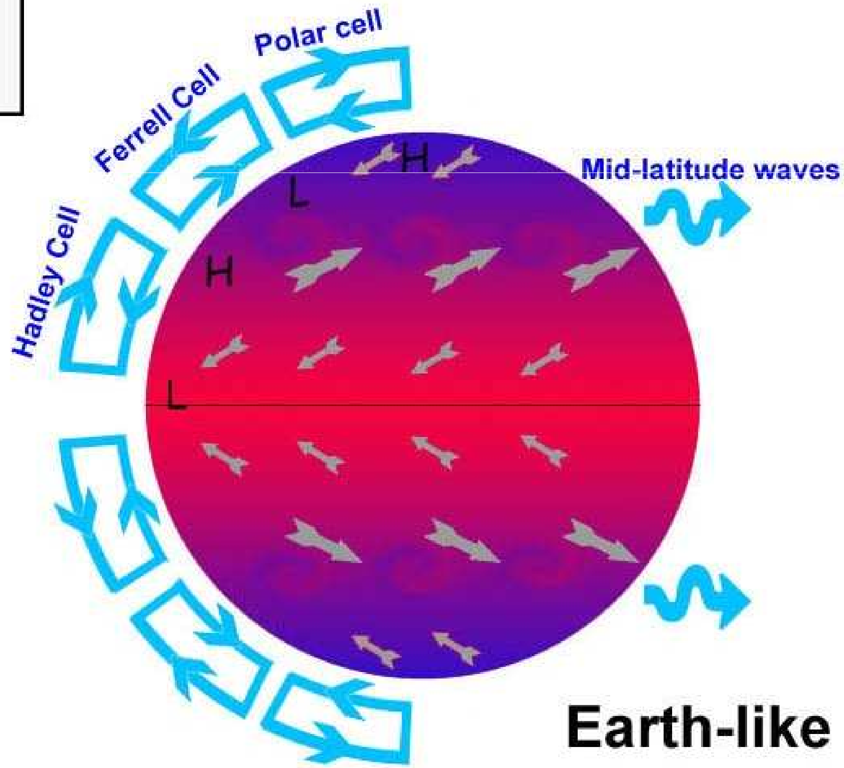
Trenberth et al. (2009)

However;

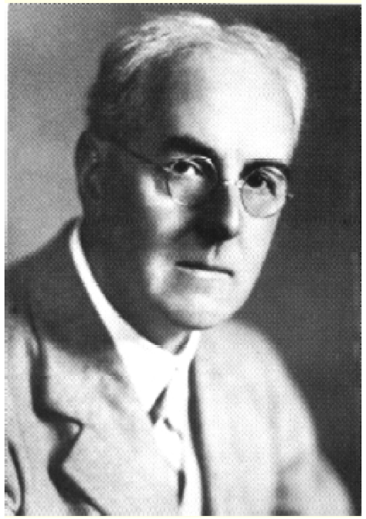
Radiative-convective equilibrium is not the whole story, because the Earth is a sphere that is heated non-uniformly



Radiative imbalances between the surface and the atmosphere, and between the tropics and polar regions, together with the planet's rotation, drive convection and the general circulations of the atmosphere and oceans

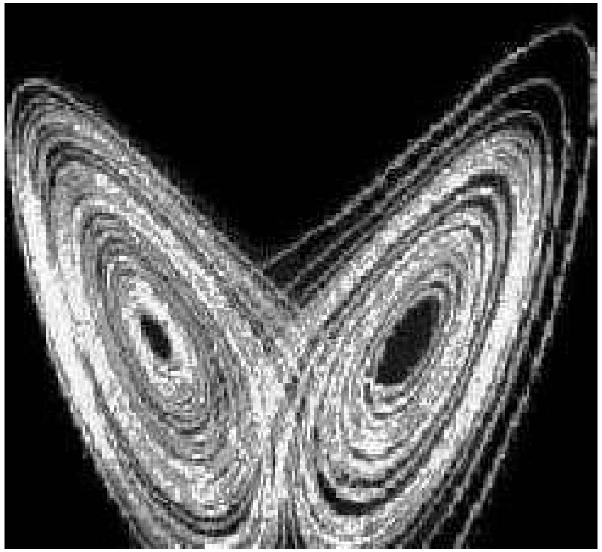


The beginnings of Numerical Weather Prediction (NWP)

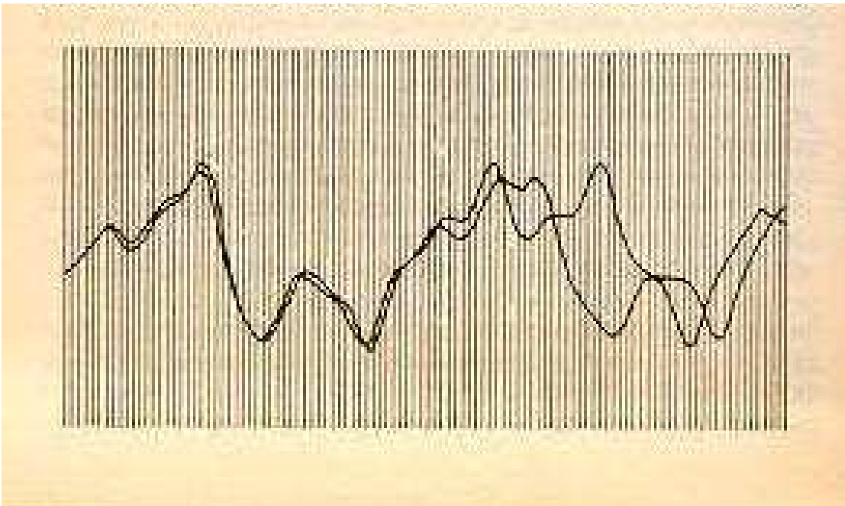


- L.F. Richardson (1881-1953)
  - Proposed scheme for weather forecasting based on solving theoretical equations (1922)
  - Envisaged room full of people (who he termed “computers” or “calculators”!) solving equations by hand and passing their results to neighbouring “computers”
  - This was before the invention of the calculators and computers we know today
- Computer models of weather and climate use these basic equations to move air around the planet in response to the radiative energy balance
  - In addition to the atmospheric circulation the entire environment must also be encapsulated including the ocean, land surface, global water cycle, etc

Limits of predictabiliy



- see popular description in:
  - *Chaos – James Gleick*
- Edward Lorenz
  - Mathematician with keen interest in weather
  - 1961: Developed primitive computer weather model



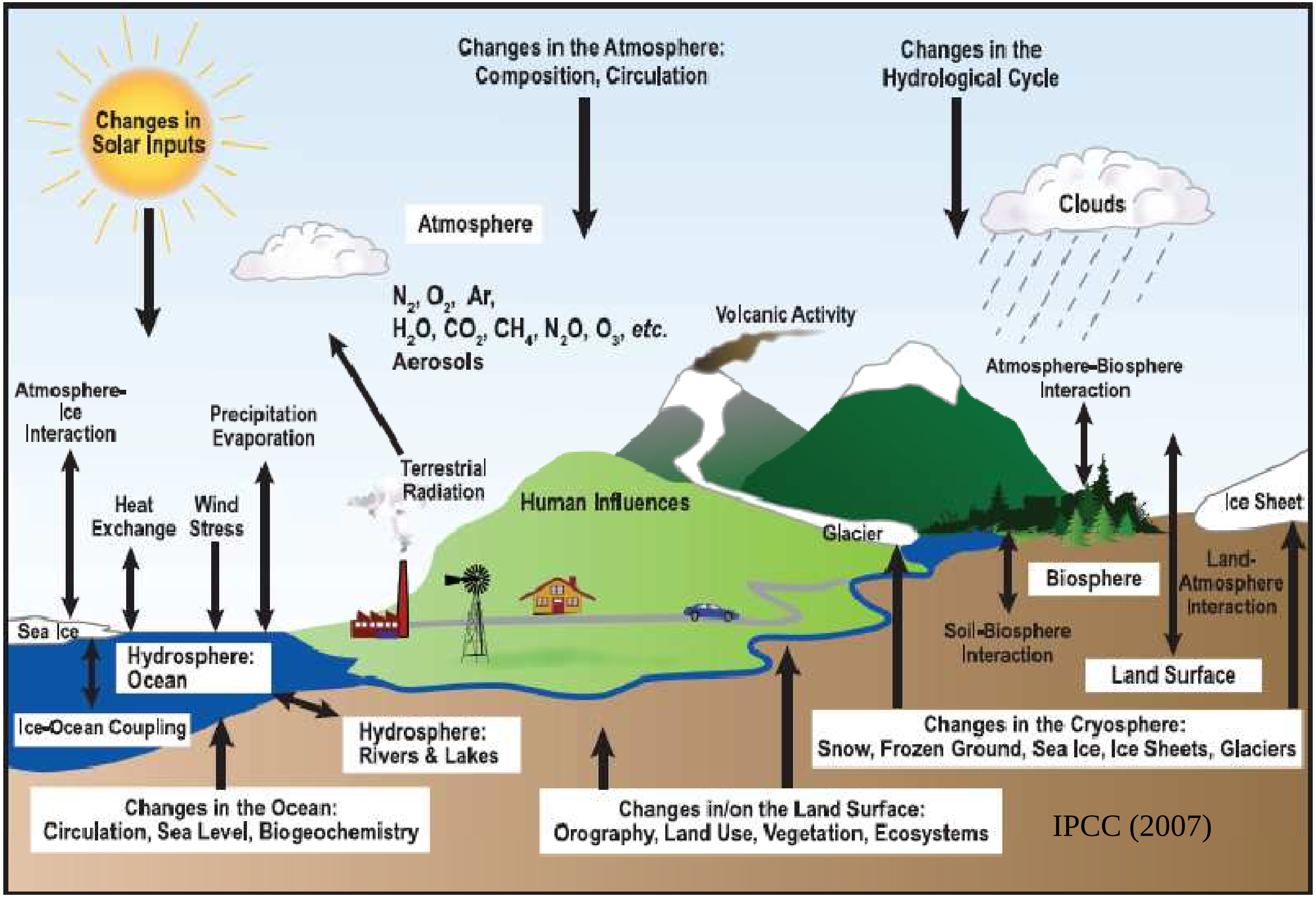
From Lorenz's 1961 printouts

Weather Forecasts and Climate Prediction

- Climate projections are fundamentally different from weather forecasts
- We are trying to predict changes in the long term statistics of the weather – the mean, the variability etc.
- Predictability comes partly from knowing the initial state, especially of the oceans and land surface, and partly from knowing something about the future "forcing" (i.e. Greenhouse gas concentrations)
- Climate models still need to represent day-to-day weather conditions
- Uncertainty in climate predictions arises from

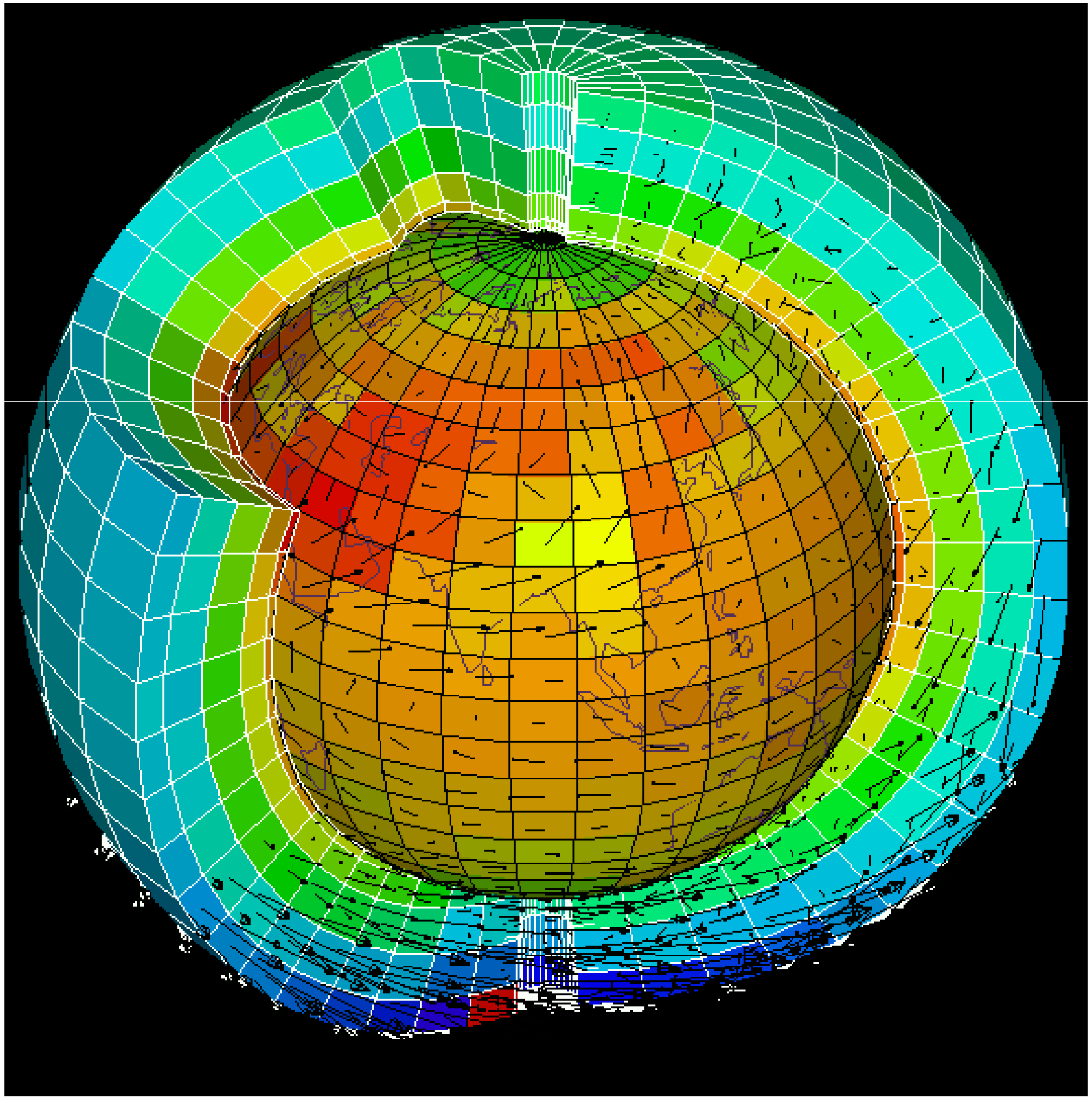
1. Imperfect models of the climate system
2. Natural variability in the climate system
3. Imperfect knowledge of the future concentrations of Greenhouse Gases in the atmosphere (scenario uncertainty)

The Climate System

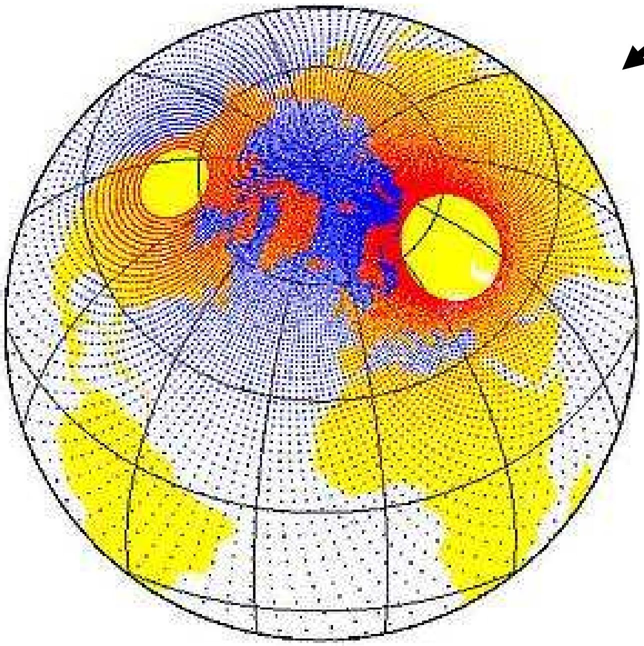


IPCC (2007)

Climate Models



- A climate model “slices and dices” the atmosphere into thousands of 3-D cubes, about 100km by 100km and about 500m deep
- A similar “grid” is also applied to the oceans



Grids:

- regular grids
- stretched grids
- rotated grids
- reduced grids

Numerical formulation:

- Finite difference
- spectral methods
- finite elements

Climate Models are huge computer codes based on **fundamental** mathematical equations of motion, thermodynamics and radiative transfer

Climate models are extensions of weather forecast models

These equations govern:

- Flow of air and water - winds in the atmosphere, currents in the ocean.
- Exchange of heat, water and momentum between the atmosphere and the earth's surface
- Release of latent heat by condensation during the formation of clouds and raindrops
- Absorption of sunshine and emission of thermal (infra-red) radiation

Conservation constraints

- Energy
  - Water vapour clearly crucial through latent heating & radiative absorption/emission
- Hydrological cycle
  - conservation of water

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

  - important contribution to the energy balance
- Momentum
  - powerful constraint on surface and upper-air wind patterns: water vapour transport
  - mountain and surface torques

Building a Climate Model

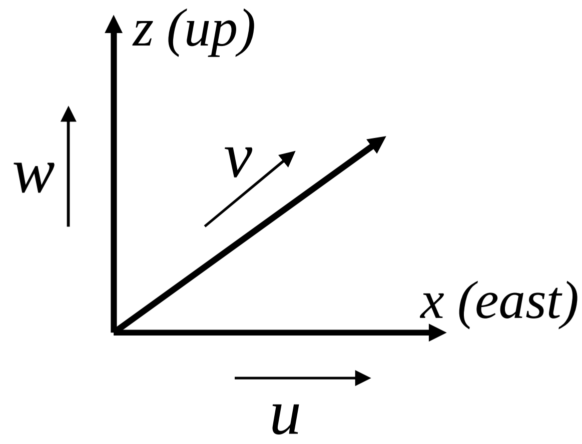
- All the physical processes can be represented in the form of mathematical equations
- These equations can be written down as computer code
- An initial state must be supplied, which is then advanced forward in small steps of time by repeated use of the governing equations

Some example equations…

$$\frac{du}{dt} - 2\Omega v \sin\phi + 2\Omega w \cos\phi + \frac{uw}{r} - \frac{uv\tan\phi}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + F_x$$

$$\frac{dv}{dt} + 2\Omega u \sin\phi + \frac{vw}{r} + \frac{u^2\tan\phi}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + F_y$$

$$\frac{dw}{dt} - \frac{u^2 + v^2}{r} - 2\Omega u \cos\phi = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + F_z$$



r is distance from the centre of the Earth

ϕ is latitude

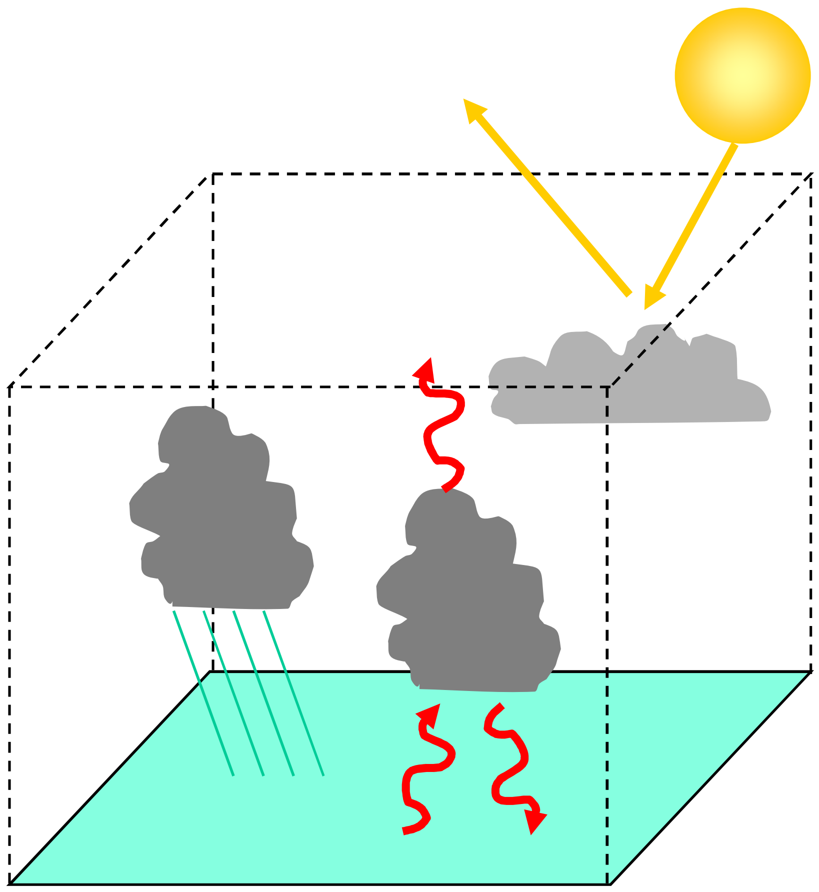
Ω Is the Earth's rotation rate

Model grid boxes

- Each grid box holds a single value of the atmospheric variables being predicted
- These are generally winds, temperature, pressure, humidity, cloud liquid water and cloud ice
- At the surface, values of soil temperature, soil moisture, sea surface temperature, sea ice coverage and thickness are also stored

Inside a model grid column

- Within a single column of the atmosphere, a lot can be happening
- Processes which occur on a scale smaller than the grid size are not explicitly modelled
- However, they can have a big impact on the model variables
- These processes have to be "parameterized"



Parameterized processes

The processes which are parameterized in most NWP models are:

Radiation, both terrestrial (longwave) and solar (shortwave), and its interaction with the atmosphere, clouds and the Earth's surface

Layer cloud formation and precipitation

Convective cloud formation and precipitation (i.e. cloud formed by buoyancy driven vertical motion)

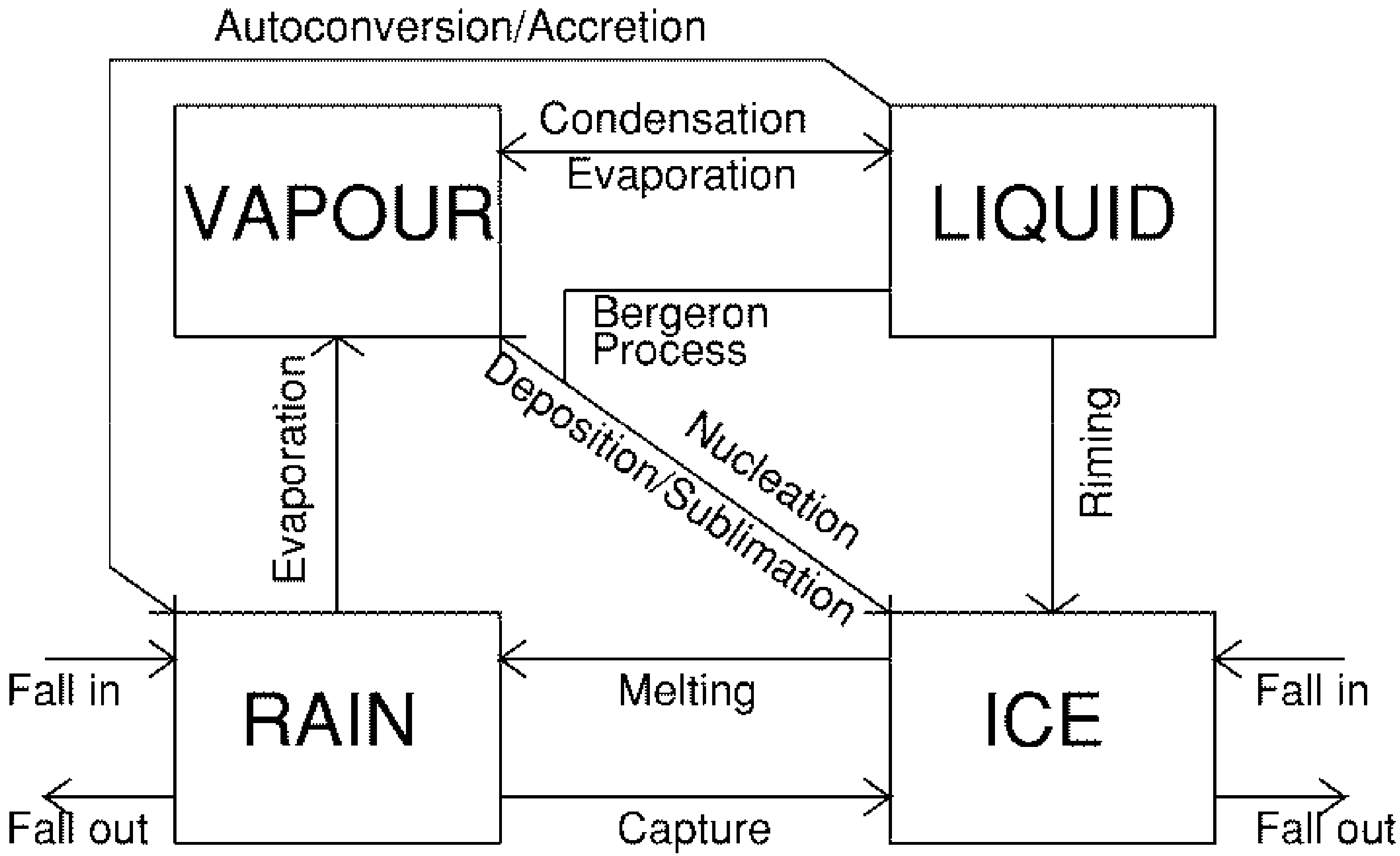
Surface processes – the exchange of heat, moisture and momentum between the Earth's surface and the atmosphere

Sub-surface processes and vegetation – soil and vegetation can store heat and moisture with significant impacts upon weather

Boundary layer processes – the vertical transfer of heat, moisture and momentum through the near surface layers of the atmosphere by turbulent processes

Gravity wave drag - These small-scale waves, generated by mountains, transfer momentum vertically and destroy

Example: Model cloud microphysics



Example: Cloud fraction C=f(RH, RHc)

For $RH \le RH_C$,

$$C = 0 \quad \text{(P292.B1)}$$

for $RH_C < RH < (5+RH_C)/6$,

$$C = (1/2)R^2 \quad \text{(P292.B2)}$$

where R satisfies

$$R^3 - 6R + 6\left(\frac{RH - RH_C}{1 - RH_C}\right) = 0 \quad \text{(P292.B3)}$$

The physically realistic root of this cubic gives

$$C = 4\cos^2(\pi/3 + \varphi/3) \quad \text{(P292.B4)}$$

where

$$\varphi = \cos^{-1}\left[\frac{3}{2^{3/2}}\left(\frac{RH - RH_C}{1 - RH_C}\right)\right] \quad \text{(P292.B5)}$$

for $(5+RH_C)/6 \le RH \le 1$,

$$C = 1 - \left[\frac{3}{2^{3/2}}\left(\frac{1 - RH}{1 - RH_C}\right)\right]^{2/3} \quad \text{(P292.B6)}$$

At $RH = (5+RH_C)/6$ both (P292.B4-5) and (P292.B6) give $C = 0.5$ and so the function given by (P292.B1-6) is continuous.

```
                                                                        CLD2RH1A.47
INTEGER I ! Do loop index                                               CLD2RH1A.48
                                                                        CLD2RH1A.49
DO I=1,NPTS                                                             CLD2RH1A.50
C---------------------------------------------------------------------  CLD2RH1A.51
CLL Calculate cloud fraction.                                           CLD2RH1A.52
C---------------------------------------------------------------------  CLD2RH1A.53
C Work with rh fraction                                                 CLD2RH1A.54
WRH=0.01*RH(I)                                                          CLD2RH1A.55
C Remove any supersaturation                                            CLD2RH1A.56
IF(WRH.GT.1.0) WRH=1.0                                                  CLD2RH1A.57
CC(I)=0.0                                                               CLD2RH1A.58
C For WRH<RHC (including WRH<0), CC remains zero.                        CLD2RH1A.59
C This treats the special MOPS rh=-85% for zero cloud cover.            CLD2RH1A.60
IF(WRH.GT.RHC .AND. WRH.LT.(5.+RHC)/6.)THEN                             CLD2RH1A.61
CC(I)=2.*COS(PC3+ACOS( PC1*(WRH-RHC)/(1.-RHC) )/3.)                     CLD2RH1A.62
CC(I)=CC(I)*CC(I)                                                       CLD2RH1A.63
ENDIF                                                                   CLD2RH1A.64
IF(WRH.GE.(5.+RHC)/6.)THEN                                              CLD2RH1A.65
CC(I)=PC2*(1.-WRH)/(1.-RHC)                                             CLD2RH1A.66
CC(I)=1.-CC(I)**(2./3.)                                                 CLD2RH1A.67
ENDIF                                                                   CLD2RH1A.68
ENDDO ! end loop over points                                            CLD2RH1A.69
                                                                        CLD2RH1A.70
RETURN                                                                  CLD2RH1A.71
END                                                                     CLD2RH1A.72
                                                                        CLD2RH1A.73
```

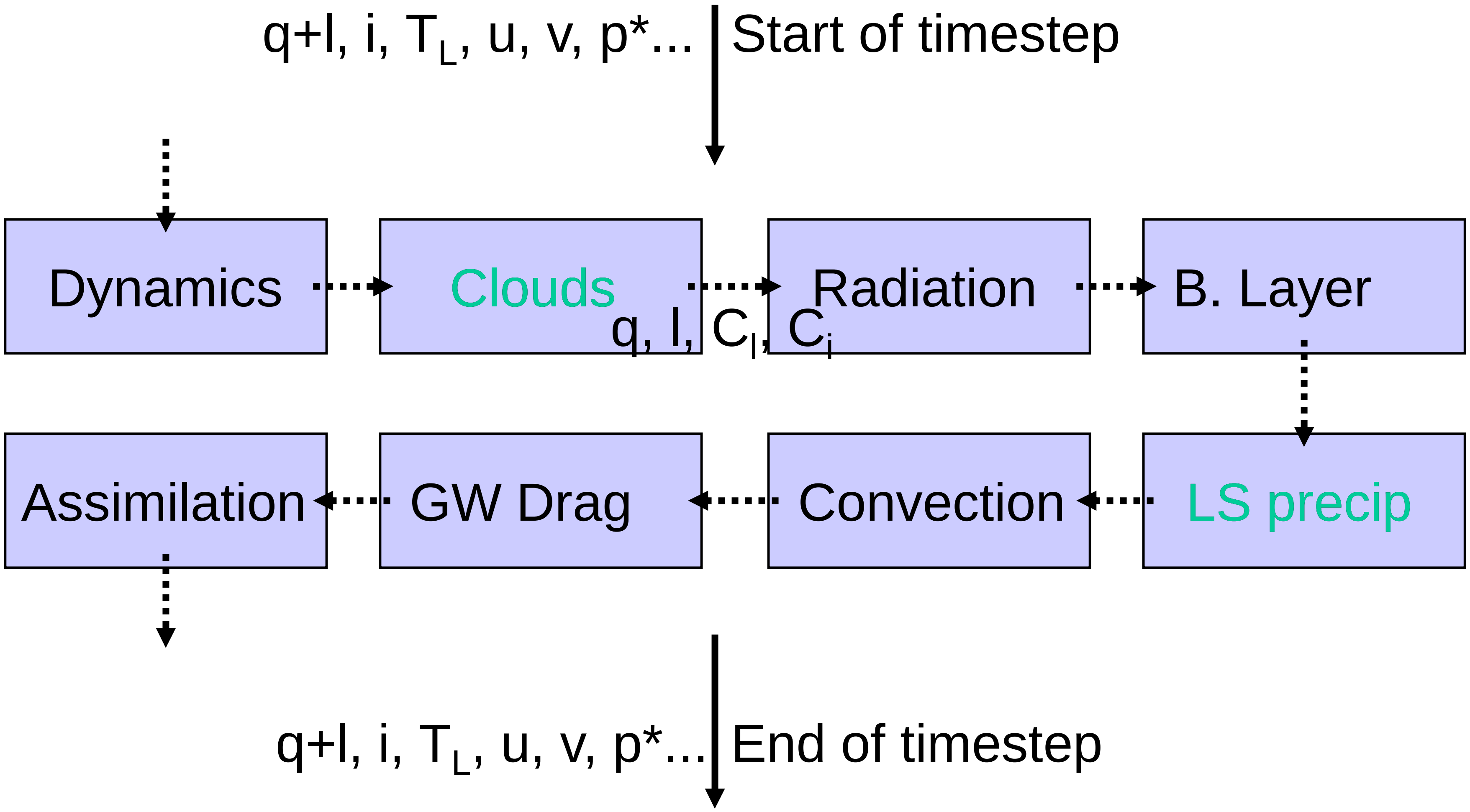
Each line of code assigned reference number

Code to calculate cloud fraction based on local relative humidity and critical relative humidity parametrization

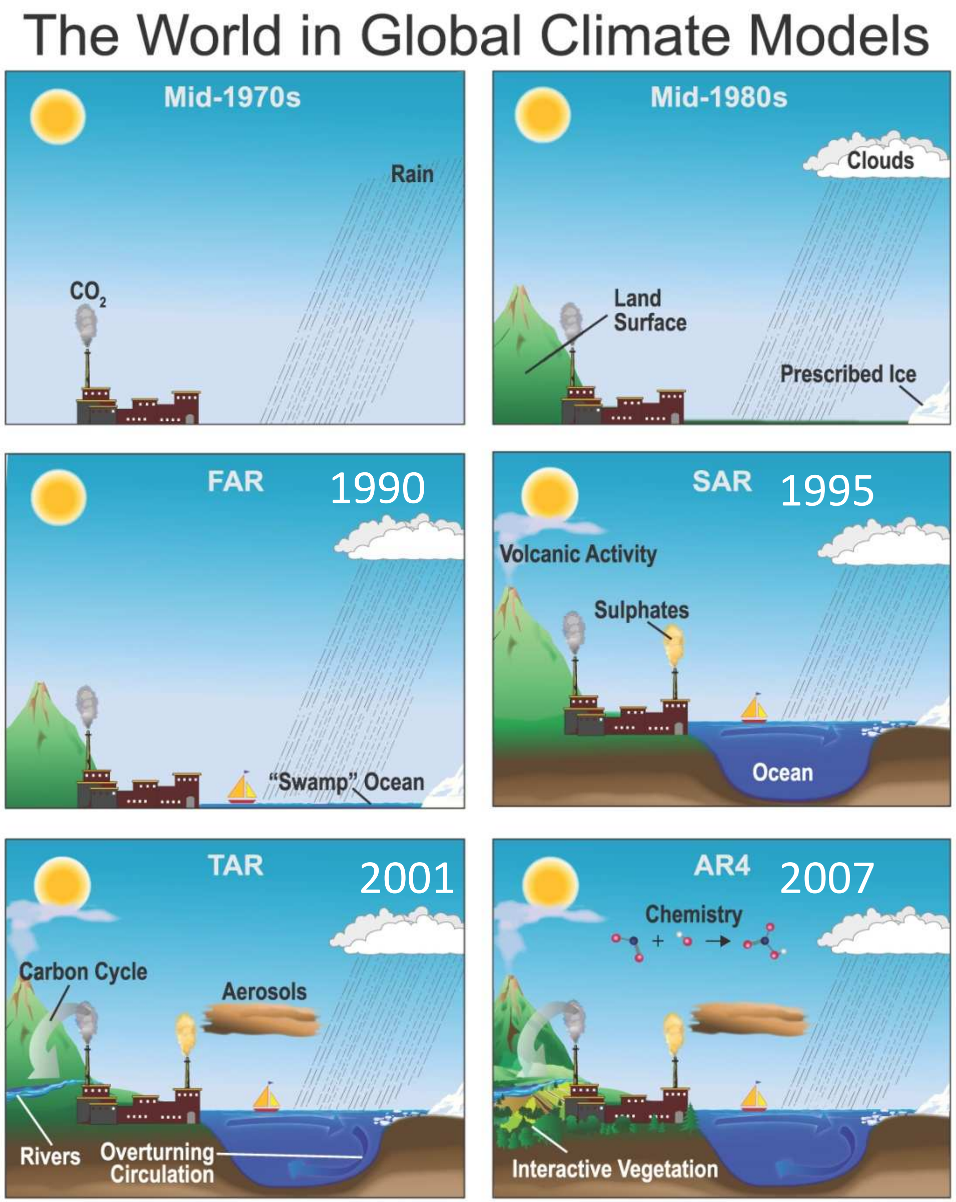
Parameterized processes

- The parameterization schemes in GCMs account for the main differences between models
- They account for some degree of the uncertainty in climate predictions
- All the parameterization schemes currently in use in GCMs are based on sound physical principles

Structure of UK Met Office model timestep



A history of Climate Models



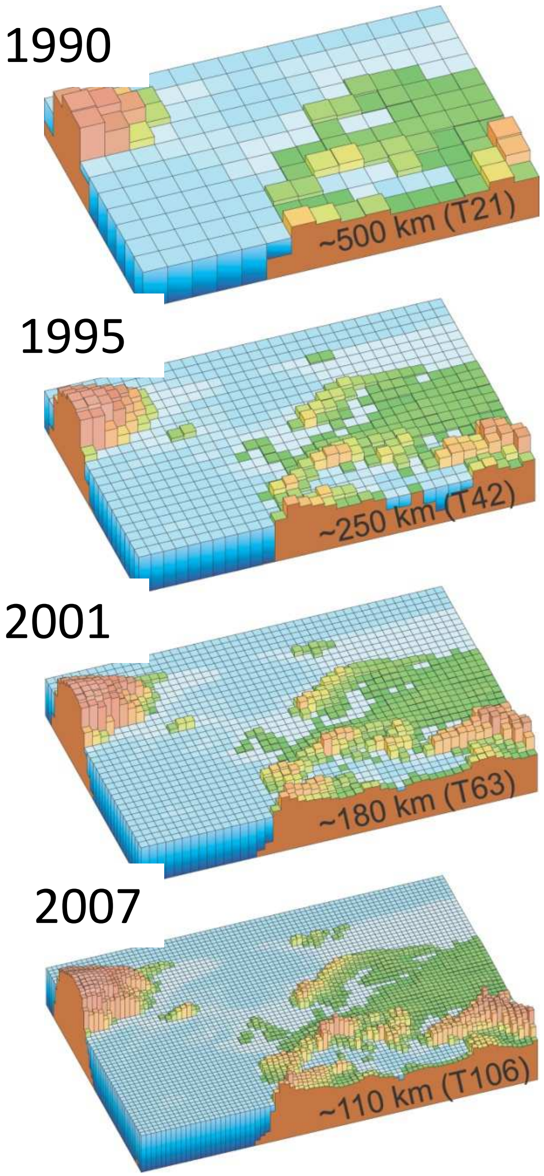
Since the 1980's Climate Models have included more elements of the Earth System

Major steps forward were the inclusion of:

Interactive land surface
Interactive oceans
Interactive carbon cycle
Interactive vegetation
Atmospheric chemistry

Figure from IPCC AR4. WG1. Chapter 1

Model grid size



The size of the grid boxes has been gradually decreasing since the 1980's

This is largely a response to increasing computing power

Smaller grid boxes mean that the equations are solved more accurately

Smaller grid also means more detail

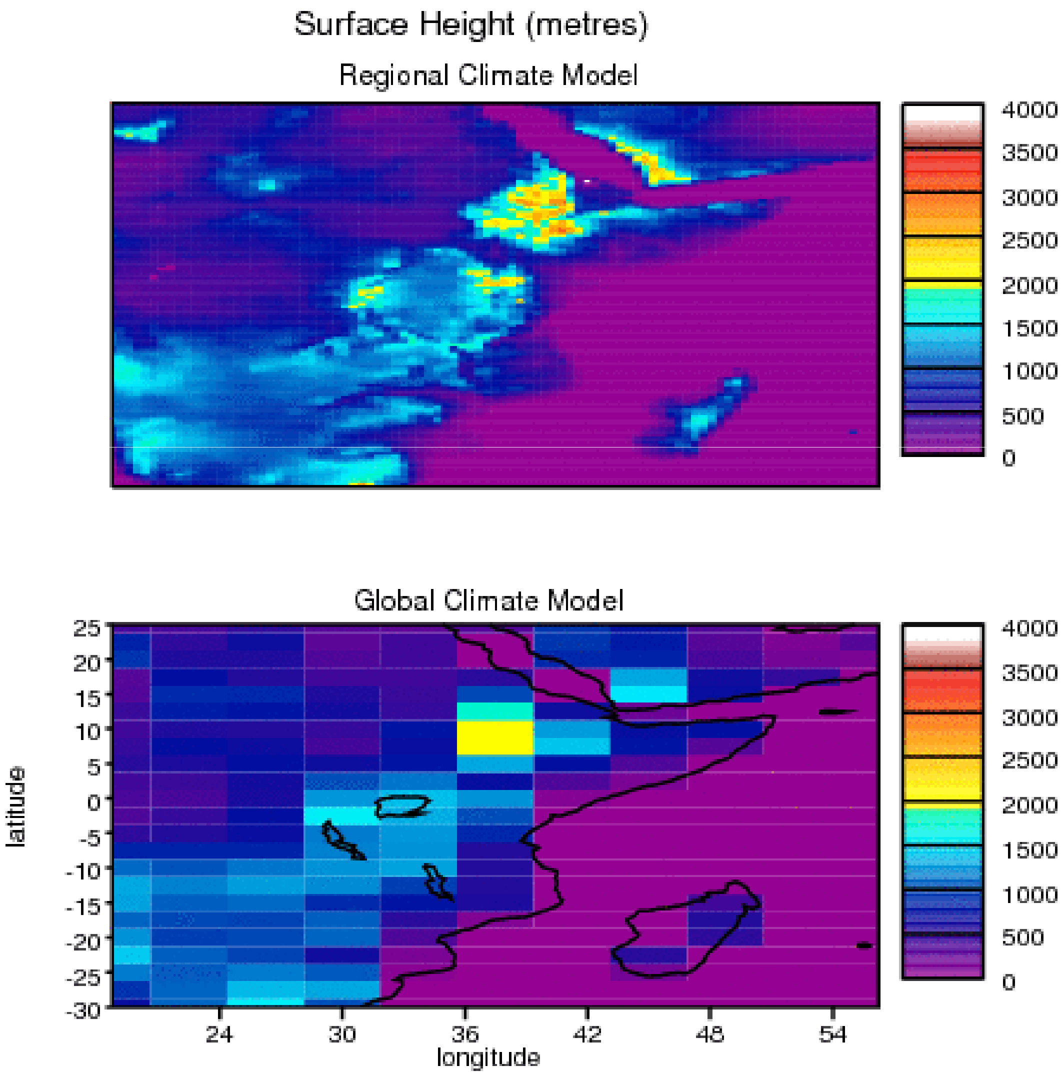
Mountains and coastlines are better represented

Figure from IPCC AR4. WG1. Chapter 1

Regional Climate Models (RCMs)

- Regional Climate Models cover a small part of the globe in more detail than a GCM
- Typical grid boxes are 25 or 50km square
- These models are particularly useful in regions with complex terrain
- Information from outside the RCM domain is fed in from an appropriate GCM
- A major use of RCMs is providing inputs for impact studies (agriculture, hydrology etc.)

Regional Climate Models



Figures show surface height information in an RCM (top) and a typical GCM (bottom) for east Africa

The RCM has a lot more detail in the mountainous regions

In this case it also represents Lake Victoria as water which the GCM doesn't

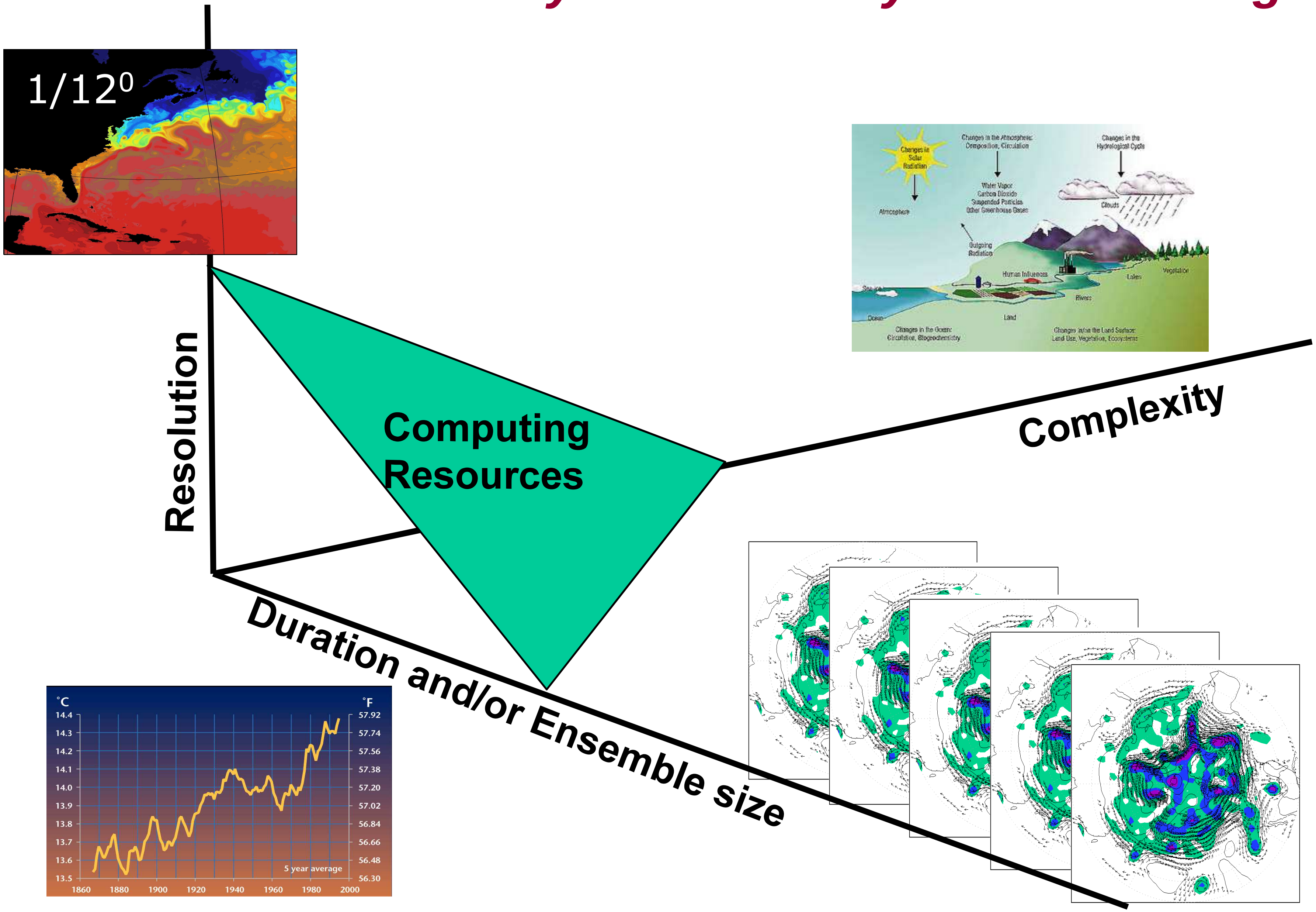
Computing for Climate Models

- To do climate change simulations you need a pretty powerful computer

The Japanese Earth Simulator (pictured) can do about 35 billion calculations per second

A century long run of a climate model takes about 1 month on a state-of-the-art supercomputer

Competing demands of resolution, complexity and uncertainty in Climate System Modelling:



Summary

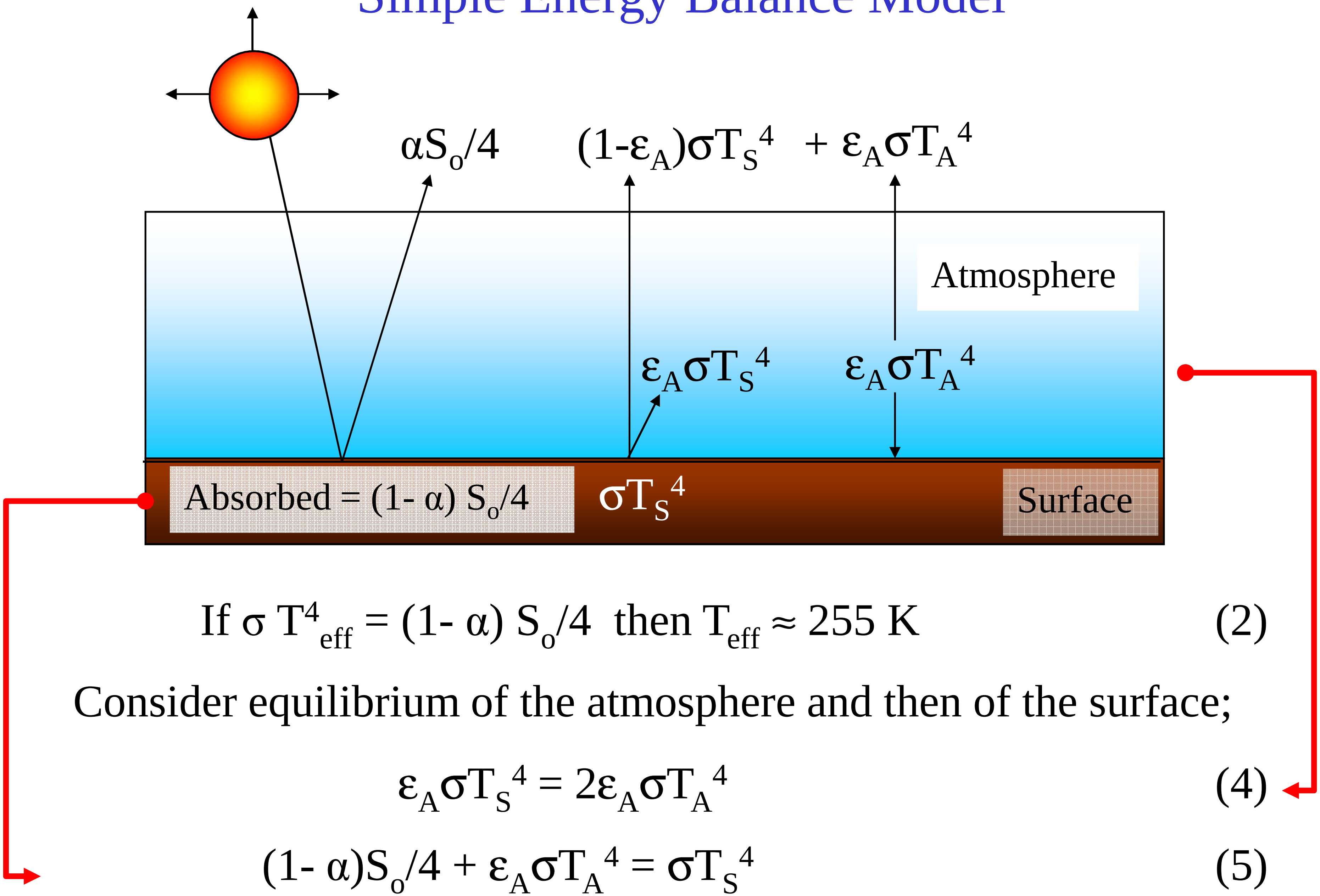
- Climate models are based on mathematical representations of the physical processes which govern climate
- These physical processes are applied simultaneously in each grid-box of the model
- There are uncertainties in how some of these processes are represented, resulting in differences between climate models
- Must verify or validate climate models before using them to make predictions

Further reading and information

- Books;
  - Washington, W.M. and Parkinson, C.L., 2005. *An introduction to three dimensional climate modeling*. University Science Books
  - Trenberth, K.E.,1995. *Climate system modeling*. Cambridge University Press
  - Randall, D.A. 2000. *General circulation model development*. Academic Press
- Web pages;
  - ECMWF seminars:
    - http://www.ecmwf.int/newsevents/training
  - Model Intercomparison Projects (MIPs):
    - http://www-pcmdi.llnl.gov/projects/model_intercomparison.php
  - IPCC:
    - http://www.ipcc.ch/ see IPCC(2007) Chapters 1 & 8
    - http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php for data portal
  - If you'd like to run a climate model yourself!
    - http://climateprediction.net/

Extra Slides

Simple Energy Balance Model



If $\sigma\, T^4_{eff} = (1-\alpha)\, S_o/4$ then $T_{eff} \approx 255$ K (2)

Consider equilibrium of the atmosphere and then of the surface;

$$\varepsilon_A \sigma T_S^{\,4} = 2\varepsilon_A \sigma T_A^{\,4} \qquad (4)$$

$$(1-\alpha) S_o/4 + \varepsilon_A \sigma T_A^{\,4} = \sigma T_S^{\,4} \qquad (5)$$

Hence

$$\sigma T_S^4 = \{(1-\alpha)S_o/4\} / (1 - \varepsilon_A/2) \qquad (6)$$

and

$$T_A = T_S/2^{1/4} \qquad (7)$$

Note that T_S is larger than T_{eff} given by (2), because of the additional downward thermal emission from the atmosphere. So, the greenhouse effect ensures that the surface is warmer with an atmosphere than without. Secondly, the atmosphere is colder than the surface and slightly colder than T_{eff}.

If we assume that $\alpha = 0.3$ and $\varepsilon_A = 0.8$ then we find that;

$$T_S = 289 \text{ K}$$

$$T_A = 243 \text{ K}$$

Which are reasonable values for the global mean surface and atmospheric temperatures.