C5: Physics of Atmospheres and Oceans

Lecture 1: Overview

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Overview

Organization and housekeeping

Planetary climate: A few example "big questions"

The fundamental physical building blocks of climate

Course Synopsis

Python and problem sheets

The objective of this course

To learn how to use the basic building-blocks of physics to understand phenomena related to climate and weather on Earth and other planets, including the growing catalogue of exoplanets.

This course is *somewhat* Earth-centric, but we try to teach the fundamental principles in a way that generalizes to all other planets.

Some basic information

Course Organizer

Anu Dudhia, dudhia@atm.ox.ac.uk

Tutorial classes

The lectures are supplemented by tutorial Classes, which offer opportunities to discuss solutions to the problem sheets.

Examinations

All material presented (except for guest lectures described as such) is examinable. Exams offer some limited choice of which questions to answer. Problem sheets involve some numerical computations requiring computer access, but not exam.

Course web site

All Course materials have been migrated to Canvas

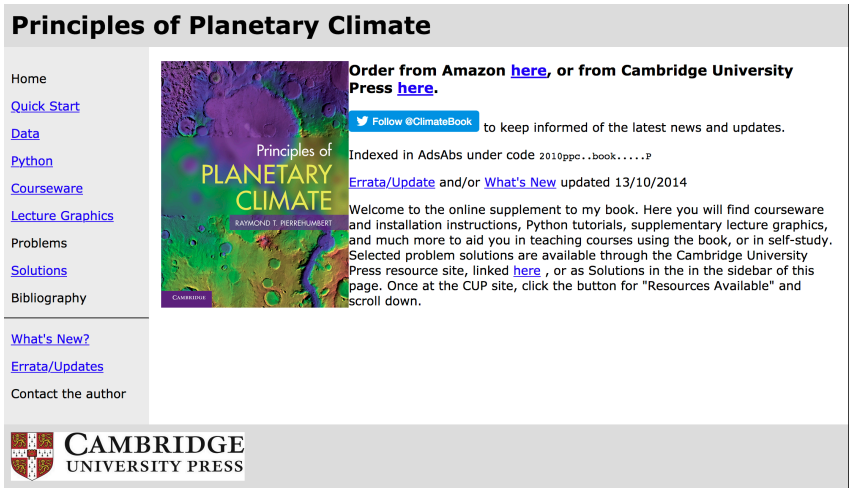
`https://login.canvas.ox.ac.uk/`

Just log in to Canvas and you should see C5 on your landing page.

- Lecture recordings are under Panopto Recordings
- Lecture materials (notes, code examples, data, etc.) are under Modules

Book(s)

Many texts are listed on the course web site. The full course does not follow any one of them closely, but for thermodynamics and radiative transfer, I especially recommend:



PlanetaryClimateBook.org

Kinds of problems we work on

- Weather: (mostly Earth, a bit for mission planning on other planets)
  What will temperature, precipitation, wind be in next few minutes to next few months?
- Climate: *What are the long-term statistical properties of temperature, precipitation, wind? How do they change if we change a controlling parameter, like brightness of the star*
- Earth climate change in the next few decades to millennia
- Paleoclimate. Recent (last few million years), deep time (a few hundred million years), deepest time (back to beginning, approx 4 billion years ago).
- Solar system planets and moons (all have now been surveyed, both from ground and through interplanetary missions)
- Exoplanets

Energy balance: why doesn't the Earth melt?

Let $L_\circledast$ be stellar flux at planets orbit (1370 $\mathrm{W/m^2}$ for Earth).
Let a be radius of planet, ρ mean density c_p mean specific heat

$$\frac{4}{3}\pi a^3 c_p \rho \frac{dT}{dt} = \pi a^2 L_\circledast$$

Data: For rocky planets $\rho \approx 5500\mathrm{kg/m^3}$, $c_p \approx 840 J/kgK$ (basalt).

Assuming heat is mixed uniformly throughout the planet (is that reasonable?) how long does it take to reach the melting point of "rock" (2500K).

So how does a planet lose heat?

i.e. what is the fundamental stabilizing feedback that causes temperature to stabilize at a finite value?

Answer: *Infrared radiation to space* (Fourier 1827)

For isothermal planet with no infrared absorbers in atmosphere:

$$\pi a^2 L_{\circledast} = 4\pi a^2 \sigma T^4$$

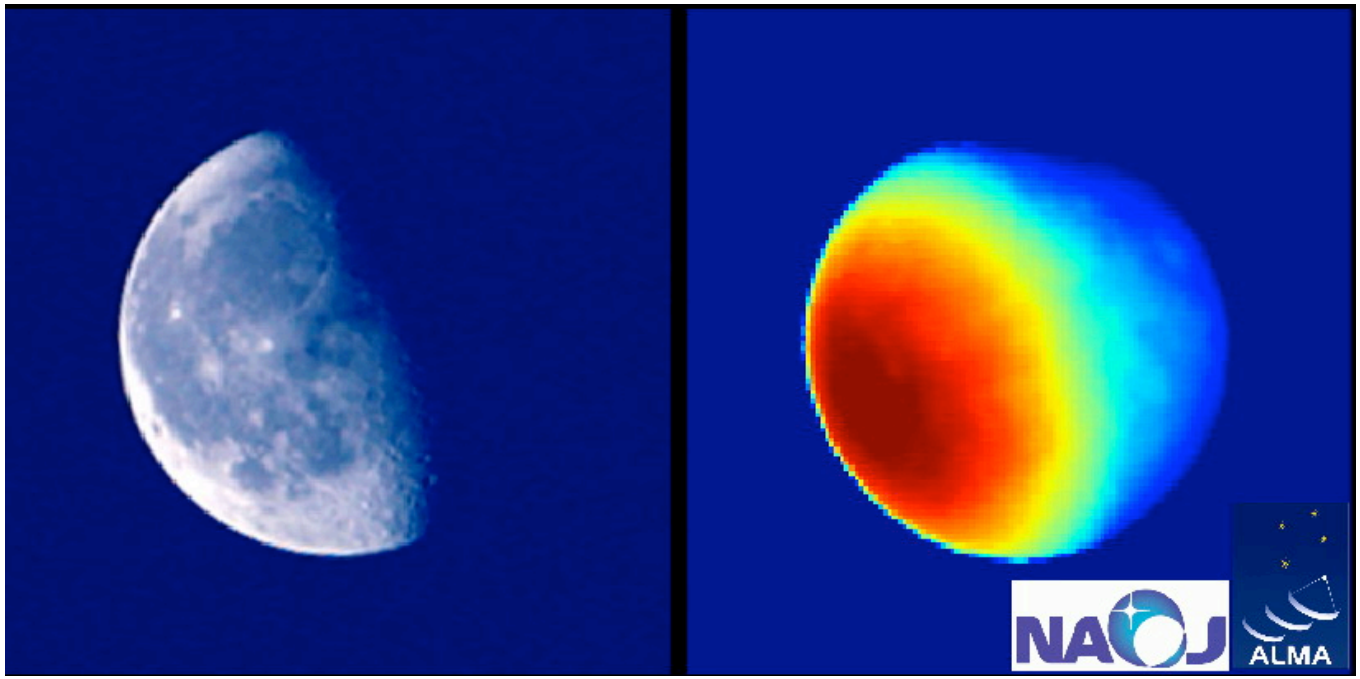
Plug in values for Earth and see what you get

What would Earth's climate be like if we didn't have an atmosphere?

What we need is a twin planet that shares the same orbit as us, but has no atmosphere or ocean?

Where could we get one of those???

The Moon!



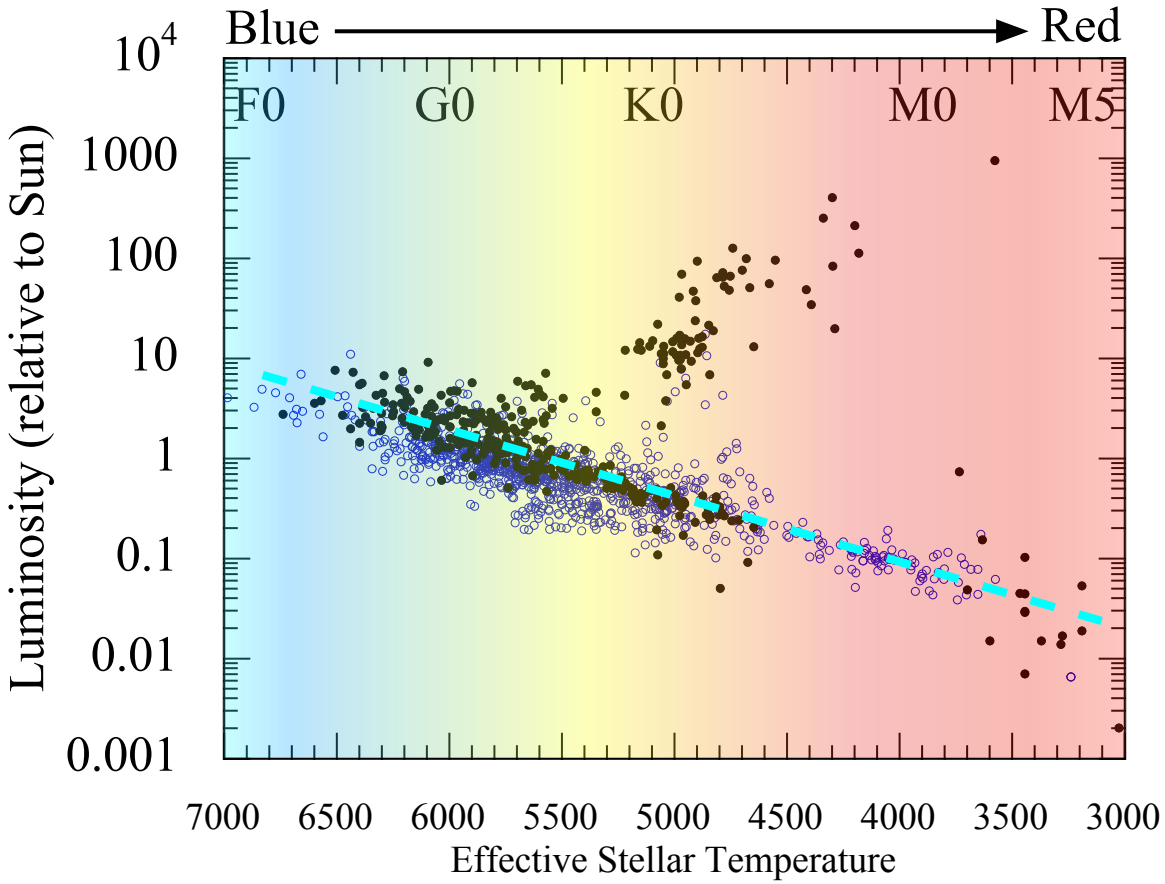
Visible (left) vs microwave (ALMA, right)

Goldilocks in space

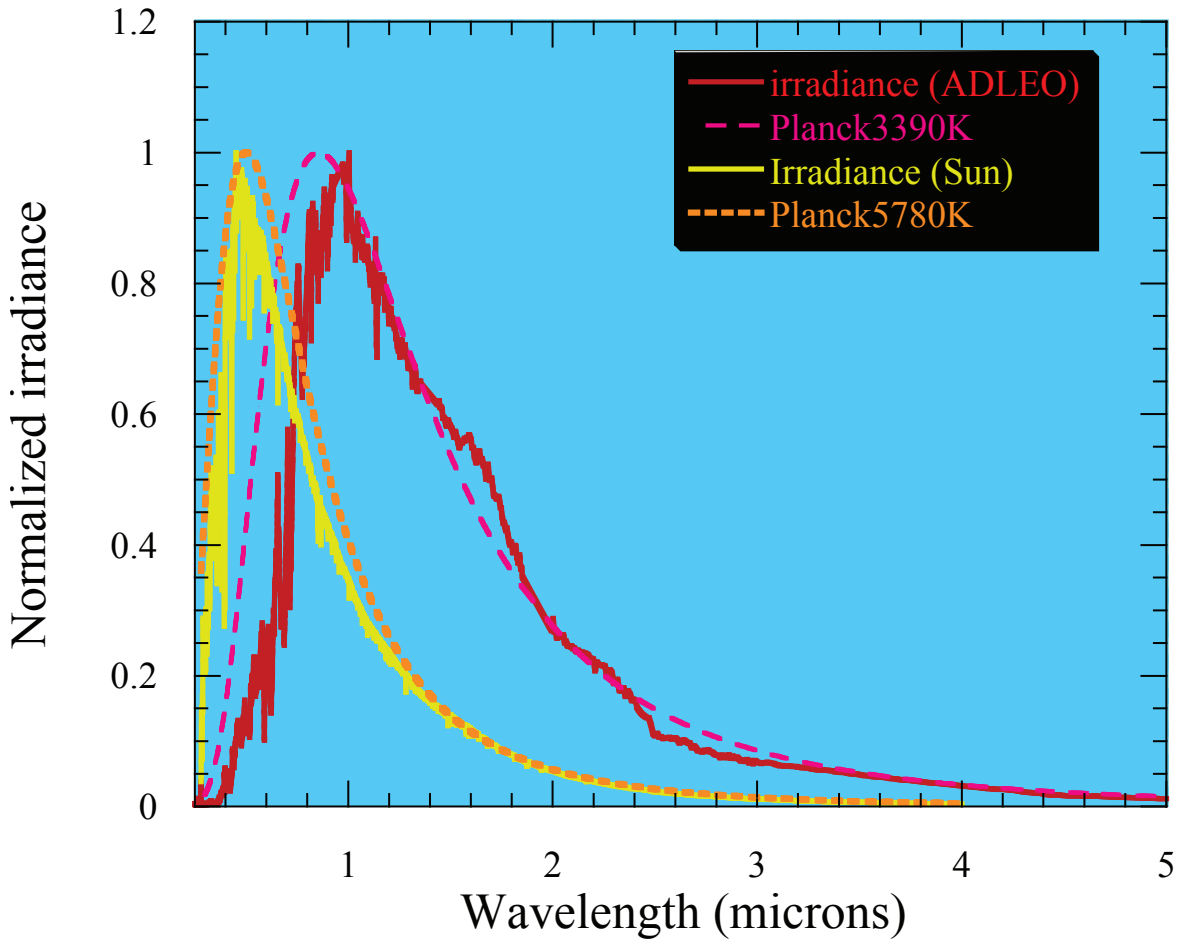
- Venus: No surface water. 90 bar CO_2 atmosphere. 737K surface temperature.
  What happened to Venus' ocean? Could it happen here?
- Earth : 1 bar N_2/O_2 atmosphere, .4 millibar CO_2 (as of today), surface ocean, life.
- Mars: 6 millibar CO_2 atmosphere, only traces of surface liquid water, cold and nearly airless
  Where did the atmosphere of Mars go?
  Could Mars have an ocean today if it had kept its atmosphere?

Generalizes to notion of *habitable zone* around stars

Exoplanets on the HR diagram



Spectrum of ADLeo vs Sun

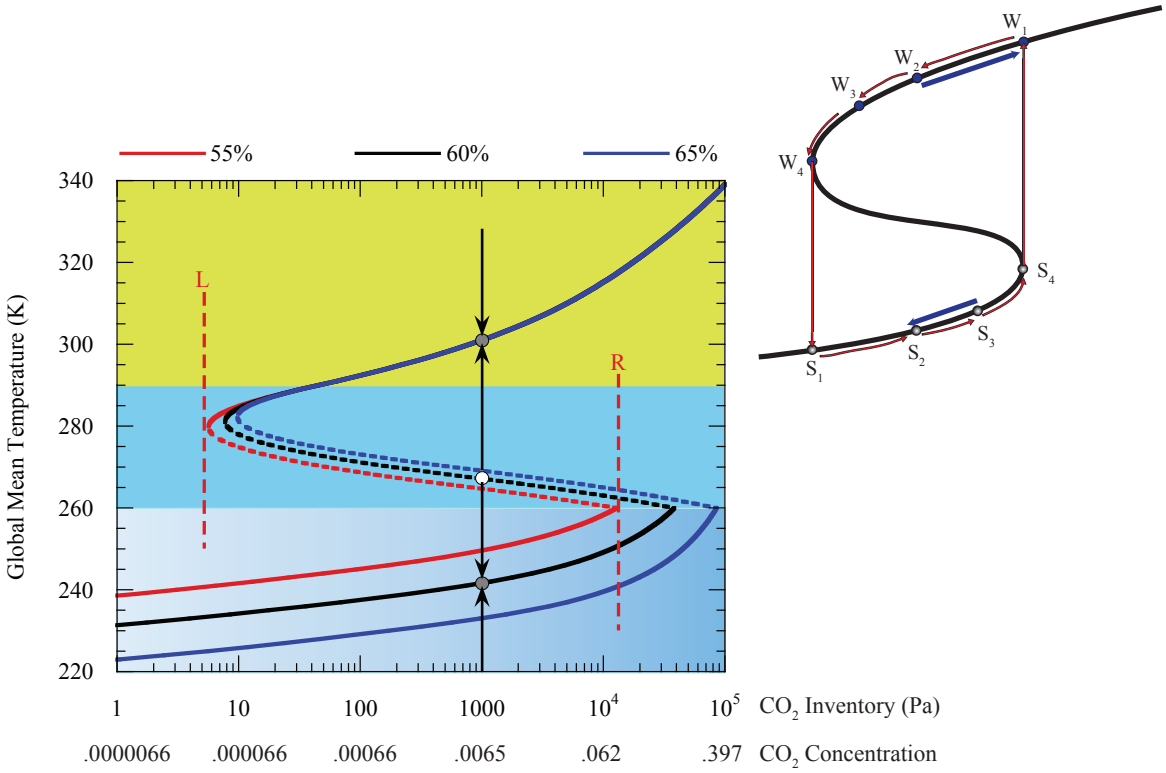


What does this do to climate?

The Faint Young Sun problem

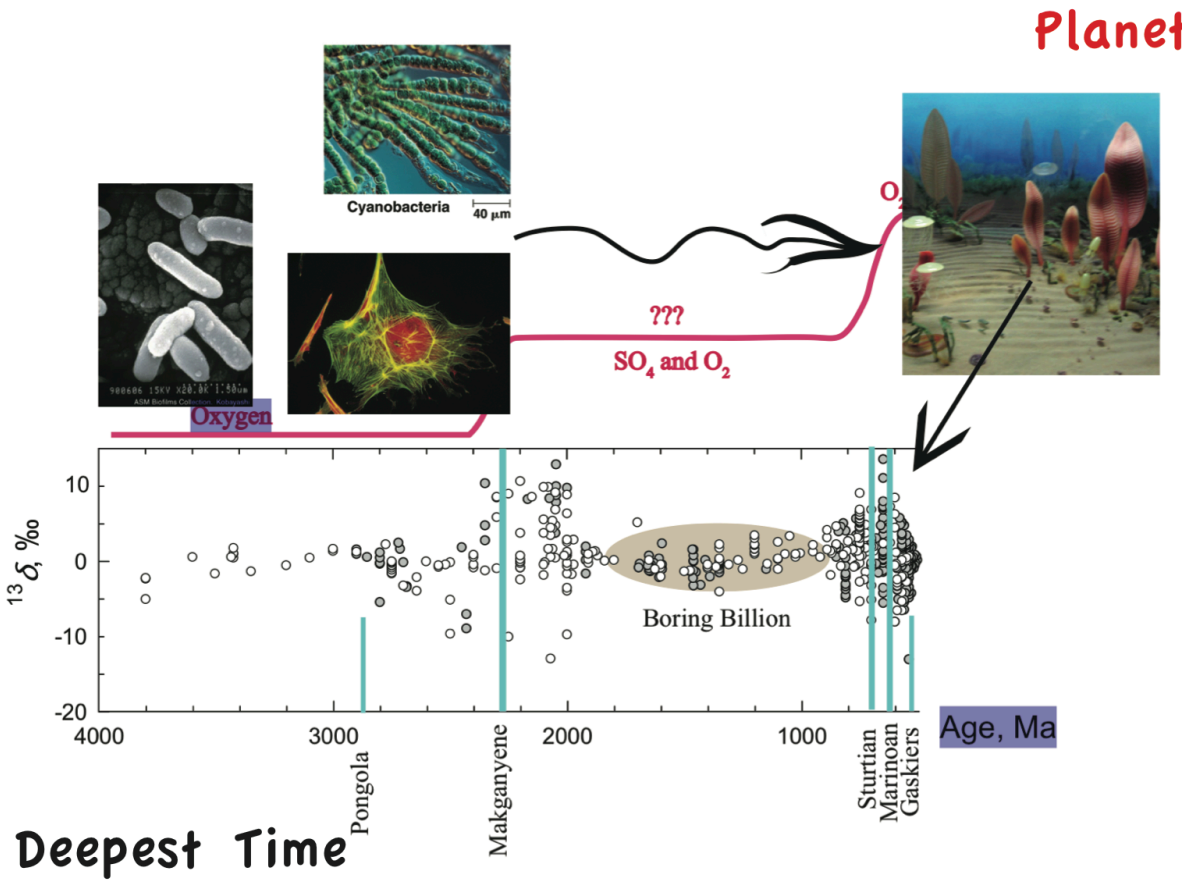
- Main sequence stars like the Sun get more luminous over time
- The sun was about 30% dimmer 3.8 billion years ago
- *All other things being equal* the Earth should have been frozen over (not obvious, but let's go to blackboard and think about it)
- But geological evidence says Earth wasn't frozen over
- So what changed so as to compensate for faint Sun?
- Did we just get lucky or is there a feedback that tends to preserve liquid surface ocean?
- Would things also work this way on other planets?

Ice-albedo feedback and Snowball Earth



What does this do to climate?

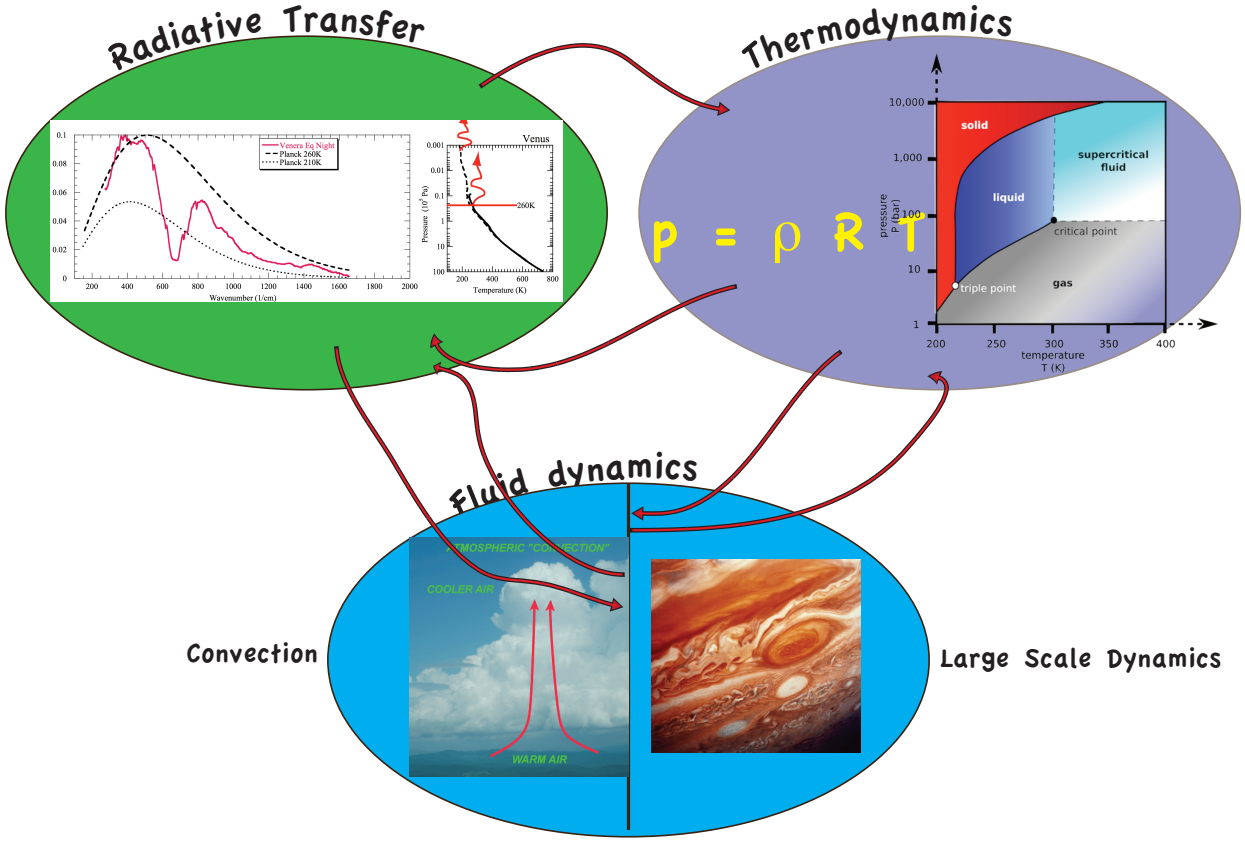
The Boring Billion



Other questions

- How much does it warm if you double Earth's CO_2?
- Why is Earth's equator hotter than the poles (on average)? What accounts for the temperature difference? How does this differ on other planets?
- Why does temperature go down with altitude (up to 10-16 km or so)?
- Why does Jupiter have a Great Red Spot, and what makes it red?
- Why are some of Earth's past climates "hothouse" climates with no surface ice anywhere?
- Why do major ice ages in the NH start 2 million years ago, and why did they arrive at intervals of 40,000 years for the first million years, but 100,000 years more recently?

The basic components of climate physics



Course Synopsis

Michaelmas Term 22 lectures

- Atmospheric composition and thermodynamics
- Radiative transfer
- Cloud Physics

Hilary Term 11 lectures

- Introductory GFD
- Instrumentation for Earth and Planetary observation
- Advanced GFD

Trinity Term 9 lectures

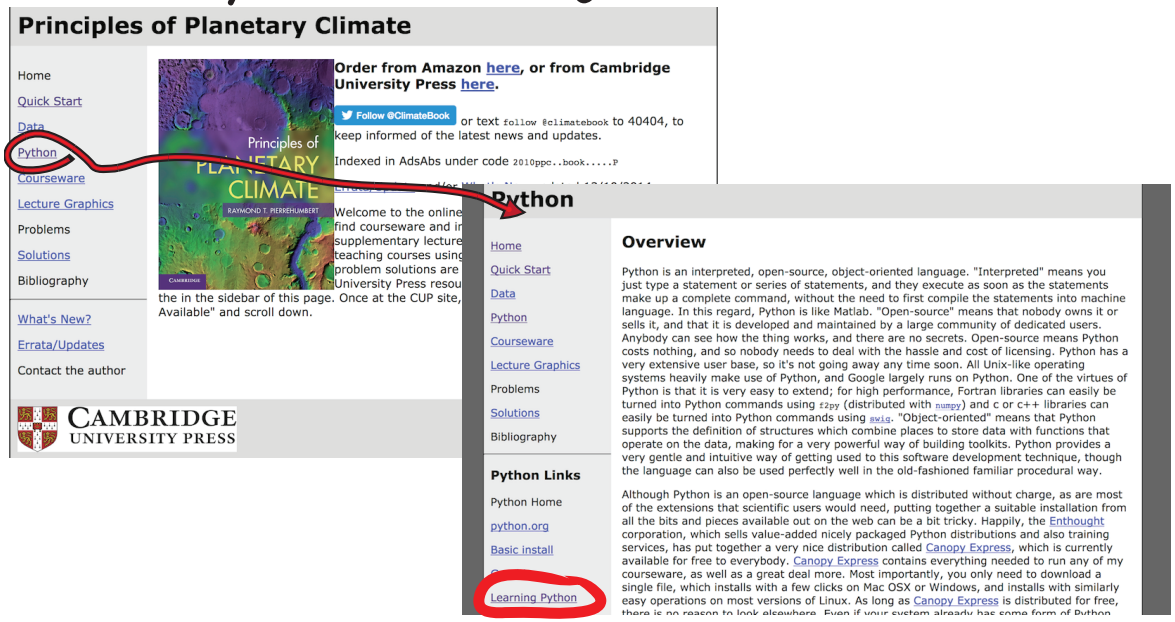
- Advanced GFD (cont'd)
- Integrative topics on climate (predictability, climate change, oceans)

Python

- Some problem sheet questions involve some basic coding to obtain numerical solutions. (Solving ODE's, Newton's Method, integration,plotting)
- It is strongly suggested you do these in `Python`, which is supported by the course
- I will provide editable example scripts for carrying out the basic kinds of calculations; the problems can be done by modifying the examples, and generally will not require coding from scratch.

Learning Python

PlanetaryClimateBook.org



Also, study the example scripts provided with the C5 Course Resources on Canvas (in Modules). For this course, you will not need the courseware associated with *Principles of Planetary Climate*, though some may find it to be a useful supplemental resource.

Access to Python

- Via web browser, by opening URL
  `https://jhub.physics.ox.ac.uk:8000`
  (Must be connected via Physics S or main Physics wifi)
- Or, download Python from `www.anaconda.com/download`, install on your own computer with single-click installation, run locally

You might also want to try out Google's notebook server, CoLab. Introduction at
`https://colab.research.google.com/notebooks/intro.ipynb`

About the problem sheets ...

- The problems are hard, and require considerable thought
- It could easily take 2-3 hours to complete each problem
- Many problems offer opportunities for open-ended exploration
- Best to start early, and not leave all problems to the last week before due-date.

Also, not all the details of derivations will be put on the slides. A lot will be done on the blackboard. Therefore, it's still necessary to take notes.

C5 Problem Set 1 (MT2021): Introductory Problems

1. **Heat Capacity**

   (a) Calculate the heat capacity of the entire atmosphere. Justify your choice of whether to use $c_p = 1000$ J/(kg.K) or $c_v = 720$ J/(kg.K) for air. [5]

   (b) Calculate the depth of ocean which has the same heat capacity as the entire atmosphere [Assume the specific heat capacity of seawater is 4200 J/(kg.K)]. [3]

   (c) In a thought-experiment the temperature of the atmosphere is decreased by 1 K everywhere and the heat thereby released is distributed uniformly in the top 100 m of the ocean. Calculate the temperature rise in this ocean layer. [2]

   [**Total: 10]**

2. **A comet collides with Earth** A spherical comet with a radius of 5 km made out of pure water ice collides with Earth. Its velocity relative to Earth *before* it is significantly affected by Earth's gravity is 20 km/s. You may ignore the effect of Earth's atmosphere on the impact. The comet hits in the ocean.

   (a) What is the energy released by the impact? [density of ice = 934 kg/m^3] [5]

   (b) Assuming all the energy goes into evaporating water, how much water vapour is added to the atmosphere, expressed as a multiple of the original mass of the comet? [latent heat of evaporation = 2.26×10^6 J/kg] [2]

   (c) Calculate the corresponding (temporary) drop in sea level. [3]

   [**Total: 10]**

3. **Earth Stood Still** Owing to an unfortunate diplomatic misunderstanding, the alien robot Gort decides to teach the Earth a lesson by stopping its rotation (relative to the galactic reference frame), through a force field that applies a drag to the Earth's material.

   (a) Estimate the rotational kinetic energy of the Earth [assume mass=6.0×10^{24} kg]. [3]

   (b) Assuming no energy leaks out through the surface during the period of spin-down, how much would the temperature of the Earth's interior increase? [mean specific heat capacity of the Earth = 800 J/(kg.K)]. [2]

   (c) Assume instead that all the heat leaks out through the crust, at a constant rate F (W/m^2), over the amount of time δt it takes for the rotation to cease. Calculate δt if this additional flux equals
   (i) the current geothermal heat flux 0.1 W/m^2, and
   (ii) the globally-averaged incident solar flux, 340 W/m^2. [5]

   [**Total: 10]**

4. **High altitude balloon** A balloon is required to carry an instrument payload of mass 150 kg to a height of 30 km, corresponding to a typical atmospheric pressure of 1225 Pa and temperature 233 K.

   (a) Ignoring the mass of the balloon itself, what radius of balloon is needed, assuming that after being charged with a measured 'bubble' of helium at launch it just becomes spherical at float altitude? [6]

   (b) Suppose the balloon fabric has a mass 10 g/m^2. What new radius of balloon is required? (you will need to solve this numerically). [4]

   [Total: 10]

5. **Rainfall** Calculate the times taken for water drops of radii
   (i) 1 μm,
   (ii) 10 μm, and
   (iii) 100 μm
   to fall a distance of 500 m in air at terminal velocity.

   [Assume Stokes's Law, that the viscous force on a spherical drop of radius a and speed v is $6\pi\mu av$. Take the dynamic viscosity μ for air to be 1.7×10^{-5} kg m^{-1}s^{-1} and the density of air at the relevant altitude to be 1.0 kg m^{-3}.]

   Check the validity of your calculation by estimating the Reynolds Number for each radius.

   [Total: 5]

6. **Statistical Mechanics**

   (a) Explain why a fluid may be considered as a continuous medium when viewed on a large enough length scale. Estimate the minimum length scale involved, in the case of air at standard temperature and pressure. [4]

   (b) Show that the time between collisions has the form $\tau \propto \sqrt{T}/p$ and estimate this time for air at S.T.P. [6]

   [Total: 10]

7. **Vorticity**

   (a) What is meant by the *vorticity* of 2D fluid flow $\mathbf{u}(x, y)$? [2]

   (b) Write down an expression for $\mathbf{u}$ representing linear flow that has vorticity. [2]

   (c) Write down an expression for $\mathbf{u}$ representing circular flow that has zero vorticity. [3]

   (d) What is the vorticity of a flow in rigid body motion with angular velocity Ω? [3]

   [Total: 10]

8. **Streamfunction** Consider the two-dimensional flow velocity

$$\mathbf{u} = \mathbf{k} \times \nabla\psi(x, y)$$

where $\mathbf{k}$ is a unit vector in the z-direction and ψ is a smooth function (the 'streamfunction').

(a) Show that this describes a flow of an incompressible fluid. [5]

(b) Under what condition is this flow also irrotational? [5]

(c) Consider the two-dimensional flow represented by the streamfunction

$$\psi = \frac{1}{2} A \ln\left(x^2 + y^2\right)$$

where A is a positive constant. By considering the variation of flow speed with distance from the origin, and the flow direction at each point, sketch the streamlines and give a physical description of the flow. Show that the flow is irrotational except at the origin. [5]

[Total: 15]

9. **Coriolis Effect** The velocity of a point at position $\mathbf{r}$ in an inertial frame I is related to its velocity in a rotating frame R by

$$\left(\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}\right)_I = \left(\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}\right)_R + \boldsymbol{\Omega} \times \mathbf{r}$$

where $\boldsymbol{\Omega}$ is the (constant) rotation angular velocity.

(a) Differentiate again to show that accelerations in the two frames are related by

$$\left(\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2}\right)_I = \left(\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2}\right)_R + 2\boldsymbol{\Omega} \times \left(\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}\right)_R + \boldsymbol{\Omega} \times \boldsymbol{\Omega} \times \mathbf{r}$$

[2]

(b) Outline (full mathematical derivation not required) how this can be used to obtain the following equation describing steady flow in a circular weather system on a rotating planet

$$\frac{u^2}{r} + fu = \frac{1}{\rho}\left(\frac{\mathrm{d}p}{\mathrm{d}r}\right)$$

explaining the origins of all three terms (Hint: start by considering circular flow on a non-rotating planet), and derive an expression for the Coriolis parameter f in terms of latitude θ and the planetary rotation rate Ω. [6]

(c) Hence explain why high-pressure systems ('anti-cyclones') in the northern hemisphere always rotate clockwise and cannot have strong winds. [2]

[Total: 10]

10. **Solar Power** The solar irradiance reaching the top of the atmosphere is 1361 W/m^2.

    (a) Calculate the radiative equilibrium temperature of Earth if it were a blackbody with an efficient means of redistributing heat over the entire surface. [2]

    (b) If the sun's radius is 7×10^5 km, calculate the effective emitting temperature of the sun's surface, and the area of the surface which emits power equivalent of a 100MW gas turbine power plant. [3]

    (c) The worldwide consumption of energy was estimated in 2008 at 1.3×10^{18} J day^{-1}. If this grows at a compound rate of 1.8 % per year, in what year will the use of energy equate to
    (i) all available solar energy incident on the Earth?, and
    (ii) the total energy output of the sun? [5]

    [Total: 10]

[Total for Problem Set: 100]

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