Imperial College London

BSc/MSci EXAMINATION June 2012

This paper is also taken for the relevant Examination for the Associateship

ENVIRONMENTAL PHYSICS

For 2nd, 3rd and 4th Year Physics Students

6 June 2012: 10.00 to 12.00

Answer all sections of Part A and two questions from Part B.
Marks shown on this paper are indicative of those the Examiners anticipate assigning.

General Instructions

Complete the front cover of each of the 3 answer books provided.

If an electronic calculator is used, write its serial number at the top of the front cover of each answer book.

USE ONE ANSWER BOOK FOR EACH QUESTION.

Enter the number of each question attempted in the box on the front cover of its corresponding answer book.

Hand in 3 answer books even if they have not all been used.

You are reminded that Examiners attach great importance to legibility, accuracy and clarity of expression.

SECTION A

1. (i) When observing our climate we often make use of in-situ observations from radiosondes to provide profiles of atmospheric temperature. At a single radiosonde station the type of temperature sensor may change with time. Give examples of two issues that could cause a bias in the long-term temperature record. For each of these issues, explain what the likely impact on the measured temperature profile would be if it is not accounted for and why. [6 marks]

(ii) After a sudden increase in CO_2 concentration the change in surface temperature as a function of time, $\Delta T_s(t)$, given by a climate model is shown to have the form,

$$\Delta T_s(t) = \frac{\Delta Q_{ext}}{\gamma}\left(1 - e^{-t/t_a}\right) \tag{1}$$

where ΔQ_{ext} is the external forcing associated with the CO_2 increase, γ is the climate feedback parameter, and t_a is the typical adjustment timescale given by, $t_a = \frac{mc}{4\pi R_E^2 \gamma}$ where m is mass and c specific heat capacity.
Use this information to explain why, in transient coupled general circulation model runs, a robust result is that in 2100 the land surface will have warmed more than the ocean. Provide a sketch of $\Delta T_S(t)$ versus t to back up your answer.

[4 marks]

(iii) Using a diagram, show the energy level arrangement in a typical n/p solar cell. Show the path for electron flow around the solar cell through a resistive load. Write down two general requirements that a photovoltaic device must satisfy to enable a voltage to develop across the cell and current to flow. [4 marks]

(iv) A householder is considering heating their home using a heat-pump with a stated coefficient of performance of 4.

(a) Define what is meant by the coefficient of performance in terms of energy flow and in two sentences, explain how the terms apply to heating a home. [2 marks]

(b) Under what conditions might the coefficient of performance be greater or less than 4? [2 marks]

(v) In 2000, global primary energy consumption was 10,029 Mtoe. In 2010 this had increased to 12,758 Mtoe. During this decade, annual global population growth averaged 1.2%.

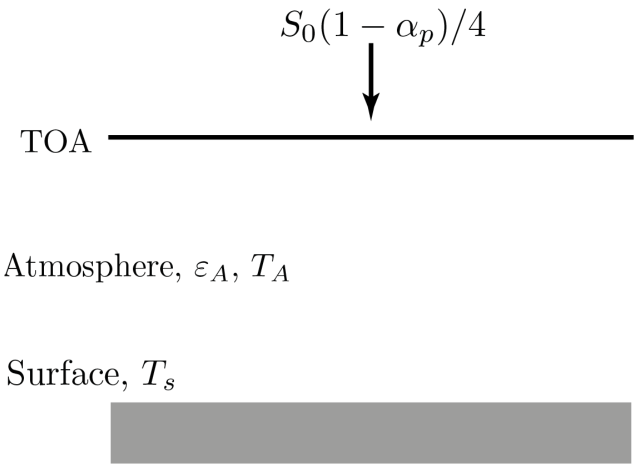
(a) Which type of country would you expect to be the main contributor to the growth in energy consumption? Name two reasons. [3 marks]

(b) What was the percentage growth in energy consumption per capita between 2000 and 2010? [3 marks]

[Total 24 marks]

SECTION B

2. We consider a simple model of the Earth, consisting of a single layer grey-body atmosphere, with infrared emissivity, ϵ_A and temperature T_A, overlying a surface of temperature T_S, which emits as a blackbody (see diagram below). The incident solar radiation at the top of the atmosphere (TOA) is $(1-\alpha_p)S_o/4$, where α_p is the planetary albedo and S_o is the solar constant. The atmosphere is completely transparent to solar radiation. We take $S_o = 1365 W.m^{-2}$, $\alpha_p = 0.3$ and $\epsilon_A = 0.8$. The Stefan-Boltzmann constant, σ is $5.67x10^{-8} W.m^{-2}K^{-4}$.



(i) Explain briefly the concept of radiative equilibrium at the TOA in terms of the incident solar radiation and outgoing longwave radiation (OLR). Give an expression for the OLR in this model by considering the contribution from the atmosphere and surface. Then, express the energy balance at the surface, within the atmosphere and at the TOA and hence obtain values for T_S and T_A. [4 marks]

(ii) We can also define the OLR at the TOA as $OLR = \epsilon' \sigma T_s^4$ where ϵ' is an effective infrared radiating efficiency. Using the equations derived in part (i) obtain a relationship between ϵ_A and ϵ' and using this or otherwise, calculate ϵ'. [2 marks]

A perturbation to the concentration of CO_2 in the atmosphere leads to a radiative forcing, ΔQ_{CO2} at the TOA which may be estimated as: $\Delta Q_{CO2} \approx 5.35 \ln(CO_2/CO_{2INITIAL})$. Here CO_2 is the perturbed concentration and $CO_{2INITIAL}$ is the initial concentration in ppmv.

(iii) Calculate the radiative forcing associated with an instantaneous doubling of CO_2. In our simple model, what would be the new OLR immediately after this doubling? Hence what would be the new value of ϵ'? Explain this change physically in the light of your answer to part (ii). [3 marks]

(iv) Now we assume the surface temperature has time to respond. What change in T_S is required to restore radiative equilibrium at the TOA? [1 mark]

In our calculations so far we have ignored climate feedbacks. Assuming a simple linear model, for this CO_2 doubling case we can write: $\Delta I = \Delta Q_{CO2} + \gamma_{BB}\Delta T_S + \Sigma\gamma\Delta T_S$

where ΔI is the change in net downward radiation at the TOA and ΔT_S is the change in surface temperature. Here the 'blackbody' response, $\gamma_{BB} = \partial I/\partial T_S$ and $\Sigma\gamma$ represents all other climate feedbacks.

(v) What does γ_{BB} represent physically? Hence is it a positive or negative feedback? Calculate γ_{BB} for the CO_2 doubling case described above. Hence calculate the surface temperature change that would be seen if radiative equilibrium is restored at the TOA. [4 marks]

(vi) The concentration of water vapour follows the Clausius-Clapeyron scaling and increases by $\approx 7\%/$ degree K surface warming. OLR reduces by $3W.m^{-2}/10\%$ increase in water vapour concentration. Assess, from this information, whether a water vapour feedback will enhance or reduce the change in T_S associated with a $2 \times CO_2$ forcing and explain your reasoning. Obtain an estimate for the water vapour feedback parameter γ_{WV}. [2 marks]

(vii) Hence obtain an estimate for the overall change in T_S associated with a doubling of CO_2 including both blackbody and water vapour feedbacks assuming radiative equilibrium at the TOA is restored. Comment on whether a runaway greenhouse effect would occur in this simple model. [2 marks]

[Total 18 marks]

3. The council of a small town comprised of 4,000 homes are considering introducing renewable power generation. The average windspeed is measured to be $5m.s^{-1}$ at 10m altitude. The town receives an annual average solar irradiance of $100W.m^{-2}$. Each home uses approximately 14kWh of electricity per day. The town conveniently operates a pumped electrical storage facility between two local lakes.

(i) Based on the information above, calculate the average electrical power demand of the town. Comment on the likely fluctuation of this number. [2 marks]

(ii) Since the average windspeed is known, sketch an approximate probability distribution for the windspeed at this location. [3 marks]

(iii) The council suggests building a single large wind turbine in fields beyond the edge of the town. Estimate a lower limit to the turbine diameter required to generate the average power calculated in part (i) and state your assumptions. The density of air is $1.2kg.m^{-3}$. [3 marks]

(iv) Local opposition to building this turbine is immense. Residents discover that micro-wind turbines of diameter 1m can be attached 3m from the ground on the side of their homes, delivering up to 1kW of electrical power. They insist that this power greatly exceeds the average power that they consume and hence the large turbine is unnecessary.

(a) What is the principle flaw in their argument? [1 mark]

(b) State what you might expect to happen to the wind-speed at 3m knowing that the roughness class for suburbia is 1.5m? [4 marks]

(c) Make a rough upper estimate for the power that might be delivered on average per household by these turbines? [1 mark]

(v) Each household has $6m^2$ of roof area suitable for photovoltaic panels. Assuming a panel efficiency of 20%, estimate the average power per household that can be delivered by the solar panels. Discuss whether this can help reduce the size of the large turbine that the council propose for supplying electricity to the town. [4 marks]

[Total 18 marks]

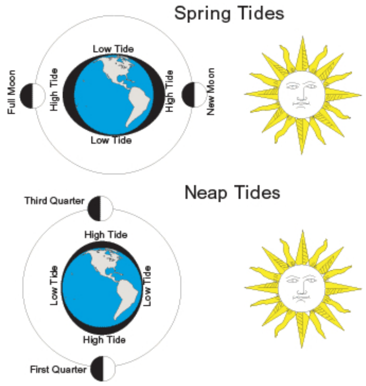
4. The UK has a large potential for tidal power - 25% of the total European tidal resource. A particularly attractive area for tidal stream power generation is the Pentland Firth, in Scotland, where tidal currents can reach peak velocities of 8 m/s.

(a) Show that the power of a tidal stream turbine can be expressed as: $P = \frac{1}{2}\xi\rho A v^3$. Here ξ is the turbine efficiency, ρ is the density of the sea water, A is the area swept out by the turbine, and v is the speed of the tidal current. What is the peak power output of a turbine with a diameter of 18 metres and an efficiency of 90% (the density of sea water is 1025 kg/m^3)? [2 marks]

(b) The velocity of the tidal current varies sinusoidally between 0 and peak velocity with (approximately) a 6-hour period. Find an equation for the velocity as a function of time, and state the average velocity of the current. [2 marks]

(c) Explain why the average power is not simply the power at the average velocity and calculate (via integration) the average power. [4 marks]

(d) On top of the 6-hourly tidal cycle, there is a longer cycle in the height of the tides, caused by the alignment of the moon and the sun (see figure below). When the moon and sun are aligned, the tide is at its maximum (spring tide). The lowest tide is called the neap tide.



Looking at the figure above, how long is the spring-neap tide cycle? [1 mark]

(e) The tidal acceleration on the earth is given by $a = \frac{2GM\Delta r}{R^3}$, where M is the mass of the object causing the tide (sun or moon),Δr is the diameter of the Earth, and R is the distance between the Earth and the object causing the tide[1]. Using this equation, show that the relative size of the neap tide compared to the spring tide is about 35%. [3 marks]

(f) The National Grid needs to take into account the variability of the tidal stream power output. Name two ways of balancing out this variability. [2 marks]

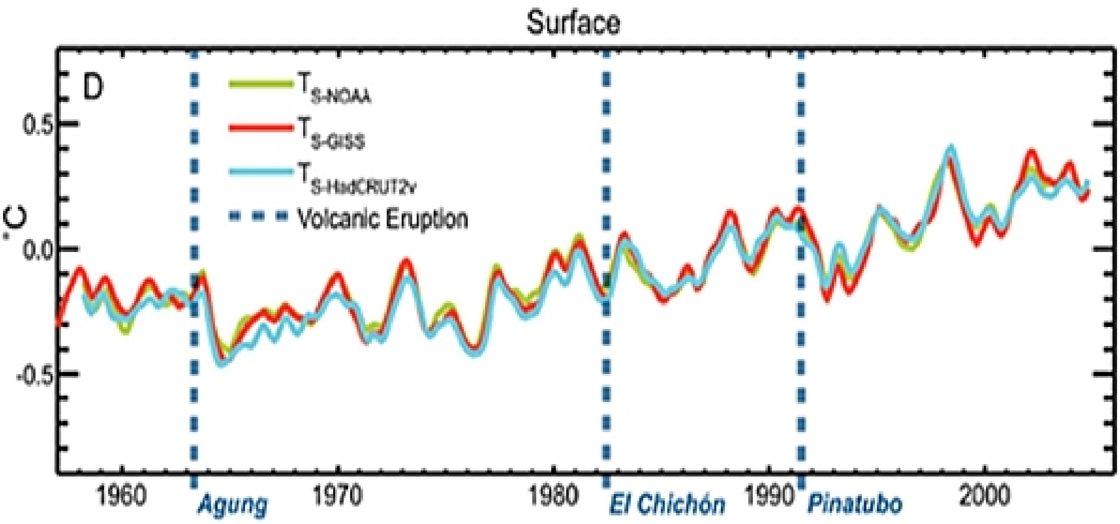
(g) The UK has an estimated total tidal stream resource of 94 TWh per year. How much is this compared to the total average power supplied to the UK by the National Grid? [2 marks]

[1] $M_{\text{Sun}} = 2.7 \times 10^{30}$ kg, $M_{\text{Moon}} = 7.3 \times 10^{22}$ kg, Radius of Earth$= 6,371$ km, $R_{\text{Sun}} = 149,598,261$ km, $R_{\text{Moon}} = 384,399$ km

(h) Wind energy is often quoted as a valuable renewable energy resource for the UK. Name two advantages of tidal stream power generation over wind power. [2 marks]

[Total 18 marks]

5. In June 1991 the Mount Pinatubo volcano erupted on the island of Luzon in the Philippines, emitting a large amount of sulphur dioxide into the lower stratosphere, which became transformed to sulphate aerosol and spread around the globe. The Earth's global mean land surface temperature record is shown below along with an indication of the Pinatubo eruption.



(i) Explain why we would expect to see a drop in global mean land surface temperature after the eruption of Pinatubo. Give appropriate definitions of any terminology you use. [2 marks]

(ii) Using a simple model of the Earth, we can show that: $T_s^4 = \frac{Q}{(1-A)\sigma}$ where T_S is the surface temperature, Q is the incident solar radiation at the top of the atmosphere, A is a constant, approximately equal to 0.4, and σ is the Stefan-Boltzmann constant, equal to $5.67 \times 10^{-8} W.m^{-2}K^{-4}$. Before the eruption, $Q = 238.9 W.m^{-2}$. Assuming the temperature drop seen in the figure above of $\approx 0.33K$ after June 1991 is entirely a result of the volcanic eruption, use equation (1) to obtain an estimate of the forcing, ΔQ, that the volcano exerted on Earth's climate system. [2 marks]

(iii) Provide a feasible explanation for why the temperature reduction is not seen immediately after the eruption. [1 mark]

(iv) The SPICE (Stratospheric Particle Injection for Climate Engineering) project is currently researching the possibility of combating Climate Change by intentionally releasing a large number of aerosols into the lower stratosphere.

(a) A change in CO_2 concentration relates to radiative forcing according to:

$$\Delta Q \sim 5.35 \ln \frac{CO_2}{CO_{2,now}} \qquad (1)$$

Here CO_2 is the new concentration and $CO_{2,now}$ is the current concentration in ppmv. If SPICE would aim to create a radiative forcing of

$-1.0\,\mathrm{W\,m^{-2}}$ by injection of aerosols, what *change* in CO_2 concentration would have the same effect? How many Gigatonnes of Carbon is that? (The atomic number of Carbon is 6, and you may assume the atmosphere comprises 2.1×10^{44} particles.) [2 marks]

(b) How many 'wedges' (proposed by the Princeton Carbon Mitigation Initiative) would this represent?

[1 mark]

(c) Identify and explain two drawbacks to the idea of the artificial injection of particles into the lower stratosphere. [2 marks]

(v) The power-output of photovoltaic solar cells will depend on the incident irradiance. Under standard test conditions, a solar panel with 72 cells connected in series has the following properties: $I_{sc} = 6.4A$, $V_{oc} = 65V$. Sketch the current voltage curve for this solar panel under standard test conditions and at 70% illumination. Label the graph with numerical values for the reduced voltage and current. [8 marks]

[Total 18 marks]