OC 403 Climate Dynamics, 2002   ANSWER TWO QUESTIONS

1. Describe the basic structure and properties of both an energy-balance and a radiative-convective model of the climate of a planet, using equations where appropriate, and stressing the assumptions and approximations made in each case. [40%]

   Compare the advantages and disadvantages of each of these types of model, in relation to

   (a) the estimation of the spatial distribution of temperature across the planet's surface

   (b) the representation of greenhouse effects due to infra-red absorption in the atmosphere. [30%]

   To what extent are models of these types capable of representing the distribution and fluxes of heat and freshwater, and to what extent can they be considered as adequate models of the climate system ? [30%]

2. To avert an imminent ice-age on the Earth-like planet Frigida, it is proposed to inject a thin layer of neutrally buoyant infra-red absorbing gas at the tropopause, where it is expected to persist. You may assume that the layer is non-reflective to either short-wave (SW) radiation from the sun, or to long-wave (LW) radiation. The fraction of outgoing long-wave radiation (OLWR) which will be absorbed, and subsequently re-radiated by the layer is given by $\delta=1-\exp(-\tau)$, where τ is its optical thickness in the infra-red. By requiring the net OLWR to be the same, above and below the layer, show that the OLWR flux will actually be reduced by the factor $f_1=(1-\delta/2)$. Calculate f_1 for τ = 0, 0.5, 1.0, 1.5 and 2.0, and sketch the results. Explain why even a perfectly absorbing layer would only achieve a limited reduction, and what that reduction would be. [30%]

   An alternative scheme involves continuously releasing large quantities of CO_2 which is expected to disperse throughout the troposphere. A two-stream grey atmosphere model suggests that the reduction factor in

OLWR between the ground and the top of the atmosphere in this case will be $f_2=1/(1+\tau/2)$, where τ is the total optical thickness of the atmosphere so achieved. Sketch the results for the same range of values of τ, and explain how and why the results for the two schemes differ. A common approximation for the greenhouse effect due to CO_2 in the atmosphere of Earth is that the resultant radiative forcing is about 4 Wm^{-2} for each doubling of the concentration of CO_2. Discuss how this approximation relates to your results for f_1 and f_2, and whether and under what circumstances this might also be a suitable approximation for evaluating the schemes proposed for Frigida. [30 %]

The atmosphere on Frigida is cloud-free, and the planetary albedo is controlled by the ground surface, and has the value $\alpha=0.4$. Taking the global and annually averaged insolation to be $S=500\ Wm^{-2}$, calculate the magnitude of the greenhouse effect (expressed as a radiative forcing) which would be achieved by the two schemes for Frigida, if an optical thickness of 2.0 can be achieved. [20%]

How do these results compare with the effect of a scheme to reduce the planetary albedo to 0.2 by planting daisies ? In what ways would these results for radiative forcing differ if these schemes were applied on Earth rather than Frigida ? [20%]

[TURN OVER]

3. The Earth during the last ice age. *Hint:* The following questions have no "right" answers – use sensible assumptions and justify them as well as you can.

   (a) Using rough estimates of ice extent and thickness, and being as quantitative as you can, estimate the difference in sea level, compared to modern, that existed during the last ice age because water was locked up in ice sheets. [30%]

   (b) What change in mean ocean salinity is implied? [10%]

   (c) What change in global mean surface temperature would be expected purely from the change in planetary (global-mean) albedo caused by increased ice cover? How would the change in radiative forcing compare to that of a CO_2 halving, which is around 4 Wm^{-2}? What change in greenhouse gas forcing resulted from the different CO_2 content during the last glacial? You may want to use that the outgoing long-wave radiation flux from the surface (at a surface temperature T °C) can be approximated by F = A + B T (where A=200 W m^{-2} and B= 2.0 W m^{-2} $°C^{-1}$), and that total solar output ("solar constant") is 1360 m^{-2}. [30%]

   (d) Compare the change in sea level obtained in part (a) to the one expected because the ocean contracted, both because it was colder and more saline during the last ice age. For simplicity, neglect in the following calculation the volume change of the ocean from water being locked up in ice sheets. Assume that ocean bottom pressure, p_B, is unchanged, so that $p_B = \int_{-H}^{0} g\rho dz = \int_{-H}^{h} g\left(\rho + \rho'\right) dz$, where H is ocean depth, z=0 is modern sea level, h is the glacial perturbation in sea level, ρ is modern density, and ρ' is the glacial perturbation compared to modern. You will have to exploit that $|h| \ll H$ and $|\rho'| \ll \rho$. Assume constant thermal and haline expansion coefficients, $\alpha = 10^{-4} K^{-1}$; and $\beta = 8\times10^{-4}\, psu^{-1}$, respectively. [30%]

4. Jupiter's moon Europa is entirely covered with water ice, possibly with a liquid ocean underneath; ice and (putative) ocean together have a vertical extent possibly of tens of kilometres. Europa's interior is constantly flexed by tidal forces, producing an amount of energy that we will assume leads to a vertical heat flux of 1 Wm^{-2} everywhere. Europa's atmosphere is negligible, so we can assume that Europa emits radiation as a blackbody. Jupiter is, on average, 5.2 times farther away from the sun than is Earth; total solar output ("solar constant") at the Earth's orbit is 1360 Wm^{-2}. Stefan's constant is 5.67×10^{-8} Wm^{-2} K^{-4}.

   (a) Calculate Europa's average surface temperature, T_S, assuming an albedo, α, of 0.5, and ignoring the heat generation in Europa's interior. [20%]

   (b) Now taking interior heat generation into account, calculate the average ice thickness, assuming that heat flux through ice, H_I, is possible only through conduction, $H_I = \frac{k}{h}(T_F - T_S)$, where h is ice thickness, T_F is the freezing point of water, assumed to be 270K, T_S is the surface temperature calculated in (a), and k, the conductivity through ice, is 2 W m^{-1} K^{-1}. [30%]

   (c) Re-calculate the average surface temperature, taking the interior heating into account. [20%]

   (d) If the heat generation from flexing were to stop, and Europa's ocean was 10 km deep, how long would it take until it was completely frozen? The latent heat of freezing and melting, per unit volume of ice, is $L_F = 3\times10^8 Ws\,m^{-3}$. [30%]

END OF PAPER

1. Consider a simple energy balance model of the meridional temperature distribution on an Earth-like planet, in which the polar regions at latitudes higher than 30 degrees are distinguished from the equatorial regions at latitudes lower than 30 degrees, so that the surface areas of the high and low latitude regions are equal. The annual and area averaged incident short-wave radiation flux is $Q_e = 500$ W m^{-2} in the equatorial region, and $Q_p = 300$ W m^{-2} in the polar region. The annual and area averaged temperatures are denoted T_e and T_p in the equatorial and polar regions, respectively.

   The outgoing long-wave radiation flux from the surface (at a surface temperature T °C) can be approximated by $F \approx A + B\,T$ (where A=200 W m^{-2} and B= 2.0 W m^{-2} °C^{-1}), and the heat flux Q_{mix} due to atmospheric and oceanic mixing between the high and low latitude regions by the parameterisation $Q_{mix} = K\,(T_e - T_p)$, also expressed in W m^{-2}.

   Derive expressions for the global average temperature, and the temperature difference between low and high latitude regions, in terms of the above quantities and the albedo values for the two regions (α_e and α_p). [30 %]

   Assuming that the albedo of a snow/ice surface is 0.70, and that that of any ice-free surface is 0.3, estimate the global average temperatures and the low-high latitude temperature differences (as a function of K) for

   (a) ice-free low-latitude, and ice-covered high-latitude regions

   (b) an ice-free planet

   (c) an ice-covered planet

   Explain why the average temperatures in each case do not depend on the mixing coefficient, nor do the temperature differences depend on the mean temperatures. To what extent are these simplifications likely to remain valid in a more realistic representation of the system considered ? [30%]

Using these results calculate the low-high latitude temperature differences in each of the above cases for K= 0, 1, 2, and 5 W m^{-2} $°C^{-1}$, and sketch your results. Explain why the curve for an ice-free planet is neither the highest nor the lowest of the three cases. [20%]

Use your results to determine the maximum value of the mixing coefficient K for which a polar ice-cap can persist when the low-latitude regions are ice-free, assuming that the critical annual average temperature for ice formation and persistence is -7.5 °C. If K is actually 2 W m^{-2} $°C^{-1}$, determine the maximum global warming (increase of global average temperature) for which a polar ice-cap could persist, and express this as the equivalent radiative forcing. Comment on your result in the light of a realistic estimate of the magnitude of the CO_2 greenhouse effect on Earth. [20%]

2. Explain the role of carbon and its compounds in the climate system, with especial reference to the characteristic time-scales of the processes involved. [40%]

Describe the present global distribution of carbon in carbonate and other sedimentary rocks, the oceans, the biosphere and the atmosphere, and the magnitude of the annual and longer-term fluxes between these reservoirs. [30%]

Explain the consequences and effects, over timescales of (a) hundreds, (b) thousands, and (c) millions of years, of the anthropogenic perturbation of the carbon cycle caused by the annual burning of several gigatons of fossil fuels during a few hundred years. [30%]

[TURN OVER]

3. Science fiction writer Larry Niven, of “Ringworld” fame, dreamed up his construction thus: “Build a ring 150 million kilometres in radius – one Earth orbit – which would make it 950 million kilometres long...We can spin it for gravity. A rotation on its axis of 1240 kilometres per second would give the Ringworld one gravity outward. We wouldn't even have to have a roof over it. Put walls 1600 kilometres high at each rim, aim it at the sun, and very little air will leak over the edges...The thing is roomy enough: three million times the area of the Earth. It will be some time before anyone complains of the crowding.”

   To explore Ringworld's climate dynamics, notice that it rotates around a G2 star, of similar colour and brightness as our sun. Between the star and Ringworld rotate 20 “Shadow Squares”, which block out the sun (see sketch) and create a 30-hour night+day cycle. The relative fraction of “day” during one 30-hour cycle is denoted ε, so that “daylight” lasts for ε*30 hours. The surface temperature, T, (inward – toward the star, and outward – away from the star) is 290K.

   (a) Assuming, first, that the Shadow Squares do not radiate energy outward, that Ringworld’s albedo, α, is 0, and that Ringworld emits radiation as a blackbody both inward and outward, calculate the ε necessary to maintain the average temperature at 290K. Total solar output (the “solar constant”) at Ringworld is 1360 Wm^{-2}, and Stefan’s constant is 5.67×10^{-8} Wm^{-2} K^{-4}. [35%]

   (b) To be more realistic, include the effects of non-vanishing albedo (α=0.3) and the greenhouse effect of Ringworld’s atmosphere (inside only), through the Budyko approximation for longwave radiation, I,

$$I = A + B\left(T - 273\right); A = 200 Wm^{-1}; B = 2 Wm^{-2} K^{-1}$$

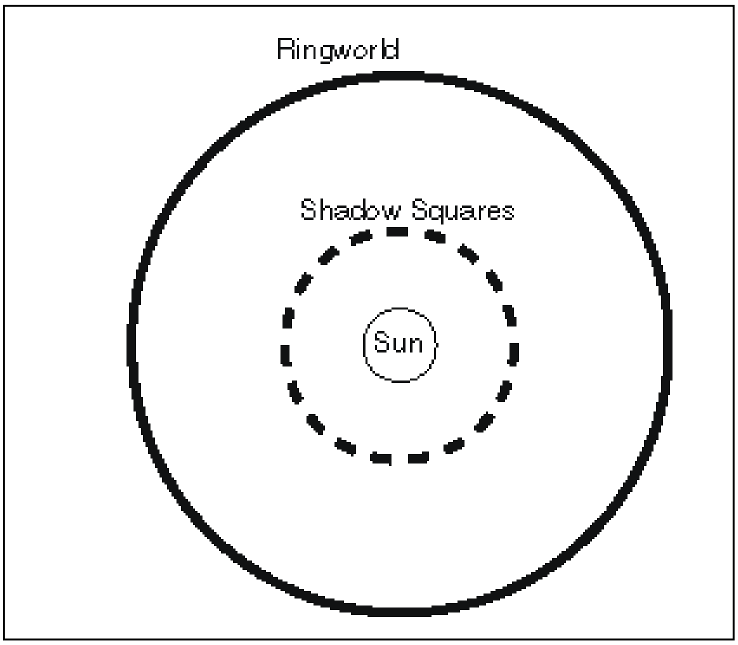
   Calculate now the ε that produces an average surface temperature of 290K, still assuming that the Shadow Squares do not radiate outward. [35%]

   (c) Larry Niven describes the Shadow Squares as perfect blackbodies, which implies that they re-radiate the incident sunlight both inward and outward. They orbit the star at a distance of 15 million kilometres; determine their temperature. From that temperature, calculate the wavelength of maximum emission intensity, using Wien's displacement law,

$$T\lambda_{max} = 2.8978\times10^{-3}\, m\,K \text{ (units: metres times Kelvin)}$$

What do you think happens with the radiation coming from the Shadow Squares when it hits Ringworld's atmosphere? Assume 20% of that radiation reaches Ringworld's surface, calculate the ε that produces an average surface temperature of 290K.

[30%]



[TURN OVER]

4. A mixed layer of depth D=35 m, temperature T, and salinity S, is in contact with an atmosphere of temperature $T_A = 10^\circ C$ through a downward heat flux of the form $H = \lambda\left(T_A - T\right)$; $\lambda = 35 Wm^{-2}K^{-1}$, and an upward freshwater flux $E - P = 10^{-8} ms^{-1}$. The mixed layer density is called ρ. Under statically stable conditions ($\rho \le \rho_0$), the mixed layer is completely isolated from the ocean underneath, which is assumed infinitely deep and with temperature T_0=0˚C, salinity S_0=35psu, and density ρ_0. As soon as $\rho > \rho_0$, however, mixed layer properties are instantaneously reset to exactly the properties of the deep ocean. Assume constant thermal and haline expansion coefficients, respectively, of $\alpha = 10^{-4} K^{-1}$; and $\beta = 8\times10^{-4} psu^{-1}$. Heat capacity per unit volume is $C = 4\times10^6 Wsm^{-3}K^{-1}$.

   (a) Formulate the ordinary differential equations that govern the time evolution of mixed layer T and S under statically stable conditions. Use that the effect of E-P on changes in salinity can be approximated by $S_0\left(E - P\right)/D$, which is constant. [20%]

   (b) Assuming the initial conditions T= T_0, S= S_0, (implying $\rho = \rho_0$), and that, initially, conditions are statically stable, calculate T and S as functions of time. [30%]

   (c) Sketch T(t) and S(t), both as functions of time and in a T-S phase diagram. [20%]

   (d) Do T and S increase monotonically in time? If not, at what time do they decrease? Make sensible approximations where appropriate. [30%]

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