Atmospheric Physics Exam 2012

Instructions

Do your best to answer all questions in the time allowed. **ALWAYS remember to check the UNITS in the question and state the UNITS in your answer!!!** Note that the number of points available are stated at the start of each question.

Formulae

Most formulae required are given here:

Thermodynamics Ideal gas law:

$$p = \rho R_m T. \tag{1}$$

First Law:

$$dq = c_p dT - v dp, \tag{2}$$

Potential temperature Lapse Rate:

$$\frac{d\theta}{dz} = \frac{\theta}{T}\left(\frac{dT}{dz} + \frac{g}{c_p}\right). \tag{3}$$

Hydrostatic balance:

$$\frac{dp}{dz} = -\rho g \tag{4}$$

Clausius Clapeyron Equation for saturation vapour pressure over a planar water surface:

$$\frac{de_s}{dT} = \frac{L_v e_s}{R_v T^2} \tag{5}$$

Potential temperature:

$$\theta = T\left(\frac{p_0}{p}\right)^{\frac{R_d}{c_p}}. \tag{6}$$

Vertical momentum equation relating the vertical acceleration to the buoyancy force:

$$\frac{dw}{dt} = F_B = g\left(\frac{\theta - \theta_{env}}{\theta_{env}}\right) \tag{7}$$

where θ is potential temperature and *env* refers to the environment of the parcel.

Teton's formula for the saturation mixing ratio r_s (kg kg^{-1})as a function of pressure p (in Pa)and temperature T (measured in Kelvin):

$$r_s(T) = \frac{380}{p} exp\left(17.5 \frac{(T - 273.16)}{(T - 32.19)}\right) \tag{8}$$

which can be differentiated to give:

$$\frac{dr_s(T)}{dT} = r_s \frac{4217}{(T - 32.19)^2} \tag{9}$$

Relative humidity

$$RH = \frac{e}{e_s} \approx \frac{r_v}{r_s}. \tag{10}$$

Microphysics

Approximate diffusion equation for radius $r > 1$ μm droplets:

$$\frac{dr}{dt} \simeq \frac{De_s(\infty)}{\rho_L r R_v T}(S - 1) \tag{11}$$

Radiation

Stephan-Boltzmann Law for black body emission :

$$E = \sigma T^4 \tag{12}$$

Optical Thickness/Depth:

$$\delta_\lambda = \int_{z_1}^{z_2} k_\lambda^e \rho sec\theta dz. \tag{13}$$

Transmittance τ is related to optical depth by

$$\tau_\lambda = e^{-\delta_\lambda} \tag{14}$$

solid angle

$$\Omega = \frac{A}{r^2} \tag{15}$$

Gas constant for dry air	R_d	287.06	J kg^{-1} K^{-1}
Gas constant for vapour	R_v	461.5	J kg^{-1} K^{-1}
Density of liquid water	ρ_l	1000	kg m^{-3}
Universal Gas Constant	R	8.314	J K^{-1} mol^{-1}
Specific heat capacity at constant pressure for dry air	c_p	1005	J kg^{-1} K^{-1}
Specific heat capacity at constant volume for dry air	c_v	718	J kg^{-1} K^{-1}
Latent heat of vaporization	L_v	2.5×10^6	J kg^{-1}
Density of liquid water	ρ_L	1000	kg m^{-3}
Vapour diffusion coefficient	D	$\approx 2.2 \times 10^{-5}$	m$^2 s^{-1}$
Stefan Boltzmann constant	σ	5.67×10^{-8}	Wm^{-2} K^{-4}
radius of the earth	r_e	6340	km
radius of the sun	r_s	0.7×10^6	km
distance between earth and sun	r_d	149.6×10^6	km
Solar Constant	S_0	1370	W m^{-2}
Planetary albedo	α_p	0.3	
Planck Constant	h	6.625×10^{-34}	J s
Constant c_1 in Planck's Law	c_1	3.74×10^{-16}	W m^{-2}
Constant c_2 in Planck's Law	c_2	1.45×10^{-2}	m K

Table 1: Constants

Questions

1. Radiation

   i (2pt) What fraction of the radiative flux emitted by the sun does the earth intercept?

   ii (1pt) In ONE sentence, explain what is the scattering phase function $P(\theta', \phi', \theta, \phi)$ where θ and ϕ are azimuth and elevation angles?

   iii (1pt) What simplifying approximation we make about P in the Rayleigh scattering regime?

   iv (1pt) Can scattering of solar radiation by clouds be treated using the Rayleigh approximation (yes/no) and why?

   v (2pt) A cloud contains droplets that scatter 99% of the incident light at visible wavelengths in the forward direction. Explain why clouds that are optically thick can have albedo exceeding 70% and are dark when viewed from below.

   vi (2pt) Atmospheric gases absorb radiation at specific wavelengths which are not discrete, but are broadened by the line broadening mechanisms of pressure broadening, Doppler broadening and natural broadening. Which one dominates in the lower troposphere and which one dominates in the stratosphere?

   vii (2pt) With the aid of a sketch of absorbing bands (the x axis should be wavelength or wavenumber), explain what it means for an atmospheric gas to be absorbing in the "strong limit" and the "weak limit".

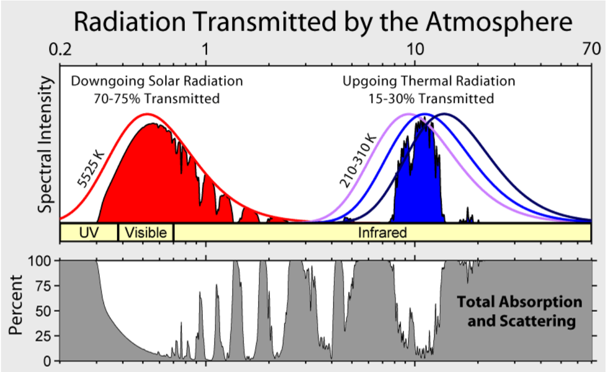

Figure 1: Upper panel shows the transmitted radiation in comparison to theoretical blackbody curves. Lower panels show the percentage absorptance

viii (2pt) On your sketch, mark the wavelength (or wavenumber) where a satellite would measure in order to "retrieve" the amount of a gas, and state in ONE sentence why you chose this wavelength.

2. Radiation: general concepts and definitions

i (3pt) Take a look at Figure 1. Approximately 75% of the solar radiation is transmitted by the atmosphere. Give the THREE major contributions to the 25% extinction by the atmosphere.

ii (1pt) A parallel beam radiation of wavelength λ is passing vertically through a layer of 1 km in thickness, containing a homogeneous gas with a density of 0.01 kg m^{-3} with an absorption coefficient k^e_λ=0.1 m^2 kg^{-1} and a zero scattering coefficient. What is the optical thickness of the layer?

iii (1pt) What is the transmissivity τ of the layer?

iv (2pt) How thick would the layer have to be to absorb half of the incidence radiation beam?

3. Microphysics

i (2pt) A process important in clouds is collision and coalescence where we imagine a large raindrop of radius R falling at its terminal velocity V_t collecting other smaller, slower moving droplets. Give the relationship for the volume of air swept out by the larger droplet in time t.

ii (2pt) We assume the cloud droplets of radius r are much smaller than the raindrop, $r << R$, and that their terminal velocities are also negligibly small (we assume they are at rest), What is the rate of change of mass dM/Dt of the raindrop for a cloud of absolute liquid water density L (kg m^{-3})?

iii (2pt) The rate of change of mass is related to the raindrop radius by $\frac{dM}{dt} = 4\pi R^2 \rho_L \frac{dr}{dt}$. Assuming a terminal fallspeed of $V_t = X_1 r^2$ where $X_1 = 1.2 \times 10^8 \text{s}^{-1}$ m^{-1}, calculate the time taken for a droplet to grow from 20μm to 30 μm by this process in a cloud with mean absolute liquid water density of $L = 1.0 \times 10^{-3}$ kg m^{-3}.

iv (2pt) Growth rates from this process are lower than we calculated here. Apart from the stated assumption $r << R$, state two further approximations that have been made in this calculation, that if corrected for, lead to the lower growth rates.

4. Ice Microphysics

i (2pt) Name two properties that an atmospheric aerosol should have to be an effective ice nuclei.

ii (1pt) Aerosols can become effective ice nuclei at supersaturations of order 10%, and yet often supersaturations **with respect to ice** in excess of 50% can be measured in the upper atmosphere at cold temperatures. In ONE sentence explain why this is the case.

iii (2pt) The observation of which kind of cloud *with which characteristic* provides evidence of a supersaturated upper troposphere?

iv (2 pt) Two air parcels at very cold temperature ($< 200K$) are lifted until ice crystals form. The two parcels are identical (same starting pressure, temperature and vertical velocity) except that parcel A contains no ice nuclei, while parcel B contains some aerosols that act as ice nuclei. At the end of the process (i.e. when the ice crystals have grown by diffusion and the relative humidity with respect to ice has reduced back towards 100%), which parcel contains the most ice crystals and why?

v (2pt) Now imagine two parcels of air at -15^oC containing an ice crystal, both with a supersaturation of 10% with respect to ice. Parcel A contains many liquid cloud droplets while parcel B has none. In which parcel does the ice crystal grow fastest and why?

vi (2pt) ice crystal numbers are often far larger than expected at temperatures warmer than -10C. Name two potential ice multiplication mechanisms.

5. Convection (6 pt)

i (2pt) Describe what the convective inhibition (CIN) is and why it is relevant - between which levels is it defined?

ii (2pt) What is the convective available potential energy(CAPE) calculated for cloudy updraught air that has a temperature excess with respect to its environment of 2K from 900 to 200 hPa?

iii (2pt) Explain (BRIEFLY in two or three sentences!!!) how convectively-generated downdraughts can lead to long-live multi-cellular convection. For example, what is the relevant machanism for new convective cells to initiate within a squall line?

iv (2pt) Given your previous answer, is the convective trigger temperature relevant for forecasting squall lines and why?