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Examination paper for FY3201 Atmospheric Physics and Climate Change

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Permitted examination support material:

Single or Bi-lingual dictionary permitted
All calculators permitted
1 side of an A5 sheet with printed or handwritten formulas permitted

Other information:

Language: English

Number of pages: 5 + cover

Number of pages enclosed:

Checked by:

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Date Signature

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Department of Physics

EXAMINATION IN FY3201 ATMOSPHERIC PHYSICS AND CLIMATE CHANGE
Faculty for Natural Sciences and Technology
27 may 2019
Time: 09:00-13:00

Number of pages: 14

Permitted help sources: 1 side of an A5 sheet with printed or handwritten formulas permitted
Single or Bi-lingual dictionary permitted
All calculators permitted

You may take:

Molar mass of dry air: ~29 kg/kmole
Molar mass of helium: ~4 kg/kmole
Molar mass of H_2O: ~18 kg/kmole

$N_A = 6.02 \times 10^{23}$ molecules/mole Boltzmann's constant $k = 1.38 \times 10^{-23}$ J/K

273.15 K = 0 °C 1 hPa = 10^2 Pa $=10^2$ N m^{-2} g=9.8 m s^{-2} and constant in z

Stefan–Boltzmann constant: $\sigma = 5.67\times10^{-8}$ W·m^{-2}·K^{-4}

Solar photospheric temperature, T_s = 5786 K Radius of the Sun = 695800 km

Radius of the Earth = 6370 km 1 AU (Earth-Sun distance) $=150 \times 10^6$ km

Latent heat of vaporization water: $L_v = 2.5 \times 10^6$ J· kg^{-1}

Latent heat of sublimation ice: $L_i = 2.8 \times 10^6$ J· kg^{-1}

Gas constant for water vapour: R_v=461 J·K^{-1}·kg^{-1}

Values for dry air: C_p=1004 J·K^{-1}·kg^{-1} C_v=718 J·K^{-1}·kg^{-1} R_d=287 J·K^{-1}·kg^{-1}

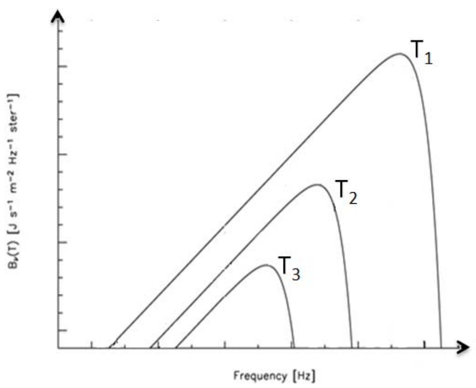
$\gamma = C_p / C_v$ $\kappa = R_d / C_p$ $R_d = C_p - C_v$ Γ_{da}=9.8 K/km

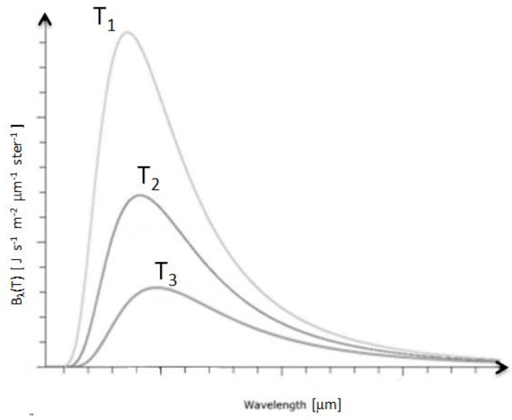
Clausius–Clapeyron relation: $e_s = 6.112\,hPa \cdot \exp\left[\frac{L_v}{R_v}\left(\frac{1}{273K} - \frac{1}{T}\right)\right]$

Answer all questions (English, Norwegian, or Swedish).
State all assumptions.
Good Luck!

1) (5%) Black body radiation

Sketch the spectral radiance (with intensity on the y-axis and wavelength on the x-axis) for three blackbodies at temperatures $T_1 > T_2 > T_3$. Label the curves with their temperatures and give the units used for the axes.



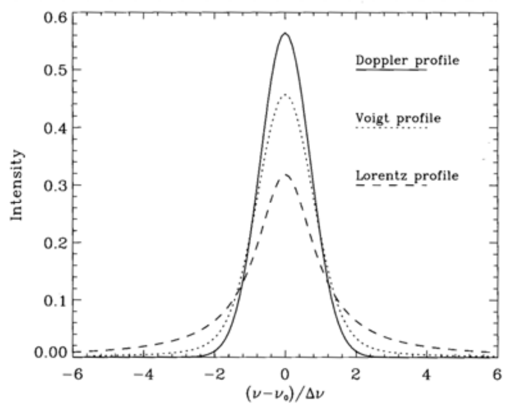


Radiance units should be correct, although I would accept either wavelength or wavenumber units (either the left or right plot). I do not need the actual temperatures on the curves or the numbers on the axes. Curves should not cross, and the hottest temperature, T1, should peak at shorter wavelengths (higher frequencies).

2) (5%) Atmospheric Spectroscopy

Greenhouse gases absorb photons at specific wavelengths corresponding to the energy differences of the internal energy states of the molecule. However, there is a range of wavelengths about the line centre, ν_o, which can also absorb. Sketch the relative absorption coefficients, k_ν, for an absorption line at temperature T for both high and low pressures. For the y-axis, use $(\nu - \nu_o)/\alpha$, the distance from the line centre measured in line-widths, α. Label the two curves with the line shape type.

By definition, a greenhouse gas is transparent in the visible and absorbs in the infrared. Since we are looking at infrared absorption, the line shape would vary between Doppler and Lorentz-collision broadened. Since the pressure might not be low enough to be pure Doppler, I would also accept Voigt for the low pressure result.



3) (20%) Atmospheric Stability

a) Assuming dry air explain what is meant by (1) a stable, (2) an unstable and (3) a neutrally stable atmosphere. (4%)

Stable: the atmospheric (environmental) temperature profile drops more slowly than the dry adiabatic rate ($\Gamma_{dalr} > \Gamma_{env}$). Any air parcel that is lifted will cool to a temperature lower than the surrounding gas at the new altitude, be heavier and sink back toward its original location.

Unstable: The atmospheric (environmental) temperature profile drops more rapidly than the dry adiabatic lapse rate ($\Gamma_{dalr} < \Gamma_{env}$). Any air parcel that is lifted will cool to a temperature but be warmer than the surrounding gas at the new altitude, be lighter and continue to rise.

Neutrally stable: The atmospheric (environmental) temperature profile drops at the same rate as the dry adiabatic lapse rate ($\Gamma_{dalr} = \Gamma_{env}$). Any air parcel that is lifted will cool to a temperature and be the same temperature as the surrounding gas at the new altitude. Thus it will remain at this position.

b) A meteorological balloon is required to take measurements up to an altitude where the pressure and temperature are 10 hPa and 225 K respectively. The balloon is constructed of a non-stretch material that remains slack (that is, not stretched tightly) until the balloon reaches its peak altitude and has expanded to its full spherical shape. If the balloon contains helium (molecular weight 4 $g \cdot mol^{-1}$), the payload weighs 100 kg and the fabric is of thickness 25 μm and density 1000 $kg \cdot m^{-3}$, what approximate radius of balloon is needed? (8%)

The bottom line is that the downward force due to gravity must be balanced by the buoyancy force. Thus, we must solve:

$g*(m_{payload} + m_{fabric}) = g*(m_{air\_10hPa} - m_{He\_10hPa})$

or $(m_{payload} + \rho_{fabric}*V_{fabric}) = (\rho_{air\_10hPa} - \rho_{He\_10hPa})*V_{balloon}$

The way to look at this is that if I replace a mass of air that is sitting at 10 hPa with a balloon whose total mass (payload, balloon material and helium) is equal to that mass of the air, it, too, will just sit at 10 hPa.

Assuming dry air, we have that at the balloon altitude, the conditions outside are

p=10 hPa = 1000 Pa

T=225 K

$\rho_d = p/(R_d*T)$=1000 Pa/(287J/kg/K*225 K) = 0.015 kg/m^3

Inside the balloon, we have

$p' = p$ = 1000 Pa

$T' = T_{He}$

$\rho' = \rho_{He} = p/(R_{He}*T') = p/(R_{He}*T_{He})$

To get T_{He}, I don't have any information on the ground temperature, and even if I did, I don't know the specific heats for helium to calculate its temperature at float. I must assume that the balloon has been at float altitude long enough so that the helium is at the same temperature as the surrounding air,

T_{He}=225K.

Since the specific gas constant is just R^*/M_{gas}, I can calculate

$R_{He} = R_d*M_d/M_{He}$= 287*29/4 J/K/kg = 2081 J/K/kg, giving ρ_{He} = 0.0021 kg/m^3

At the float altitude, the balloon is spherical with radius R. The approximate volume of balloon material is $4\pi R^2 * t$, where t is the thisckness of the material. Therefore:

$(m_{payload} + m_{fabric}) = 100\ kg + 25x10^{-6}\ m * 4\pi R^2 * 1000\ kg/m^3$

Here we have approximated the volume of the balloon material as the balloon area*thickness. Once could also say that it is the difference between the volume of the outer diameter of the balloon ($4/3\pi R^3$) and the volume of the inner-diameter of the balloon ($4/3\pi(R-t)^3$). The first yields

$4\pi R^2 * t$ while the latter yields

$4/3\pi * t * (3R^2 - 3R * t + t^2)$

Even if the balloon radius were 25μm, the difference would be on the order of 10^{-13} and would approach 0 for larger radii

Mass of air displaced = $\rho_d * 4/3\pi R^3$

Mass of air taking its place = $\rho_{He} * 4/3\pi R^3$

$F_{buoyancy} = g(\rho_d - \rho_{He})\pi * R^3$

And this must balance the total weight of the balloon, $(m_{payload} + m_{fabric})$ if it is floating:

$F_{gravity} = g*(m_{payload} + m_{fabric}) = g*(100\ kg + 25x10^{-6} * 4\pi R^2 * 1000)$

$= g*(100 + 0.1 * \pi R^2)$

So we need to solve for R:

$g(\rho_d - \rho_{He})\pi R^3 = g*(100 + 0.1 * \pi R^2)$

$(0.015 - 0.0021)\pi R^3 = (100 + 0.1 * \pi R^2)$

I could also say that since they are both at the same pressure and temperature: $\rho_{He} = \rho_d * Rd/RHe$, so my left hand side of the equation becomes:

$g * \rho_d (1 - R_d/R_{He}) * 4/3\pi R^3 = g * \rho_d (1 - M_{He}/M_d) * 4/3\pi R^3 = g * \rho_d (1 - 27/4) * 4/3\pi R^3 =$

$= g * \rho_d (0.86) * 4/3\pi R^3$

Either way, I can now solve the cubic for R, or if you just come down to something like:

$\rho_d (0.86) * 4/3\pi R^3 = (100 + 25x10^{-6} * 4\pi R^2 * 1000)$

or since the density of air at the float altitude is 0.014 kg/m3

$(0.015 * 0.86 * 4/3\pi) * R^3 = 100 + 0.314 * R^2$

Or

$100 = 0.056 * R^3 – 0.314 * R^2$

If you can solve cubic equations, this comes out to be **R=14.3 m**, but really, any of the above equations would give full points as long as you had it in terms of one density and R.

Now, due to the wonders of the new digital exam system, someone in the chain cut and pasted the question and lost the formatting. Thus, a 25 μ balloon came out to be 25 mm! This makes the mass of the balloon $100*\pi R^2$, and the diameter of the **balloon 5618 m**! Obviously, this is ridiculous, but that is what it comes out to be with the mistake in the digital copy that was sent to you. So, it will be accepted.

c) Assuming the mean temperature of 255 K between the surface, where the pressure is 1000 hPa, and the balloon altitude at 10 hPa, what is the altitude of the balloon in metres? (4%)
Ah, a problem where we have a constant temperature between two pressure levels and you are asked to calculate the difference in height between these pressure levels. This cries out for the hypsometric equation:
$Z_2 - Z_1 = R*\langle T\rangle/g*\ln(p_1/p_2)$. So taking the 1 subscript to be 1000 hPa = 100000 Pa, and the 2 subscript to be 10 hPa = 1000 Pa, we have:
$Z_2 - 0 = 287*255/9.8 * \ln(100)$ = **34390.7 m or about 34 km**, well into the stratosphere.

d) Assuming the atmosphere is stable with respect to vertical motion, estimate the temperature at the surface where the pressure is 1000 hPa. (4%)
Here you need to use the potential temperature. If the atmosphere is neutrally stable, then the potential temperature would be constant in altitude. It is most convenient to use the float altitude where the temperature is 255 K and the pressure is 10 hPa to calculate that θ = 225 K. Then the temperature at any other altitude, where θ is still 225 K, is.
$T=\theta*(P/P_0)^{\kappa}$, where $\kappa = R_d/C_p = 0.286$. If the altitude is the surface, where P:=1000 hPa, then P_0=10 hPa gives T at the surface to be T=839 K. This is, of course, the maximum temperature that would create stable conditions, so any temperature lower than this would also be stable. That is, a parcel at 839 K on the ground, if transported up to 34 km, would just be at the temperature of the surrounding air. Below 34 km, it would be cooler than the surrounding air. Thus, any parcel at a lower temperature at the ground would be cooler than its surroundings up to and including 34 km, so the atmosphere is very stable. So we could say, **$T_{ground} \leq 839$ K**

If one tries to use the idea of the first order approximation to a constant θ, a constant lapse rate of Γ_{dalr}=9.8 K/km, one comes up with about 562 K. Since this is only a first order approximation, it is unlikely to hold over 34 km! However, I will give 1 point for this solution.

Either way, it shows how Hollywood gets it wrong in movies like “The day after tomorrow”, where they say that the storm is bringing air down from the stratosphere and will freeze everything. In fact, that air would be over 900 K, and freezing would be the last of your problems!

4) (20%) Atmospheric thermodynamics, water vapour and structure

a) Calculate the period of oscillation of an air parcel given that $dT/dz = -6.5$ K·km^{-1} and T = 270 K. (6%)

The formula for the Brunt-Väisälä frequency is $N^2 := g/T*(\Gamma_d - \Gamma)$, where Γ_d is the dry adiabatic lapse rate, g/C_p, and Γ is the atmospheric lapse rate is:
$\Gamma = -dT/dZ = 6.5\ K\cdot km^{-1} = 0.0065$ K/km.
Substituting in the values
$N^2 = 9.8/270*(0.00976-0.0065)$ (remember, both in K/km or K/m, and g/Cp will give K/m)
This gives $N^2 = 1.183x10-4\ (rad/s)^2$, or the buoyancy frequency N=0.0109 rad/s. For a frequency in Hz, divide by 2π to get N = 0.0017 Hz. This makes the period <u>**τ_{Brunt} = 577.53 sec or 9.62 minutes**</u>.

b) Air at a temperature 20°C and pressure 1000hPa has a dew point of 15°C. What is (1) its relative humidity and (2) its water vapour mass mixing ratio? (6%)

Consider this practice for the problem below. The expression for the saturation vapour pressure of water vapour is listed in the equations, giving at T_d=288.15: $e_s(T_d)$=17.37 hPa. Now, we know that $\mu(T_o,P_o) = \mu_s(T_d,P_o)$, which, when cancelling all the ε and Po factors in the expression for mass mixing ratio means that $e(T_o) = e_s(T_d)$, so $e(T_o)$ = 17.37 hPa. How much water could the air hold at T_o? Well just calculate $e_s(T_o)$ using the formula to get $e_s(T_o$=293.15)=23.94 hPa. The <u>**Relative humidity is $e(T_o)/e_s(T_o)$ = 17.37/23.94 = 72.5%**</u>
To find the mass mixing ratio of water in the air, just multiply $e_s(T_d)$=17.37 hPa by ε=Mv/Md and divide by Po=1000 hPa. This gives **$\mu(T_o,P_o)$=0.0107, which is the mixing ratio, μ, in the parcel at T=293.15 K, P=1000 hPa**.

c) Air initially at sea level with a temperature 20°C and dew point 15°C is forced to rise over a mountain of height 1000 m. What are the temperature, dew point and relative humidity of the air when it has sunk to a level 200m above sea level on the other side of the mountain? (assume no precipitation takes place). (8%)

Since we are allowed to assume that no precipitation takes place, the process will be reversible and the conditions 0→1000 m→200 m will be the same as if the parcel went from 0→200 m. We will also assume the surface pressure to be 1000 hPa.

The question is whether the air will be saturated at 200 m. To do this we need to know what the environmental conditions are.

First we assume that no condensation takes place. This will allow the parcel to be transported to 200 m and cool according to the adiabatic lapse rate. Then we can calculate the pressure at this altitude again assuming no condensation takes place by conserving potential temperature. We can then check to see if the saturated mass mixing ratio at this new temperature pressure, T1 and P1, is greater than the mass mixing ratio in the parcel. If it is, then our assumption of no condensation holds. If not, we should adjust T by the latent heat of vaporization for the amount of water vapour turned into liquid water, and then adjust P accordingly.

The parcel moving upward will decrease temperature according to the dry adiabatic lapse rate, T=To-g/Cp*Z. For the pressure at this altitude, we can derive from the hydrostatic equation and the ideal gas law that dP/P = -

g/(R*T)*dZ and integrate from 0 to Z. However, we could also use the fact that an atmosphere with a temperature gradient equal to the dry adiabatic lapse rate will have a constant potential temperature at each altitude. Thus, at Po, $\theta = To*(Po/(P=Po))^{\kappa}$, or θ =To= 293.15 K. To get the pressure at any other altitude, we can solve the potential temperature equation for P:
$P = Po*(T/\theta)^{1/\kappa} = Po(T/\theta)$^$(C_p/R)$, where T is given by $T=To-g/C_p*Z$. This is exactly the result you get if you integrate the hydrostatic equation.

So, at Z=200 m, **T=291.2 K, giving P=976.897 hPa**
If no condensation takes place in the parcel, this will also be the temperature of the parcel at this pressure. If condensation has taken place, the parcel will be warmer.

Now we just need to determine if the moisture in the parcel becomes saturated as it moves to 200 m. We have assumed the surface pressure; Po, to be 1000 hPa, so, first calculate the saturated mass mixing ratio of water at the surface, which is the mass mixing ratio of water in the parcel.

We are given To = 20 C = 293.15K, and T_d=15 C = 288.15. The expression for $\mu_s = \varepsilon \cdot e_s(T_d)/Po$, where ε is (approximately) equal to the ratio of the mass of water vapour to that of dry air, or 18/29 = 0.62.

The expression for the saturation vapour pressure of water vapour is listed in the equations, giving at T_d=288.15: es=17.37 hPa. This would give a saturation mass mixing ratio at a temperature of T_d=288.15K, P=1000 hPa of μ_s=0.0107, which is the mixing ratio, μ, in the parcel at T_o=293.15 K, P=1000 hPa.

Now calculate the saturated mixing ratio at 200 m. If the saturated mixing ratio at 200 m is greater than the amount of water we have in the parcel, then we are safe to just calculate the adiabatic temperature of a parcel moving with constant θ.

We have calculated that at 200 m the air temperature is 291.2 K and the pressure is 976.9 hPa. Calculating μ_s at this pressure and temperature gives μ_s = 0.0134. Since this is greater than the amount of water in the parcel, μ=0.0107, the parcel has not saturated, **no condensation has taken place and the parcel pressure and temperature are equal to the air pressure and temperature, T=291.2 K, P=976.9 hPa.**

You might try this with an isothermal profile. Now P=Po*exp(-Z/H), where H is the scale height $H=R*T_o/g$=8585.1 m, or P=976.973 hPa. In fact, this only differs from the potential temperature calculation in the second decimal place by 8 parts in 100. This will yield a slightly higher pressure, giving a lower value of μ_s at 200 m that differs in the 7th decimal place. This would also be acceptable.

5) **(20%) Radiation**

a) (4%)Define (that is give the units) and the connection between:

1. Spectral radiance

   $W \cdot m^{-2} \cdot sr^{-1} \cdot nm$. The energy flux in a unit wavelength unit that is emitted in a direction within a unit solid angle. Could be given as W=photon/s, and wavelength units (nm, m, μ, etc) or frequency or wavenumber units (Hz or cm^{-1}) for all answers.

2. Radiance

   $W \cdot m^{-2} \cdot sr^{-1}$. The energy flux integrated over wavelength that is emitted in a direction within a unit solid angle. This would be the Spectral radiance integrated over wavelength to represent the total energy within that wavelength band.

3. Irradiance

   $W \cdot m^{-2}$. The energy flux integrated over wavelength and solid angle. Represents the total energy flux into a hemisphere.

b) Mars has a radius of 3389.5 km and the distance to the sun is 1.524 AU (astronomical units). If its surface albedo is 0.250, calculate its radiative equilibrium temperature assuming no atmosphere. (6%)

If one remembers the solar constant, Fe=1367 $W \cdot m^{-2}$, one could scale that. However, the solar temperature is given so the total power emitted at each unit are of the surface of the sun would be $Fs=\sigma T^4$, or
$5.67\times10^{-8}\ W \cdot m^{-2} \cdot K^{-4} * (5786\ K)^4 = 6.35x10^7\ W \cdot m^{-2}$.
So the total energy emitted by the sun in watts would be this times the surface area of the sun=4*π*Rs^2. This yields $3.9x10^{26}$ Watts. This energy is emitted over 4π sr, or into a sphere. At the orbit of the Earth, this energy would be spread over a sphere of area of $4*\pi*(Reo)^2$, where Reo = $150x10^9$ m. That is, one would divide by this area, so that the solar flux at any orbital distance is given by: $Fs*(Rs/R_{orbit})^2$. So at the Earth's orbit we have
$Fe=6.35x10^7\ W \cdot m^{-2}*(6.958x10^8/1.5x10^{11})^2=1367.36\ W \cdot m^{-2}$. At the orbit of Mars, $Rmo=Reo*1.524=2.29x10^{11}$ m, so the using Rmo as R_{orbit} yields a flux at Mars $Fm=588.7\ W \cdot m^{-2}$.

If one remembered the Fe, and then scaled the Earth value, one would use $Fe*4\pi Re^2/(4\pi Rm^2)$, which comes out to be $Fe*(1/1.524)^2$, giving the same value $Fm=588.7\ W \cdot m^{-2}$

Now, we have Fm, and an albedo or 0.25. With no other information, we need to take the no atmosphere situation and calculate radiative balance.
$Fm*(1-A)*\pi(Rm)^2 = \sigma(Tm)^4*4*\pi(Rm)^2$. Solving for Tm, we obtain:
$Tm=(1/4*(1-A)*Fm/\sigma)^{1/4}$. Substituting in values we get **Tm=210 K**

c) The surface temperature of Mars is measured to be 242 K, what is the long-wavelength optical depth and transmission of the Martian atmosphere assuming the short-wavelength transmission is 1? (4%)

So here we are asking you to include an atmosphere. I will refer you to the notes of lecture 3, where the beam coming to the earth is reduced by $T_{s\lambda}$, in this case 1, and the outgoing radiation reduced by $T_{L\lambda}$ by atmospheric absorption. One also has to take into account that the energy absorbed in the long wavelengths will heat the atmosphere, which itself will radiate in both directions as $\sigma(Ta)^4$. This yields radiative balance equations (input equal to output) at the top of the atmosphere and the surface of the earth. Eliminating Ta from these two equations and solving for Tm, we get the equation:

$$\sigma_B \cdot T_m^4 = \frac{1}{4}(1-A) \cdot F_m \cdot \frac{1+T_{s\lambda}}{1+T_{L\lambda}}$$

We can solve for $T_{L\lambda}$ in this equation as:

$T_{L\lambda}$=(1/4*(1-A)*Fm*(1+$T_{S\lambda}$)/(σ(Tm)^4))-1

With $T_{S\lambda}$=1, and Tm = 242 K, and albedo A=0.25, we get

$T_{L\lambda}$=(1/4*(1-A)*Fm*2)/(σ(Tm)^4))-1

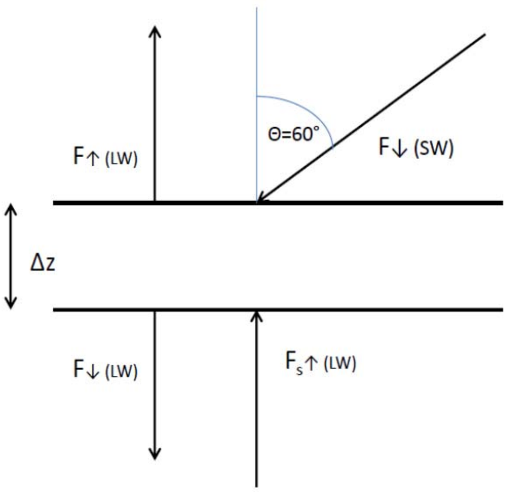
or

$T_{L\lambda}$ = 0.13527, or about 13% transmission.

Since $T_{L\lambda}$ =exp(-τ), where τ is the optical depth, we can solve for τ to be:

τ = -ln($T_{L\lambda}$) = 2, so the atmosphere is optically thick.

d) In the figure below, a layer in the atmosphere of thickness Δz and density ρ resevies and emits radiation. The layer receives short-wavelength radiation F↓(SW) that is at a zenith angle of θ=60°, and long-wavelength radiation F_s↑(LW) from directly below. In the layer, the species that absorb short wavelength radiation have a mixing ration of ν_{abs}(SW) and a mass-absorption coefficient of k_{abs}(SW). The mixing ratio of species that absorb long wavelength radiation have a mixing ratio of ν_{abs}(LW) and a mass-absorption coefficient k_{abs}(LW). The flux of short wavelength radiation, F↓(SW), is given for a surface normal (90°) to the direction of the incoming radiation. Assuming the layer is in radiative equilibrium, calculate the temperature of the layer. (6%)



ρ = 0.2 kg·m^{-3}

F↓(SW) = 800 W·m^{-2}

k_{abs}(SW) = 100 m^2·kg^{-1}

k_{abs}(LW) = 100 m^2·kg^{-1}

ν_{abs}(SW) = 1.0x10^{-5}

ν_{abs}(LW) = 3.0x10^{-4}

Δz = 500 m

F_s↑(LW) = 200 W·m^{-2}

The situation we have is that the layer is heated by absorption of both short and long wavelength radiation, but is cooled by the emission of long wavelength radiation.

Absorption of short wavelength radiation

The energy per m^2 incident on the layer from short wavelength radiation would be $F\downarrow(SW)\cdot\cos(\theta)$, where $F\downarrow(SW)$ is the vertical downward flux.
The optical depth of the layer is given by:

$\tau_{sw} = k_{abs}(SW)\cdot\rho\cdot\nu_{abs}(SW)\cdot\Delta z = 0.10$

Remember, the optical depth is defined as the vertical distance, and one needs to account for the horizontal motion with the angle θ. Thus, the transmission will be:

$T_{sw} = e^{-\tau sw/\cos(\theta)} = 0.82$ and of course the absorption would be

$\alpha_{sw} = 1 - T_{sw} = 1 - e^{-\tau/\cos(\theta)} = 0.18$

So, the short wavelength radiative energy absorbed is the layer, *SW* ($\Delta F_a(SW)$):

$\Delta F_a(SW) = \alpha_{sw}\cdot F\downarrow(SW)\cdot\cos(\theta) = 72.5\ Wm^{-2}$

Absorption of long wavelength radiation

The energy per m^2 incident on the layer from long wavelength radiation would be $F_s\uparrow(LW)$, the vertical upward flux from the surface.
The optical depth for long wavelength radiation is given by:

$\tau_{LW} = k_{abs}(LW)\cdot\rho\cdot\nu_{abs}(LW)\cdot\Delta z = 3.0$

Again, the transmission and absorption long wavelength radiation for this vertical beam is:

$T_{LW} = e^{-\tau} = 0.05$, $\alpha_{LW} = 1 - T_{LW} = = 1 - e^{-\tau LW} = 0.95$

And as a result, the long wavelength radiative energy absorbed in the layer, *LW* ($\Delta Fa(LW)$) *is:*

$\Delta F_a(LW) = \alpha_{LW}\cdot F_s\uparrow(LW) = 190.0\ Wm^{-2}$

The final term we need is the cooling of the layer by the emission of long wavelength radiation

The layer at temperature T will emit long wavelength radiation per square metre as:

$\Delta F_E(LW) = \varepsilon\sigma T^4$

Where T ε is the long wavelength emissivity. Now, Mr. Kirchoff has told us that emissivity is equal to absorptivity, α_{LW}, and we have already calculated that above to be 0.95.

Now, at the top-side of the layer (taking energy leaving the layer as negative) we have:

$-\Delta F_E(LW) + \Delta F_a(SW) = 0 = -\varepsilon\sigma T^4 + \alpha_{sw}\cdot F\downarrow(SW)\cdot\cos(\theta)$

And at the bottom side:

$-\Delta F_E(LW) + \Delta F_a(LW) = 0 = -\varepsilon\sigma T^4 + \alpha_{LW}\cdot F_s\uparrow(LW)$.

Combining these, we have

$\alpha_{sw}\cdot F\downarrow(SW)\cdot\cos(\theta) + \alpha_{LW}\cdot F_s\uparrow(LW) = 2\cdot\varepsilon\sigma T^4$

Or $T = ((\alpha_{sw}\cdot F\downarrow(SW)\cdot\cos(\theta) + \alpha_{LW}\cdot F_s\uparrow(LW))/(2\varepsilon\sigma))^{1/4}$

Substituting in values, we get **$T=222$ K**

There is only **one** correct answer so you must **choose the best answer**.
Answer A, B, C… (Capital letters).
Correct answer gives +3; incorrect or blank answers give 0.

Write the answers for the multiple choice questions **on the answer sheet you turn in** using a table similar to the following:

Question	a	b	c	d	e	f	g	h	i	j
Answer										

6) At which wavelength does the Earth's blackbody irradiance peak?

   A) ~150 nm B) ~550 nm C) ~1500 nm **D) ~15000 nm** E) ~150000 nm

7) If the atmospheric absorption of carbon dioxide at 15 μm becomes saturated, what happens if carbon dioxide levels continue to increase?
   A) Total absorption stays the same because it is saturated
   B) Total absorption begins to decrease near the band centre as it saturates
   C) The absorption continues to increase but only near the band centre
   D) Total absorption increases as lines farther from the band centre begin to saturate
   E) None of the above

8) If an atmospheric lapse rate of 6 K/km is measured, which of the following is true?
   A) The temperature falls with altitude and the atmosphere is absolutely unstable
   B) The temperature falls with altitude and the atmosphere is conditionally unstable
   C) The temperature rises with altitude and the atmosphere is conditionally stable
   D) The temperature rises with altitude and the atmosphere is conditionally unstable
   E) The temperature rises with altitude and the atmosphere is absolutely stable

9) Describe the change in the Earth's visible albedo if the polar ice caps melt.
   A) It will increase
   B) It will first increase and then decrease
   C) It will not change
   D) It will first decrease and then increase
   E) It will decrease
   F) None of the above.

10) In which layer of the atmosphere is ozone the major species?

A) Stratosphere
B) Mesosphere.
C) Troposphere.
D) Thermosphere.
E) Exosphere.
F) None of the above.

11) A small cloud droplet will evaporate __________ a large cloud droplet?

A) At the same rate as
B) More slowly than
C) Faster than
D) It will not evaporate
E) None of the above

12) Which two atmospheric layers would the mean temperature profiles be stable against convection?

A) Mesosphere and Stratosphere
B) Mesosphere and Thermosphere
C) Mesosphere and Troposphere
D) Stratosphere and Thermosphere
E) Stratosphere and Troposphere
F) The atmosphere is never stable against convection

13) From what phenomenon does the Coriolis effect arise?

A. Curvature of the Earth's surface
B. Rotation of the spherical Earth around its axis
C. Rotation of the spherical Earth around the sun
D. Effect of winds high in the atmosphere.
E. Motion of the oceans in their basins
F. None of the above.

14) In late afternoon at the Equator, in which direction would you look to find a rainbow?

A) North
B) South
C) East
D) West
E) There are no rainbows at the equator due to the high sun angles

15) If no feedbacks are includes, what would the climate sensitivity factor be for a ±1% change in solar irradiance?

A) 72 °C per fractional change in solar irradiance
B) 30 °C per fractional change in solar irradiance
C) 200 °C per fractional change in solar irradiance
D) -72 °C per fractional change in solar irradiance
E) -30 °C per fractional change in solar irradiance
F) -200 °C per fractional change in solar irradiance