NTNU

Department of Physics (IFY)

Examination paper for FY3201/FY8902 Atmospheric physics and climate change

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Examination date: 9 June 2023

Examination time (from-to): 09:00-13:00

Permitted examination support material: Code G:

Textbook (or printed pdf of textbook) with no annotations inside

One SIDE of A5 paper with handwritten or printed notes

ALL calculators are allowed.

Other information:

Language: English

Number of pages (front page excluded): 7 pages

Number of pages enclosed: 7 pages (plus cover sheet)

Informasjon om trykking av eksamensoppgave

Originalen er:

1-sidig X **2-sidig □**

sort/hvit □ **farger X**

skal ha flervalgskjema □

Checked by:

Date Signature

Students will find the examination results in Studentweb. Please contact the department if you have questions about your results. The Examinations Office will not be able to answer this.

For multiple choice questions, each incorrect or blank answer will score zero points. Answers have been randomized and are not exact. You must choose the best answer. For all calculations use SI units!

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
Molar mass of CO_2: ~44 kg/kmole

$273\ K = 0\ ^oC$ $\quad$ $1\ hPa = 10^2\ Pa = 10^2\ N\ m^{-2}$ $\quad$ $1\ atm = 1013\ hPa$ $\quad$ $g=9.8\ m\ s^{-2}$ constant in z $\quad$ $c=3\ x10^8\ m\cdot s^{-1}$

Avagadro's number: $N_A = 6.02x10^{23}$ molecules/mole
Boltzmann's constant $k = 1.38x10^{-23} J/K$

Stefan–Boltzmann constant: $\sigma = 5.67\times10^{-8}\ W\cdot m^{-2}\cdot K^{-4}$
Planck Constant: $h=6.63x10^{-34}\ J\cdot s$

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

Radius of the Earth = 6370 km
1 AU (Earth-Sun distance) =$150x10^6$ km

Radius of Venus = 6051 km
Venus-Sun distance = 0.72 AU

Radius of Mars = 3396 km
Mars-Sun distance = 1.52 AU

Latent heat of vaporization water: $L_v=2.5x10^6\ J\cdot kg^{-1}$
Density of liquid water = $1000\ kg\cdot m^{-3}$

Latent heat of sublimation ice: $L_i=2.8x10^6\ J\cdot kg^{-1}$
Density of water vapour = $5x10^{-3}\ kg\cdot m^{-3}$

Gas constant for water vapour: $R_v=461\ J\cdot K^{-1}\cdot kg^{-1}$
Surface tension of water droplet $75x10^{-3}\ N\cdot m^{-1}$

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

$\gamma = C_p / C_v$ $\quad$ $\kappa = R_d / C_p$ $\quad$ $R_d=C_p - C_v$ $\quad$ $\Gamma_{dalr}=9.8\ K/km$

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

Some integrals that may be of use:

$$\int x^m e^{(a\,x)}\,dx = \frac{x^m e^{(a\,x)}}{a} - \frac{m\int x^{(m-1)} e^{(a\,x)}\,dx}{a}$$

$$\int x\,e^{(a\,x)}\,dx = \frac{e^{(a\,x)}(a\,x-1)}{a^2}$$

$$\text{For a} > 0 \quad \int_o^\infty e^{(-a\,x)}\,dx = \frac{1}{a}$$

$$\int_X^\infty e^{(-a\,x)}\,dx = \frac{e^{(-a\,X)}}{a}$$

$$\int \frac{1}{a+b\,x}\,dx = \frac{\ln(a+b\,x)}{b}$$

PERIODIC TABLE OF ELEMENTS

Atomic #
Symbol
Name
Weight

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals
- Alkali metals
- Alkaline earth metals
- Lanthanoids (Lanthanides)
- Actinoids (Actinides)
- Transition metals
- Post-transition metals

Metalloids

Nonmetals
- Other nonmetals
- Noble gases

Pnictogens (15) · Chalcogens (16) · Halogens (17)

Shells: K L M N O P Q

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 **H** Hydrogen 1.008 1																	2 **He** Helium 4.0026 2
2	3 **Li** Lithium 6.94 2 1	4 **Be** Beryllium 9.0122 2 2											5 **B** Boron 10.81 2 3	6 **C** Carbon 12.011 2 4	7 **N** Nitrogen 14.007 2 5	8 **O** Oxygen 15.999 2 6	9 **F** Fluorine 18.998 2 7	10 **Ne** Neon 20.180 2 8
3	11 **Na** Sodium 22.990 2 8 1	12 **Mg** Magnesium 24.305 2 8 2											13 **Al** Aluminium 26.982 2 8 3	14 **Si** Silicon 28.085 2 8 4	15 **P** Phosphorus 30.974 2 8 5	16 **S** Sulfur 32.06 2 8 6	17 **Cl** Chlorine 35.45 2 8 7	18 **Ar** Argon 39.948 2 8 8
4	19 **K** Potassium 39.098 2 8 8 1	20 **Ca** Calcium 40.078 2 8 8 2	21 **Sc** Scandium 44.956 2 8 9 2	22 **Ti** Titanium 47.867 2 8 10 2	23 **V** Vanadium 50.942 2 8 11 2	24 **Cr** Chromium 51.996 2 8 13 1	25 **Mn** Manganese 54.938 2 8 13 2	26 **Fe** Iron 55.845 2 8 14 2	27 **Co** Cobalt 58.933 2 8 15 2	28 **Ni** Nickel 58.693 2 8 16 2	29 **Cu** Copper 63.546 2 8 18 1	30 **Zn** Zinc 65.38 2 8 18 2	31 **Ga** Gallium 69.723 2 8 18 3	32 **Ge** Germanium 72.630 2 8 18 4	33 **As** Arsenic 74.922 2 8 18 5	34 **Se** Selenium 78.971 2 8 18 6	35 **Br** Bromine 79.904 2 8 18 7	36 **Kr** Krypton 83.798 2 8 18 8
5	37 **Rb** Rubidium 85.468 2 8 18 8 1	38 **Sr** Strontium 87.62 2 8 18 8 2	39 **Y** Yttrium 88.906 2 8 18 9 2	40 **Zr** Zirconium 91.224 2 8 18 10 2	41 **Nb** Niobium 92.906 2 8 18 12 1	42 **Mo** Molybdenum 95.95 2 8 18 13 1	43 **Tc** Technetium (98) 2 8 18 13 2	44 **Ru** Ruthenium 101.07 2 8 18 15 1	45 **Rh** Rhodium 102.91 2 8 18 16 1	46 **Pd** Palladium 106.42 2 8 18 18	47 **Ag** Silver 107.87 2 8 18 18 1	48 **Cd** Cadmium 112.41 2 8 18 18 2	49 **In** Indium 114.82 2 8 18 18 3	50 **Sn** Tin 118.71 2 8 18 18 4	51 **Sb** Antimony 121.76 2 8 18 18 5	52 **Te** Tellurium 127.60 2 8 18 18 6	53 **I** Iodine 126.90 2 8 18 18 7	54 **Xe** Xenon 131.29 2 8 18 18 8
6	55 **Cs** Caesium 132.91 2 8 18 18 8 1	56 **Ba** Barium 137.33 2 8 18 18 8 2	57–71	72 **Hf** Hafnium 178.49 2 8 18 32 10 2	73 **Ta** Tantalum 180.95 2 8 18 32 11 2	74 **W** Tungsten 183.84 2 8 18 32 12 2	75 **Re** Rhenium 186.21 2 8 18 32 13 2	76 **Os** Osmium 190.23 2 8 18 32 14 2	77 **Ir** Iridium 192.22 2 8 18 32 15 2	78 **Pt** Platinum 195.08 2 8 18 32 17 1	79 **Au** Gold 196.97 2 8 18 32 18 1	80 **Hg** Mercury 200.59 2 8 18 32 18 2	81 **Tl** Thallium 204.38 2 8 18 32 18 3	82 **Pb** Lead 207.2 2 8 18 32 18 4	83 **Bi** Bismuth 208.98 2 8 18 32 18 5	84 **Po** Polonium (209) 2 8 18 32 18 6	85 **At** Astatine (210) 2 8 18 32 18 7	86 **Rn** Radon (222) 2 8 18 32 18 8
7	87 **Fr** Francium (223) 2 8 18 32 18 8 1	88 **Ra** Radium (226) 2 8 18 32 18 8 2	89–103	104 **Rf** Rutherfordium (267) 2 8 18 32 32 10 2	105 **Db** Dubnium (268) 2 8 18 32 32 11 2	106 **Sg** Seaborgium (269) 2 8 18 32 32 12 2	107 **Bh** Bohrium (270) 2 8 18 32 32 13 2	108 **Hs** Hassium (277) 2 8 18 32 32 14 2	109 **Mt** Meitnerium (278) 2 8 18 32 32 15 2	110 **Ds** Darmstadtium (281) 2 8 18 32 32 17 1	111 **Rg** Roentgenium (282) 2 8 18 32 32 18 1	112 **Cn** Copernicium (285) 2 8 18 32 32 18 2	113 **Nh** Nihonium (286) 2 8 18 32 32 18 3	114 **Fl** Flerovium (289) 2 8 18 32 32 18 4	115 **Mc** Moscovium (290) 2 8 18 32 32 18 5	116 **Lv** Livermorium (293) 2 8 18 32 32 18 6	117 **Ts** Tennessine (294) 2 8 18 32 32 18 7	118 **Og** Oganesson (294) 2 8 18 32 32 18 8

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

6	57 **La** Lanthanum 138.91 2 8 18 18 9 2	58 **Ce** Cerium 140.12 2 8 18 19 9 2	59 **Pr** Praseodymium 140.91 2 8 18 21 8 2	60 **Nd** Neodymium 144.24 2 8 18 22 8 2	61 **Pm** Promethium (145) 2 8 18 23 8 2	62 **Sm** Samarium 150.36 2 8 18 24 8 2	63 **Eu** Europium 151.96 2 8 18 25 8 2	64 **Gd** Gadolinium 157.25 2 8 18 25 9 2	65 **Tb** Terbium 158.93 2 8 18 27 8 2	66 **Dy** Dysprosium 162.50 2 8 18 28 8 2	67 **Ho** Holmium 164.93 2 8 18 29 8 2	68 **Er** Erbium 167.26 2 8 18 30 8 2	69 **Tm** Thulium 168.93 2 8 18 31 8 2	70 **Yb** Ytterbium 173.05 2 8 18 32 8 2	71 **Lu** Lutetium 174.97 2 8 18 32 9 2
7	89 **Ac** Actinium (227) 2 8 18 32 18 9 2	90 **Th** Thorium 232.04 2 8 18 32 18 10 2	91 **Pa** Protactinium 231.04 2 8 18 32 20 9 2	92 **U** Uranium 238.03 2 8 18 32 21 9 2	93 **Np** Neptunium (237) 2 8 18 32 22 9 2	94 **Pu** Plutonium (244) 2 8 18 32 24 8 2	95 **Am** Americium (243) 2 8 18 32 25 8 2	96 **Cm** Curium (247) 2 8 18 32 25 9 2	97 **Bk** Berkelium (247) 2 8 18 32 27 8 2	98 **Cf** Californium (251) 2 8 18 32 28 8 2	99 **Es** Einsteinium (252) 2 8 18 32 29 8 2	100 **Fm** Fermium (257) 2 8 18 32 30 8 2	101 **Md** Mendelevium (258) 2 8 18 32 31 8 2	102 **No** Nobelium (259) 2 8 18 32 32 8 2	103 **Lr** Lawrencium (266) 2 8 18 32 32 8 3

Ptable.com

1) (5 pts) A parcel of air at 900 hPa has a temperature of 20 °C. It is lifted adiabatically until the parcel temperature drops to 13 °C. What is the pressure at this altitude?

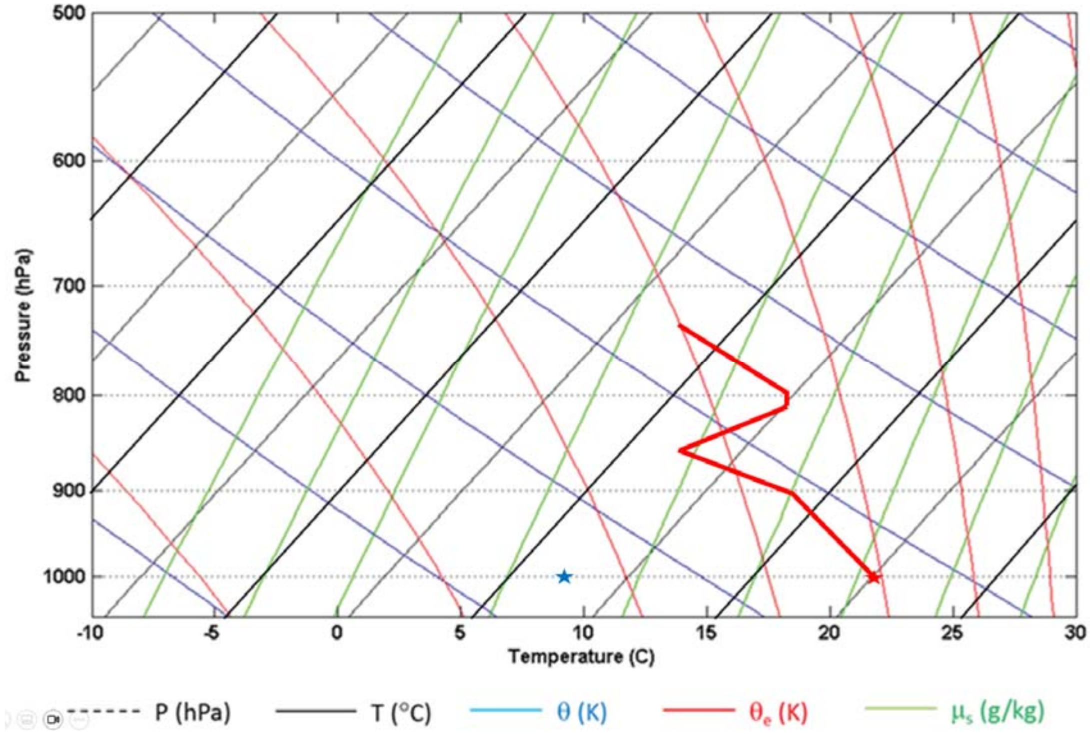
2) (5 Pts) A parcel of air at 1000 hPa and 25 °C is lifted adiabatically to its lifting condensation level at 800 hPa where the parcel temperature is T=7 °C, what was the relative humidity of the parcel before lifting?

3) (20 pts) In the balloon sounding on the SkewT-LnP diagram below, the atmospheric temperature is plotted in red as a function of pressure. At 1000 hPa is 20 °C and the dew point is 7 °C.

   a) At what pressure is the lifting condensation level (LCL)?

   State the stability conditions (stable, unstable, neutrally or conditionally stable) of the atmosphere to small vertical displacements in the following pressure ranges:

   b) Between 1000 and 900 hPa
   c) Between 900 and 850 hPa
   d) Between 850 and 800 hPa
   e) Between 800 and 750 hPa



Questions 4-8 are multiple choice, and no calculations need to be shown.

4) (4 pts) The ___________ and the __________ are layers of the atmosphere that can become unstable.
   a) troposphere, ionosphere
   b) mesosphere, troposphere
   c) stratosphere, thermosphere
   d) mesosphere, cryosphere

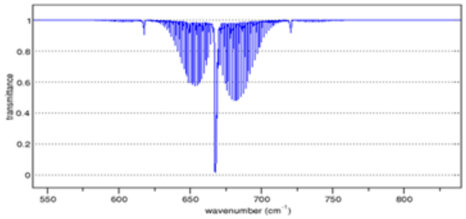
5) (4 pts) What is the major species in the stratosphere?
   a) Molecular Oxygen
   b) Atomic Oxygen
   c) Molecular Nitrogen
   d) Ozone
   e) None of the above.

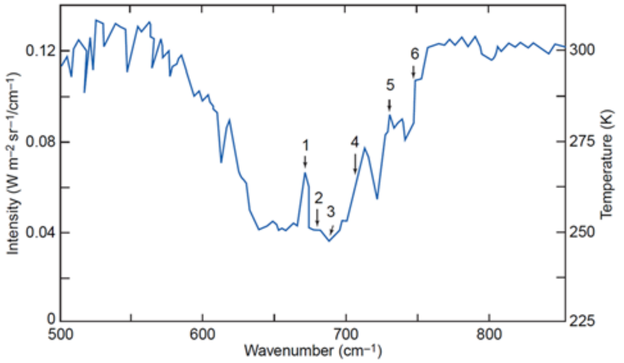
6) (4 pts) Sketch the relative spectral radiance as a function of wavelength for three blackbodies at temperatures $T_1 > T_2 > T_3$. Label the curves with their temperatures and put units on the axes, but you do not need to put numerical values on the axes.

7) (4 pts) Relative to the Earth's surface, what effect does the Coriolis force have on masses of air or water that are changing latitude?
   a) The results are unpredictable; currents can veer right or left in either hemisphere.
   b) They turn to the left in the northern hemisphere and to the right in the southern hemisphere.
   c) They turn to the right in the northern hemisphere and to the left in the southern hemisphere.
   d) They turn to the right in both hemispheres.
   e) They turn to the left in both hemispheres.

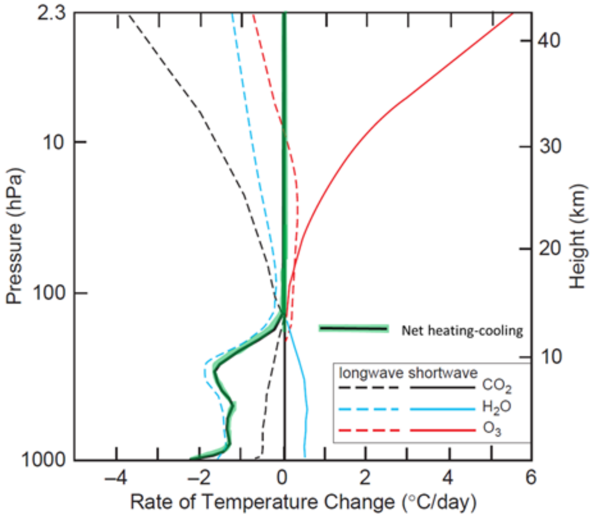
8) (4 pts) What wavelengths of sunlight are absorbed by molecular nitrogen in the troposphere?
   a) Infrared.
   b) Ultraviolet.
   c) Radio waves.
   d) Microwaves.
   e) Visible.
   f) None of the above.

9) (5 Pts) Shown below is the carbon dioxide 15-micron band. The top figure is the unsaturated absorption spectrum taken in the laboratory, and below is the intensity of the outgoing radiation from Earth measured by satellite showing the carbon dioxide. Can you explain why the intensity (and temperature) of the outgoing radiation at point 1 is higher than that at points 2 and 3?





10) (5 Pts) Shown below are the vertical profiles of the time rate of change of temperature due to the absorption of solar radiation (solid curves) and the absorption and emission of infrared radiation (dashed curves) by water vapor (blue), carbon dioxide (black), and ozone (red). The heavy black/green solid curve represents the net heating or cooling effect of the three gases. The figure shows that the net effect of the absorption and emission of radiation by greenhouse gases is to cool the air in the troposphere about 1°C per day. Can you explain why an increase of greenhouse gases would, nevertheless, result in warming the air in the troposphere?



11) (5 Pts) What ozone column (in molecules·m^{-2}) corresponds to 1 Dobson Unit (DU)?

12) Nitrogen dioxide, (NO_2) is a pollutant released by diesel and petrol internal combustion engines as well as industrial processes that causes smog. Mainly produced by traffic in cities, the narrow valleys and fjords where Norwegian cities are located tend to concentrate levels. However, the yearly average mass density across Norway 32.33 $\mu g \cdot m^{-3}$, which is low by European standards.

   a) (5 Pts) What is the average number density of NO_2 in molecules$\cdot m^{-3}$?

   b) (5 Pts) At 1000 hPa and 22 C, the density of NO_2 measured one day in Bergen was 29.95 $\mu g \cdot m^{-3}$ what is the volume mixing ratio of NO_2?

   c) (5 pts) Originally, the Martian atmosphere was thought to consist only of 95% CO_2, 3% N_2 and 2% Ar. However, recently, it was discovered that it also contains 0.2% O_2. By how much did the initial estimate of the mean molecular weight of the Martin atmosphere change when this additional species, O_2 was taken into account.

13) On Venus g_v=8.87 $m \cdot s^{-2}$, the specific gas constant for dry air is R_{dv} = 195.5 $J \cdot K^{-1} \cdot kg^{-1}$, and the specific heat at constant pressure, C_{pv} = 846 $J \cdot K^{-1} \cdot kg^{-1}$. The pressure at the surface is 92000 hPa, and the temperature 753 K. The temperature falls off linearly with a lapse rate of 8 K/km (note non-SI units of hPa and km).

   a) (2 Pts) What is the buoyancy period at 59 km, and is the atmosphere stable with respect to vertical motion there?
   b) (6 Pts) What is the temperature and pressure at 59 km?

   The Venusian atmosphere is composed of 96.5% CO_2 and approximately 3.5% N_2, neither of which absorb solar radiation. However, there is a 150-ppm mixing ratio of sulfur dioxide (SO_2) at the surface that absorbs at in the UV/visible with an absorption coefficient k = 0.11 $m^2 \cdot kg^{-1}$. The Sun is at a solar **ZENITH** angle (angle of the Sun from overhead) of χ= 45 degrees. You may assume no scattering, and take the optical depth of incoming solar radiation (averaged over all wavelengths), the density of air, and the mass mixing ratio of the absorber to be defined as:

$$\tau(Z) = \int_{Z}^{\infty} \rho(z)\,\mu(z)\,k\,dz$$

$$\rho(z) = \rho 0\,\mathbf{e}^{\left(-\frac{z}{Hm}\right)}$$

$$\mu(z) = \mu 0\,\mathbf{e}^{\left(-\frac{z}{Hv}\right)}$$

   Where $\rho(z)$ is the mass density of air, $\mu(z)$ is the mass mixing ratio of SO_2. H_m is the scale height of the atmosphere is H_m = 13 km, and the scale height of the SO_2, is H_v = 8 km. At the surface, the pressure is 92000 hPa, the total density, $\rho 0$=85 kg·m-3 and the temperature is 753 K

c) (6 Pts) Calculate the optical depth τ and its derivative with height $d\tau/dz$ at a height of 5 km in the atmosphere.

d) (6 Pts) Calculate the heating rate in Kelvin·day^{-1} due to short wavelength radiation at 11 km if the downward solar flux at the top of the atmosphere is 2600 W/m^2 and the solar ZENITH angle is χ=45 degrees. At 11 km, the total density is ρ=36.5 kg·m^{-3}, the absorber mass mixing ratio is 0.0559 g·kg^{-1}, the optical depth is τ=1 and its derivative, $d\tau/dz$, is -0.22 km^{-1}.