Resit Examination Climate System and Atmosphere, July 11, 2022

Write down your name, and student number on the first sheet of paper, and your name on every following paper (Part 1: 4.5 points; Part 2: 4.5 points; 1 point for free).

Use of supporting material is not allowed, except for a simple calculator.
Some constants and equations (not all are needed):

$S_0 = 1361\ Wm^{-2}$;

$g = 9.81\ ms^{-2}$;

$c_p = 1005$ J/kg;

Albedo of Earth = 0.298;

Average temperature near the earth surface 288 K;

Ω: 7.27×10^{-5} rad s^{-1}

$\sigma = 5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$.

Saturated water vapor pressure in Pa (T in °C):

$e_s = 611 * \exp[17.67 * T/(T + 273.15)]$

1 mole = 6.023×10^{23} molecules

$R_g = 8.3143\ JK^{-1}mol^{-1}$; $R = 287\ J\ kg^{-1}K^{-1}$;

$$pV = nR_gT = \rho \frac{R_g}{m_a} T = \rho RT$$

$$p_s = g \int_0^\infty \rho dz$$

Equation of motion: $\frac{D\mathbf{u}}{Dt} + \frac{1}{\rho}\nabla p + g\hat{\mathbf{z}} + f\hat{\mathbf{z}} \times \mathbf{u} = \mathcal{F}$

Total angular momentum at the latitude φ: $A = \Omega a^2 \cos^2\varphi + ua \cos \varphi$

Coriolis parameter $f = 2\Omega\sin\varphi$

Coriolis acceleration $-2\Omega \times U = (2\Omega\sin\varphi\ v - 2\Omega\cos\varphi\ w, -2\Omega\sin\varphi\ u, 2\Omega\cos\varphi\ u)$

Rossby number: $R_0 = U/fL$

Volume of a sphere = $4/3\pi r^3$

Geostrophic wind: (u_g, v_g) **=** $(-1/f\rho\ \ p/\partial y, 1/f\rho\ \ \partial p/\partial x) = (-g/f\ \partial z/\partial y, g/f\ \partial z/\partial x)$

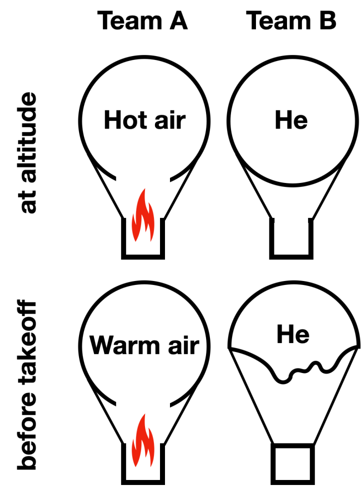
Earth radius = 6370 km

Part1. Short Essay questions (4.5 of a total of 9 points, be complete and concrete – note that "complete" is not the same as "lengthy")

1. Two adjacent, isolated, stable columns of air of equal total mass and constituent gas mole fractions differ in their (vertically constant) temperature; one being warmer than the other.
    a. Which – if any – of the two has the higher density at surface level and why? **(0.5)**
    b. Which – if any – of the two has a higher pressure at 5 km altitude and why? **(0.5)**
2. In the tropics, convection commonly mixes the air column all the way up to the tropopause.
    a. Sketch, for the tropical latitude band, the typical time-averaged vertical tropospheric profiles of (i) *temperature*, (ii) *potential temperature* and (iii) *equivalent potential temperature*. **(0.5)** *For coordinates, use pressure [mbar] and temperature [K]).*
    b. Relating to your sketch, describe the conceptual differences between the three temperatures scales. **(0.5)**
3. Earth receives radiation from the Sun, and radiates heat back to space.
    a. Draw a figure of the annually-averaged, zonally averaged (or 'meridional') distributions of (i) the solar radiation absorbed at Earth's surface, (ii) radiation emitted back to space and (iii) the difference between (i) and (ii). Regarding the flow of heat on Earth, what is a clear implication to be inferred from curve (iii)? **(0.5)**
    b. Due to human activities, mainly since the beginning of the Industrial Revolution, the incoming and outgoing radiation terms are not, even on a global level, balanced. The system is being 'radiatively forced'. What is the resulting thermal behaviour of the Earth-and-lower-atmosphere system to this radiative forcing? **(0.5)**
4. Explain how the polar jetstream works. Under current global warming conditions, the Arctic region is observed to warm much faster than the rest of the planet, how will the polar Jetstream respond to the Arctic warming (intensify, weaken or no change)? Explain why. **(0.5)**
5. The surface (say, 0-50m), subsurface (say, 50-500m) and deep (say, 500-5000m) oceans are circulated by different processes, and on different timescales. For the largest-scale of these circulations describe …
    a. … the driving process (location, mechanism, role of the atmosphere) **(0.5)**
    b. … the general pathway (circulation route, timescales). **(0.5)**

Part2. Problem solving (4.5 of a total of 9 points)

1. Two amateur teams are competing for the highest balloon flight. Team A flies a hot air balloon, team B flies a helium balloon. Takeoff is from a grass field at sea level in fair weather (1000 mbar, 20°C, air density: 1.18 kg/m^3).



   For team A, consider a perfectly spherical, non-elastic hot air balloon of r = 5 m (ignore, for your volume considerations, that there's a cutout at the bottom that allows a gas burner to heat the air inside the balloon). The balloon, including its payload (burner, gas tanks), weighs 50 kg.

   For team B, consider a (potentially) perfectly spherical, non-elastic, hermetically sealed helium balloon of r = 2 m. At takeoff however, the balloon has been filled with helium to only half its nominal volume, and therefore looks rather floppy. It will swell to it final spherical shape (r = 2m) during ascent. Density of helium at 1000 mbar is 0.1634 kg/m^3. Baloon B, including its payload (say, a science instrument), weighs 10 kg.

   For all following questions, assume a vertically constant temperature profiles of 20°C, and ignore the differences in water vapor pressure inside and outside balloon A.

   Balloon A:

   a. Prior to takeoff, balloon A is heated to reduce the density of the air inside it (part of the expanding air will escape from the cutout at the bottom; consider how density varies with temperature in this situation!). At what temperature will the balloon exactly hover at ground level (that is, have a bouyancy of zero kg)? **(0.5)**

   b. The air in balloon A is further heated to 100°C, a line is cut, and the balloon flight starts. At takeoff, what is the density of the air inside balloon A? What is the buoyancy in kg? **(0.5)**

   c. During ascent, the air pressure drops, and the density difference between the air in- and outside the balloon becomes smaller. Assuming the air in balloon A is kept constant at 100°C, t what pressure level will the balloon stop ascending? **(0.5)**

   Balloon B:

   d. At surface level, what is the bouyancy of balloon B in kg? **(0.5)**

   e. At what pressure level will balloon B be fully expanded/spherical, and what will its buoyancy in kg be at that pressure level? **(0.5)**

   f. To what pressure level will balloon B ascend? **(0.5)**

g. Just from looking at these ceiling pressures, and just to round off the storyline, which teams wins the altitude challenge? **(0.01)**

h. Hypothetically, if team B had inserted *more* helium into their balloon, would its ceiling altitude have been *higher/lower*? Would it have ascended *faster/slower*? Why? **(0.24)**

The hot air balloon runs out of fuel and lands. The helium balloon doesn't run out of fuel and doesn't burst. So it can stay aloft for a *very* long time (it's a so-called "superpressure" balloon).

i. From its ceiling pressure, and still assuming a 20°C vertically constant temperature profile, calculate the final altitude of balloon B. If you couldn't work out the ceiling pressure in (f), assume it to be 320 mbar. *Remember, the scale height H (in m) is RT/Mg (with R=8.314 J mol^{-1} K^{-1}; M=0.029 kg mol^{-1} for Earth's atm.), and $P=P_0\,exp(-z/H)$.* **(0.5)**

Assume the balloon indeed flies at the 320 mbar level and is observed, at 55°N, to be carried along by a geostrophic wind blowing between a high- and a low-temperature region. The high-temperature region is located 500 km south of the balloon and has its 320 mbar level at 9810 meters. The cold-temperature region is located 500 km to the balloon's North, and has its 320 mbar level at 9610 meters.

j. What are the speed and the direction of travel of the balloon? **(0.75)**