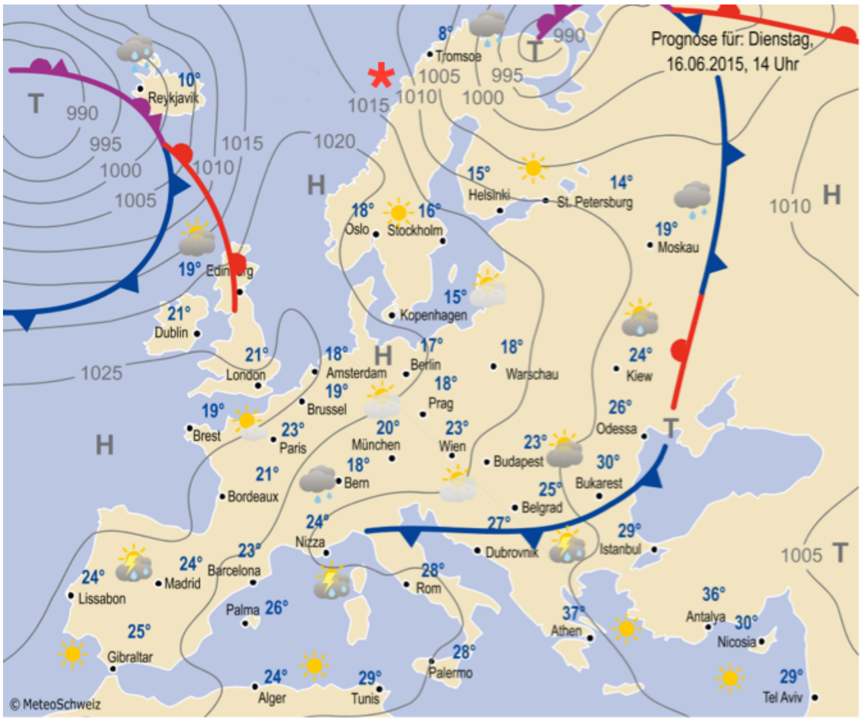
Atmospheric Physics

1) (20 pts)
Pressure Fields and the Geostrophic Wind: Consider the following map from yesterday's weather bulletin.



a) Name and describe the different lines visible on this map (the grey, blue, red and purple lines).

b) Given that the width of Iceland is approximately 500km, estimate the velocity magnitude of the geostrophic wind above Reykjavik. Take the latitude of the city to be 64°. Note that the pressure gradient can be expressed as $\boldsymbol{P} \equiv -\frac{1}{\rho}\nabla p = -\nabla\Phi$, where $\nabla\Phi$ is the gradient of geopotential. Assume that the density of air is $\rho = 0.8\text{kgm}^{-3}$ and that in the map the grey numbers are in hectopascals.

c) Now consider the red star, approximately 1000km east of Iceland. How will the geostrophic wind be different (magnitude and direction) here compared to that which was calculated in the previous question?

2) (10 pts)
Radiative Equilibrium: Very recent research has shown that measurements of the solar constant from instruments calibrated by the World Radiation Center in Davos had a bias (overestimation) of approximately 0.3%. Please calculate by how much the planetary equilibrium temperature changes when correcting for this error.

3) (20 pts)
Energy Balance: It is mid-summer but at Weissflujoch in Davos there is still snow that hasn't yet melted.

On a sunny day (no clouds), melt starts in the mid-morning.

a) Calculate the melt rate in $kgm^{-2}hour^{-1}$, given the following meteorological situation:
    - Direct beam solar radiation I_b = 770Wm^{-2} incoming at a solar zenith angle of Θ_{Dir} = 23°
    - Diffuse solar irradiance from the entire hemisphere of $I_d = 230Wm^{-2}$ (assumed to be a fixed percentage of the direct beam radiation on a clear-sky day)
    - Albedo of the snow surface: α = 0.8
    - Air temperature: T_A = 10°C
    - Wind Speed: u = 5 ms^{-1}
    - Bulk Transfer coefficient: C_H = 0.003
    - Density of air: ρ = 0.8 kg m^{-3}
    - Heat capacity of Air: 1005 J kg^{-1} K^{-1}
    - Melt energy (Ice): 3.34 10^5 J kg^{-1}
    - Stefan Boltzmann constant: σ = 5.67 10^{-8} W m^{-2} K^{-4}

    Assume that ground heat flux and latent heat exchange can be neglected.

b) At mid-afternoon, the sun reaches a zenith angle of 35°. Re-calculate the melt rate. Take into account the effect of atmospheric absorption on direct beam radiation for the changing path length across the atmosphere. Assume that the atmosphere has a vertical extent of 8km and that the diffuse radiation will represent the same relative proportion with respect to the beam radiation (after atmospheric absorption) as in the morning. In addition, the albedo has decreased to 0.7 because of liquid water accumulating near the surface.

Atmospheric Chemistry

1) (10 pts)

a) What is the primary chemical mechanism of ozone production in the troposphere?

b) What is the primary chemical mechanism of ozone production in the stratosphere?

c) Why are the answers for (a) and (b) not the same?

2) (15 pts)

a) Consider the theoretical maximum yields for O_3 production for CH_4 and CO. If emissions are 3×10^{13} and 4×10^{13} moles yr^{-1} for CH_4 and CO, respectively, what is the production rate of tropospheric O_3 production from these two mechanisms?

b) A more detailed photochemical model yields a value of 6 to 10×10^{13} moles yr^{-1}. What are two differences that might cause a difference in estimated numbers from part (a) and this value?

3) (5 pts)

Describe the three mechanisms necessary for aerosols to form warm cloud precipitation.

4) (20 pts)

Consider two loss mechanisms for SO_2 vapor: gas-phase oxidation by OH, and oxidation in the aqueous-phase after uptake.

a) Which process is more important in the stratosphere?

b) Name one impact on air quality or climate that results from oxidation products of SO_2.

c) At a fixed cloud droplet pH of 3.5 and $H_2O_{2(aq)}$ concentration of 47 μM, the lifetime of HSO_3^- is 0.9 seconds. Explain why the lifetime of SO_2 with respect to the aqueous-phase loss pathway under these conditions is also 0.9 seconds. You may use chemical or mathematical equations, but a one-sentence answer is also sufficient. *Hint*: it may be useful to consider the relationship between partial pressure of SO_2 and the $[HSO_3^-]$ concentration at fixed pH.

d) What is the lifetime of SO_2 with respect to the gas-phase reaction SO_2 + OH for an OH radical concentration of 10^6 molecule s^{-1}, and first-order reaction rate constant of 1.6×10^{-12} cm^6 $molecules^{-2}$ s^{-1}? Compared to conditions described in (c), is the loss rate of SO_2 by the gas-phase or aqueous-phase process faster?

Possibly useful information for Question 4 part c (but not required to answer question):

- Recall that the lifetime of a species with respect to a reaction is $\tau = m/L$, where τ is the lifetime, m is the mass concentration of a species, and L is loss with respect to a particular mechanism.

- For any species i, mass concentration m_i is proportional to the partial pressure p_i of species according to the molecular weight M_i, gas constant R, and temperature T:

$$m_i = \frac{M_i}{RT} p_i$$

- At an acidity of pH = 3.5, the reaction of HSO_3^- with $H_2O_{2(aq)}$ dominates the aqueous S(IV) → S(VI) conversion pathway, and other reaction pathways can be neglected. Also, for a fixed pH and $H_2O_{2(aq)}$ concentration, we can write the HSO_3^- oxidation reaction with first-order reaction constant k' which incorporates the fixed hydrogen and hydrogen peroxide concentrations, as used in your exercise assignment:

$$\frac{d[HSO_3^-]}{dt} = \frac{d[S(IV)]}{dt} = -k'[HSO_3^-]$$

$$k' = k_4[H^+]_0[H_2O_{2(aq)}]_0/(1 + K[H^+]_0)$$

$$\tau_{HSO_3^-} = \frac{1}{k'}$$

Note that [.] denotes the molar concentration of a species and the subscript 0 indicates a fixed value.

SOLUTIONS

Atmospheric Physics

1)

a) Grey lines: Isobars, they show lines of equal pressure (credit may also be given for: lines of equipotential). (2 pts)
Blue lines: Cold front. Boundary of a region where colder air is pushing into warmer air and displacing that warmer air at ground level. (2 pts)
Red lines: Warm front. Boundary of a region where warm air is advancing towards colder (more dense) air and is thus being driven upwards above that colder air. (2 pts)
Purple lines: Occluded front. When a cold front encounters a warm front and then overtakes it. (2 pts)

b) Make use of the equation for the geostrophic wind:

$$V_g = -\frac{1}{f}\frac{\partial \phi}{\partial n}$$

in natural coordinates, where $f = 2\Omega \sin \phi_l$ is the Coriolis parameter. Ω is the angular velocity of the Earth and $\phi_l = 64°$ is the latitude. Hence
$f = 2\left(\frac{2\pi}{24\times60\times60}\right)\sin 64° \approx 0.13\times10^{-3}\, rad\, s^{-1}$
Using the equation given in the question, we can convert between the approximate pressure gradient taken from the map and the gradient of geopotential:

$$|V_g| \approx \frac{1}{f\rho}\frac{\Delta p}{\Delta x} = \frac{1}{\frac{4\pi}{86400}\sin 64° \times 0.8}\frac{500}{250\times10^3} \approx 19.12 ms^{-1}$$

(8 pts)

c) By observing the direction of the pressure gradient at the red star and making note of the fact that the geostrophic wind always blows with the low pressure region to its left and high pressure to its right, we can conclude that it should blow towards the south. In fact to be more precise, it will blow in a south-south-easterly direction. The magnitude or strength of the wind depends upon the Coriolis parameter f, and the local pressure gradient. The parameter f is unchanged because the latitude of the red star is approximately the same as the latitude of Reykjavik. However the strength of the geostrophic wind will be lower than the wind over Reykjavik because the isobars are more widely spaced over the red star. (4 pts)

SOLUTIONS

2) In radiative equilibrium the absorbed energy from the sun equals the emitted blackbody radiation from the earth.

$$(1-\alpha)\cdot F_{solar}\cdot A_{receive} = F_{earth}\cdot A_{emit} \quad (1)$$

It is important to notice that the radiation from the sun is received by only half of the earth's surface, while blackbody radiation is emitted from the entire surface of the sphere. The projection of the surface of the earth that interferes perpendicularly with the sunrays equals the surface of a circle with the radius of the earth.
Hence:

$$A_{receive} = \pi\cdot r_{earth}^2;\ A_{emit} = 4\pi\cdot r_{earth}^2$$

The flux density of incoming and outgoing radiation are the solar constant F_{solar} = 1368 Wm^{-2} and the blackbody radiation $F_{earth} = \sigma T^4$ respectively.

Solving (1) for the equilibrium temperature T, yields:

$$T = \left(\frac{0.7\cdot 1368 W/m^2}{4\cdot\sigma\frac{W}{K^4m^2}}\right)^{1/4} = 254.90\text{K} \quad (2)$$

Correcting the overestimate of 0.3%, increases the solar constant to:

$$F_{solar}^{corr} = F_{solar} - F_{solar}\cdot 0.003 = 1363.9\ W/m^2$$

Replacing the original with the corrected solar constant in (2) yields the new equilibrium temperature:

$$T_{corr} = 254.71\text{K}$$

This corresponds to a change in equilibrium temperature of -0.21K or -0.0751%.

SOLUTIONS

3a) Instantaneous melt M results from the sum of net shortwave radiation SW^{net}, net longwave radiation LW^{net} and sensible heat flux F_{HS}.

$$M = SW^{net} + LW^{net} + F_{HS} \quad \text{(3pts)}$$

The three components are computed as follows:

$$SW^{net} = (1-\alpha)(I_b cos\Theta_{Dir} + I_d) = 188\, W/m^2 \;\; (2pts)$$

$$LW^{net} = \varepsilon_{atm}\sigma T_{atm}^4 - \sigma T_{snow}^4 = -60\, W/m^2 \quad \text{(2pts)}$$

$$F_{HS} = (\rho \cdot c_p)\cdot C_H \cdot |u| \cdot (T_{atm} - T_{snow}) = 120\, W/m^2 \quad (2pts)$$

and they sum up to:

$$M = 248\, W/m^2 \;\; (1pt)$$

This energy flux corresponds to an hourly energy input of:

$$E_{hourly} = M \cdot 3600s = 9 \cdot 10^5 \;\; Ws/m^2 \;\; = 9 \cdot 10^5\, J/m^2 \; (1pt)$$

With a melt energy of $E_{melt} = 3.34 \cdot 10^5 \;\; J/kg$, the hourly melt will amount to:

$$Meltmass = \frac{9 \cdot 10^5\, J/(hour \cdot m^2)}{3.34 \cdot 10^5 \;\; J/kg} = 2.67 \frac{kg}{hour \cdot m^2} \;\; (2pts)$$

3b) Afternoon melt:

Only the shortwave radiation has changed. Longwave and sensible heat flux remain the same. The incoming direct beam radiation changes linearly with the ratio of path lengths through the atmosphere d:

$$I_b' = I_b \frac{d}{d'} = I_b \frac{\cos 35°}{\cos 25°} = 685\, W/m^2 \;\; (2pts)$$

The component perpendicular to the surface is reflected according to the new albedo value α'. Hence the net incoming beam radiation amounts to:

$$I_{b\perp}' = I_b' \cdot cos35° \cdot (1-\alpha') = 561\, W/m^2 \;\; (2pts)$$

Incoming diffuse radiation will be the same percentage of the beam radiation as in the morning:

$$I_d' = I_b' \frac{I_d}{I_b} = 204 \;\; W/m^2 \;\; (2pts)$$

Computing the sum of longwave, shortwave and sensible heat flux as in the morning and dividing by the melt energy yields an afternoon melt of:

$$Meltmass = 3.12 \frac{kg}{hour \cdot m^2} \;\; (1\, pt)$$