1. **Angular momentum and Hadley cell** *(6 points)*

   Consider a zonally symmetric circulation (i.e., one with no longitudinal variations) in the atmosphere. In the inviscid upper troposphere one expects such a flow to conserve absolute angular momentum, i.e.,

   $$\frac{DA}{Dt} = 0, \tag{1}$$

   where A is the absolute angular momentum per unit mass (parallel to the Earth's rotation axis)

   $$A = r\,(u + \Omega r) = \Omega R^2 \cos^2 \varphi + uR \cos \varphi \quad . \tag{2}$$

   Ω is the Earth rotation rate, u the eastward wind component, $r = R \cos \varphi$ is the distance from the rotation axis, R the Earth's radius, and φ latitude.

   a) Show, for inviscid zonally symmetric flow, that the relation $\frac{DA}{Dt} = 0$ is consistent with the zonal component of the equation of motion

   $$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{3}$$

   in (x, y, z) coordinates, where $y = R\varphi$.

   b) Use angular momentum conservation to describe in words how the existence of the Hadley circulation explains the existence of both the subtropical jet in the upper troposphere and the near-surface trade winds.

   c) If the Hadley circulation is symmetric about the equator, and its edge is at 20° latitude, determine the strength of the subtropical jet. Use (1, 2).

   d) Is the Hadley Cell geostrophically driven or not?

2. **Estimates of overturning** *(4 points)*

   It is observed that water sinks in to the deep ocean in polar regions of the Atlantic basin at a rate of 15 Sv. (Atlantic basin: $80,000,000\,km^2 area \times 4\,km$ depth.) a) How long would it take to 'fill up' the Atlantic basin?

   b) Supposing that the local sinking is balanced by large-scale upwelling, estimate the strength of this upwelling. Hint: Upwelling = $area \times w$. Express your answer in $m\ y^{-1}$.

   c) Compare this number with that of the Ekman pumping ! The order of magnitude of the Ekman vertical velocity w_E can be estimated as from a typical wind stress variation of $0.2 N m^{-2}$ per 2000 km in y-direction:

   $$w_E \simeq -\frac{\Delta \tau_x}{\rho\ f_0 \Delta y} \tag{4}$$

Notes on submission form of the exercises: *Working in study groups is encouraged, but each student is responsible for his/her own solution. The answers to the questions can be send until the due date (12:00) to Hanna Knahl (hanna.knahl@awi.de), Alexander Thorneloe (alexander.thorn@awi.de).*