1. **Scaling of the dynamical equations** *(2 points)*

We work in the rotating frame of reference of the Earth. The equation can be scaled by a length-scale L, determined by the geometry of the flow, and by a characteristic velocity U. We can estimate the relative contributions in units of m/s^2 in the horizontal momentum equations:

$$\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{U/T\sim 10^{-8}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{U^2/L\sim 10^{-8}} = \underbrace{-\frac{1}{\rho}\nabla p}_{\boldsymbol{\delta \mathbf{P}/(\rho \mathbf{L})\sim 10^{-5}}} + \underbrace{2\boldsymbol{\Omega}\times\mathbf{v}}_{\mathbf{f_0 U\sim 10^{-5}}} + \underbrace{fric}_{\nu U/H^2\sim 10^{-13}} \tag{1}$$

where fric denotes the contributions of friction due to eddy stress divergence (usually $\sim \nu\nabla^2\mathbf{v}$). Typical values are given in Table 1. The values have been taken for the ocean.

a) Please repeat the estimate for the atmosphere using Table 1.

b) The Rossby number Ro is the ratio of inertial (the left hand side in (1)) to Coriolis (second term on the right hand side in (1)) terms

$$Ro = \frac{(U^2/L)}{(fU)} = \frac{U}{fL} \quad . \tag{2}$$

Ro is small when the flow is in a so-called geostrophic balance. Please calculate Ro for the atmosphere and ocean using Table 1.

	Quantity	Atmosphere	Ocean
horizontal velocity	U	$10\ \ ms^{-1}$	$10^{-1}\,ms^{-1}$
horizontal length	L	$10^6\,m$	$10^6\,m$
horizonal Pressure changes	δP (horizontal)	$10^3\,Pa$	$10^4\,Pa$
time scale	T	$10^5\,s$	$10^7\,s$
Coriolis parameter at 45°N	$f_0 = 2\Omega\sin\varphi_0$	$10^{-4}\,s^{-1}$	$10^{-4}\,s^{-1}$
density	ρ	$1\ \ kgm^{-3}$	$10^3\,kgm^{-3}$
viscosity (turbulent)	ν	$10^{-5}\,kgm^{-3}$	$10^{-6}\,kgm^{-3}$

Table 1: Table shows the typical scales in the atmosphere and ocean system.

2. **Advection** *(3 points)*

   A ship is steaming northward at a rate of 10 km/h. The surface pressure increases toward the northwest at a rate of 5 Pa/km. What is the pressure tendency recorded at a nearby island station if the pressure aboard the ship decreases at a rate of 100Pa/3h?

3. **Circulation and temperature in May 2017 and 2018** *(2 points)*

   Consider the temperatures on May 8 in the years 2017 and 2018 in Fig. 1. The temperature differences over Central and Northern Europe are striking. Explain the temperature differences over this area by the large-scale atmospheric circulation. The associated circulation can be derived from the Sea Level Pressure (Pa) patterns in Fig. 2 (geostrophic balance). Explain your observation in words (not more than 4 sentences).

   Data from Kalnay et al., The NCEP/NCAR 40-year reanalysis project, Bull. Amer. Meteor. Soc., 77, 437-470, 1996.

4. **Questions about the course** *(3 points)*

   a) Please write down the barotropic potential vorticity equation for large-scale motion!

   b) What are the two dominant terms in the horizontal momentum balance for the large-scale dynamics at mid-latitudes?

   c) What are the names of the 3 meridional cells in the atmosphere?
   Draw a picture with the direction!

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 Fernanda Matos (Fernanda.Matos@awi.de), Ahmadreza Masoum (Ahmadreza.Masoum@awi.de).*

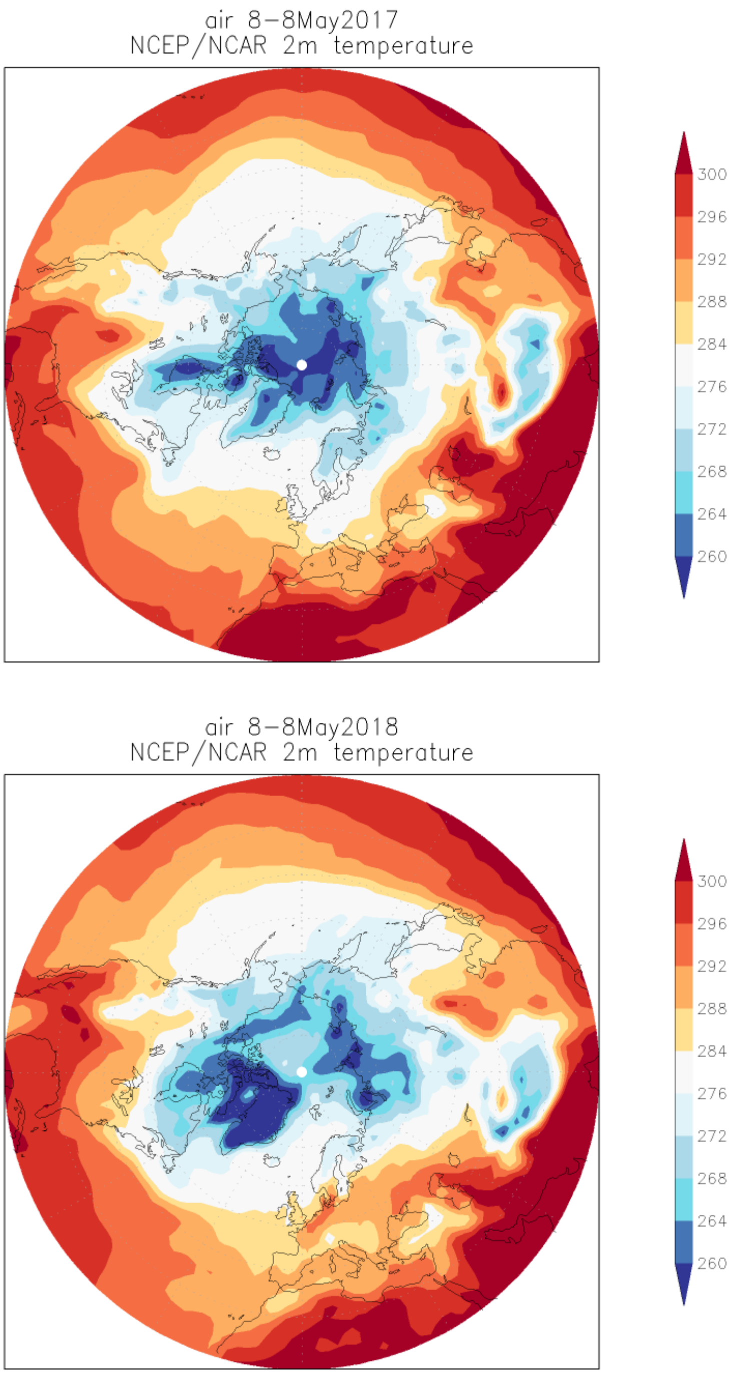

Figure 1: Surface Air Temperature (K) for May 8 in the years 2017 (upper) and 2018 (lower panel). Data are from the NCEP/NCAR reanalysis project (Kalnay et al., Bull. Amer. Meteor. Soc., 77, 437-470, 1996).

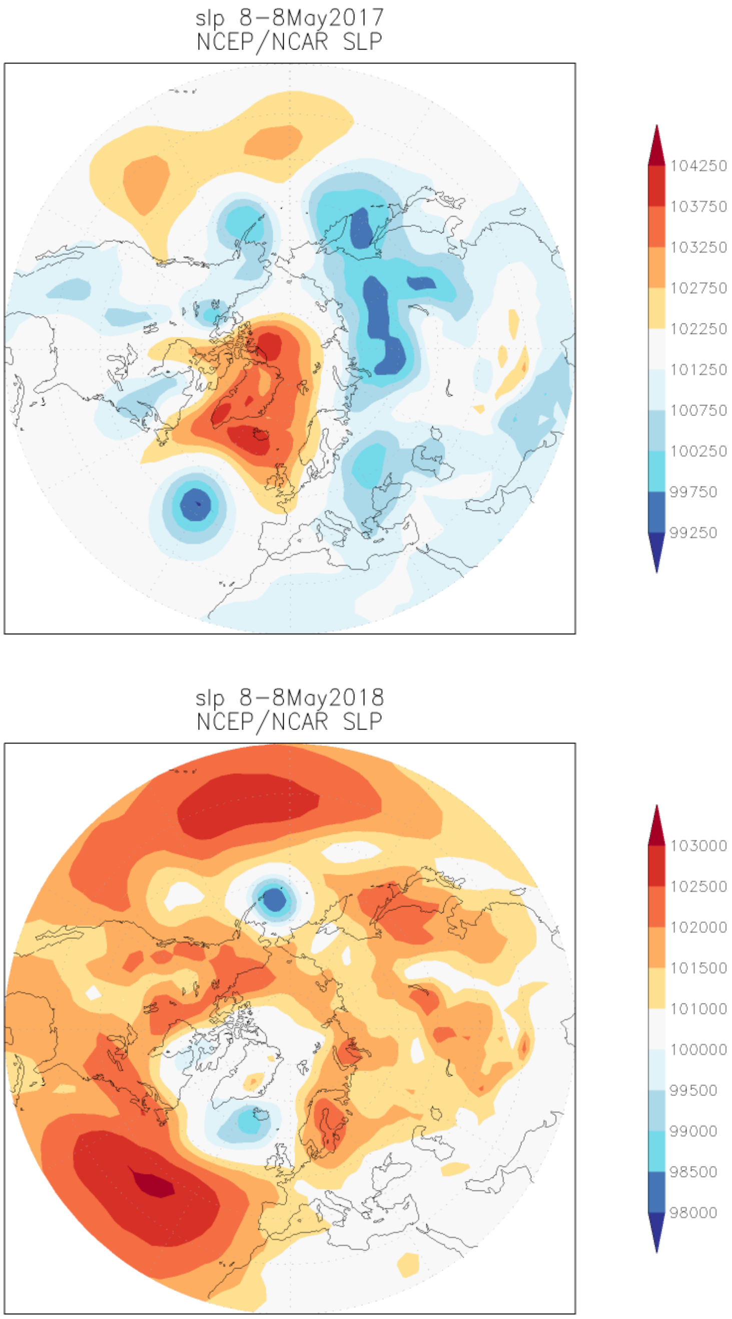

Figure 2: As in Fig. 1, but for Sea Level Pressure (Pa). The circulation in 2017 is characterized by a high pressure over Greenland, Iceland, and the Nordic Sea, and by surrounded low pressure systems.