Exercise 2 - Dynamics - Atmospheric processes

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1 Cold core cyclone

Figure 1 shows a cross-section through a cold core cyclone.

- Draw qualitatively the height of the 500 hPa isobar starting at 5500 m on the left (i.e. in the same way as the 1000 hPa isobar shown in blue).
- Draw qualitatively the magnitude and direction of the horizontal pressure gradient force at 300 m and at 5500 m.
- Based on your drawing, explain why cold core cyclones are intensifying with height.

Since the air column in the middle of the cyclone is colder relative to its surroundings, the thickness in that column is smaller than in the surrounding warmer air. Therefore the 500 hPa isobar will "dive" deeper in the cold air than the 1000 hPa isobar does. Consequently, the horizontal pressure gradient force, directed inward toward the center of the cyclone, increases in magnitude with increasing height. Thus, cold core cyclones, like those that populate the mid-latitudes on Earth, intensify with height.

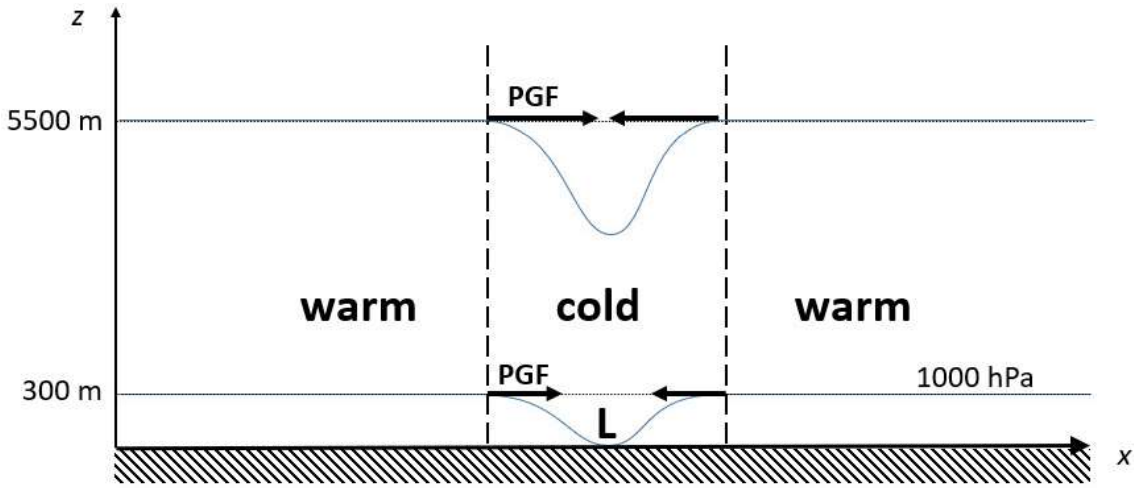

Figure 1: Vertical cross-section through a cold core cyclone (the x-axis is horizontal and the z-axis vertical). 'Warm' and 'cold' refer to the column average virtual temperatures in the three columns (separated by dashed lines). The blue solid line represents the 1000 hPa and 500 hPa isobars, dotted lines are the 300 m and 5500 m altitude lines. 'L' is the location of the lowest sea-level pressure. The thick arrows represent the pressure gradient force (PGF), which is much larger at 5500 m.

2 Jet stream

Figure 2 shows a meridional cross-section in the midlatitudes of the **Southern Hemisphere**. Assume that there is no wind and no pressure gradient close to the surface (i.e. at 1000 hPa) and that the column average virtual temperature (over the whole troposphere) is colder towards the South Pole and warmer towards the Equator.

- Draw qualitatively the height of the 500 hPa and 300 hPa isobars (the 1000 hPa isobar is already shown).
- Draw the forces of the geostrophic balance and the direction of the geostrophic wind at these two levels. Remember that the Coriolis parameter is $f = 2\,\Omega\, sin\Phi$, where Φ is the latitude, defined negative in the Southern Hemisphere.
- Based on your drawing, explain why we have a jet stream in the midlatitudes. Explain the link between the meridional temperature gradient shown on Figure 2 and why there exists such a gradient.
- What is the direction of the jet stream in the Southern Hemisphere? How does it compare to the Northern Hemisphere?

The existence of a meridional temperature gradient implies that, on average, the isobars will slope increasingly more with heights, with lower thickness towards the poles (hypsometric equation). Thus, the pressure gradient force will increase with increasing height until the tropopause, creating a maximum of wind speed just below the tropopause. Such a merdional temperature gradient exists because of the differentiasl solar heating between the equator and the poles. The jet stream is westerly in the Southern Hemisphere, as shown by the direction of the geostrophic wind in Figure 2. The jet stream is also westerly in the Northern Hemisphere.

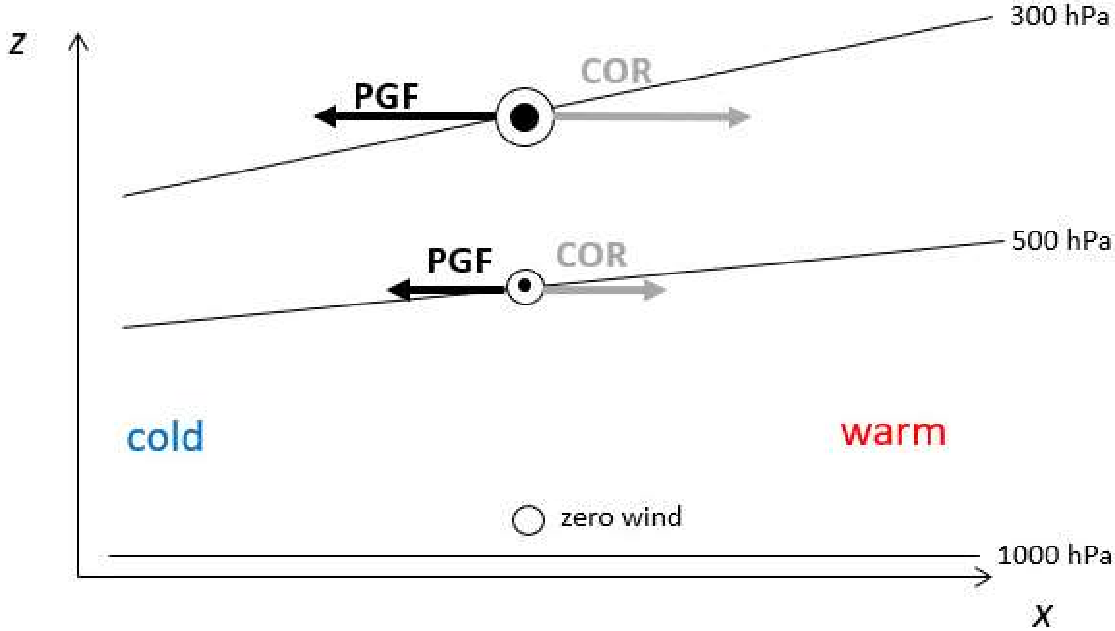

Figure 2: Meridional cross section through the midlatitudes of the Southern of Hemisphere (the x-axis points towards the equator, the South Pole is towards the left). The z-axis points upwards. The isobars are sloping increasingly more with increasing height under this configuration, as demanded by the hypsometric equation. The direction of the geostrophic wind is shown as circles on the isobars.

3 Analysis of storm Ciarán

In this exercise, we will analyse the explosive cyclogenesis of the storm Ciarán which occurred on 02 November 2023. Figures 3 and 5 show the synoptic situation on 01 November 2023 at 12 UTC and 02 November 2023 at 00 UTC over Western Europe.

Analysis of the upper troposphere

1. Identify on Fig. 3 the jet streak over the North Atlantic and mark it with a "**J**".

2. Draw the direction of the geostrophic wind in the jet streak with an arrow.

3. In the exit region of the jet streak, draw the direction of the geostrophic **acceleration vector** and the direction of the **ageostrophic wind** with an arrow. Label clearly the arrows.

4. Indicate where there is upper-level divergence and convergence of the ageostrophic wind with a "**D**" and "**C**", respectively.
   Figure 3 shows the analysis of the jet streak.

upper-level divergence.

Analysis of the lower troposphere

The storm Ciarán is the low pressure system that is located over the Atlantic at the latitude of Britanny (Fig. 3 and Fig. 5).

1. Estimate the pressure difference of the centre of Ciarán between 01 November at 12 UTC and 02 November at 00 UTC. Provide your answer in hPa and indicate the tendency with a "+" or a "-" sign (i.e. "-" if the pressure decreased or "+" if it increased). *The low has deepened from 972 hPa to 954 hPa, namely a difference of -16 hPa in 12 h, which can be considered an explosive cyclogenesis..*

2. Based on your previous analysis of the jet streak, what can explain this very rapid cyclogenesis? Make use of the pressure tendency equation to support your answer. You do not need to make any calculation, just use the equation in a qualitative way.

   The cyclone is located at the left exit of the jet streak, which corresponds to a region of upper-level divergence. The pressure tendency equation states that the time rate of change of pressure is directly proportional to the net mass divergence in the atmospheric column. Upper-level divergence will remove air from the column, thus leading to a decrease of surface pressure. The intensity of the jet streak makes the magnitude of the ageostrophic wind and hence the upper-level divergence very large, thus leading to a very rapid decrease of surface pressure.

3. Draw a schematic of the vertical structure of storm Ciarán by indicating with arrows if there is divergence or convergence in the lower and upper troposphere. Indicate with an arrow the vertical motion inside this low pressure system and what is the direction of it. *Figure 4 shows an idealised schematic of the vertical structure of this low-pressure system. The upper-level divergence and associated decrease of surface pressure leads to low-level*

convergence and hence to upward motions.

4. Indicate on Fig. 5 where you expect the strongest surface winds associated with Ciarán and explain why you chose this location.
   Figure 5 shows the location of the strongest surface wind speed with a red circle. This

   corresponds to the zone of the largest pressure gradient, which is directly proportional to wind speed. Note that the highest wind gusts above 200 km/h measured in Britanny were likely due to a sting jet, which is not geostrophic.

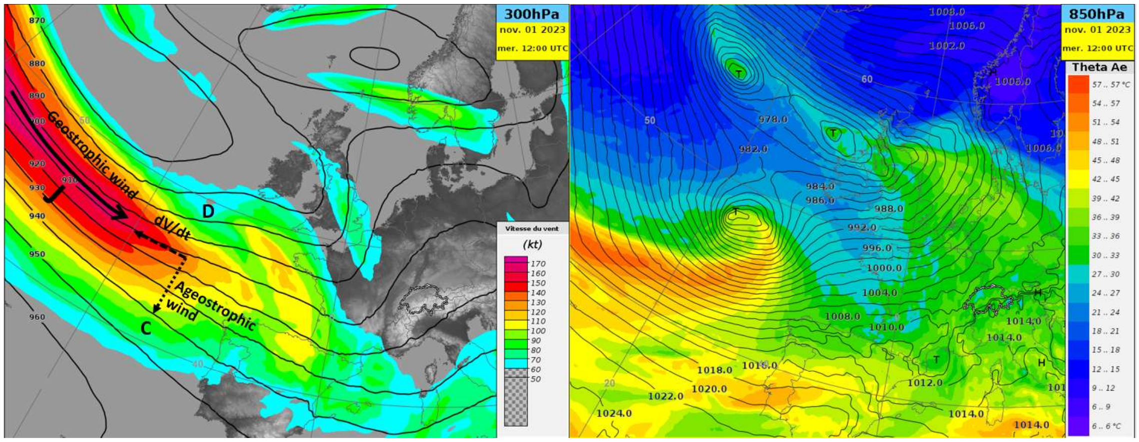

Figure 3: Synoptic situation over western Europe on 01 November at 12 UTC. (left panel): wind speed (colours, only values above 60 knots ≈ 30 m s^{-1} are shown) and geopotential height (solid contours, labels in decametre) at 300 hPa. (right panel): equivalent potential temperature (colours in °C and mean sea-level pressure (solid contours, labels in hectopascals).

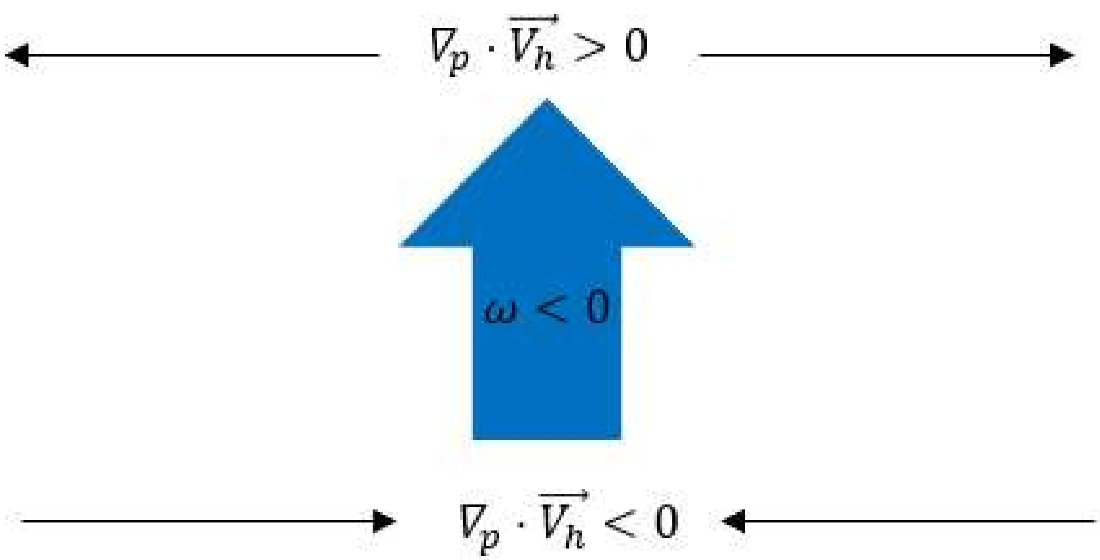

Figure 4:

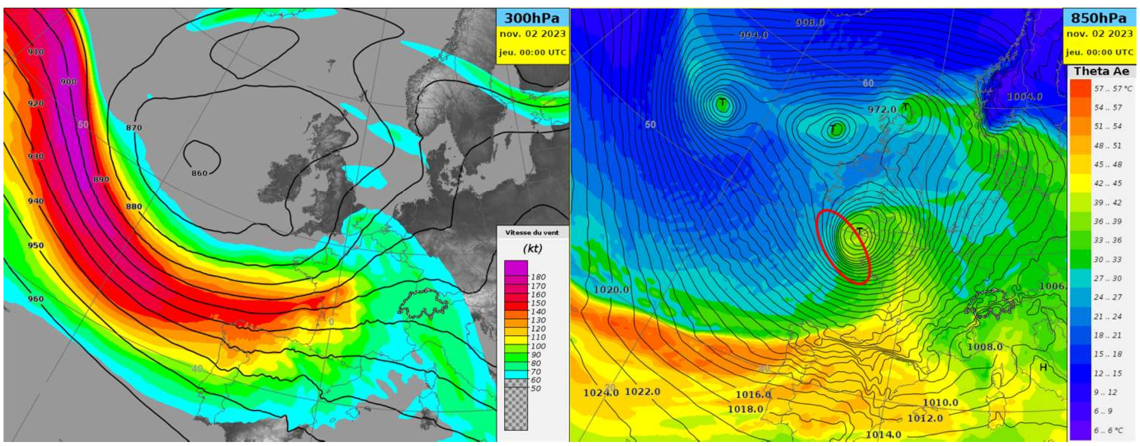

Figure 5: Same as Fig. 3 but for 02 November at 00 UTC.