Large-scale dynamics of the mid-latitude atmosphere : Part III

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Topics covered :

Two weeks ago

- Conservation of momentum: the equation of motion
- Hydrostatic balance, geostrophic balance
- Thermal wind balance

Last week

- Going beyond geostrophy: the ageotrophic wind
- Diagnosis of vertical motions with the ageostrophic wind: jet stream, trough/ridges
- Fronts and the Norwegian cyclone model

This week

- Extratropical cyclones: going beyond the polar front theory

Books

- J.E. Martin, «Mid-latitude atmospheric dynamics, a first course», 2006 → JEM
- J.M. Wallace & P.V. Hobbs, «Atmospheric science, an introduction survey», 2006 → W&H

What are the limitations of the polar front theory?

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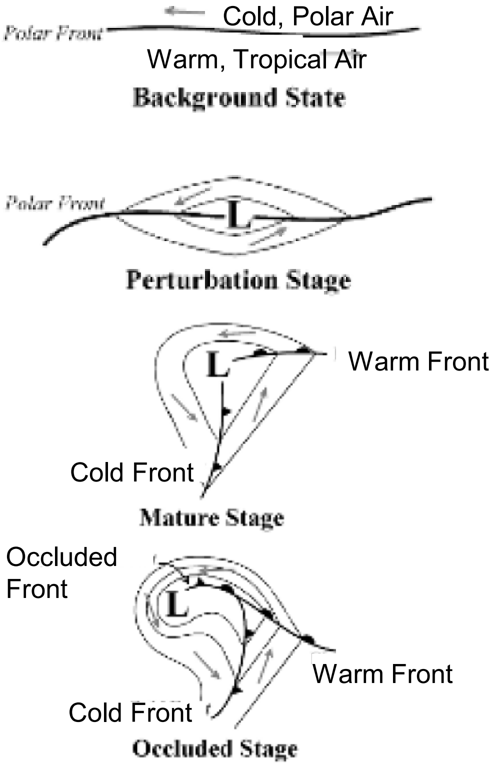
- It assumes there is **an existing front**
- It does not explain **why a perturbation** along a frontal boundary **will intensify**
- It does not explain what leads to the **dissipation of an extratropical cyclone** (EC)
- It does not explain how the **EC interacts with the upper-level** dynamics

→ we are going to **address some of these limitations** today



Baroclinic instability and vertical structure of an extratropical cyclone

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What does baroclinic mean?

- A **baroclinic** fluid is one in which temperature is not uniform on a constant pressure surface (i.e. **density depends on both pressure and temperature**).
- Differential solar heating between the poles and the equator creates a **meridional temperature gradient**

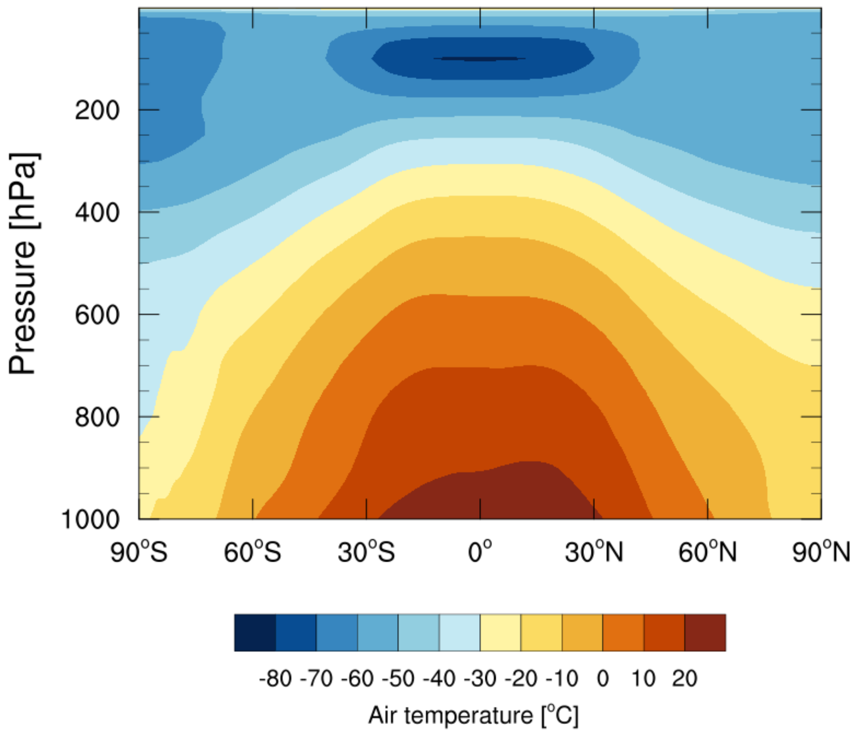
→ the temperature is not uniform on a constant pressure surface

→ the **atmosphere is baroclinic**

Quiz on seasonal and latitude dependence:

- Seasons: the atmosphere is most baroclinic in winter
- Geography: the atmosphere is most (least) baroclinic in the mid-latitudes (tropics)

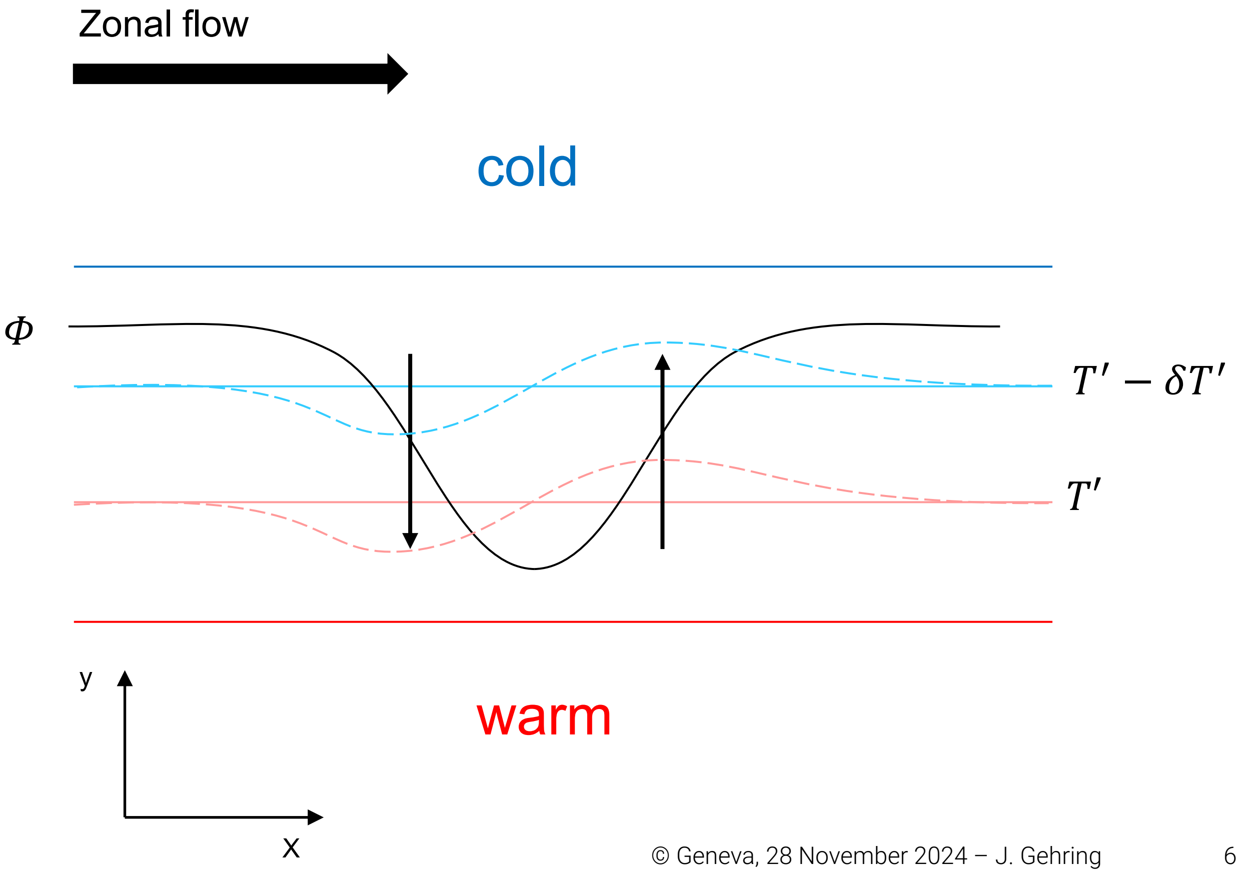
Zonal mean air temperature from ERA Interim data 1978-2018



Why is a baroclinic atmosphere unstable?

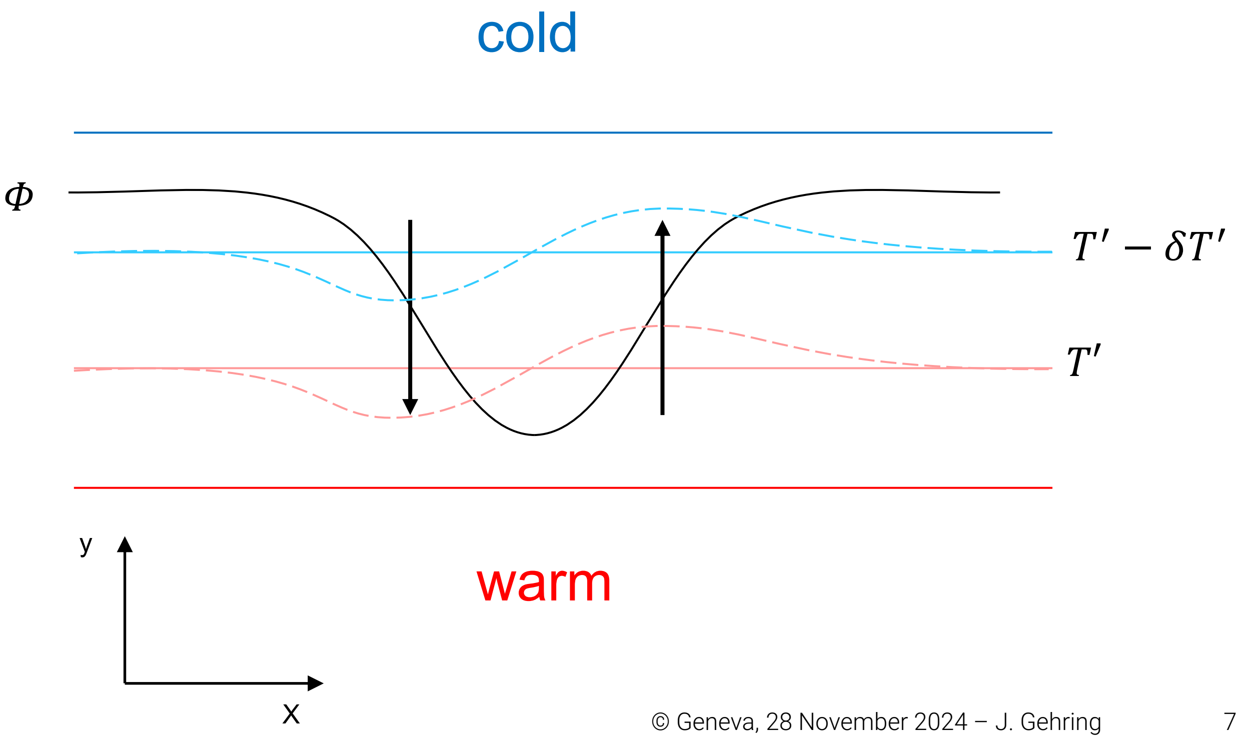
JEM Sec. 8.2

- Differential heating → meridional temperature gradient
- Wave-like perturbation in the geopotential height field
- Speed of this wave is the same as the background westerly flow
- Cold (warm) air advection upstream (downstream) of the trough axis



Is such a wave unstable?

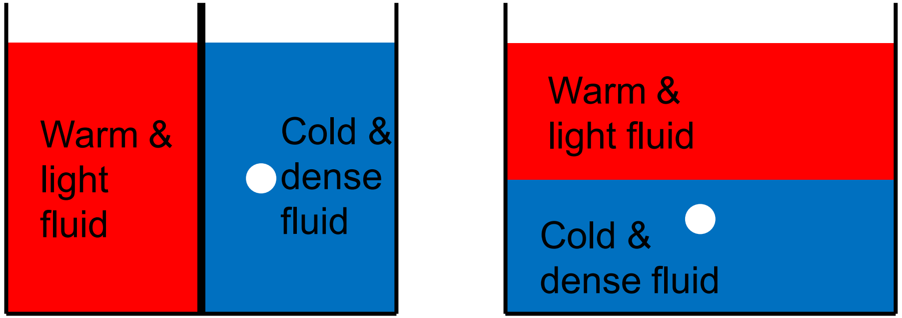
- For the introduction of such a wave-like perturbation to be unstable:
  i. The temperature anomalies must become larger
  ii. The kinetic energy of the wave motion must increase



The energetic aspect

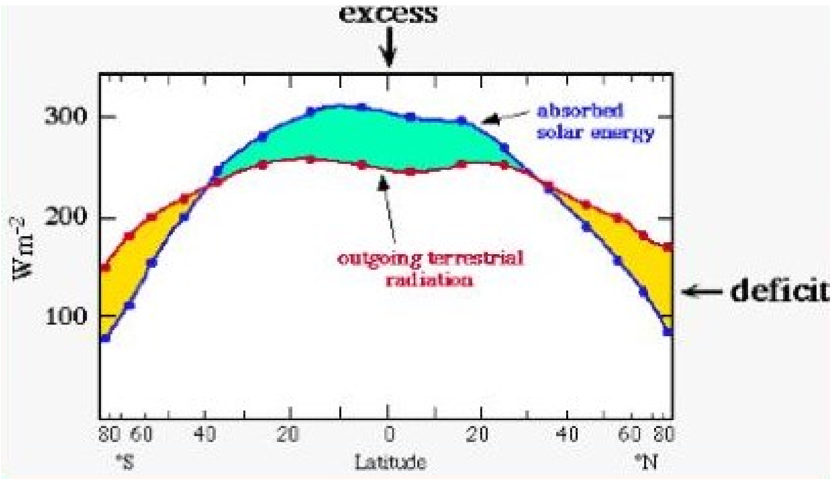
JEM Sec. 8.2

- The **pole-to-equator temperature gradient** represents a **density contrast**
- Centre of gravity at the mid-height point
- Remove the wall → **potential energy converted into kinetic energy**
- Lower center of gravity → lower potential energy → more stable



The role of extratropical cyclones in the atmospheric energy cycle

- Need a mechanism to **redistribute heat meridionally**
- Extratropical cyclones **converts** the available **potential** energy into **kinetic** energy
- Extratropical cyclones **transport polar air equatorward and tropical air poleward →** redistribute the heat meridionally



How to get a surface low pressure ?

JEM Sec. 8.3

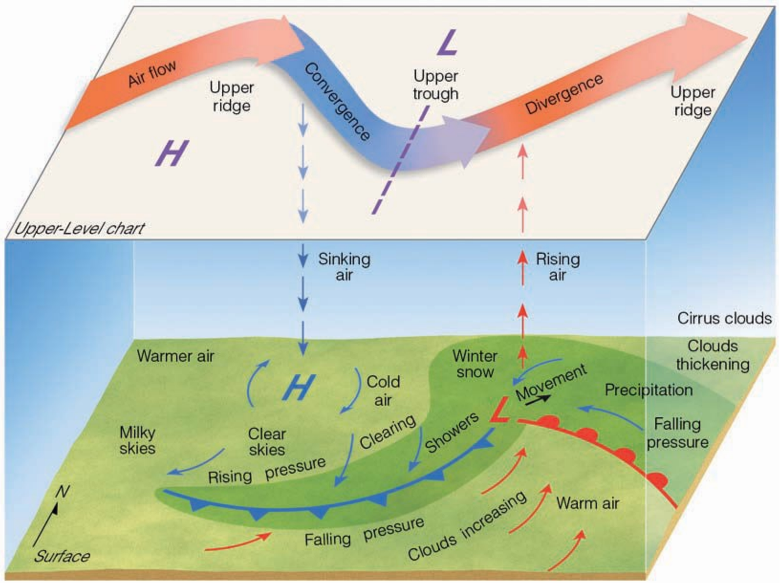
- Integrating the continuity equation ($\nabla_p \cdot \vec{V_h} = -\frac{\partial \omega}{\partial p}$) from $p = 0$ to $p = p_s$ (the surface pressure) yields the **pressure tendency equation**:

$$\frac{\partial p_s}{\partial t} \approx -\int_0^{p_s} (\nabla \cdot \vec{V})\partial p$$

→ The **surface pressure** tendency is the result of **net mass convergence** in the column

→ **Net mass divergence** (convergence) in the column leads to **sea-level pressure fall** (rise)

- Surface convergence in a low pressure system is the result of surface friction



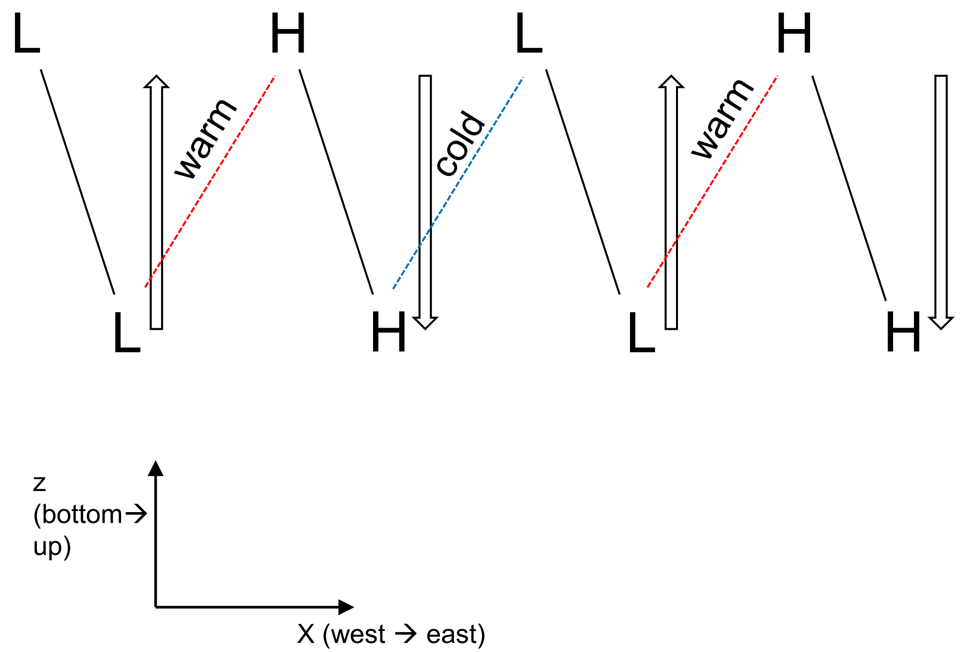
From Ahrens, 2009, *Meteorology Today*

The vertical structure

JEM Sec. 8.2

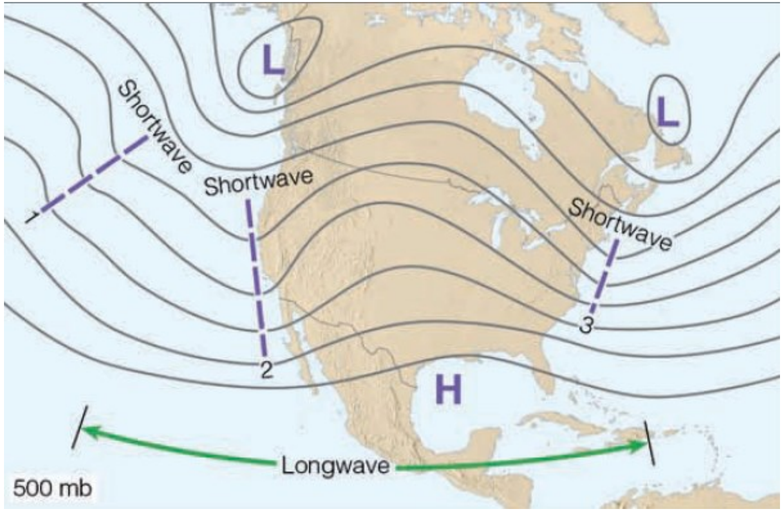
- Pattern of **highs and lows**
- **Lows** are associated with **upper-level divergence** and **upward** motions
- Upper-level divergence maximum is found ahead of the trough axis → **westward tilt of the geopotential height axes**
- **thermal axes tilt eastward**

→ Mid-latitude disturbances are characterised by **thermally direct** circulations in which **warm air rises and cold air sinks**



The most unstable wavelengths

- **Spontaneous conversion of potential energy to kinetic energy →** background zonal baroclinic flow is **unstable** to certain wave-like perturbation
- Wavelengths of 3000 to 4500 km are the **most unstable**.
- Corresponds to the wavelength of **mid-latitude shortwaves**
- Shortwaves are very **unpredictable**, yet have a large influence on weather

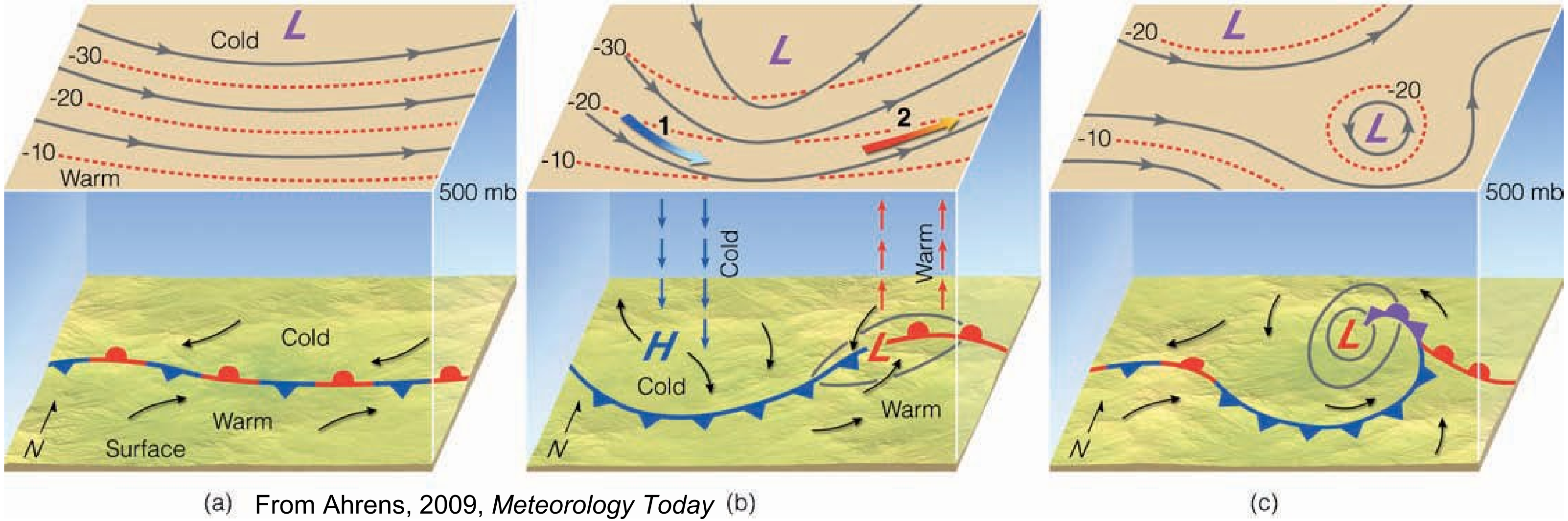


From Ahrens, 2009, *Meteorology Today*

[(1)] Jules Charney (1947) and Eric Eady (1949) developed the theory of baroclinic instability independently and found the same result.

Cyclone decay

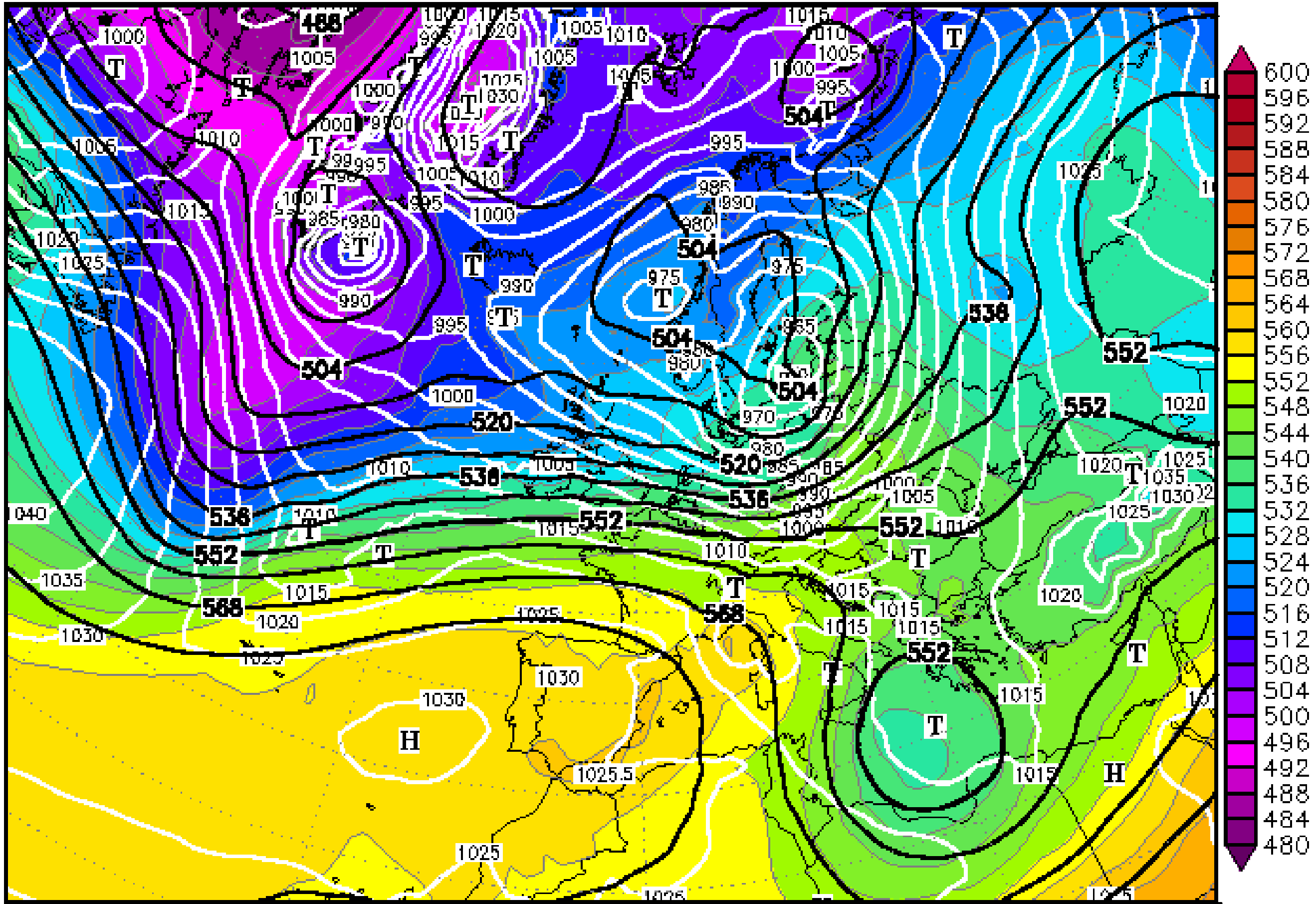
- Mature stage: **westward tilt → maximum upper-level divergence** above the sea level pressure minimum
- Dissipation stage: **geopotential height minima vertically aligned** → cyclone decays



From Ahrens, 2009, *Meteorology Today*

The vertical structure applied to Eunice

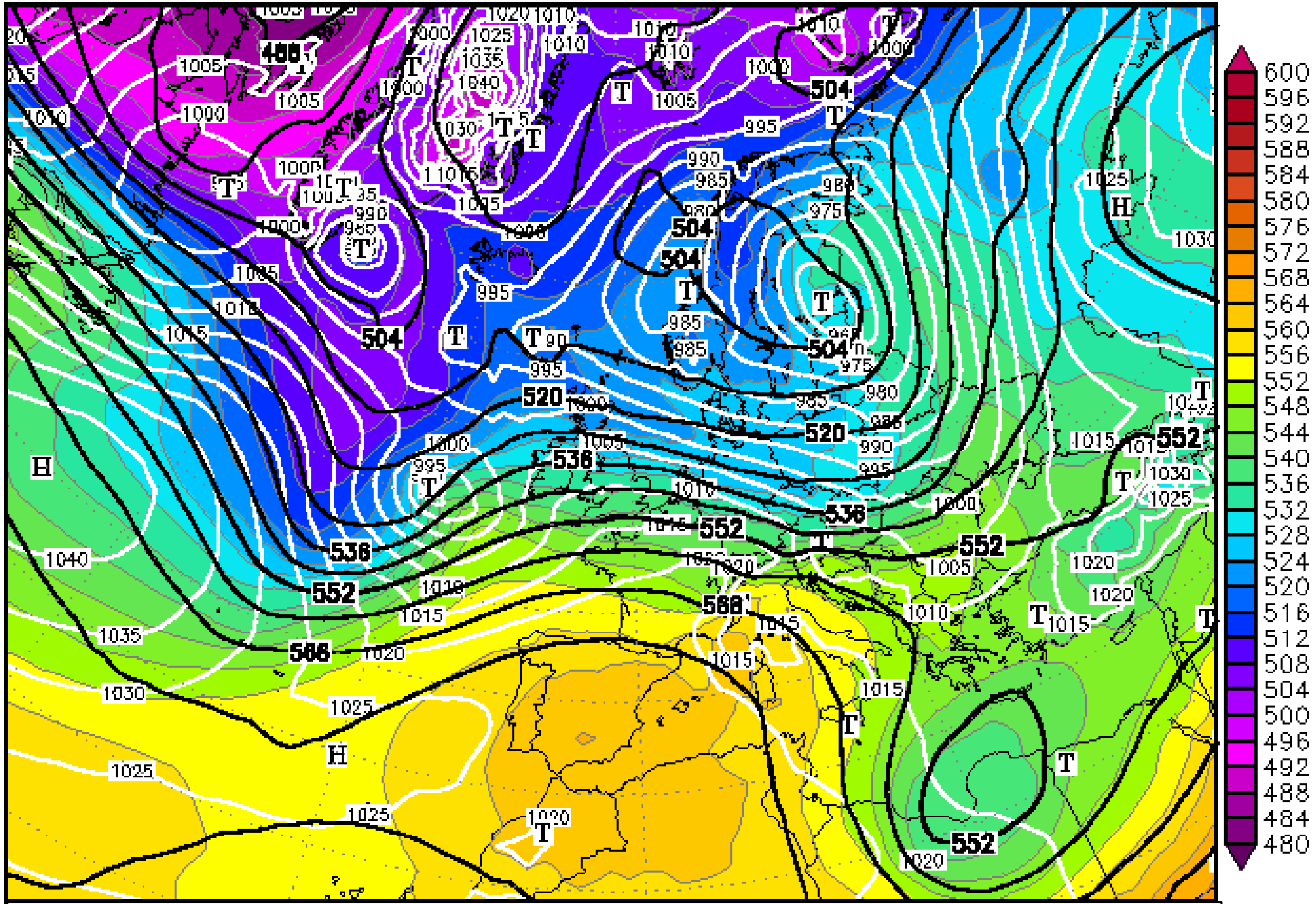
- The surface pressure trough is located **ahead of the upper-level** trough (westward tilt)



500 hPa geopotential height (black contours, dam), 500 to 1000 hPa thickness (colour, dam) and mean sea-level pressure (white contours, hPa) **17 Feb 2022 at 06 UTC**, analysis from the Global Forecast System (GFS), copyright wetter3.de

The vertical structure applied to Eunice

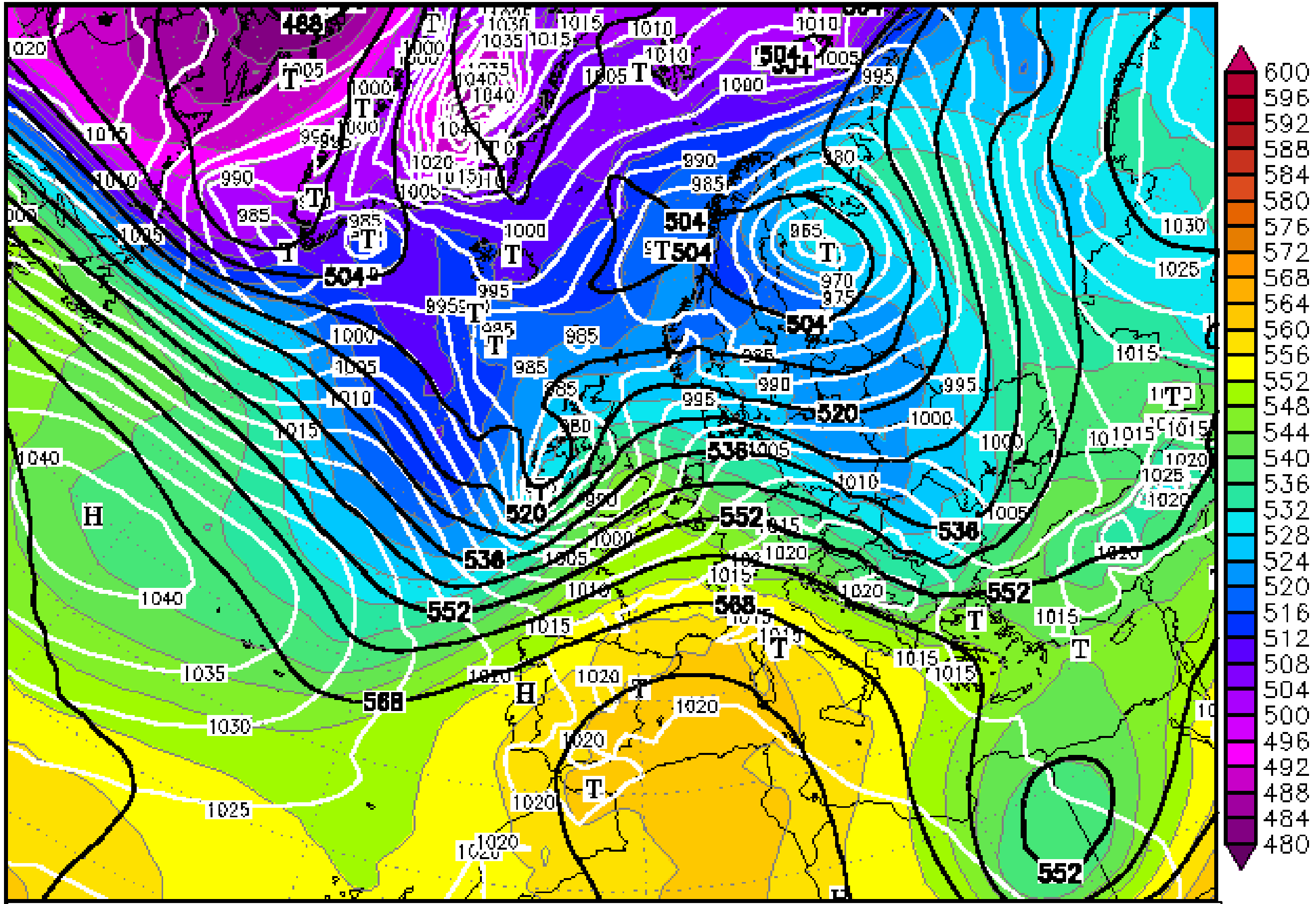
- The low pressure intensifies
- **Westward tilt**
- Warm air advection downstream of the trough axis **strengthens the upper-level ridge**



500 hPa geopotential height (black contours, dam), 500 to 1000 hPa thickness (colour, dam) and mean sea-level pressure (white contours, hPa) **17 Feb 2022 at 18 UTC**, analysis from the Global Forecast System (GFS), copyright wetter3.de

The vertical structure applied to Eunice

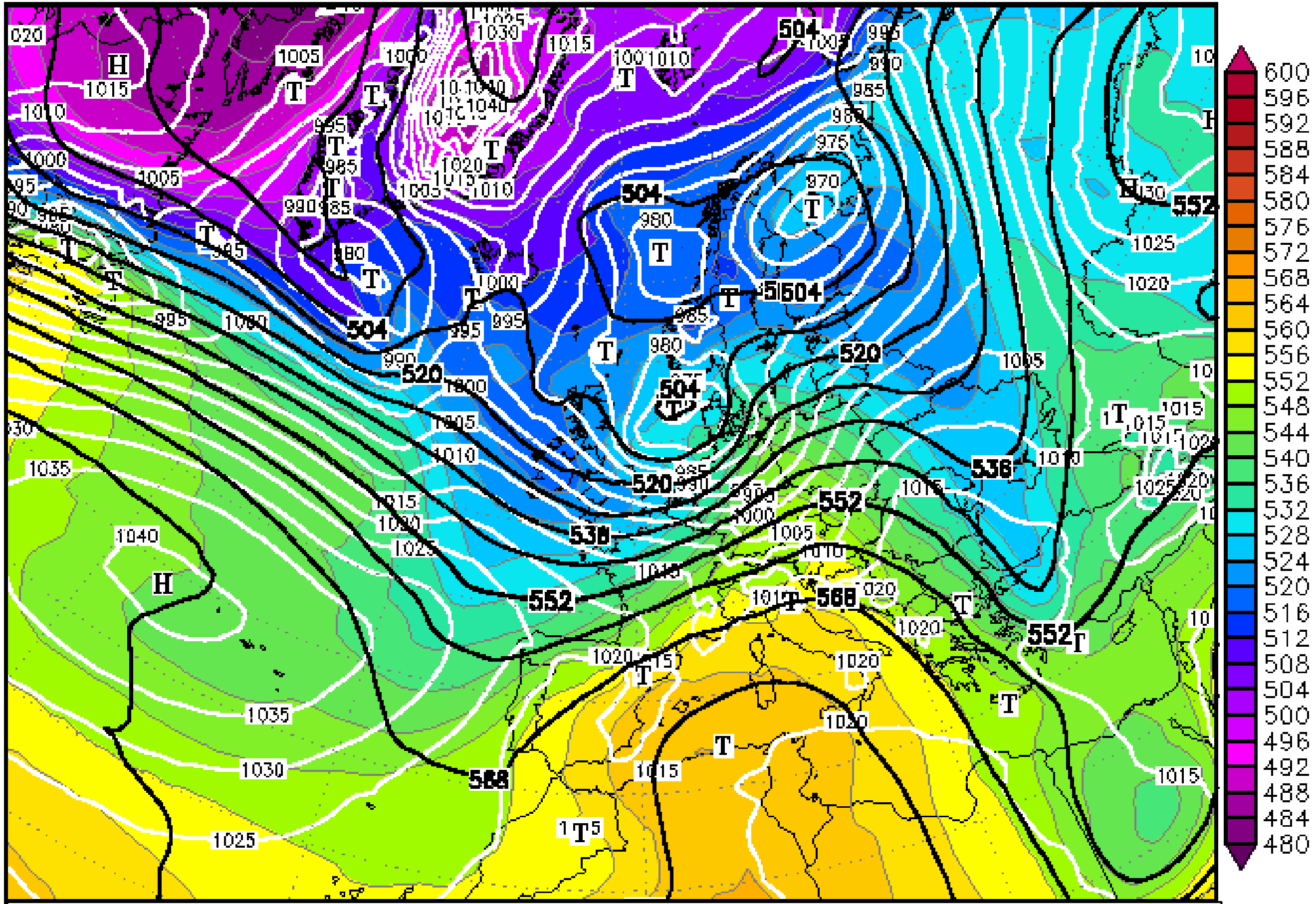
- Cyclone moves away from the peak of the warm sector: **vertically aligned with the upper-level trough**



500 hPa geopotential height (black contours, dam), 500 to 1000 hPa thickness (colour, dam) and mean sea-level pressure (white contours, hPa) **18 Feb 2022 at 06 UTC**, analysis from the Global Forecast System (GFS), copyright wetter3.de

The vertical structure applied to Eunice

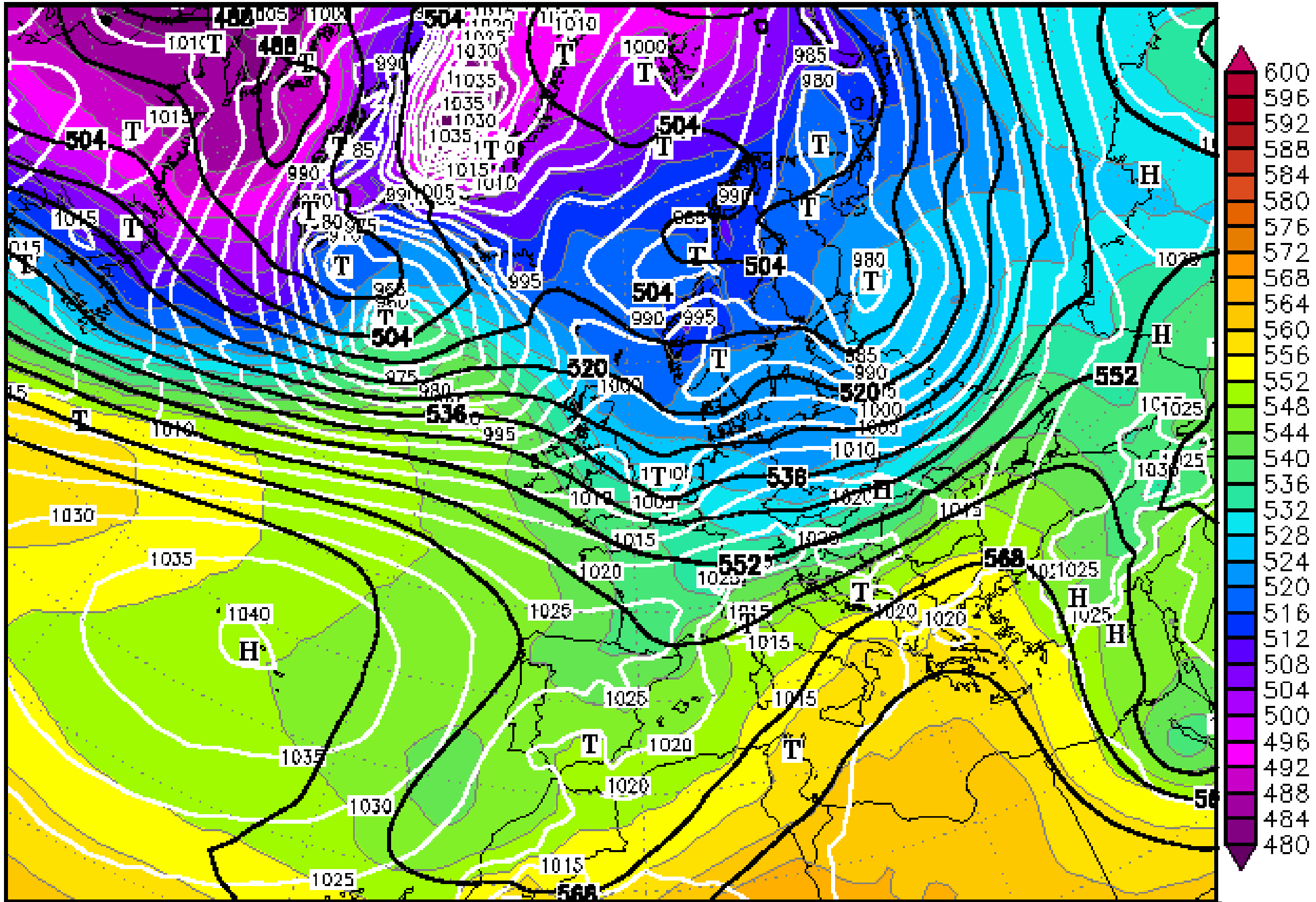
- Cyclone perfectly aligned with the 500 hPa geopotential height minimum



500 hPa geopotential height (black contours, dam), 500 to 1000 hPa thickness (colour, dam) and mean sea-level pressure (white contours, hPa) **18 Feb 2022 at 18 UTC**, analysis from the Global Forecast System (GFS), copyright wetter3.de

The vertical structure applied to Eunice

- **Cyclone decays**



500 hPa geopotential height (black contours, dam), 500 to 1000 hPa thickness (colour, dam) and mean sea-level pressure (white contours, hPa) **19 Feb 2022 at 18 UTC**, analysis from the Global Forecast System (GFS), copyright wetter3.de

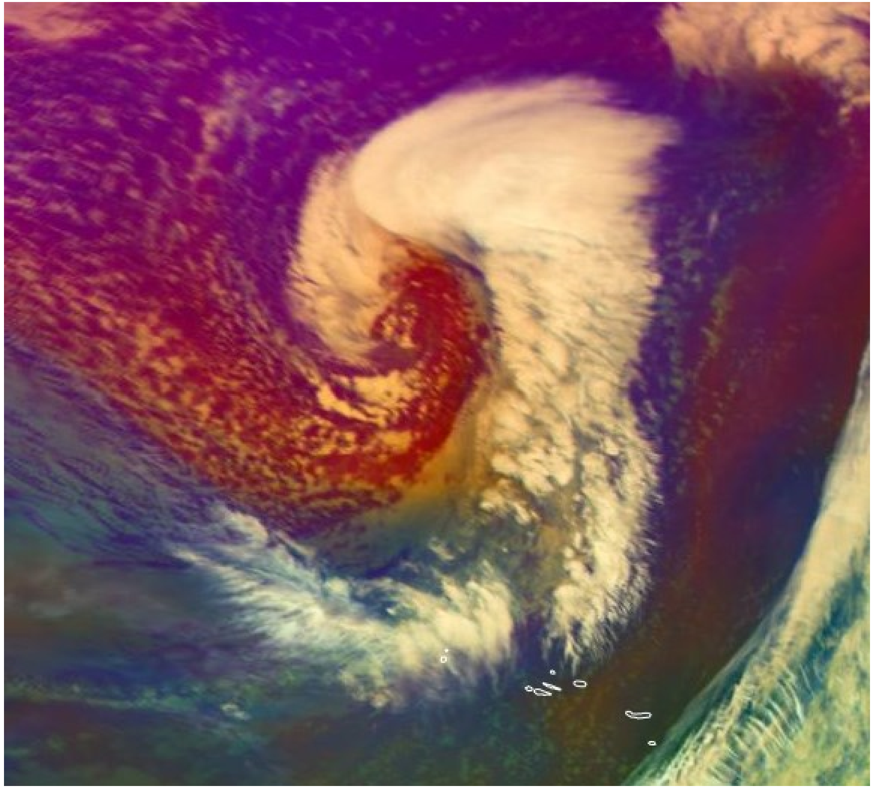
Baroclinic instability and vertical structure: take home messages

- **Differential solar heating** → meridional temperature gradient → **baroclinic atmosphere**
- Density contrast between the cold (dense) polar air and the warm (lighter) tropical air represents **an unstable state**
- A small perturbation of the background westerly flow will **convert the available potential energy into kinetic energy**
- Extratropical cyclones **redistribute heat** by transporting polar air equatorward and tropical air poleward
- **Cyclone decay**: it becomes vertically aligned with the upper-level trough → surface pressure rises

A Lagrangian perspective of extratropical cyclones: the conveyor belt model

The conveyor belt model

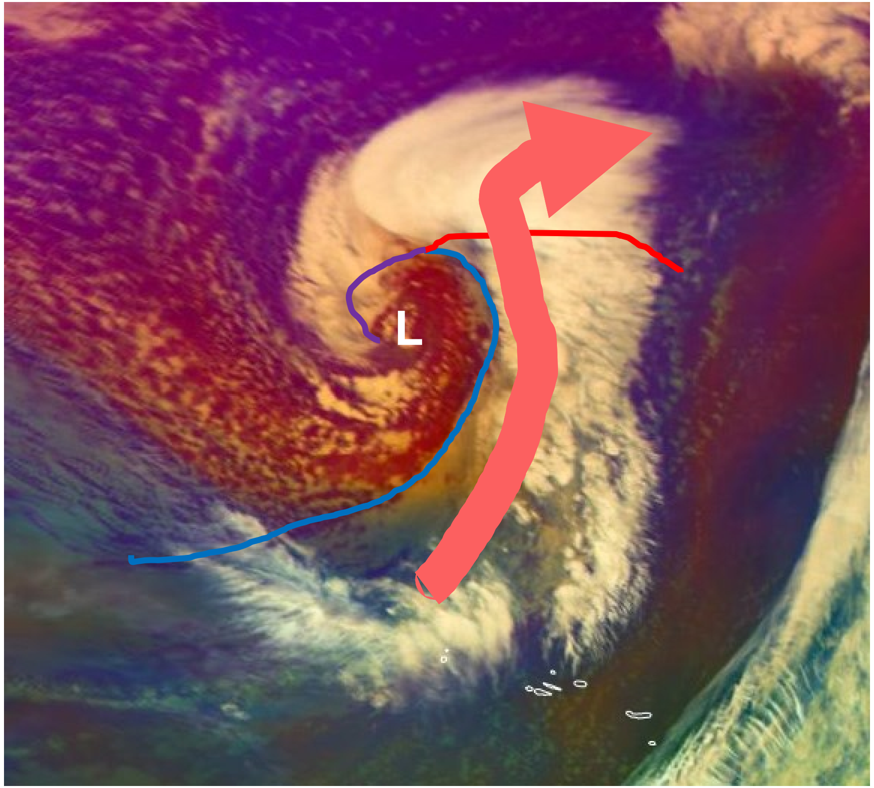
- What explains the «comma» shape of the clouds around an extratropical cyclone?
- How does the air flows around the cyclone?



Satellite image of an extratropical cyclone over the northern Atlantic on 12 November at 00 UTC from Eumetsat airmass RGB product

The conveyor belt model

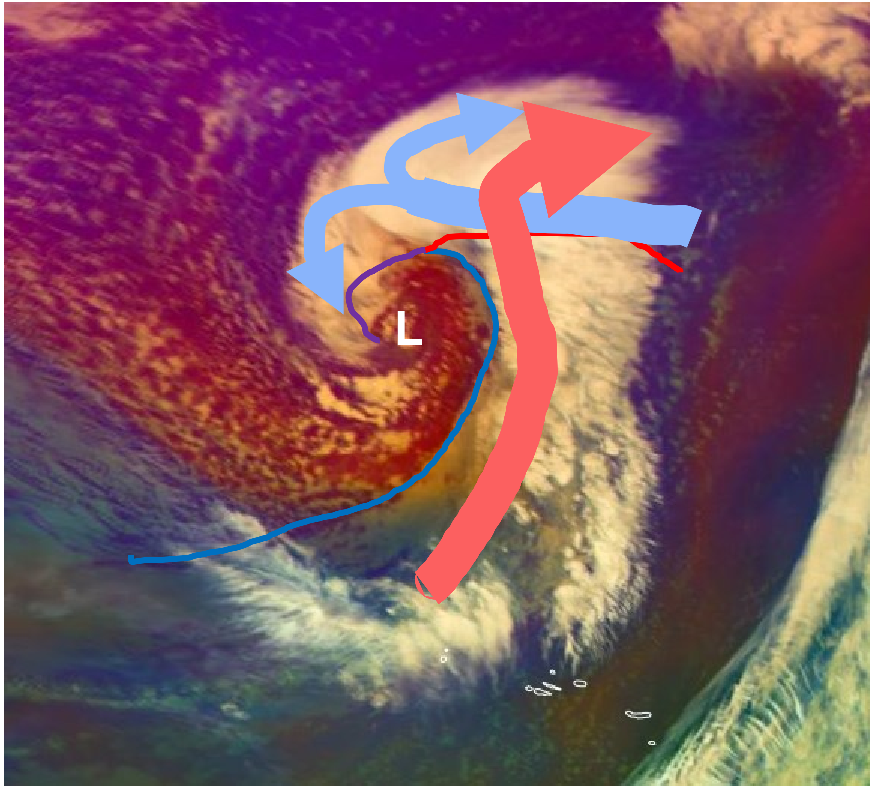
- The **warm conveyor belt** (WCB) : **rising warm** and **moist** air.
- WCBs are the **primary cloud- and precipitation-generating flow** in extratropical cyclones and can lead to **extreme precipitation**
- **Latent heat release** intensifies the vertical motion and the horizontal temperature gradient (frontogenetic)



Satellite image of an extratropical cyclone over the northern Atlantic on 12 November at 00 UTC from Eumetsat airmass RGB product

The conveyor belt model

- The **cold conveyor belt :** starts from the surface ahead of the warm front and rises slowly as it moves westward[1].

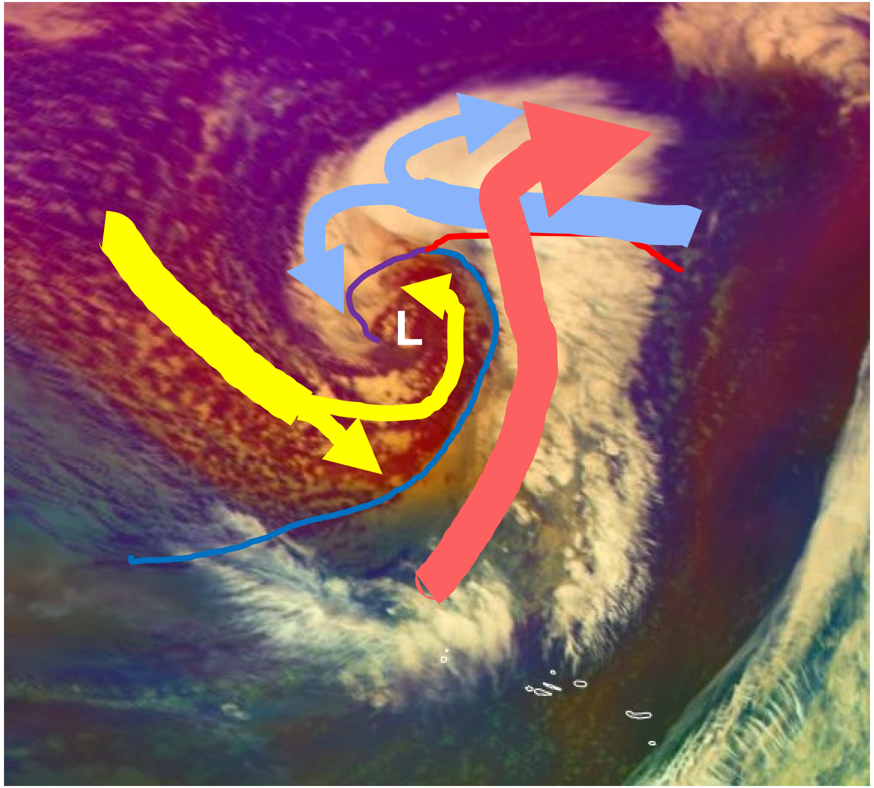


Satellite image of an extratropical cyclone over the northern Atlantic on 12 November at 00 UTC from Eumetsat airmass RGB product

(1) Relative to the cyclone's motion

The conveyor belt model

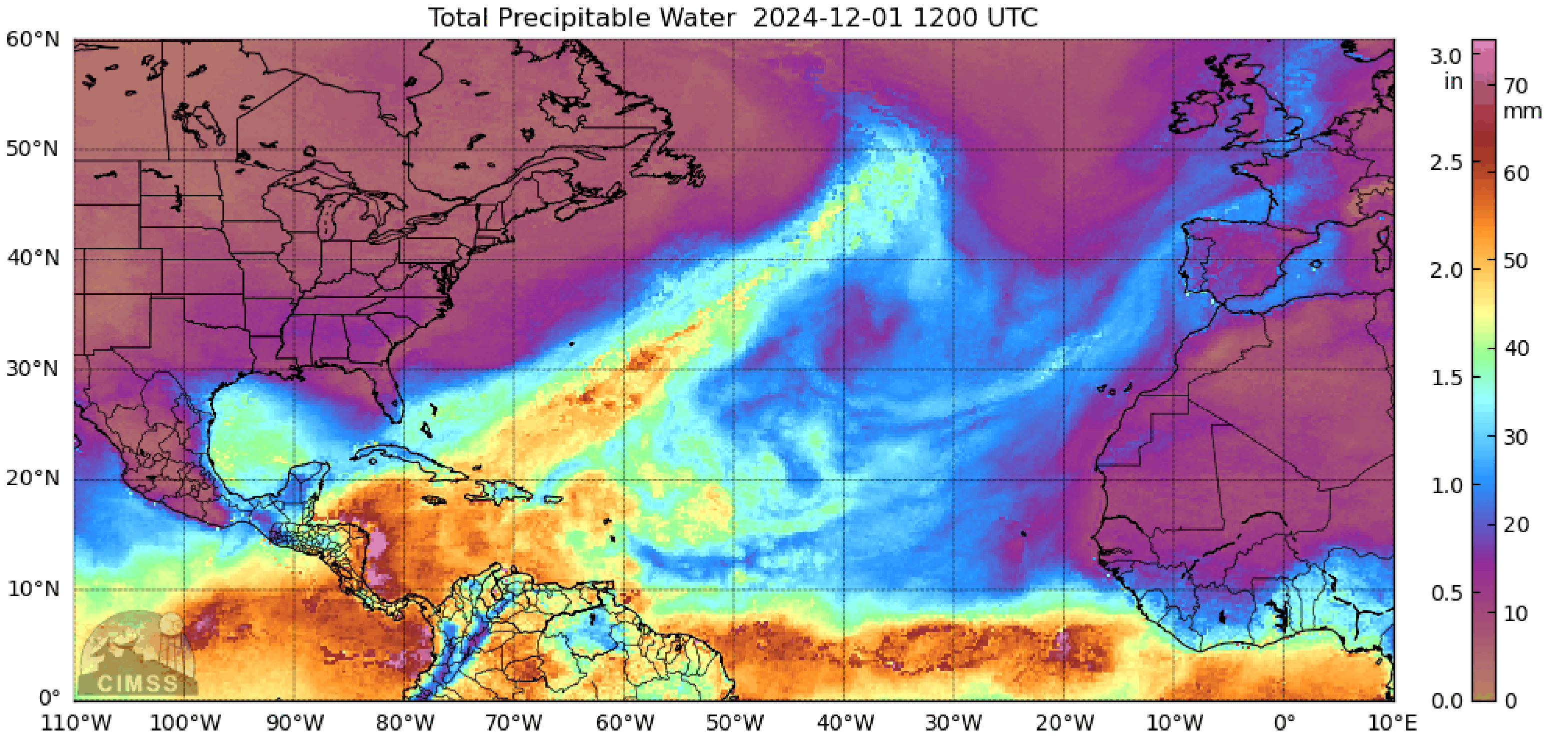
- The **dry conveyor belt:**
  - Sinks behind the cold front → clear sky area in the cold sector.
  - One branch turns towards the cyclone centre and leads to the **dry slot**, often visible in satellite images



Satellite image of an extratropical cyclone over the northern Atlantic on 12 November at 00 UTC from Eumetsat airmass RGB product

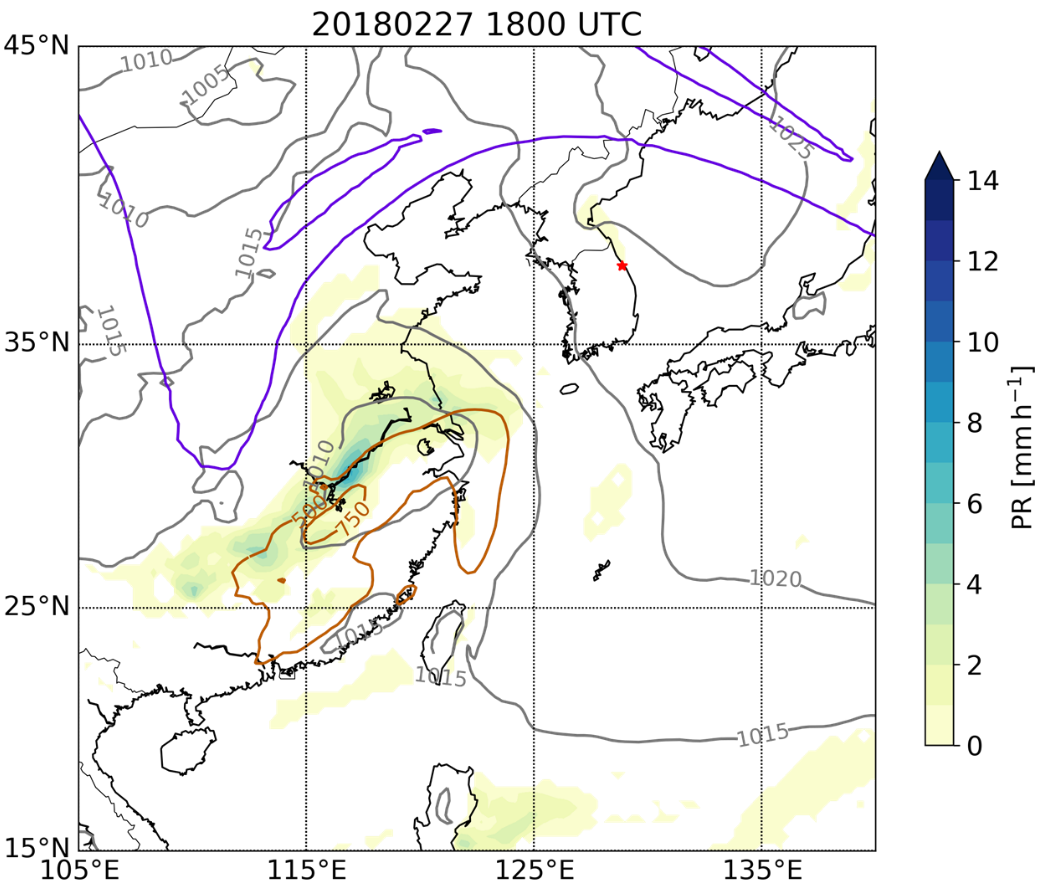
The link between warm conveyor belts and atmospheric rivers

- Narrow filaments of enhanced water vapour transport: the **atmospheric rivers** (ARs)
- ARs are often associated with extratropical cyclones



Putting it altogether: case study over Korea

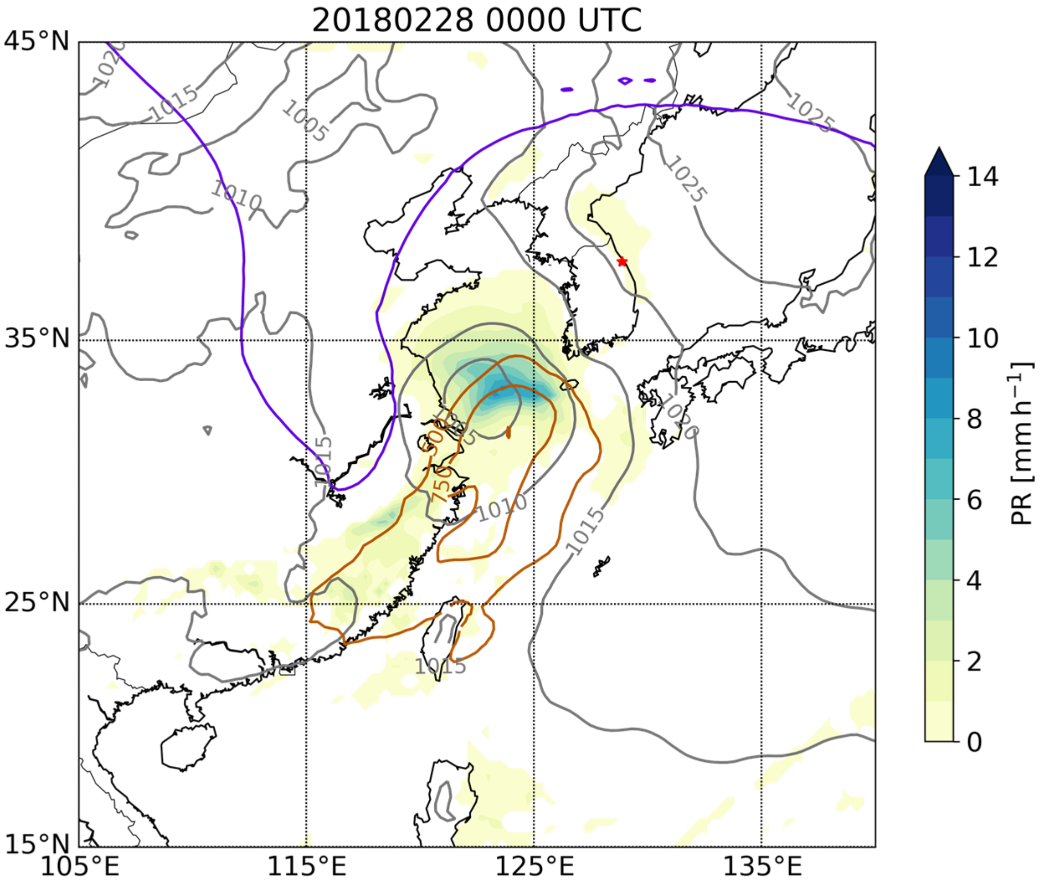
- An **upper-level trough** (blue contour) is located over eastern China with a **surface low-pressure** (grey contours) downstream



From Gehring et al. (2020)

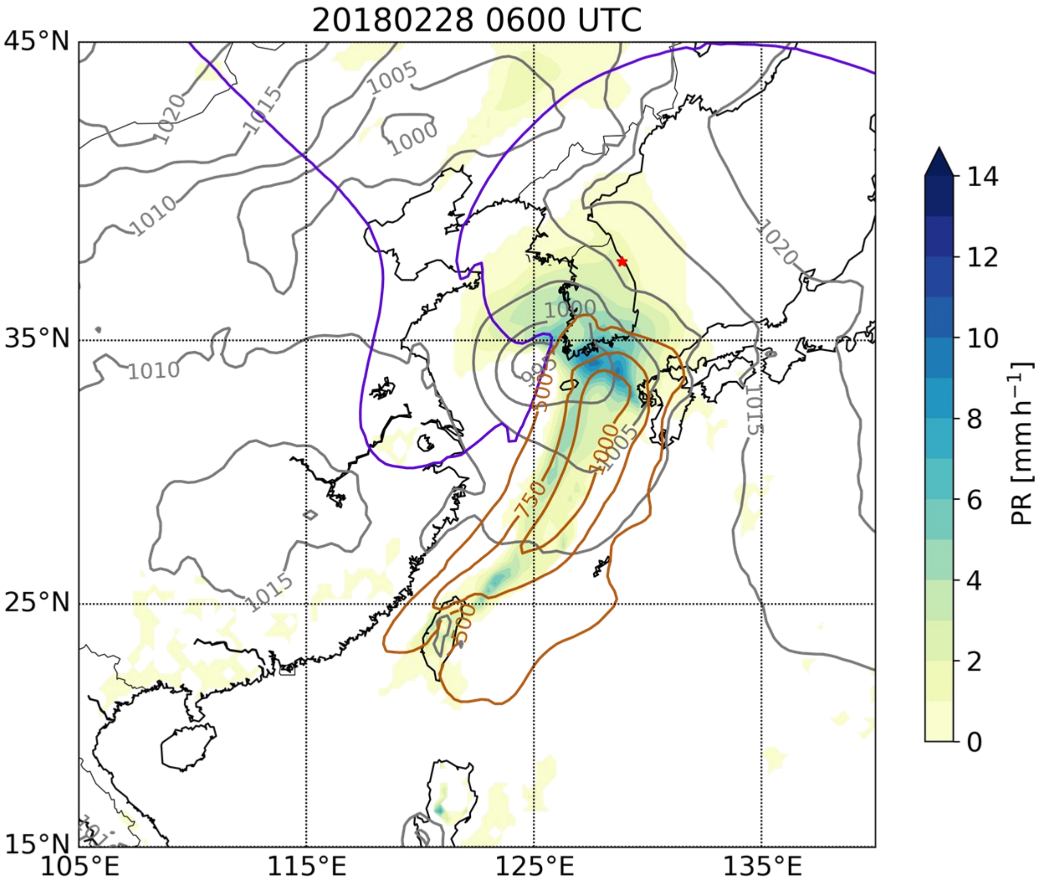
Putting it altogether: case study over Korea

- The surface **low intensifies** as a result of the strong **upper-level divergence**



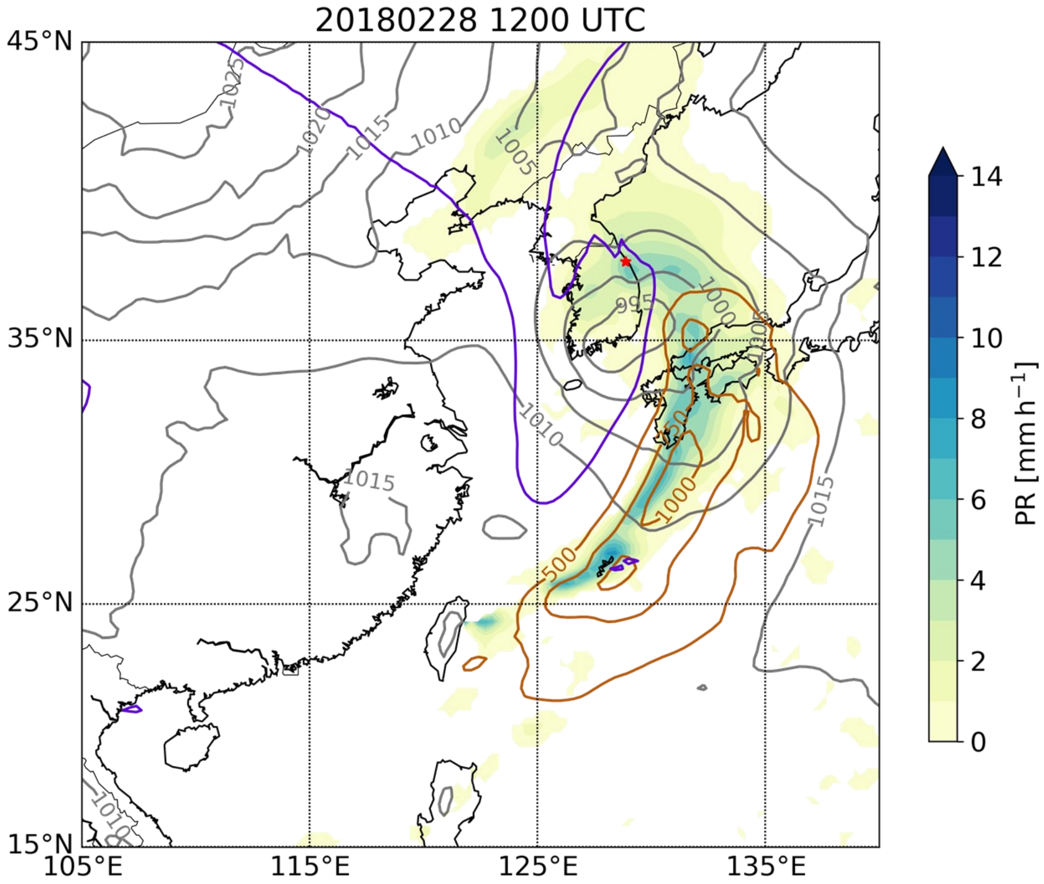
Putting it altogether: case study over Korea

- The surface **low further intensifies** probably as a result of **latent heat release** in the **warm conveyor belt** (WCB)
- Intense moisture : the **atmospheric river**



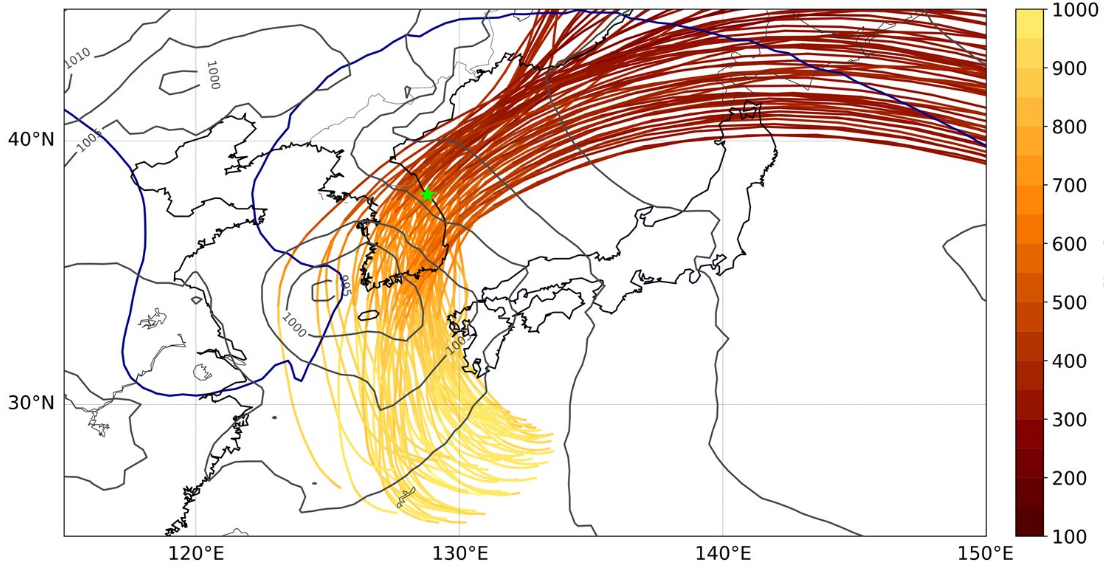
Putting it altogether: case study over Korea

- The surface low becomes vertically aligned with the upper-level trough



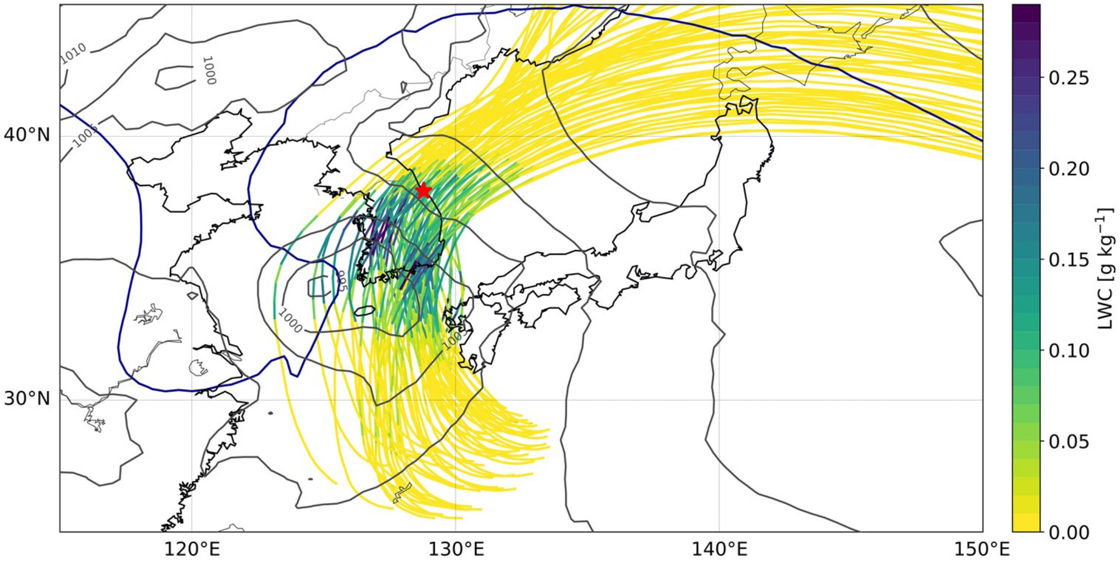
The warm conveyor belt shown with trajectory analysis

- Analysis of air trajectories shows a rising air mass ahead of the cold front



The warm conveyor belt shown with trajectory analysis

- The liquid water content (LWC) along the trajectories increases during the ascent as a result of **condensation**
- The **latent heat release** due to condensation **intensifies** the vertical motions and impact the upper-level dynamics



The conveyor belt model: take home messages

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- Analysis of air parcel trajectories in extratropical cyclones (ECs) reveal the presence of **three distinguished airstreams** with different temperature and humidity contents : the warm conveyor belt (WCB), the cold conveyor belt and the dry conveyor belt
- These conveyor belts explain the **comma-shape** structure of the clouds in an EC
- The airstream responsible for most of the cloud and precipitation in an EC is the …
- Latent heat release in the WCB … the upward motions and the horizontal temperature gradient
- WCBs and **atmospheric rivers** are often associated with each other and represent two complementary perspectives to study the **moisture transport** and **precipitation associated** with ECs