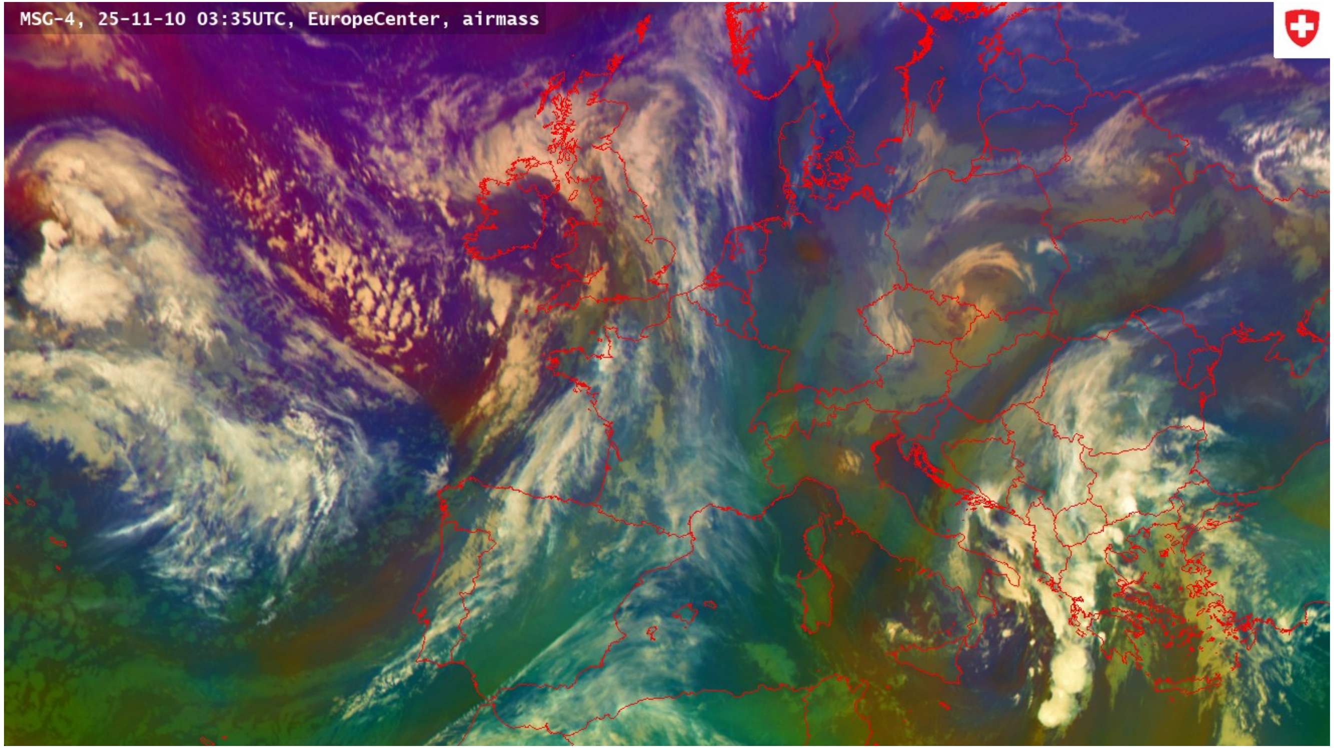
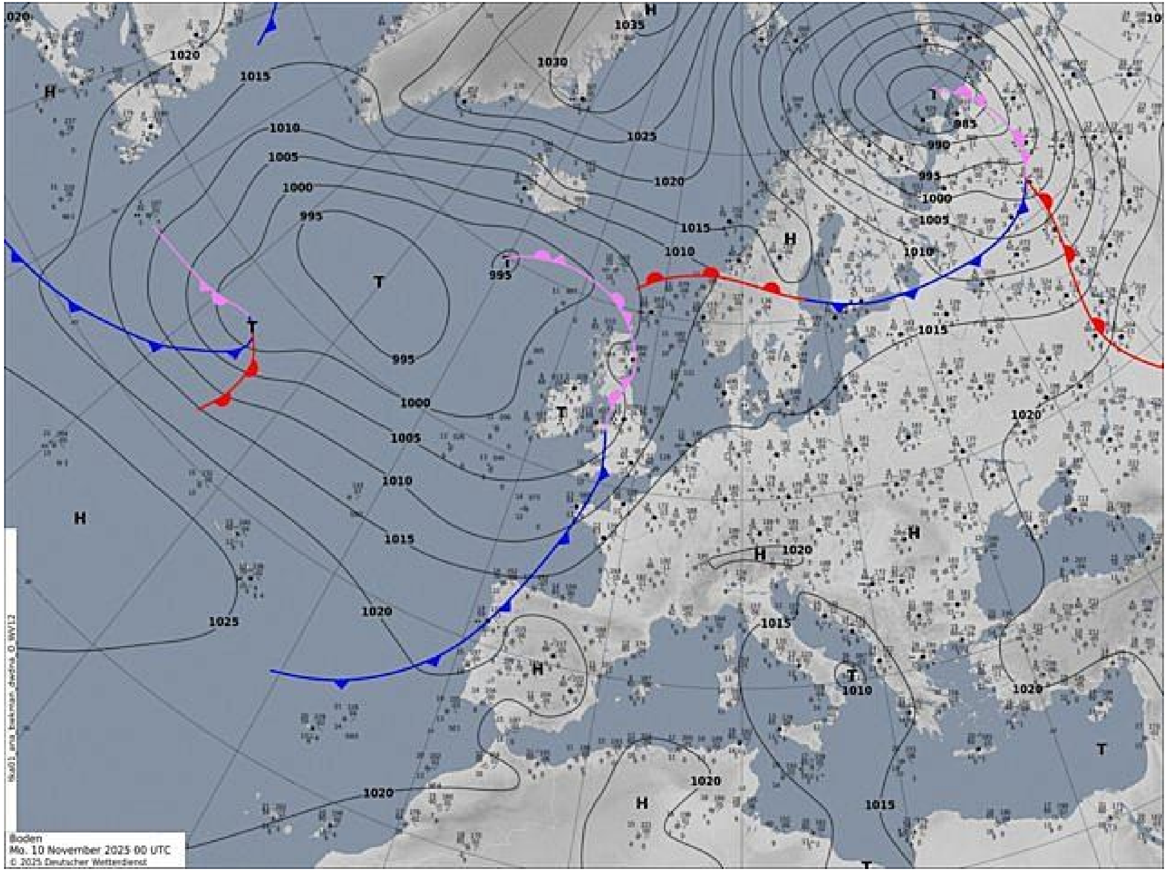
Large-scale dynamics of the mid-latitude atmosphere : Part III

Josué Gehring – Meteorologist at MeteoSwiss

Satellite image of the day

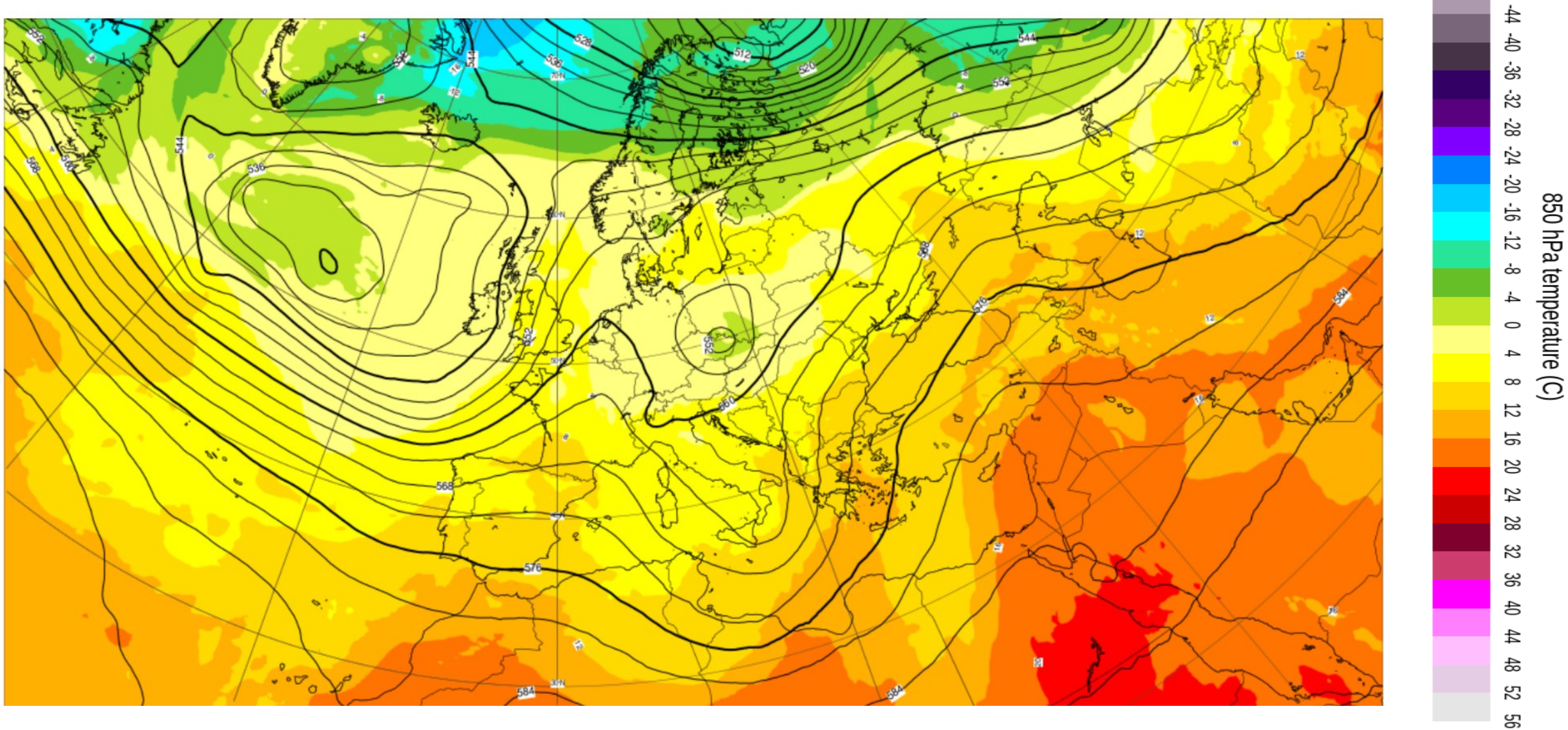


Frontal analysis



500 hPa geopotential height and 850 hPa temperature

Base time: Mon 10 Nov 2025 00 UTC Valid time: Mon 10 Nov 2025 00 UTC (+0h) Area : Europe



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

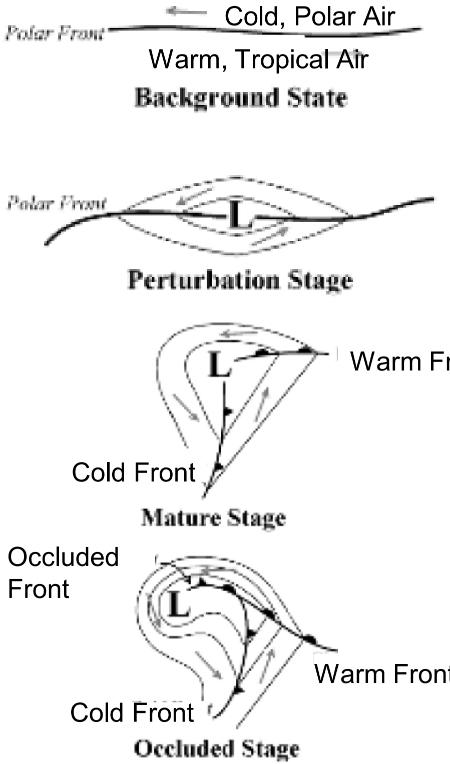
- Extratropical cyclones: going beyond the polar front theory
- Impact of climate change on extratropical cyclones

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?

sli.do
#1461754

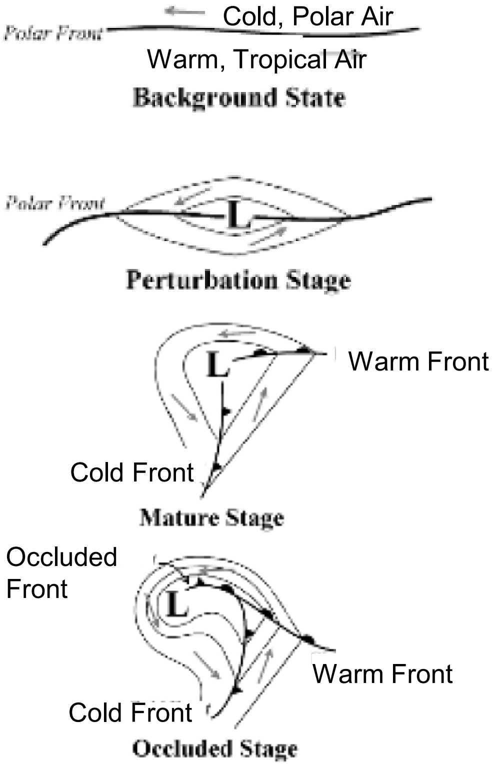


What are the limitations of the polar front theory?

sli.do
#1461754

- 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

sli.do
#1461754

What does baroclinic mean?

- **Baroclinic** : density depends on both pressure and temperature
- Differential solar heating → **meridional temperature gradient**

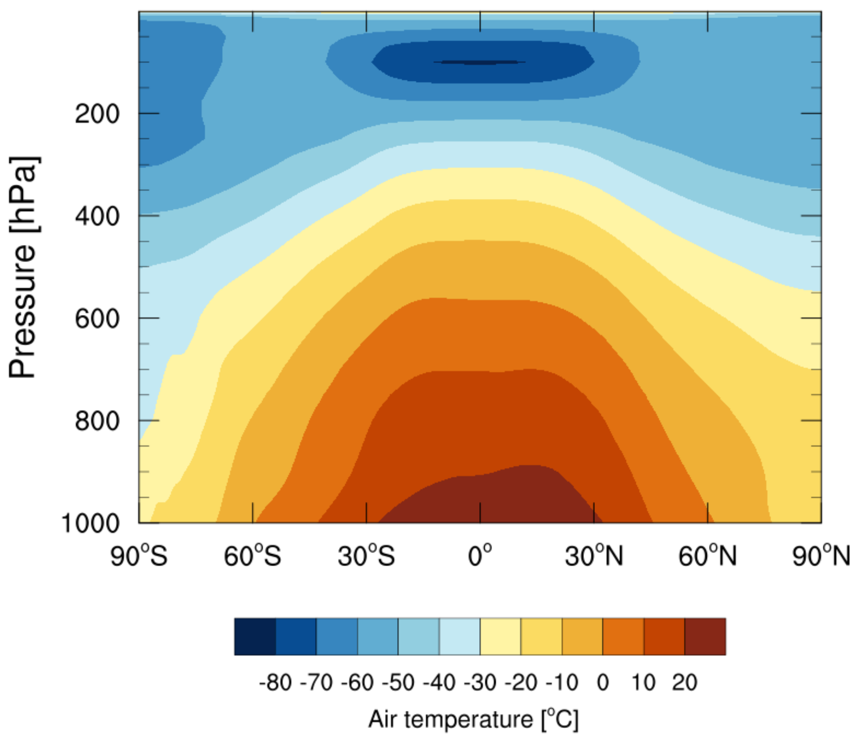
→ the temperature is not uniform on a constant pressure surface

→ the **atmosphere is baroclinic**

Quiz

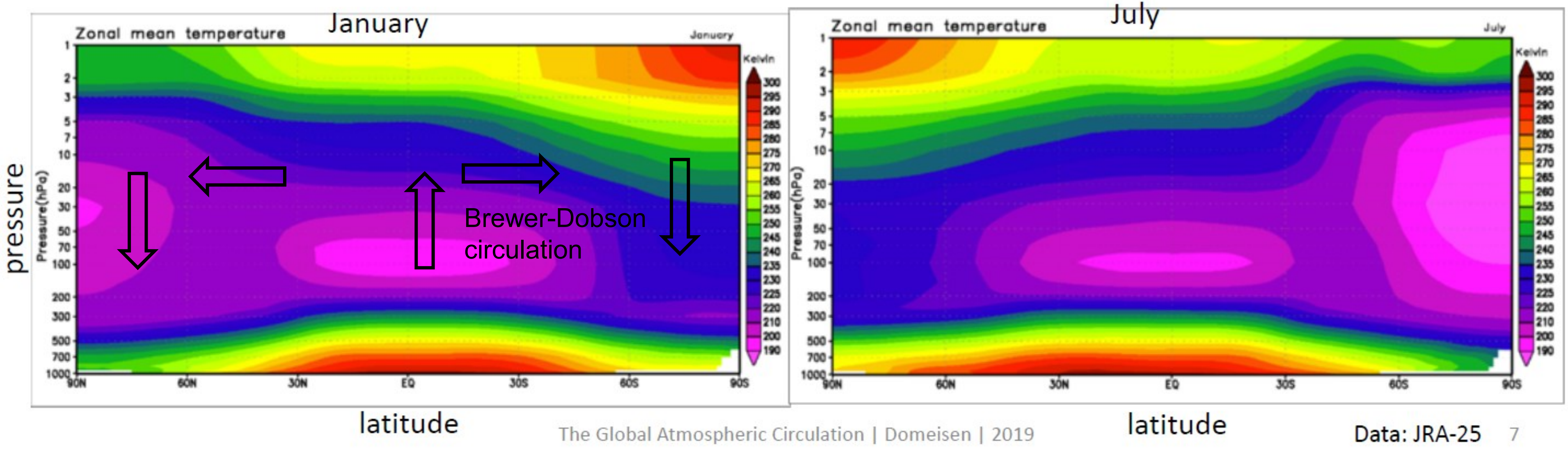
- The atmosphere is most baroclinic ...
- The atmosphere is least baroclinic ...

Zonal mean air temperature from ERA Interim data 1978-2018



Short excursion in the stratosphere (not part of exam)

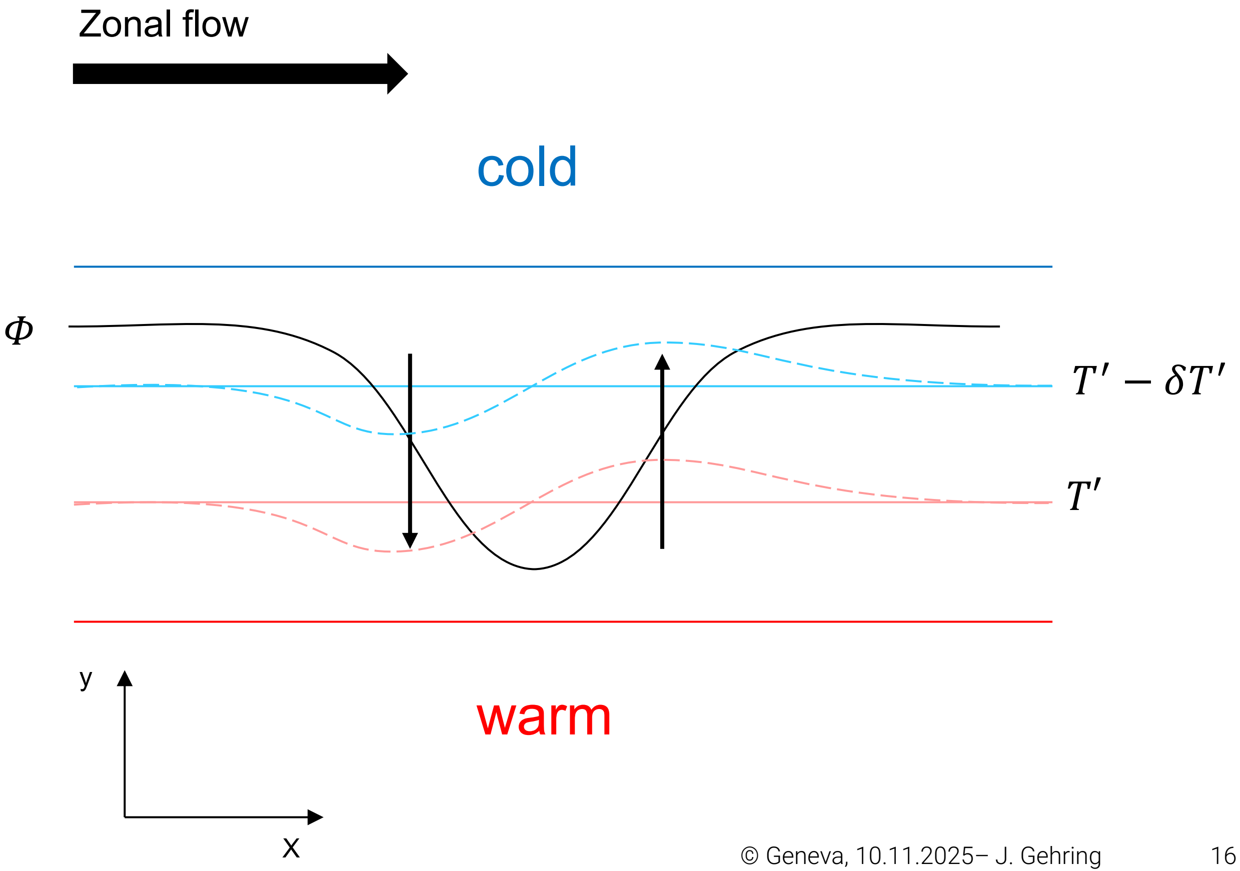
- Polar stratosphere is on yearly average warmer than tropical stratosphere, but …
- In the winter hemisphere, polar stratosphere is as cold or even colder (southern hemisphere) as the tropical stratosphere
- Stratosphere **not in radiative balance**, its thermal structure is a consequence of the Brewer-Dobson circulation



Why is a baroclinic atmosphere unstable?

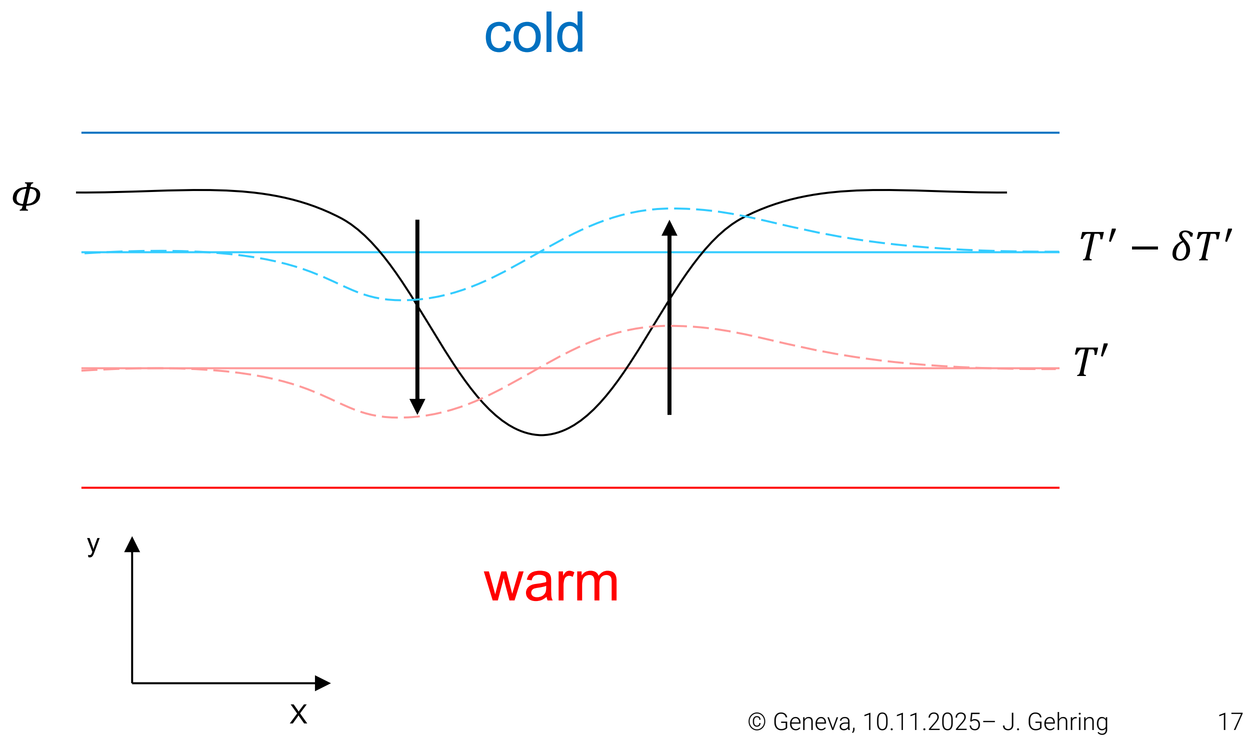
JEM Sec. 8.2

- 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?

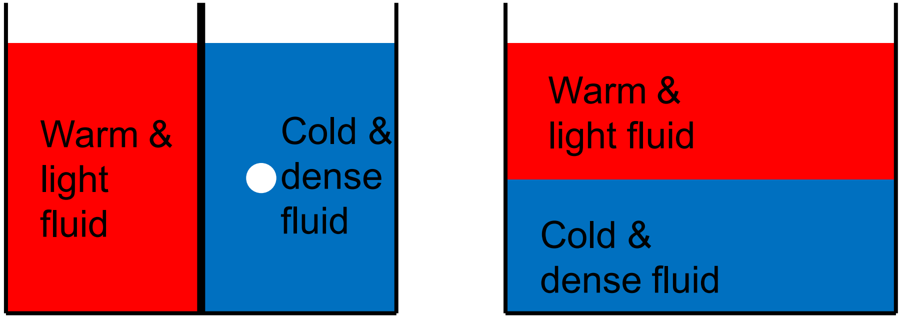
- For the introduction of such a wave-like perturbation to be unstable:
  i. The temperature anomalies must become larger
  ii. The kinetic energy of the wave motion must increase



The energetic aspect

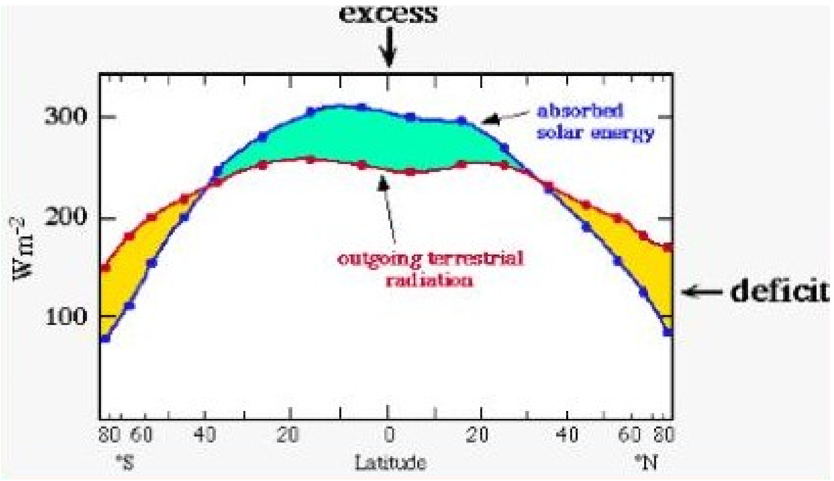
sli.do
#1461754

- The **pole-to-equator temperature gradient** represents a **density contrast**
- Centre of gravity at the mid-height point
- **Quiz!**



The role of extratropical cyclones in the atmospheric energy cycle

- Need a mechanism to **redistribute heat meridionally**
- Extratropical cyclones **convert** 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

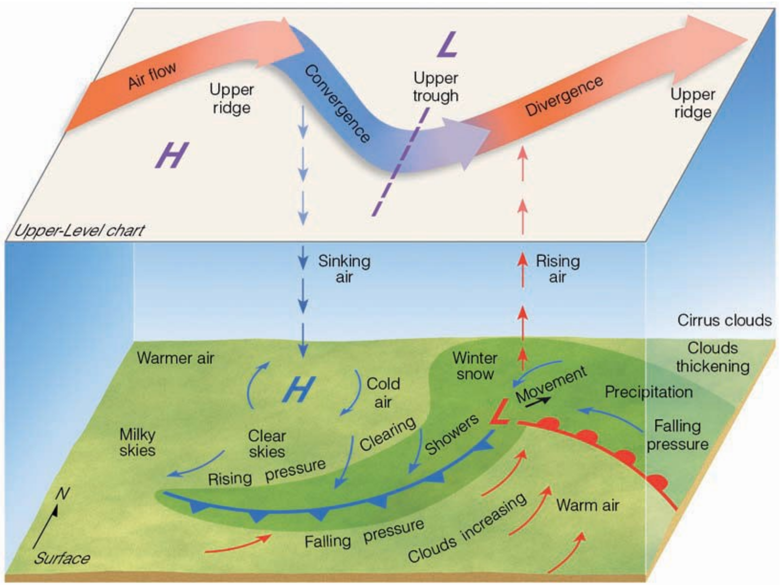
- Integrating the continuity equation ($\nabla_p \cdot \overrightarrow{V_h} = -\frac{\partial \omega}{\partial p}$) from $p = 0$ to $p = p_s$ (the surface pressure) yields the **pressure tendency equation**:

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

→ 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



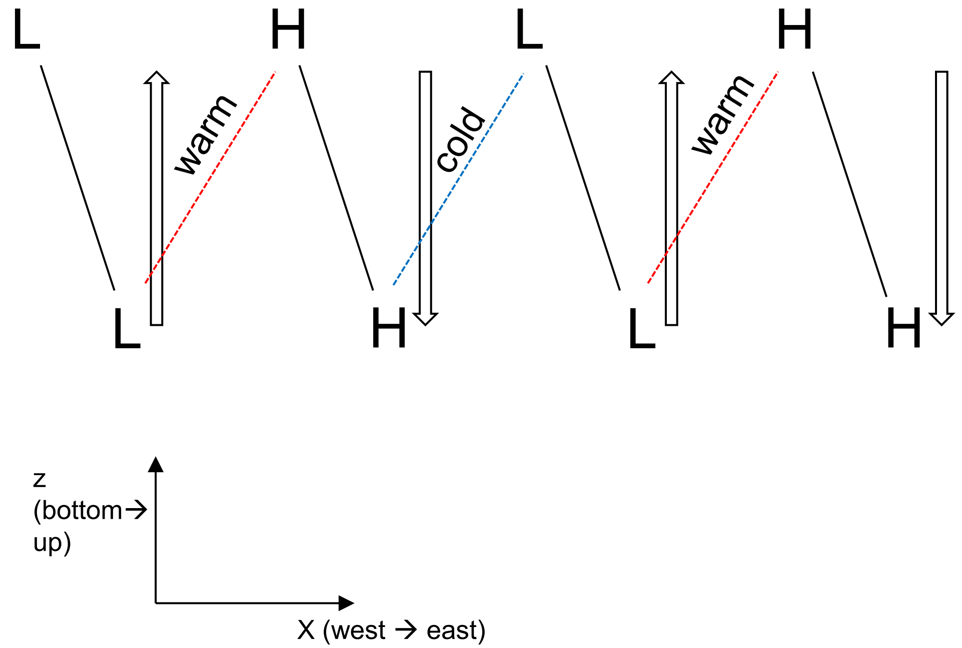
From Ahrens, 2009, *Meteorology Today*

The vertical structure

JEM Sec. 8.2

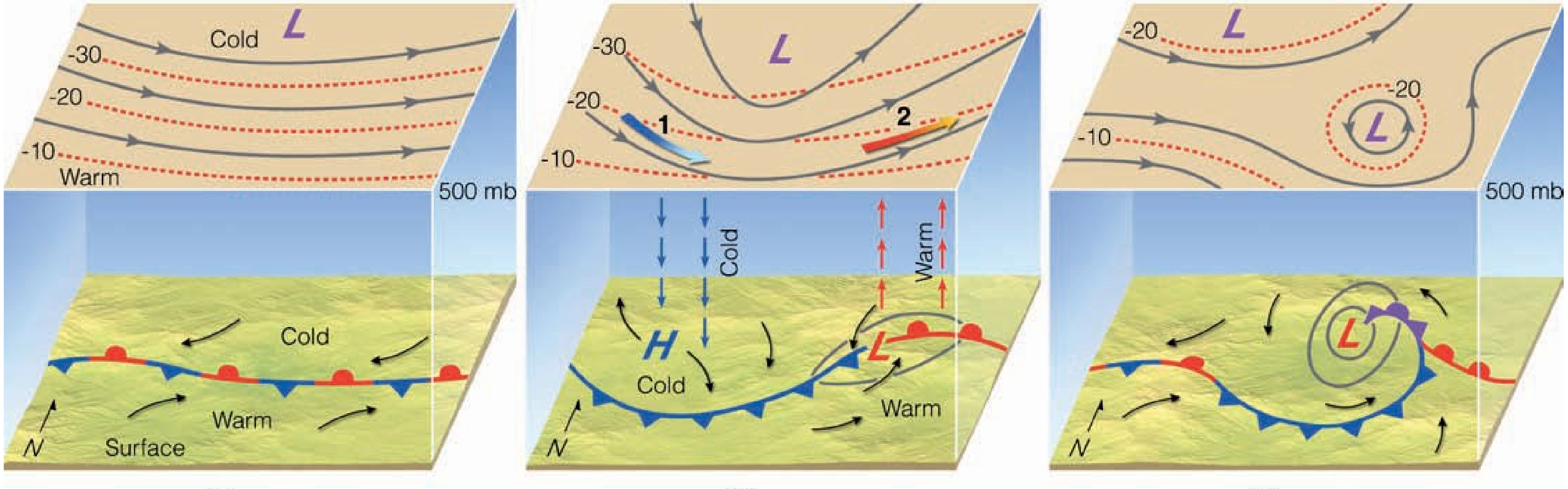
- Pattern of **highs and lows**
- **Lows** are associated with **upper-level divergence** and **upward** motions
- Upper-level divergence maximum is found ahead of the trough axis → **westward tilt of the geopotential height axes**
- **thermal axes tilt eastward**

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



Cyclone decay

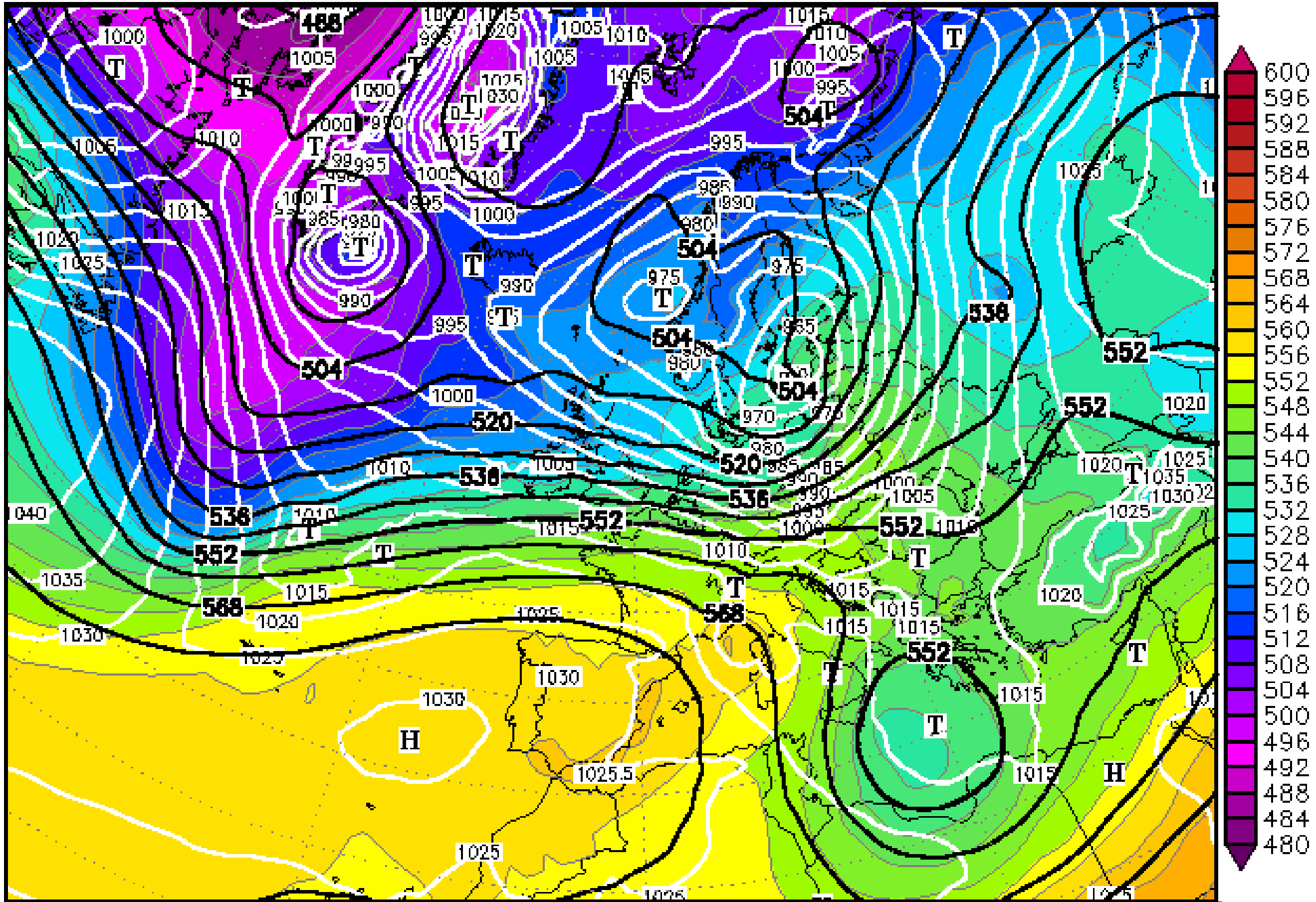
- Mature stage: **westward tilt →** maximum **upper-level divergence** above the sea level pressure minimum
- Dissipation stage: **geopotential height minima vertically aligned** → cyclone decays



(a) From Ahrens, 2009, *Meteorology Today* (b) (c)

The vertical structure applied to Eunice

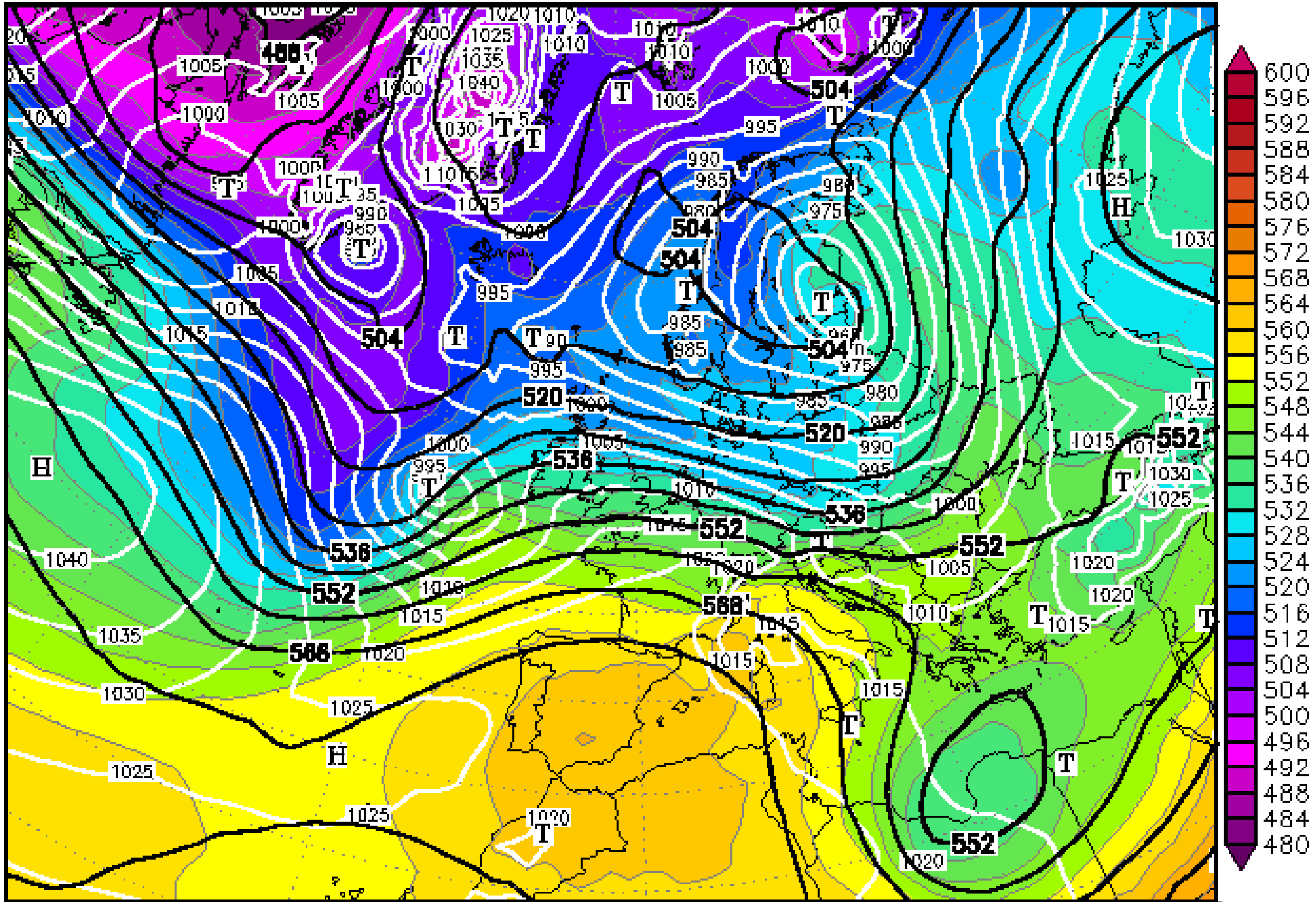
- The surface pressure trough is located **ahead of the upper-level** trough (westward tilt)



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

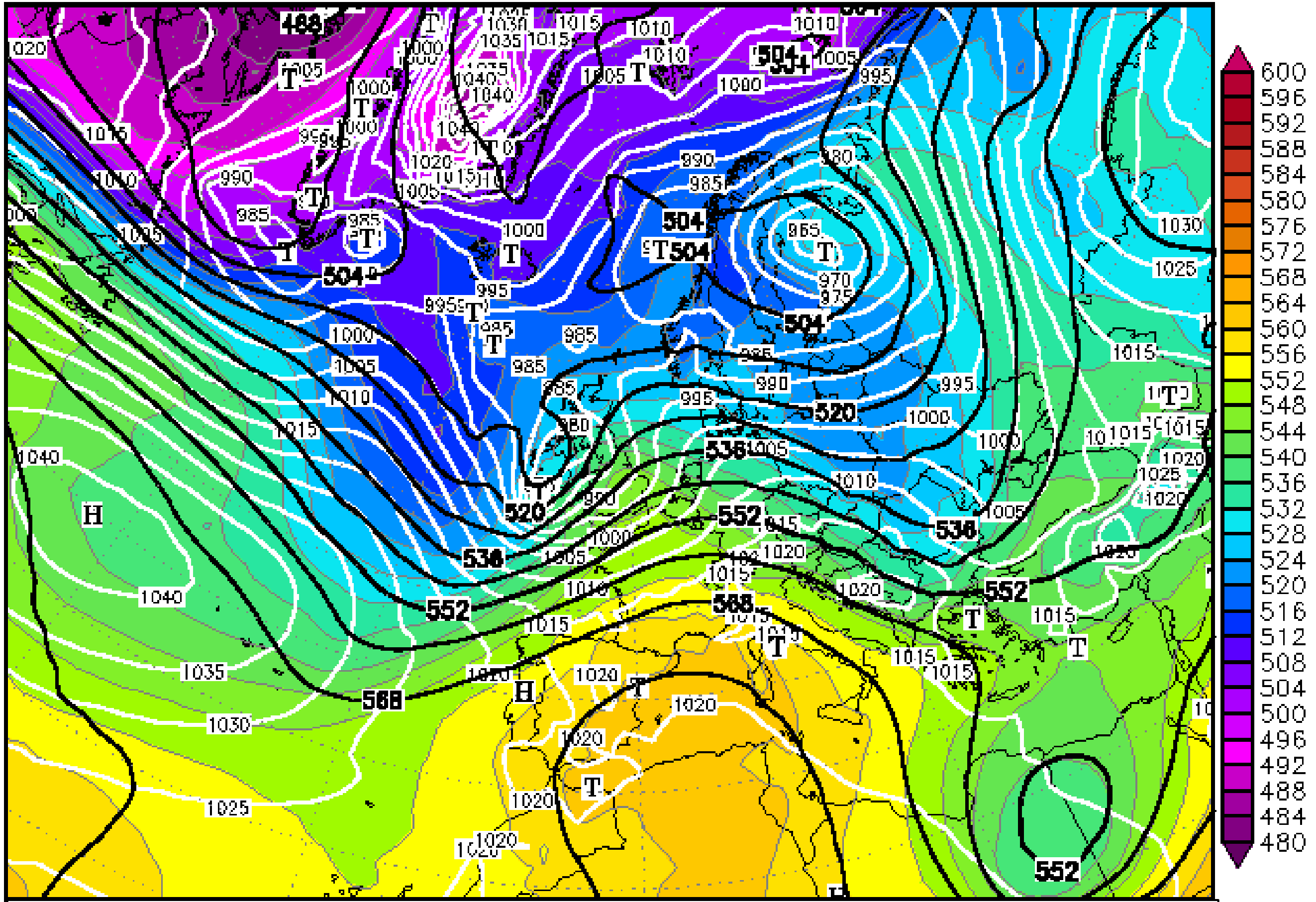
- The low pressure intensifies
- **Westward tilt**
- Warm air advection downstream of the trough axis **strengthens the upper-level ridge**



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

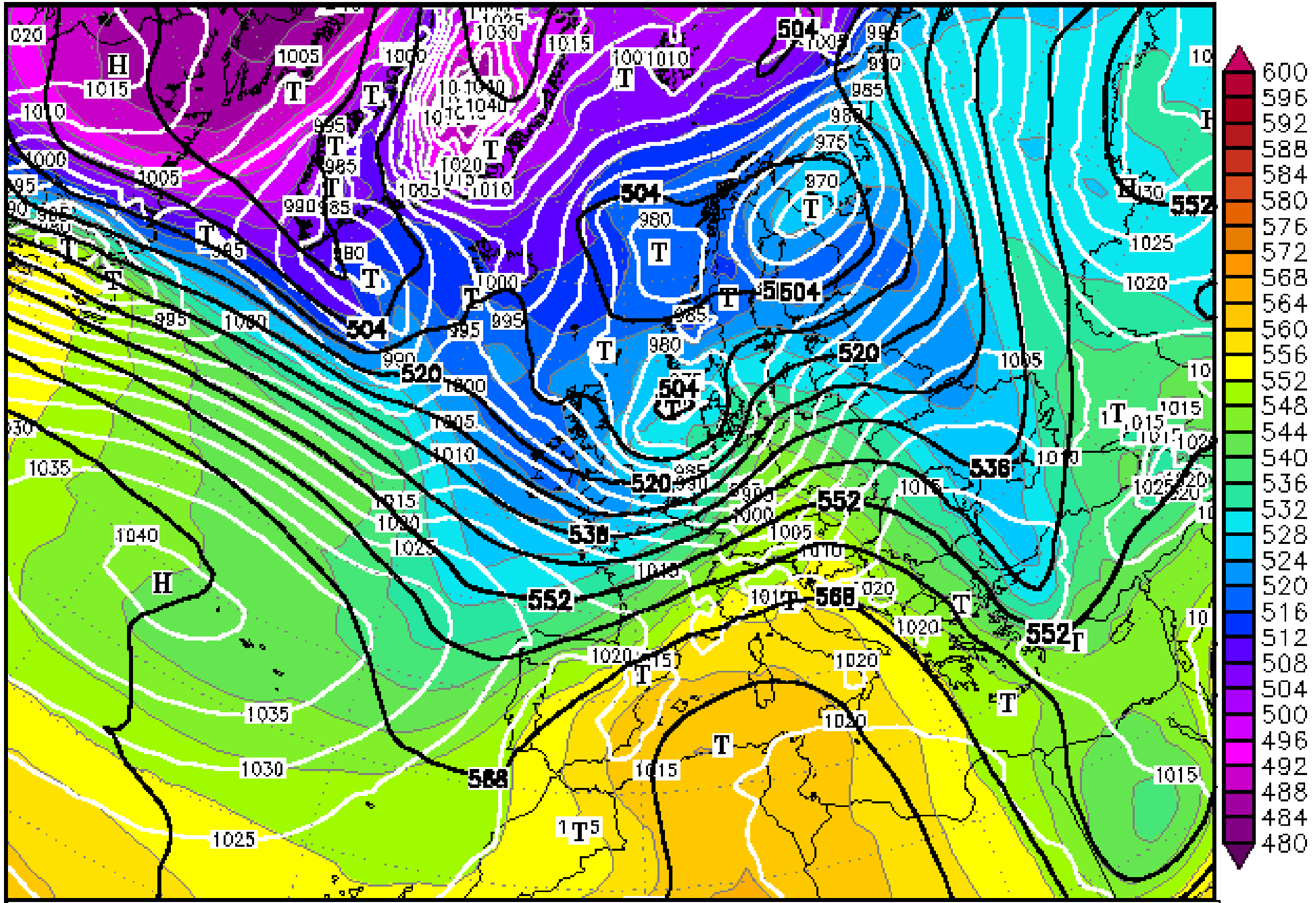
- Cyclone moves away from the peak of the warm sector: **vertically aligned with the upper-level trough**



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

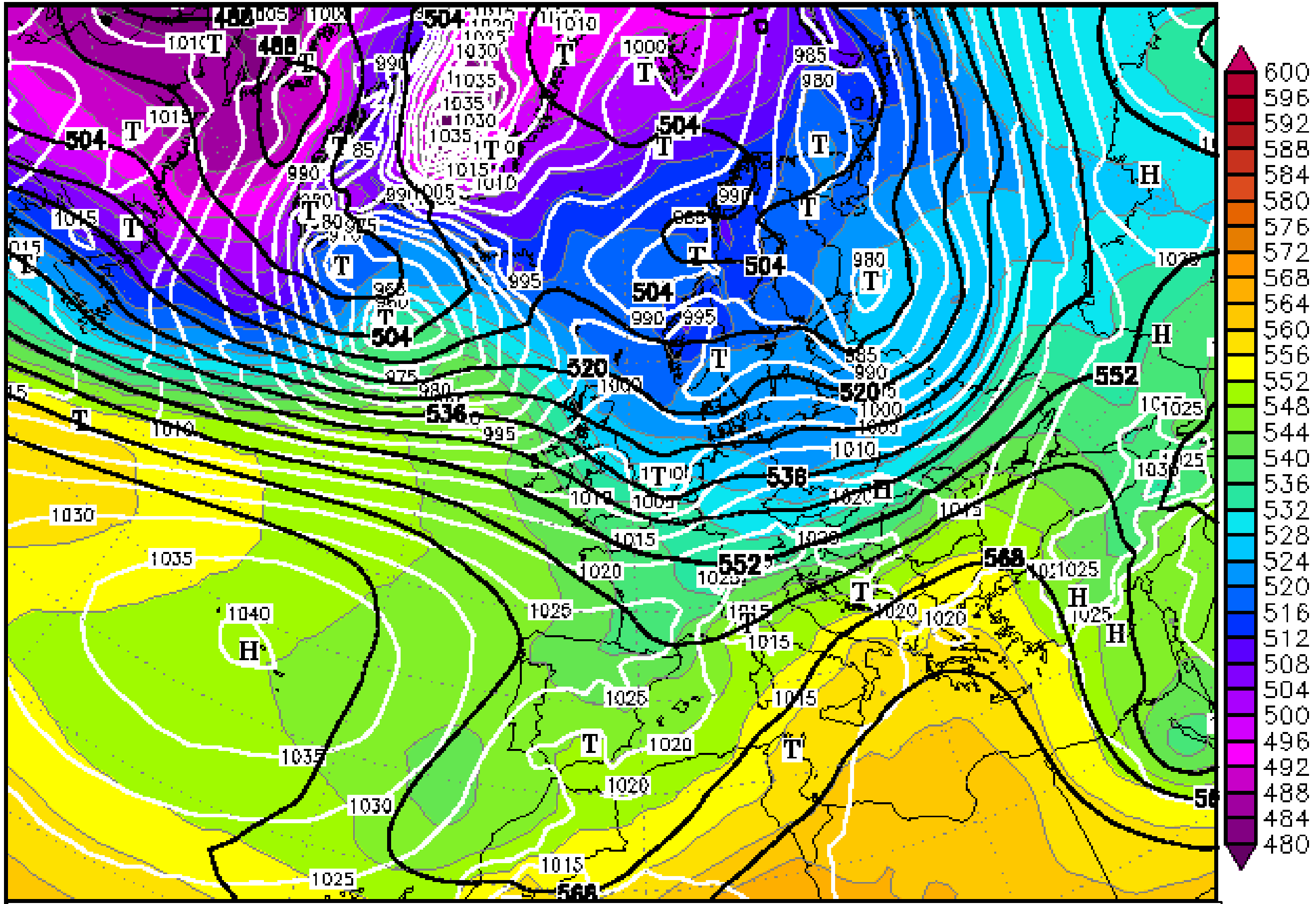
- Cyclone perfectly aligned with the 500 hPa geopotential height minimum



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

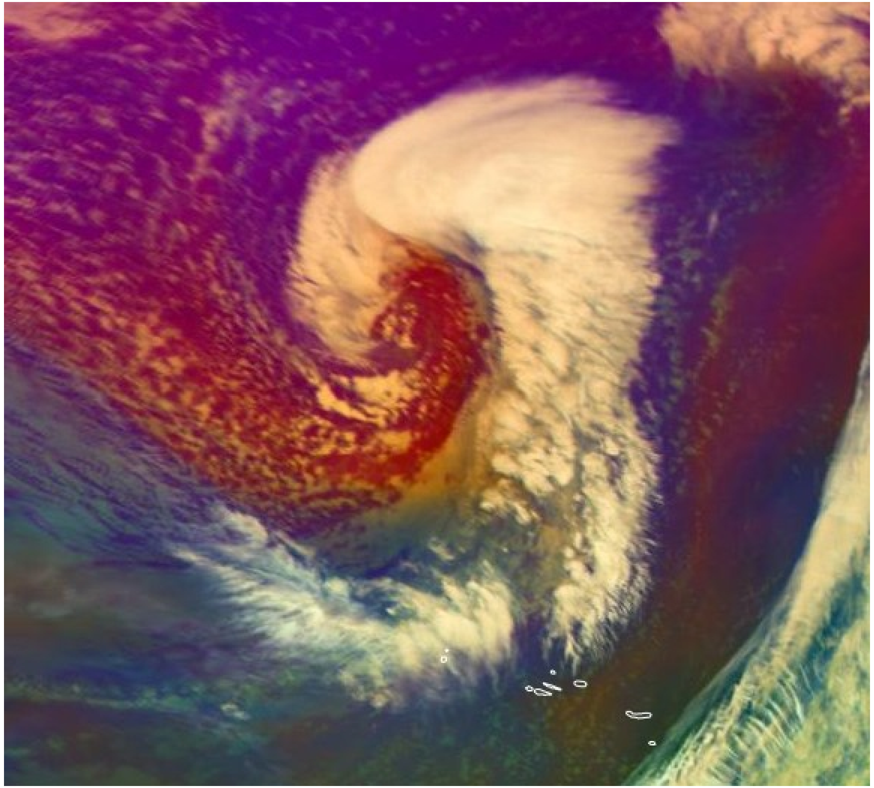
Baroclinic instability and vertical structure: take home messages

Take 5 min to write your own take home messages

A Lagrangian perspective of extratropical cyclones: the conveyor belt model

The conveyor belt model

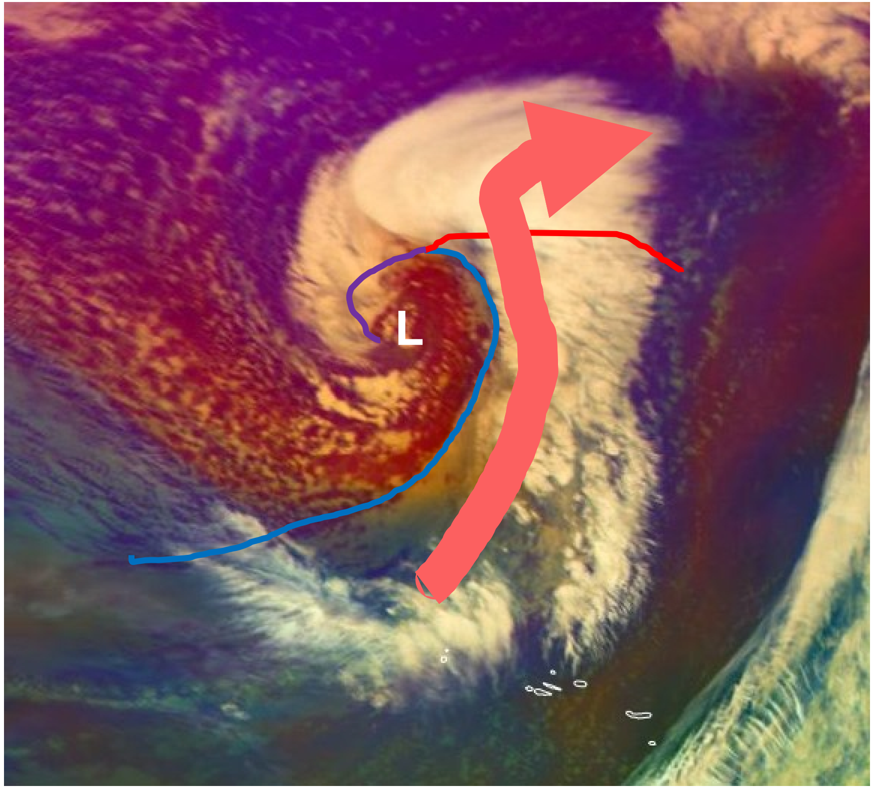
- What explains the «comma» shape of the clouds around an extratropical cyclone?
- How does the air flows around the cyclone?



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

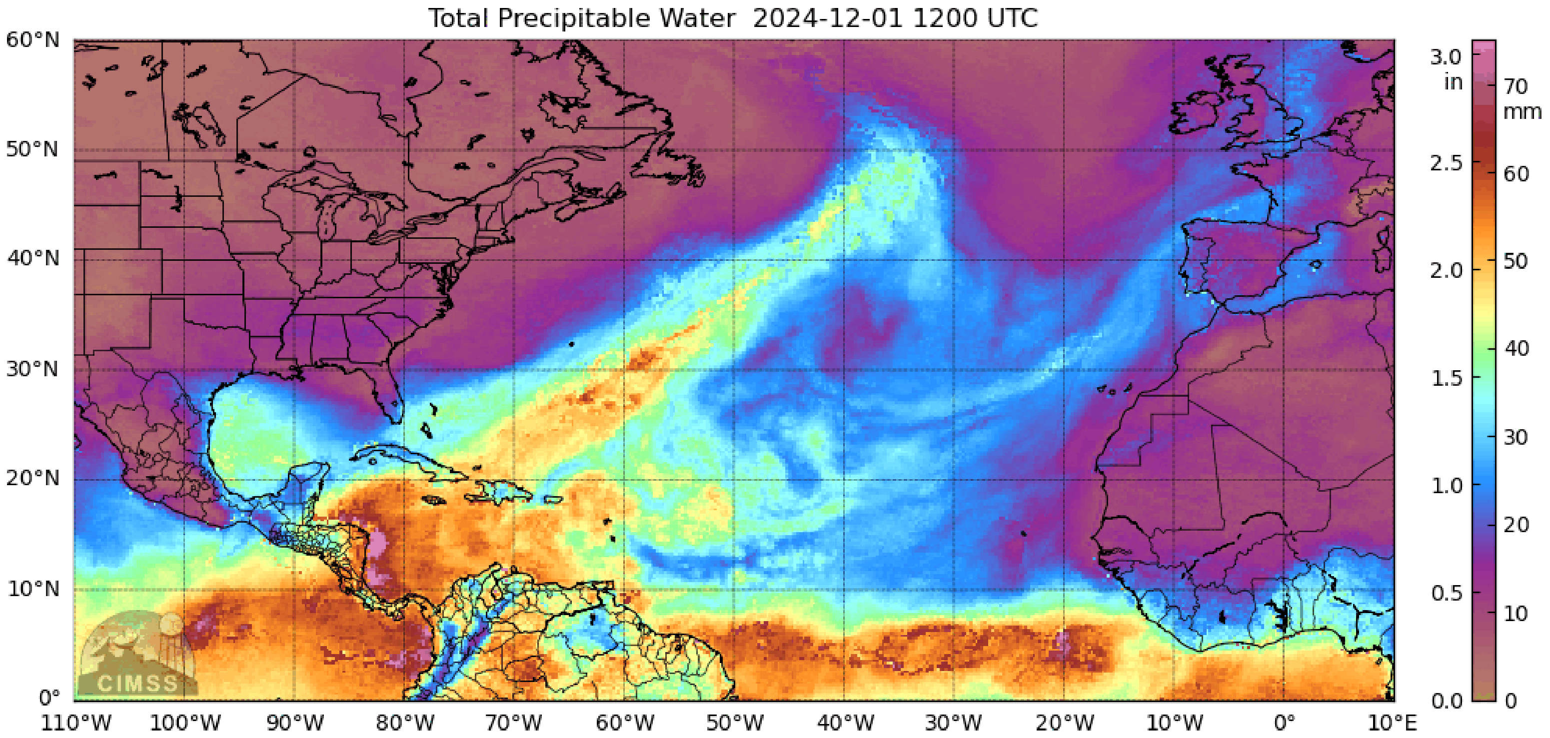
- The **warm conveyor belt** (WCB) : **rising warm** and **moist** air.
- WCBs are the **primary cloud- and precipitation-generating flow** in extratropical cyclones and can lead to **extreme precipitation**
- **Latent heat release** intensifies the vertical motion and the horizontal temperature gradient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



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

The link between warm conveyor belts and atmospheric rivers

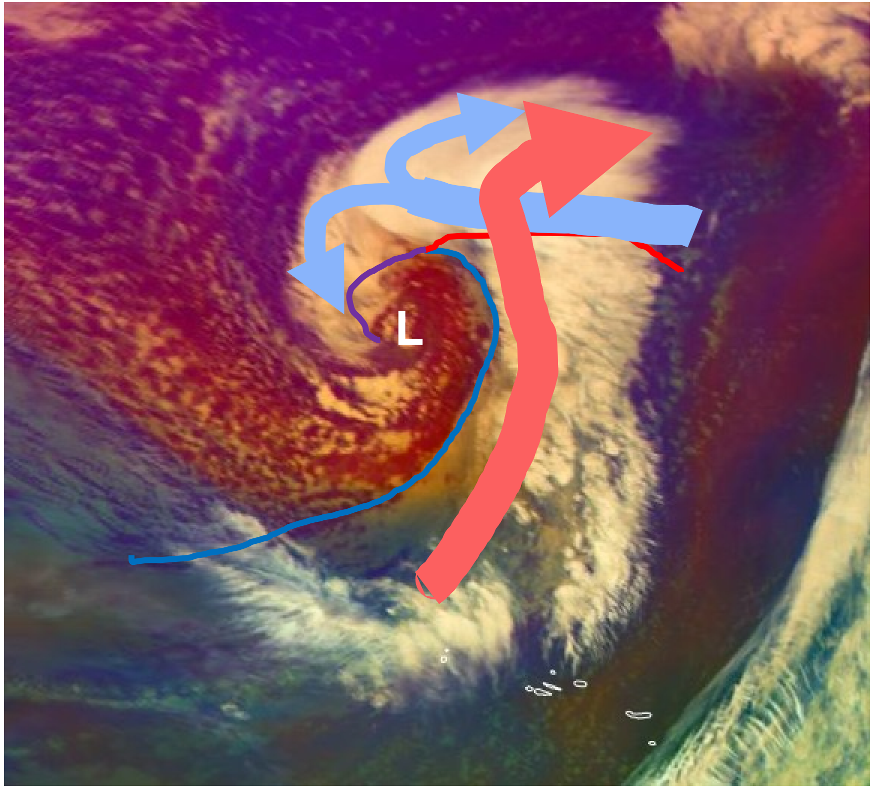
- Narrow filaments of enhanced water vapour transport: the **atmospheric rivers** (ARs)
- ARs are often associated with extratropical cyclones



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).

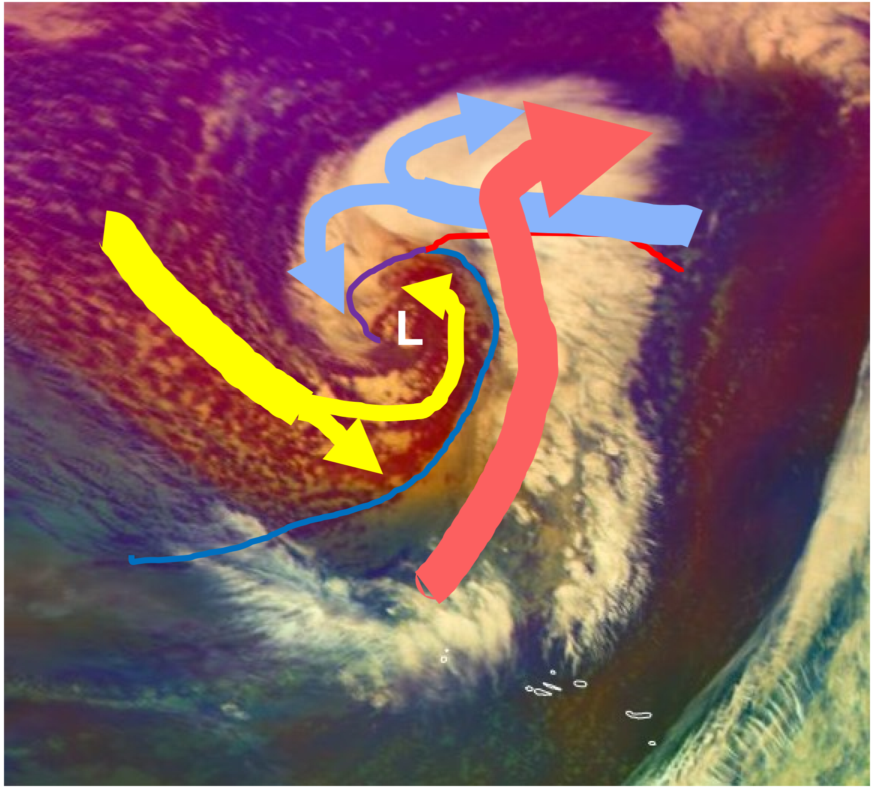
(1) Relative to the cyclone's motion



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 **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

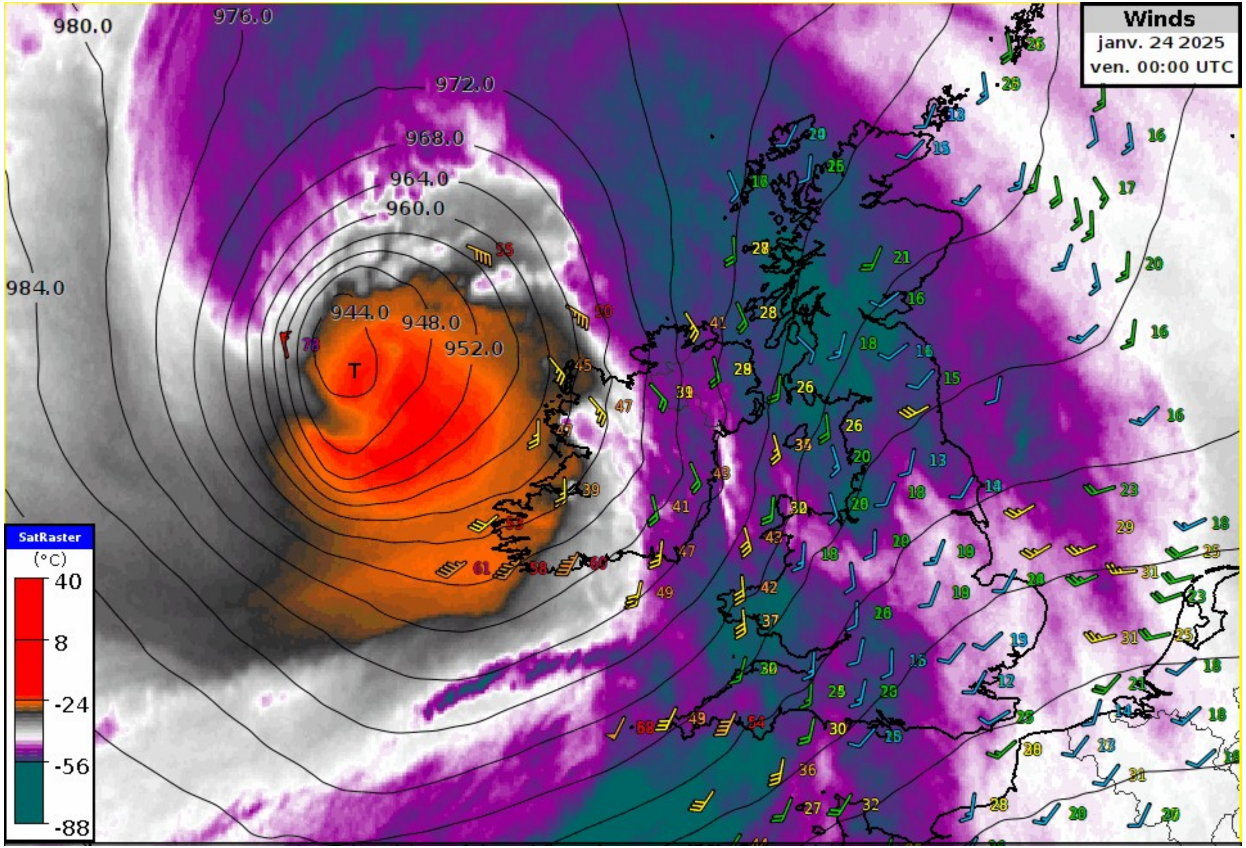


Satellite image of an extratropical cyclone over the northern Atlantic on 12 November at 00 UTC from Eumetsat airmass RGB product

Sting jet: example with storm Éowyn

Sting jet

- Airstream descending from the mid-troposphere to the surface and causing **extreme wind gusts** (>180 km/h) over a narrow region (< 100 km)
- Often associated with **clouds banding** at the tip of the cloud head, taking the shape of a sting
- Important mechanism**: cooling** due to precip. **evaporation/sublimation** & conditional symmetric instability
- **Satellite** observations and surface **wind measurements** consistent with a sting jet

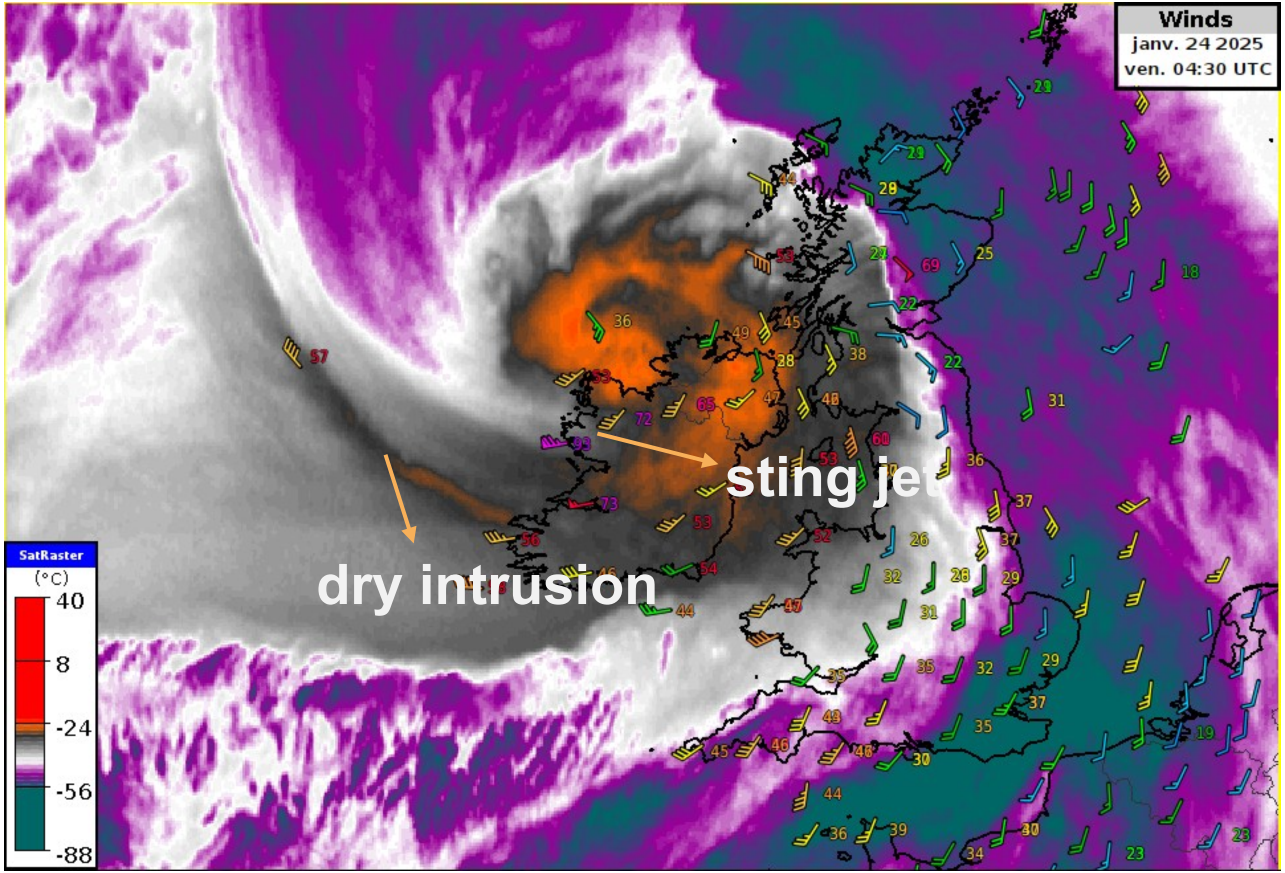


MétéoSuisse

Sting jet: example with storm Éowyn

Sting jet

- The **sting jet** can be observed over w. Ireland
- Relatively **narrow band** of gusts > 90 kt → consistent with sting jet
- **Dry air intrusion** is visible in water vapor channel



The conveyor belt model: take home messages

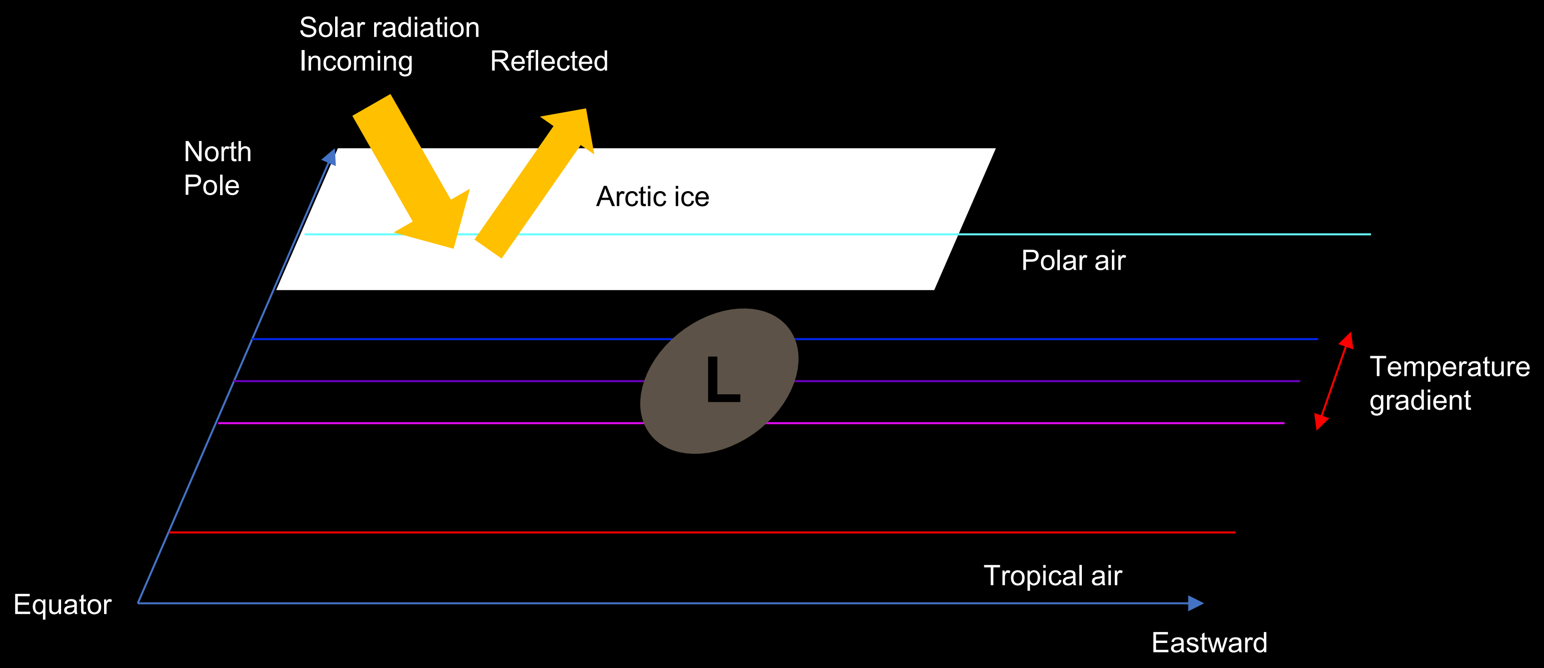
sli.do
#1461754

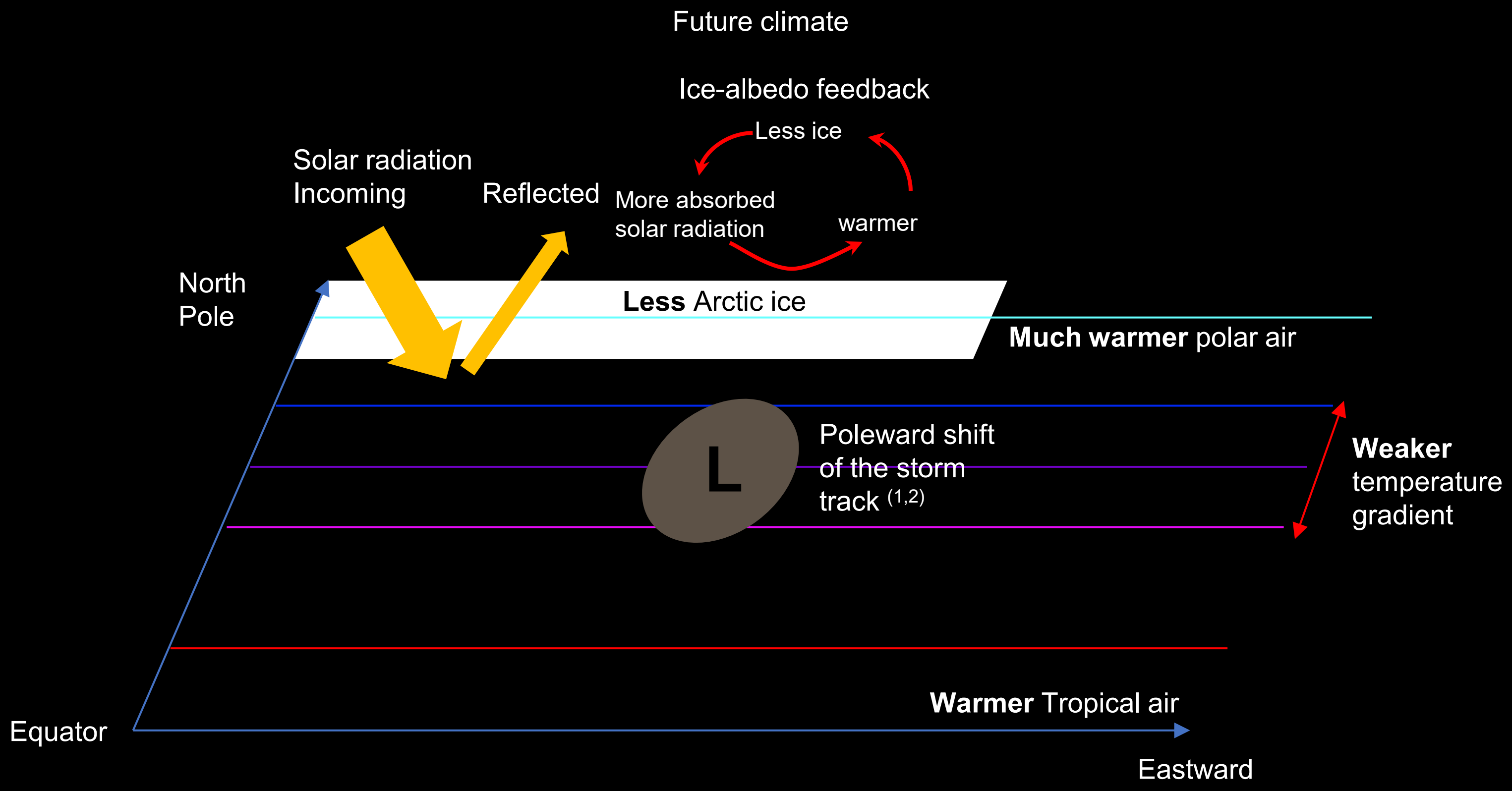
- Analysis of air parcel trajectories in extratropical cyclones (ECs) reveal the presence of **three distinguished airstreams** with different temperature and humidity contents : the warm conveyor belt (WCB), the cold conveyor belt and the dry conveyor belt
- These conveyor belts explain the **comma-shape** 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

Impact of climate change on ETCs

1. meridional temperature gradient
2. Humidity
3. Intensity, precipitation

Pre-industrial climate

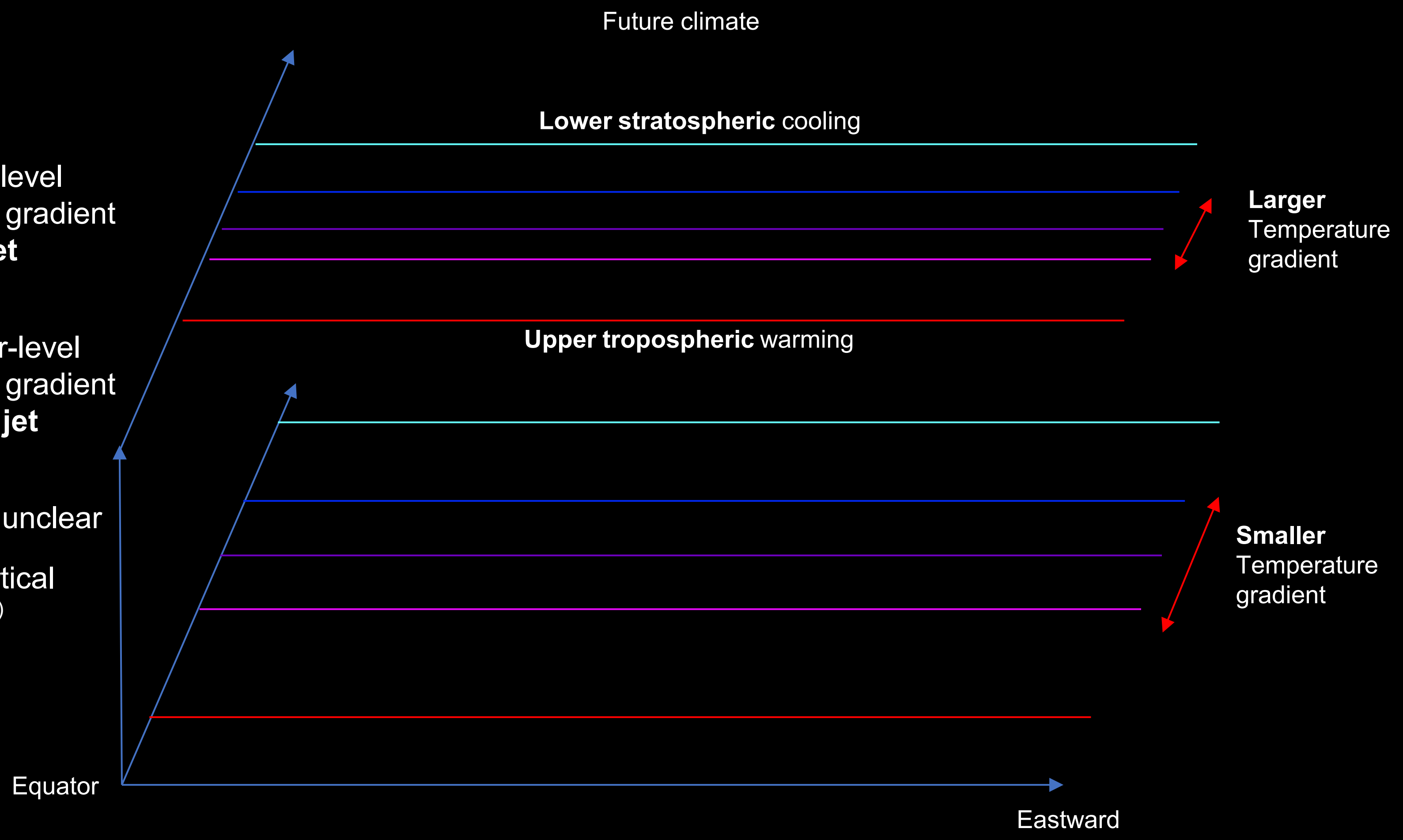




(1) Sinclair *et al*. 2020
(2) Priestley *et al.* 2022

Pre-industrial climate

- Smaller low-level temperature gradient → **weaker jet stream**
- Larger upper-level temperature gradient → **stronger jet stream**
- Net effect is unclear
- Stronger vertical wind shear[1]



(1) Stendel *et al*. 2021

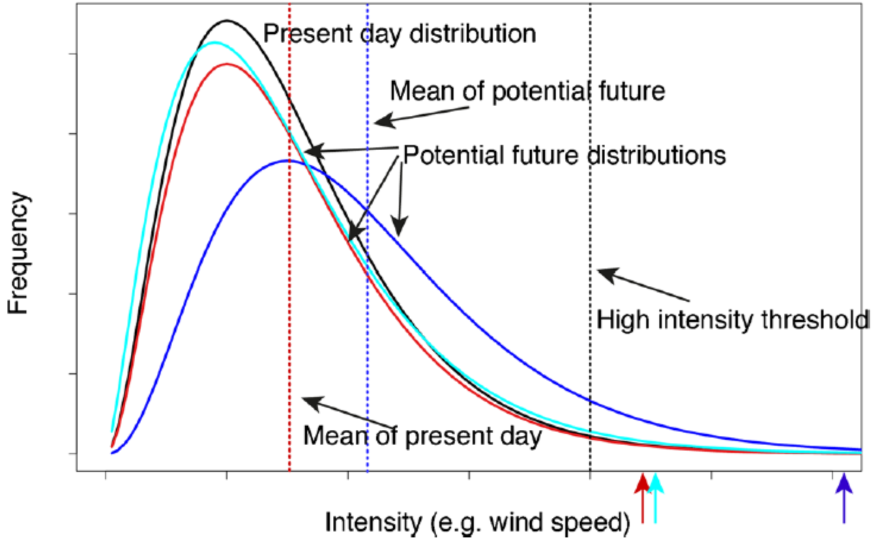
Impact of climate change on ETCs : humidity

- A warmer atmosphere can hold **more water vapour** (Clausius-Clapeyron relation) : 7% per 1 °C of warming
- Higher potential for **extreme precip** associated with ETCs
- **Larger latent heat release** during cloud and precipitation formation
- ETCs more driven by **latent-heat processes**[(1)]
  - Changes in the vertical temperature profile: **stronger static stability**
  - Net effect **unclear** and probably small[(2)]
- Larger latent heat cooling during precip. evaporation/sublimation → potentially **stronger sting jets**[(3)]

(1) Sinclair *et al*. 2020
(2) Catto *et al.* 2019
(3) Martínez-Alvarado *et al.* 2018

Impact of climate change on ETCs : frequency

- **Total number** of ETCs should **decrease** by ~ 5 % by the end of the 21st century
- Number of **extreme** ETCs should **increase** by ~4 % in the Northern hemisphere winter [(1)]
- Extreme ETCs are often driven by latent heat release processes → the strongest ETCs are expected to be **even stronger**



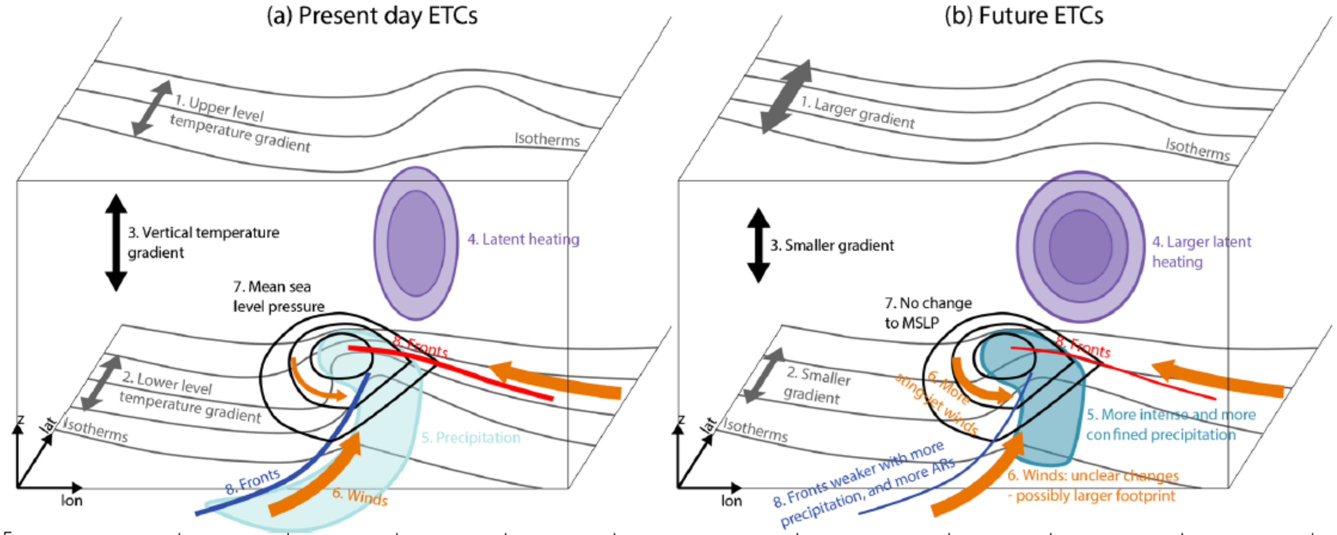
From Catto *et al.* 2019

(1) Priestley *et al.* 2022

Impact of climate change on ETCs : summary

Features with **high confidence**:

1. Larger upper-level gradient
2. Smaller lower-level gradient
3. Stronger static stability
4. Larger latent heating
5. More intense precipitation



Feature	1	2	3	4	5 (intensity)	5 (extent)	6	7	8
Confidence	High	High	High	High	High	Low	Low	Medium	Low

From Catto *et al.* 2019

Conclusion

- Impact of climate change on ETCs
  - **Decrease** in the **total number** of ETCs
  - **Intensification** of the most extreme ones
  - Potential for more **extreme precipitation**
  - **Unclear changes** of **wind**, potentially larger footprint and more sting jets
- ETCs will continue to play a **crucial role** in climate extremes

References/Supplementary material

Scientific literature:

- Barnes EA, Hartmann DL. Detection of Rossby wave breaking and its response to shifts of the midlatitude jet with climate change. J Geophys Res. 2012;117.
- Barnes, Elizabeth A., and James A. Screen. “The Impact of Arctic Warming on the Midlatitude Jet-stream: Can It? Has It? Will It?” *WIREs Climate Change*, vol. 6, no. 3, 2015, pp. 277–86, https://doi.org/10.1002/wcc.337.
- **Catto, Jennifer L., et al. “The Future of Midlatitude Cyclones.” Current Climate Change Reports, vol. 5, no. 4, Dec. 2019, pp. 407–20, https://doi.org/10.1007/s40641-019-00149-4.**
- Harvey, B. J., et al. “Equator-to-Pole Temperature Differences and the Extra-Tropical Storm Track Responses of the CMIP5 Climate Models.” Climate Dynamics, vol. 43, no. 5, Sept. 2014, pp. 1171–82, https://doi.org/10.1007/s00382-013-1883-9.
- Martínez-Alvarado O, Gray SL, Hart NCG, Clark PA, Hodges K, Roberts MJ. Increased wind risk from sting-jet windstorms with climate change. Environ Res Lett. 2018;13(4):044002.
- Priestley, Matthew D. K., and Jennifer L. Catto. “Future Changes in the Extratropical Storm Tracks and Cyclone Intensity, Wind Speed, and Structure.” *Weather and Climate Dynamics*, vol. 3, no. 1, Mar. 2022, pp. 337–60, https://doi.org/10.5194/wcd-3-337-2022.
- Sinclair, Victoria A., et al. “The Characteristics and Structure of Extra-Tropical Cyclones in a Warmer Climate.” *Weather and Climate Dynamics*, vol. 1, no. 1, Jan. 2020, pp. 1–25, https://doi.org/10.5194/wcd-1-1-2020.
- Stendel, Martin, et al. “Chapter 15 - The Jet Stream and Climate Change.” *Climate Change (Third Edition)*, edited by Trevor M. Letcher, Elsevier, 2021, pp. 327–57, https://doi.org/10.1016/B978-0-12-821575-3.00015-3.

MétéoSuisse blogs:

- https://www.meteosuisse.admin.ch/portrait/meteosuisse-blog/fr/2024/02/depression-changement-climatique-partie1.html

https://www.meteosuisse.admin.ch/portrait/meteosuisse-blog/fr/2024/02/depression-changement-climatique-partie-2.html