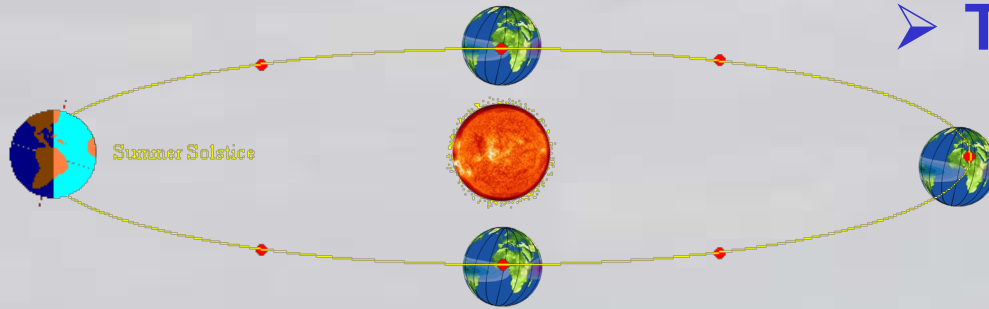


WHY DO WE HAVE THE GLOBAL CIRCULATION ?

➤ The Sun is shining ...

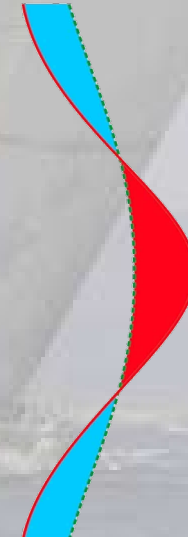
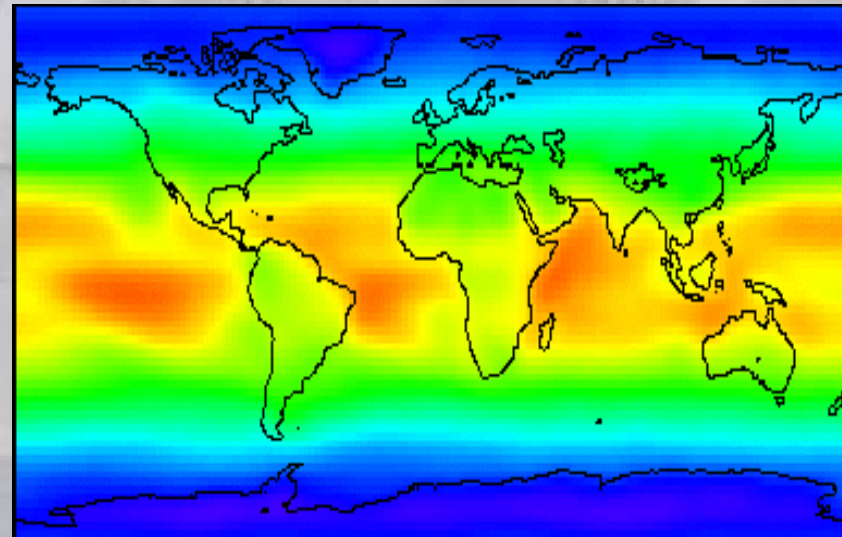
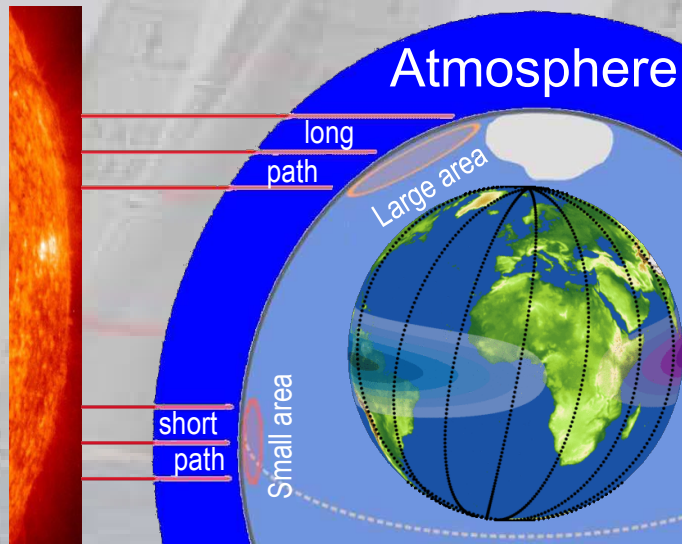


➤ The Earth...

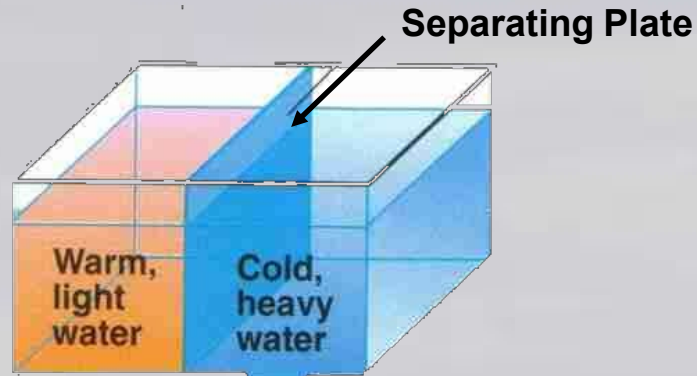
- ... is a sphere, circumference 40000 km / 21600 nm
- ... orbits the Sun 1 / year
- ... rotates around its axis 1 / day

➤ This results in ...

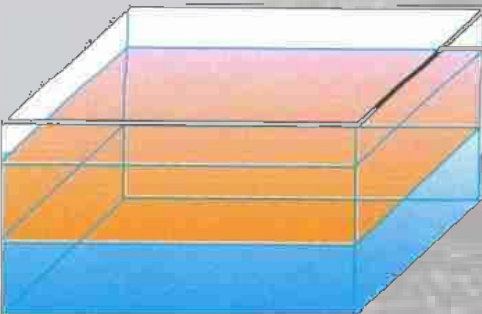
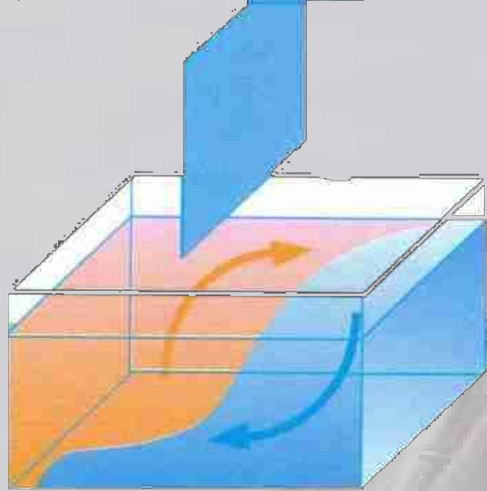
... Meridional (N/S) Temperature-Gradient, which directly (physically) drives the Global Circulation.



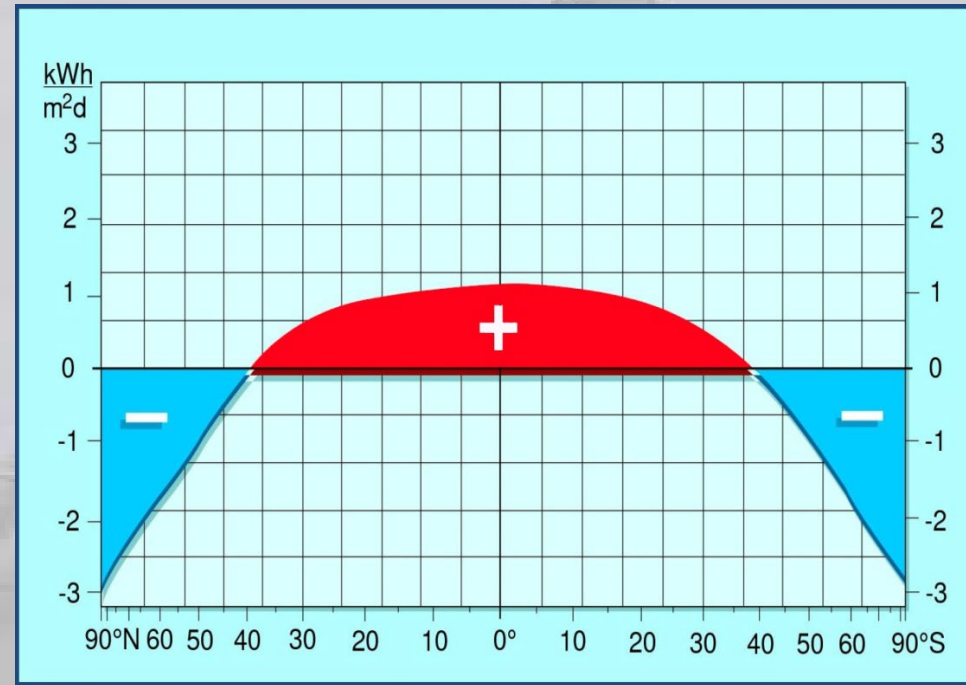
Energy Aspects

$$E_{\text{pot}} + E_{\text{kin}} = \text{const.}$$


$E_{\text{pot}} > \text{min}$



$E_{\text{pot}} = \text{min}$



North Pole

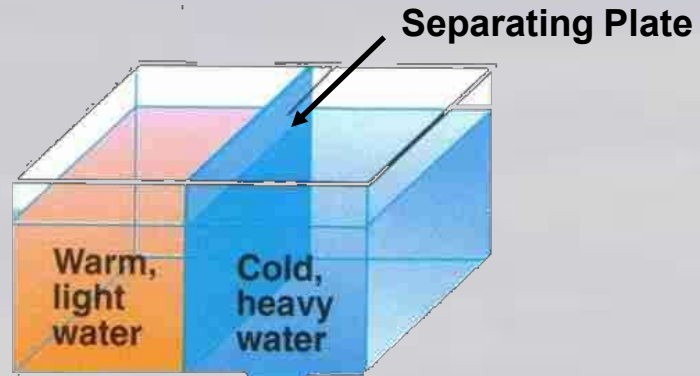
Equator

South Pole

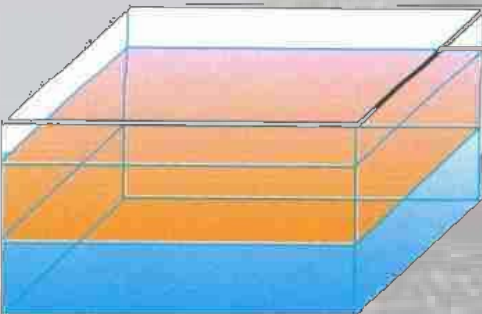
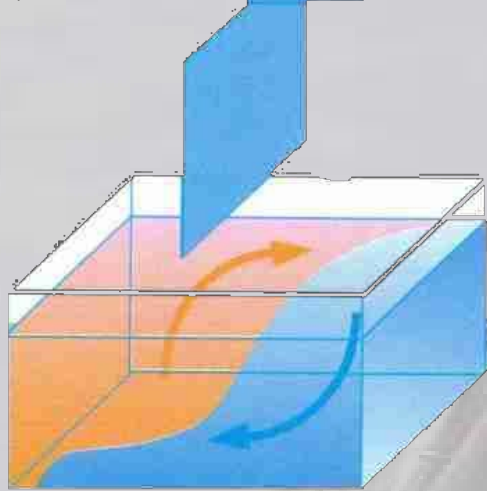
E_{pot} Decrease $\Leftrightarrow E_{\text{kin}}$ Increase

WIND !

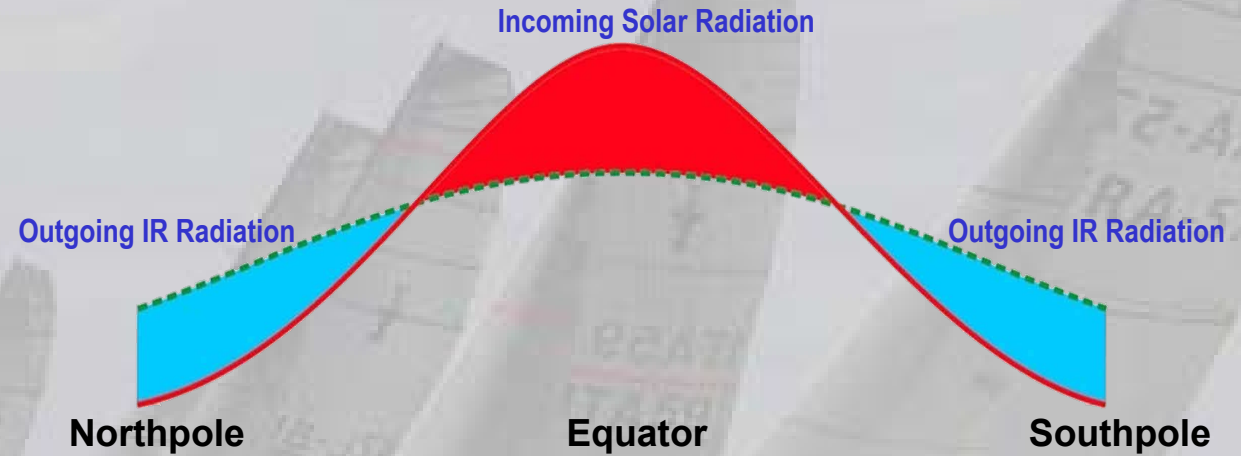
Energy Aspects

$$E_{\text{pot}} + E_{\text{kin}} = \text{const.}$$


$$E_{\text{pot}} > \min$$



$$E_{\text{pot}} = \min$$

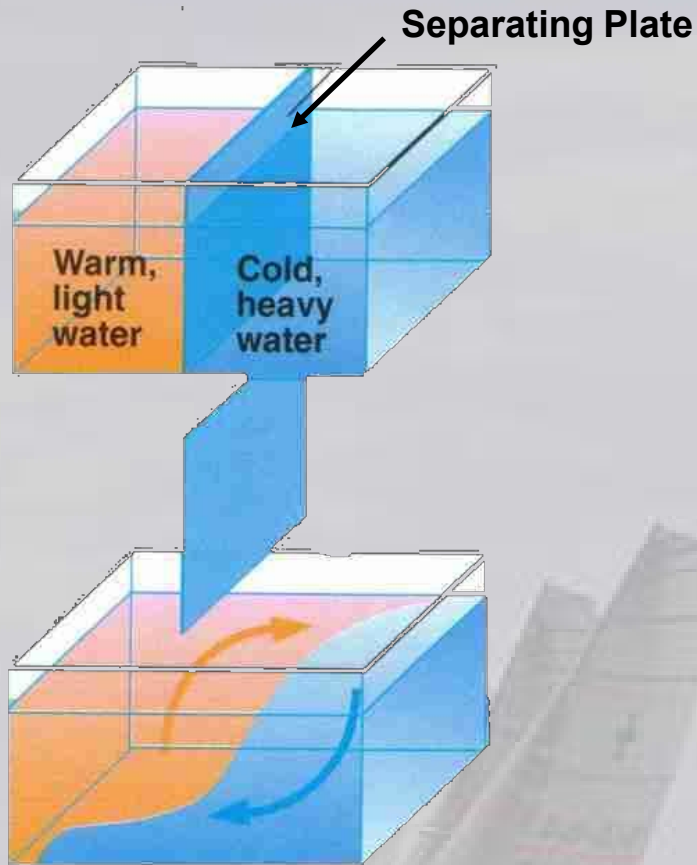


$$E_{\text{pot}} \text{ Decrease} \Leftrightarrow E_{\text{kin}} \text{ Increase}$$

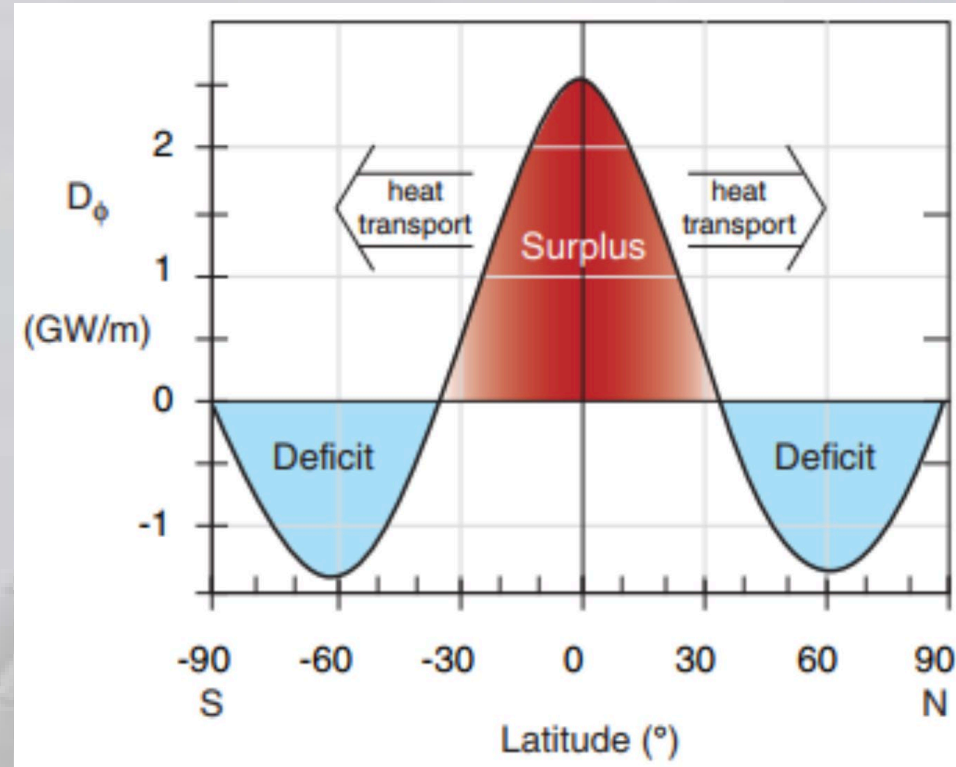
WIND !

Energy Aspects

$E_{\text{pot}} + E_{\text{kin}} = \text{const.}$



$E_{\text{pot}} > \text{min}$



South Pole

Equator

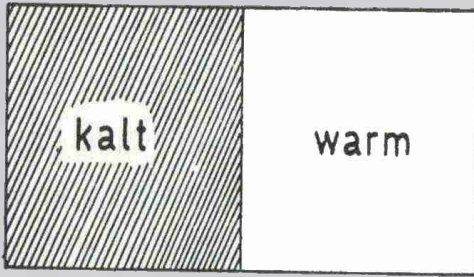
North Pole

$E_{\text{pot}} = \text{min}$

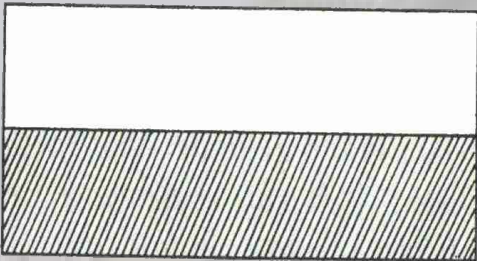
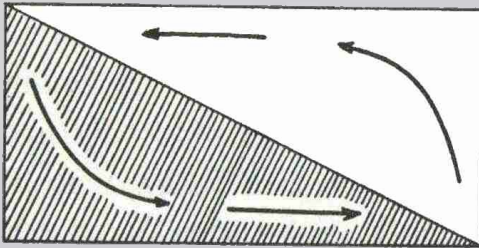
E_{pot} Decrease $\Leftrightarrow E_{\text{kin}}$ Increase

WIND !

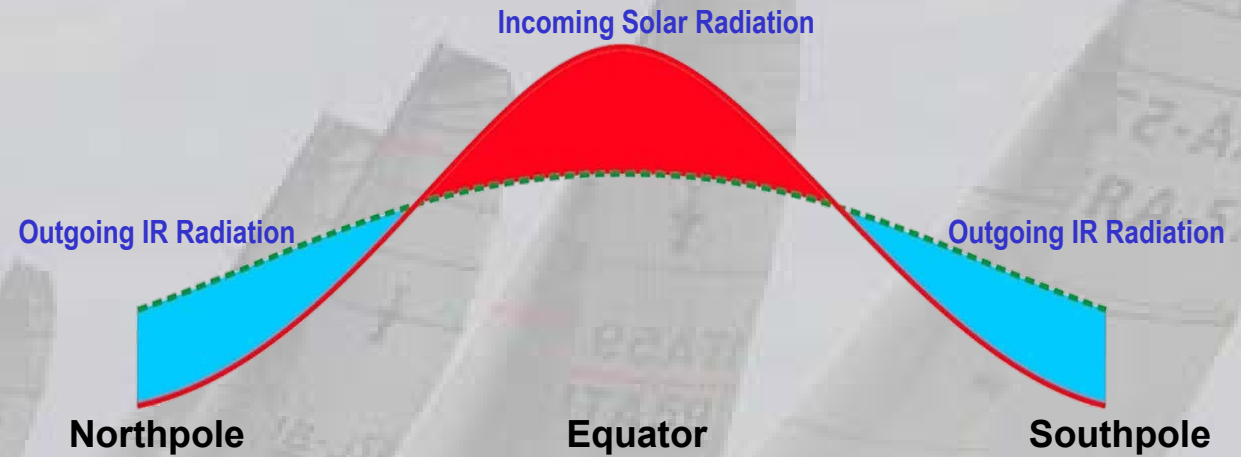
Energy Aspects

$$E_{\text{pot}} + E_{\text{kin}} = \text{const.}$$


$E_{\text{pot}} > \text{min}$

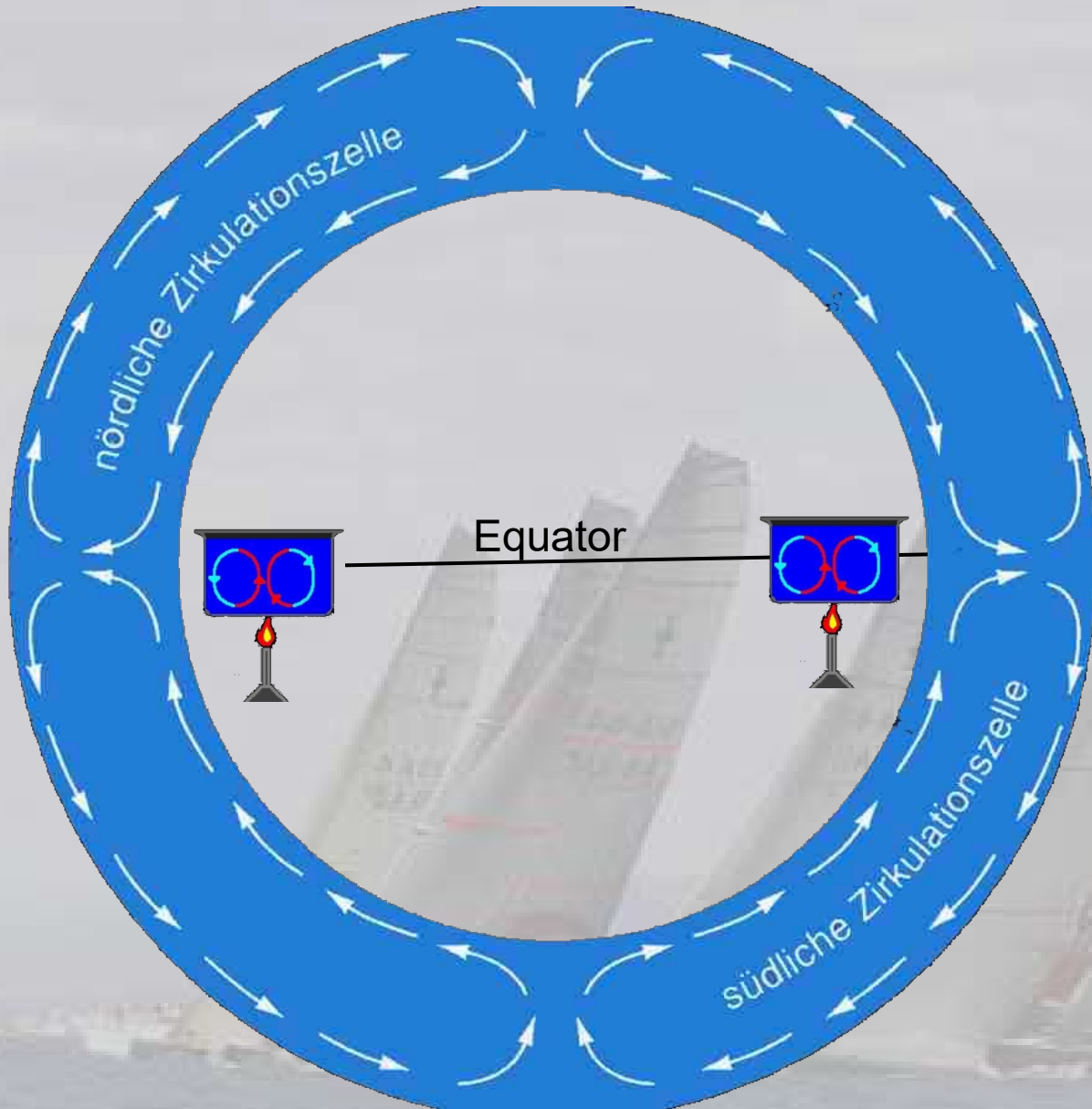


$E_{\text{pot}} = \text{min}$



E_{pot} Decrease $\Leftrightarrow E_{\text{kin}}$ Increase
WIND !

GLOBAL CIRCULATION WITHOUT CORIOLIS FORCE



The heating of the atmosphere by solar radiation near the Equator is a direct heat engine, i.e. warm air is cooled down by lifting

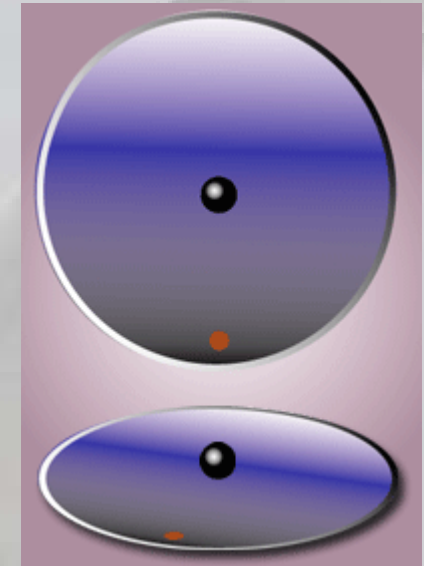
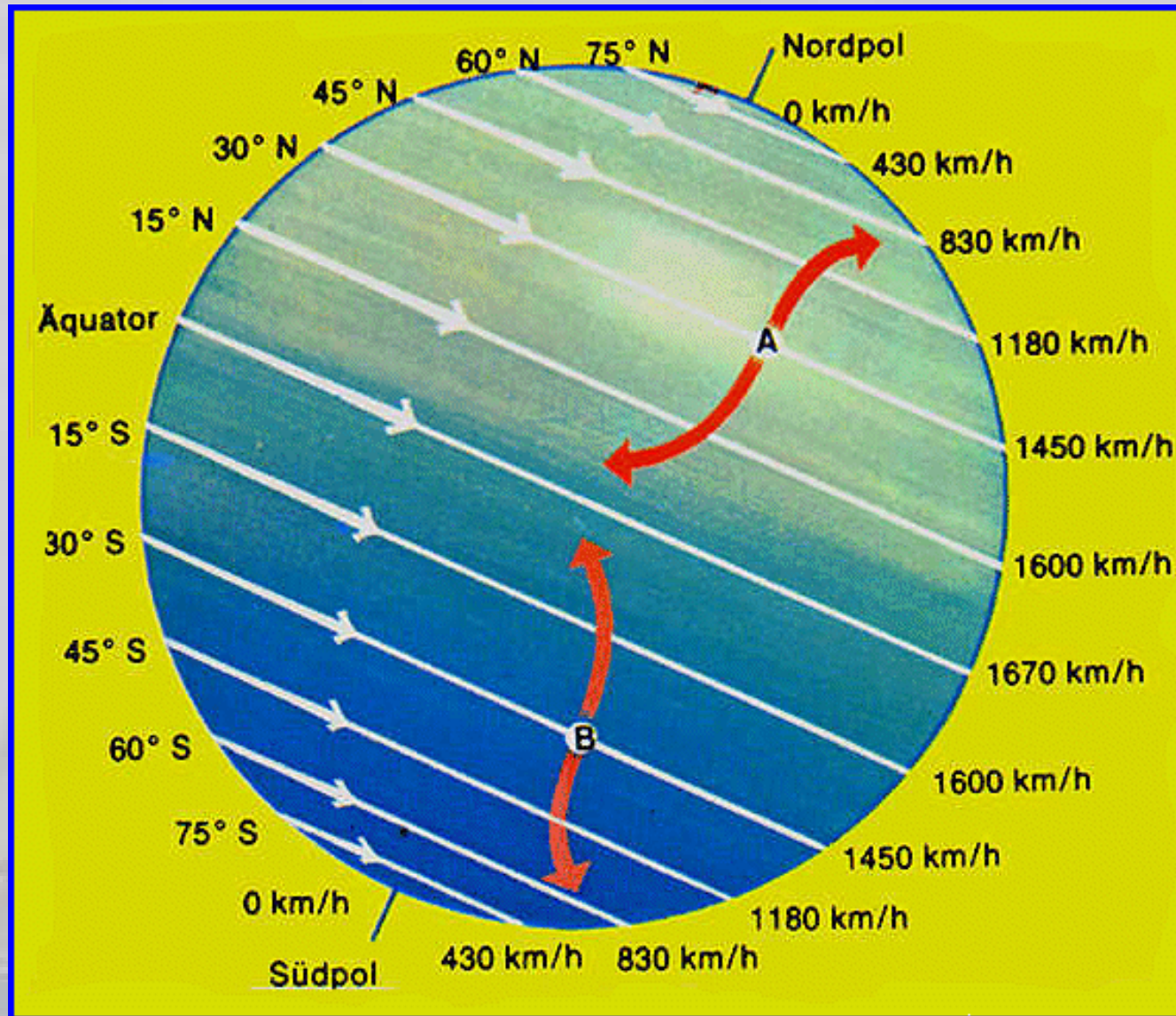
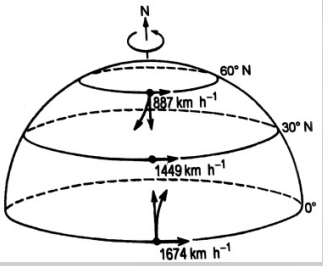
If cold air comes under subsidence (to higher pressure) and is thus heated, it would be an indirect heat engine

GLOBAL CIRCULATION WITHOUT CORIOLIS FORCE

Hadley 1735



CORIOLIS FORCE



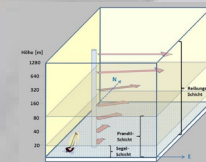
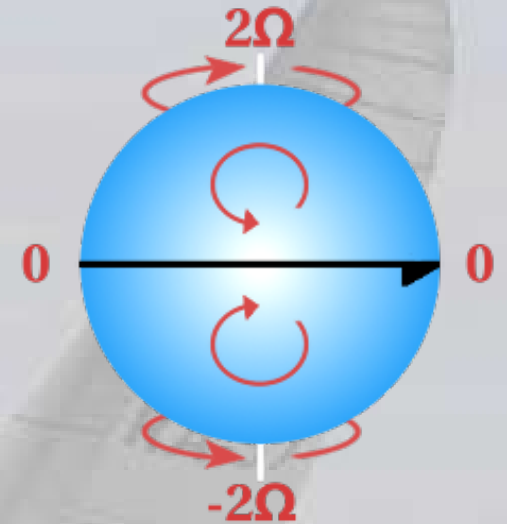
CORIOLIS FORCE ...



- ... $\Omega = 2 * \pi / 86.164$ Earth's Angular velocity
86.164 Siderial Day / 86.400 Solar Day
- ... $2 * \Omega * \sin(\phi = \text{latitude})$ Coriolis frequency
- ... Coriolis Force = wind velocity * Coriolis frequency
- ... Acts perpendicular to the direction of motion
Is a Pseudo (fictitious) Force does not perform physical work
Deflects air particles Northern Hemisphere to the right
Southern Hemisphere to the left

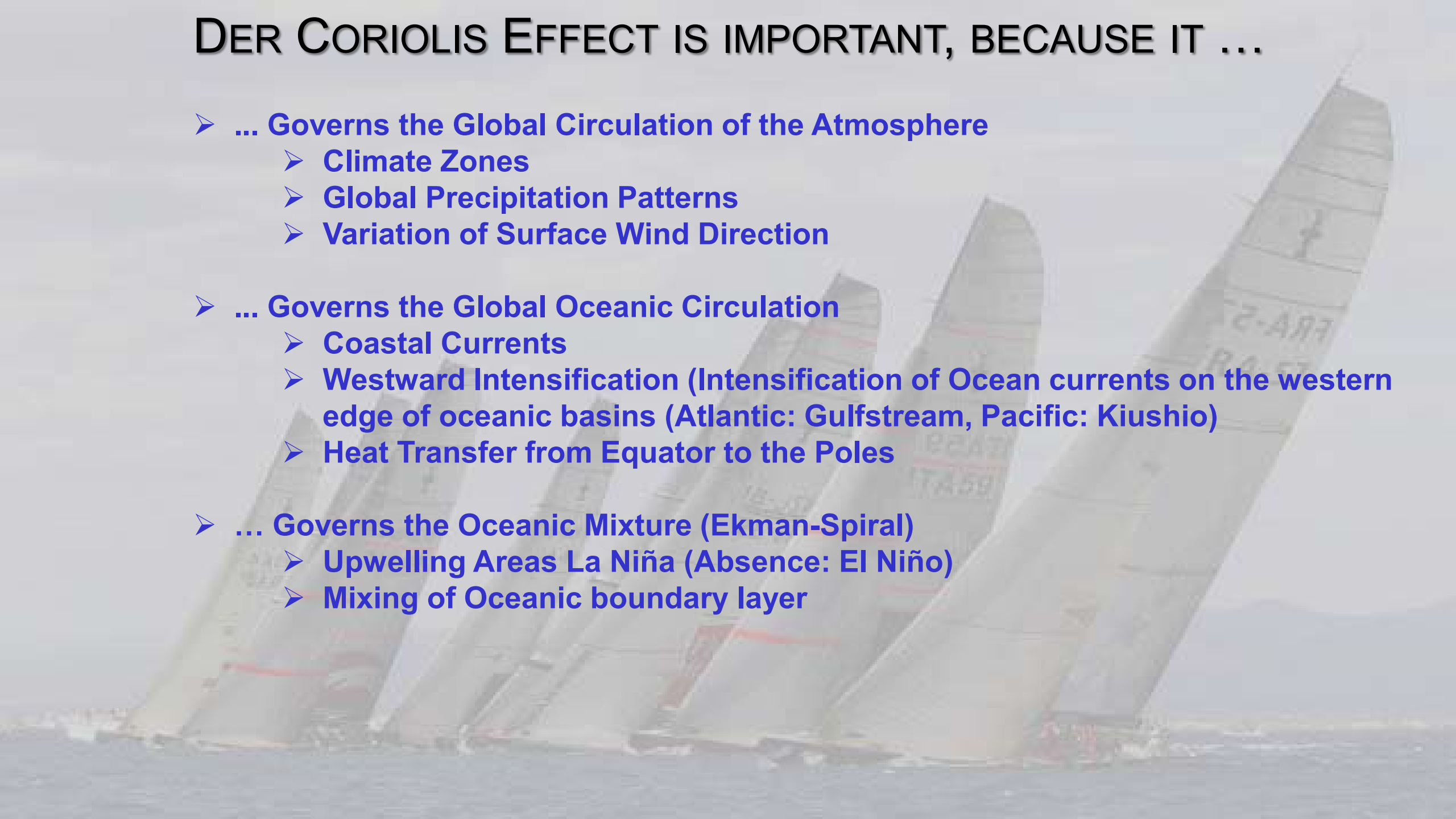
Veering of the wind with increasing height (boundary layer only)
Decrease of friction $\Leftrightarrow$ Increase of windspeed

- ... Determines the direction of rotation of Lows and Highs
Northern Hemisphere: Low: counterclockwise High: clockwise
Southern Hemisphere: Low: clockwise High: counterclockwise



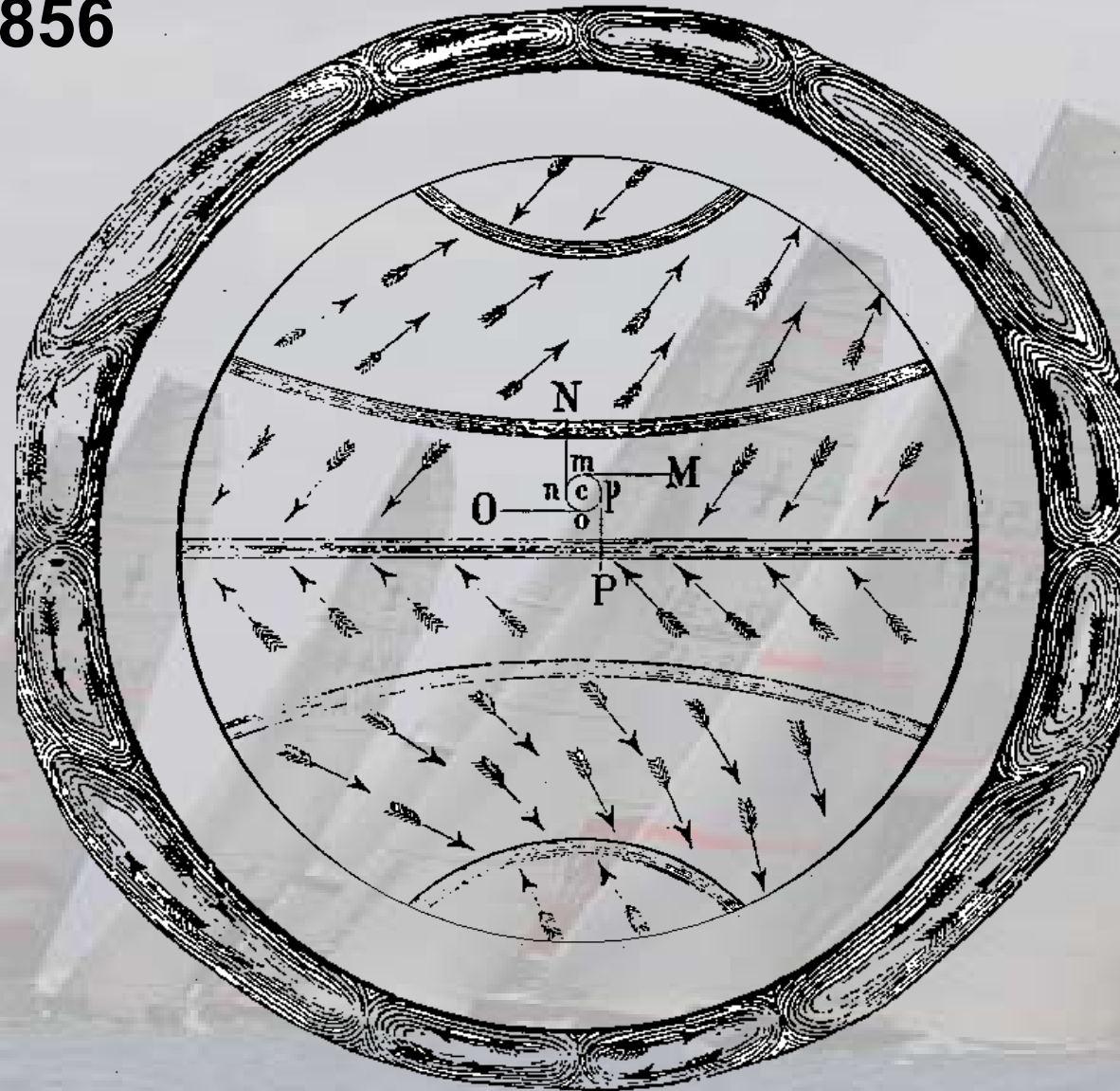
DER CORIOLIS EFFECT IS IMPORTANT, BECAUSE IT ...

- ... **Governs the Global Circulation of the Atmosphere**
 - **Climate Zones**
 - **Global Precipitation Patterns**
 - **Variation of Surface Wind Direction**
- ... **Governs the Global Oceanic Circulation**
 - **Coastal Currents**
 - **Westward Intensification (Intensification of Ocean currents on the western edge of oceanic basins (Atlantic: Gulfstream, Pacific: Kuroshio))**
 - **Heat Transfer from Equator to the Poles**
- ... **Governs the Oceanic Mixture (Ekman-Spiral)**
 - **Upwelling Areas La Niña (Absence: El Niño)**
 - **Mixing of Oceanic boundary layer**

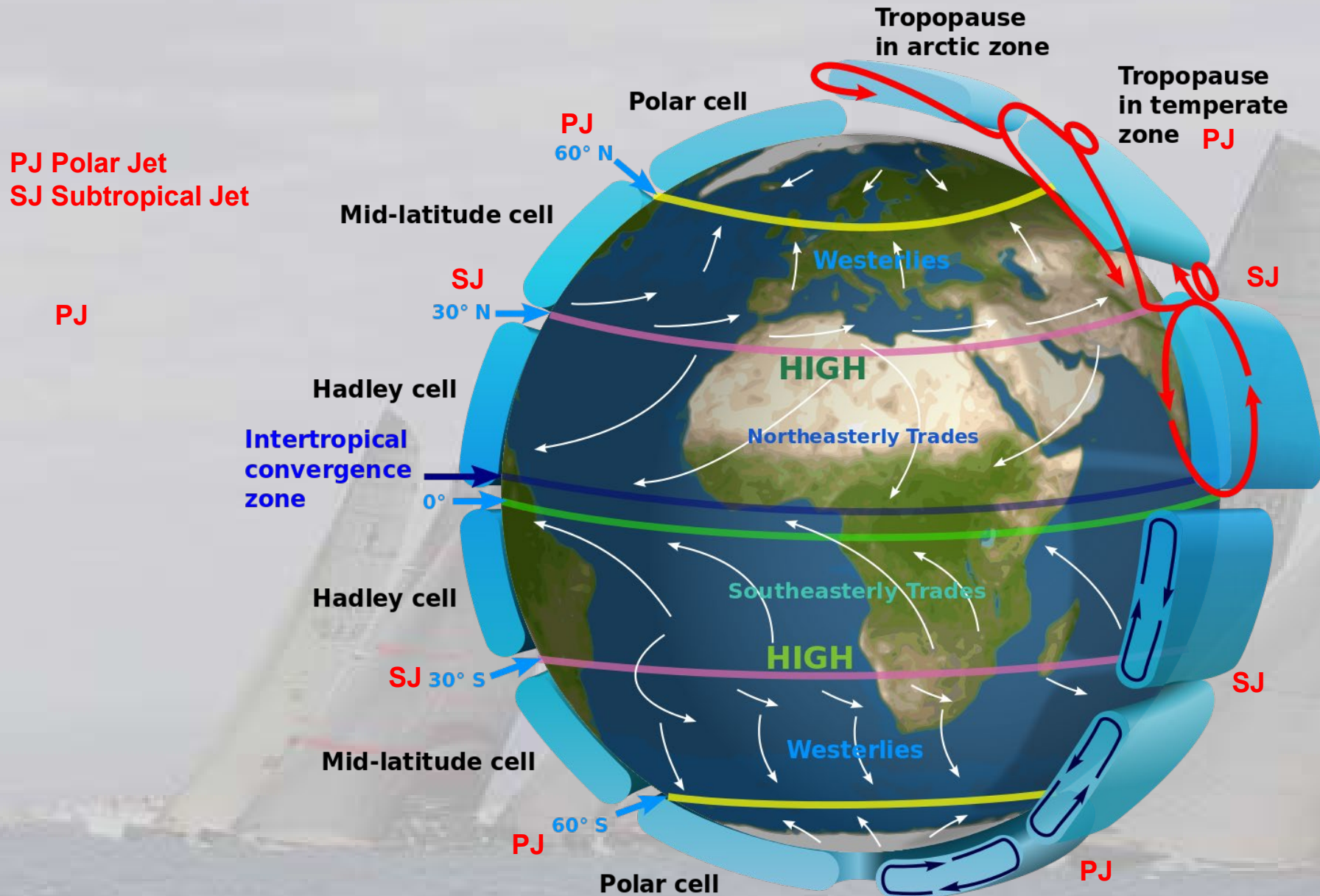


GLOBAL CIRCULATION WITH CORIOLIS FORCE

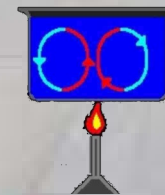
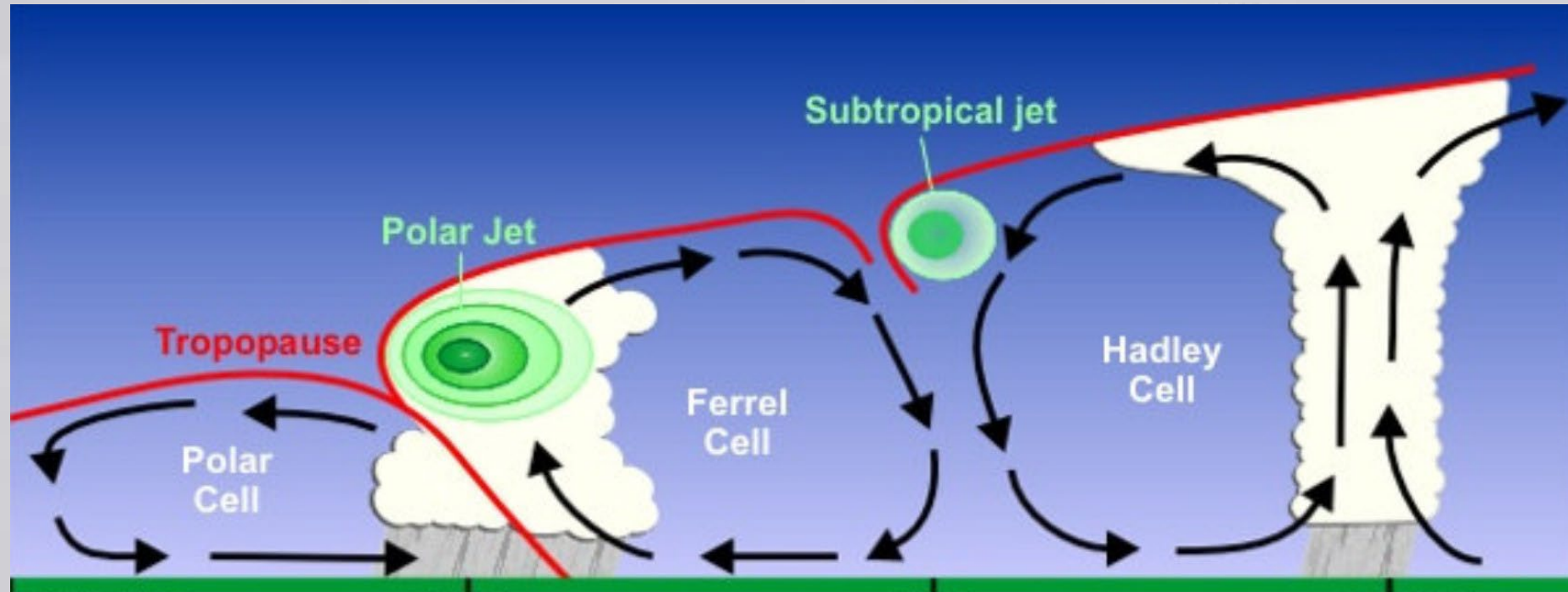
Dove 1856



GLOBAL CIRCULATION WITH CORIOLIS FORCE



CROSS-SECTION HADLEY - / FERREL - AND POLAR - CELL

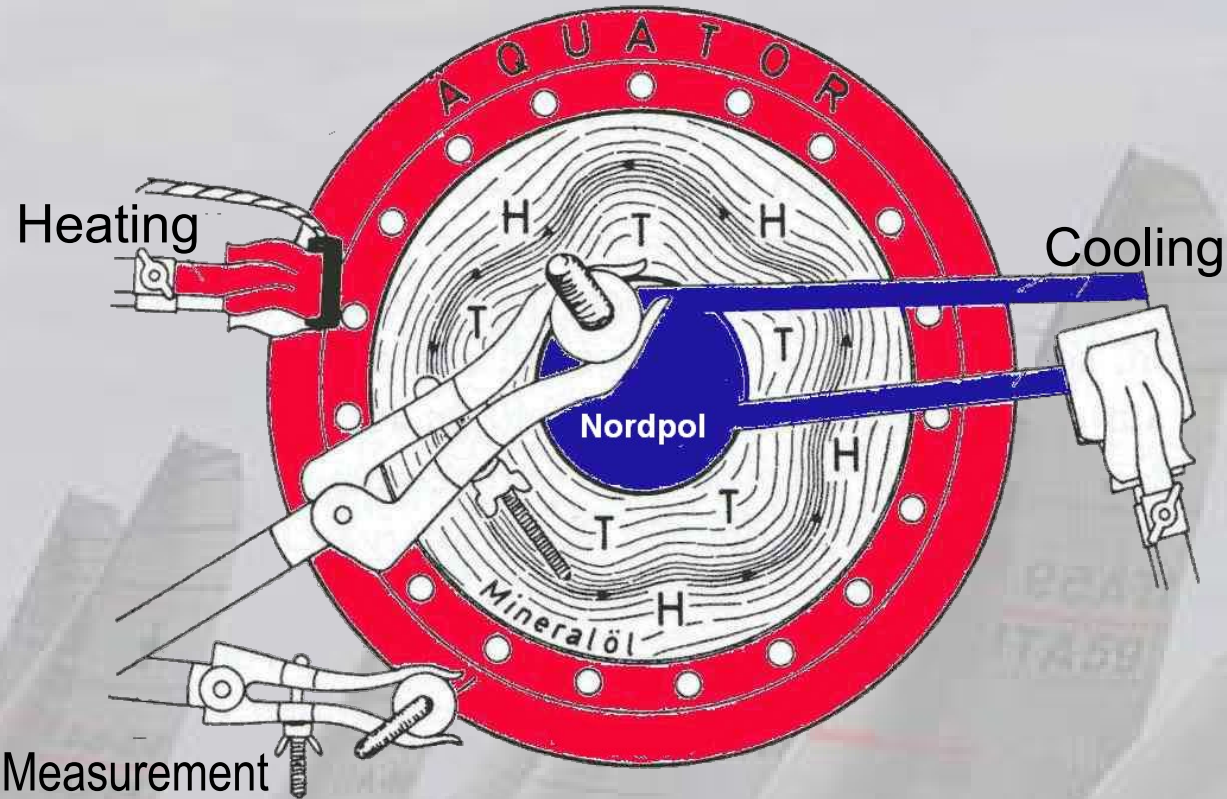


reverse

direct

thermal circulation

SIMULATION IN A ROTATING TANK



Temperature Measurement

Abb. 10. Simulation der Strömungsverhältnisse auf der rotierenden Erde durch ein Experiment im Lamont Geological Observatory. Eine mit Mineralöl gefüllte zylindrische Schale wird in Rotation versetzt. Die Heizung am Schalenrand und die Kühlung an der Drehachse erfolgt mit Wasser. Durch Aluminiumpulver werden die (hier schematisch angedeuteten) Zirkulationen in der Flüssigkeit sichtbar gemacht. Man erkennt die Ausbildung eines „Starkwindbandes“ und „Wellen“ (Hochkeile und Tieftröge), die große Ähnlichkeit zu den in der Atmosphäre auftretenden Stromfeldern zeigen

NORTHERN HEMISPHERE CIRCULATION 500 hPa

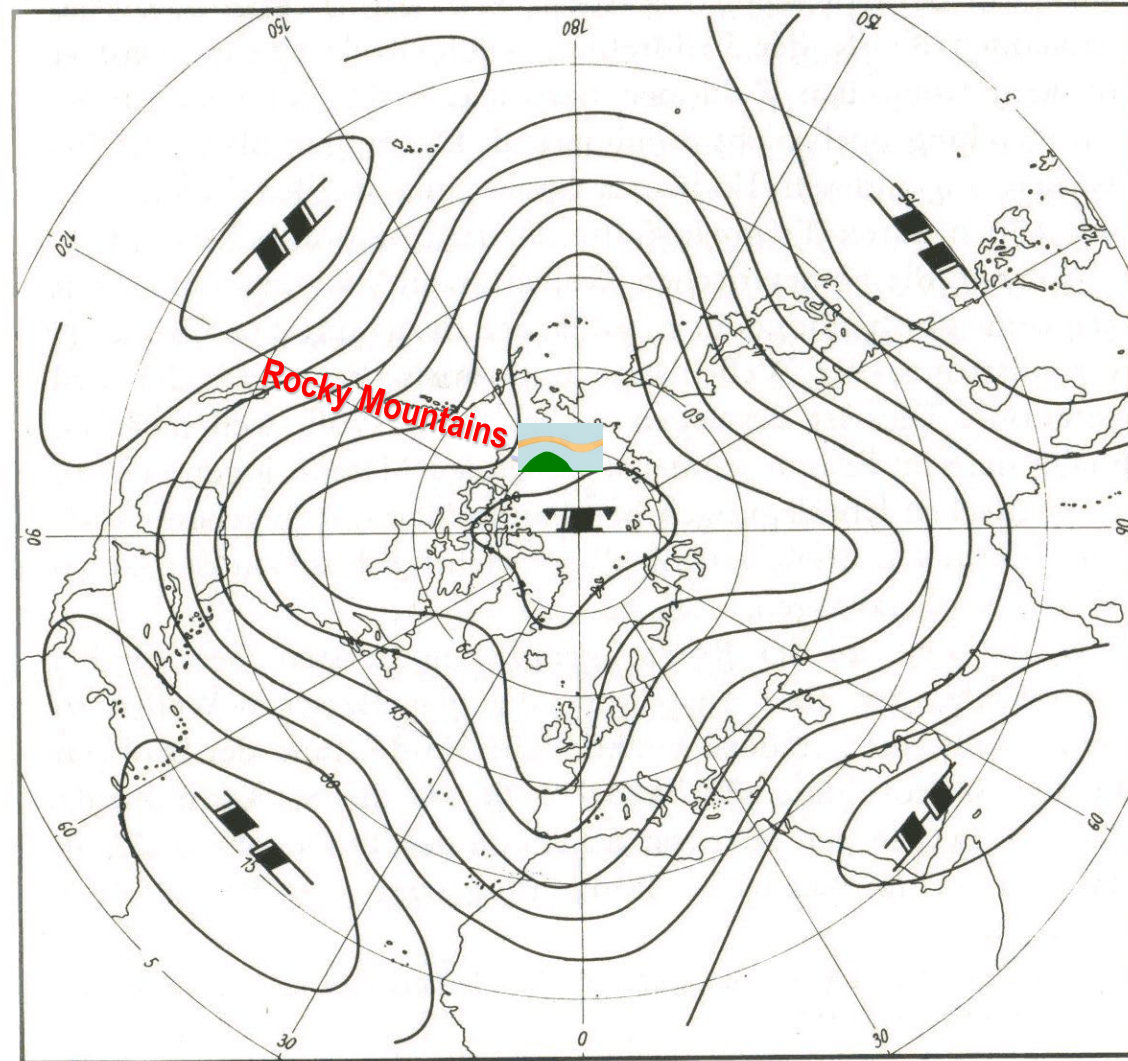
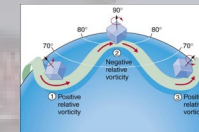
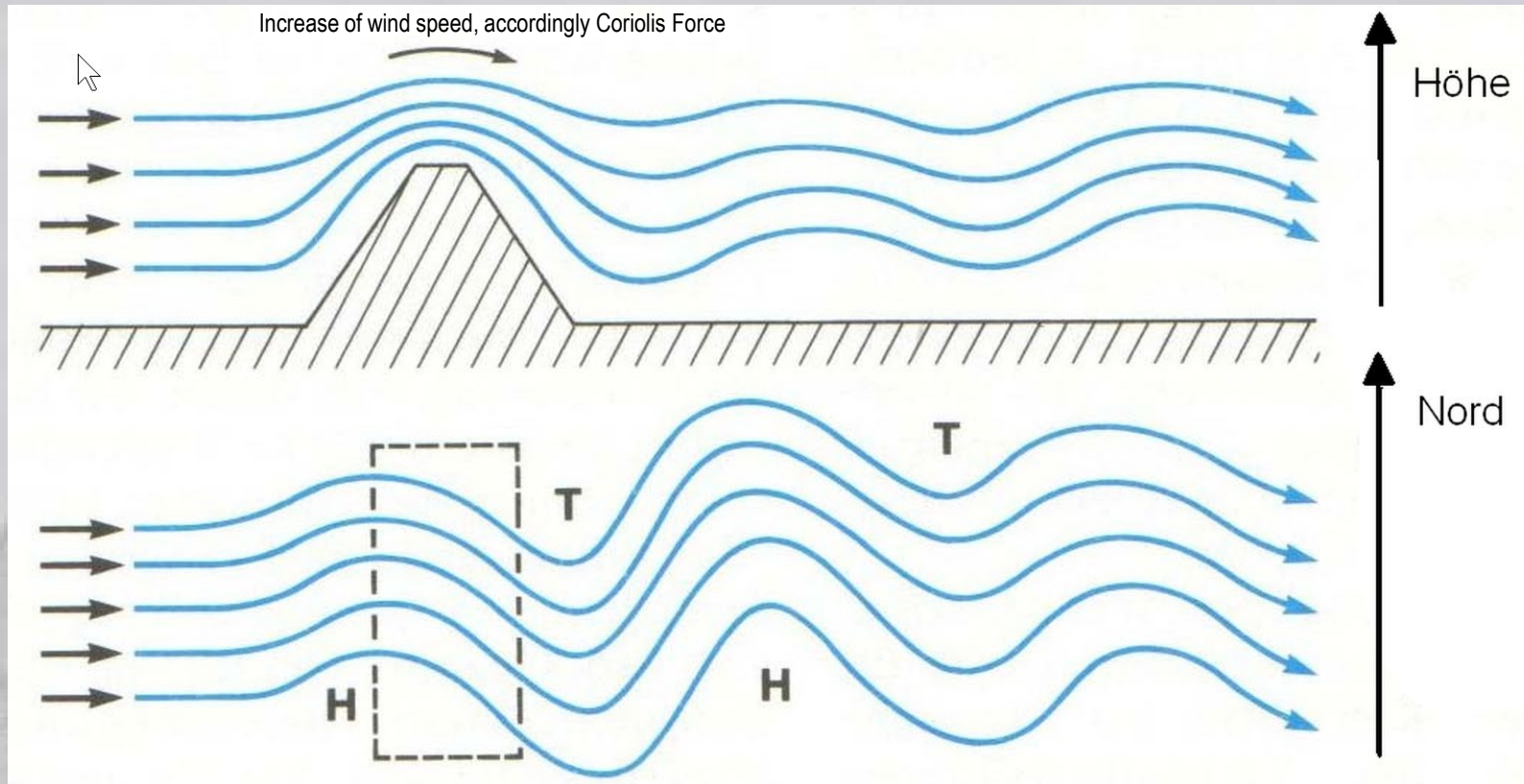


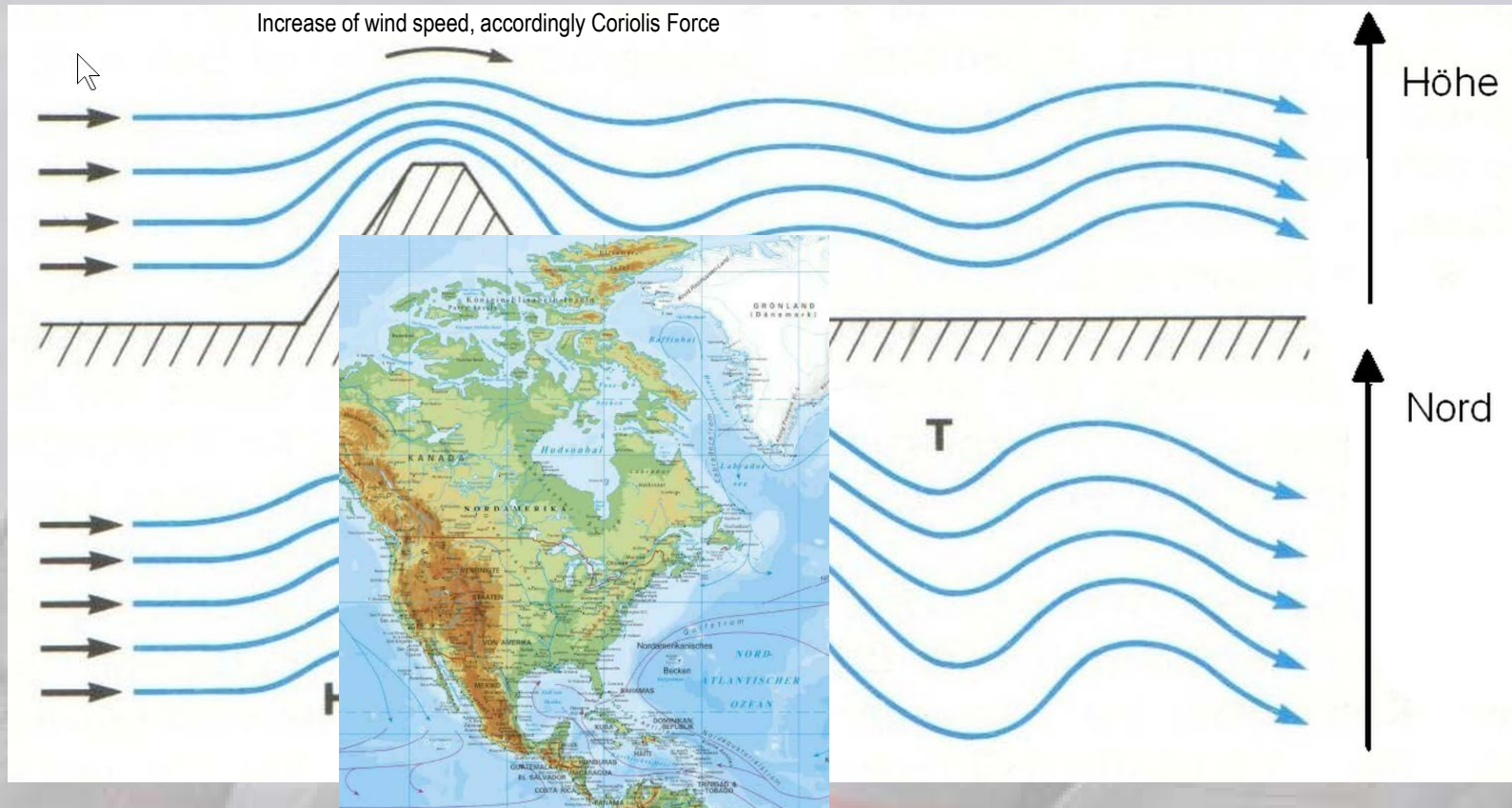
Abb. 28. Schematische Darstellung von planetarischen Wellen mit der Wellenzahl 4 in der freien Atmosphäre



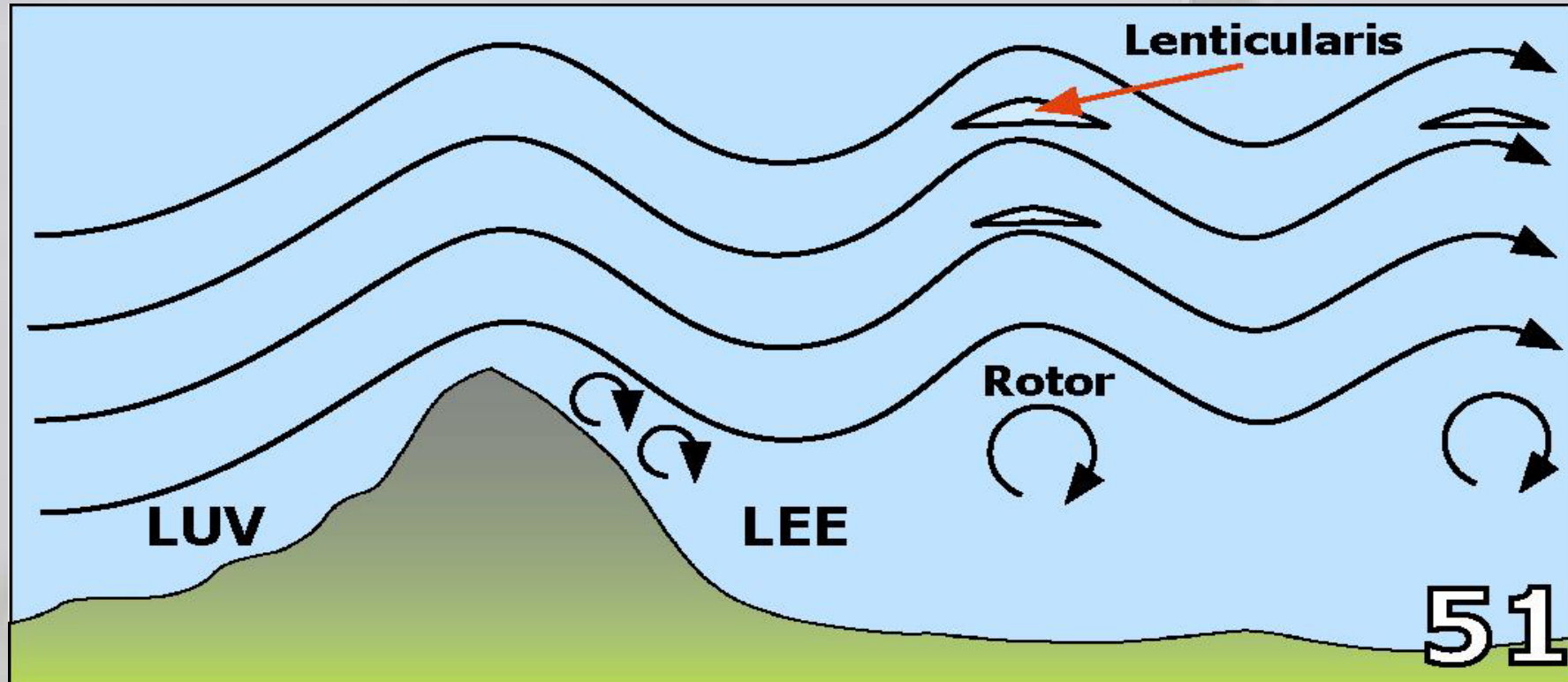
Air flow over mountains



Air flow over mountains



Air flow over mountains



Air flow over mountains



COUPLING OF UPPER AIR FLOW AND SURFACE PRESSURE FIELD

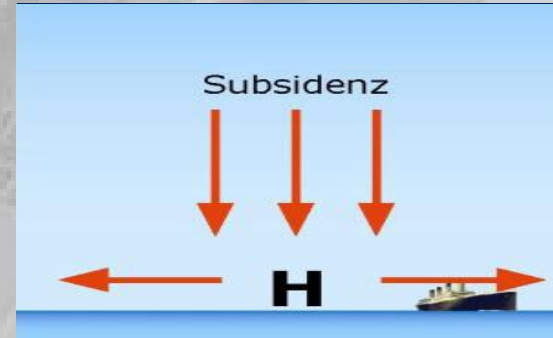
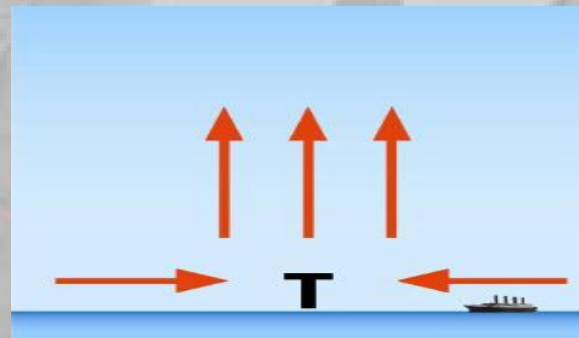
Impact of the upper air flow on ...

- ... development of vortices
- ... vertical motion
- ... cyclogenesis

Upper air -

Divergence

Convergence



Surface -

Convergence

Divergence

COUPLING OF UPPER AIR FLOW AND SURFACE PRESSURE FIELD

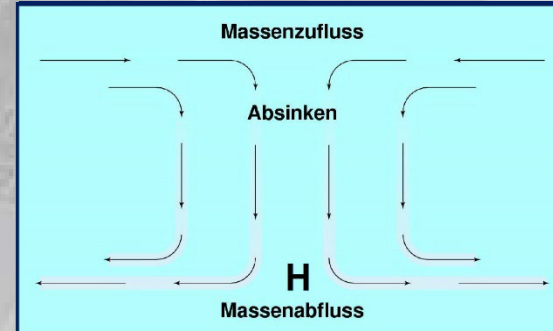
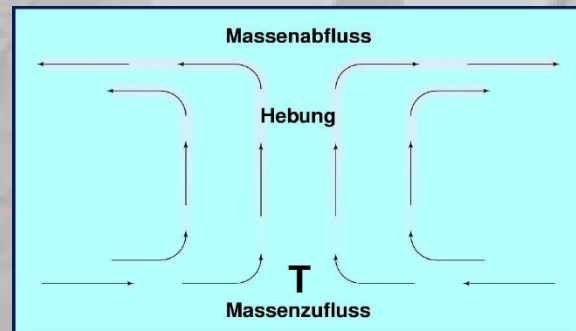
Impact of the upper air flow on ...

- ... development of vortices
- ... vertical motion
- ... cyclogenesis

Upper air -

Divergence

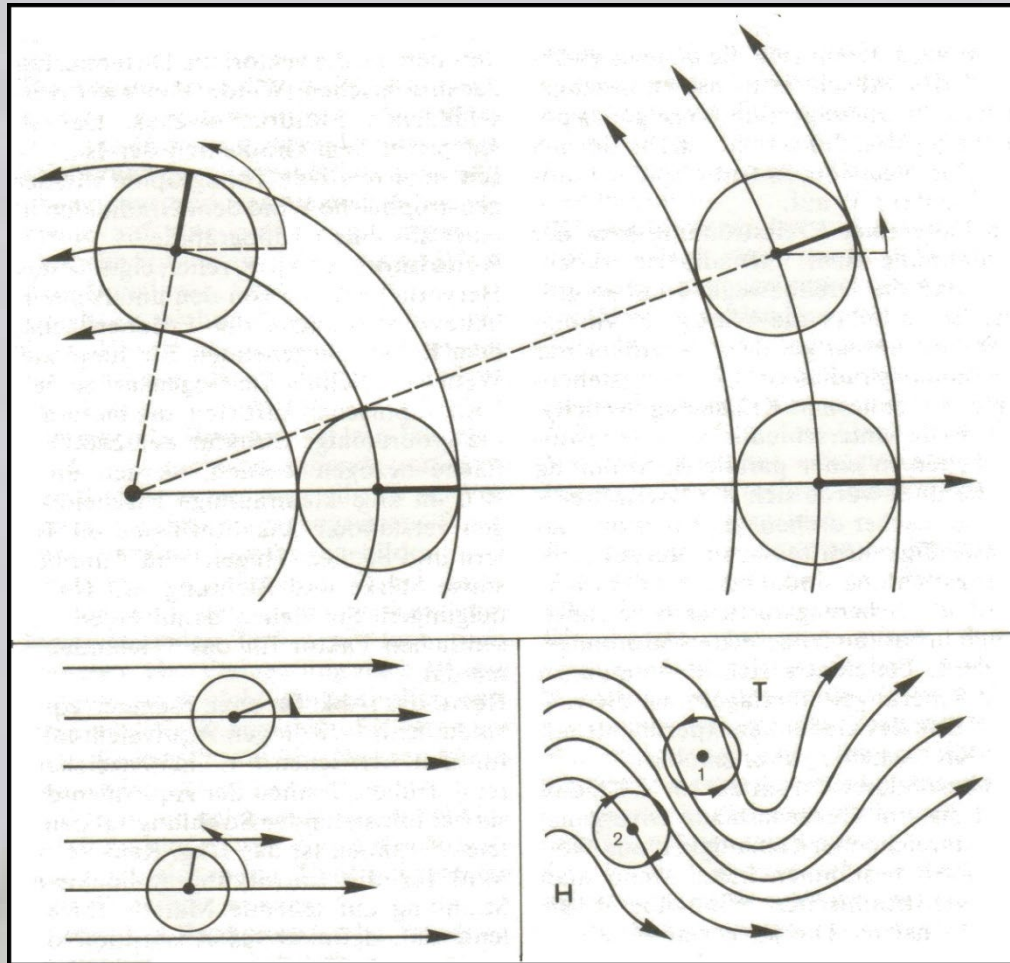
Convergence



Surface -

Convergence

Divergence



**Generation of rotation
(disc in horizontal flow)**

**In flow with curved trajectories
due to curvature effects**

or

**In flow with straight parallel trajectories
due to wind shear effects**

Vorticity is a measure of vortex

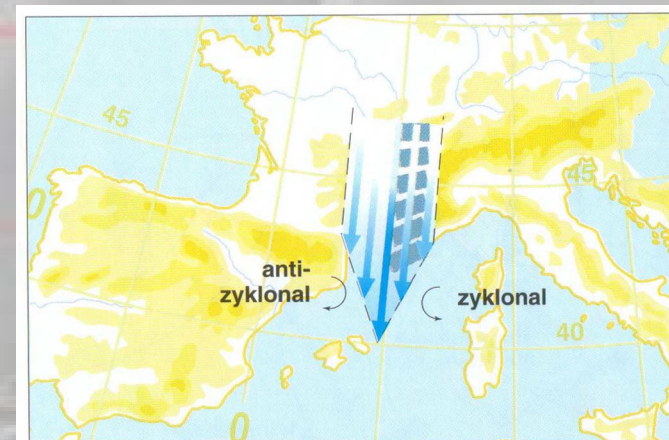
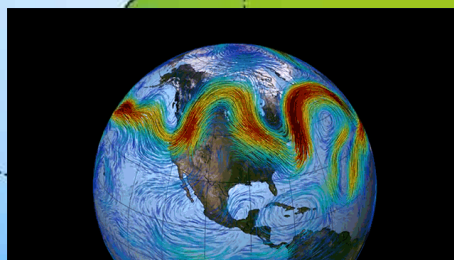
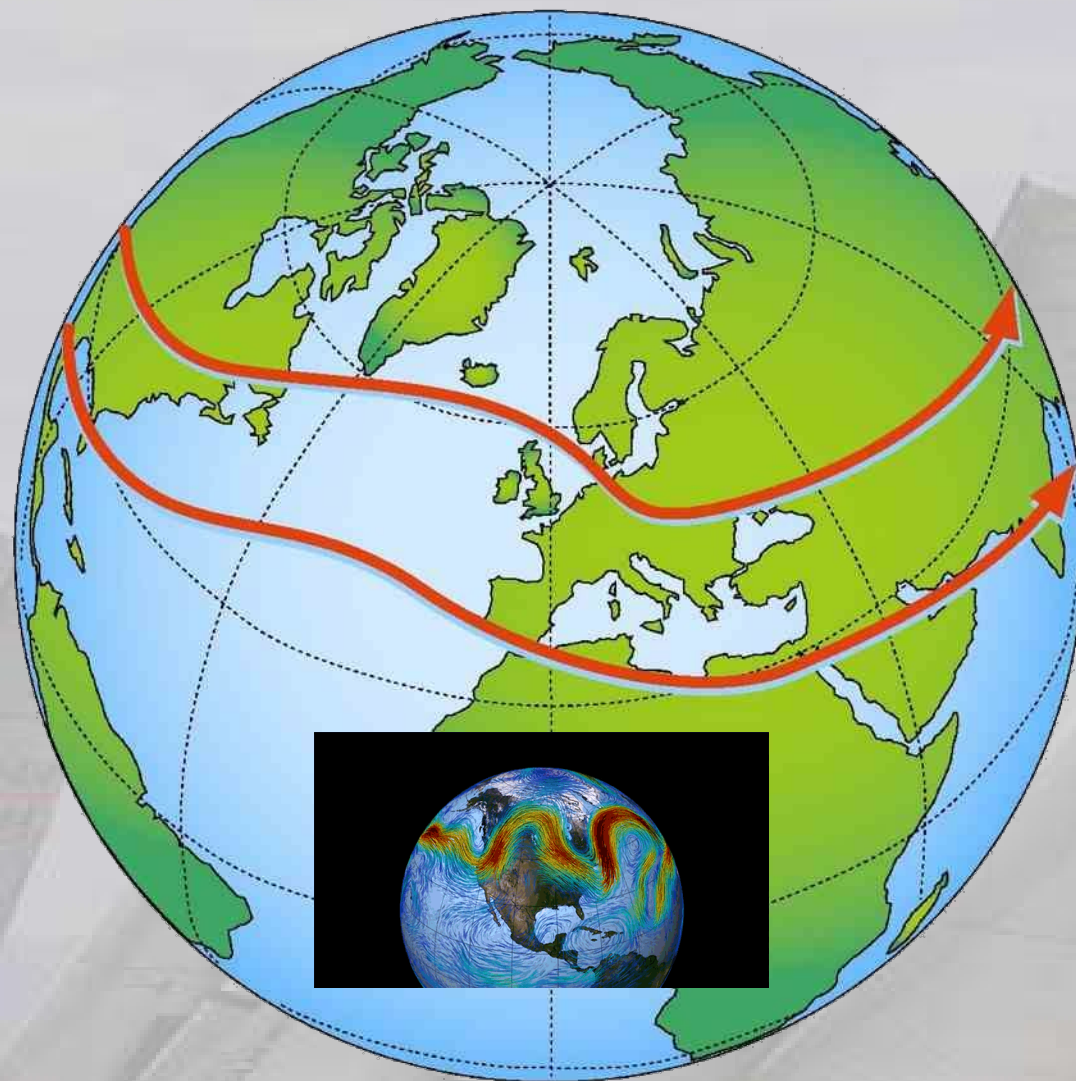
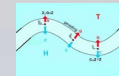


Abb. 23.7 Entstehung von Scherungs-Vorticity in einem bodennahen Starkwindfeld

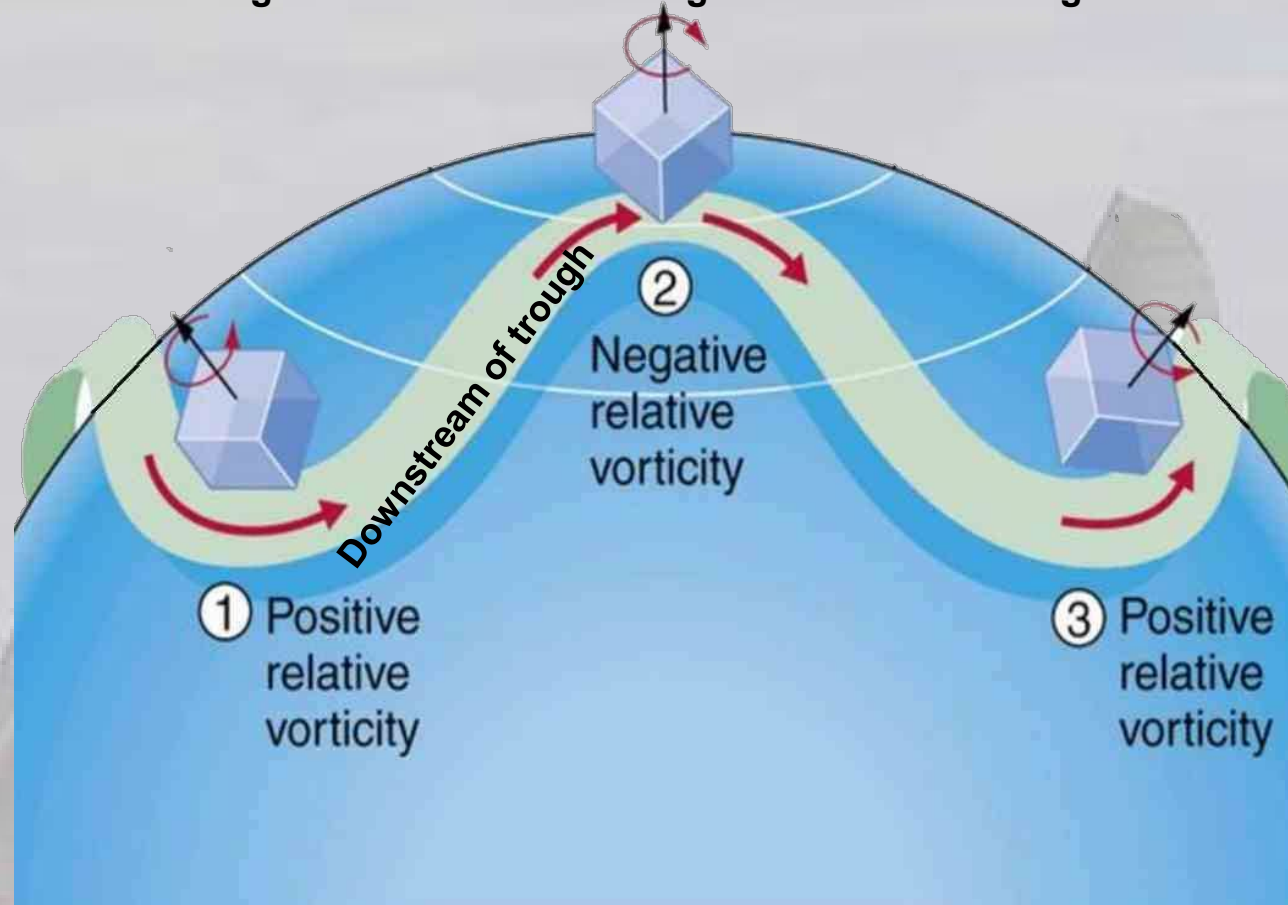


**Vorticity:
Upper air flow:**

**Maximum
Trough**

**Minimum
Ridge**

**Maximum
Trough**



Lifting by

- Positive vorticity advection

Subsidence by

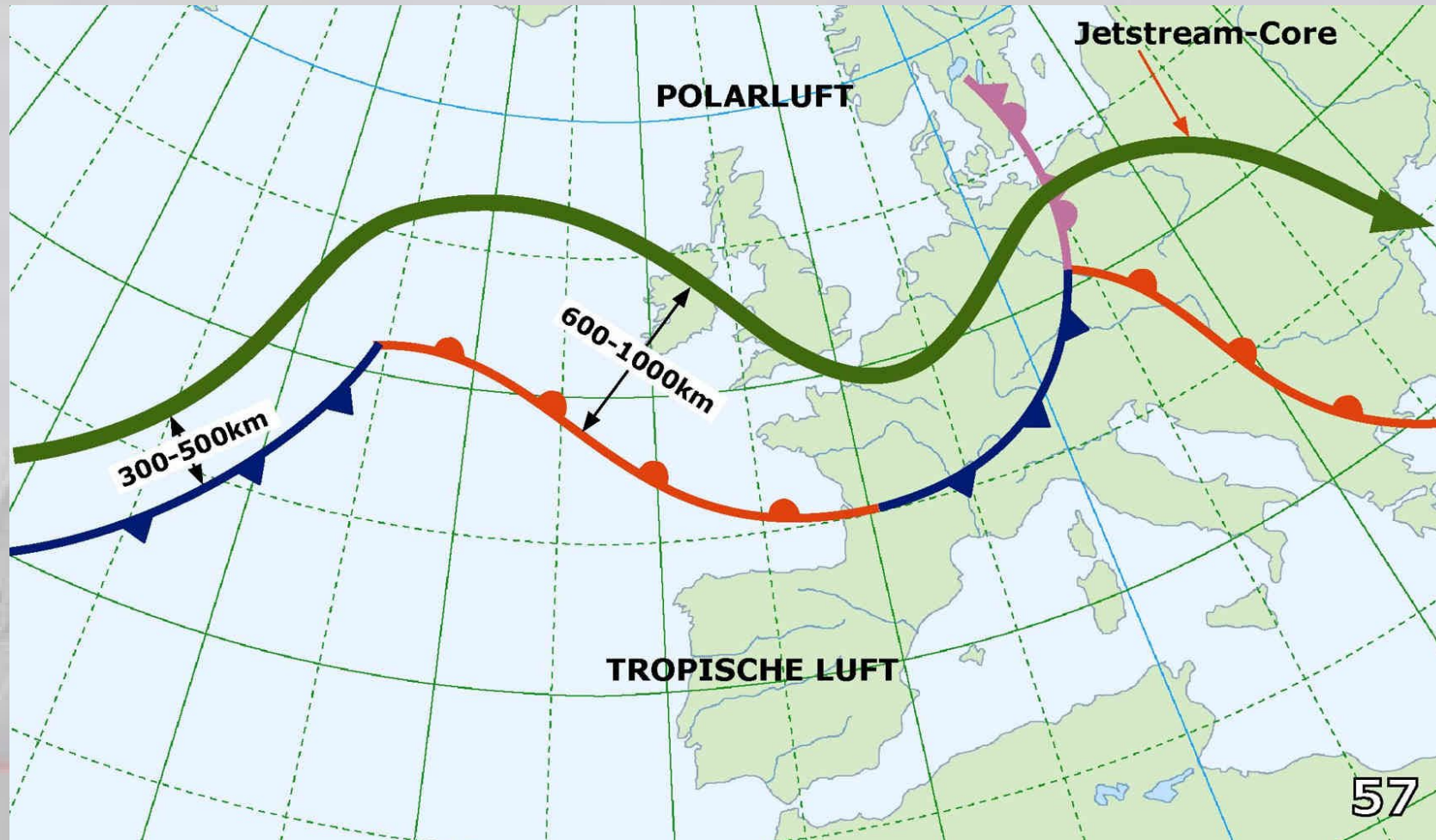
- Negative vorticity advection

Vorticity:
Upper air flow:

Minimum
Ridge

Maximum
Trough

Minimum
Ridge

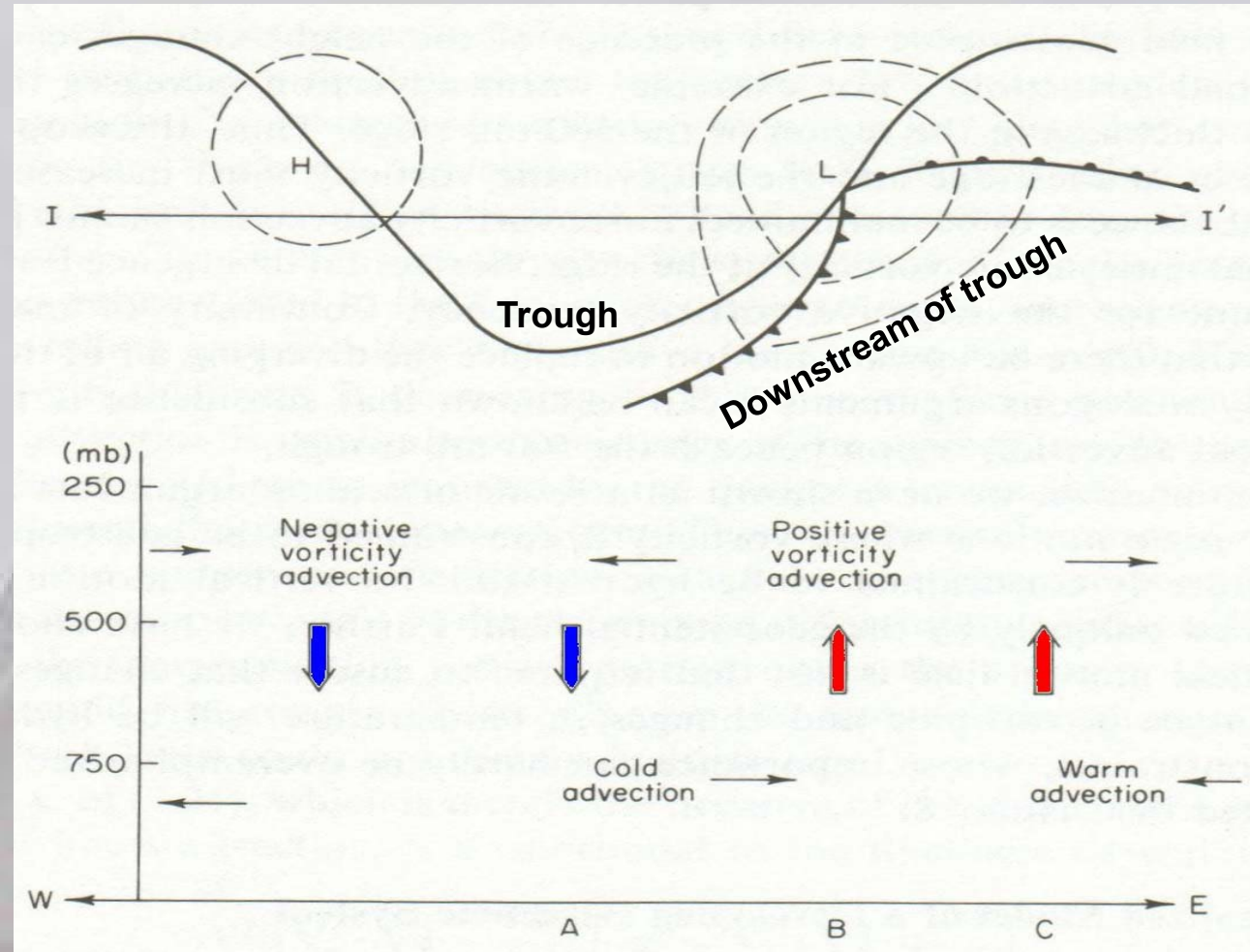


Vorticity:
Upper air flow:

**Minimum
Ridge**

**Maximum
Trough**

**Minimum
Ridge**



Lifting by

- **Positive vorticity advection**
- **Warm air advection**

Subsidence by

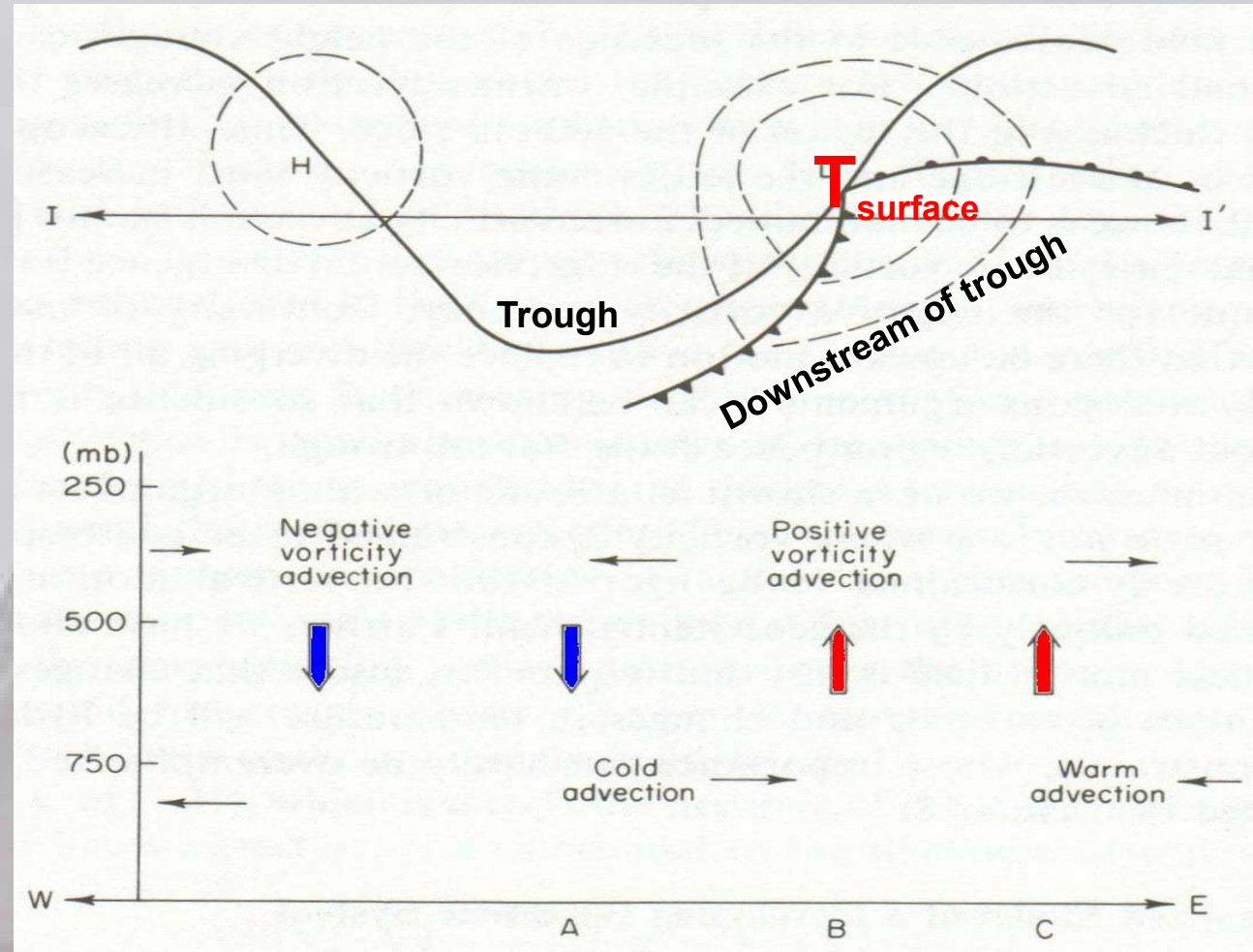
- **Negative vorticity advection**
- **Cold air advection**

Vorticity:
Upper air flow:

**Minimum
Ridge**

**Maximum
Trough**

**Minimum
Ridge**



Lifting by

- **Positive vorticity advection**
- **Warm air advection**

Subsidence by

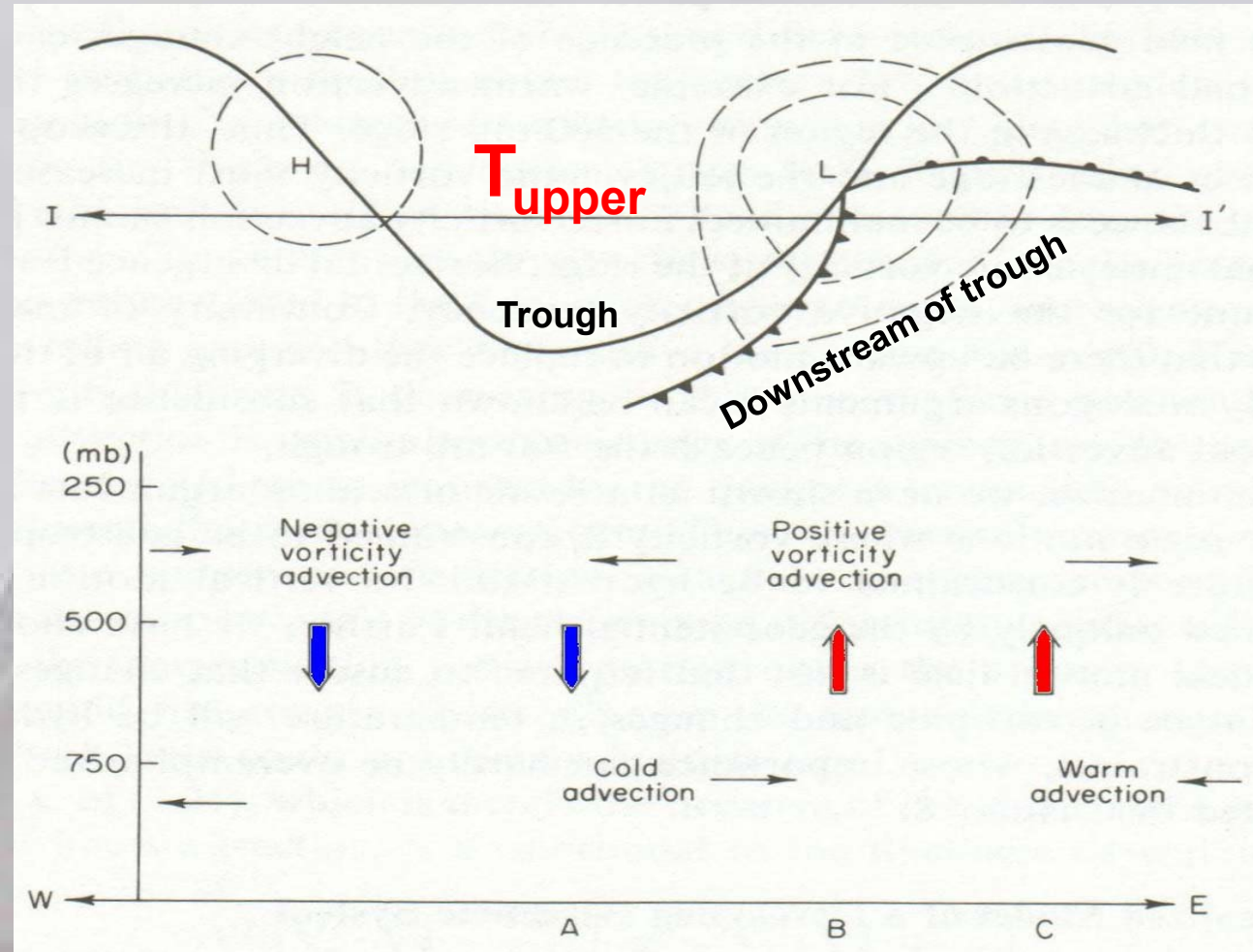
- **Negative vorticity advection**
- **Cold air advection**

Vorticity:
Upper air flow:

**Minimum
Ridge**

**Maximum
Trough**

**Minimum
Ridge**



Lifting by

- Positive vorticity advection
- Warm air advection

Subsidence by

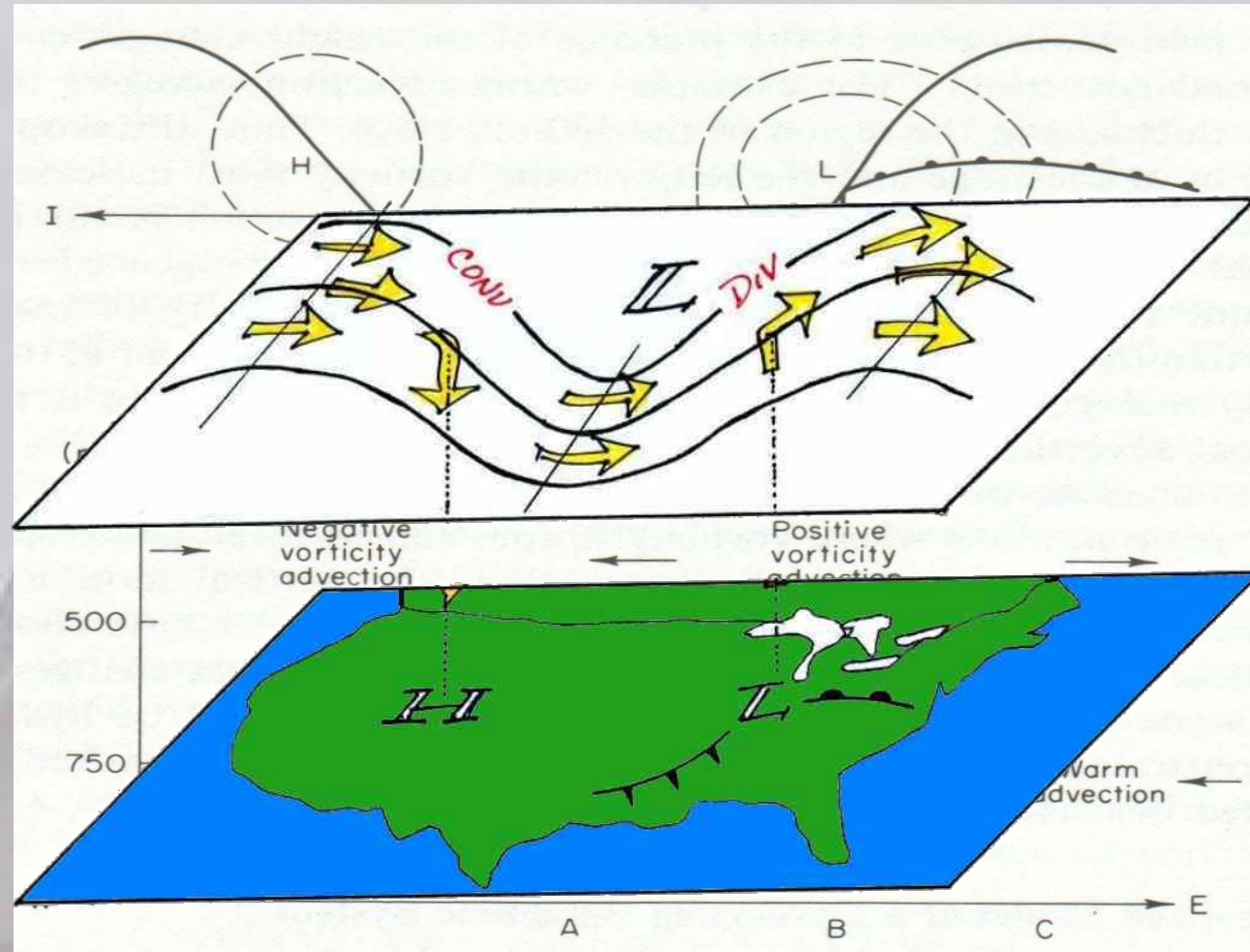
- Negative vorticity advection
- Cold air advection

Vorticity:
Upper air flow:

**Minimum
Ridge**

**Maximum
Trough**

**Minimum
Ridge**



Lifting by

- Positive vorticity advection
- Warm air advection

Subsidence by

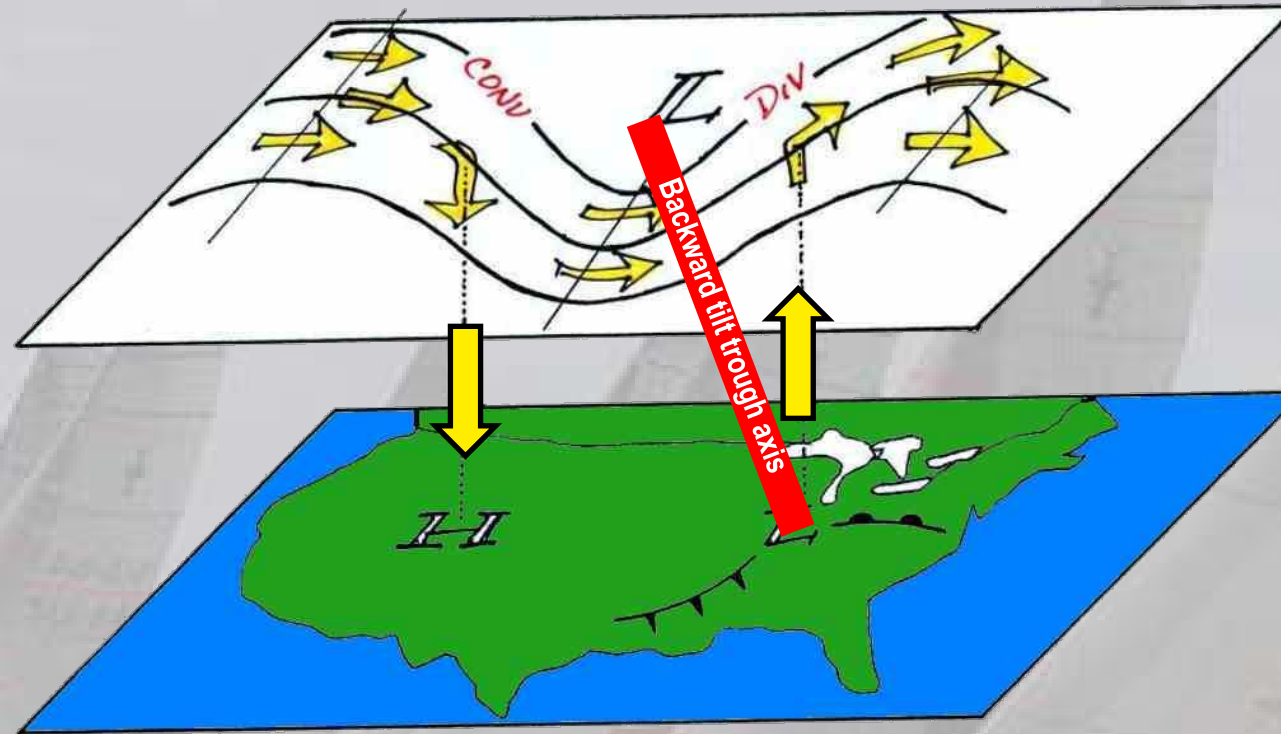
- Negative vorticity advection
- Cold air advection

Vorticity:
Upper air flow:

**Minimum
Ridge**

**Maximum
Trough**

**Minimum
Ridge**



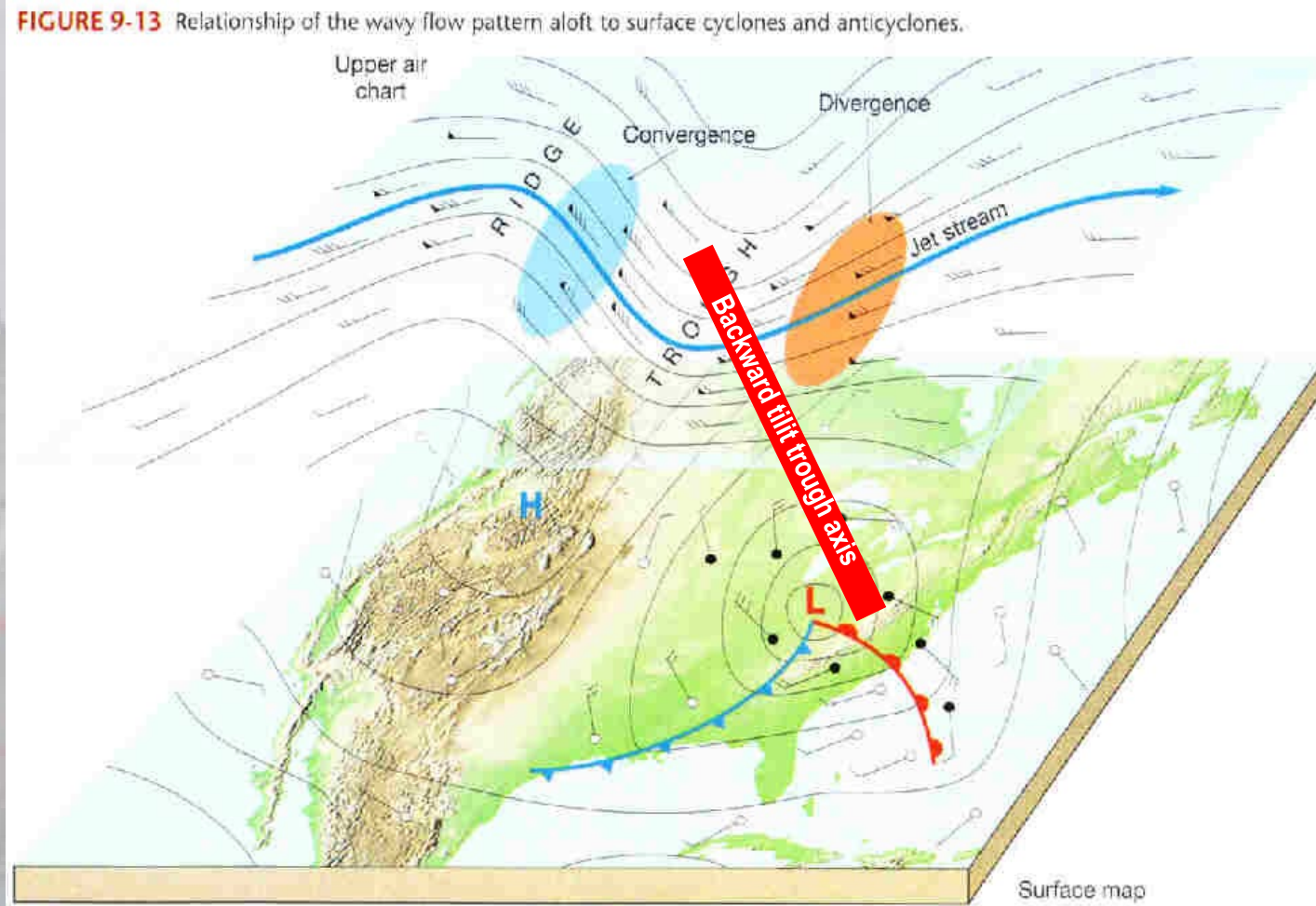
Lifting by

- Positive vorticity advection
- Warm air advection

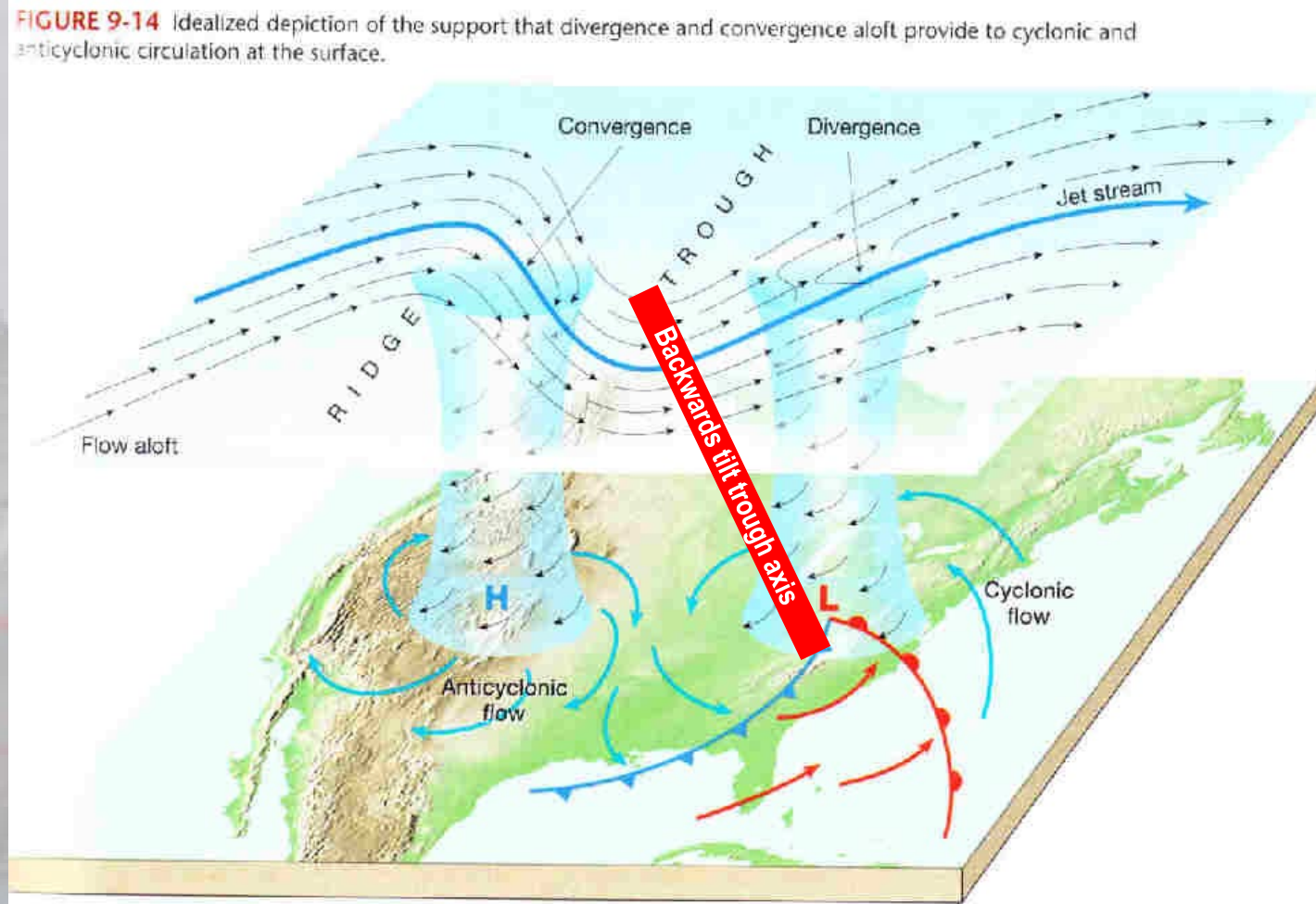
Subsidence by

- Negative vorticity advection
- Cold air advection

COUPLING OF UPPER AIR FLOW AND SURFACE PRESSURE FIELD



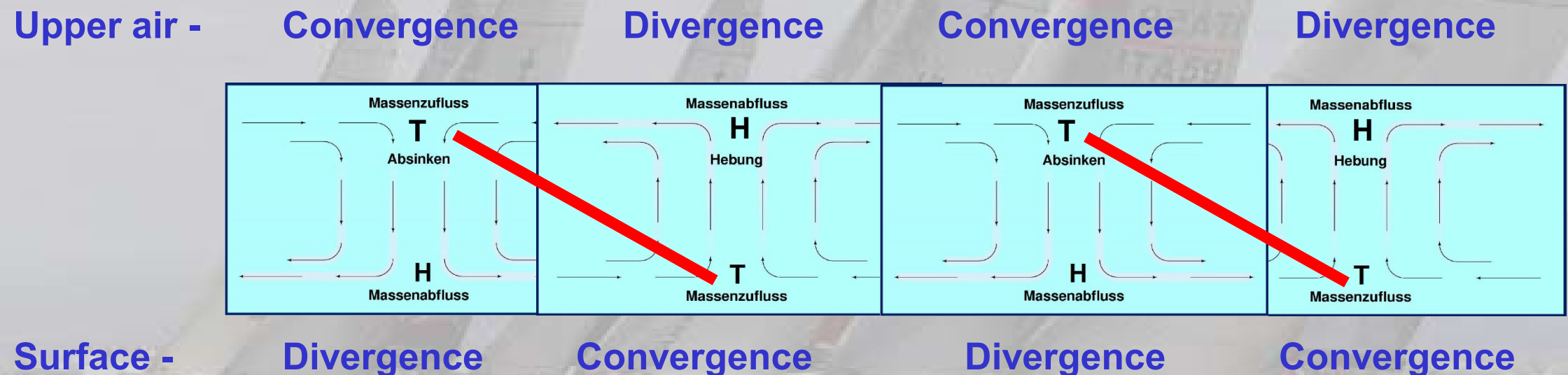
COUPLING OF UPPER AIR FLOW AND SURFACE PRESSURE FIELD



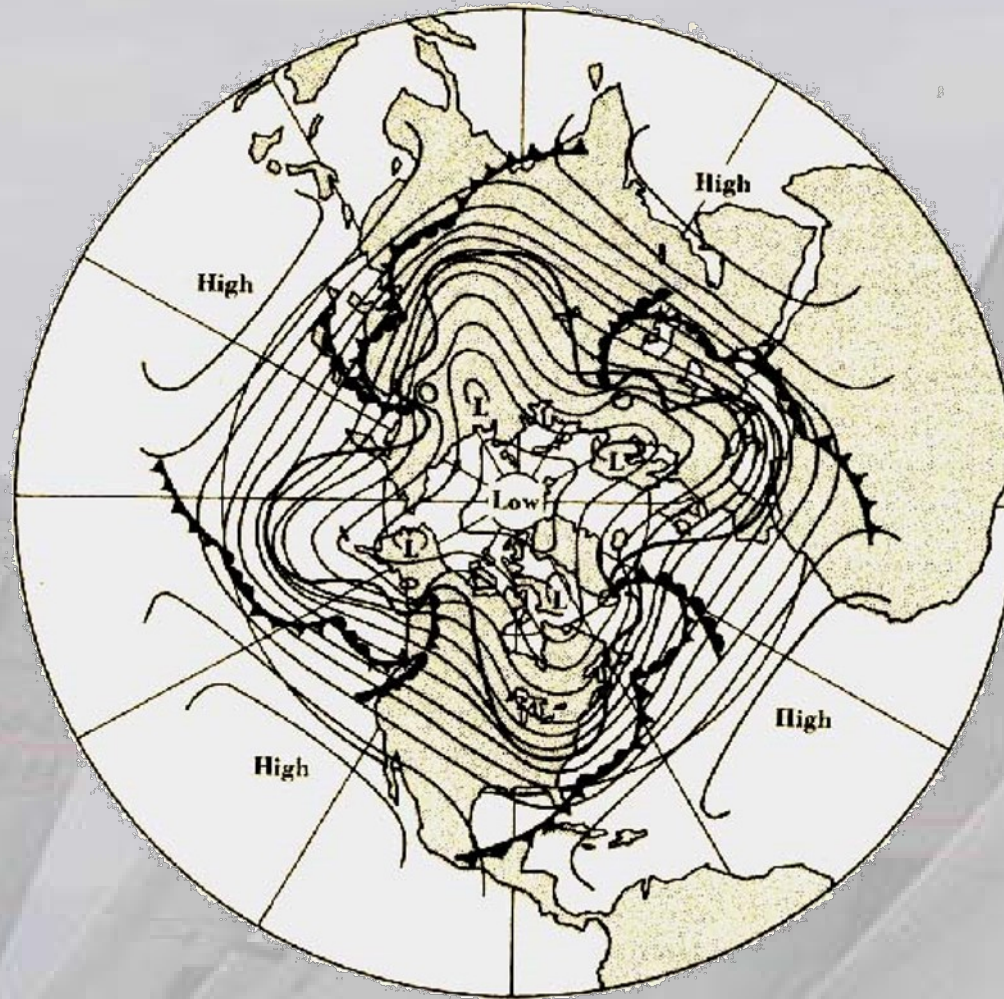
COUPLING OF UPPER AIR FLOW AND SURFACE PRESSURE FIELD

Impact of the upper air flow on ...

- ... development of vortices
- ... vertical motion
- ... Cyclogenesis



NORTHERN HEMISPHERE CIRCULATION MSL PRESSURE



SAT Zirkumpolar



SAT Global Mercator

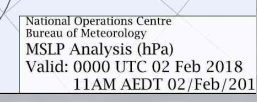


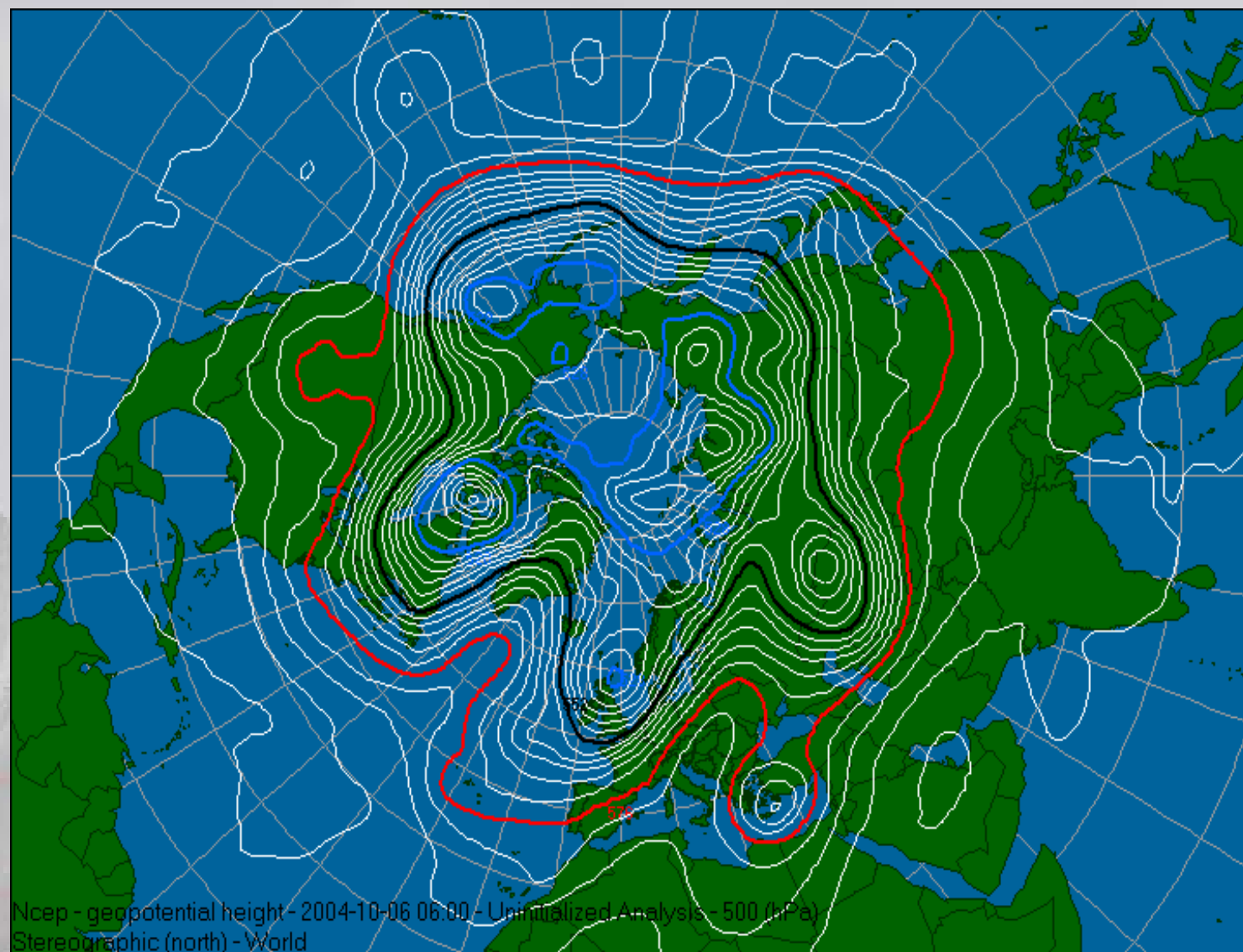
SAT Global Hammer



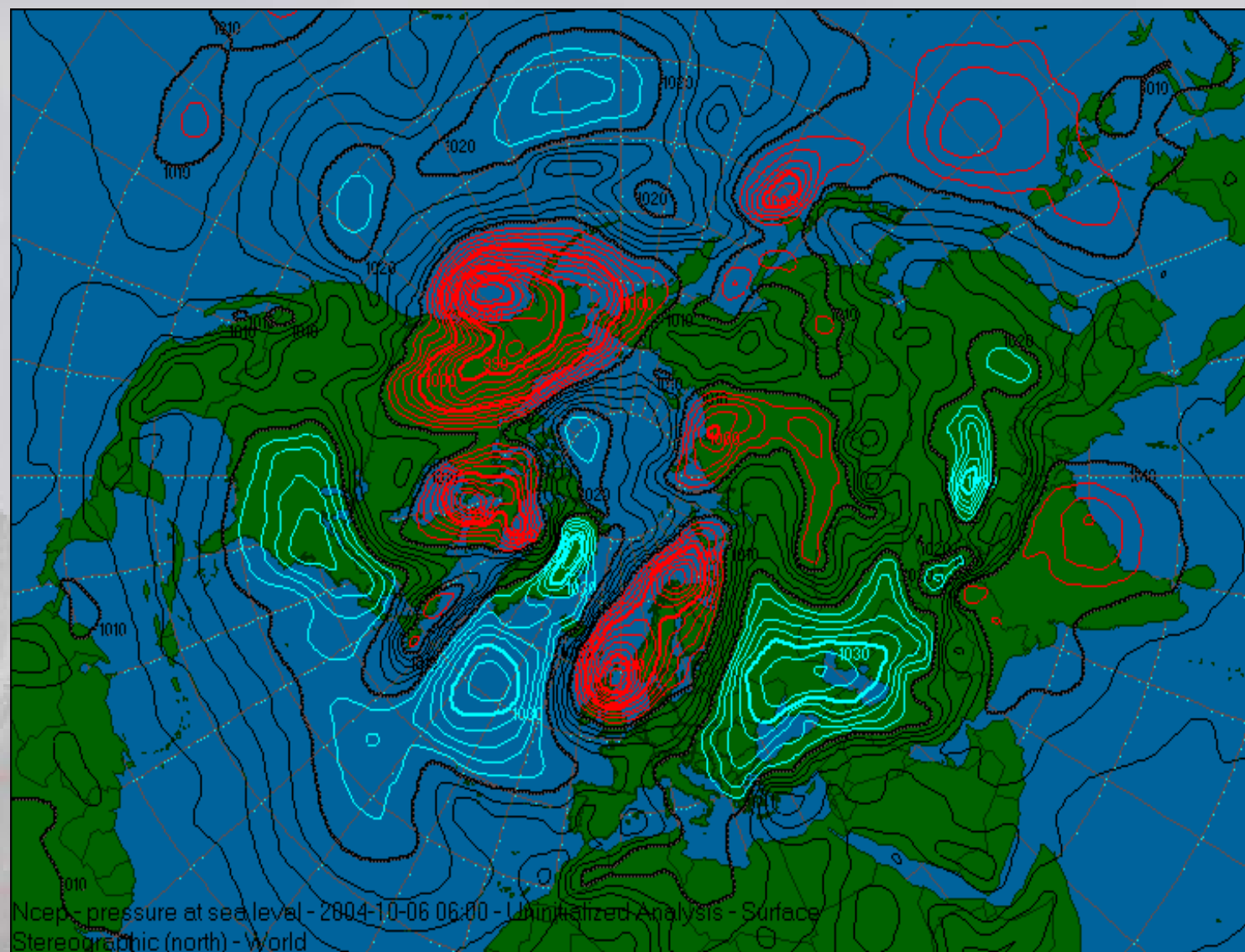
SAT Europa 5km

Fig. 13.15 Schematic chart showing four cyclone families at sea level and four long waves aloft. (After Palmén.)



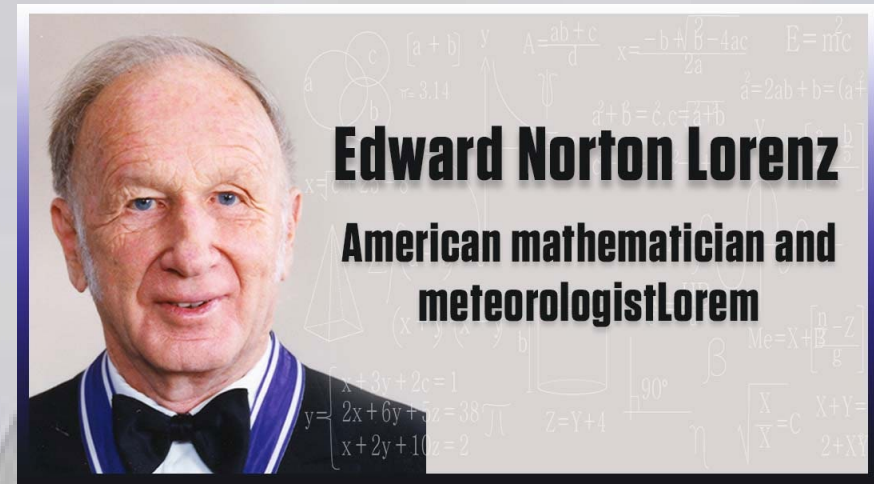


2-A97
RA-57



2-A97
RA-57

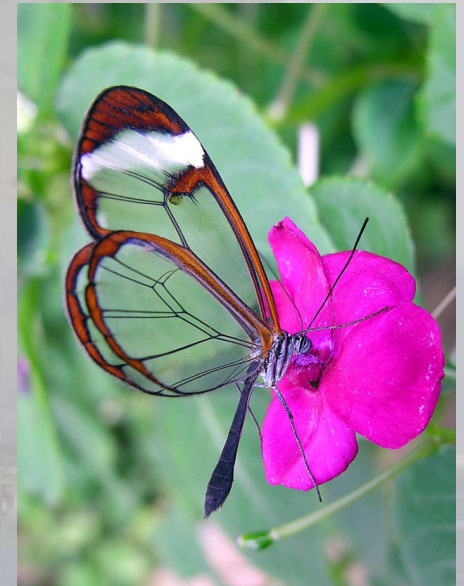
EDWARD N. LORENZ 1917 - 2008



- 1961 Chaos – Theory
- Experiments using different Computers
 - Same NWP model, same initial state – after 4 days diverging results
- Experiments using the same computer
 - Same NWP model, disturbed initial state – after 4 days diverging results

Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas ?

This is the basis for the later development of Ensemble Forecast Technology



EDWARD N. LORENZ 1917 - 2008

1955 Available Potential Energy and the Maintenance of the General Circulation

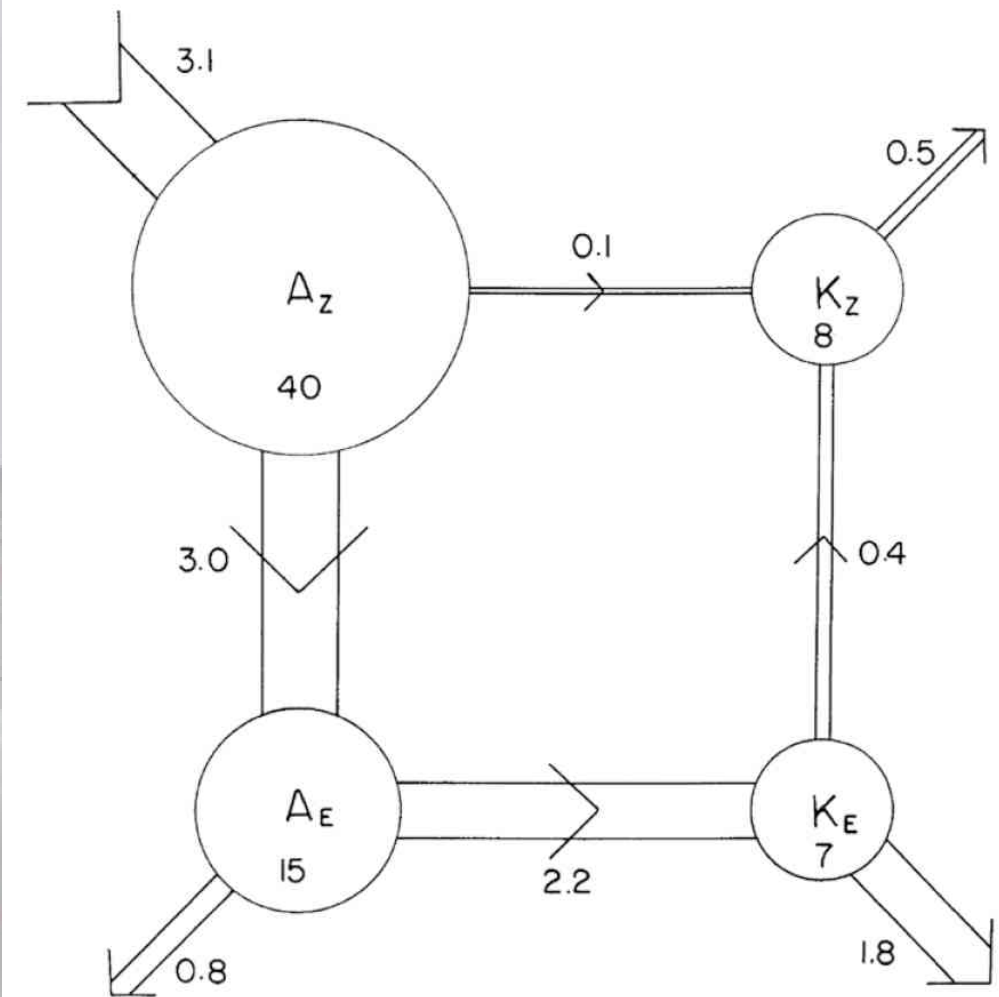
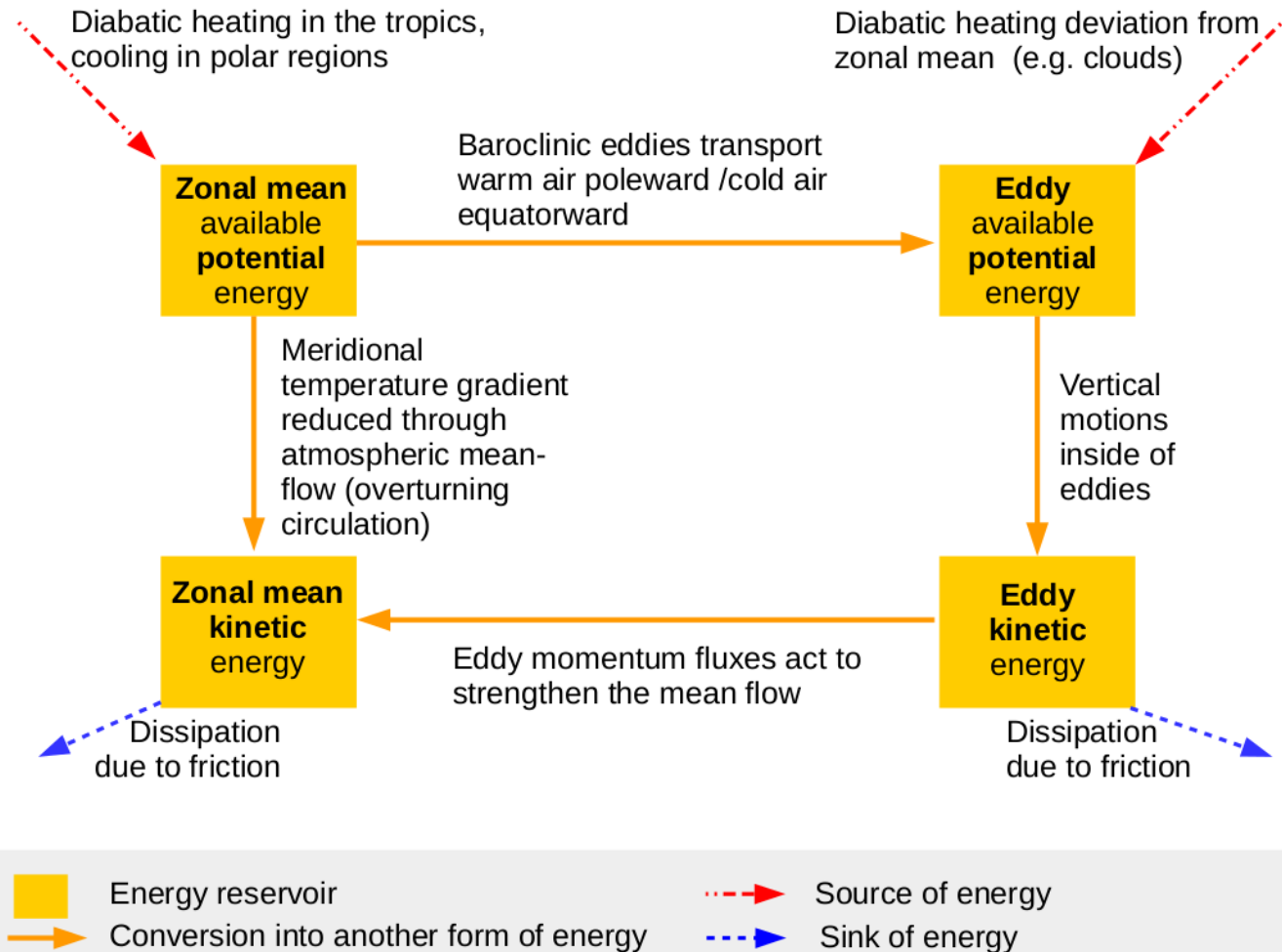


Figure 2. Estimates of the annual-mean, depth-integrated, area-averaged energy cycle among the zonal-mean and eddy available potential and kinetic energy components in the Northern Hemisphere. A denotes available potential energy, K denotes kinetic energy, and the subscripts Z and E denote the zonally averaged and eddy components. Units are 10^5 J/m² for energies and W/m² for generation and dissipation (exterior arrows) and conversion (connecting arrows) rates. From Lorenz (1967), adapted from Oort (1964).

CHECKLIST GLOBAL CIRCULATION

Global Circulation

- ✓ Global Circulation is driven by solar radiation and geometrical (Earth as sphere) and astronomical parameters (slant Earth axis)
- ✓ Coriolis Force
 - ✓ $\Omega = 2 * \pi / 86.164$
 - ✓ $2 * \Omega * \sin(\phi=\text{latitude})$ Coriolis frequency
 - ✓ Coriolis Force = wind velocity * Coriolis frequency
 - ✓ Increases with latitude, Zero at Equator
 - ✓ Proportional to windspeed
 - ✓ Acts perpendicular to direction of motion
 - ✓ Acts to the right (Northern Hemisphere) and left (Southern Hemisphere), respectively
- ✓ Circulation Cells: Hadley~ (suptropical), Ferrel~ (mid-latitude), Polar~ (Polar regions)

CHECKLIST GLOBAL CIRCULATION

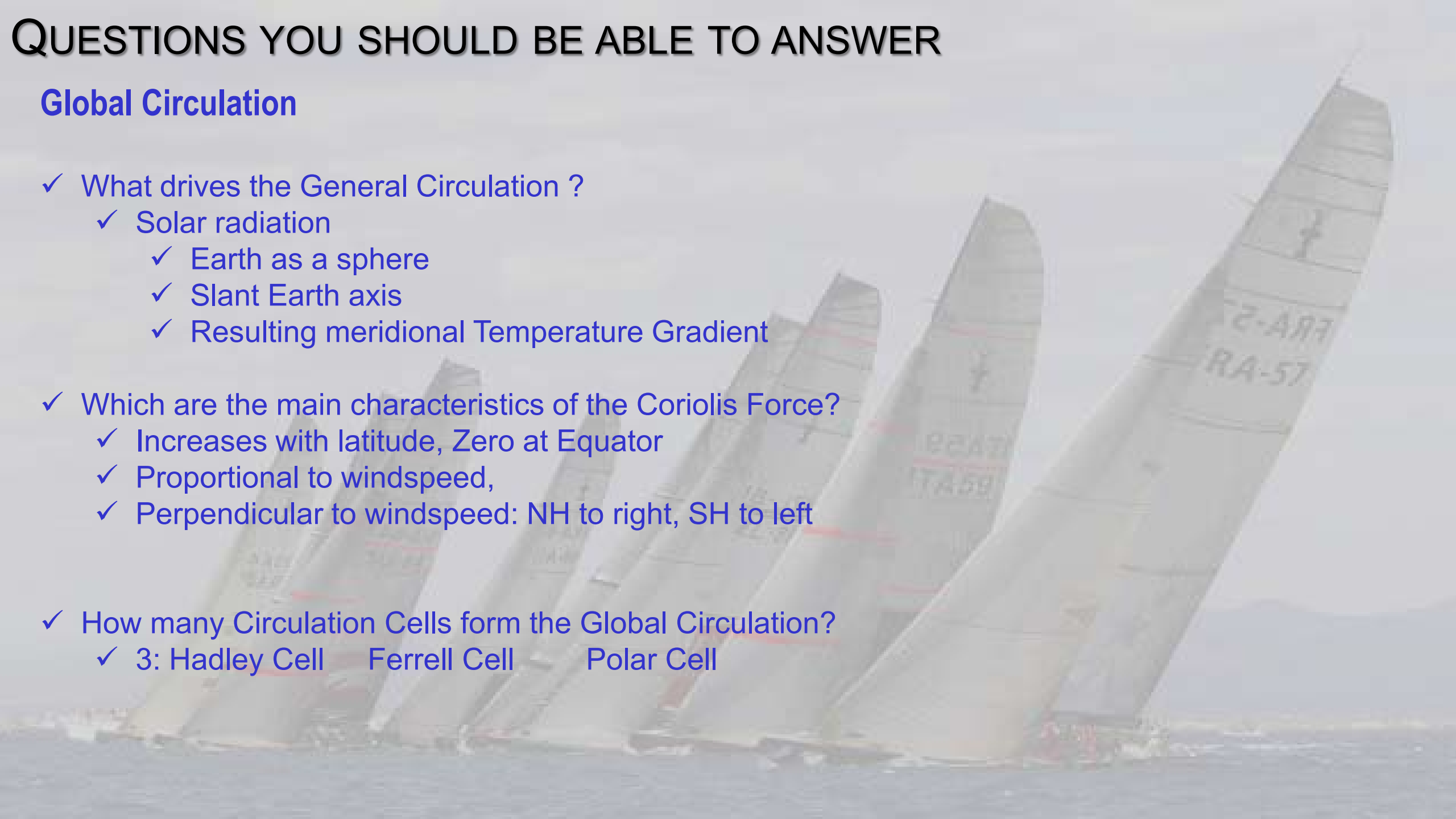
Global Windsystems

- ✓ Global Windsystems (MSLP, Upper Air), Wavenumber, Upper Air Trough/Ridge (Tank experiment)
- ✓ Innertropical Convergence Zone (ITCZ), Trade winds, Subtropical High, Westerly Winds
- ✓ Impact of Rocky Mountains on Global Circulation, Leeward trough, Downstream advection of warm-moist air NE-ward to Newfoundland by SW wind near East Coast of USA
- ✓ Advection of polar cold air from Labrador Sea by NW winds
- ✓ Intensification of meridional (N-S) temperature gradient by four center pressure pattern
- ✓ Formation of frontal zone, Cyclogenetic orographic effects by Greenland mountains

QUESTIONS YOU SHOULD BE ABLE TO ANSWER

Global Circulation

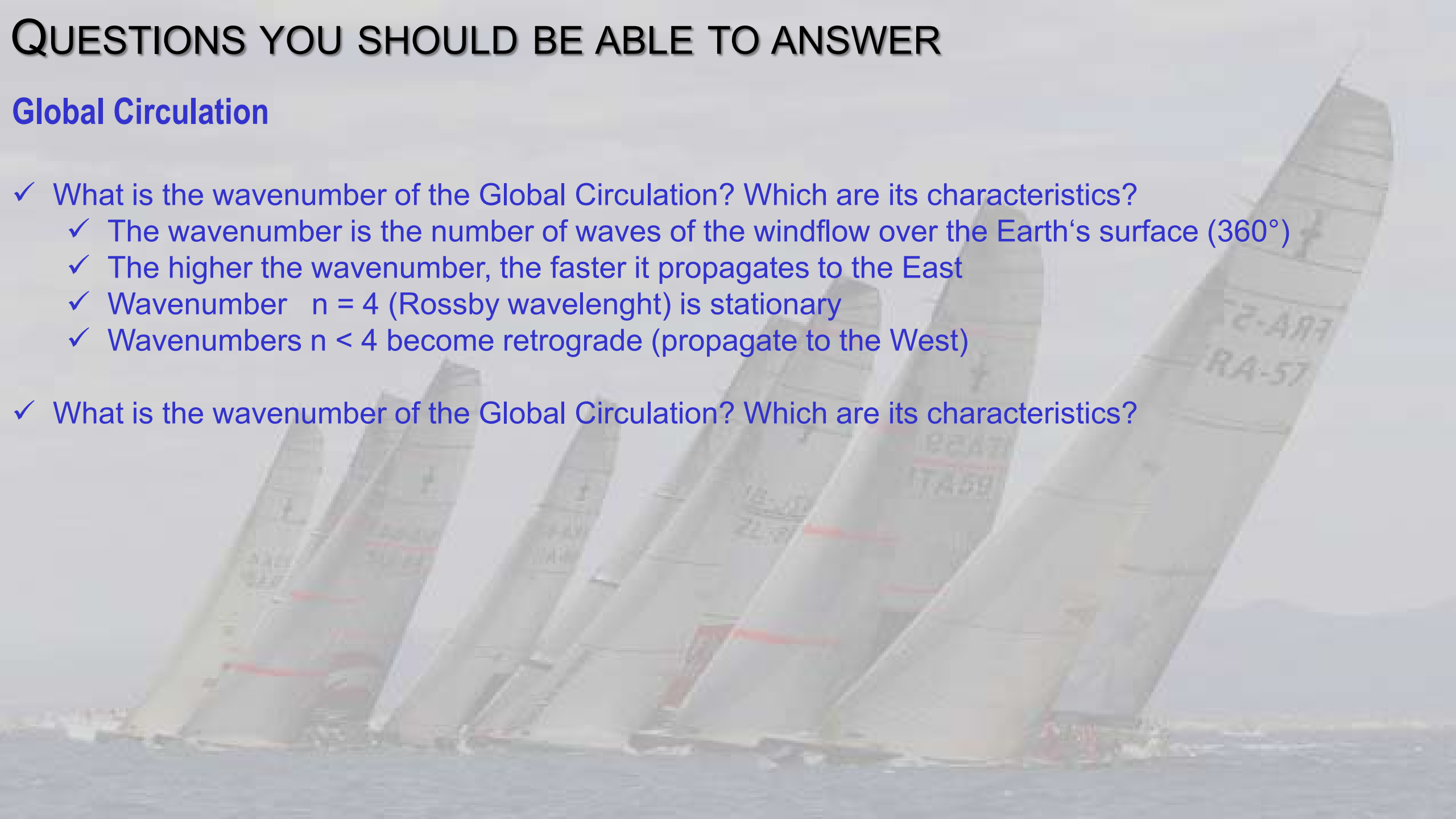
- ✓ What drives the General Circulation ?
 - ✓ Solar radiation
 - ✓ Earth as a sphere
 - ✓ Slant Earth axis
 - ✓ Resulting meridional Temperature Gradient
- ✓ Which are the main characteristics of the Coriolis Force?
 - ✓ Increases with latitude, Zero at Equator
 - ✓ Proportional to windspeed,
 - ✓ Perpendicular to windspeed: NH to right, SH to left
- ✓ How many Circulation Cells form the Global Circulation?
 - ✓ 3: Hadley Cell Ferrell Cell Polar Cell



QUESTIONS YOU SHOULD BE ABLE TO ANSWER

Global Circulation

- ✓ What is the wavenumber of the Global Circulation? Which are its characteristics?
 - ✓ The wavenumber is the number of waves of the windflow over the Earth's surface (360°)
 - ✓ The higher the wavenumber, the faster it propagates to the East
 - ✓ Wavenumber $n = 4$ (Rossby wavelenght) is stationary
 - ✓ Wavenumbers $n < 4$ become retrograde (propagate to the West)
- ✓ What is the wavenumber of the Global Circulation? Which are its characteristics?



Thank you for your attention !

