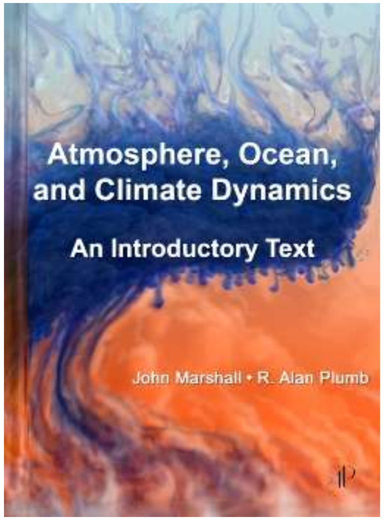
GEF 1100 – Klimasystemet

Chapter 8: The general circulation of the atmosphere

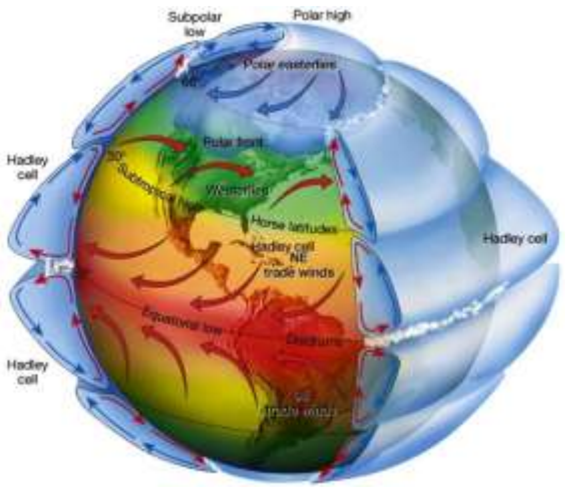


Prof. Dr. Kirstin Krüger (MetOs, UiO)

UiO : University of Oslo

Lecture Outline – Ch. 8

Ch. 8 – The general circulation of the atmosphere (GCA)



1. Motivation
2. Observed circulation*
    - 2.1 The tropical Hadley circulation
    - 2.2 The Intertropical Convergence Zone (ITCZ)*
    - 2.3 The monsoon circulation
3. Mechanistic view of the circulation
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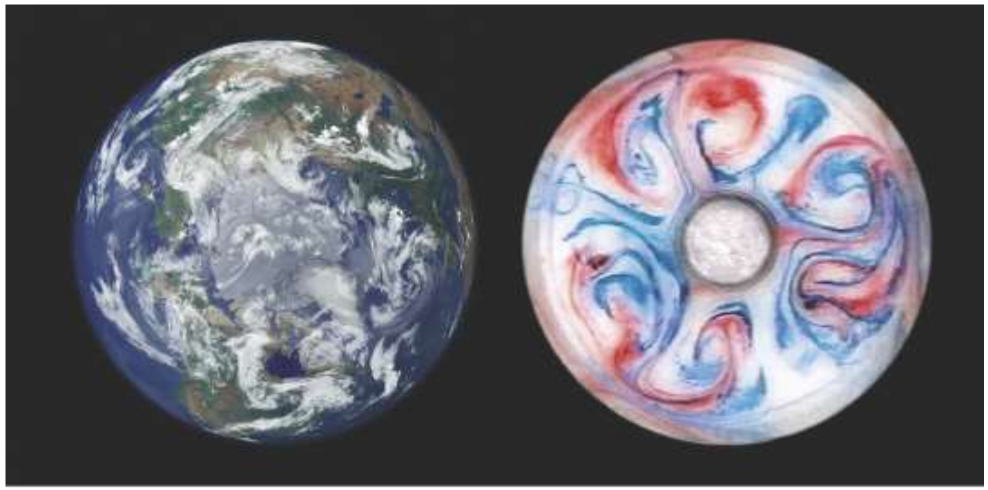
    - 3.2 The extratropical circulation
4. Large-scale atmospheric energy and momentum budget
5. Summary
6. Take home message

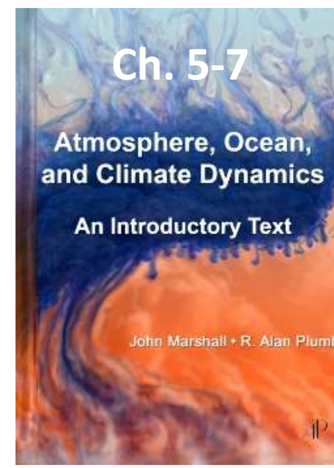
*Add-ons, not in book.

Motivation

Fram vessel



- Early days: Discovery of the earth (with sailing boats)
- Understanding of the GCA (see photo)
- Application of Chapters 5-7



Marshall and Plumb (2008)

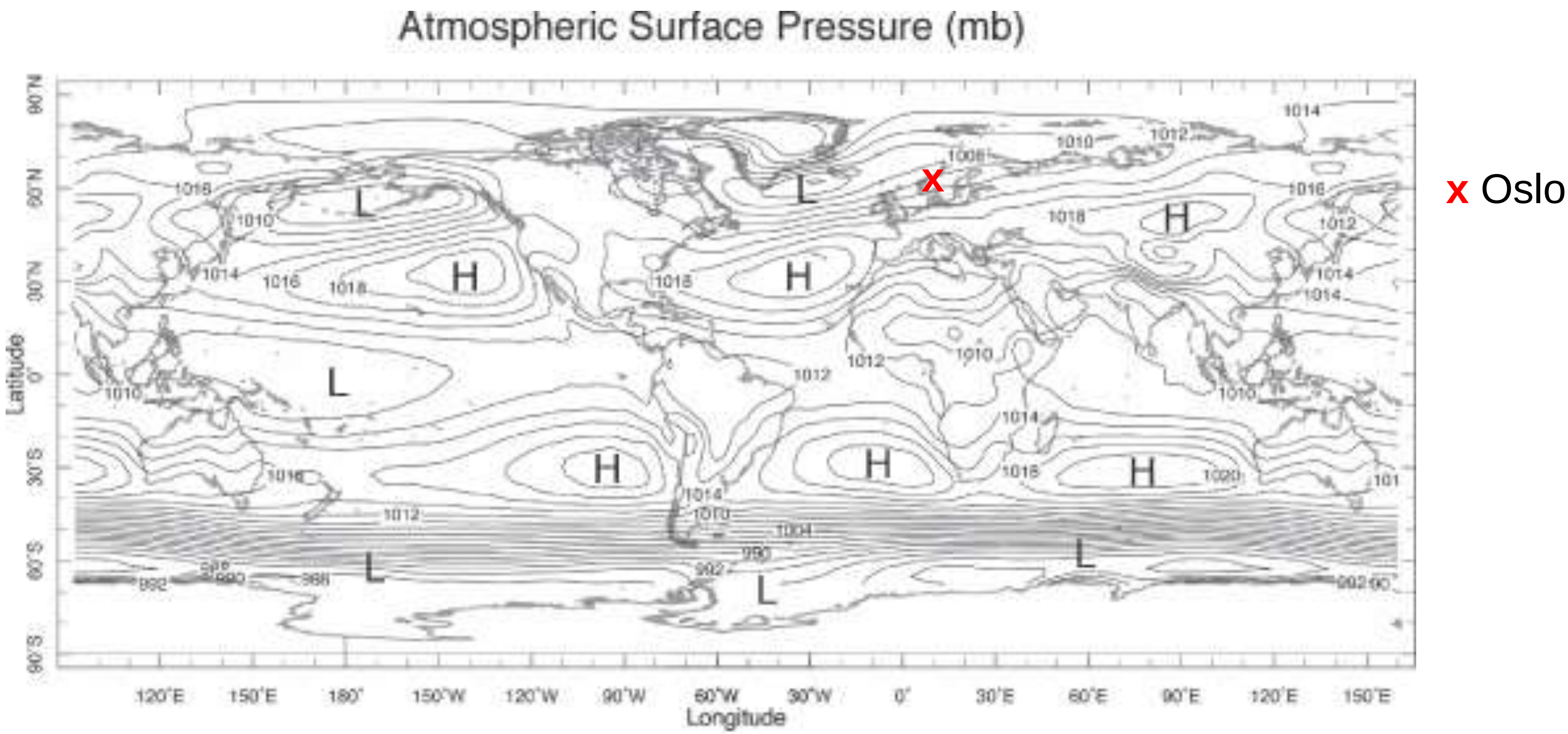


Figure 7.27: The annual-mean surface pressure field in mbar, with major centers of high and low pressure marked. The contour interval is 5 mbar.

Marshall and Plumb (2008)

Sea level pressure (SLP) [mb]

Zonal wind [m/s]

Meridional wind [m/s]

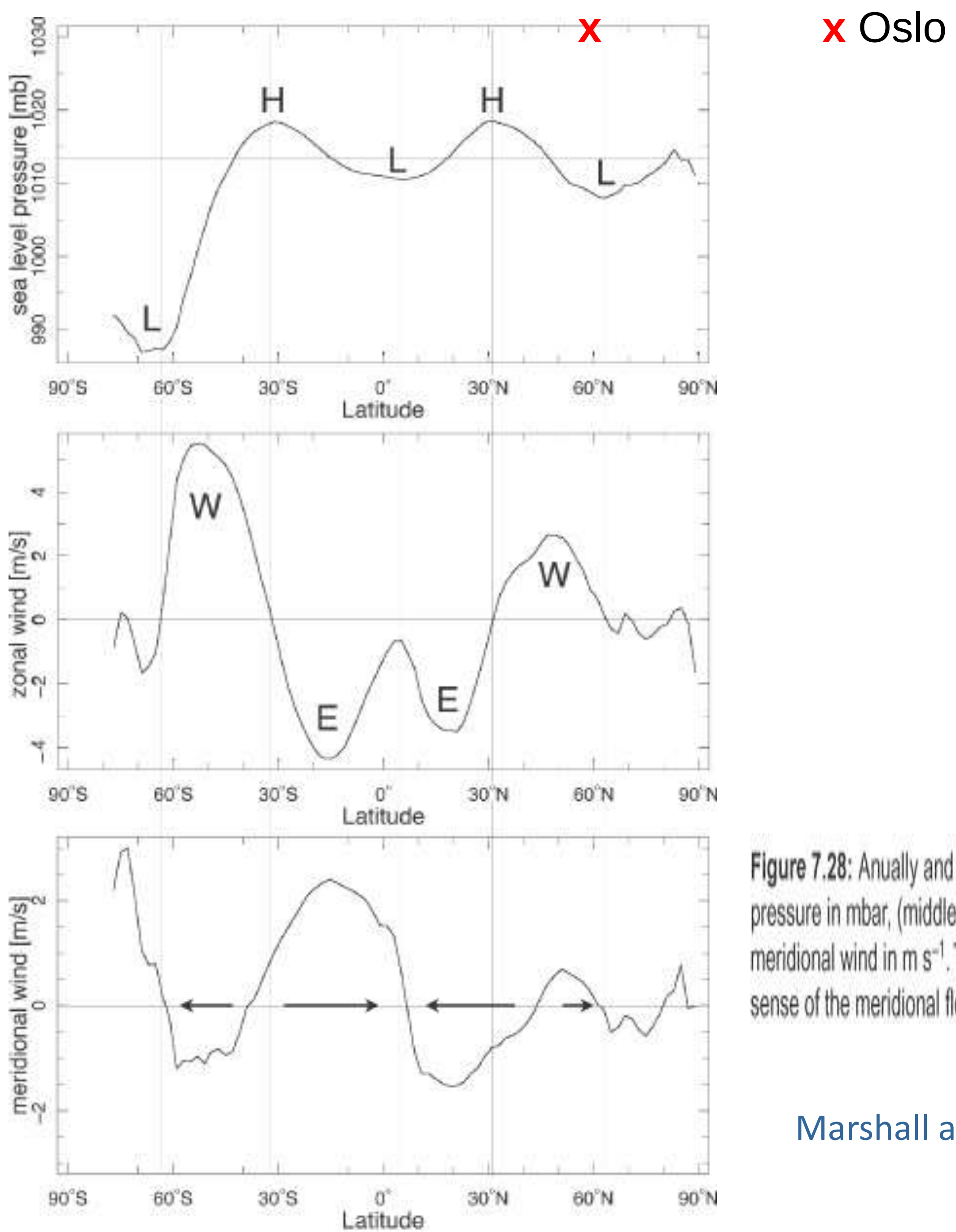


Figure 7.28: Anually and zonally averaged (top) sea level pressure in mbar, (middle) zonal wind in m s^{-1}, and (bottom) meridional wind in m s^{-1}. The horizontal arrows mark the sense of the meridional flow at the surface.

Marshall and Plumb (2008)

The general circulation of the atmosphere

The general circulation describes the total of all large-scale air movements on earth.

General circulation = horizontal circulation + vertical circulation

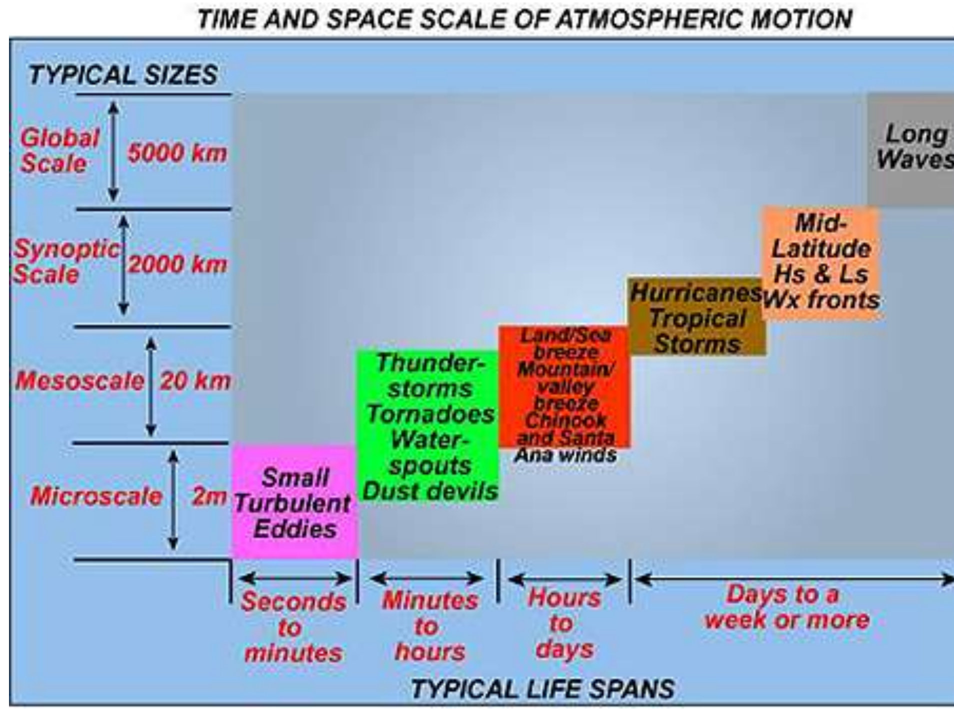
Atmospheric circulation – scales

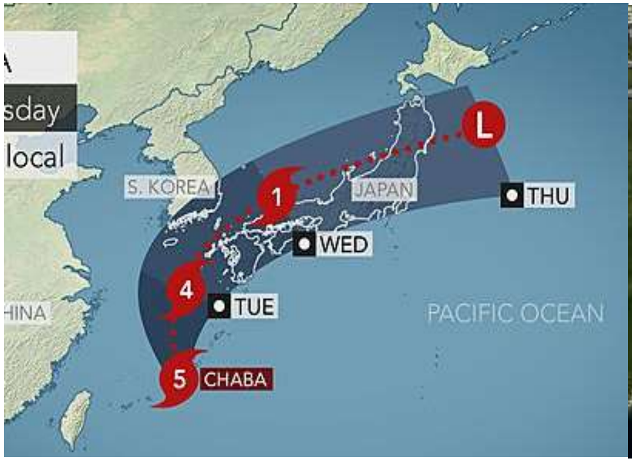
Microscale
- Size: meters
- Time: seconds

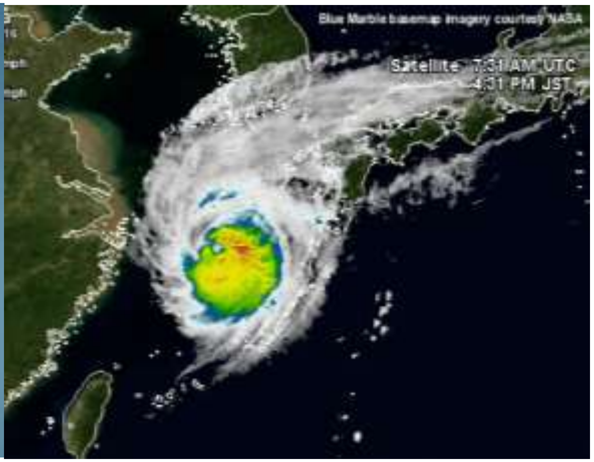
Mesoscale
- Size: kilometres
- Time: minutes to hours

Macroscale Synoptic
- Size: 100s to 1000s kilometres
- Time: days

Global (planetary)
- Size: Global
- Time: Days to weeks

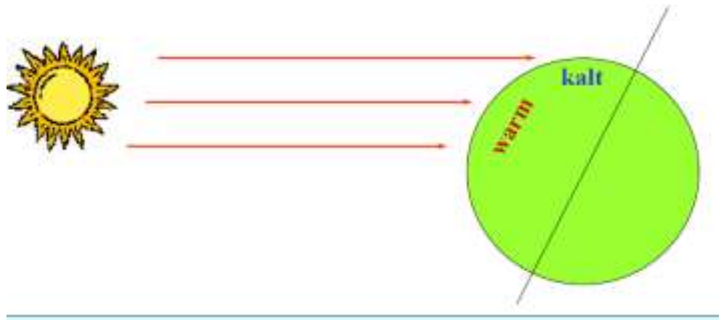




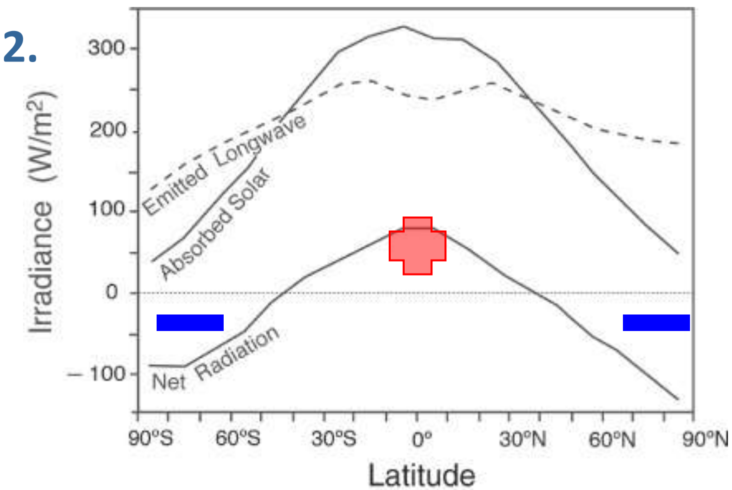


Super typhoon Chaba 04.10.16

1.

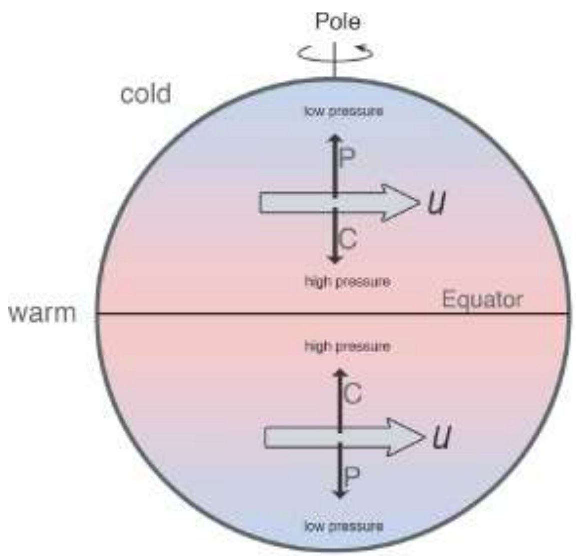


2.



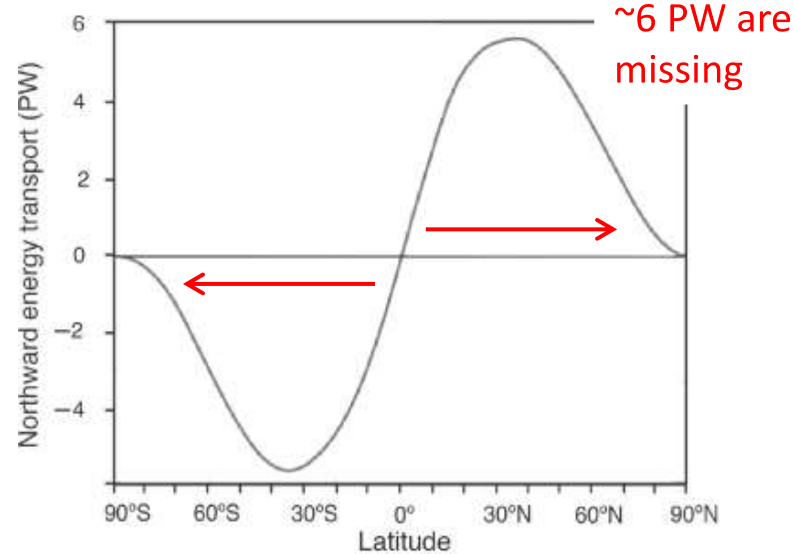
Surplus of radiation balance in the tropics and deficit in the polar regions!

3.



Horizontal temperature gradient > by hydrostatic balance > horizontal pressure gradient "P" balanced by Coriolis force "C" > geostrophic balance> westerly wind (*U*>0)

4.



Poleward energy transport

Marshall and Plumb (2008)

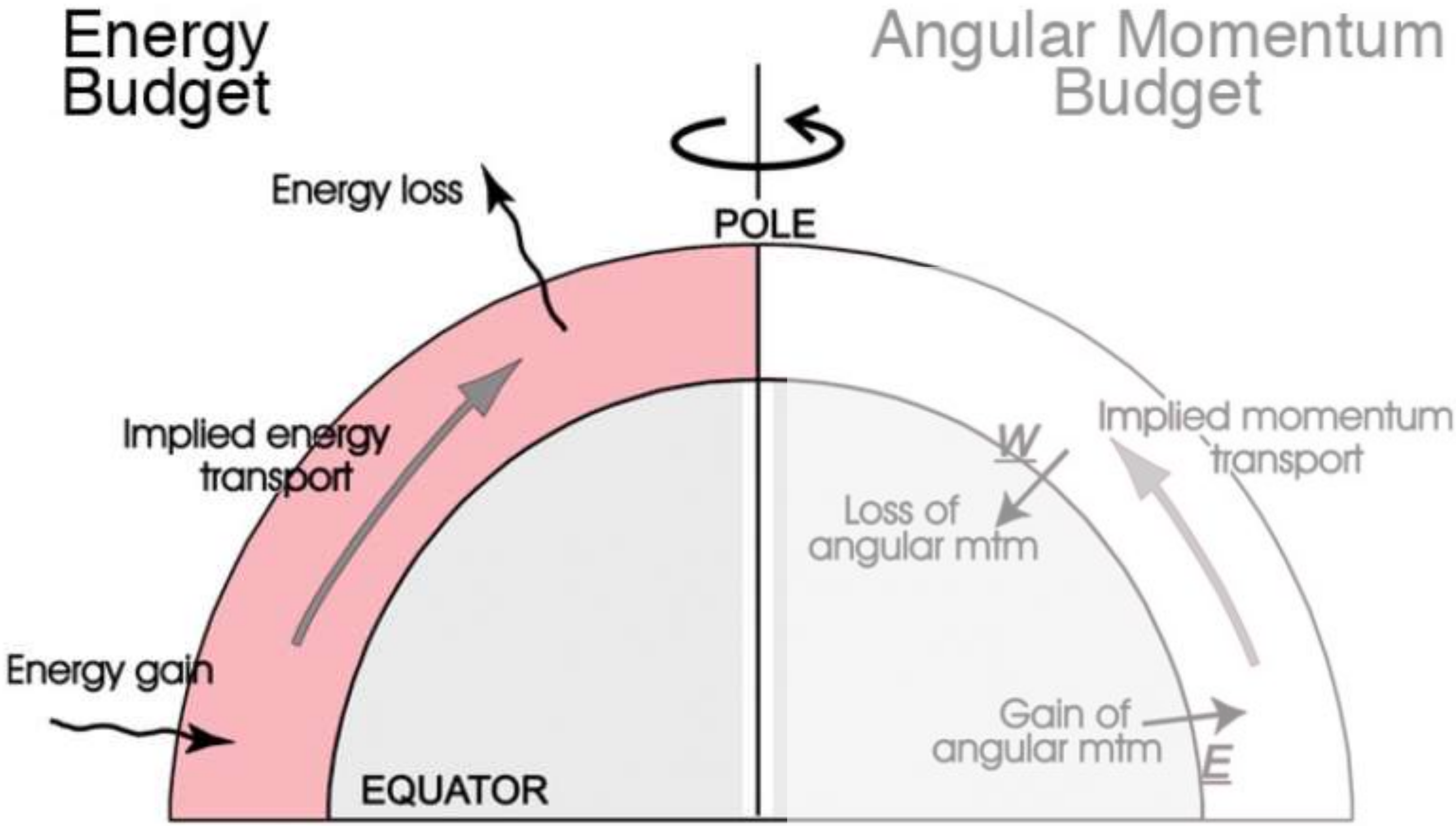
Kinetic energy of the atmosphere – general circulation

The **horizontal difference in temperature** between the tropical heat- excessive areas and the polar heat-deficient areas are directly or indirectly responsible for **98% of the atmospheric kinetic energy**.

The **horizontal wind field** of the synoptic disturbances and the **eddies** contain the **largest part of this kinetic energy.**

The air movements triggered by **convective activity** (Chapter 4) supply the remaining share of the atmospheric energy (2%).

Energy and angular momentum budget



Marshall and Plumb (2008)

Figure 8.1: Latitudinal transport of (left) energy and (right) angular momentum (mtm) implied by the observed state of the atmosphere. In the energy budget there is a net radiative gain in the tropics and a net loss at high latitudes; to balance the energy budget at each latitude, a poleward energy flux is implied. In the angular momentum budget the atmosphere gains angular momentum in low latitudes (where the surface winds are easterly) and loses it in middle latitudes (where the surface winds are westerly). A poleward atmospheric flux of angular momentum is thus implied.

General circulation of the atmosphere (GCA)

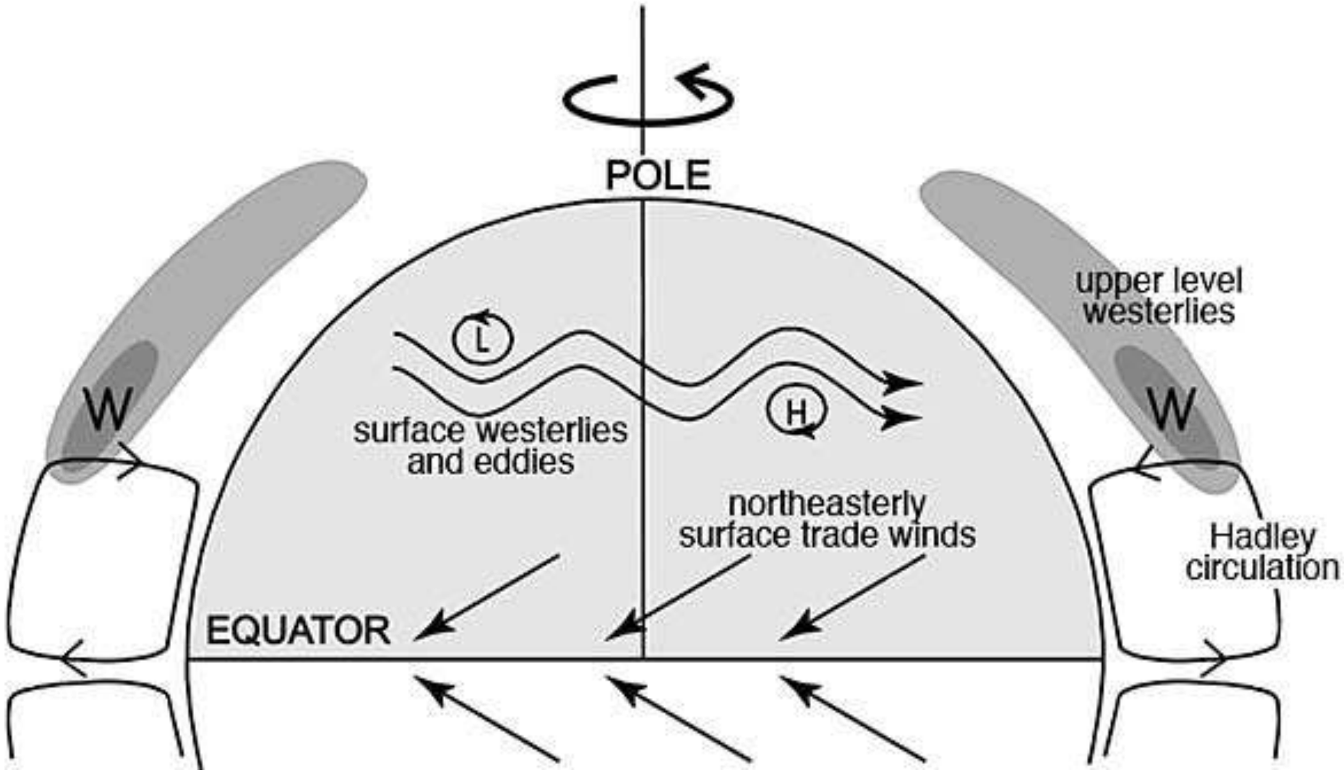


Figure 8.2: Schematic of the observed atmospheric general circulation for annual-averaged conditions. The upper level westerlies are shaded to reveal the core of the subtropical jet stream on the poleward flank of the Hadley circulation. The surface westerlies and surface trade winds are also marked, as are the highs and lows of middle latitudes. Only the northern hemisphere is shown. The vertical scale is greatly exaggerated.

Marshall and Plumb (2008)

GCA – horizontal and vertical flow

Polar High
circumpolar easterlies

subpolar low pressure channel

Polar front
Westerly wind drift

subtropical high pressure zone

northeastern trades

intertropical convergence
equatorial counter flow

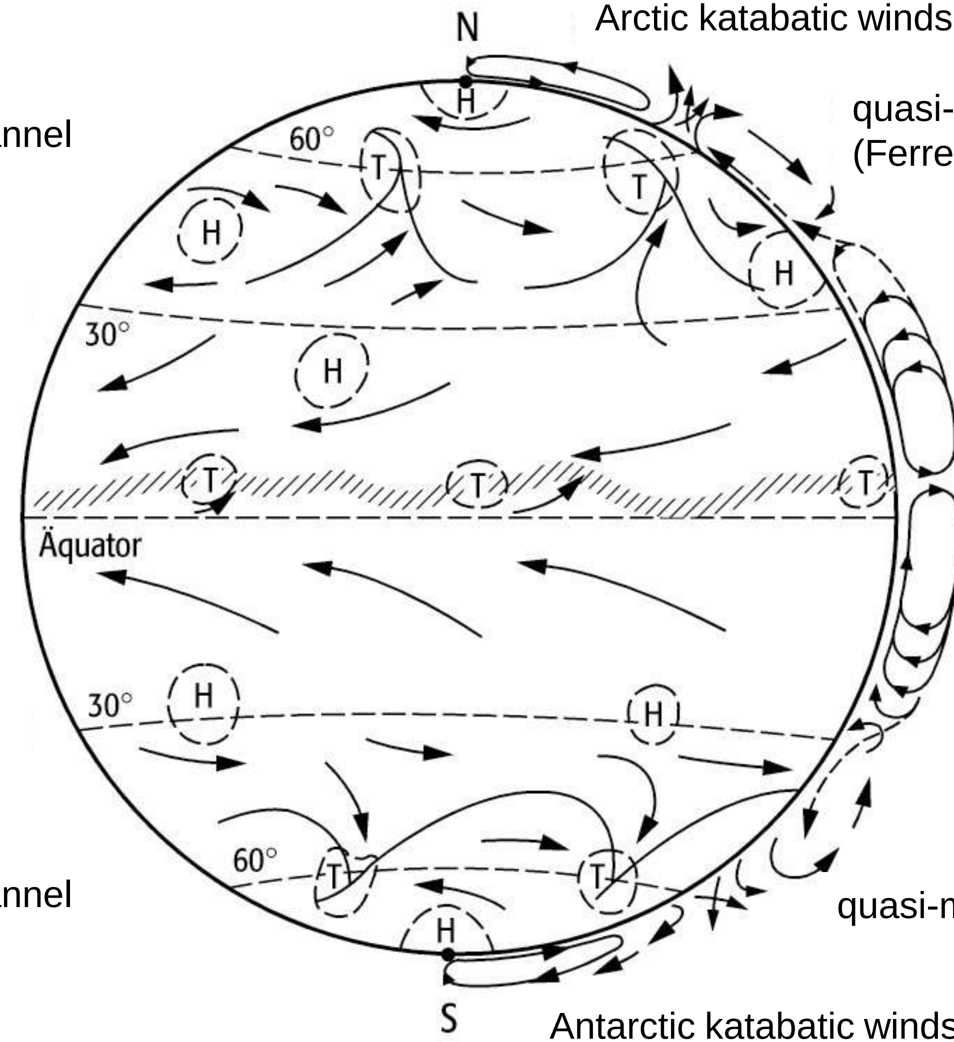
southeastern trades

subtropical high pressure zone

Polar front
Westerly wind drift

subpolar low pressure channel

Polar High
circumpolar easterlies



Arctic katabatic winds

quasi-meridional circulation (Ferrel cell)

northern Hadley cell

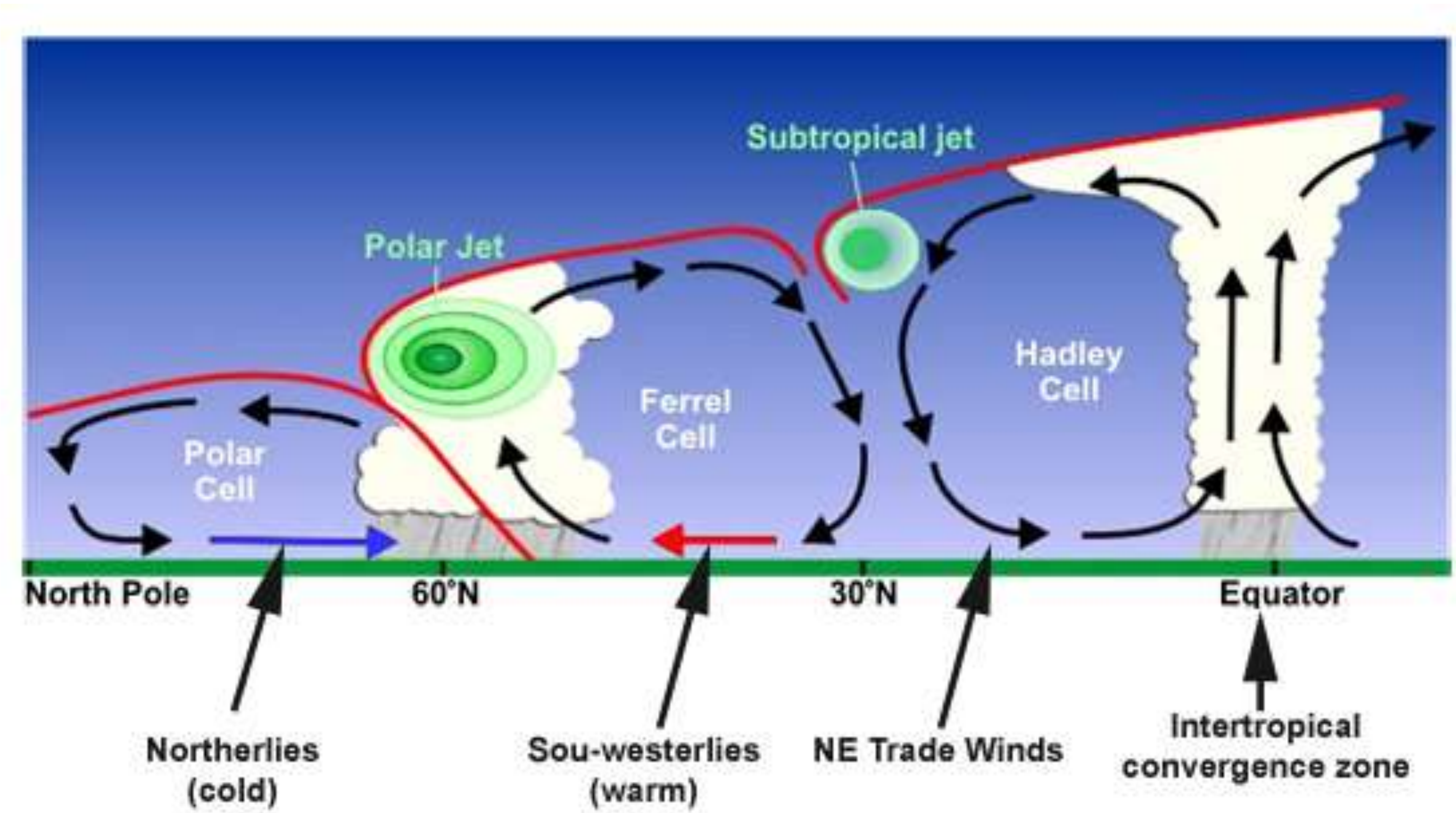
southern Hadley cell

quasi-meridional circulation

Antarctic katabatic winds

T:= **L**ow pressure; **H**igh pressure

GCA: vertical-meridional flow

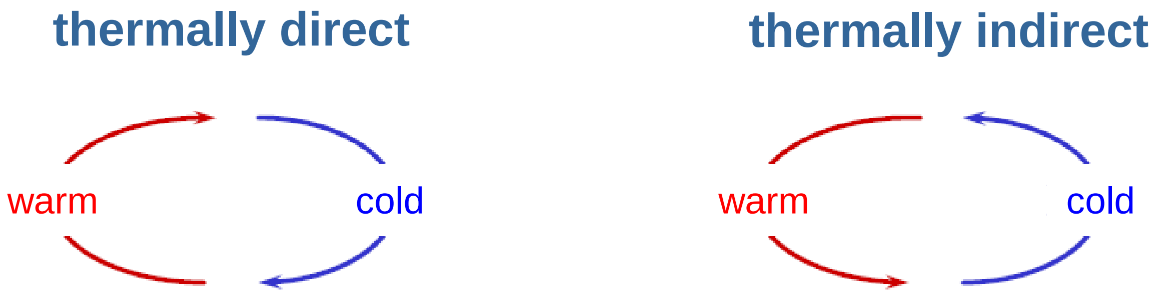


www.enso.info

Thermal direct circulation

Thermally direct circulation: a circulation, in which warm air rises and cold air sinks, with available potential energy transforming into kinetic energy.

Thermally indirect circulation: opposite case.



Note: The **Hadley circulation** in the tropics is **thermally direct**.
The **Ferrel circulation (**middle latitudes) is **thermally indirect**.

Recap see also Ch. 5

Hadley circulation - summary

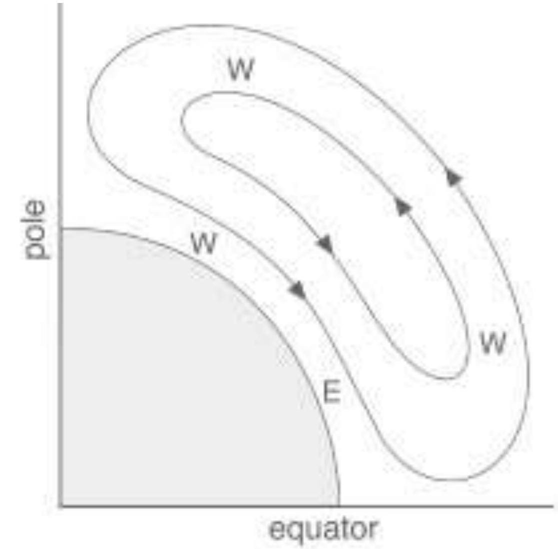


Figure 5.19: The circulation envisaged by Hadley (1735) comprising one giant meridional cell stretching from equator to pole. Regions where Hadley hypothesized westerly (W) and easterly (E) winds are marked.

History: Hadley suggested one meridional cell with rising in the tropics and descend over the Pole, the Hadley Cell, in 1735.

- Circulation symmetrical to the equator,

- **meridional overturning circulation in the tropics,**

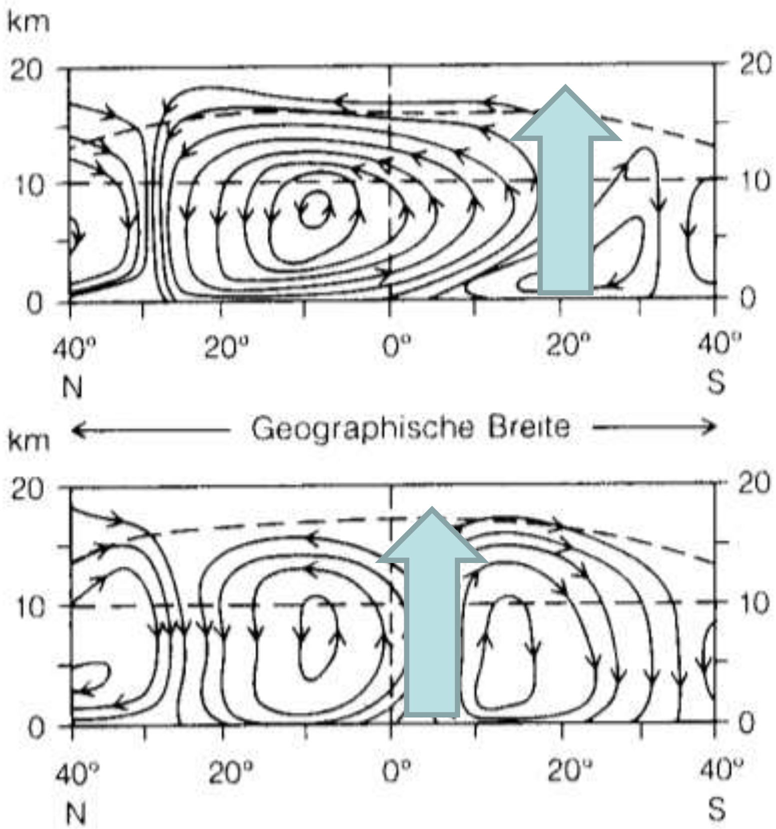
- zonal components (**easterlies** in the **lower troposphere**, **westerlies** in the **upper troposphere**) due to the earth's rotation,

- large regionally and seasonally variations.

Recap see also Ch. 5

Hadley cell’s seasonal cycle

(see also Fig. 5.21)

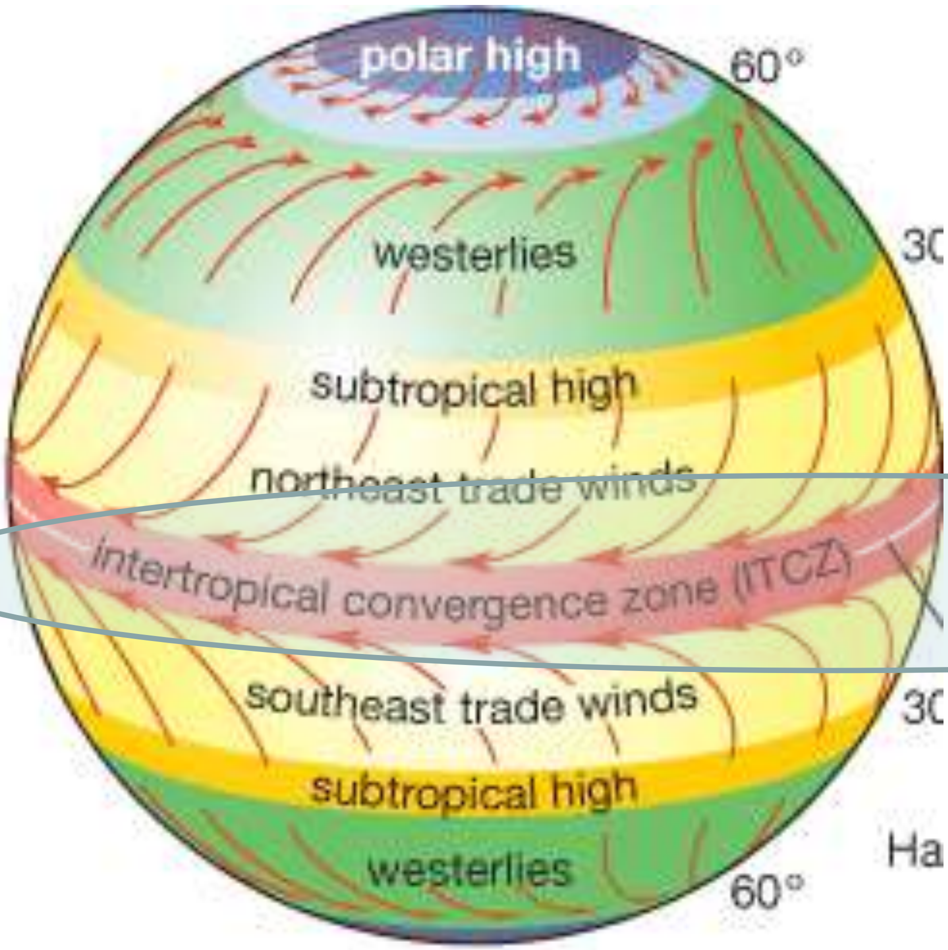


Northern winter/
Southern summer

Northern spring
(Mar-May)

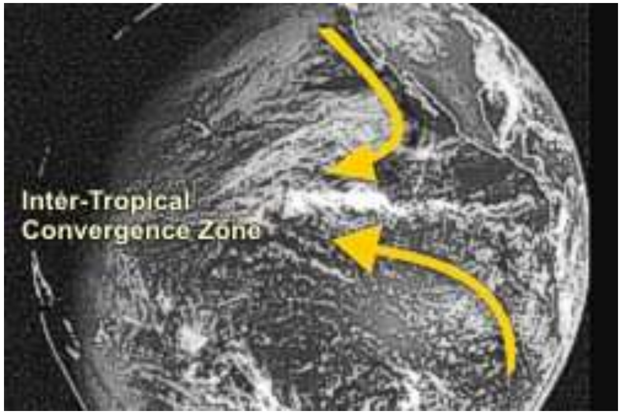
Roedel, 1997

ITCZ: InterTropical Convergence Zone



ITCZ:
Intertropical **C**onvergence **Z**one

Development of the ITCZ
thermally induced in the tropics



The area of the **ITCZ lies in a band of warm sea water and the equatorial dry zone**, a narrow band where **cold upwelling water** from deeper layers in the ocean reaches the surface.

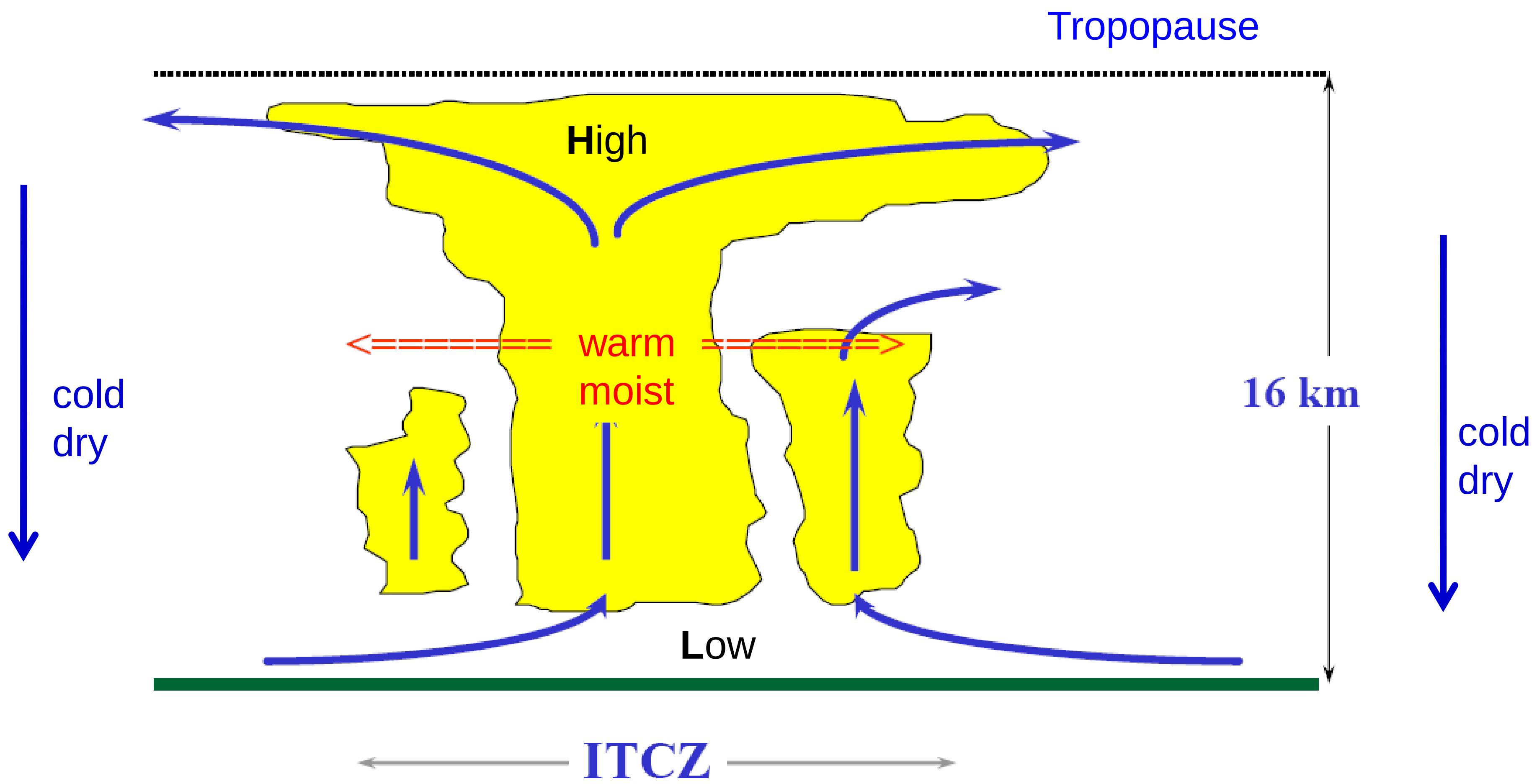
Land masses on the respective **summer hemisphere are warmer** than the adjacent **oceans**. In winter the land masses are colder than the ocean.

The **climatological precipitation and vertical movements** in the atmosphere are closely linked.

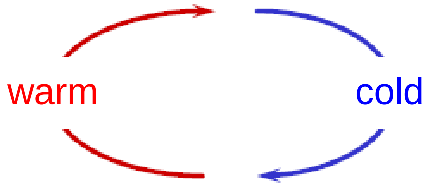
On average over a longer time period **air rises over moisture areas and sinks over dry areas**.

Circulation patterns in the tropics are in the mean characterized by ascending warm air and descending cold air, which means it is **primarily a thermally driven circulation**.

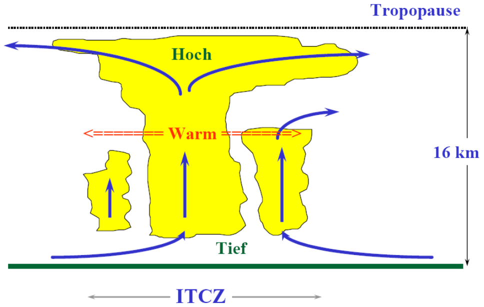
ITCZ



thermally direct cell



ITCZ – Summary



For the **ascending branch**, in which clouds and precipitation form, the following **applies**:

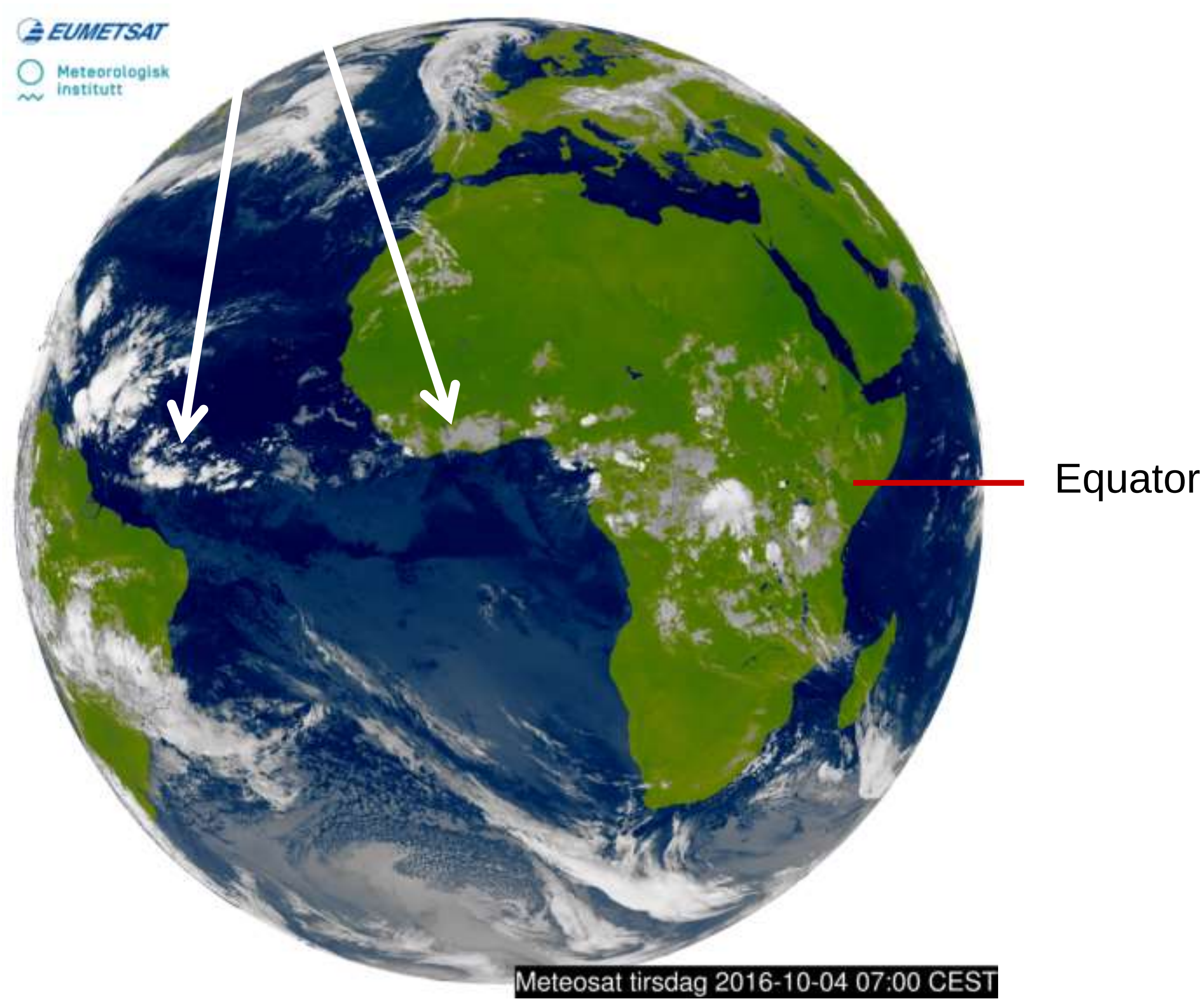
1. In nearly the entire troposphere, the **temperatures** are **higher than in** the **surroundings**.

2. A weak **low** is located **in** the **lower troposphere** (cyclonic flow), a weak **high in** the **upper troposphere** (anticyclonic flow).

3. The **mass flow** is directed **upwards**, with a maximum in the central troposphere.

4. In the **lower troposphere** the **horizontal air** movements **converge**, in the **upper troposphere** they **diverge**.

ITCZ: October 04, 2016, 07:00 CEST

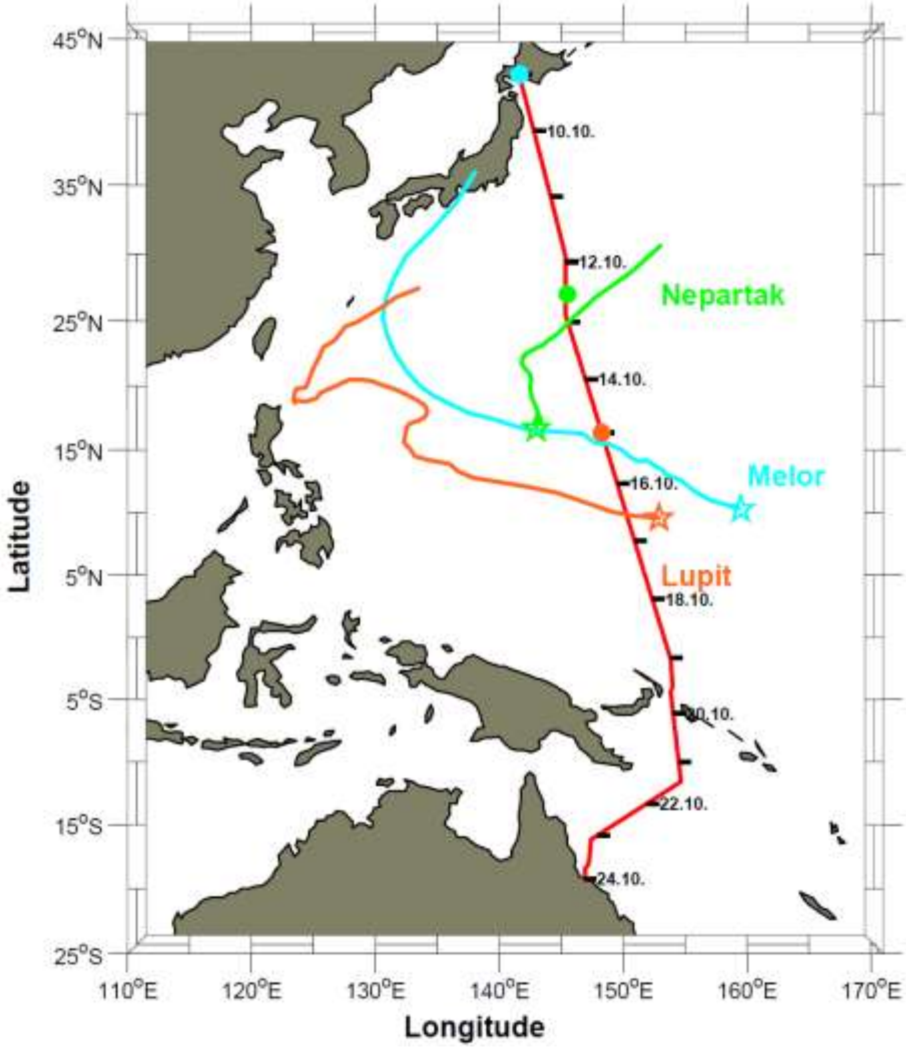


CEST: Central European Summer Time

www.yr.no/satellitt

TransBrom SONNE cruise Oct 2009

Cruise and tropical cyclones tracks

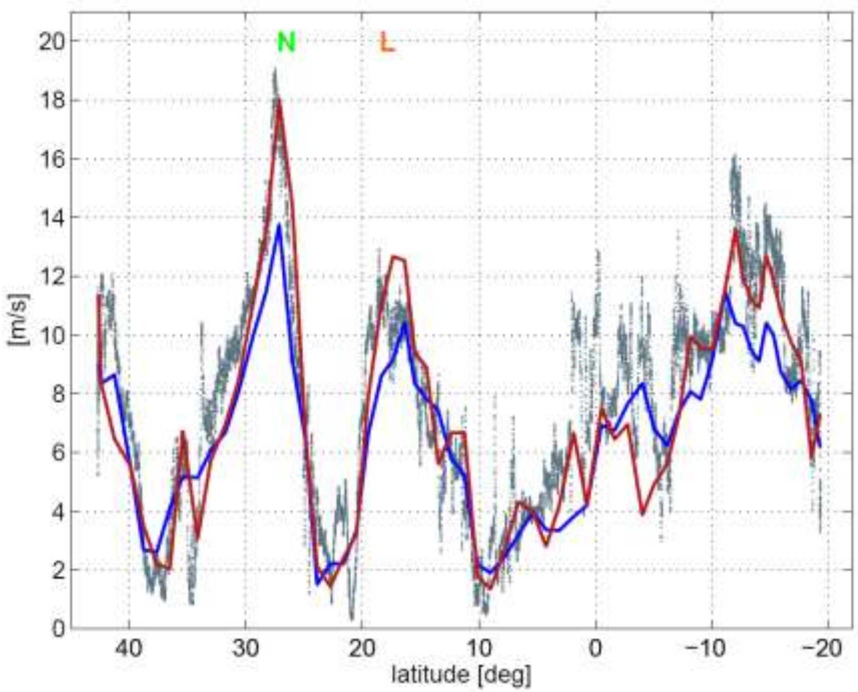


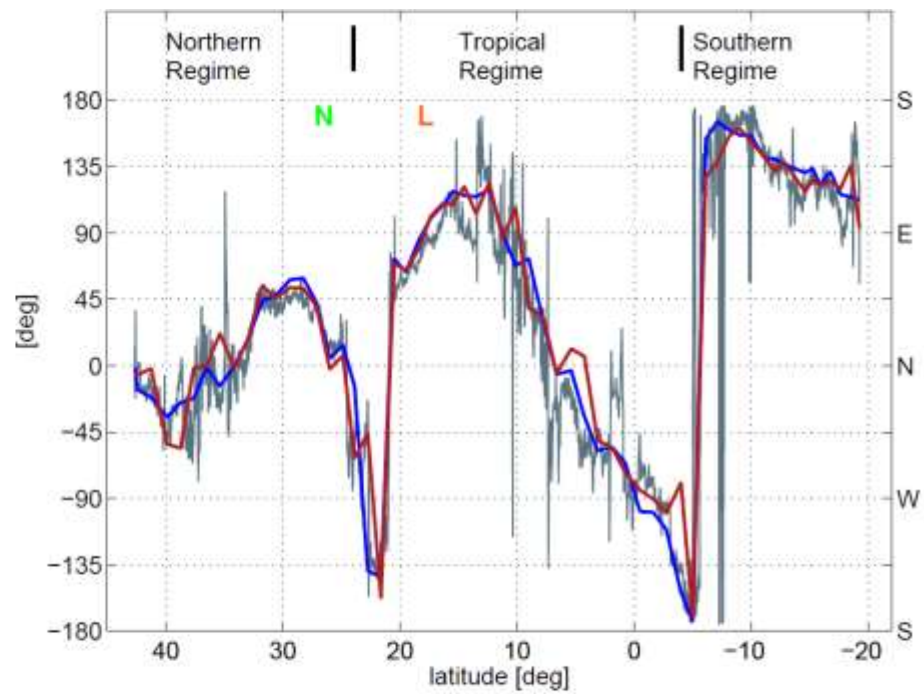
Melor

Krüger and Quack, 2013 ACP

TransBrom SONNE cruise Oct 2009

Average surface wind speed and direction



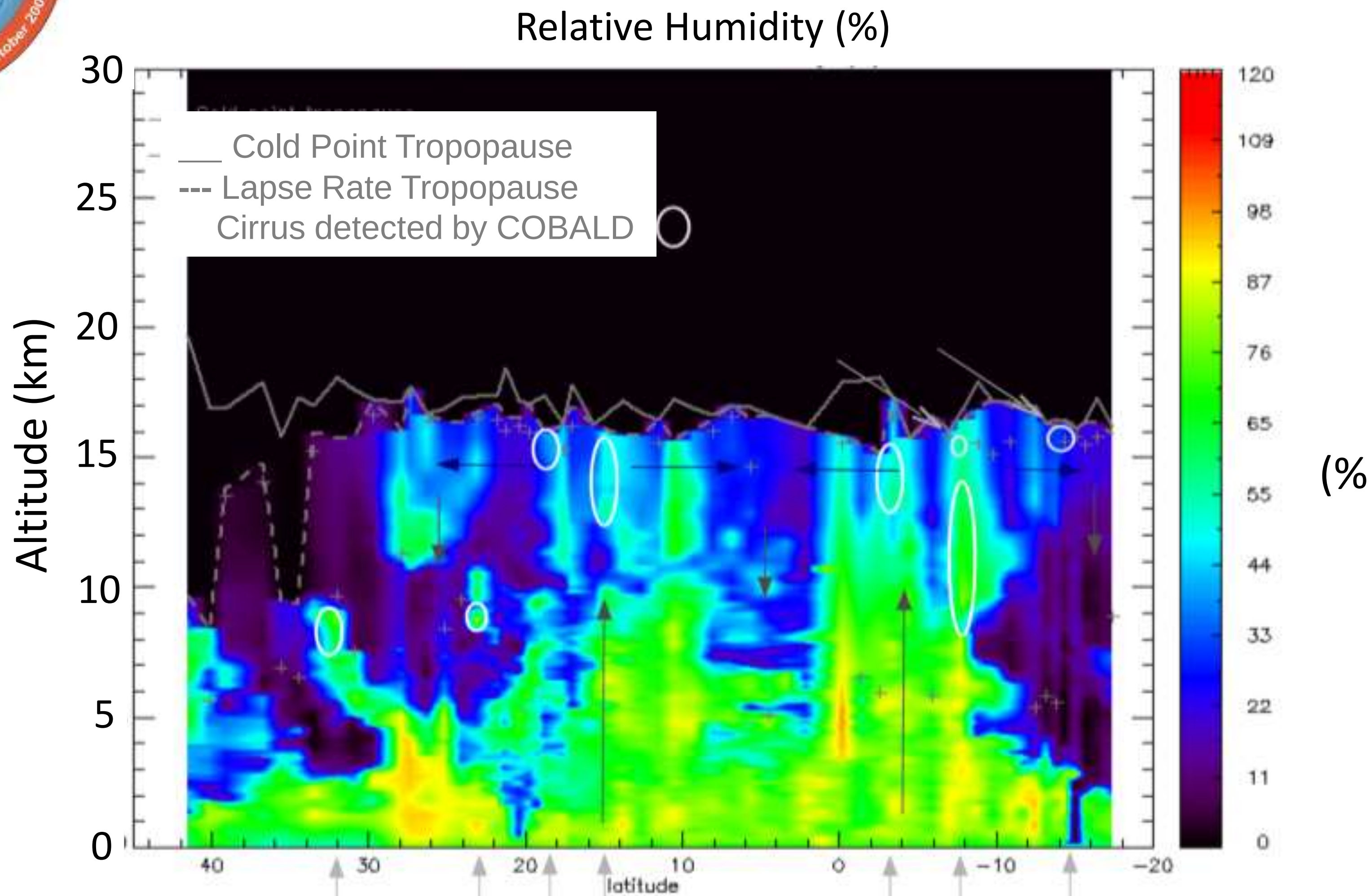


Tomakomai/Japan

Townsville/ Australia

Krüger and Quack, 2013 ACP

TransBrom SONNE cruise Oct 2009

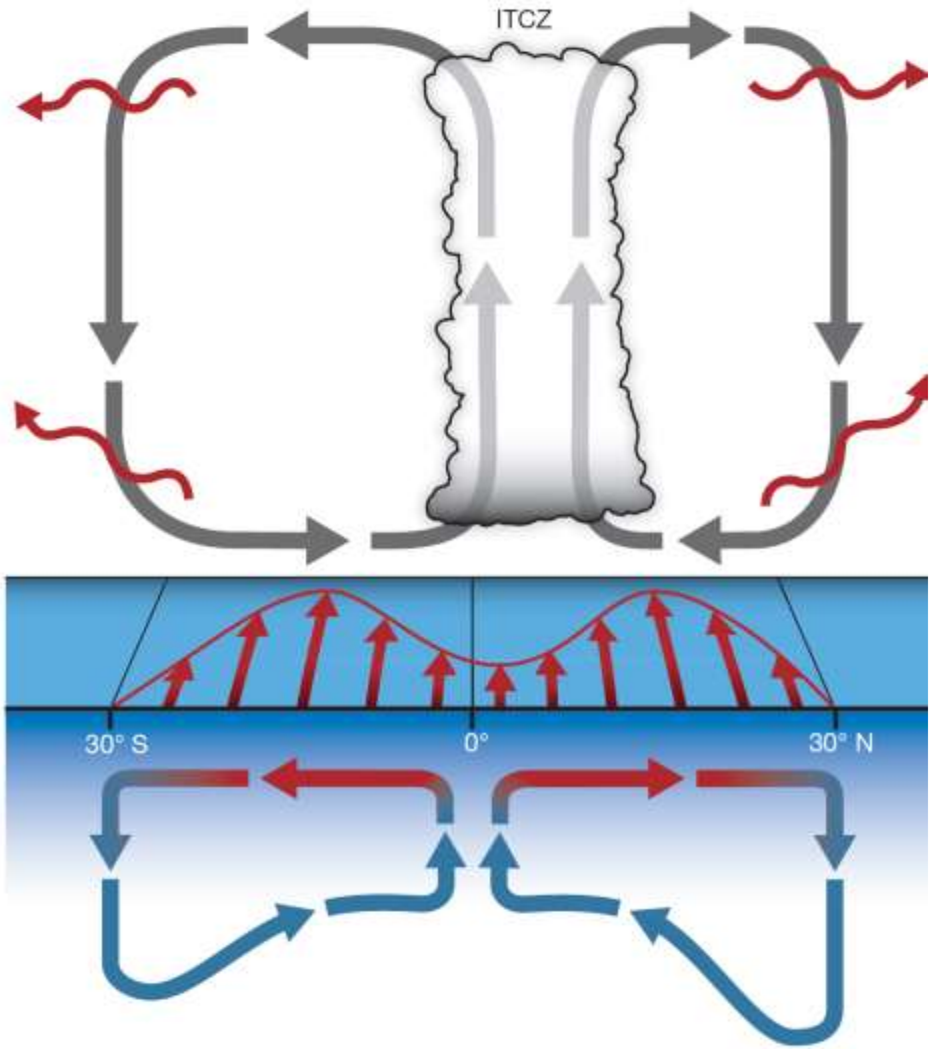


Tomakomai/Japan

Townsville/ Australia

In the tropical West Pacific a **double ITCZ** was observed.

ITCZ – Atmosphere-Ocean Interactions



Schneider et al (Nature, 2014)

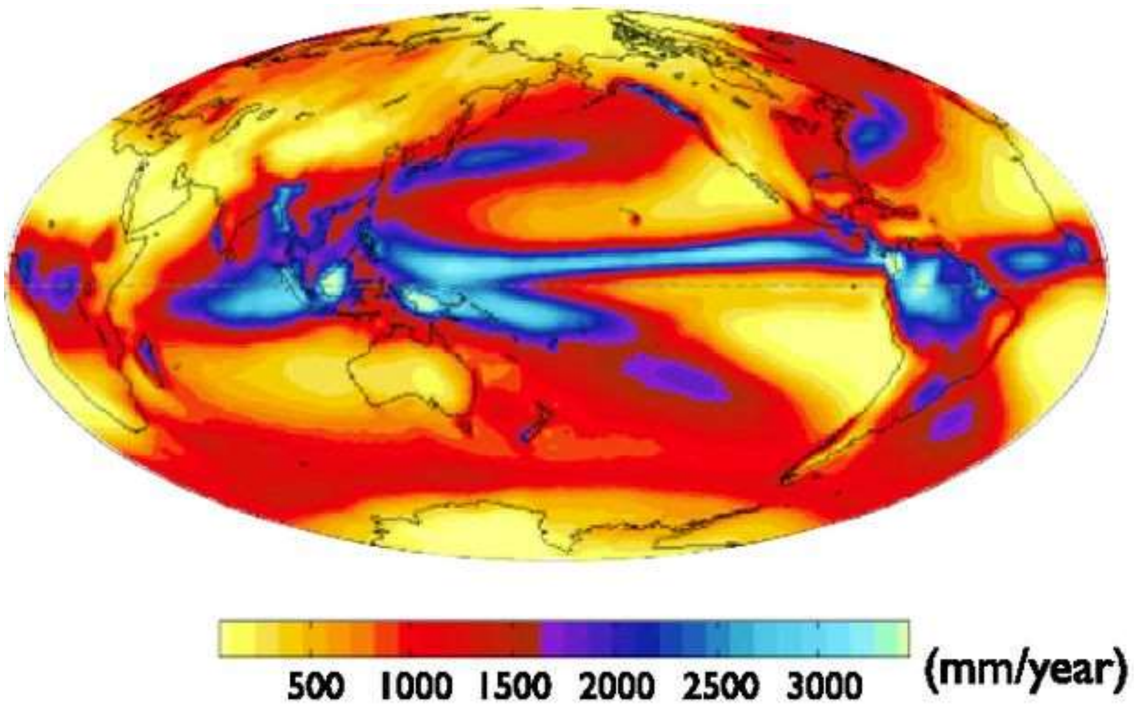
Atmospheric circulation
(Hadley circulation)

Energy flux (poleward)

Surface Easterly winds

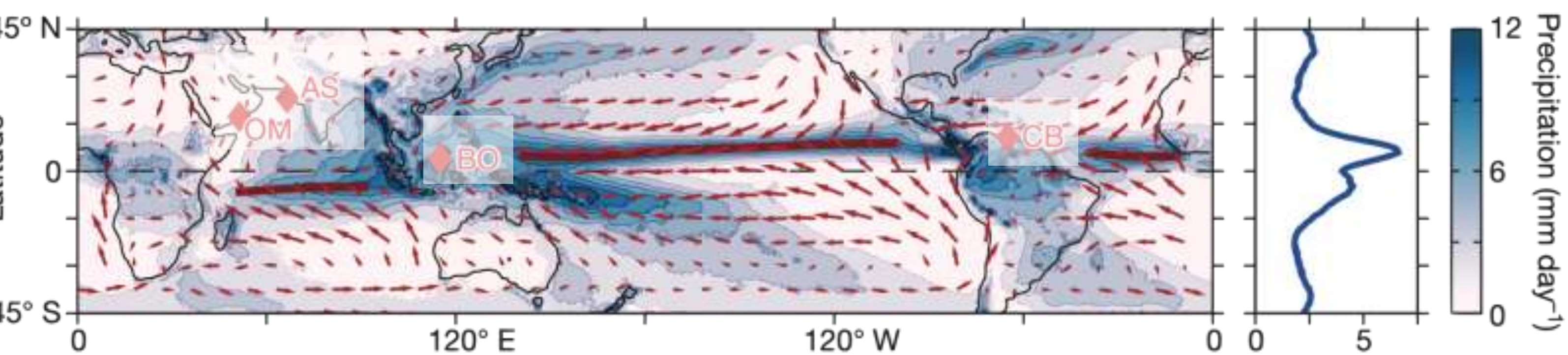
Ocean circulation (warm/cold)
Equatorial oceanic upwelling connected with the ITCZ.

ITCZ and precipitation: annual mean



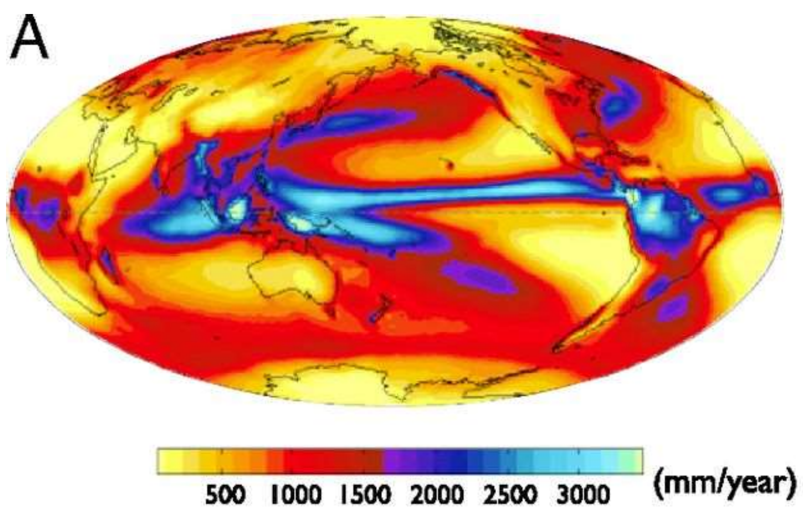
Upper figure: 1985–2004 Global Precipitation Climatology Project (Hwang and Frierson, 2013).

Lower figure: Tropical Rainfall Measuring Mission Multisatellite Precipitation Analysis for 1998–2012; and **surface wind** *are for ERA-I,* **position of the ITCZ** *(Schneider et al 2014).*

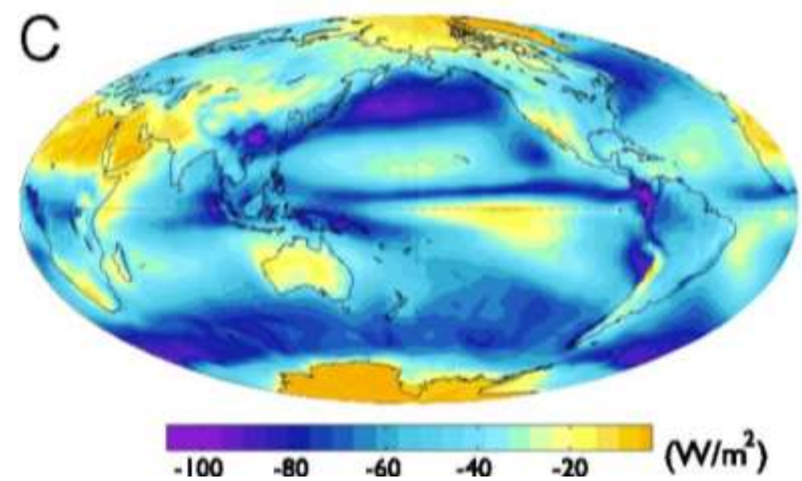


ITCZ – precipitation – radiation

Precipitation



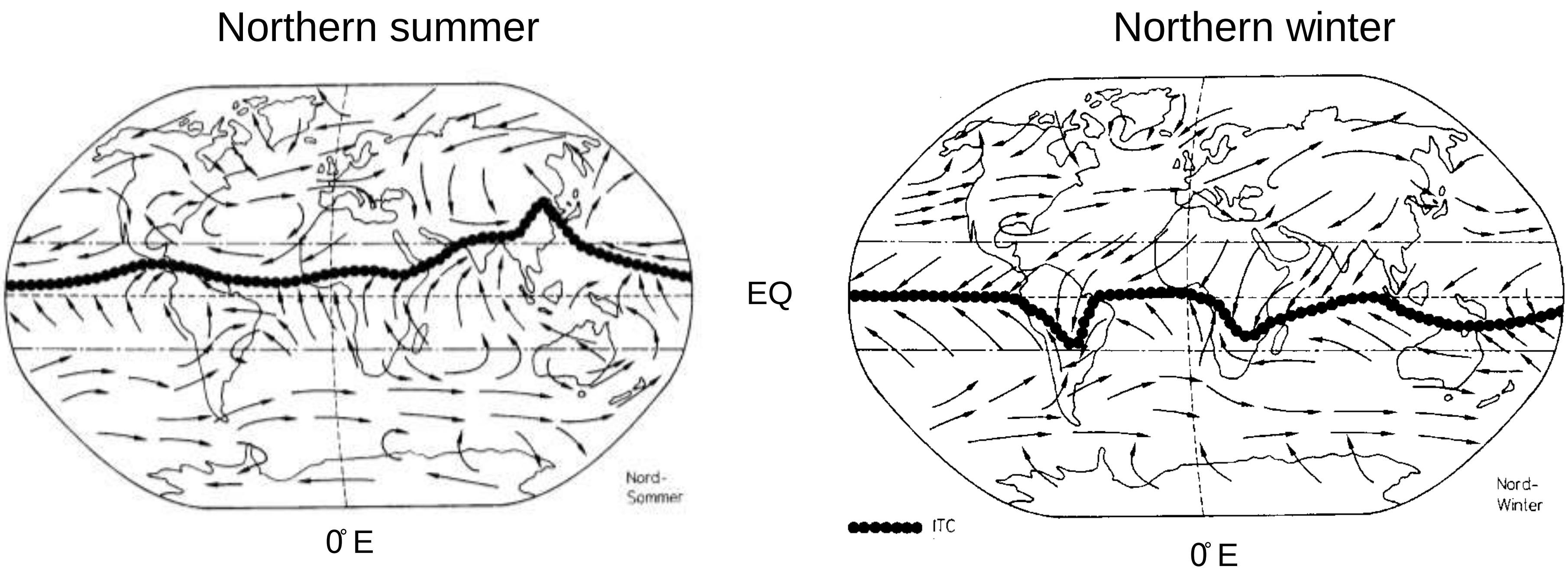
Short wave cloud radiative forcing



Annual mean precipitation, 1985–2004 from (*A*) the Global Precipitation Climatology Project (GPCP), version 2.1, (*C*) Shortwave cloud radiative forcing from satellite observations [Cloud and the Earth’s Radiant Energy System (CERES)], 2001–2010.

Hwang, and Frierson (*PNAS* 2013)

Seasonal course of ITCZ



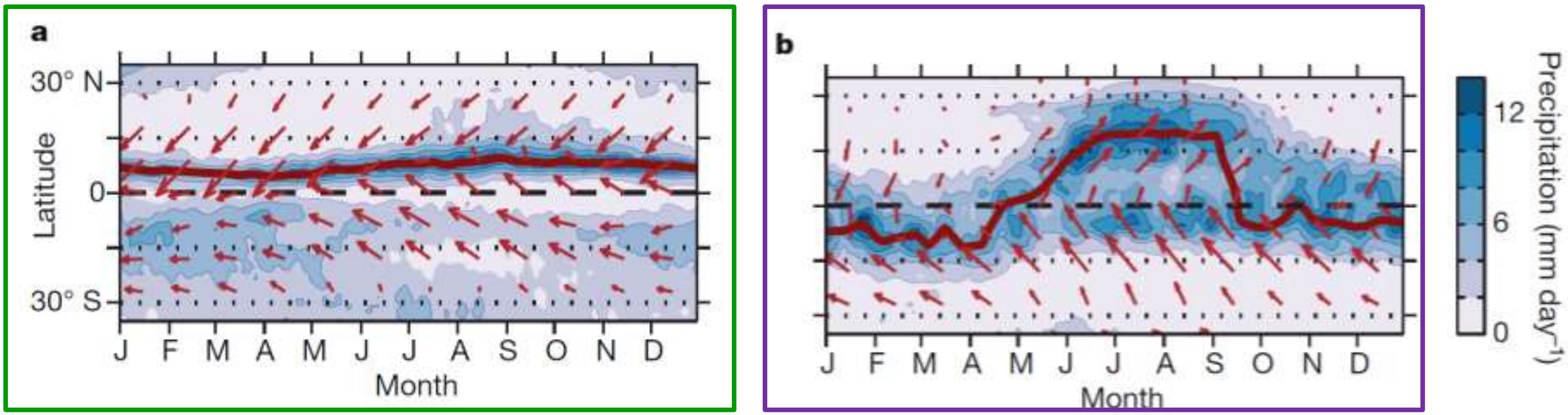
Roedel, 1997

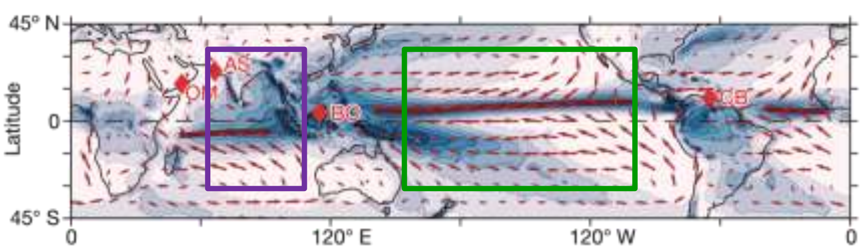
Figure: Surface winds and position of the ITCZ (after Lamb (1972) and Gross (1972)).

Seasonal migration of the ITCZ

Pacific(160˚E–100˚W)

Indian Ocean (65˚E–95˚E)





Precipitation

ITCZ

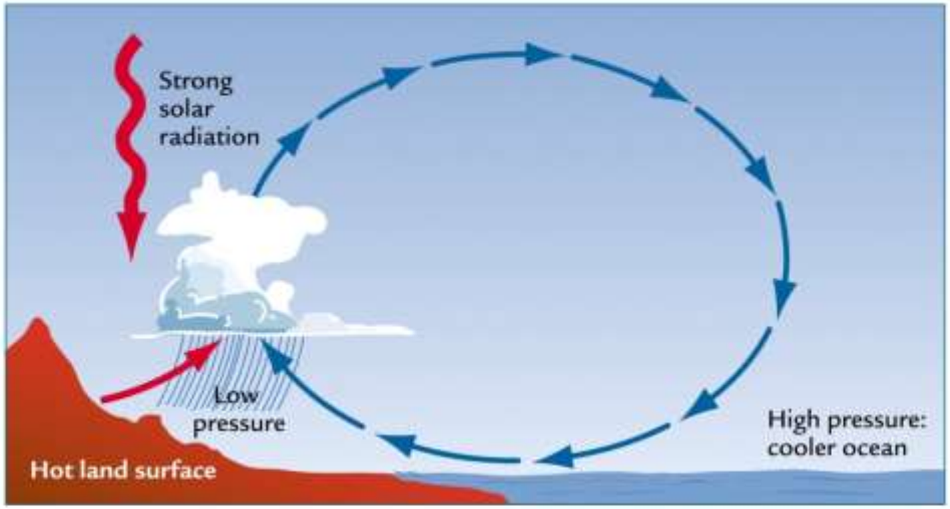
Surface winds

Schneider et al (Nature, 2014)

Monsoon circulation

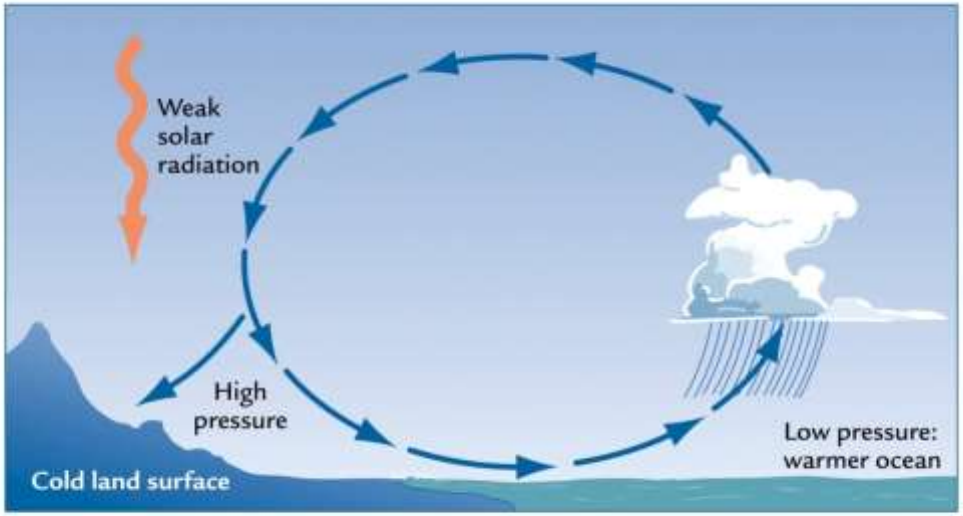
arabic ‘mawsim’ = season

Summer



A Summer monsoon

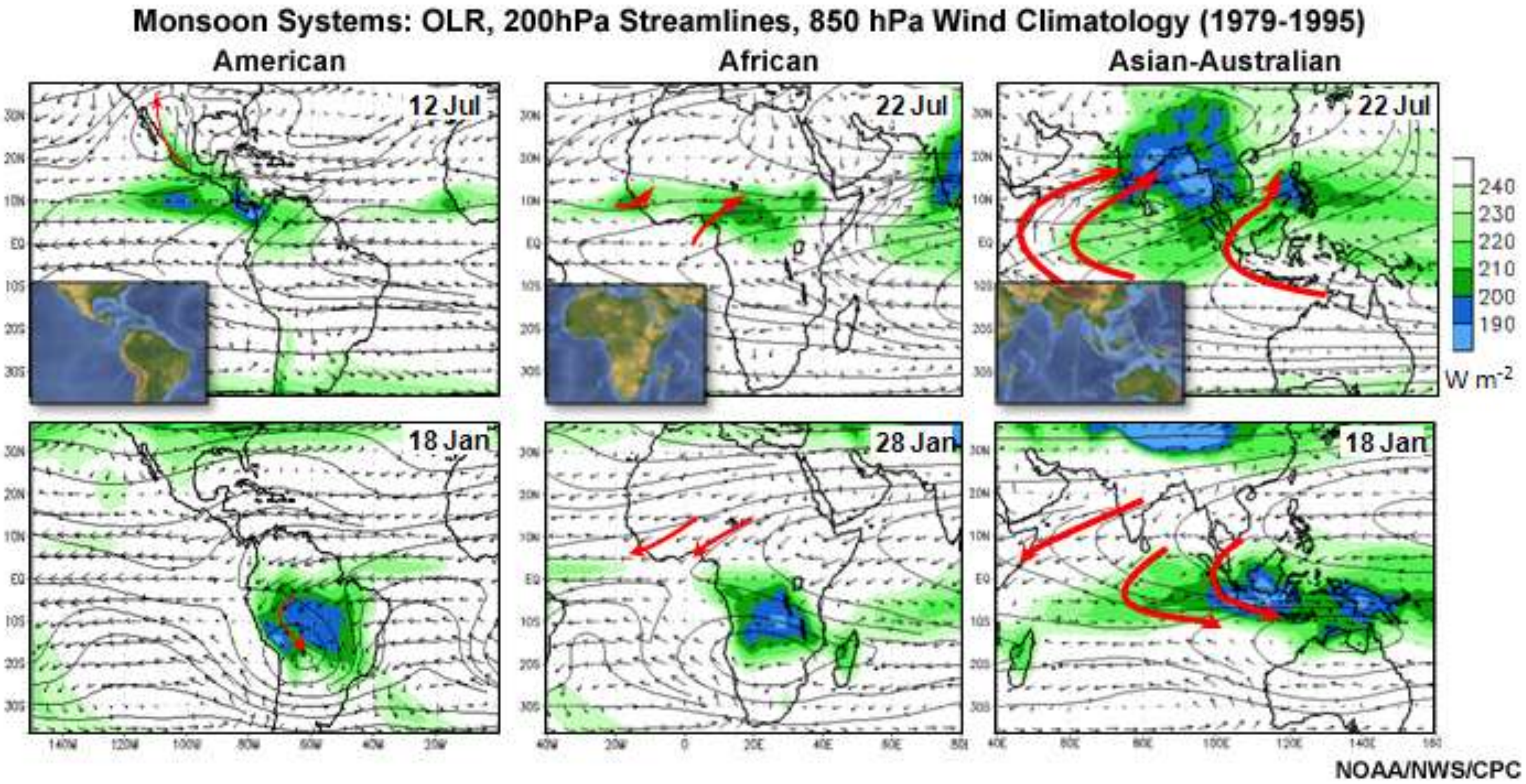
Winter



B Winter monsoon

Ruddiman, 2001

Monsoon systems

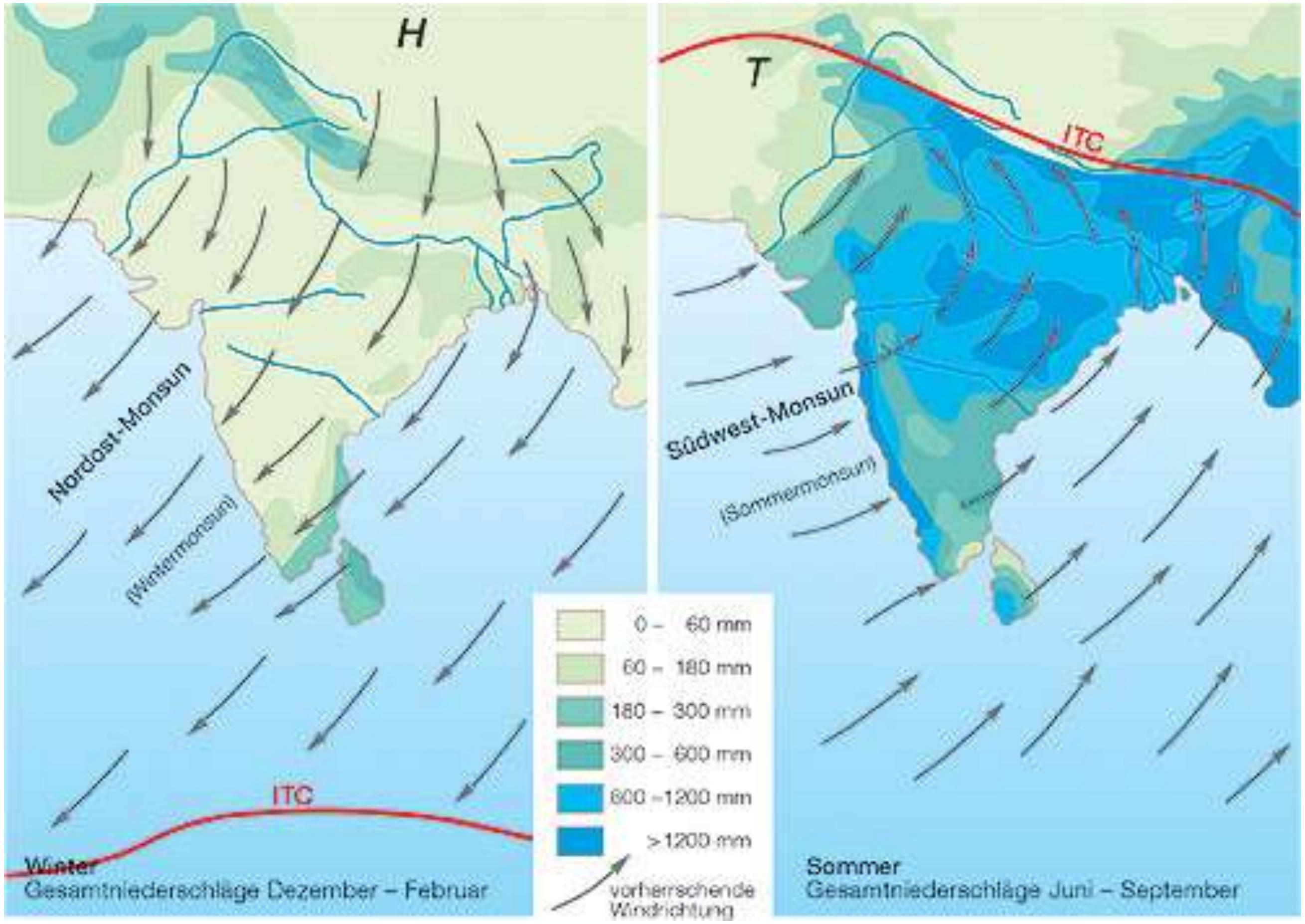


OLR:
Outgoing longwave radiation

www.meted.ucar.edu

Indian monsoon circulation

Seasonal variations and horizontal asymmetries



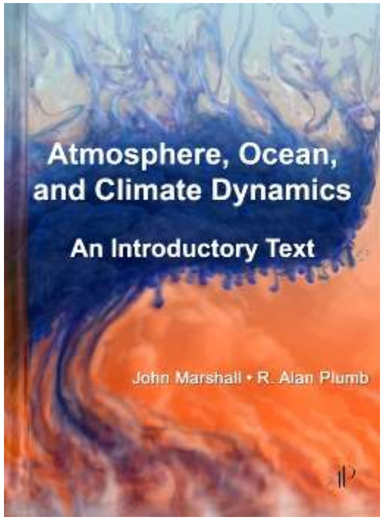
Take home message

- Energy and momentum budgets demands on the General Circulation of the Atmosphere.

- Observed atmospheric winds and major climate zones reveal distinct temporal and horizontal variations (i.e., Hadley cell, ITCZ, monsoon circulation).

GEF 1100 – Klimasystemet

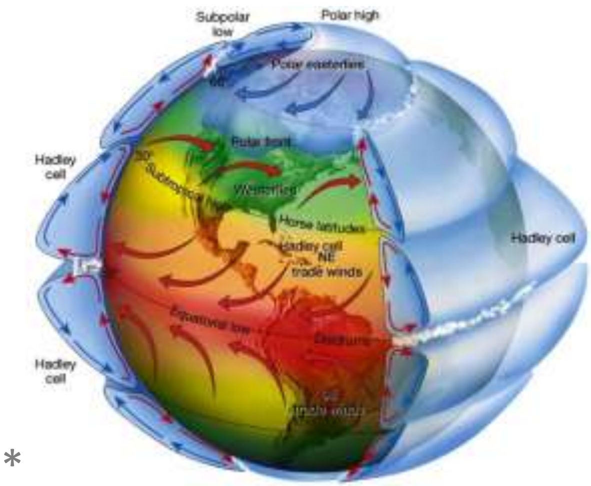
Chapter 8: The general circulation of the atmosphere



Prof. Dr. Kirstin Krüger (MetOs, UiO)

Lecture Outline – Ch. 8

Ch. 8 – The general circulation of the atmosphere (GCA)



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*Add-ons, not in book.

Can we explain the observed atmospheric circulation?

- Based on fluid dynamics,
- *simple* representation of the atmosphere,
- driven by latitudinal gradients in solar forcing?

Neglect:

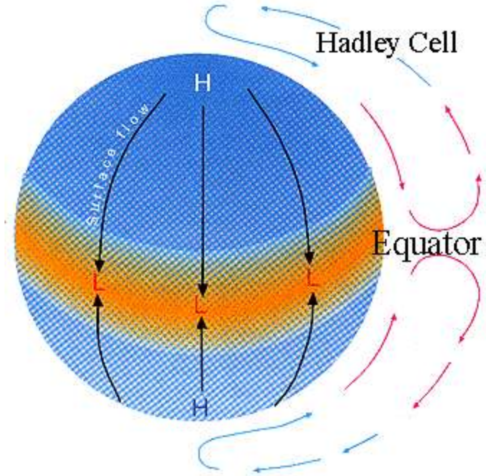
Temporal (seasons and diurnal variations) and surface (oceans, continents, mountains) variations.

Assume:

Atmosphere response to a **longitudinal uniform**, **rotating planet** (Earth) and to **latitudinal gradient of heating** (max at equator).

Effect of the rotating earth

- **If the earth didn't rotate, we would have a single-cell circulation** in each hemisphere.

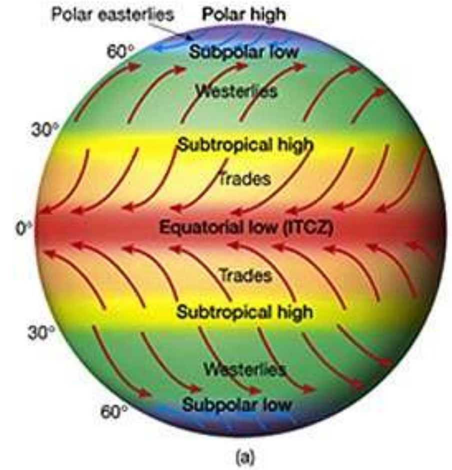


- But because in reality earth follows a movement on a rotating sphere, a three cell circulation in each hemisphere develops:

- Polar cell

- Ferrel cell

- Hadley cell



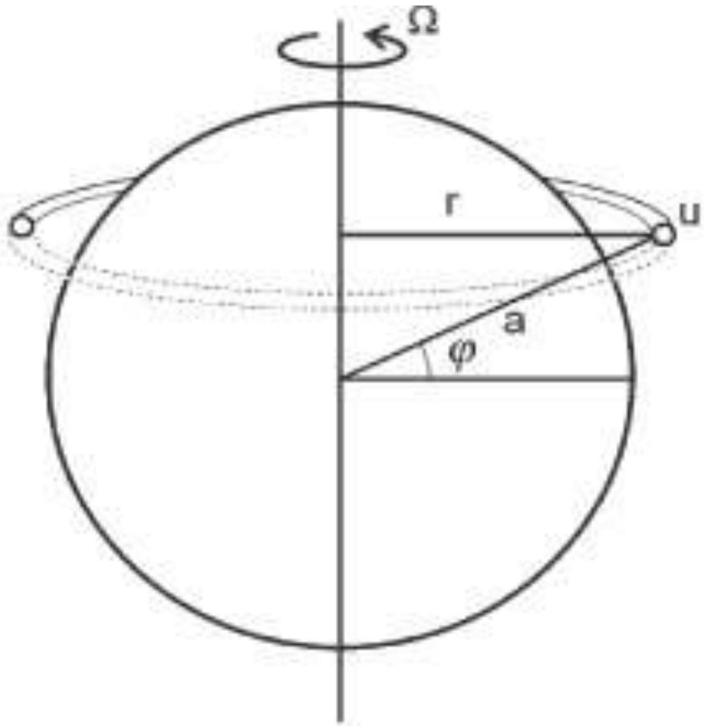
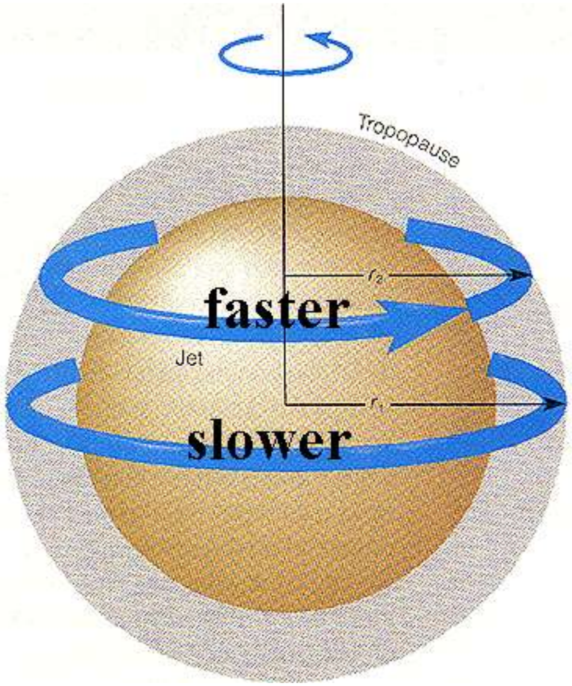


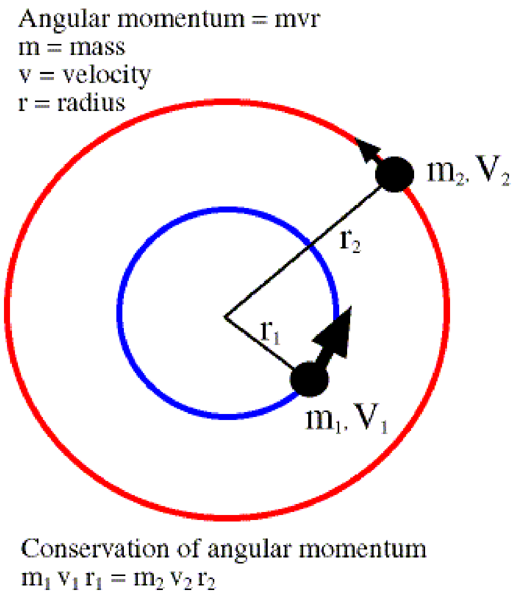
Figure 8.3: Schematic of a ring of air blowing west → east at speed u at latitude φ. The ring is assumed to be advected by the poleward flow of the Hadley circulation conserving angular momentum.

Marshall and Plumb (2008)

Subtropical jet

- develops because of the conservation of angular momentum





Hadley circulation - NH

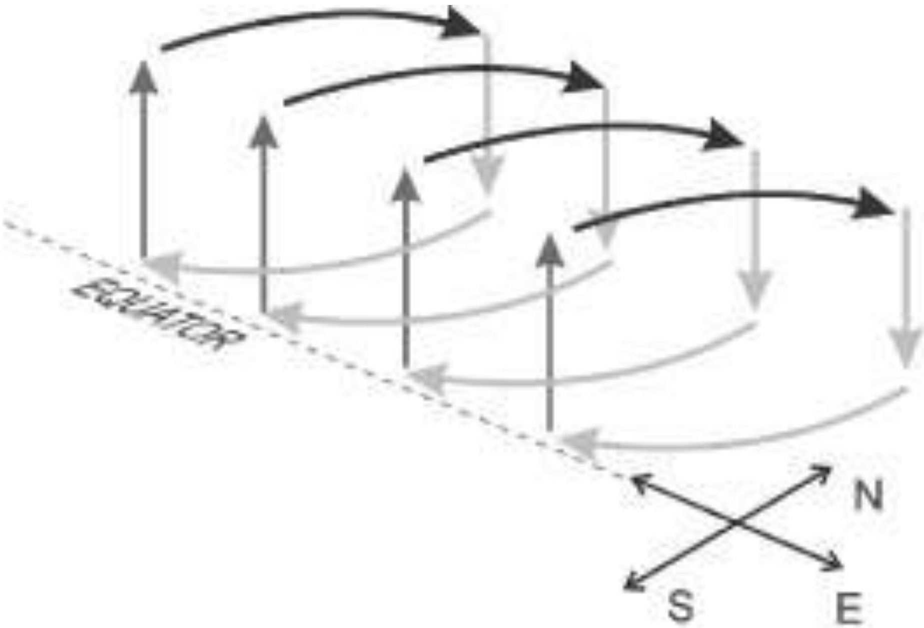
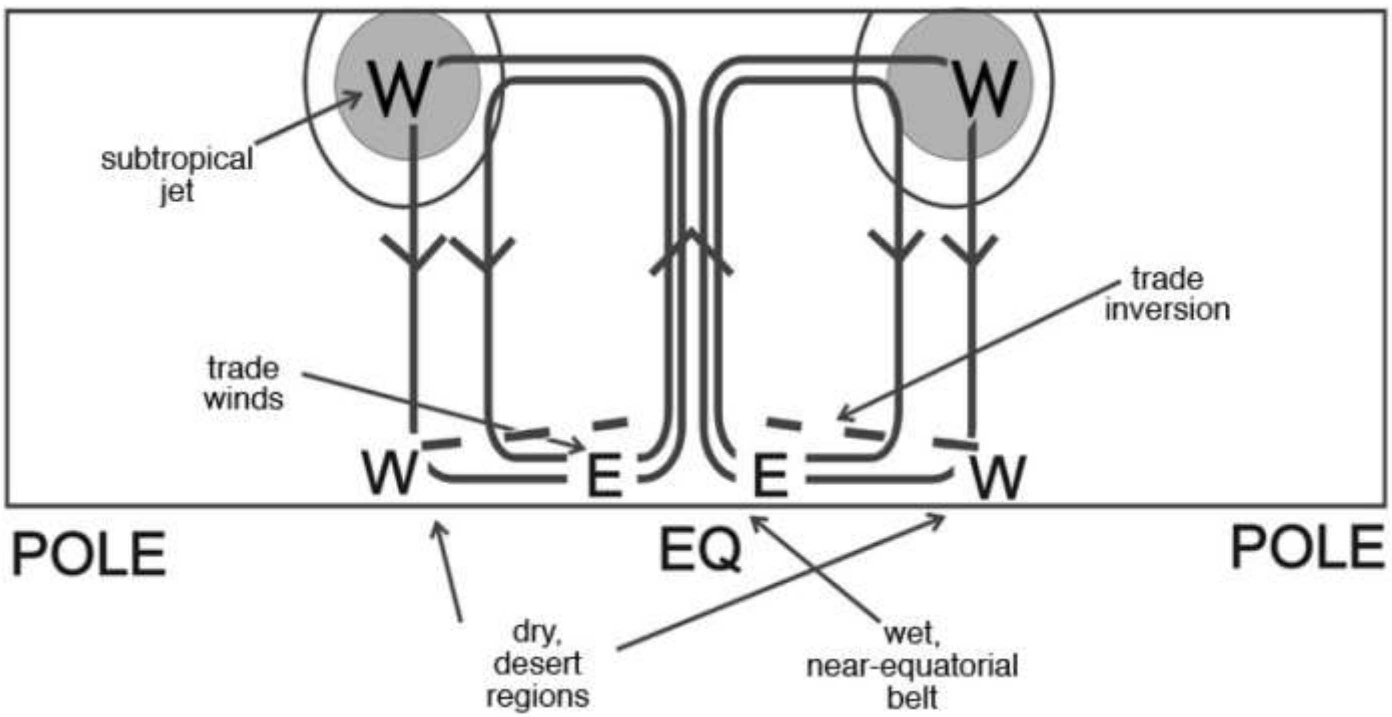


Figure 8.4: Schematic of the Hadley circulation (showing only the northern hemispheric part of the circulation; there is a mirror image circulation south of the equator). Upper level poleward flow induces westerlies; low level equator-ward flow induces easterlies.

Marshall and Plumb (2008)

Hadley circulation schematic



Marshall and Plumb, 2007

Extratropical circulation – Baroclinic instability

- Strong horizontal temperature gradient in mid-latitudes implies:

  - westerly wind increase with height (thermal wind balance Eq. 7-24)

  - pressure horizontal gradients and by geostrophic balance > **weak meridional circulation.**

But:

- Poleward heat transport required to balance energy budget, but how if Hadley Cell transport heat only up to subtropics?
- Daily observations tell us strong zonal asymmetries (low and high pressure systems)

  ⟶Thus the axisymmetric model can only partly be correct.

  ⟶Mid-latitudes is full of eddies (weather systems).

Extratropical circulation – Baroclinic instability

Break-down of thermal wind by baroclinic* instabilities:

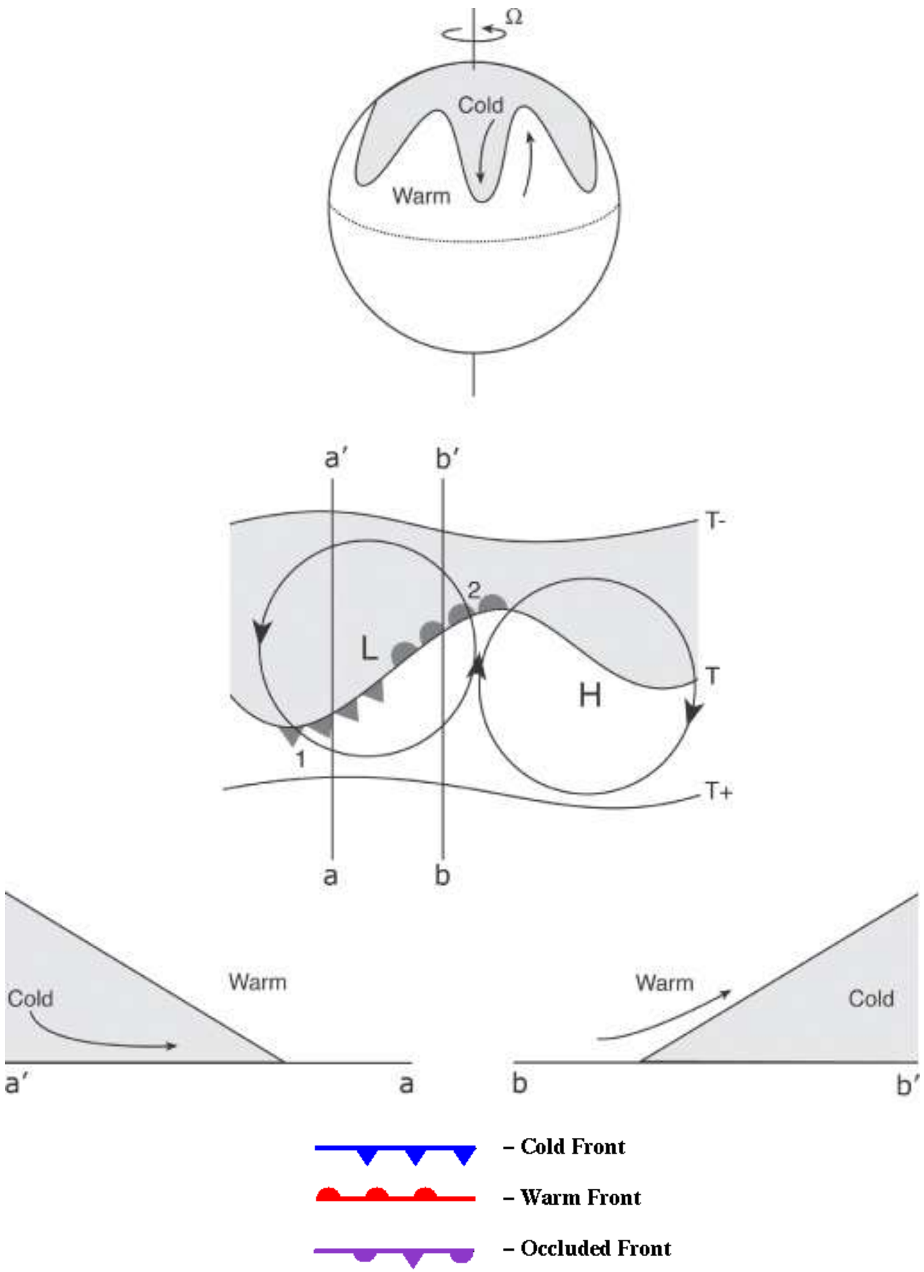
- Due to the faster rotation rate (greater *f*) in mid-latitudes *eddies (wave like structures)* develop.

Figure 8.7: Top: Baroclinic eddies in the "eddy" regime viewed from the side. Bottom: View from above. Eddies draw fluid from the periphery in toward the centre at point A and vice versa at point B. The eddies are created by the instability of the thermal wind induced by the radial temperature gradient due to the

Marshall and Plumb (2008)

Baroclinic flow: $\rho=\rho(p,T)$
Barotropic flow: $\rho=\rho(p)$

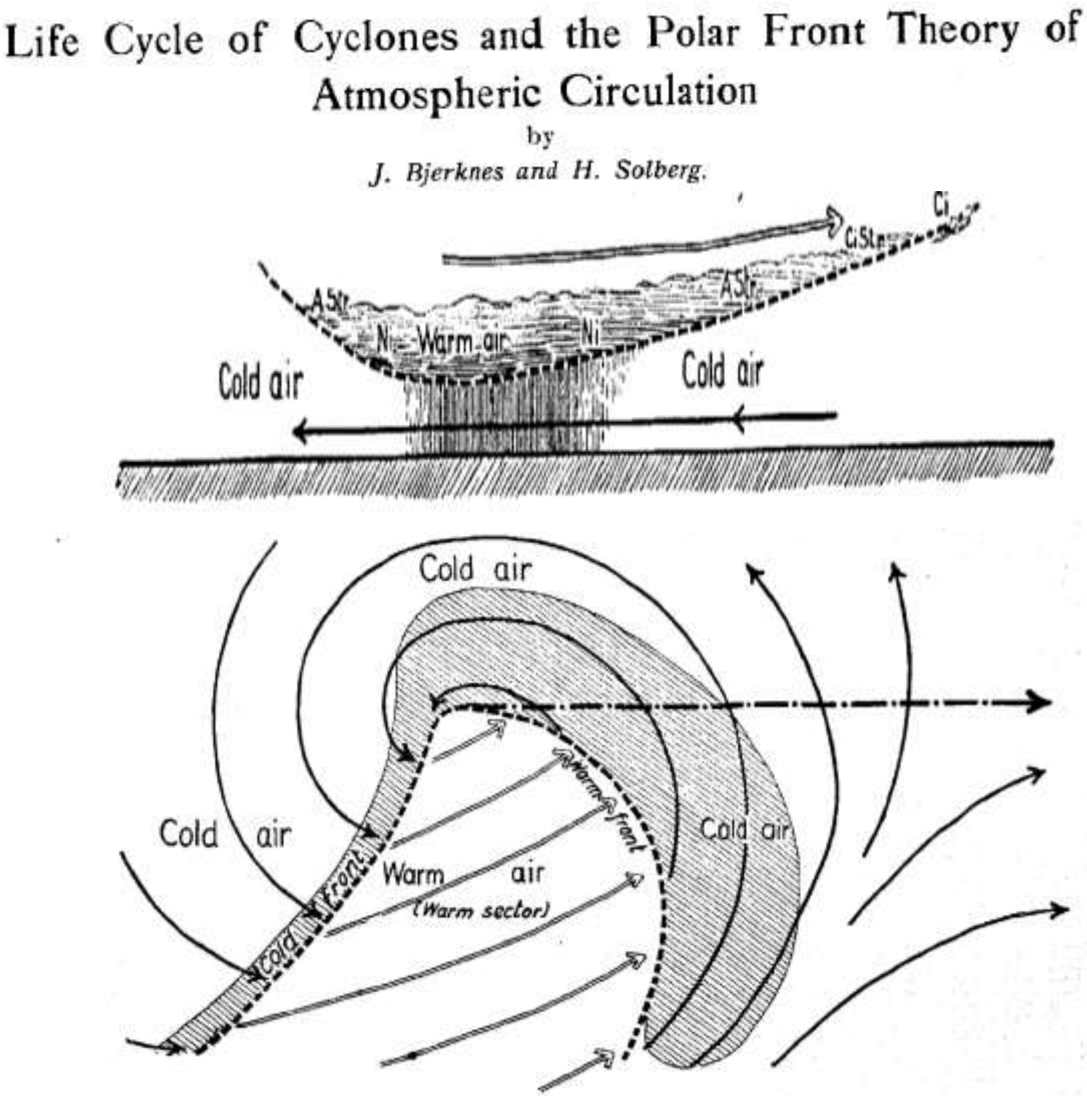
Extratropical circulation – baroclinic instability

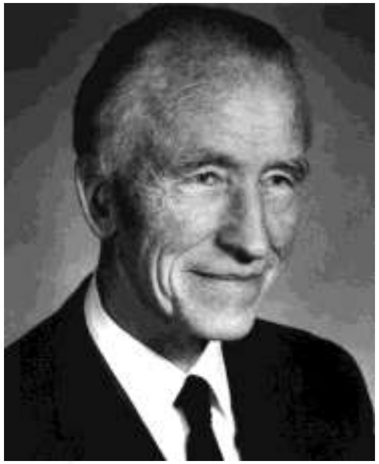


Mid-latitude weather systems:

- Eddies “stir” the atmosphere.
- Eddies carry cold/warm air equatorward/ poleward
  > meridional heat transport.

Marshall and Plumb (2008)





Jacob Bjerknes
1897-1975

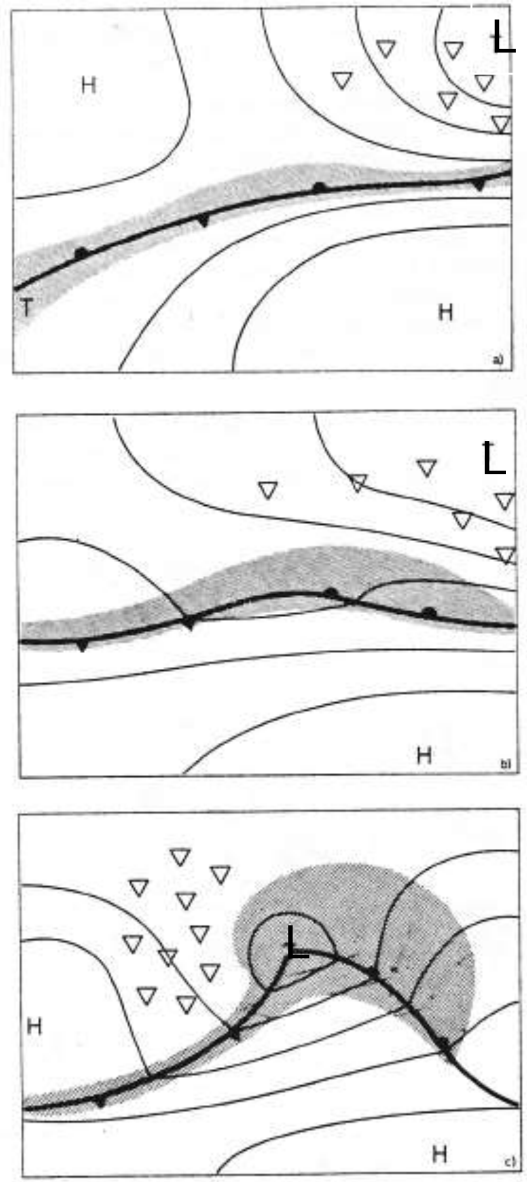
Bjerknes and Solberg (1922)

Life cycle of an ideal cyclone

a)

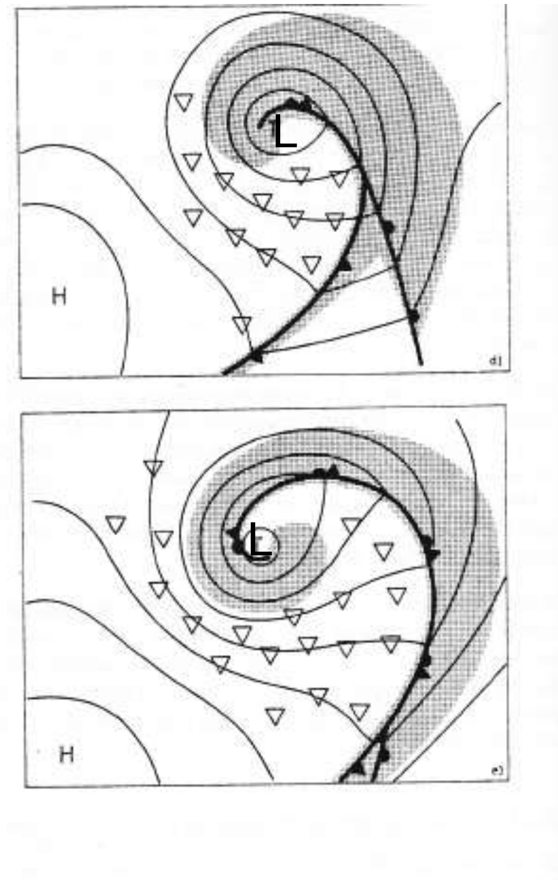
b)

c)



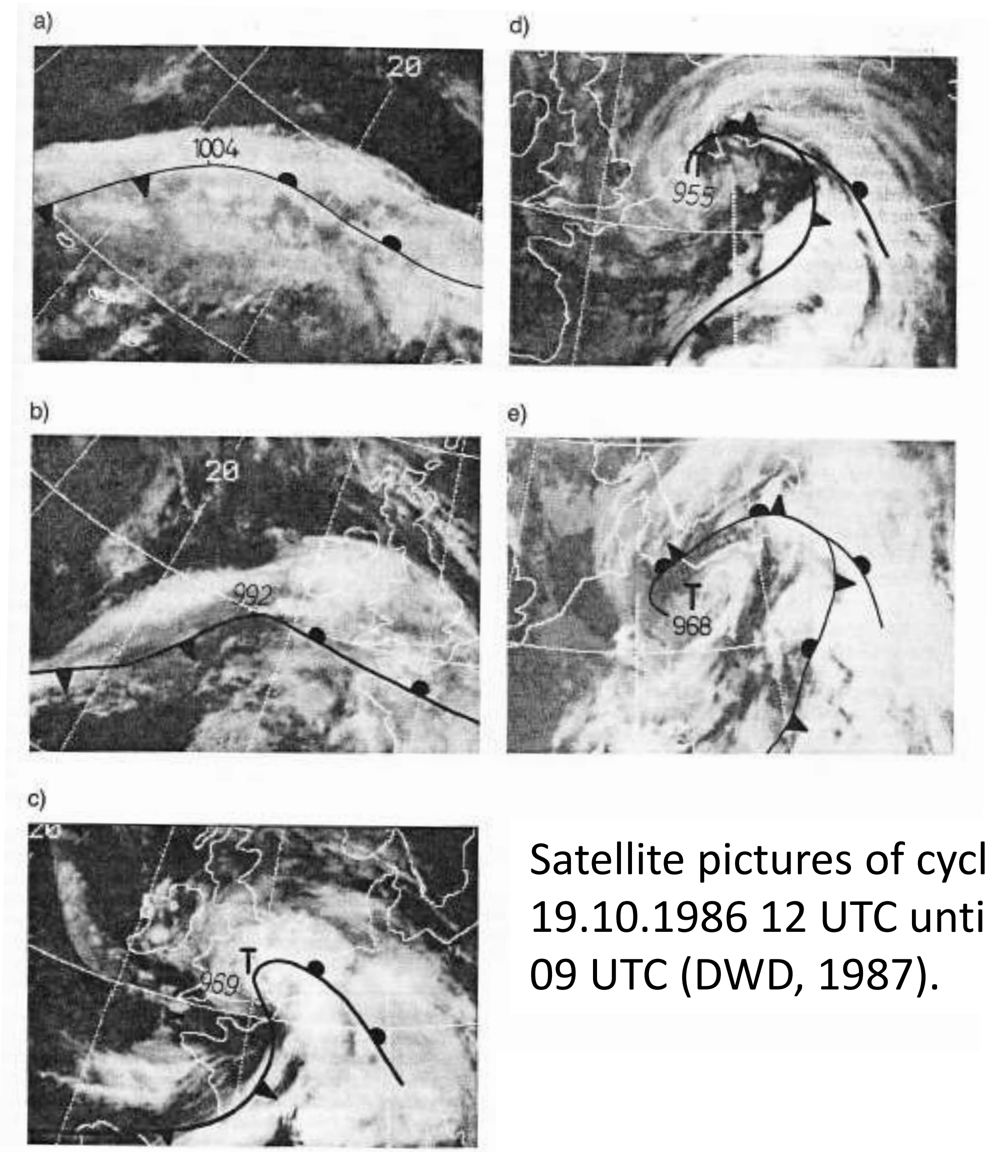
d)

e)



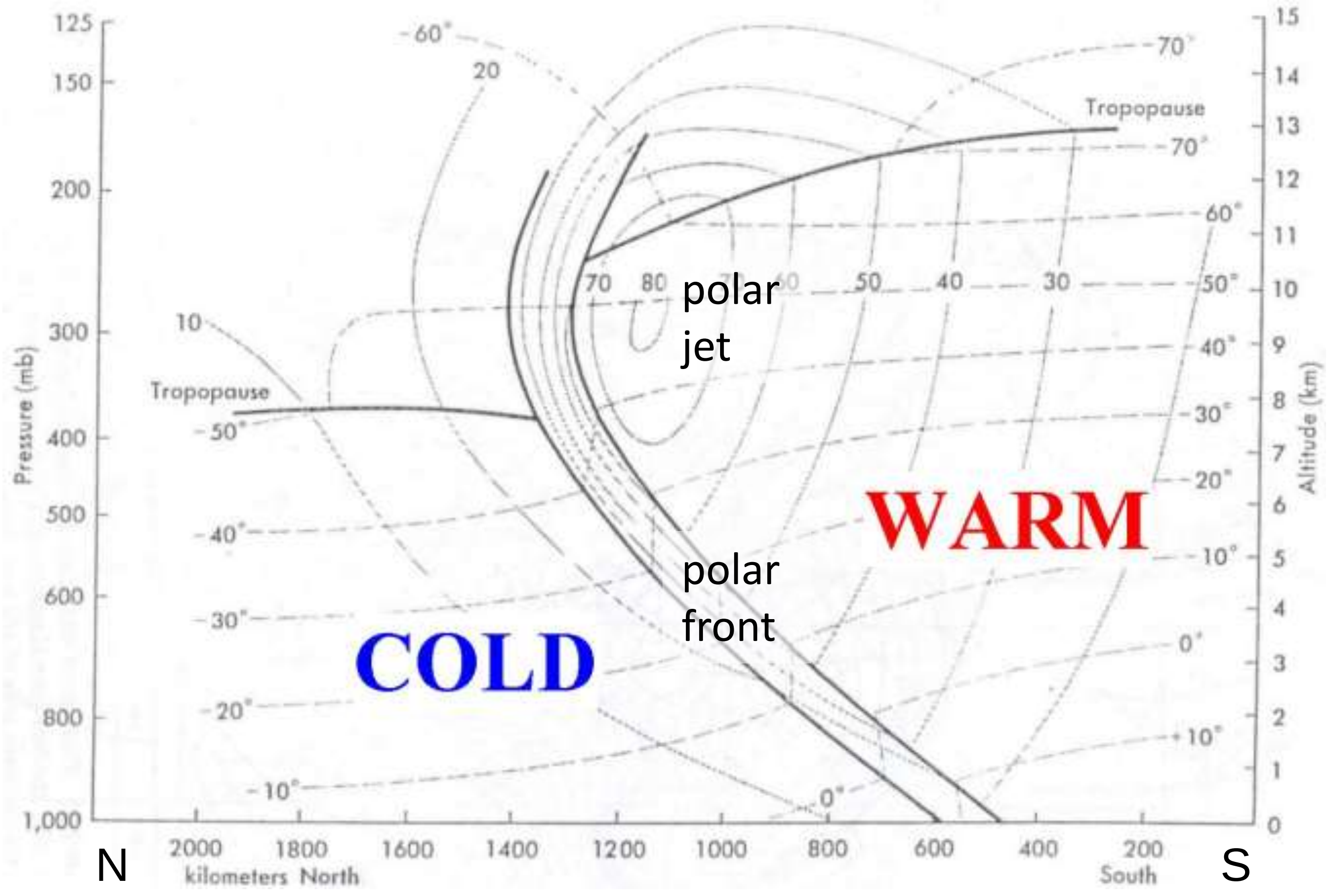
Life cycle of a polar front cyclone (after J. Bjerknes), shown in 12h intervals (DWD, 1987)

Satellite image cyclogenesis



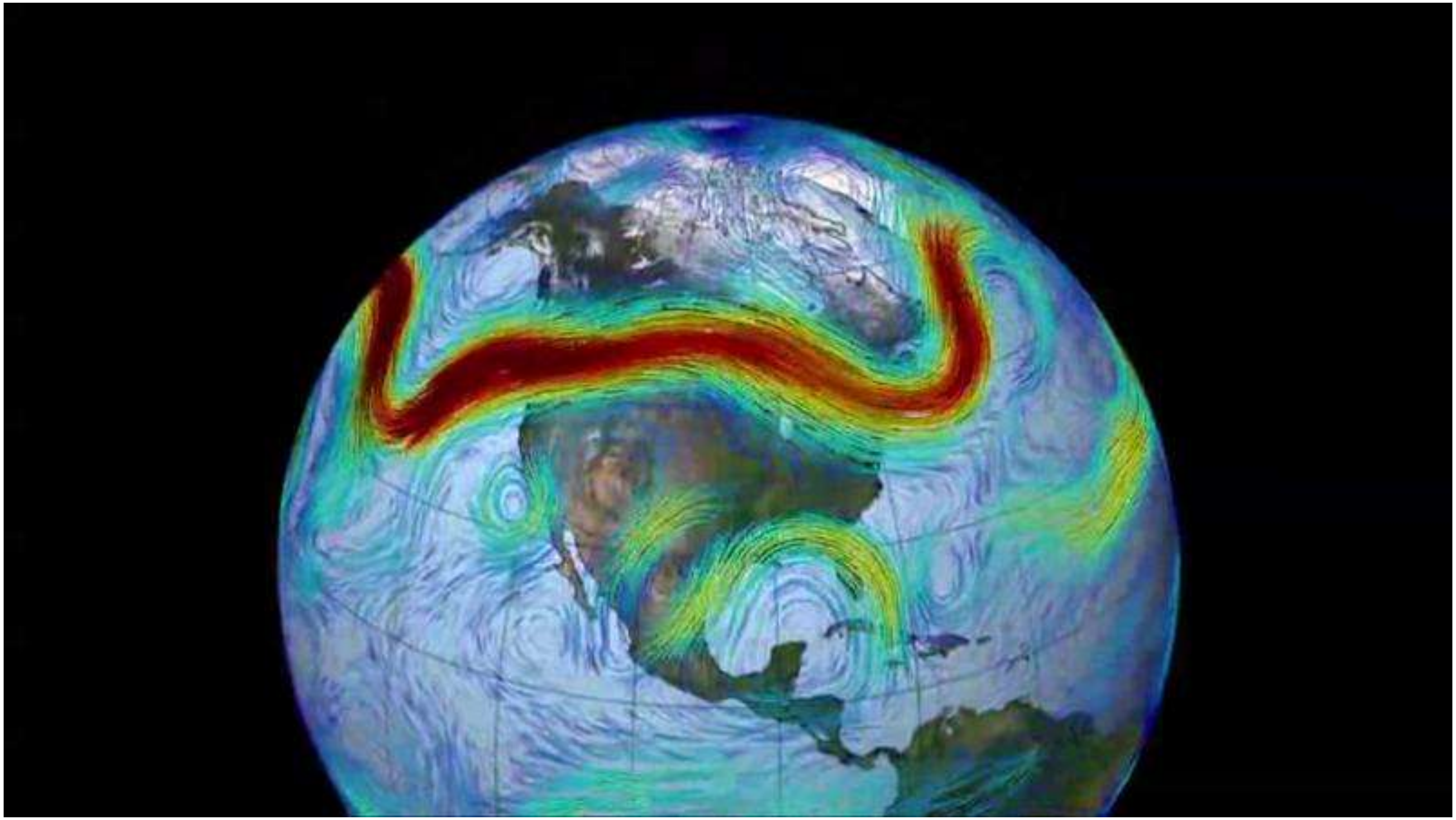
Satellite pictures of cyclonesis from 19.10.1986 12 UTC until 21.10.1986 09 UTC (DWD, 1987).

Polar jet and polar front



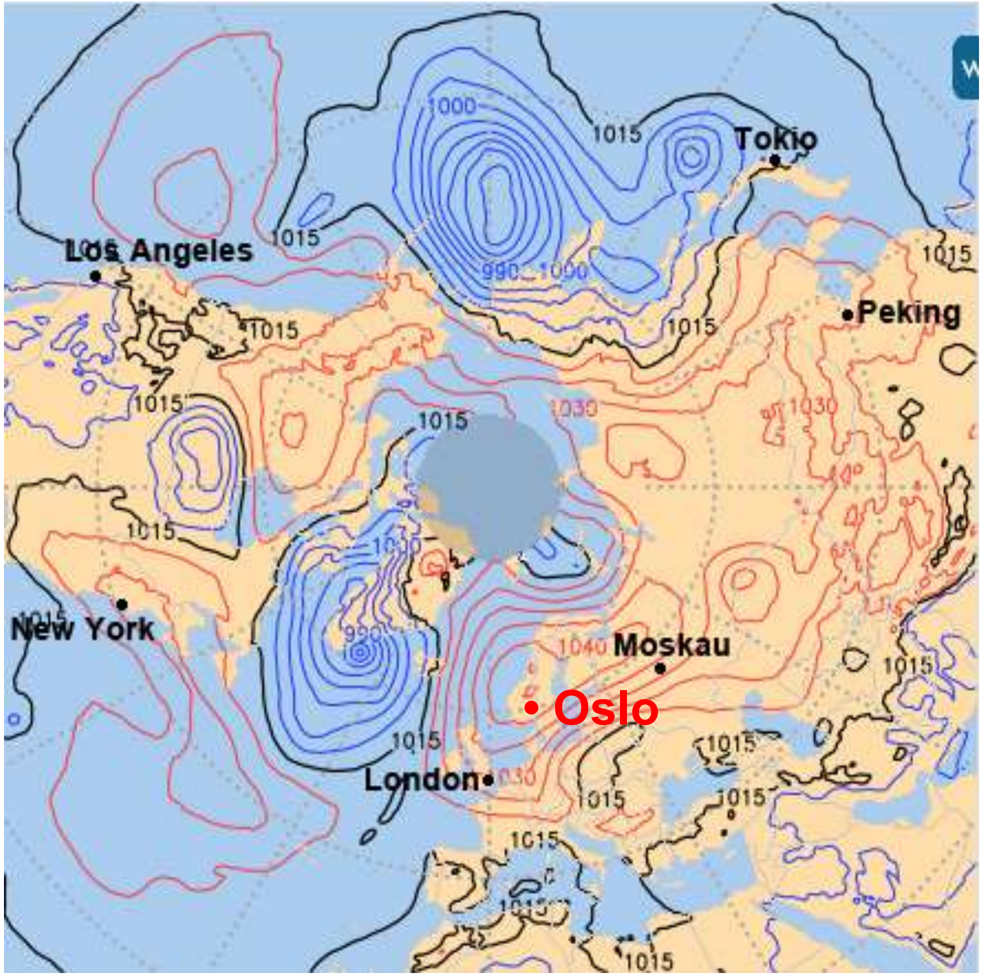
Dotted isotachs marked every 10 ms^{-1} (from 10 to 80 ms^{-1}) show the jet in thermal wind balance with the temperature field. Dashed lines are isotherms marked every 10ºC (from 10 to -70ºC). (Palmén and Newton, 1969)

Polar jet



Today's sea level pressure (hPa)

ECMWF model: Thursday 06.10.2016 00 UTC (02 LT)

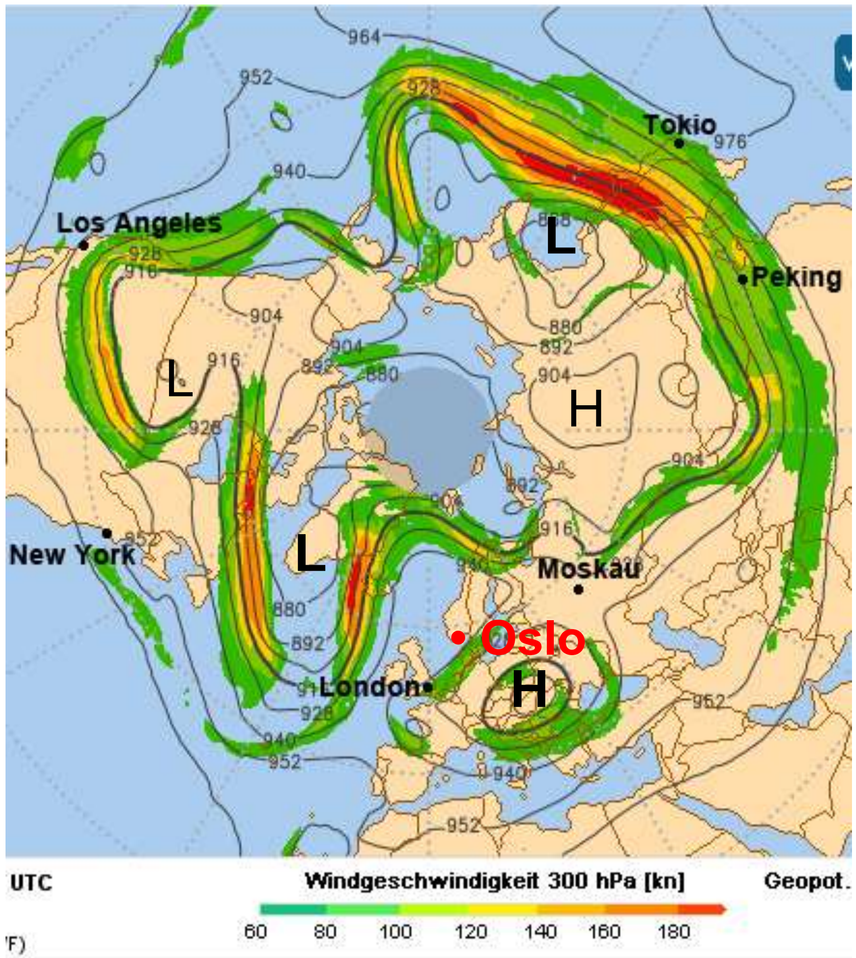


www.wetteronline.de

Quiz: Where is the polar jet located over Europe/North Atlantic?

Today's polar jet: wind (kn) and Geopotential (gpdm) at 300 hPa

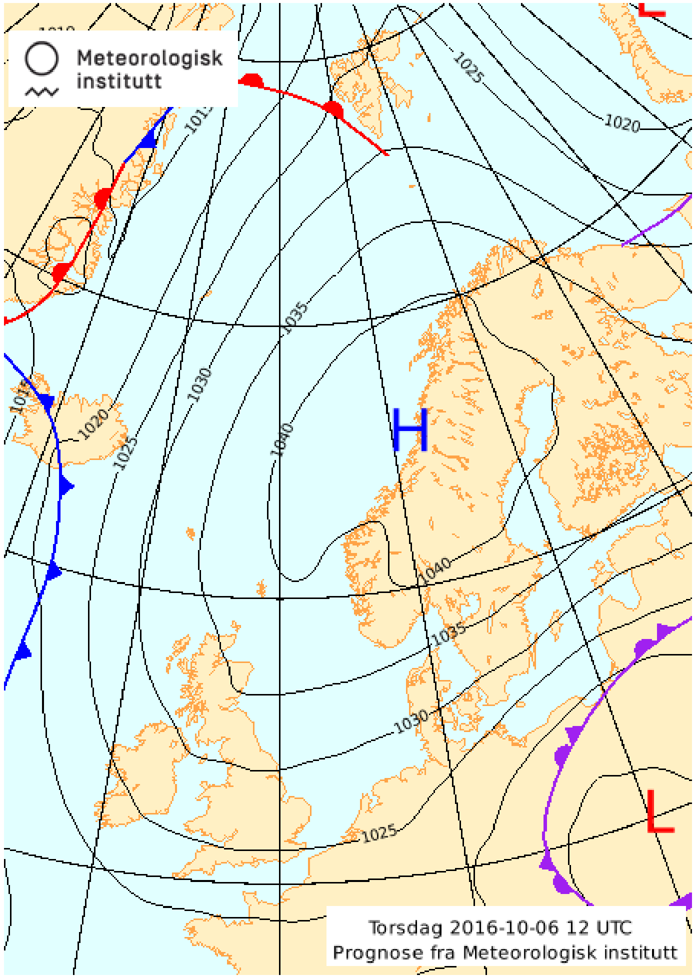
ECMWF model: Thursday 06.10.2016 00 UTC (02 LT)



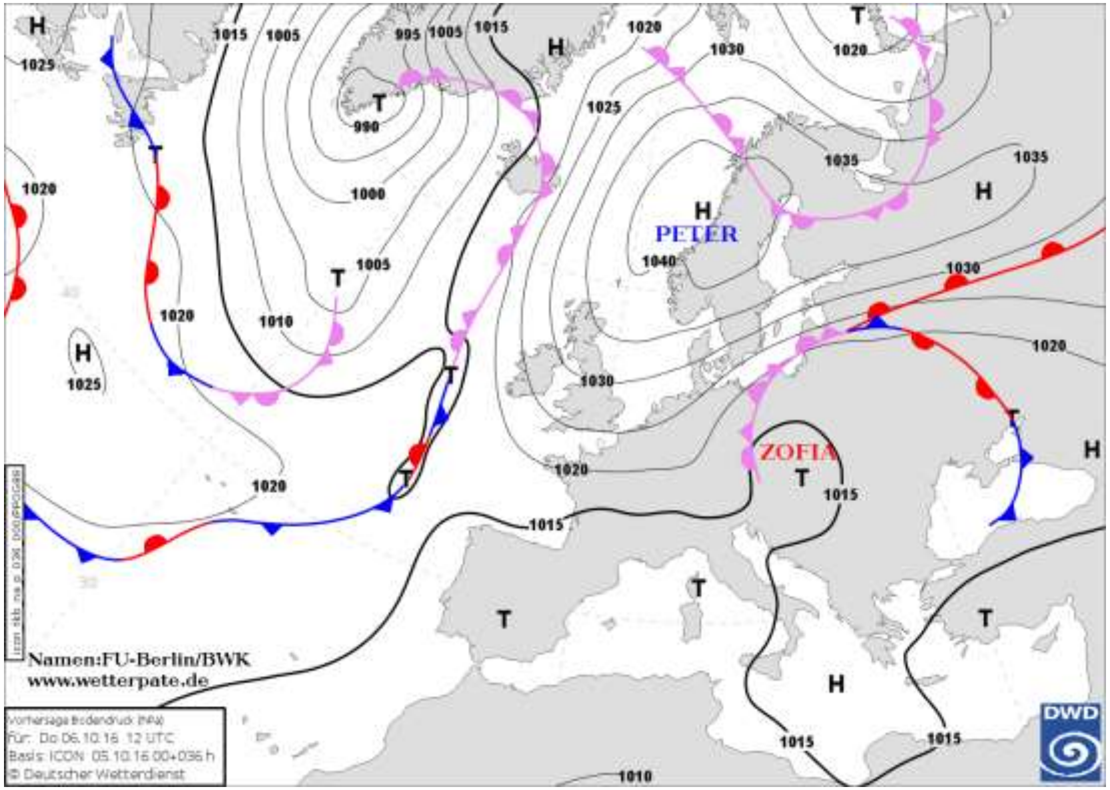
www.wetteronline.de

Quiz: Which wind is observed over Oslo today?

Today‘s weather map (14:00 LT): Norway and Europe



www.yr.no

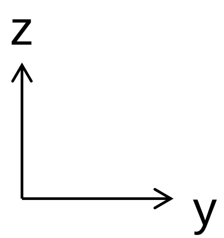


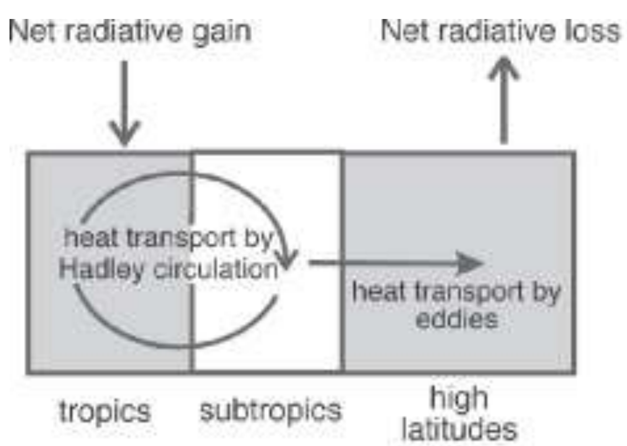
www.dwd.de

Large-scale atmospheric energy budget

Energy transport:

1. ***Conversion*** of potential energy (from solar heating) into kinetic energy > upward heat transport
2. ***Poleward transport*** of heat from low to high latitudes > balancing the radiative budget





Marshall and Plumb (2008)

Energy transport

Northward energy flux?

Consider northward energy E at latitude φ, across atmospheric area dA with height dz and longitudinal width $d\lambda$ ($dA = a\cos\varphi\, d\lambda\, dz$).

- $$E = \underbrace{\underbrace{c_p T + gz}_{\text{dry static energy}} + \underbrace{Lq}_{\text{latent heat}}}_{\text{moist static energy}} + \underbrace{\frac{1}{2}\boldsymbol{u}\cdot\boldsymbol{u}}_{\text{kinetic energy density}}$$ (Eq. 8-14)

- Net northward energy flux for dA is:

$$\overline{\mathcal{H}}_{atmos} = \iint \rho v E\, dA$$
$$= a\cos\varphi \int_0^{2\pi}\int_0^{\infty} \rho v E\, dz\, d\lambda$$
$$= \frac{a}{g}\cos\varphi \int_0^{2\pi}\int_0^{p_s} vE\, dp\, d\lambda$$ (Eq. 8-15)

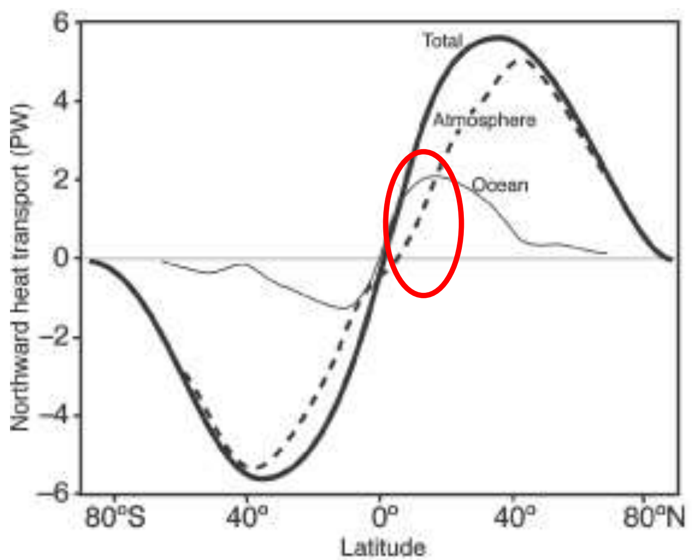
- northward mass flux: $\rho v\, dA$
- northward energy flux: $\rho v E\, dA$
- replace ρdz by -dp/g (hydrostatic balance)

---

a: Earth radius, *E: Energy,* c_p*: specific heat at constant pressure p,* T: temperature, g: gravity acceleration, L: latent heat, q: humidity, $\boldsymbol{u}$: velocity, v: meridional velocity, $\overline{\mathcal{H}}_{atmos}$: net northward energy flux, p_s: surface pressure

Energy transport in **tropics**

- Kinetic energy term (<1 %) can be neglected in Eq. 8.14
- $\overline{\mathcal{H}}^{\lambda}{}_{tropics} = \frac{2\pi a}{g} \cos\varphi \int_0^{p_s} v\,(c_p T + gz + Lq)\, dp$ (Eq. 8-16)
- In the net annually average, the energy flux by Hadley cell is weakly poleward.
- Ocean heat transport **exceeds** atmosphere in the tropics (see also Chapter 11).



Marshall and Plumb (2008)

*Petawatt (PW) 10^{15} watts
W= J/s = N·m/s = kg m^2/s^3

Energy transport in **mid-latitudes**

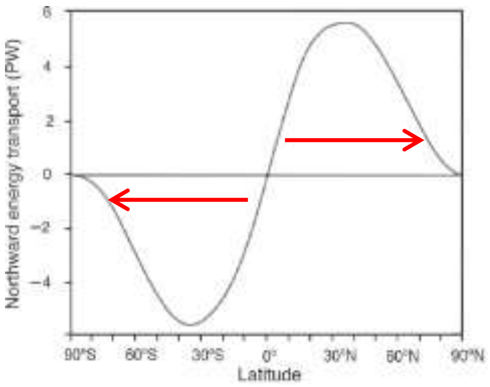
Transport by mid-latitude eddies:

- **Northward heat flux** to consider order of magnitude estimate of the net energy flux:

$$\overline{\mathcal{H}}^{\lambda}{}_{midlat} \sim 2\pi \frac{ac_p}{g} \cos\varphi \, p_s \; [v][T] \quad \text{(PP. 155)}$$

$$\Longrightarrow \overline{\mathcal{H}}^{\lambda}{}_{midlat} \sim 8 \text{ PW}$$

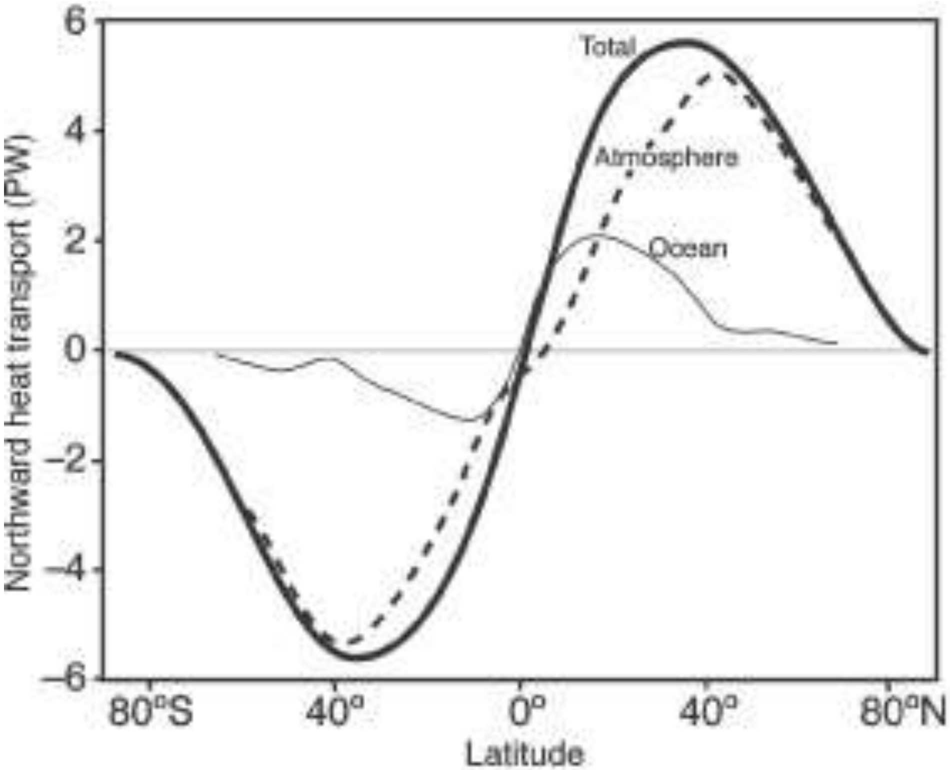
- Radiative imbalance: ~6 PW (Chapter 5)



a= 6371 km, c_p= 1005 J kg^{-1} K^{-1}, g = 9.81 ms^{-2}, $p_s \simeq 10^5$ Pa, $[v_{45°}] \simeq$ 10 m/s, $[T_{45°}] \simeq$ 3 K, Petawatt (PW) = 10^{15} Watts

Marshall and Plumb (2008)

Northward heat transport (PW*)



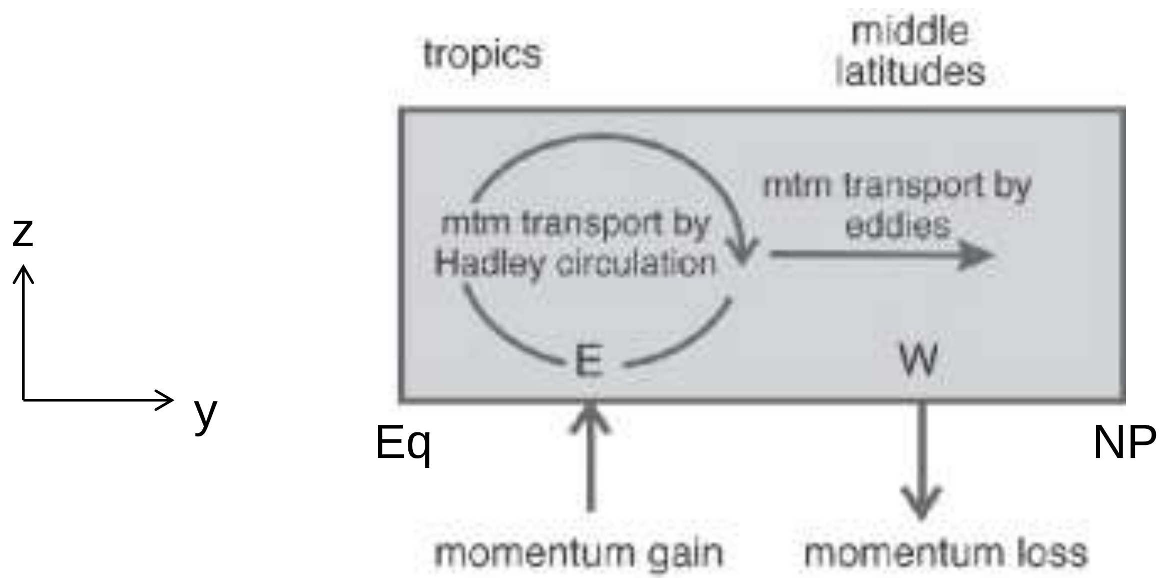
Trenberth and Caron (2001)

Figure 8.13: The ocean (thin) and atmospheric (dotted) contributions to the total northwards heat flux (thick) based on the NCEP reanalysis and top of the atmosphere radiation measurements (in PW = 10^{15} *W*) by (i) estimating the net surface heat flux over the ocean, (ii) the associated oceanic contribution, correcting for heat storage associated with global warming and constraining the ocean heat transport to be -0.1 PW at 68° S, and (iii) deducing the atmospheric contribution as a residual. The total meridional heat flux, as in Fig. 5.6, is also plotted (thick).

---

*Petawatt (PW) 10^{15} Watts
W= J/s = N·m/s = kg m^2/s^3

Momentum transport



by atmosphere

Marshall and Plumb (2008)

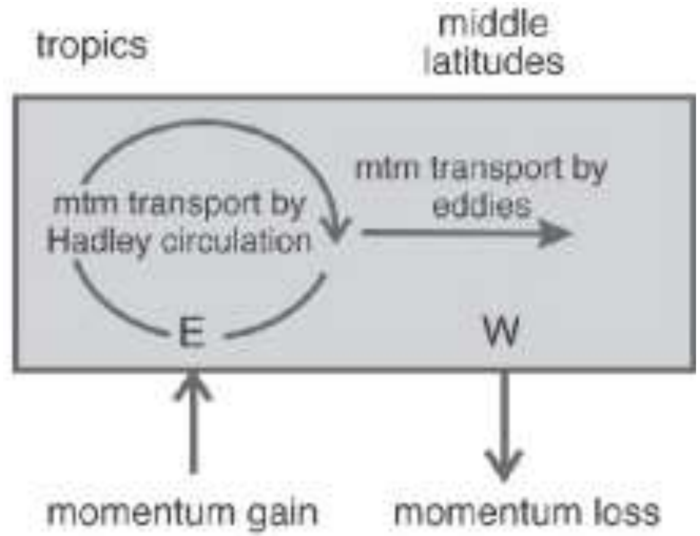
Momentum transport

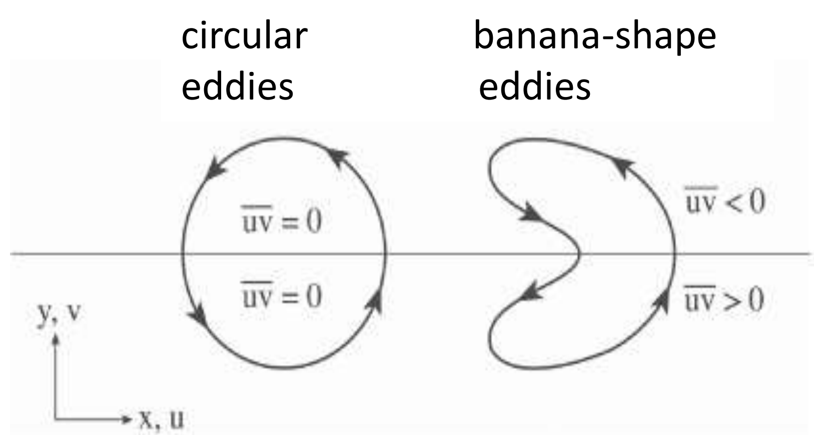
Tropics:

Net export of westerly momentum out of **low latitudes** must be **balanced by supply** of **momentum** into this region $\Longrightarrow$ **surface** winds must be **easterly** (Hadley circulation).

Mid-latitudes:

Loss of momentum from the atmosphere to the surface (eq. due to drag on near surface Westerlies) must be **balanced by supply of poleward transport of westerly momentum via eddies**; $\longrightarrow$ shift of low latitudes westerlies to mid-latitudes.

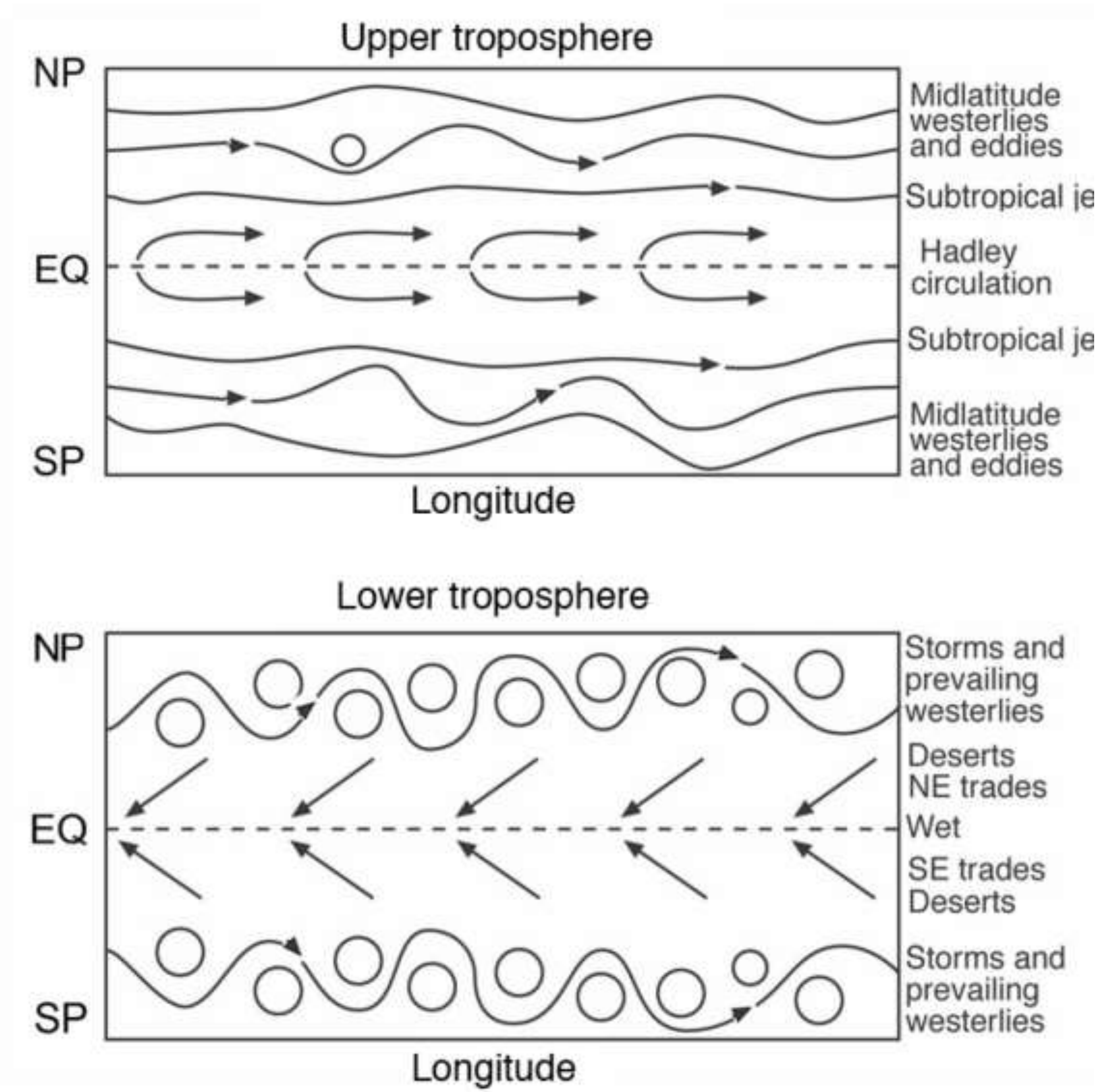




$\overline{uv} > 0$: Northward westerly momentum
$\overline{uv} < 0$: Southward westerly momentum

Marshall and Plumb (2008)

5. Summary - *simple* representation of the atmosphere



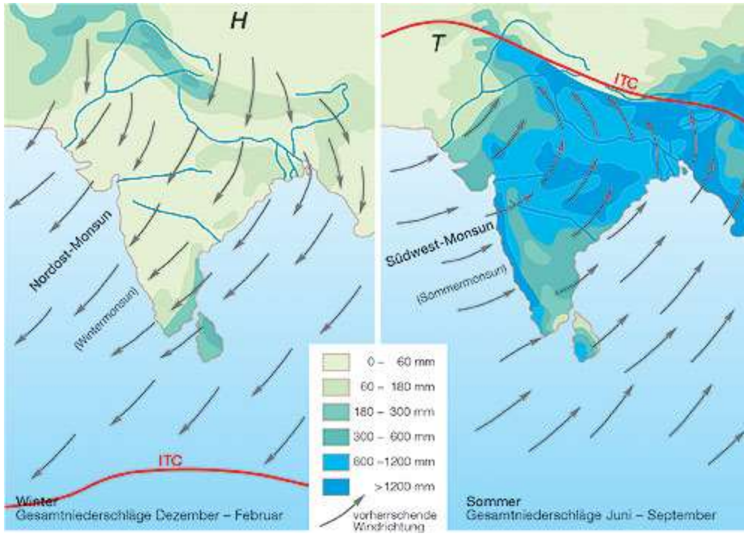
Marshall and Plumb (2008)

Deviations from simple GCA

Seasonal variations and horizontal asymmetries:

Tropics:
e.g. Monsoon, Hadley circulation and ITCZ vary seasonally and horizontally

Mid- and high latitudes:
e.g. storms/ jet streams maximize during winter



Indian monsoon

Jet streams

GCA – more complex

Polar High
circumpolar easterlies

subpolar low pressure channel

Polarfront
Westwinddrift

subtropical high pressure zone

northeastern trades

intertropical convergence
equatorial counter flow

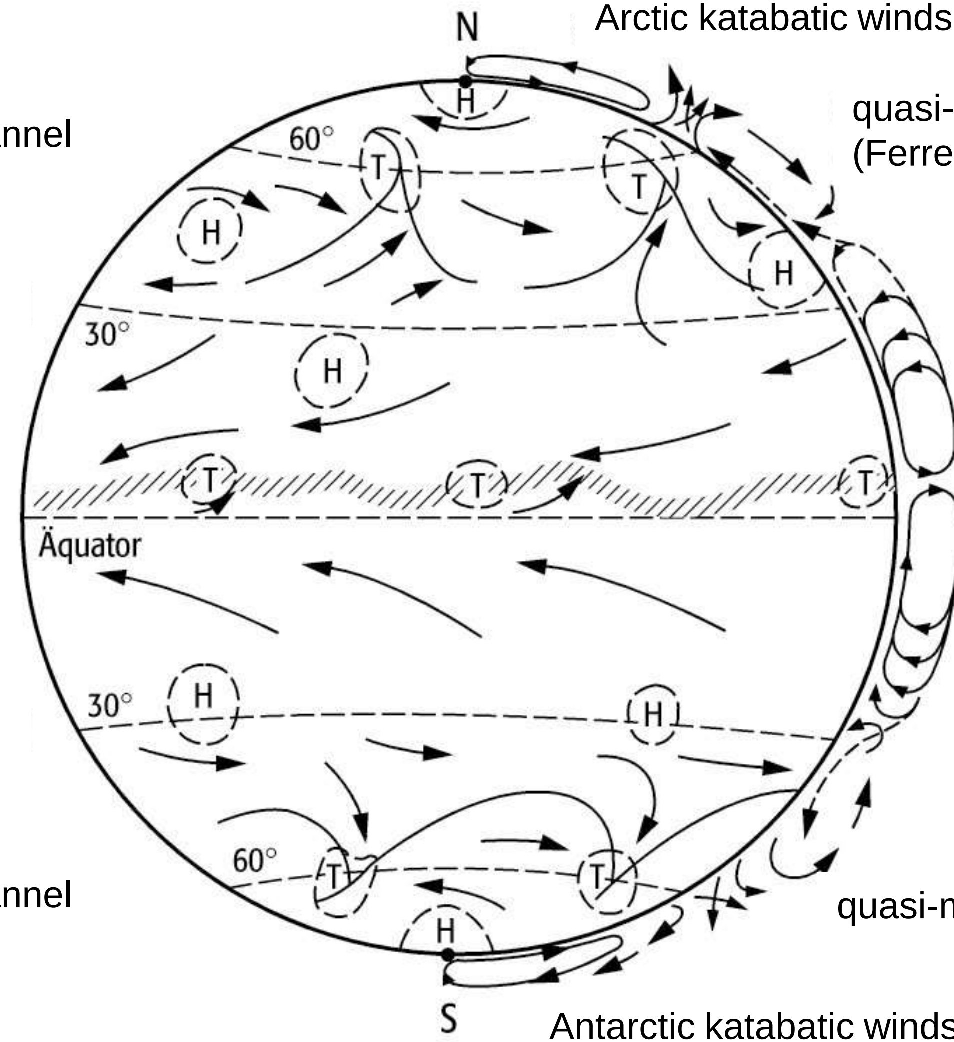
southeastern trades

subtropical high pressure zone

Polarfront
Westwinddrift

subpolar low pressure channel

Polar High
circumpolar easterlies



Arctic katabatic winds

quasi-meridional circulation (Ferrel cell)

northern Hadley cell

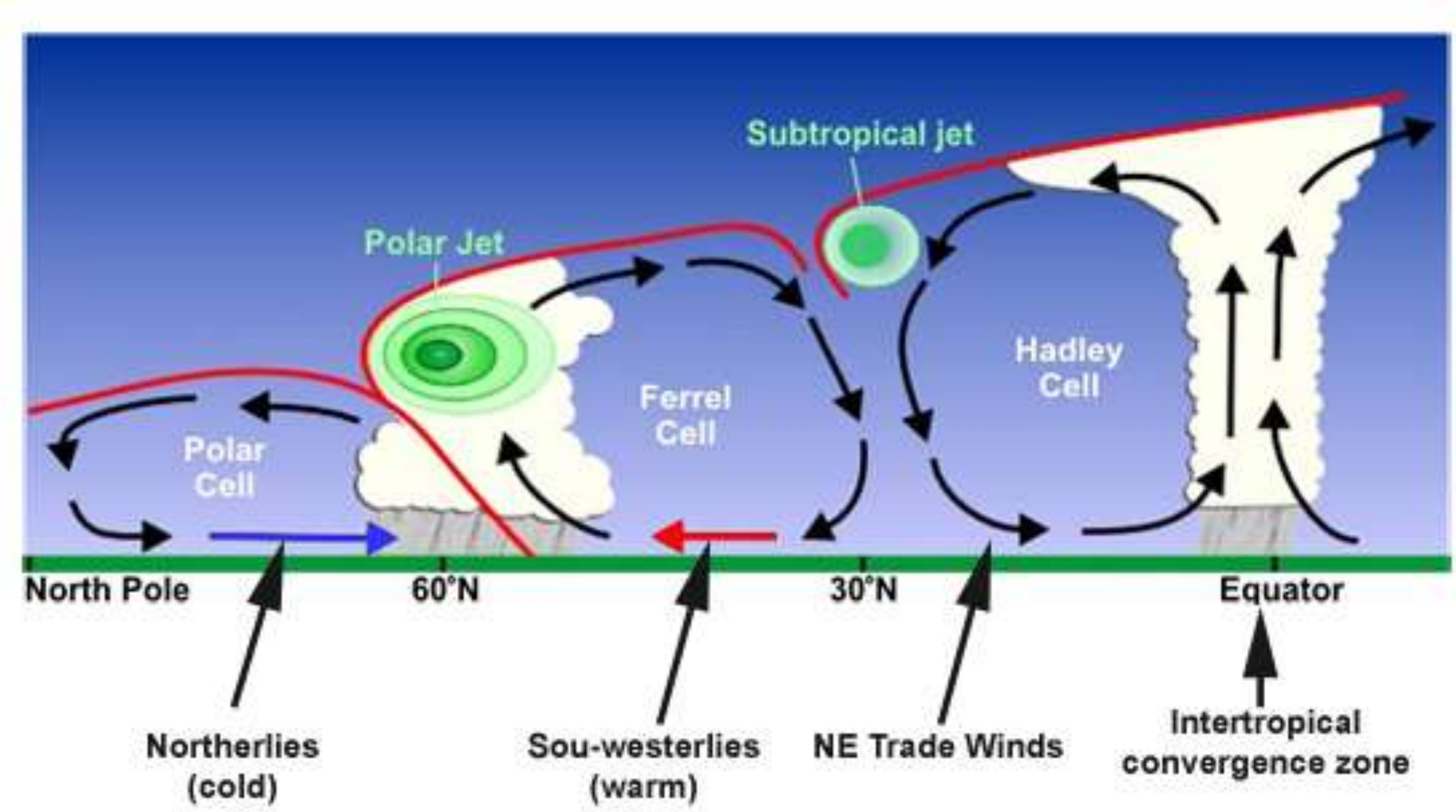
southern Hadley cell

quasi-meridional circulation

Antarctic katabatic winds

www.wissenschaft-online.de

GCA: vertical-meridional flow



www.enso.info

Take home message

- Energy and momentum budgets demands on the GCA.
- Observed atmospheric winds and major climate zones can be explained by dynamic atmosphere on a longitudinal uniform, rotating Earth with latitudinal gradient of solar heating.
- However, distinct deviations on temporal and horizontally variations exist (i.e., Hadley cell, ITCZ, Asian monsoon).
- Geostrophic, hydrostatic and thermal wind balances together with conservation of angular momentum explain most of the observed wind patterns.

Quiz

What is the polar jet?

a) The maximum **W**esterly wind in the polar stratosphere.

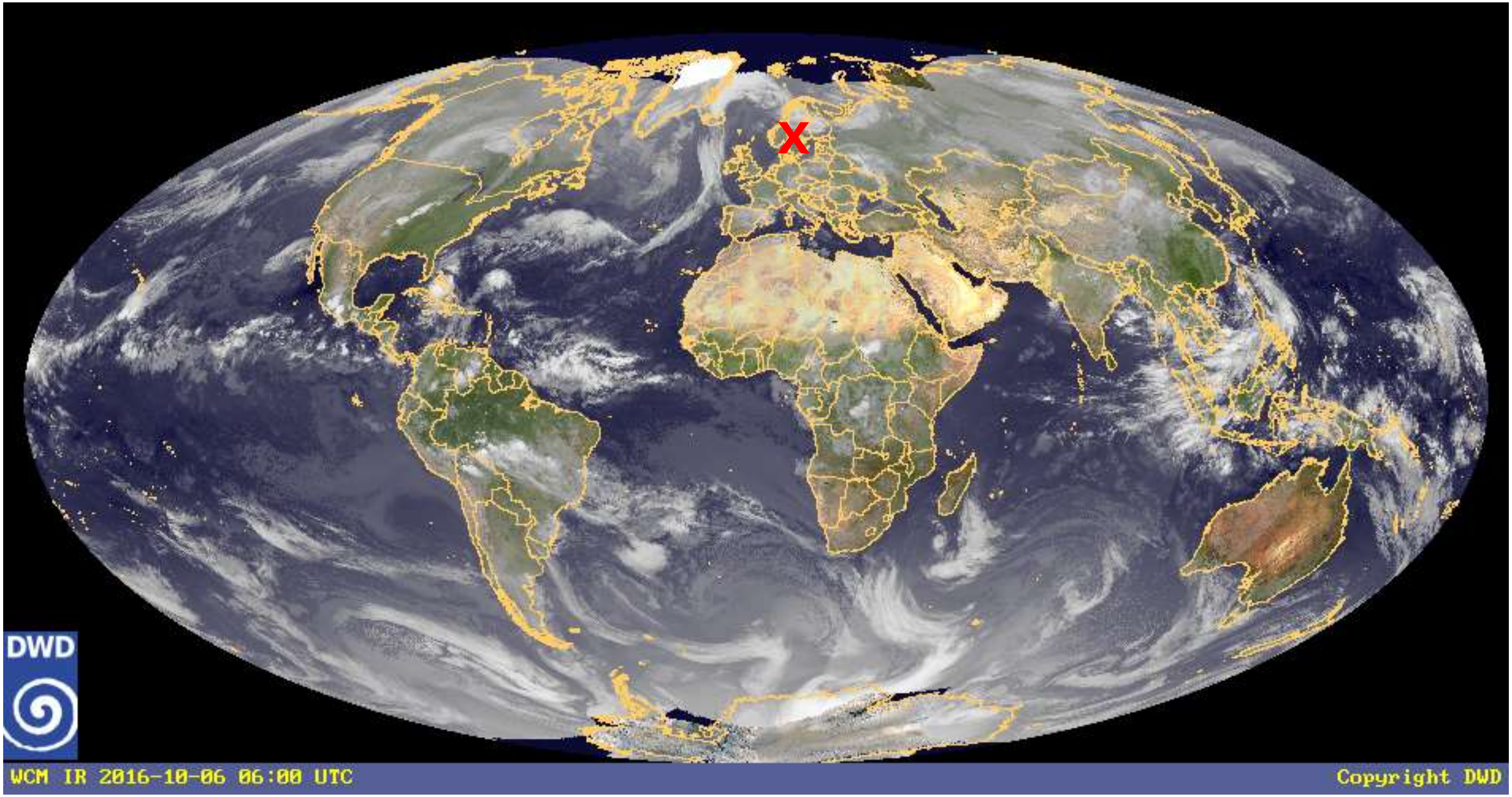
b) The maximum wind in the subtropical upper troposphere.

c) The maximum **W** wind band in the upper troposphere meandering at high latitudes.

d) The maximum **E** wind in the summer upper mesosphere.

Quiz:
Where lies the polar jet?
Where lies the ITCZ?

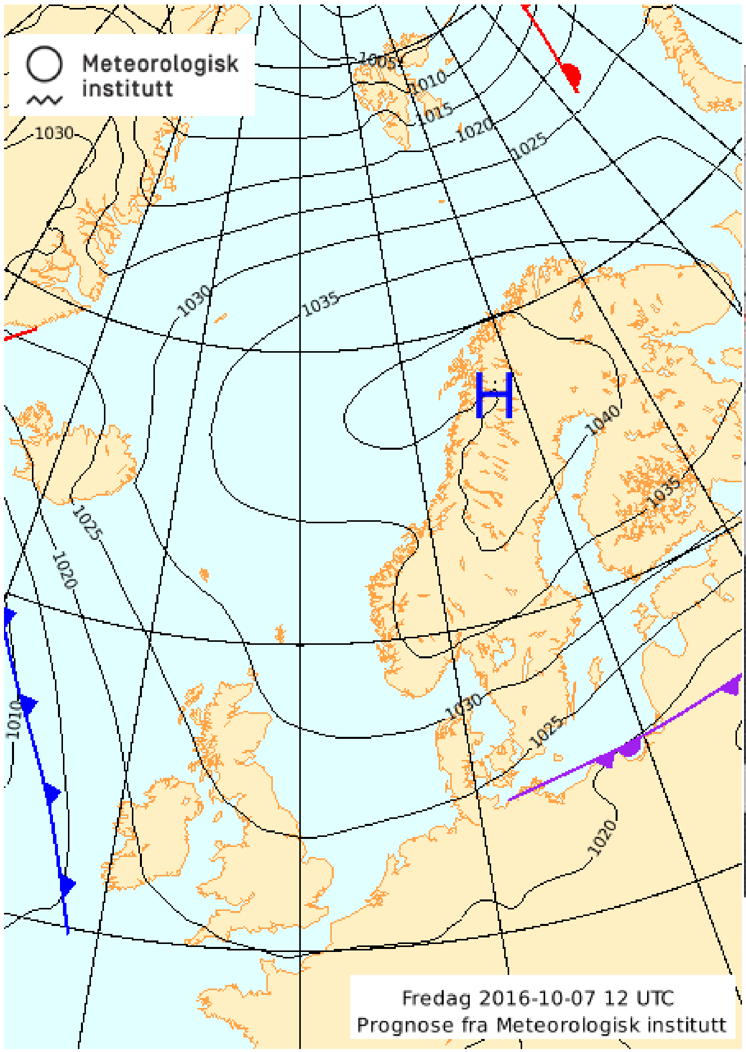
Today's satellite map - Globe



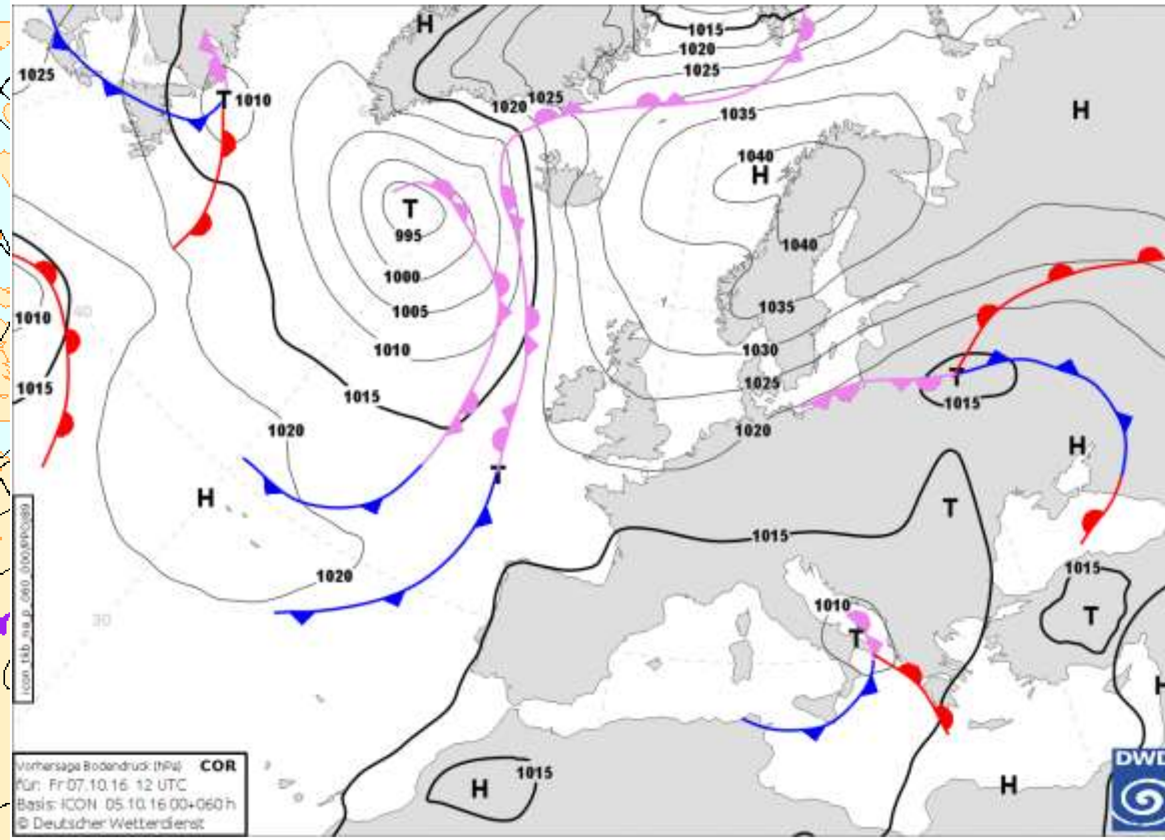
www.dwd.de

x Oslo

Weather forecast for tomorrow

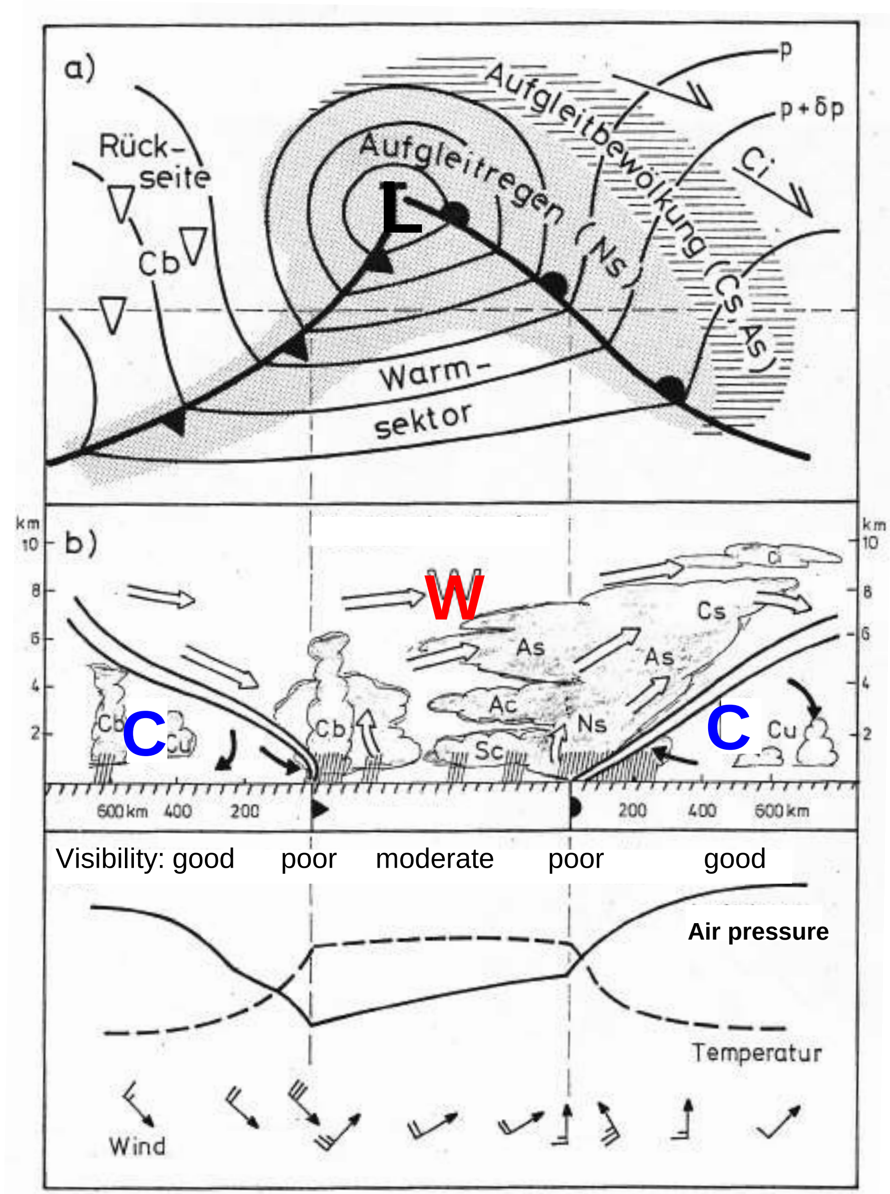


www.yr.no



www.dwd.de

Cyclone passage - weather



DWD 1987