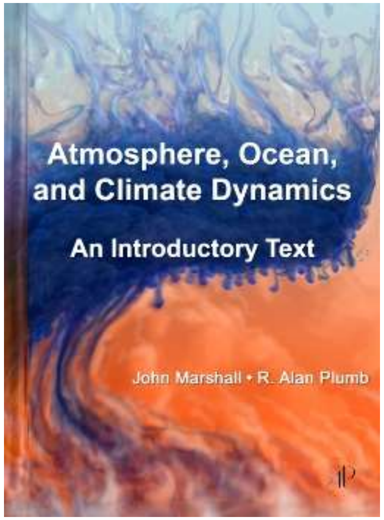
GEF 1100 – Klimasystemet

Chapter 8: The general circulation of the atmosphere

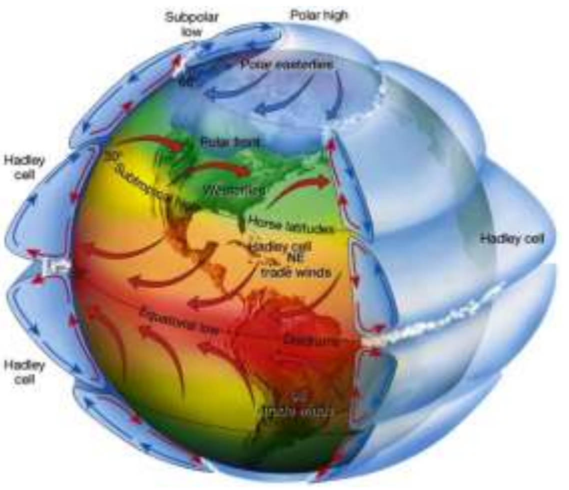


Prof. Dr. Kirstin Krüger (MetOs, UiO)

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
   - 3.1 The tropical Hadley circulation
   - 3.2 The extratropical circulation

4. Large-scale atmospheric energy and momentum budget

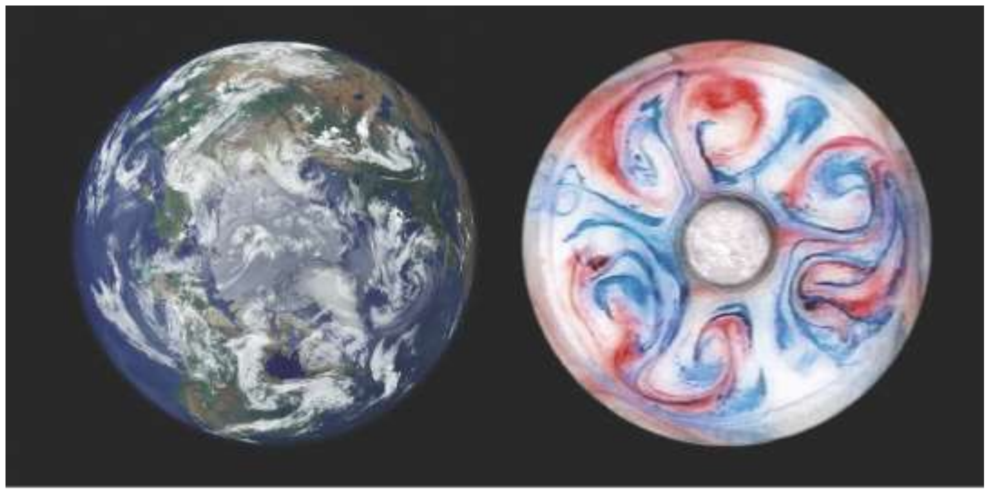
5. Summary

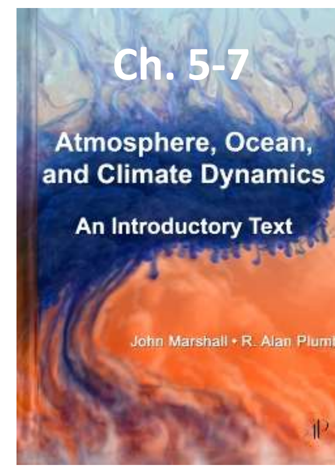
6. Take home message

*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)

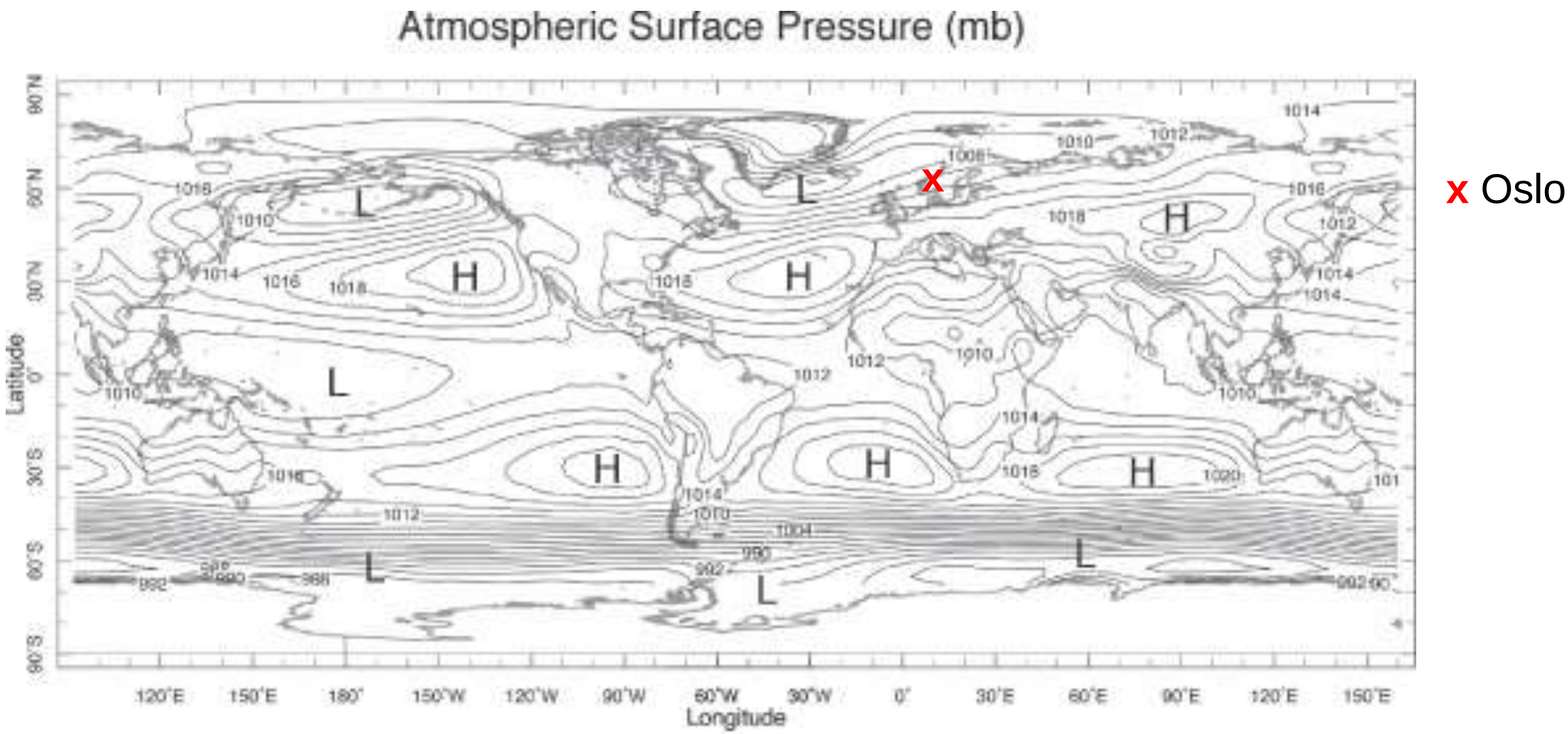


Figure 7.27: The annual-mean surface pressure field in mbar, with major centers of high and low pressure marked. The contour interval is 5 mbar.

Marshall and Plumb (2008)

x Oslo

Sea level pressure (SLP) [mb]

Zonal wind [m/s]

Meridional wind [m/s]

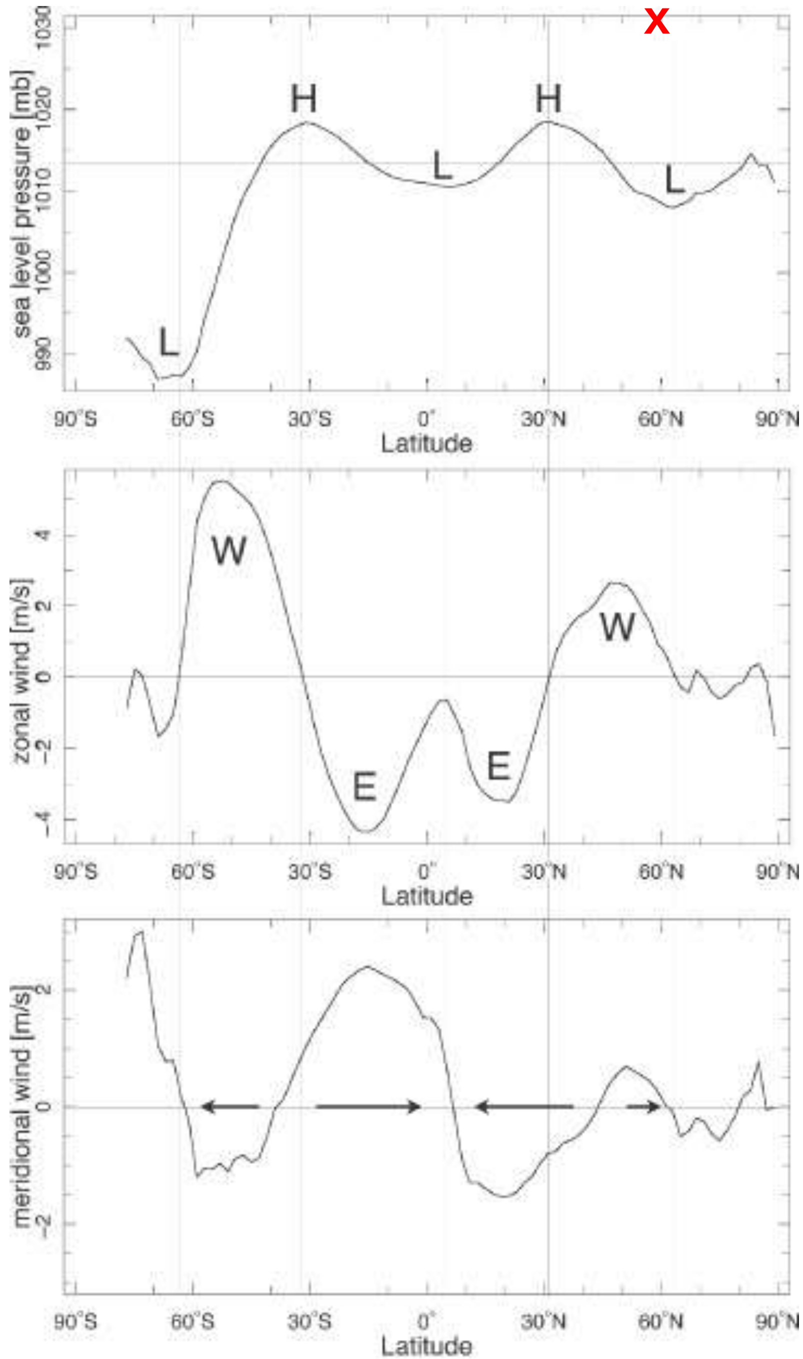


Figure 7.28: Anually and zonally averaged (top) sea level pressure in mbar, (middle) zonal wind in m s^{-1}, and (bottom) meridional wind in m s^{-1}. The horizontal arrows mark the sense of the meridional flow at the surface.

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

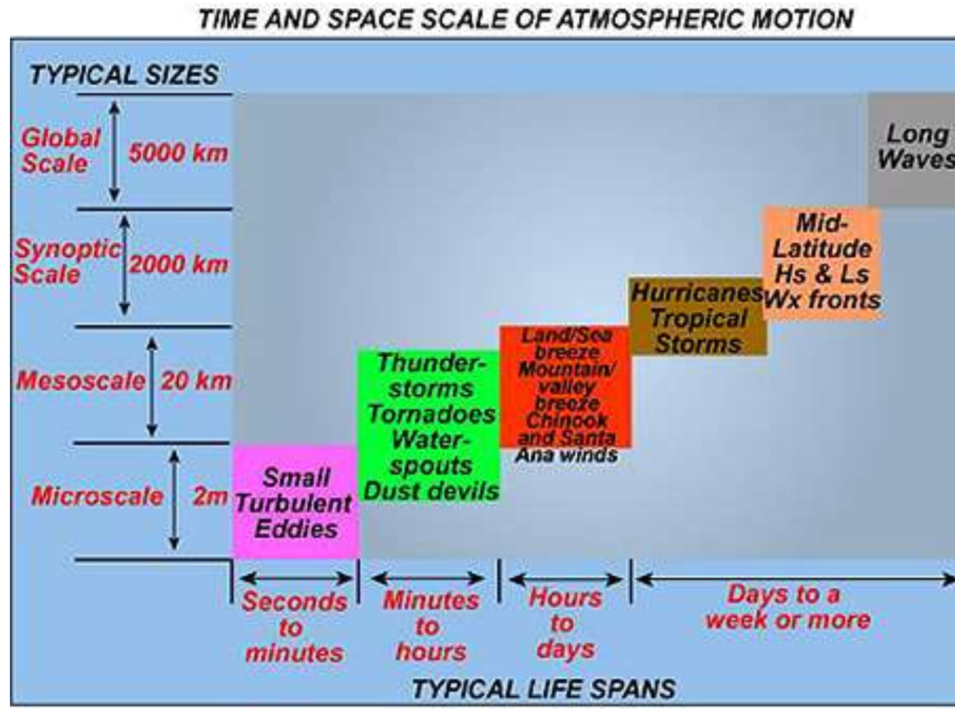
Atmospheric circulation – scales

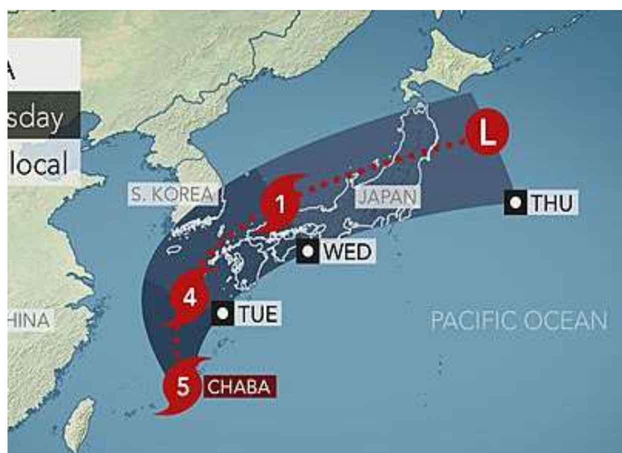
Microscale
- Size: meters
- Time: seconds

Mesoscale
- Size: kilometres
- Time: minutes to hours

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

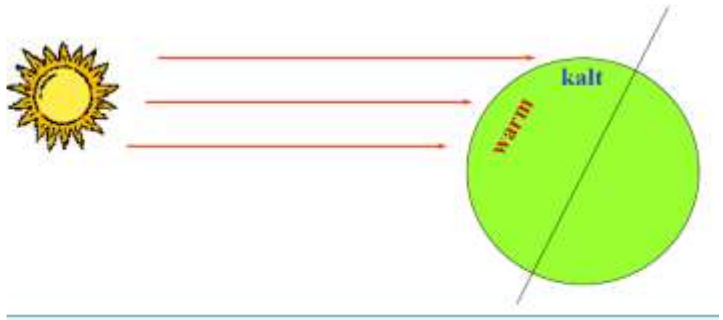
Global (planetary)
- Size: Global
- Time: Days to weeks



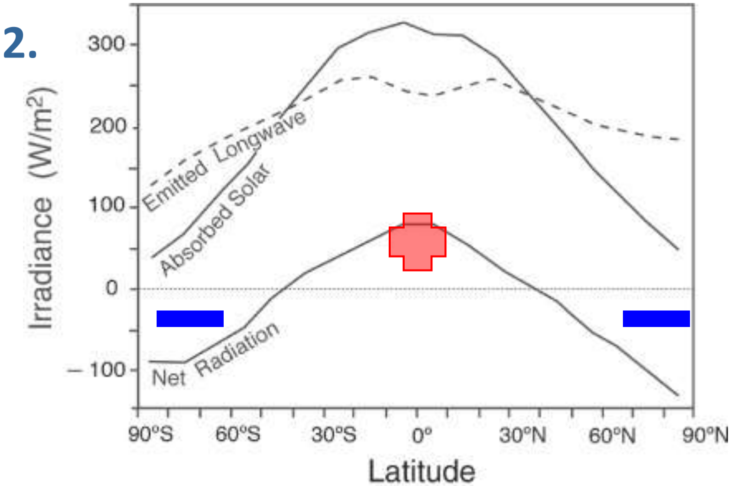


Super typhoon Chaba 04.10.16

1.

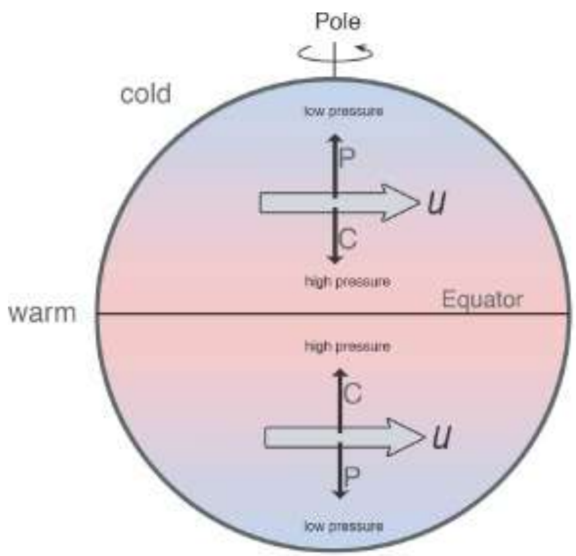


2.



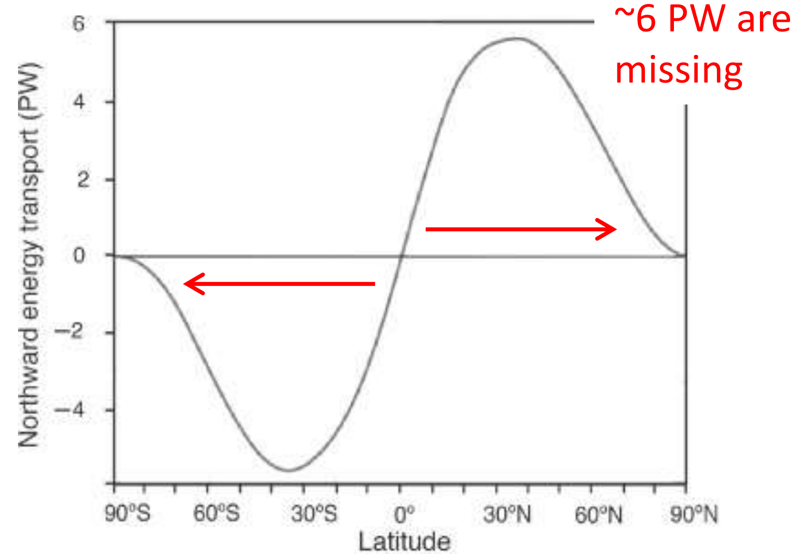
Surplus of radiation balance in the tropics and deficit in the polar regions!

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)

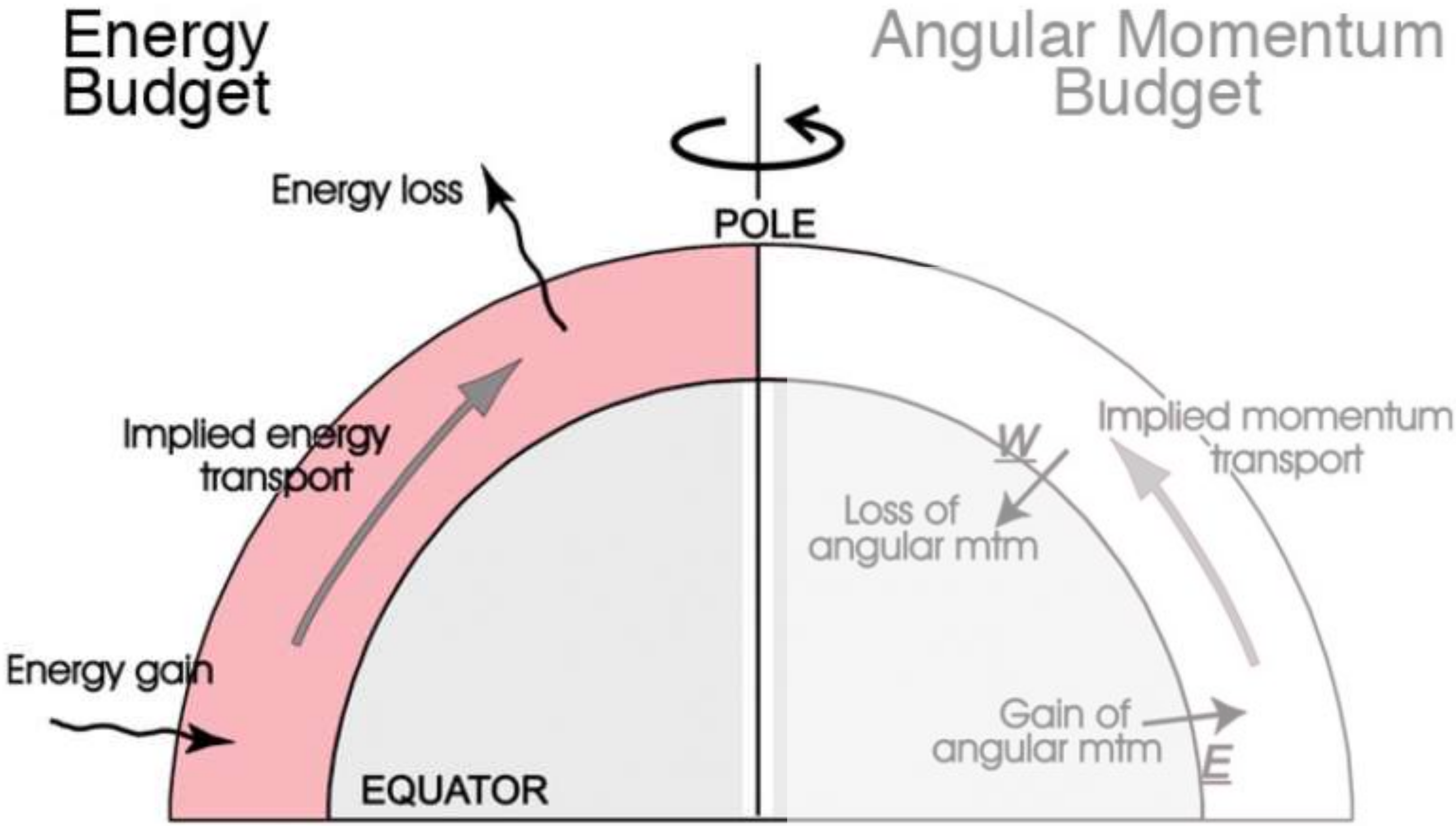
Kinetic energy of the atmosphere – general circulation

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)

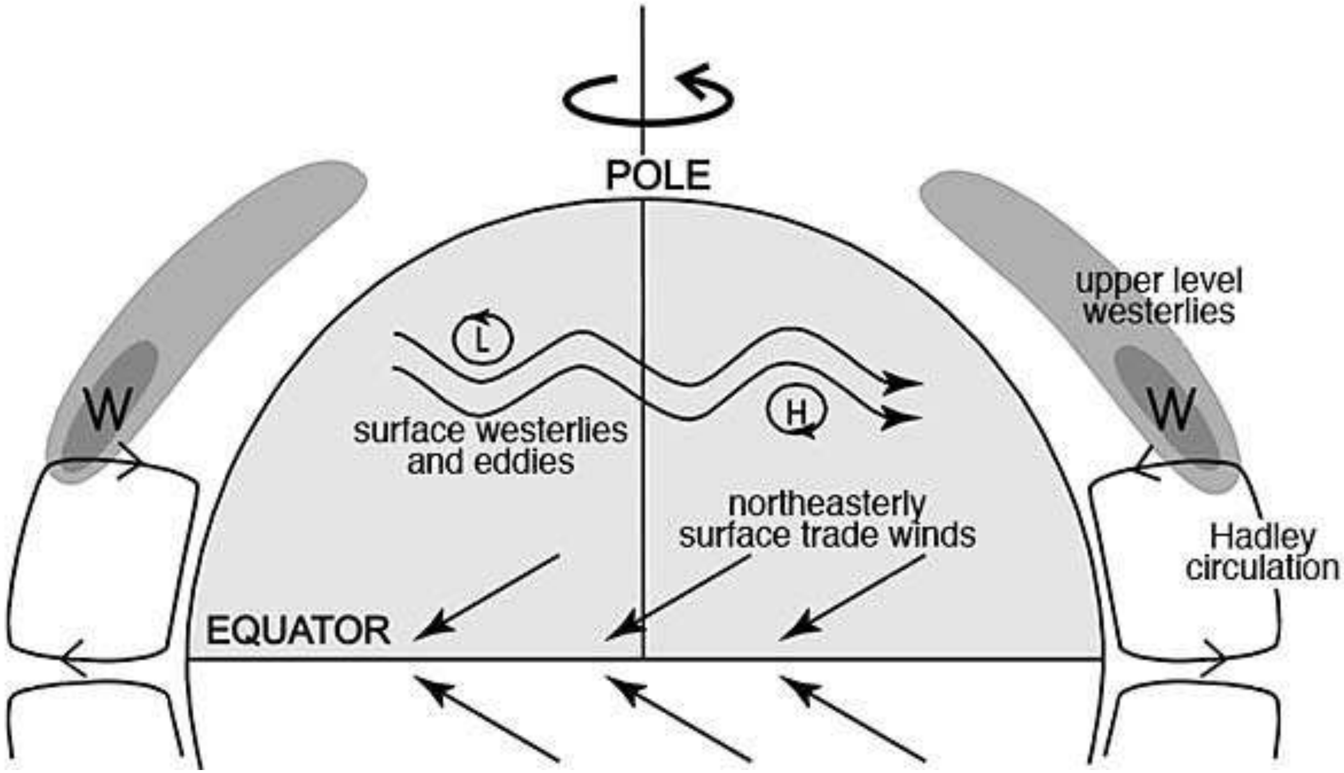


Figure 8.2: Schematic of the observed atmospheric general circulation for annual-averaged conditions. The upper level westerlies are shaded to reveal the core of the subtropical jet stream on the poleward flank of the Hadley circulation. The surface westerlies and surface trade winds are also marked, 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

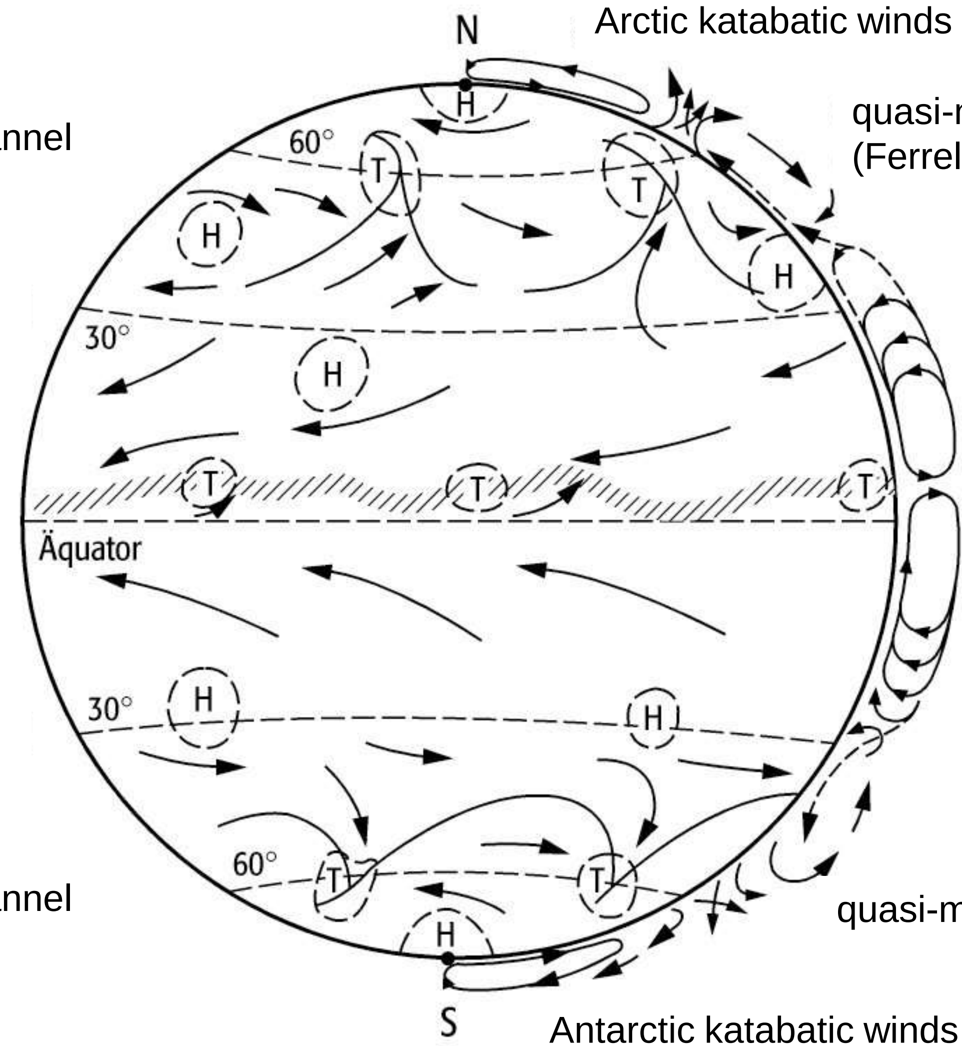
southeastern trades

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

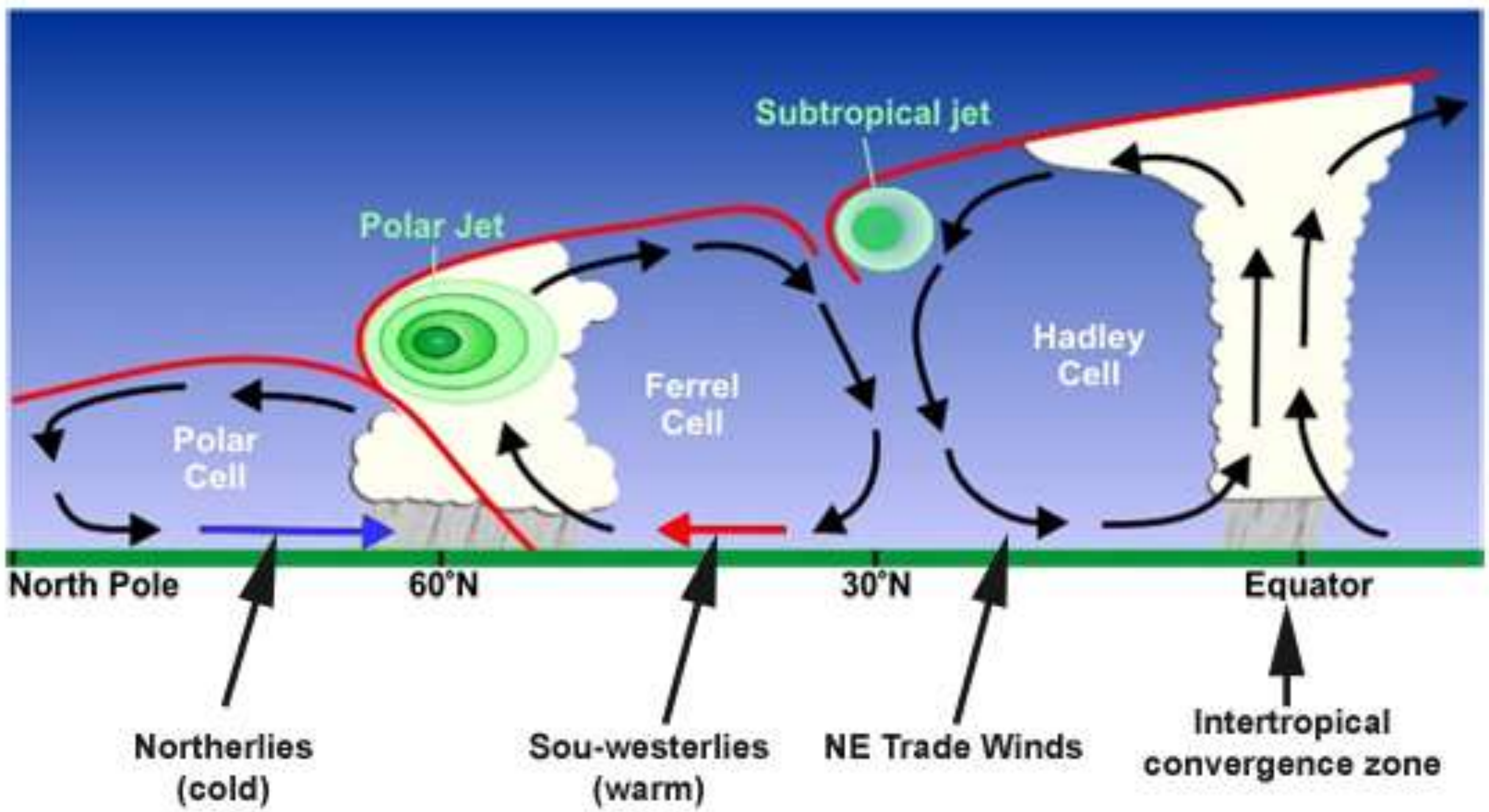
southern Hadley cell

quasi-meridional circulation

Antarctic katabatic winds

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

GCA: vertical-meridional flow



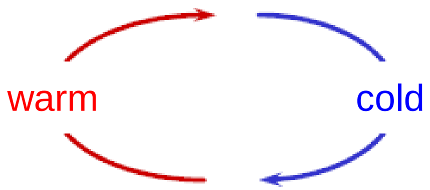
www.enso.info

Thermal direct circulation

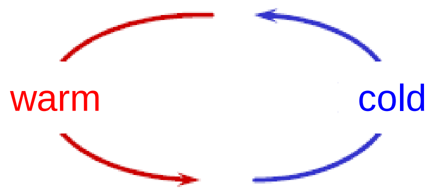
Thermally direct circulation: a circulation, in which warm air rises and cold air sinks, with available potential energy transforming into kinetic energy.

Thermally indirect circulation: opposite case.

thermally direct



thermally indirect



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

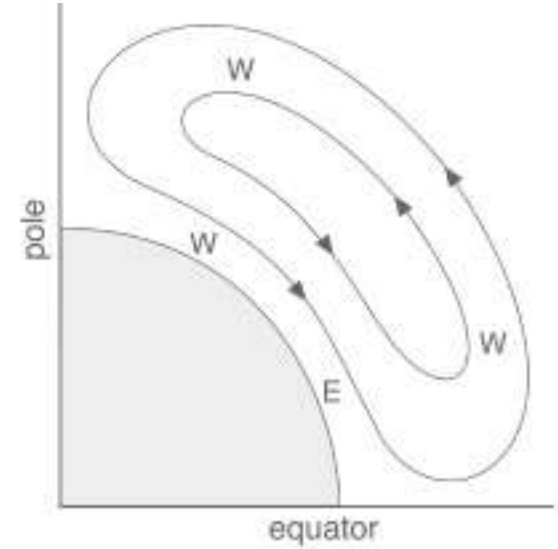


Figure 5.19: The circulation envisaged by Hadley (1735) comprising one giant meridional cell stretching from equator to pole. Regions where Hadley hypothesized westerly (W) and easterly (E) winds are marked.

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,**

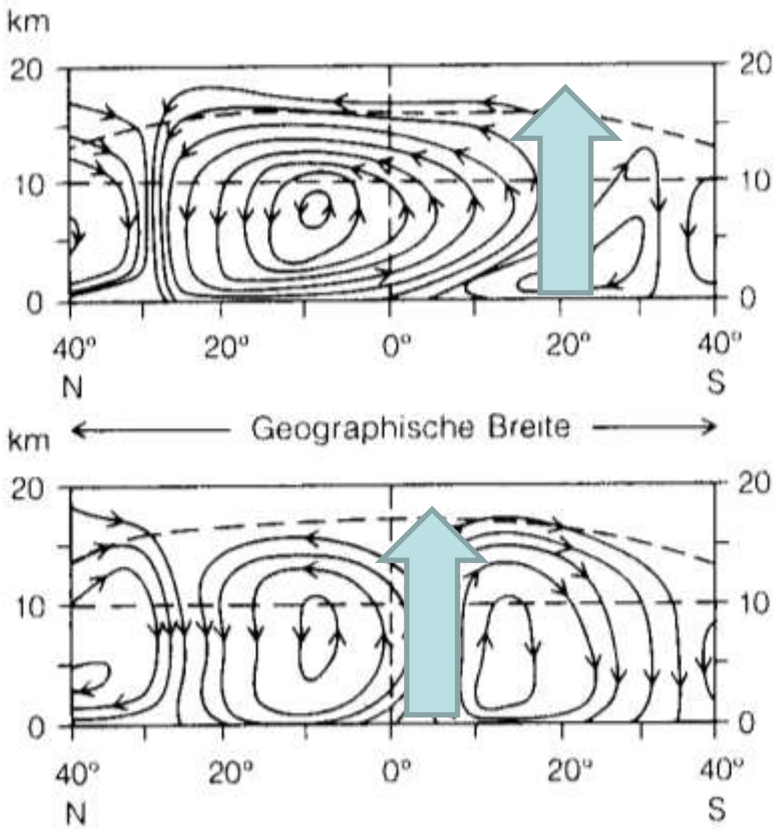
- zonal components (**easterlies** in the **lower troposphere**, **westerlies** in the **upper troposphere**) due to the earth's rotation,

- large regionally and seasonally variations.

Recap see also Ch. 5

Hadley cell's seasonal cycle

(see also Fig. 5.21)

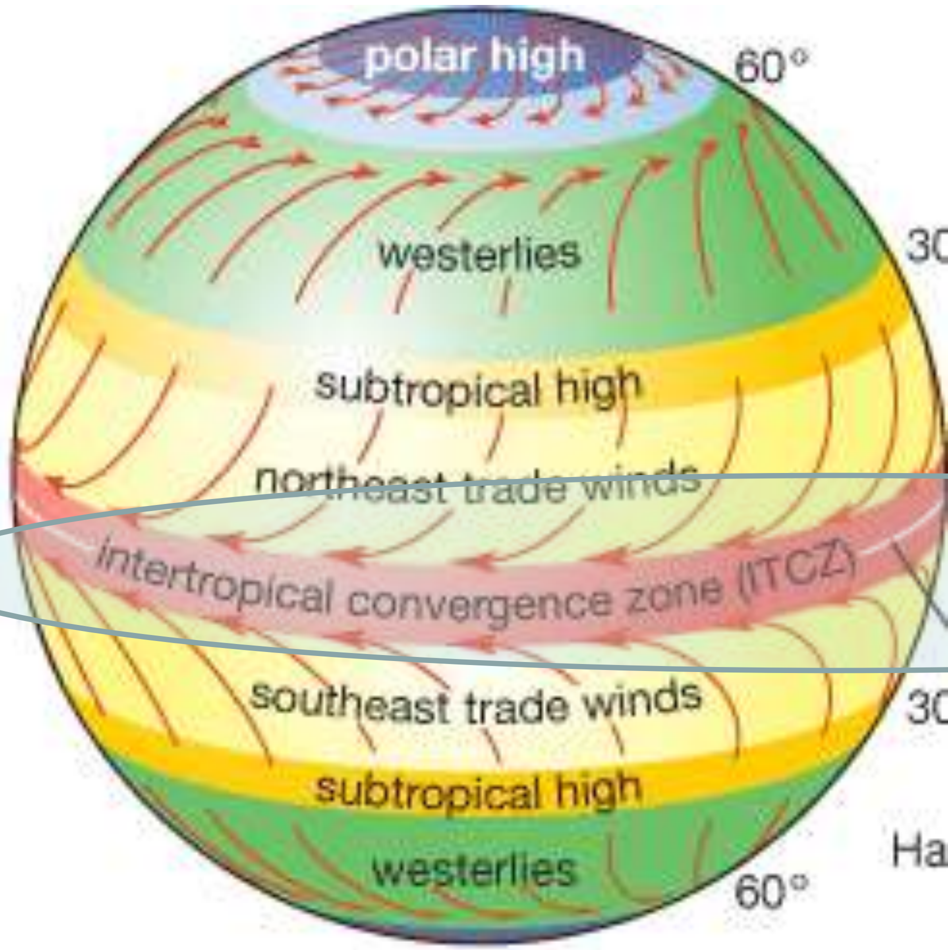


Northern winter/
Southern summer

Northern spring
(Mar-May)

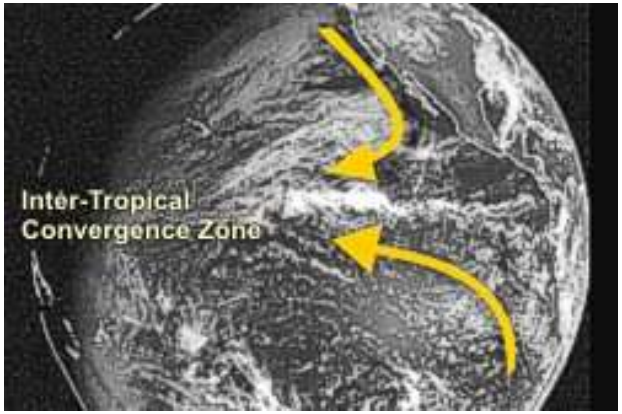
Roedel, 1997

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.

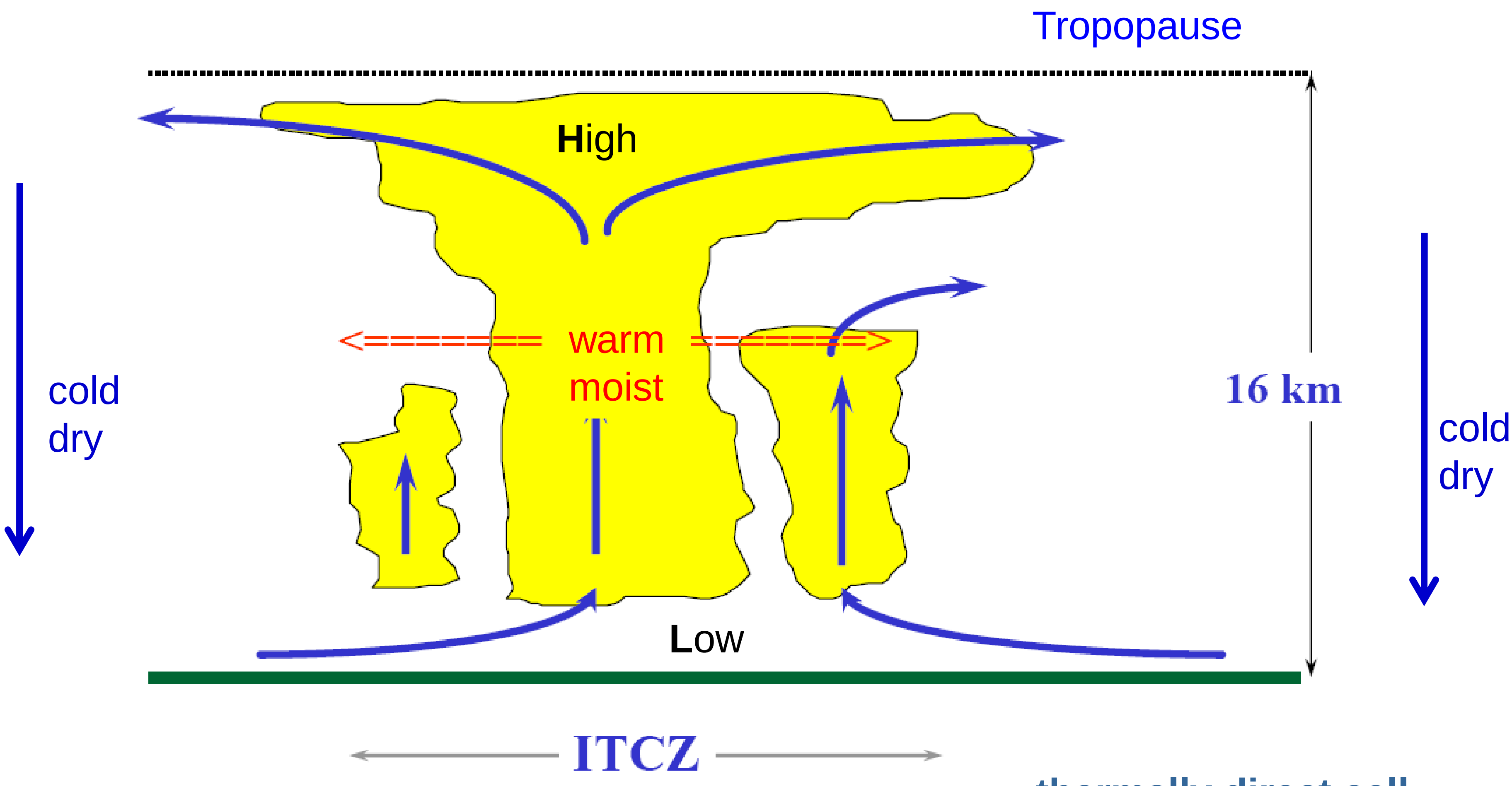
Land masses on the respective **summer hemisphere are warmer** than the adjacent **oceans**. In winter the land masses are colder than the ocean.

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

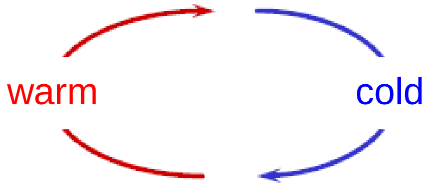
On average over a longer time period **air rises over moisture areas and sinks over dry areas**.

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**.

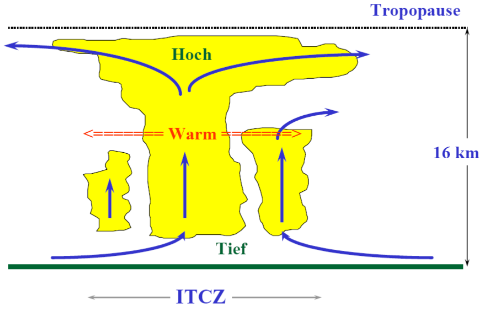
ITCZ



thermally direct cell



ITCZ – Summary



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

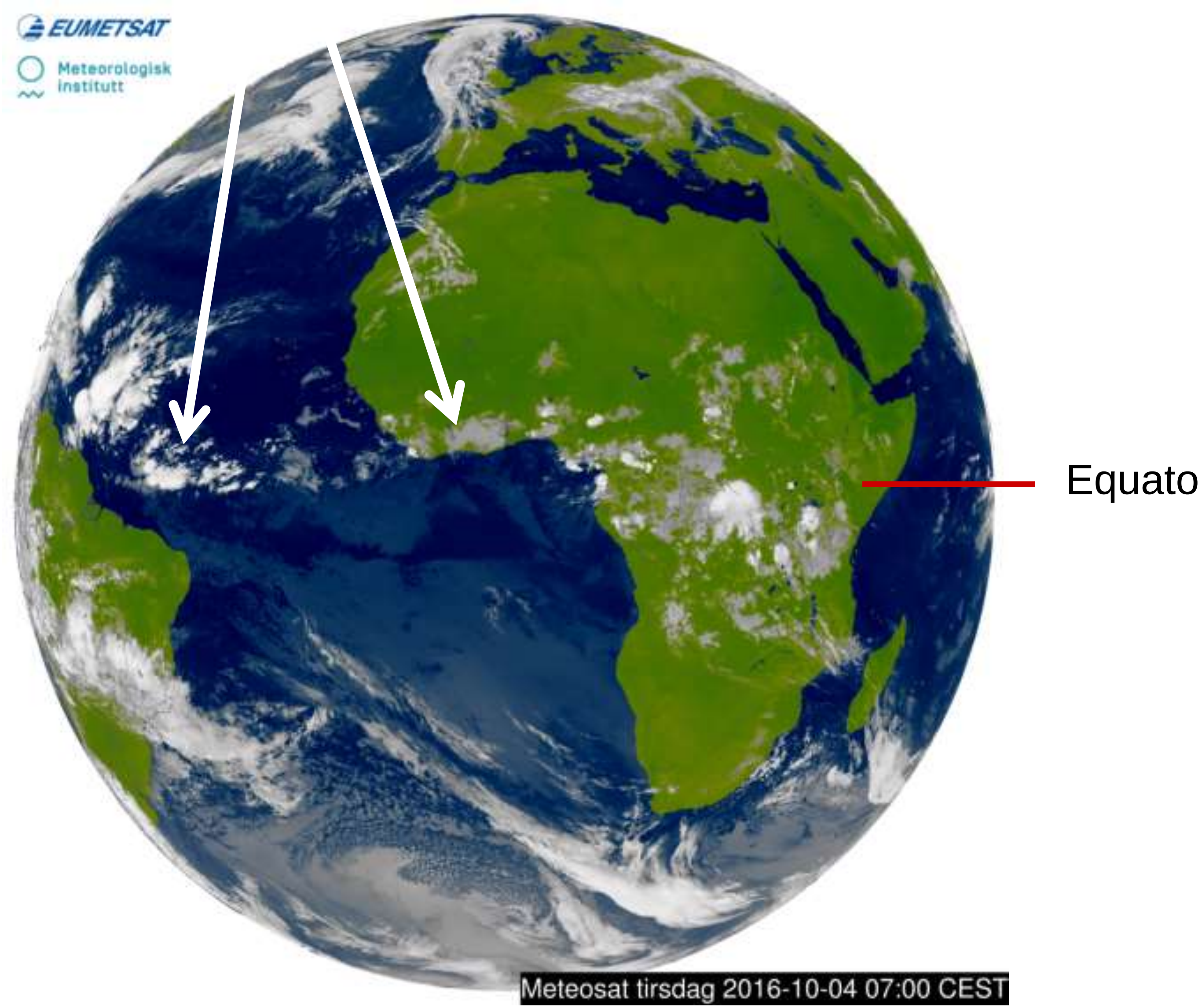
1. In nearly the entire troposphere, the **temperatures** are **higher than in** the **surroundings**.

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

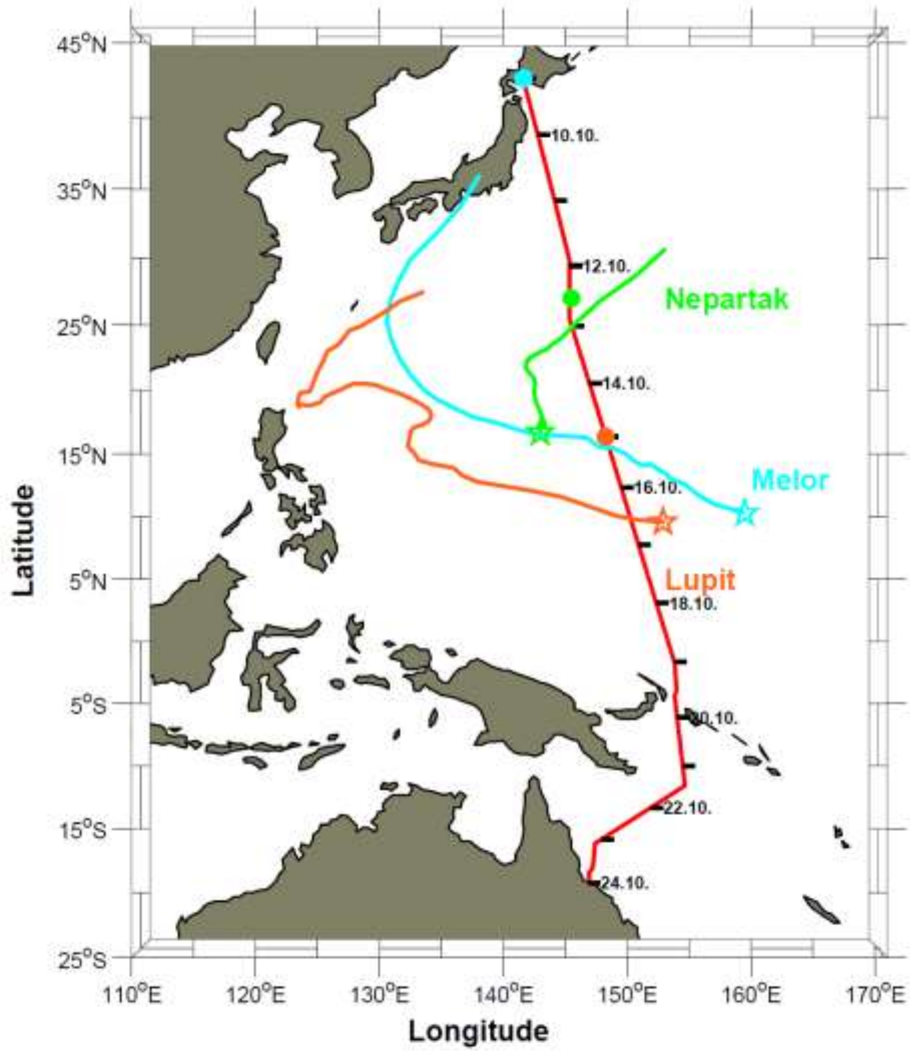


CEST: Central European Summer Time

www.yr.no/satellitt

TransBrom SONNE cruise Oct 2009

Cruise and tropical cyclones tracks

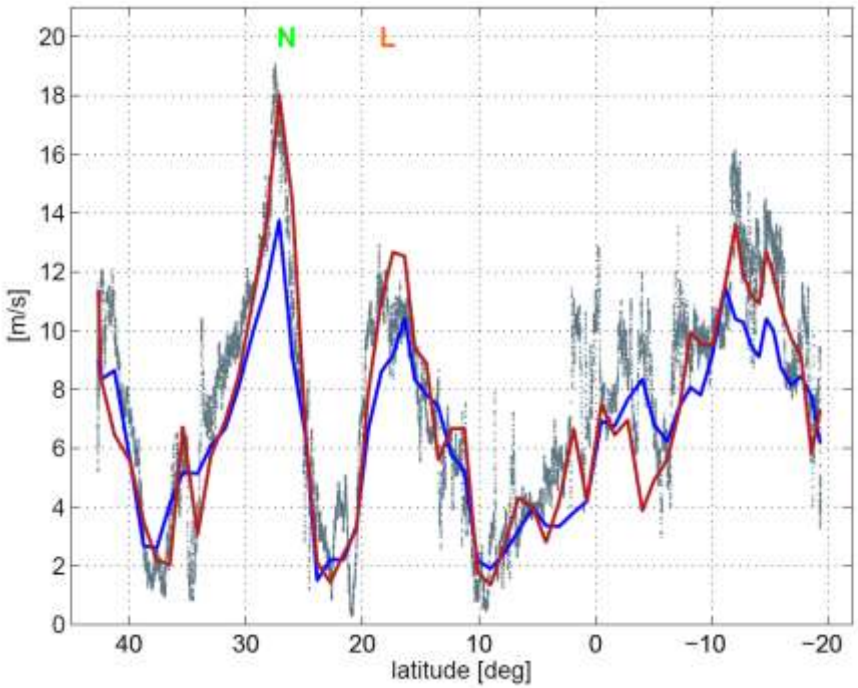


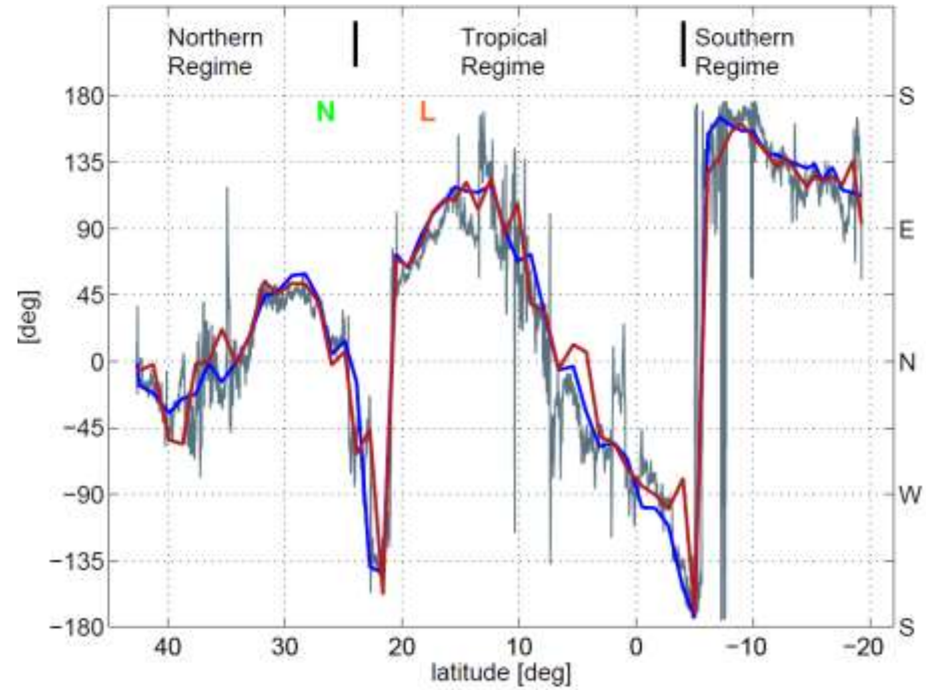
Melor

Krüger and Quack, 2013 ACP

TransBrom SONNE cruise Oct 2009

Average surface wind speed and direction

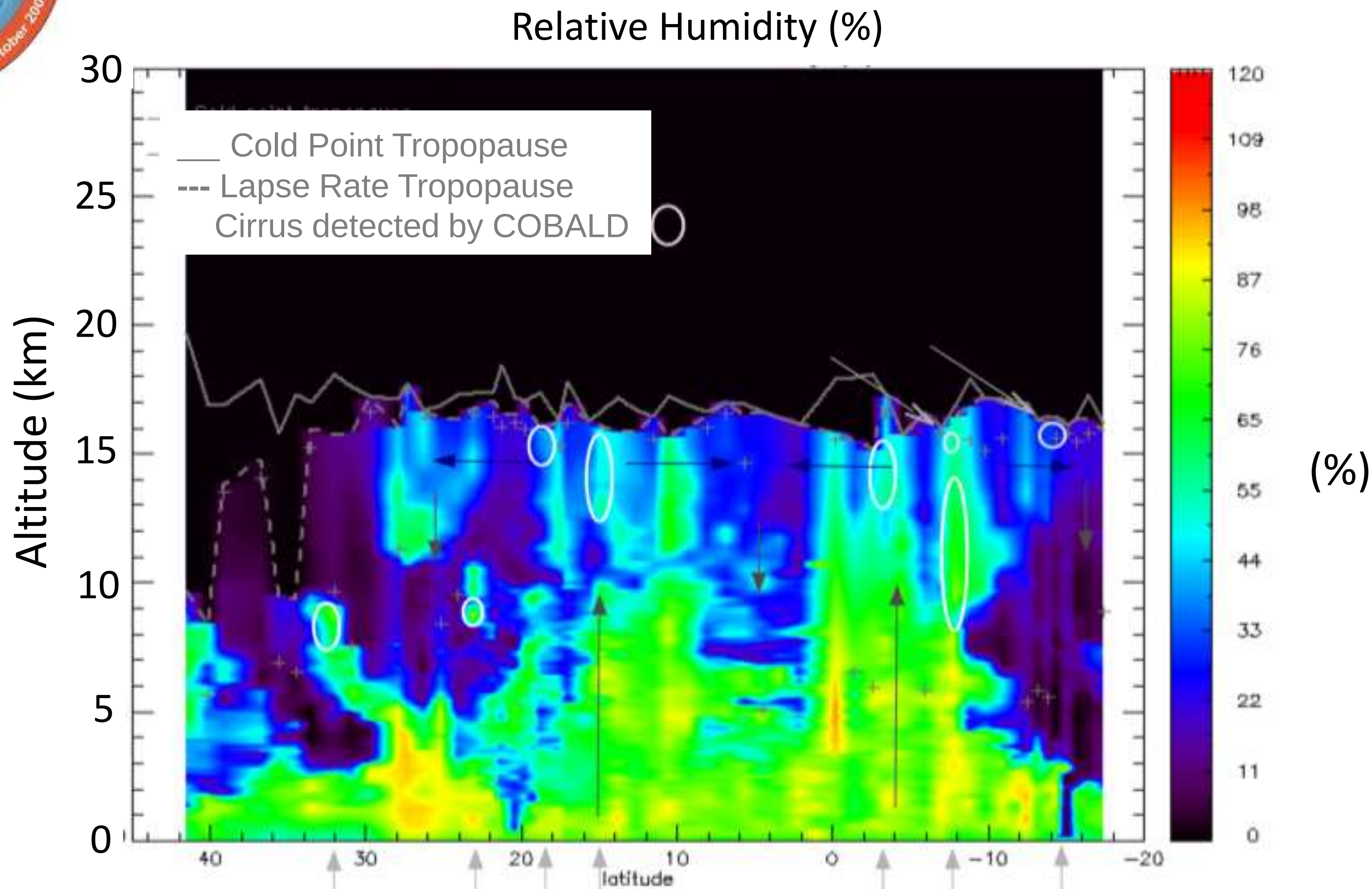




Tomakomai/Japan → Townsville/ Australia

Krüger and Quack, 2013 ACP

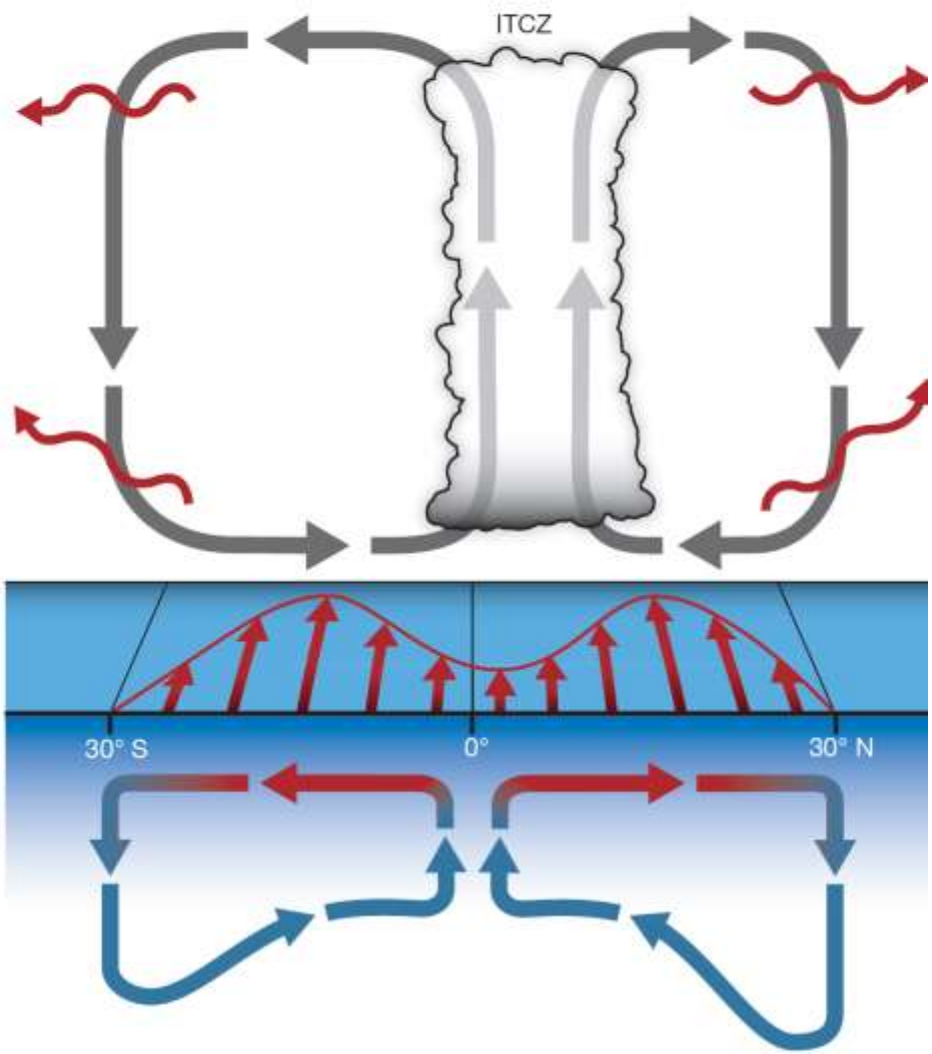
TransBrom SONNE cruise Oct 2009



Tomakomai/Japan  Townsville/ Australia

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

ITCZ – Atmosphere-Ocean Interactions



Schneider et al (Nature, 2014)

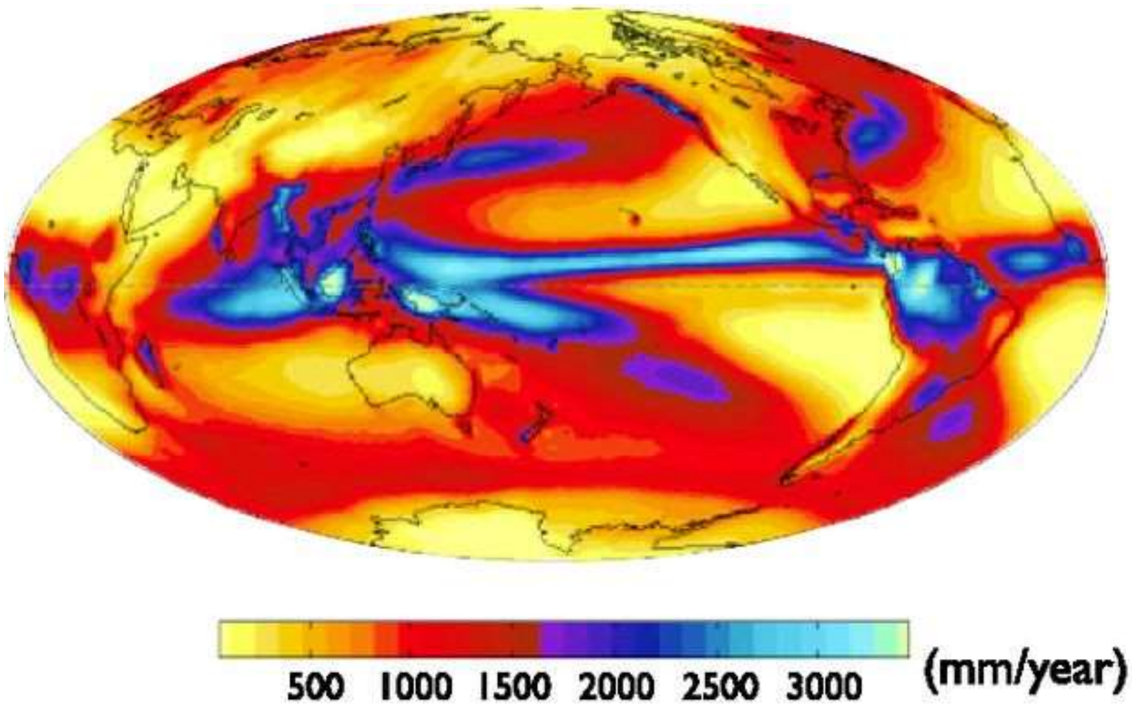
Atmospheric circulation
(Hadley circulation)

Energy flux (poleward)

Surface Easterly winds

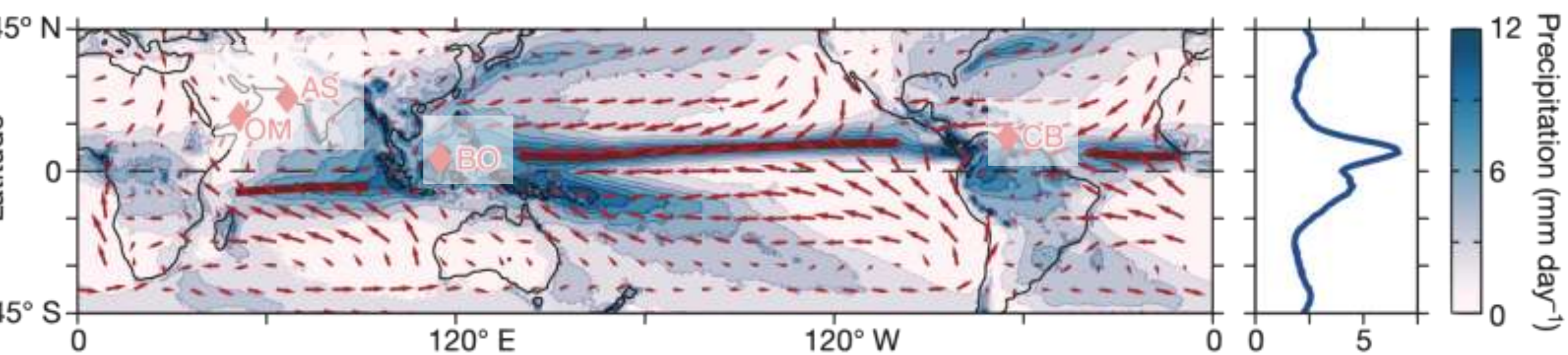
Ocean circulation (warm/cold)
Equatorial oceanic upwelling connected with the ITCZ.

ITCZ and precipitation: annual mean

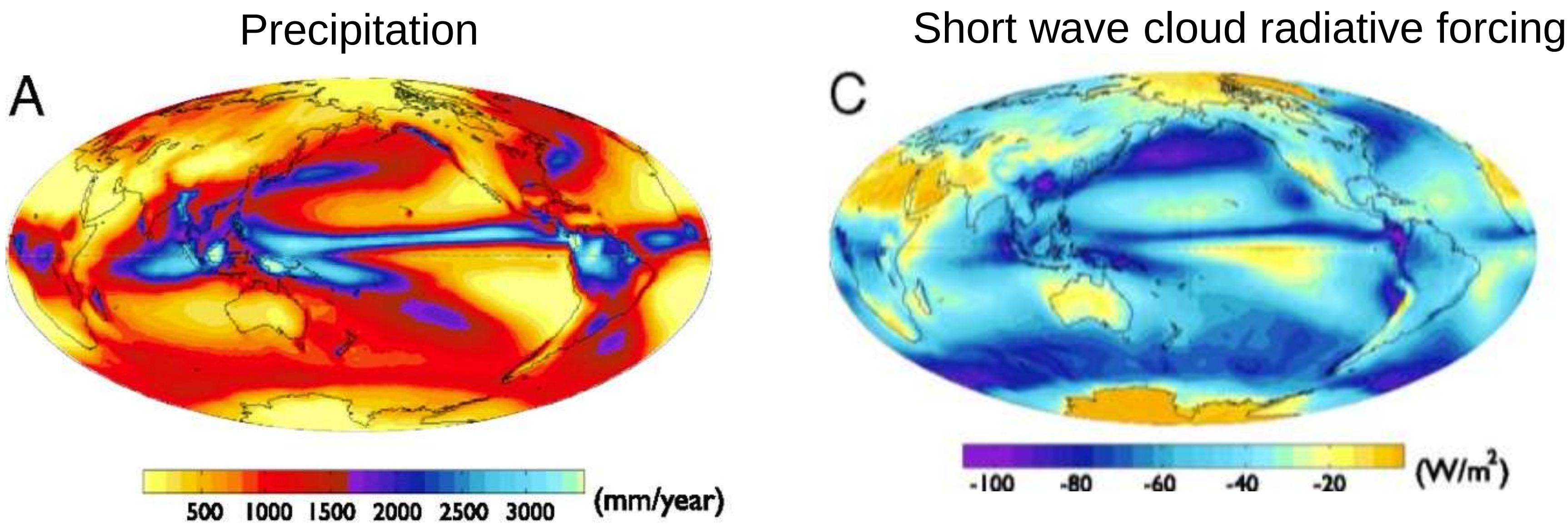


Upper figure: 1985–2004 Global Precipitation Climatology Project (Hwang and Frierson, 2013).

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).*



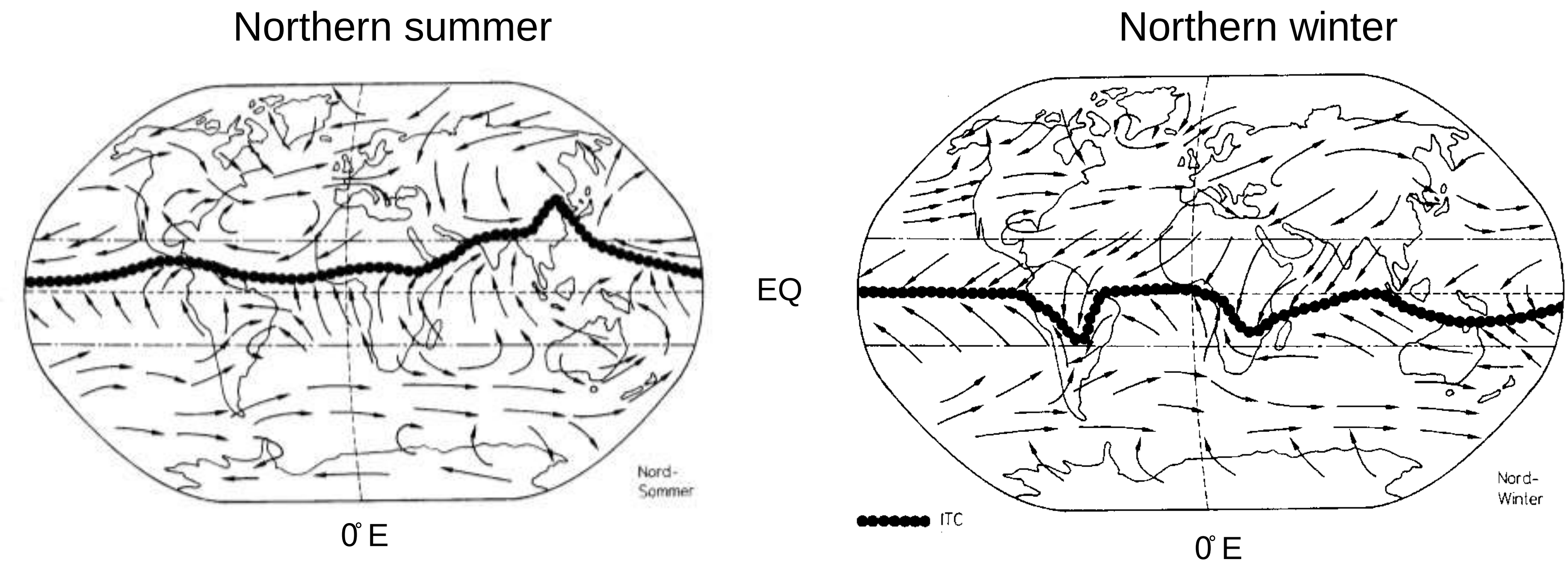
ITCZ – precipitation – radiation



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



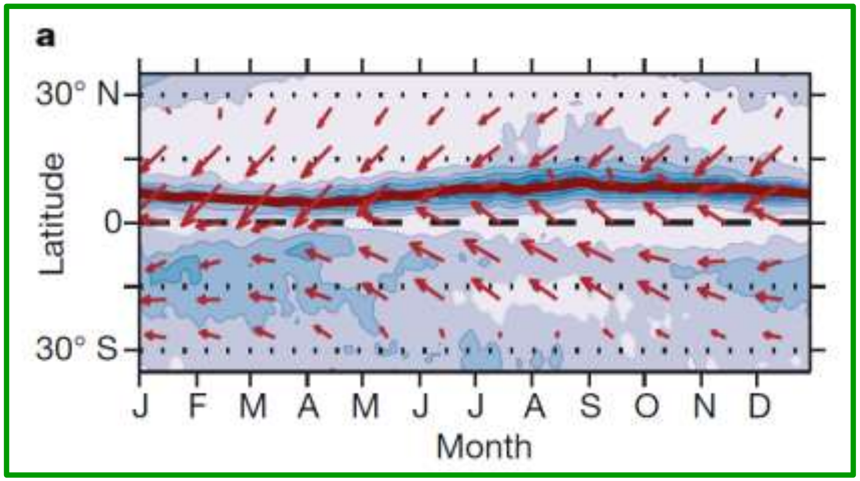
Roedel, 1997

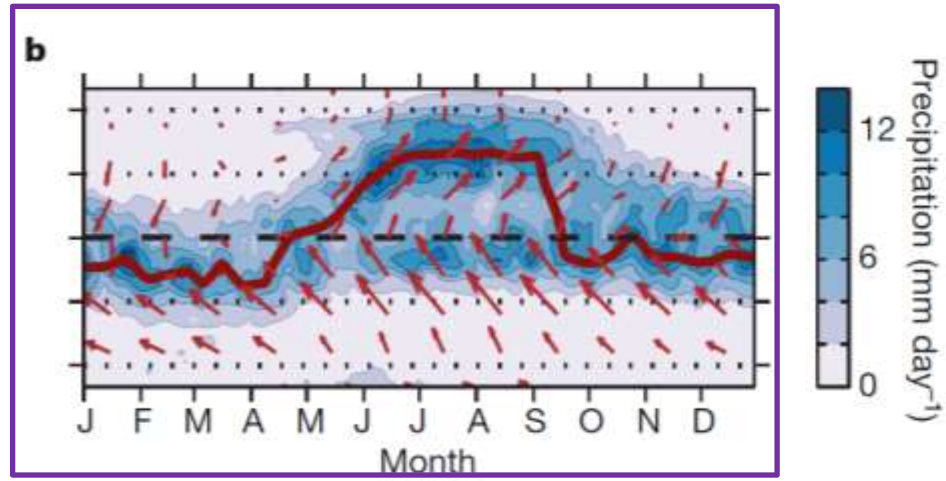
Figure: Surface winds and position of the ITCZ (after Lamb (1972) and Gross (1972)).

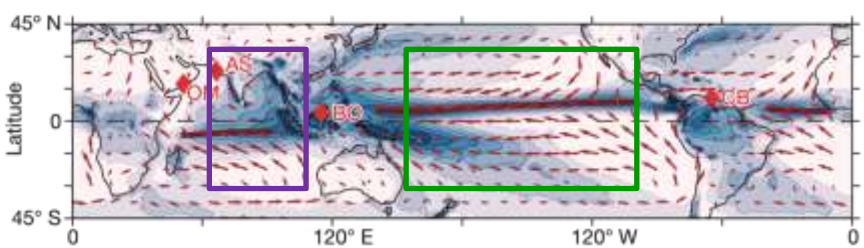
Seasonal migration of the ITCZ

Pacific(160˚E–100˚W)

Indian Ocean (65˚E–95˚E)







Precipitation

ITCZ

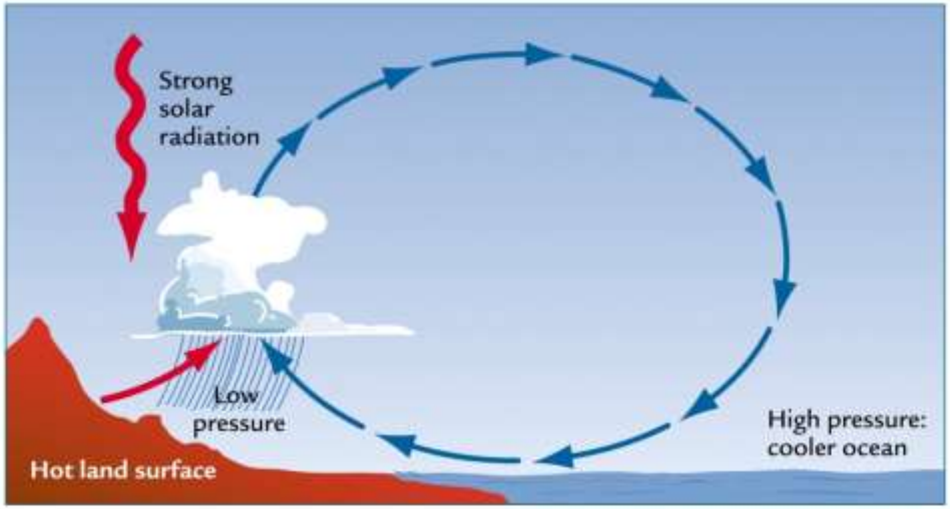
Surface winds

Schneider et al (Nature, 2014)

Monsoon circulation

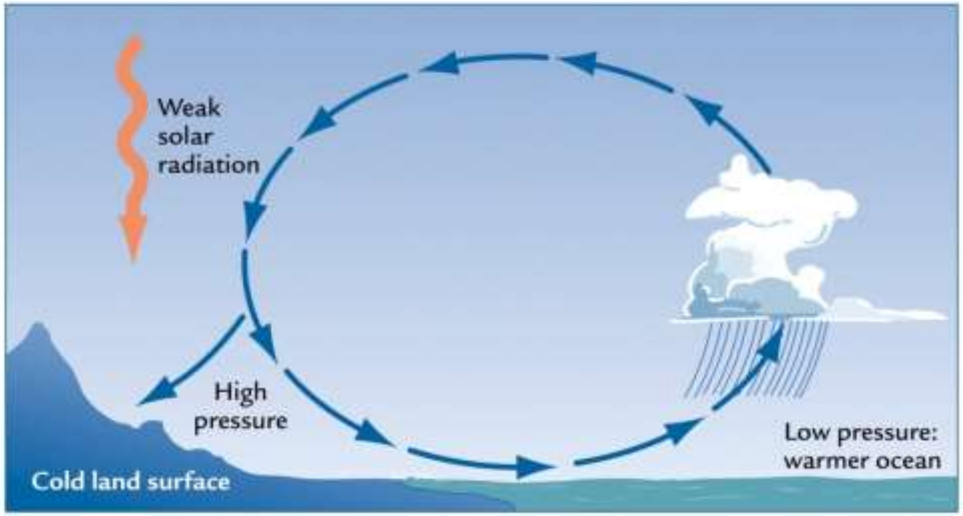
arabic ‘mawsim’ = season

Summer



A Summer monsoon

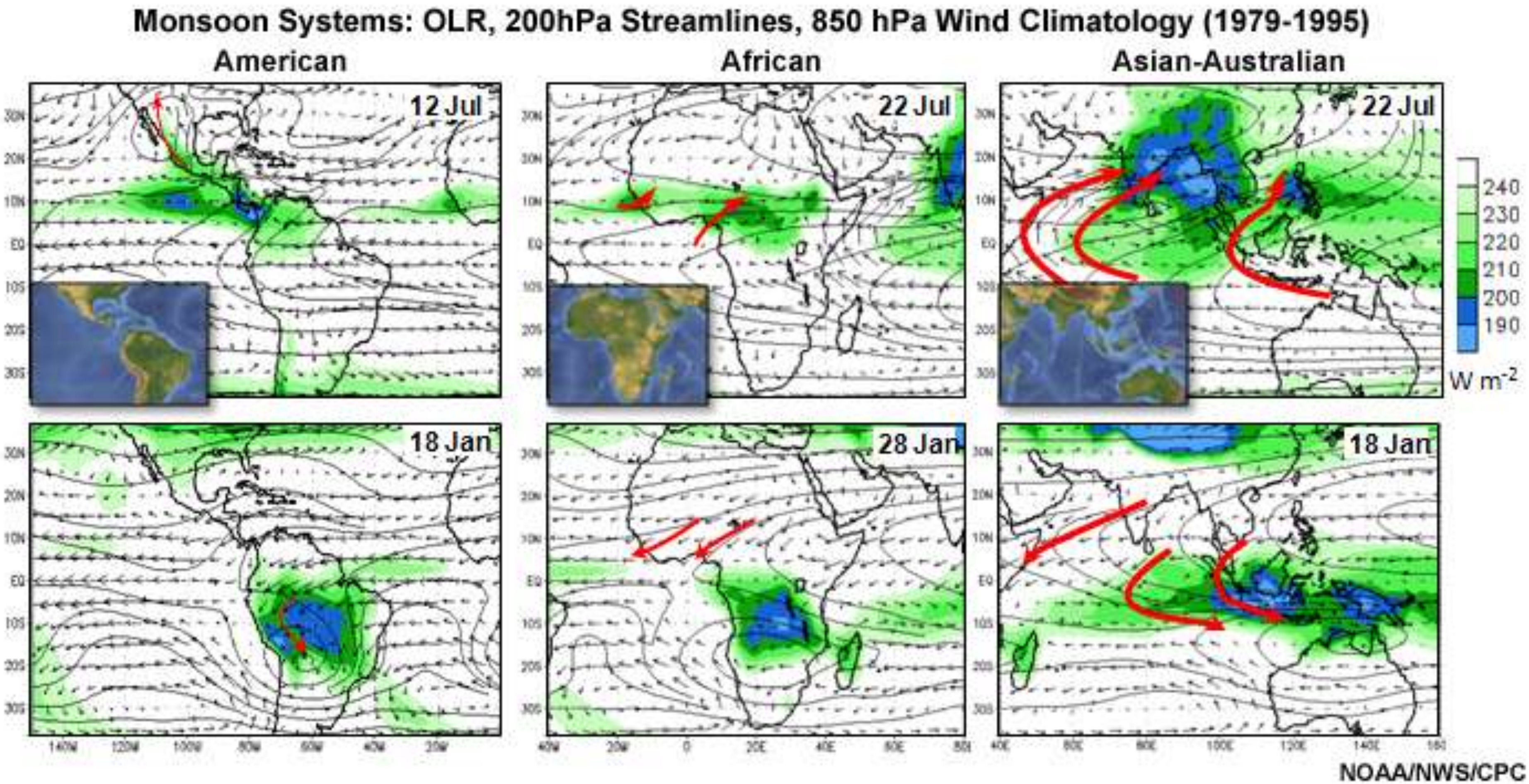
Winter



B Winter monsoon

Ruddiman, 2001

Monsoon systems

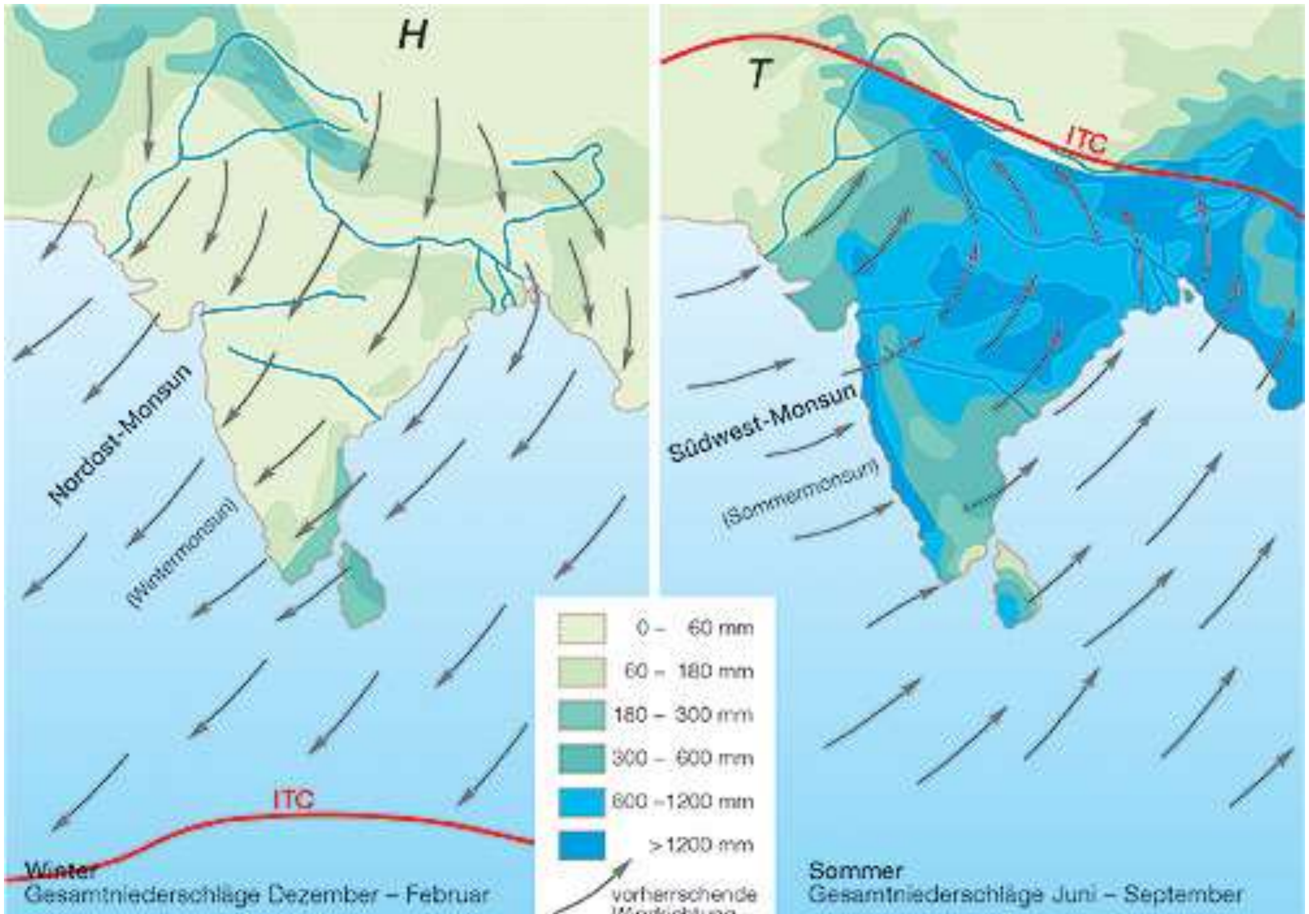


OLR:
Outgoing longwave radiation

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).