Atmospheric dynamics

Ramesh Vellore
IITM
2020-21
rameshv@tropmet.res.in

Geophysical Fluid Dynamics

- ***An amount of energy from the Sun is intercepted by the Earth. While almost this amount of energy is ultimately radiated back to space, Earth's spherical shape and rotation causes local imbalance between incoming and outgoing radiation. This discrepancy gives rise to motions. Understanding the structure and dynamics of the atmosphere is central to forecasting weather and understanding climate.***

- ***This training course aims to build a fundamental set of physical principles and apply them to understanding large-scale atmospheric motions.***

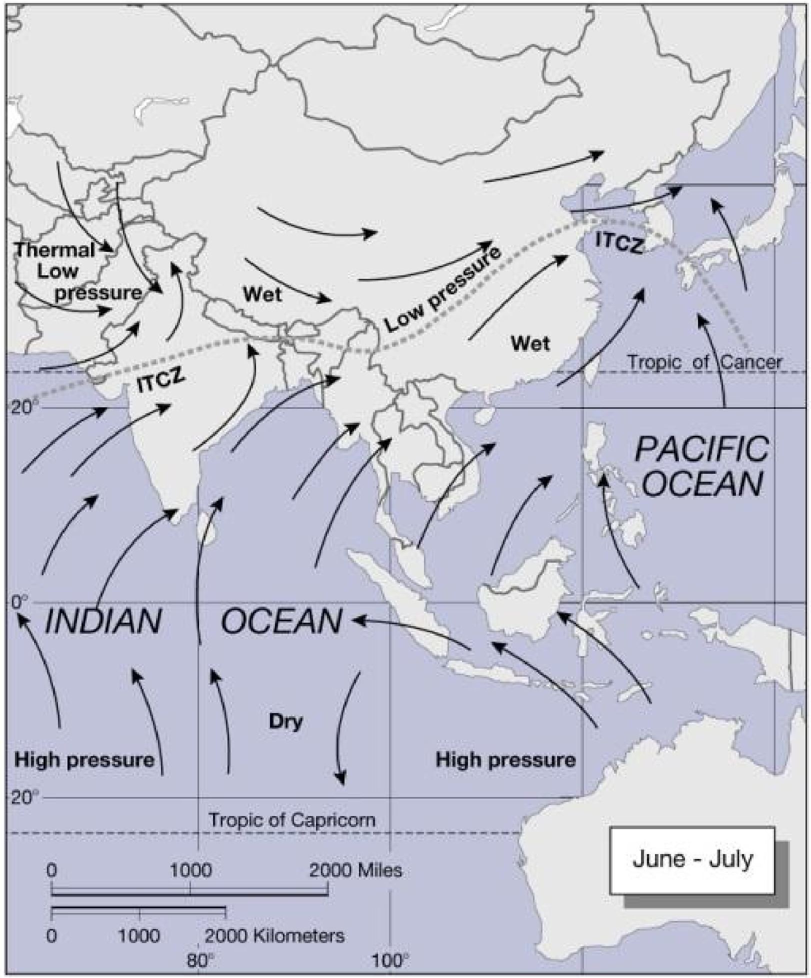
- ***Mathematical descriptions of the atmospheric dynamics are constructed and interpreted in terms of their physical significance.***
  - ***By the end of this course we will have investigated phenomena such as the forces in the atmosphere , the thermodynamics of the atmosphere, the wave motions and planetary waves, the planetary boundary layer, and aspects of the general circulation of the atmosphere.***

Recommended text books

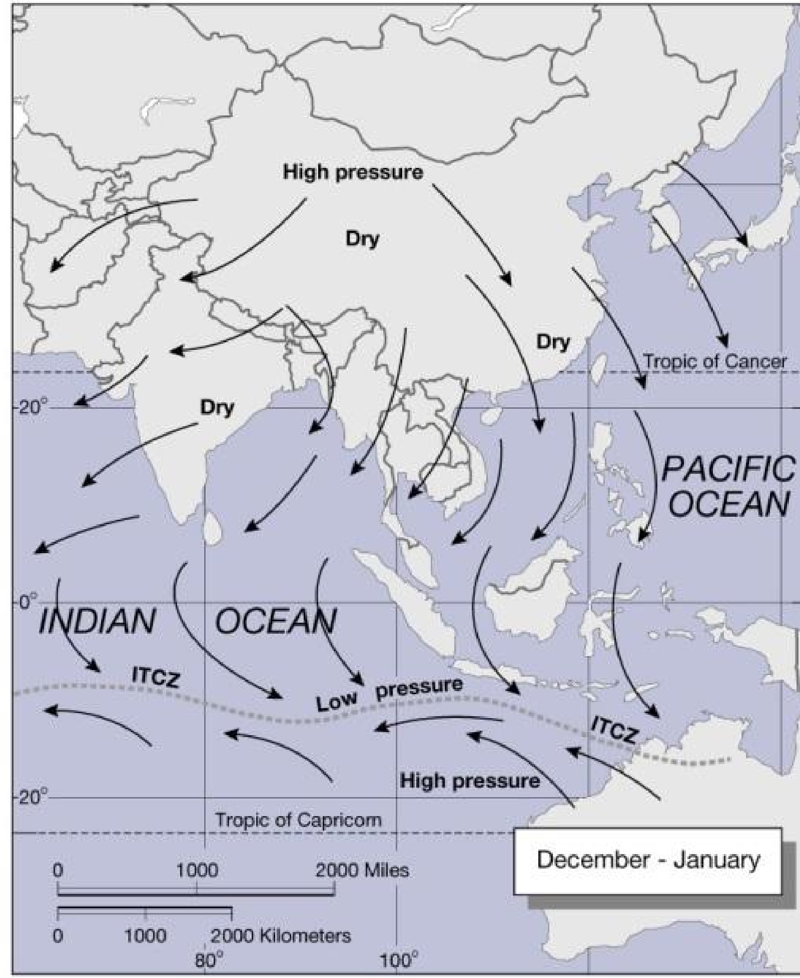
- *Holton, J. R. and Hakim (2013): An introduction to dynamic meteorology, International Geophysics Series.*
- *Wallace, J. M., and P. V. Hobbs, (2006): Atmospheric Science: An introductory Survey, Academic Press.*
- *Hess, S. L. (1959): Introduction to theoretical meteorology, Holt, New York.*

- *Gill (1982): Atmosphere-Ocean Dynamics, International Geophysical Series*
- *Barry and Carleton (2001): Synoptic and dynamic climatology.*
- *Roland Stull (1988): An introduction to Boundary Layer Meteorology, Kluwer Academic Press.*
- *Robert Brown (1991): Fluid mechanics of the atmosphere, International Geophysics Series.*
- *Joseph Pedlosky (2003): Waves in the ocean and atmosphere – Introduction to wave dynamics, Springer-Verlag.*
- *Carmen Nappo, (2002): An introduction to atmospheric gravity waves, International Geophysics Series.*
- *John Green (1999): Atmospheric Dynamics. Cambridge Atmospheric and Space Science series.*
- *Kraus and Businger (1994): Atmosphere-Ocean interaction. Oxford University Press.*
- *Geoffrey Vallis (2006): Atmospheric and Oceanic fluid dynamics, Cambridge University Press.*

Monsoons: What you are familiar



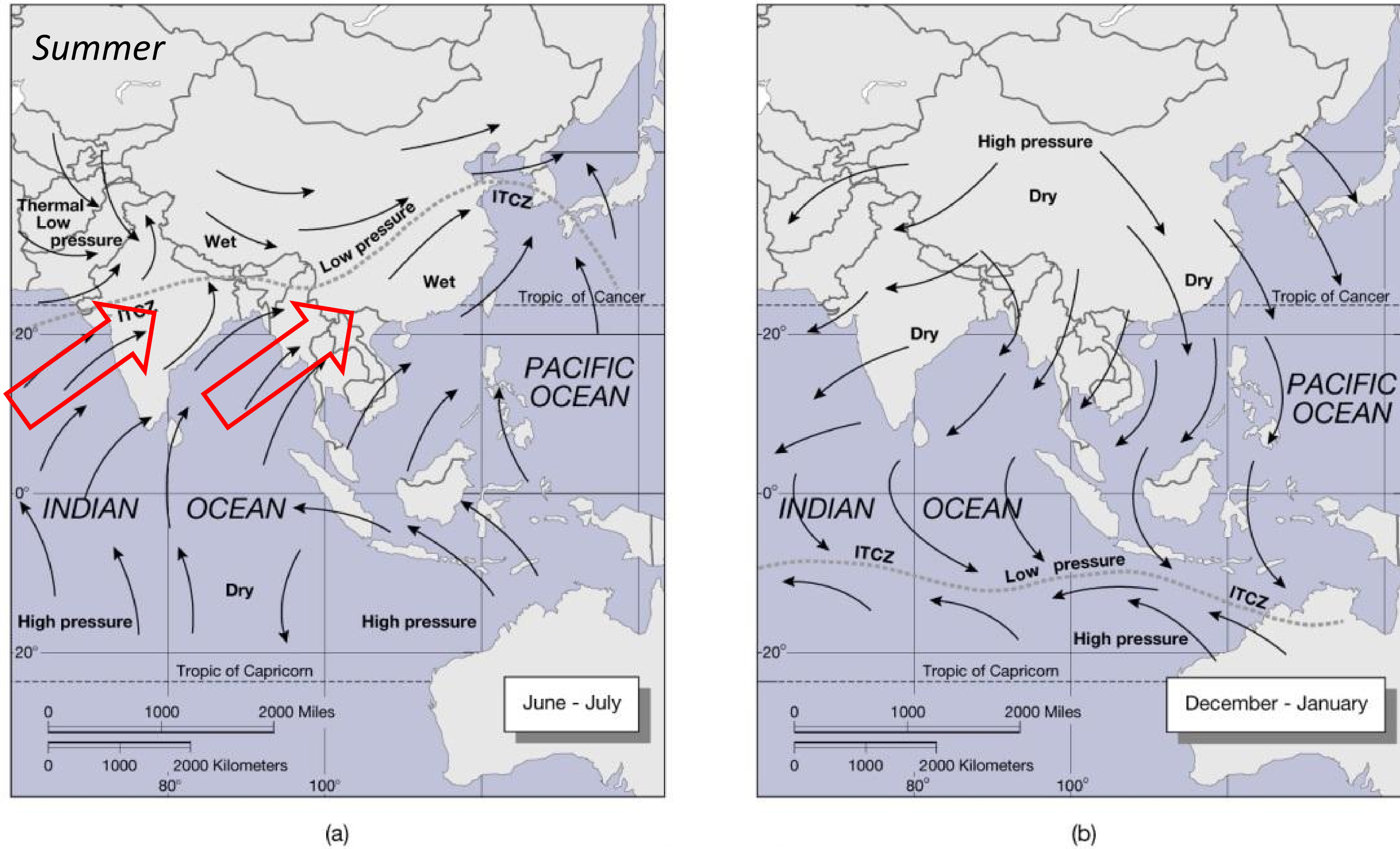
(a)



(b)

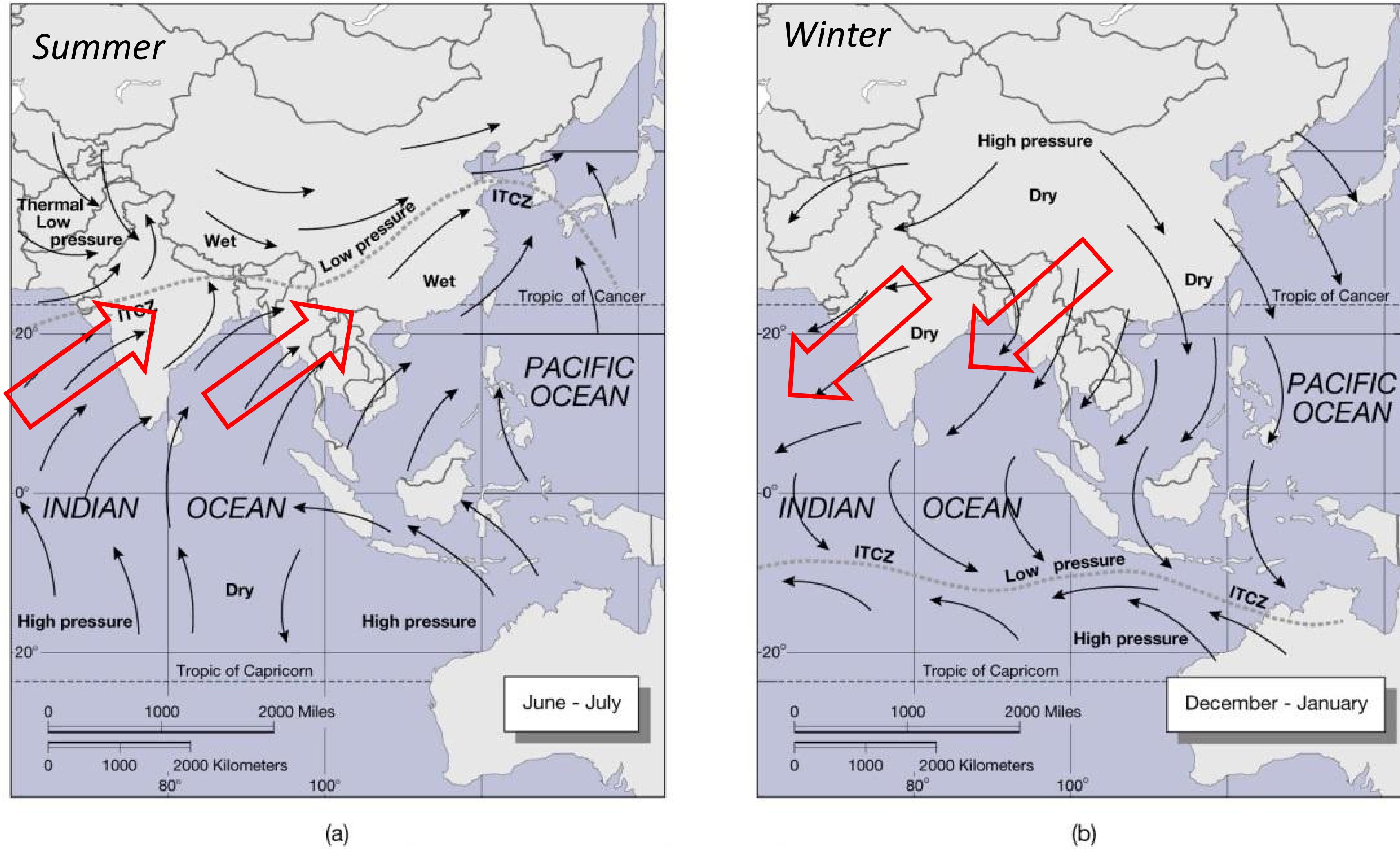
What looks different in these?

Monsoons: What you are familiar

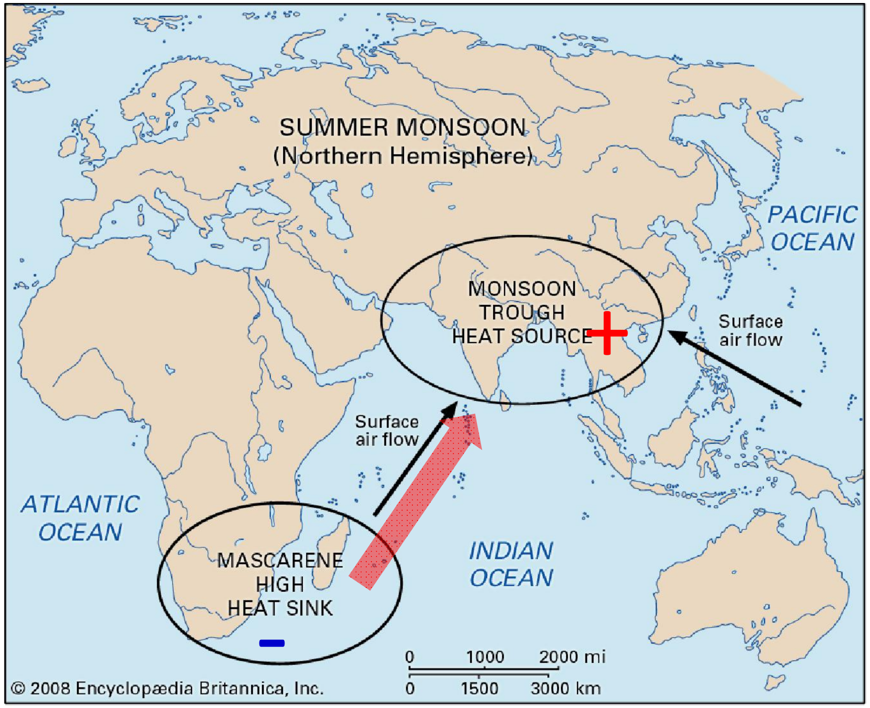


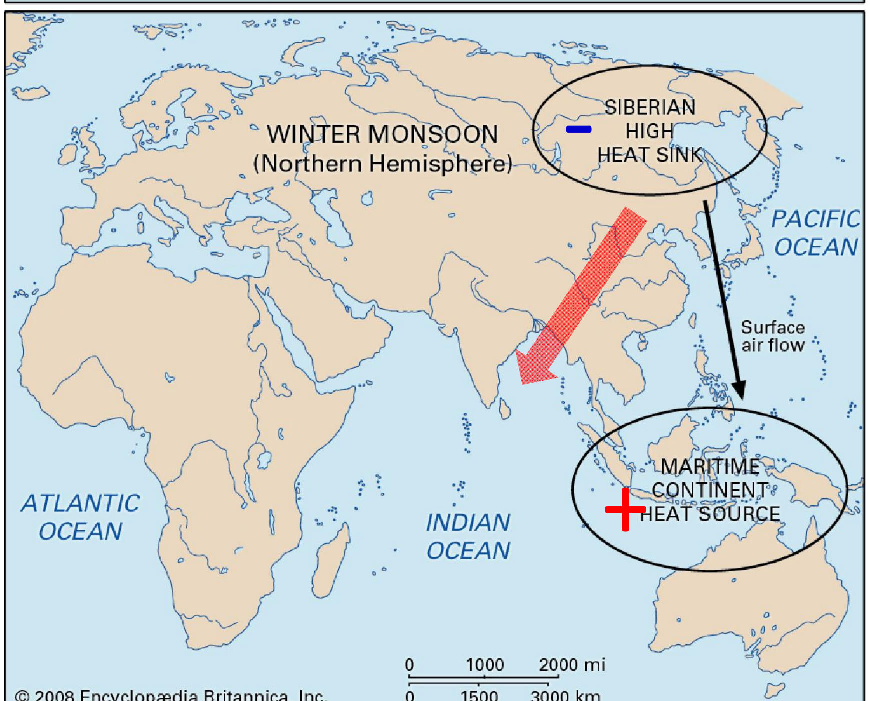
What looks different in these?

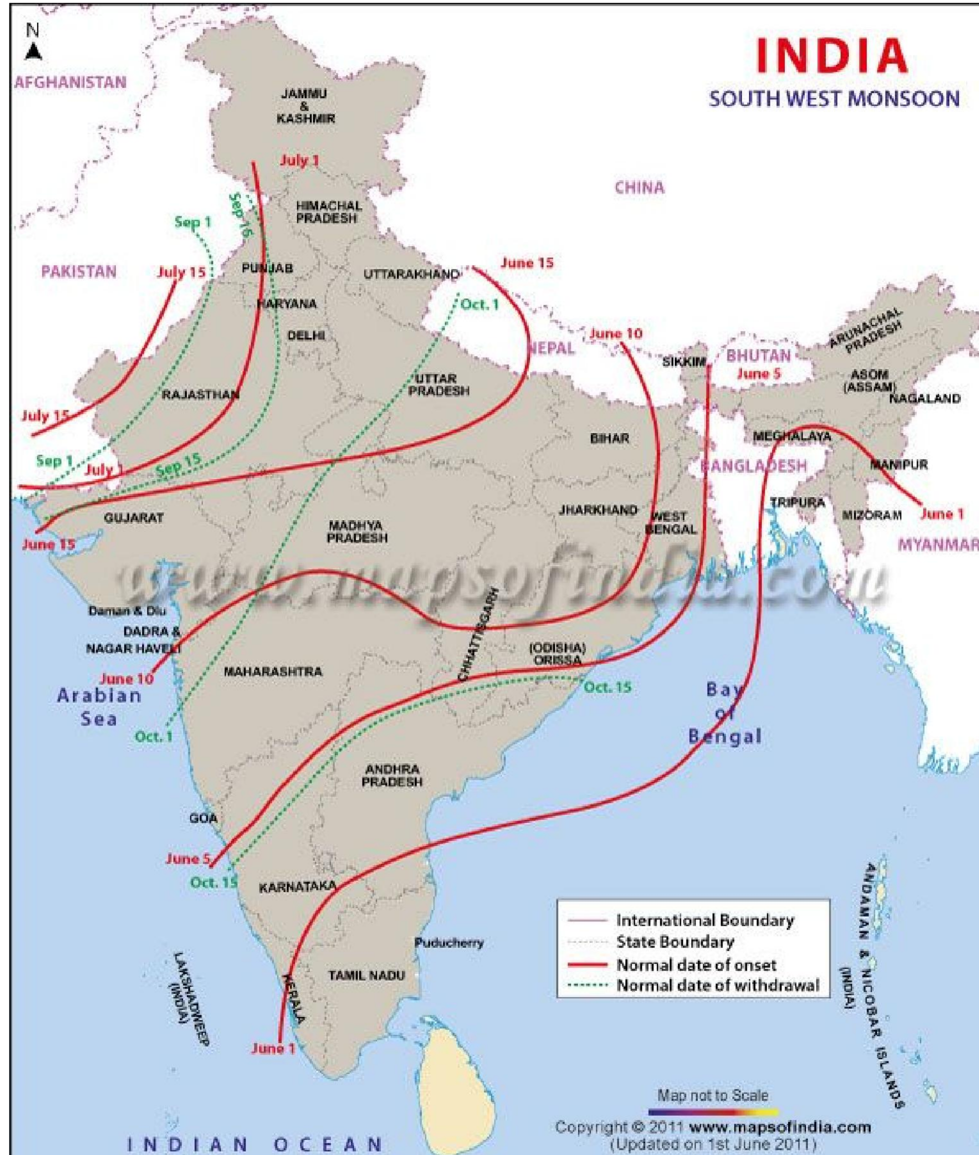
Monsoons: What you are familiar

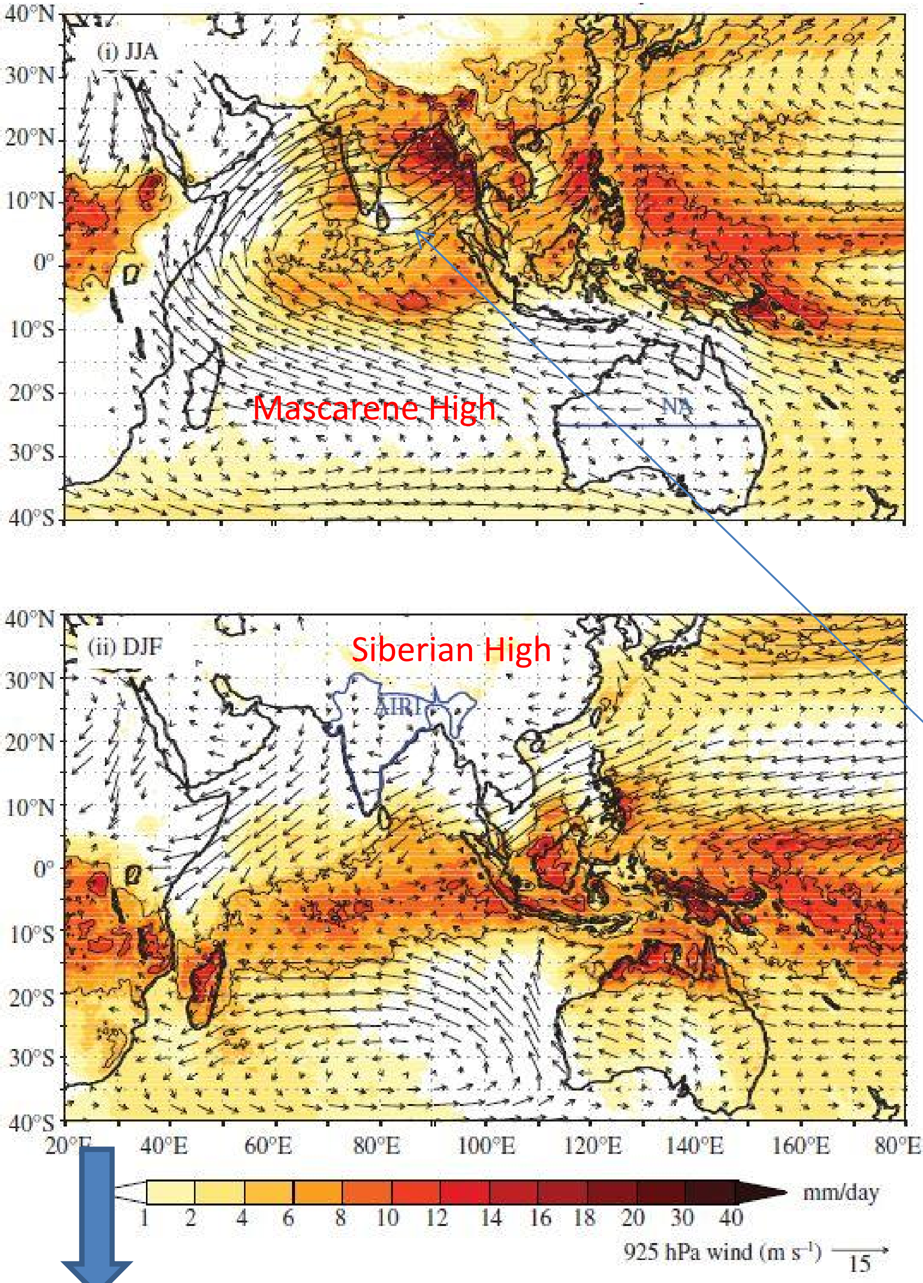


What looks different in these?


SUMMER MONSOON
(Northern Hemisphere)
PACIFIC OCEAN
MONSOON TROUGH HEAT SOURCE
Surface air flow
Surface air flow
ATLANTIC OCEAN
MASCARENE HIGH HEAT SINK
INDIAN OCEAN
0 1000 2000 mi
0 1500 3000 km
© 2008 Encyclopædia Britannica, Inc.


WINTER MONSOON
(Northern Hemisphere)
SIBERIAN HIGH HEAT SINK
PACIFIC OCEAN
Surface air flow
ATLANTIC OCEAN
INDIAN OCEAN
MARITIME CONTINENT HEAT SOURCE
0 1000 2000 mi
0 1500 3000 km
© 2008 Encyclopædia Britannica, Inc.


INDIA
SOUTH WEST MONSOON
N
AFGHANISTAN
PAKISTAN
CHINA
NEPAL
BHUTAN
BANGLADESH
MYANMAR
JAMMU & KASHMIR
HIMACHAL PRADESH
PUNJAB
HARYANA
DELHI
UTTARAKHAND
RAJASTHAN
UTTAR PRADESH
BIHAR
SIKKIM
ARUNACHAL PRADESH
ASOM (ASSAM)
NAGALAND
MEGHALAYA
MANIPUR
TRIPURA
MIZORAM
GUJARAT
MADHYA PRADESH
JHARKHAND
WEST BENGAL
CHHATTISGARH
(ODISHA) ORISSA
Daman & Diu
DADRA & NAGAR HAVELI
MAHARASHTRA
GOA
ANDHRA PRADESH
KARNATAKA
Puducherry
TAMIL NADU
KERALA
LAKSHADWEEP (INDIA)
ANDAMAN & NICOBAR ISLANDS (INDIA)
Arabian Sea
Bay of Bengal
INDIAN OCEAN
July 1
July 15
July 15
July 1
June 15
June 15
June 10
June 10
June 5
June 5
June 1
June 1
Sep 1
Sep 15
Sep 1
Sep 15
Oct. 1
Oct. 1
Oct. 15
Oct. 15
International Boundary
State Boundary
Normal date of onset
Normal date of withdrawal
Map not to Scale
Copyright © 2011 www.mapsofindia.com
(Updated on 1st June 2011)
www.mapsofindia.com

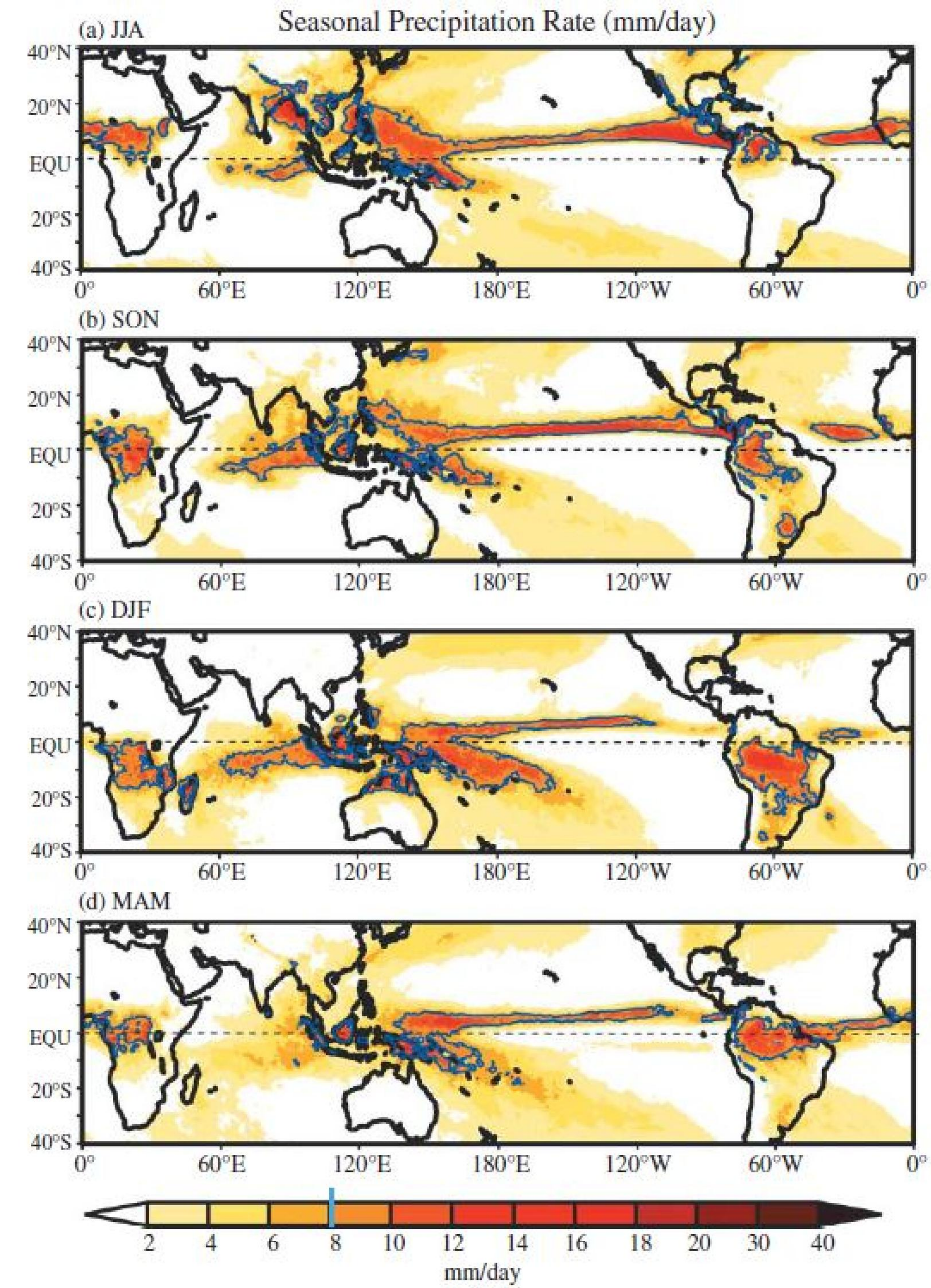


Precipitation (colour contours: mm day^{-1}) and 925 hPa velocity vectors (m s^{-1})

The lower tropospheric flow continues northward and then eastward toward the Western Ghats, a chain of mountains extending down the west coast of India where upslope flow produces a precipitation maximum. The flow then converges into the trough over the Bay of Bengal.

There are two reasons for the precipitation maximum located in the northeast sector of the Bay. First, the SST is warm and remains warm because of the very low upper ocean salinity. The low salinity is a result of the precipitation itself and river runoff into the Bay from three of the largest rivers on the planet. The second reason for the maximum precipitation is because of the mountain ranges to the east of the Bay.

Maximum precipitation is now found in a band stretching from Sumatra in the east andextending slightly poleward toward Madagascar and East Africa in the west

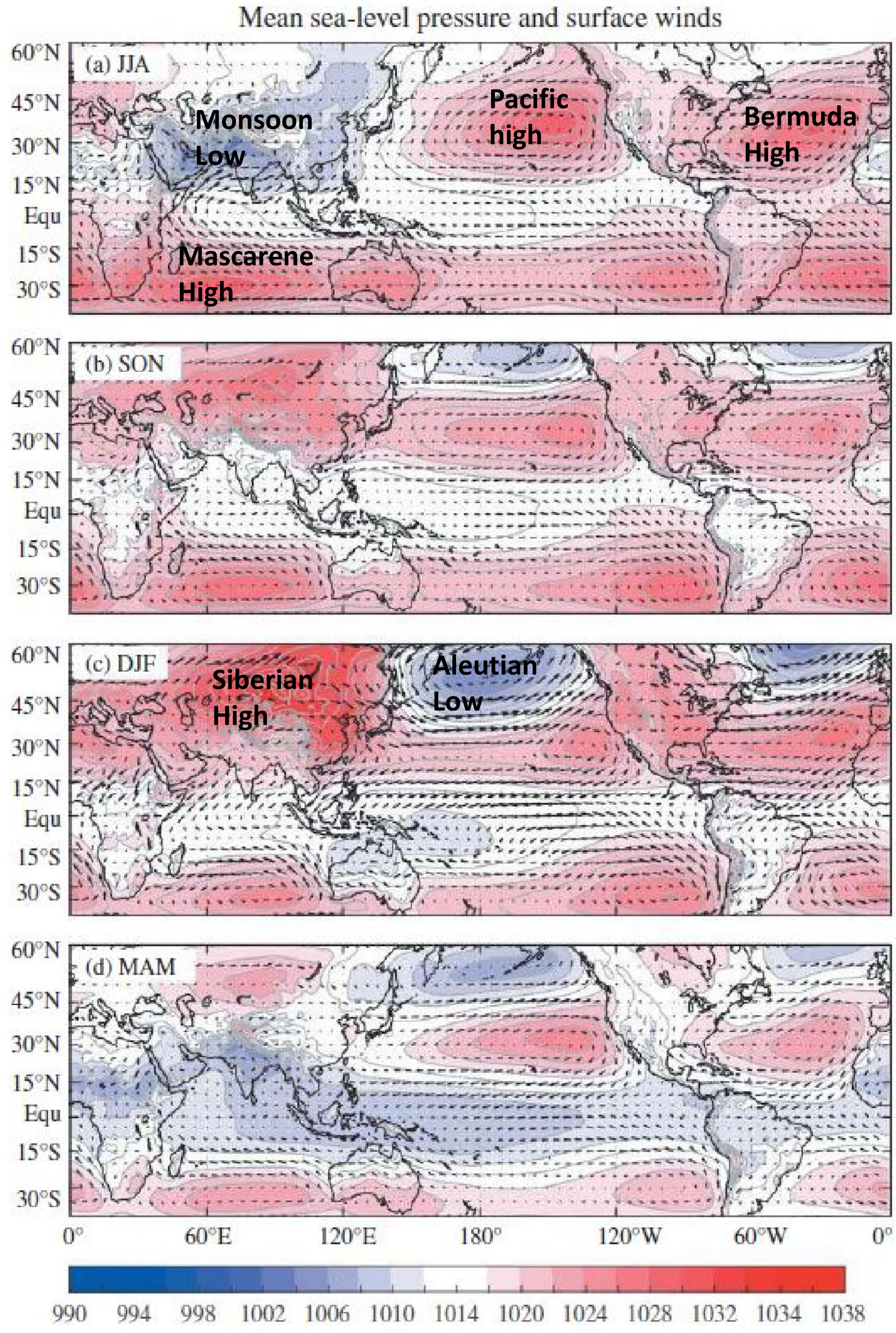


Boreal summer JJA: The NH rainfall rates are at their most intense. There are high rainfall rates in the warm pool region of the western Pacific but the largest occurs in the Northern Bay of Bengal (16 – 18mm day^{-1}). There is also substantial rainfall across Central and West Africa, the latter associated with the West African Monsoon

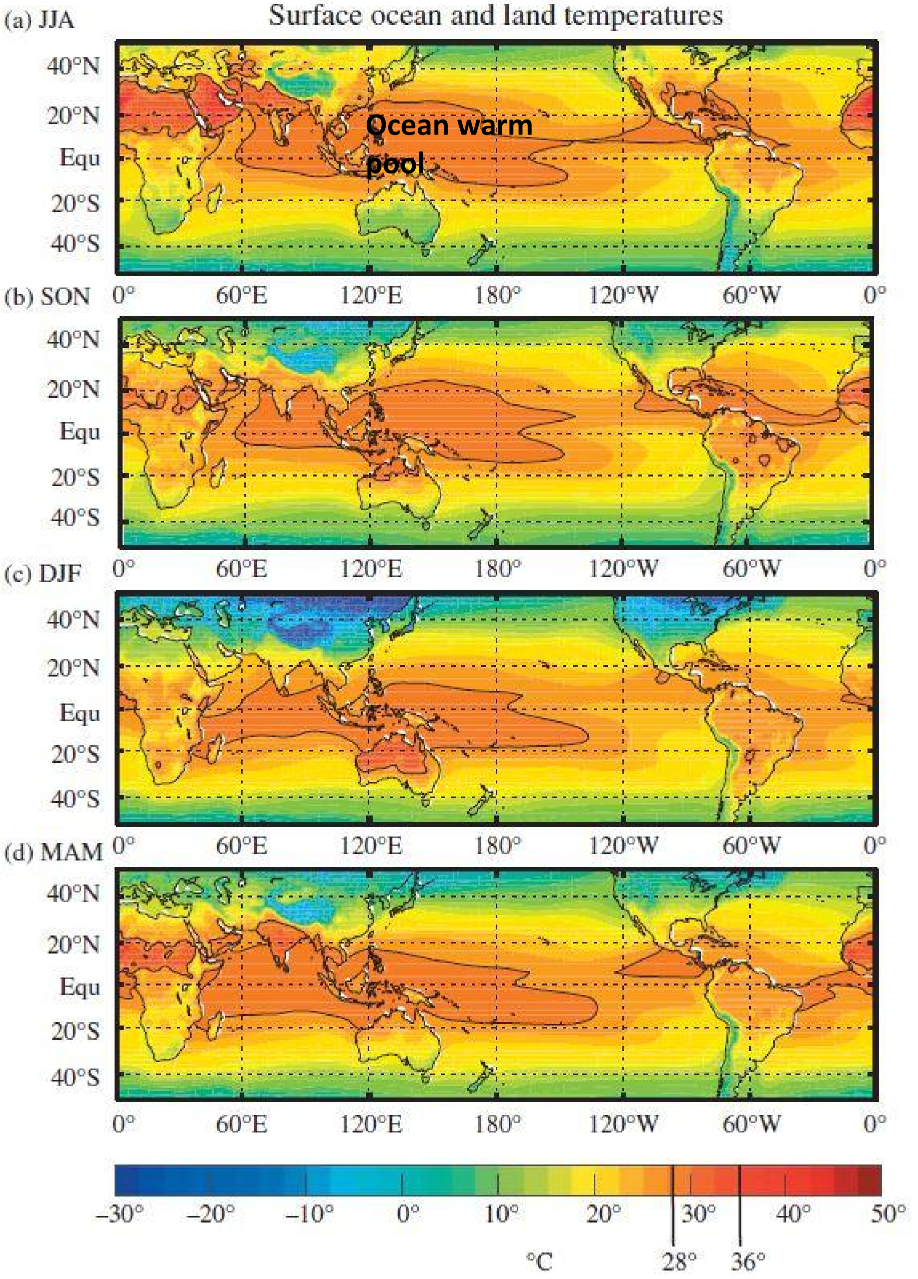
Boreal autumn SON: Rainfall rate maxima can be found in equatorial Africa and South America. During SON, especially at the latter end of the period, the Indian Ocean & coast of Africa receives substantial rainfall. These are referred to as the *"short rains."*

Austral summer DJF: The locus of maximum rainfall has moved south of the equator with extensive rainfall over southern Africa, North Australia, and Brazil.

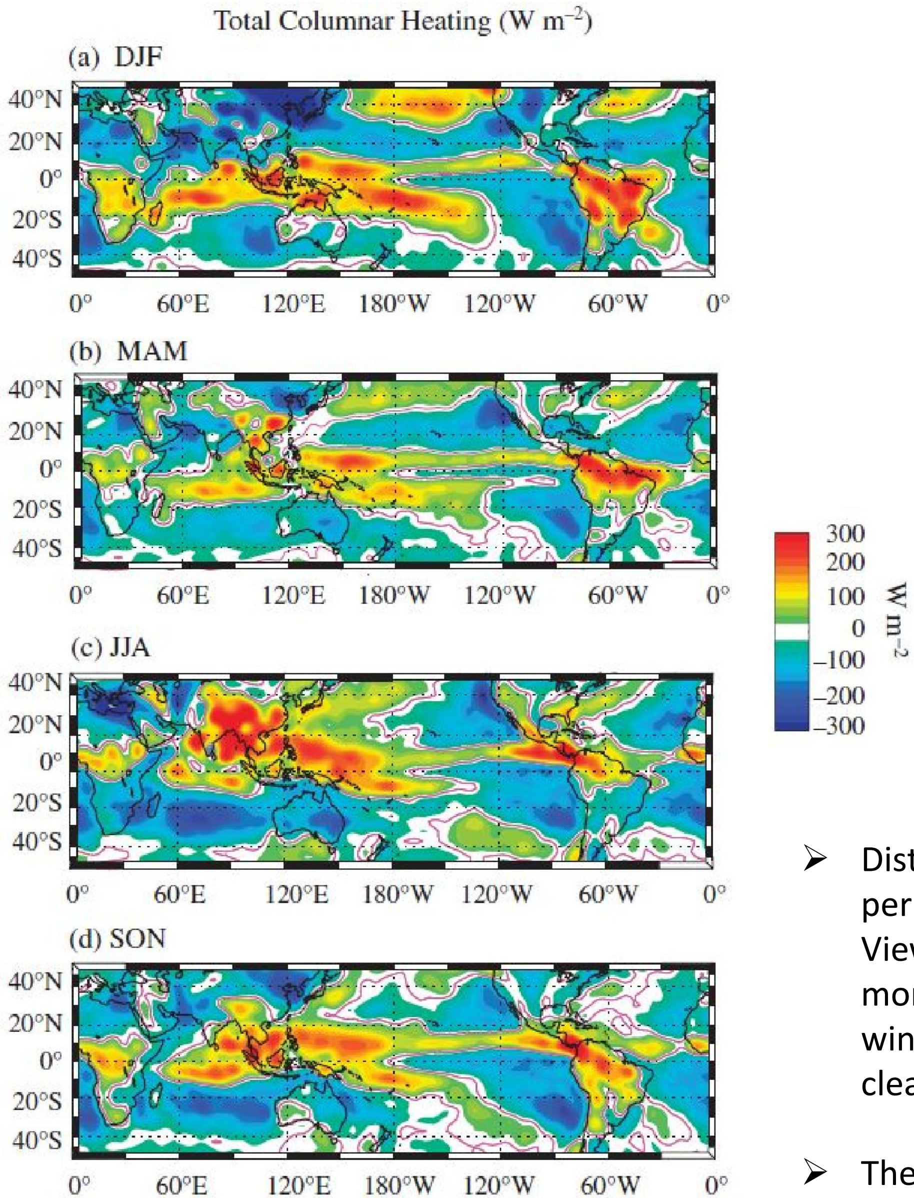
Austral autumn MAM: The second equinoctial maximum occurs over equatorial Africa, Indonesia, and equatorial South America. Rainfall also occurs along the Indian Ocean coast of equatorial East Africa. These are the *"long rains."*

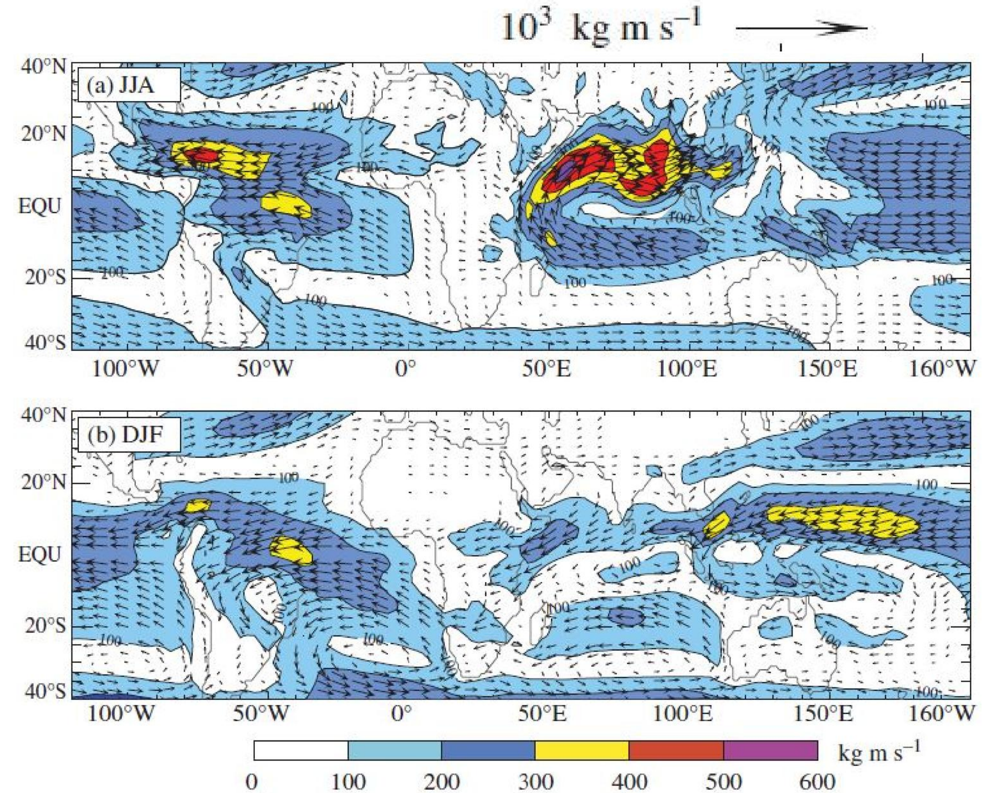


Mean sea-level pressure and surface winds
(a) JJA
Monsoon Low
Pacific high
Bermuda High
Mascarene High
(b) SON
(c) DJF
Siberian High
Aleutian Low
(d) MAM
60°N
45°N
30°N
15°N
Equ
15°S
30°S
0°
60°E
120°E
180°
120°W
60°W
0°
990
994
998
1002
1006
1010
1014
1020
1024
1028
1032
1034
1038



Surface ocean and land temperatures
(a) JJA
Ocean warm pool
(b) SON
(c) DJF
(d) MAM
40°N
20°N
Equ
20°S
40°S
0°
60°E
120°E
180°
120°W
60°W
0°
−30°
−20°
−10°
0°
10°
20°
30°
40°
50°
°C
28°
36°

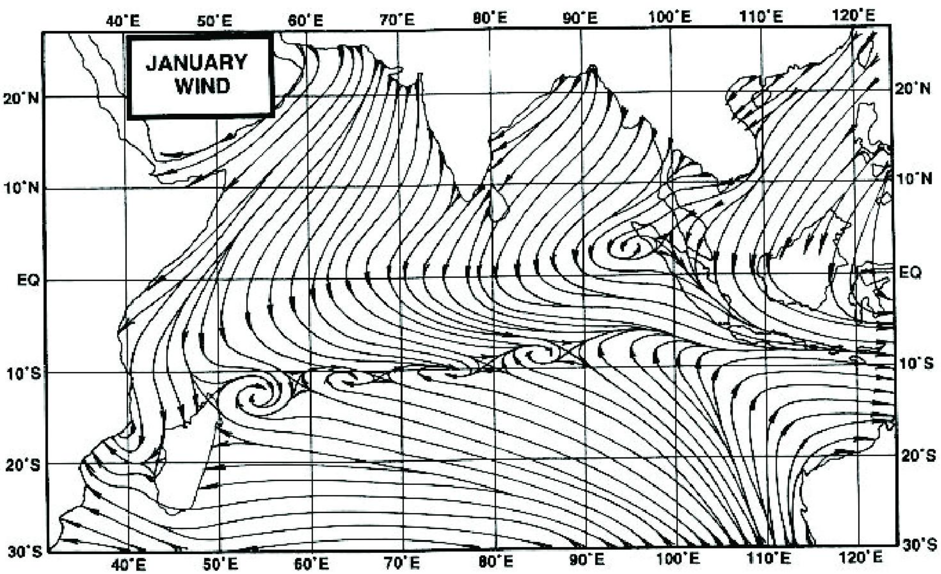




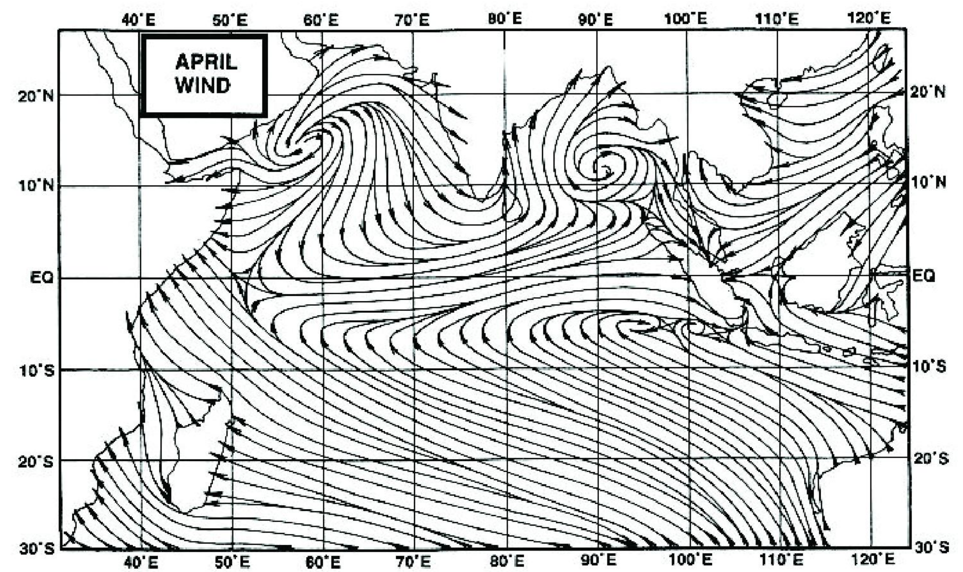
- Distribution of mean vertically integrated moisture transport for the period (a) June–September (JJA) and (b) December–February (DJF). Viewed in the context of moisture transport, the Asian–Australian monsoon system appears in both the boreal summer and the boreal winter as strong inter-hemispheric systems with moisture sources clearly defined in the trade wind regimes of the winter hemisphere.

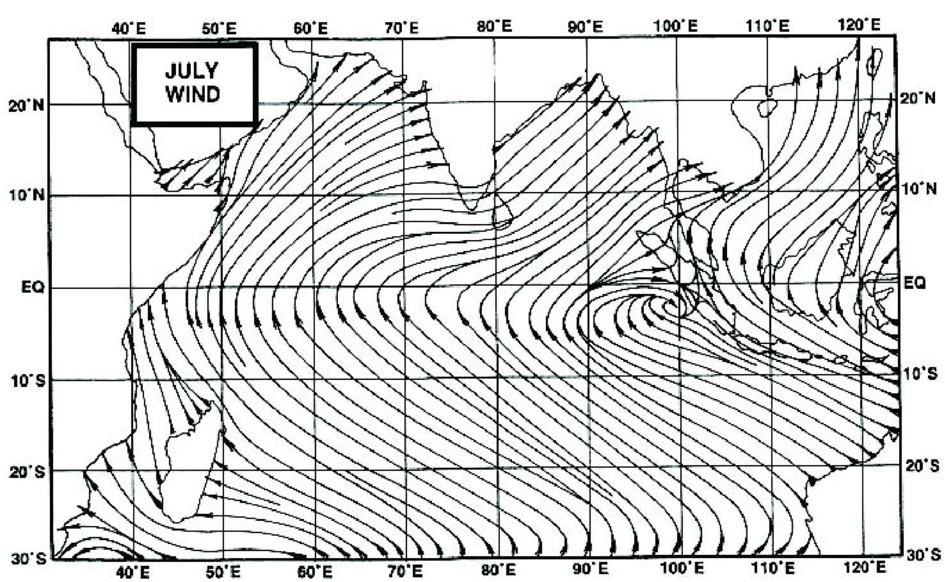
- The African summer and winter monsoons are less clearly defined in terms of moisture transport and are similar in magnitude to the North Australian summer monsoon. Weak moisture fluxes into northwest Africa may be seen, for example, but the region is dominated by strong westward moisture fluxes associated with the trade wind across the Atlantic and into the Americas.

Winter/Northeast monsoon

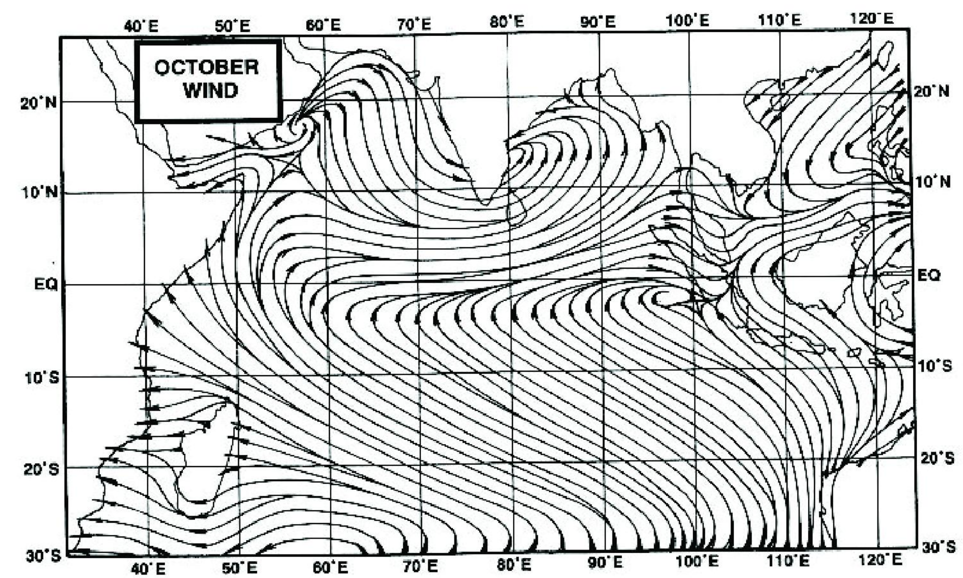


Pre-monsoon



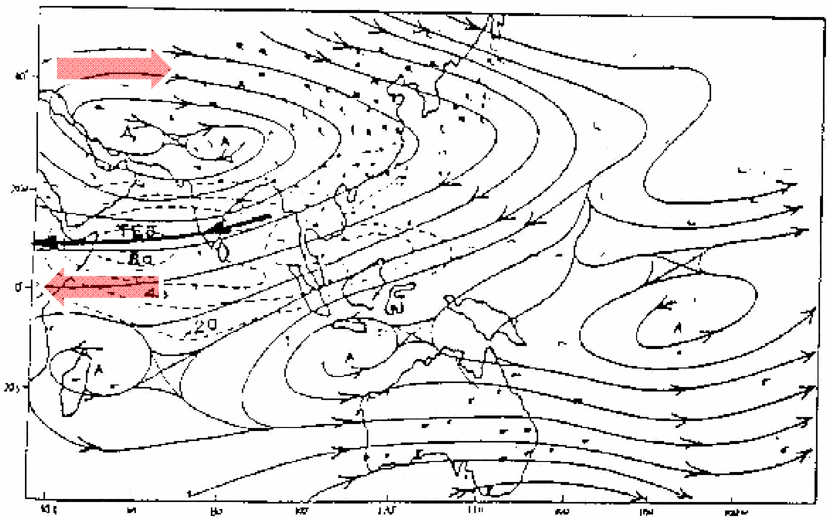


Southwest Monsoon

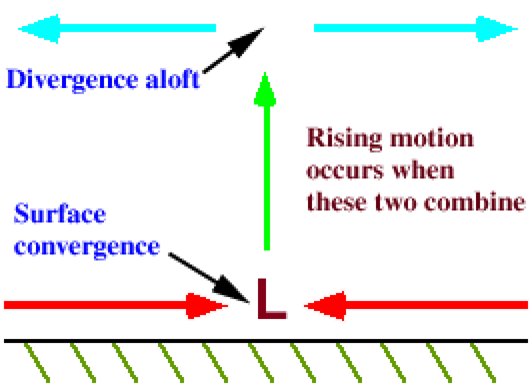


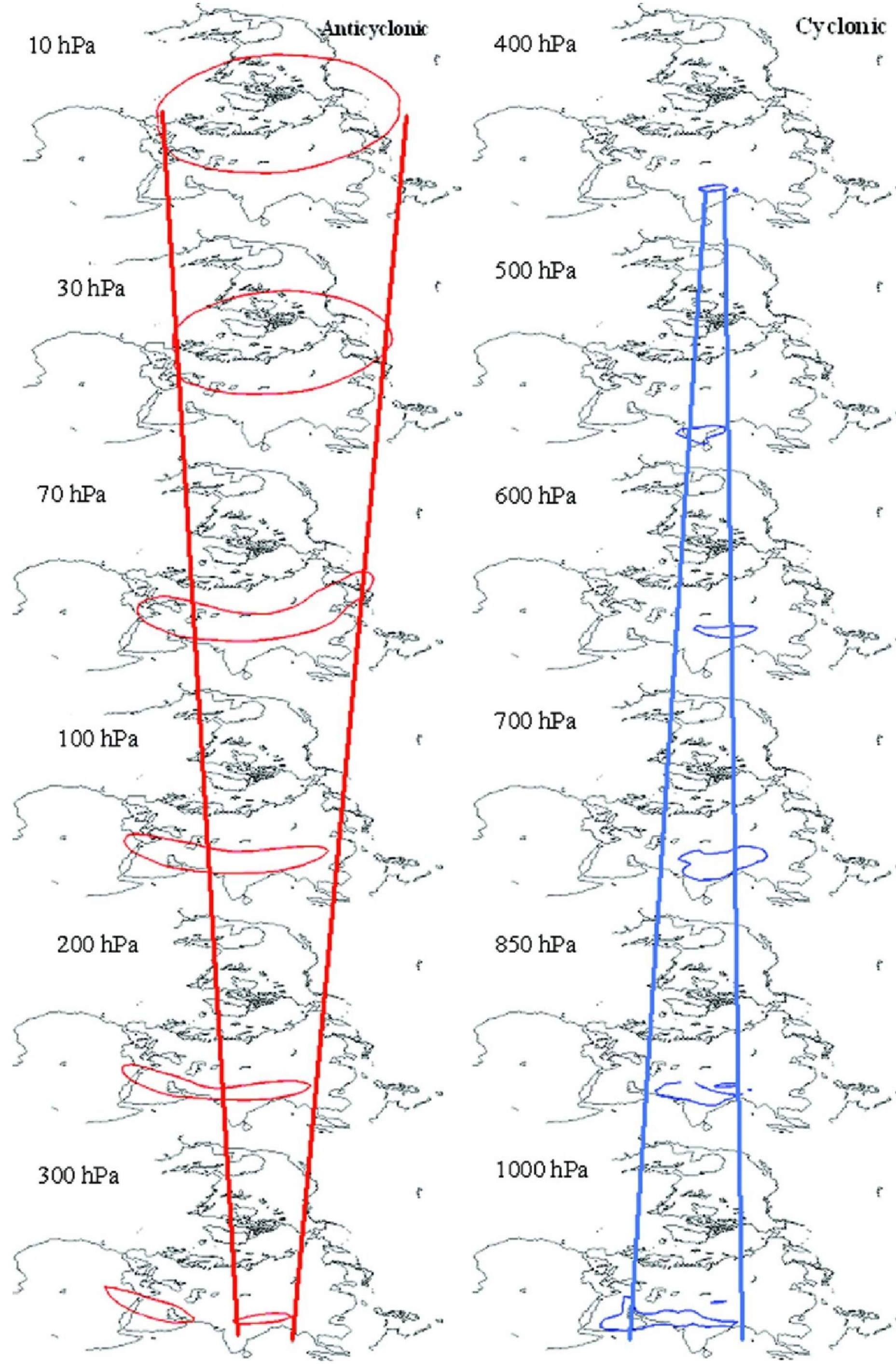
Post-monsoon

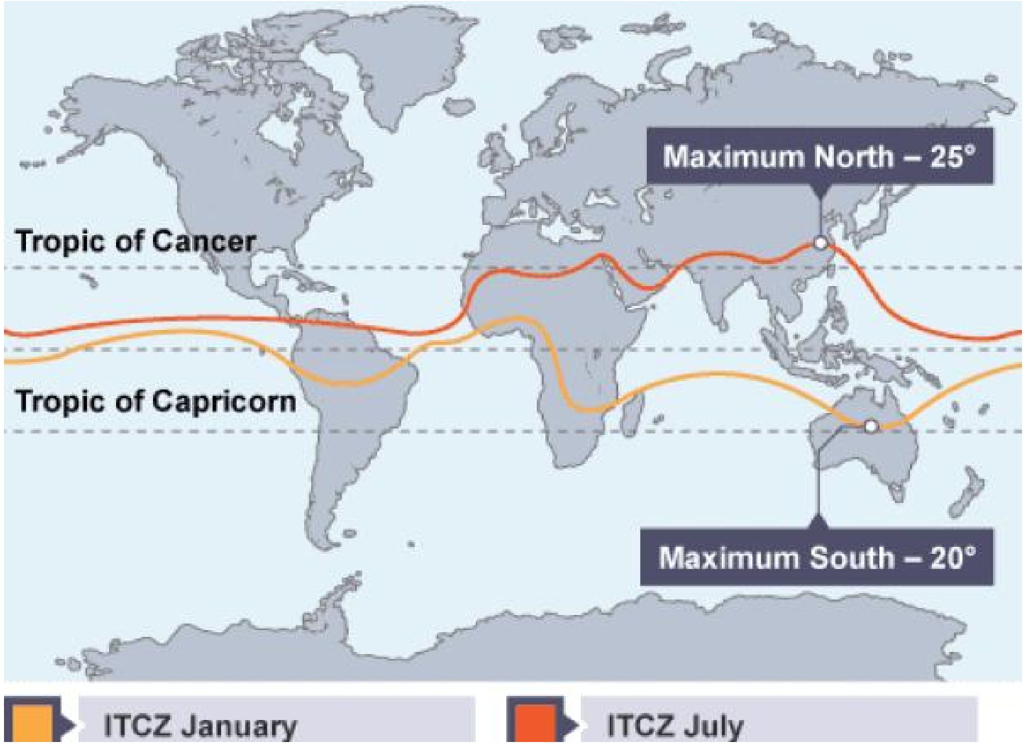
Schematic picture of the cone, showing the shape of the anticyclonic flows at different levels from 1000 to 10 hPa levels and cyclonic flows down to the surface.

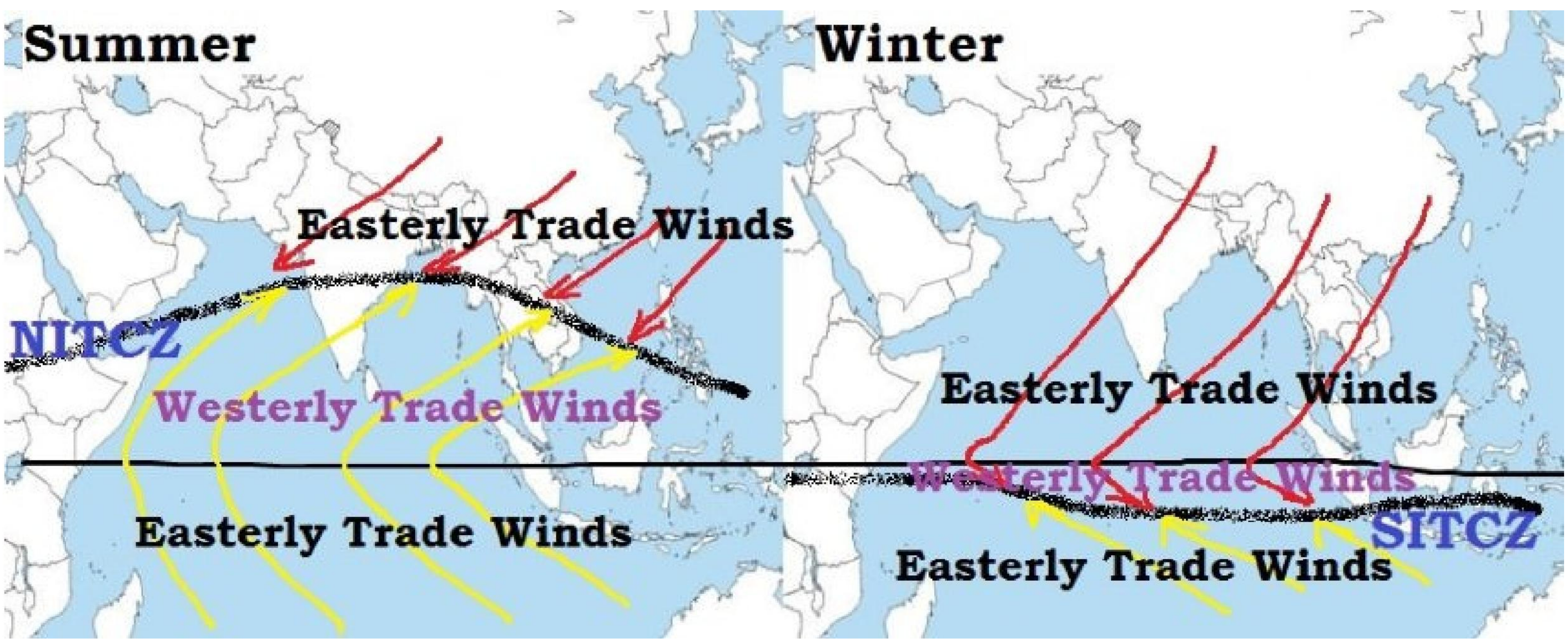


Summer monsoon upper level flow

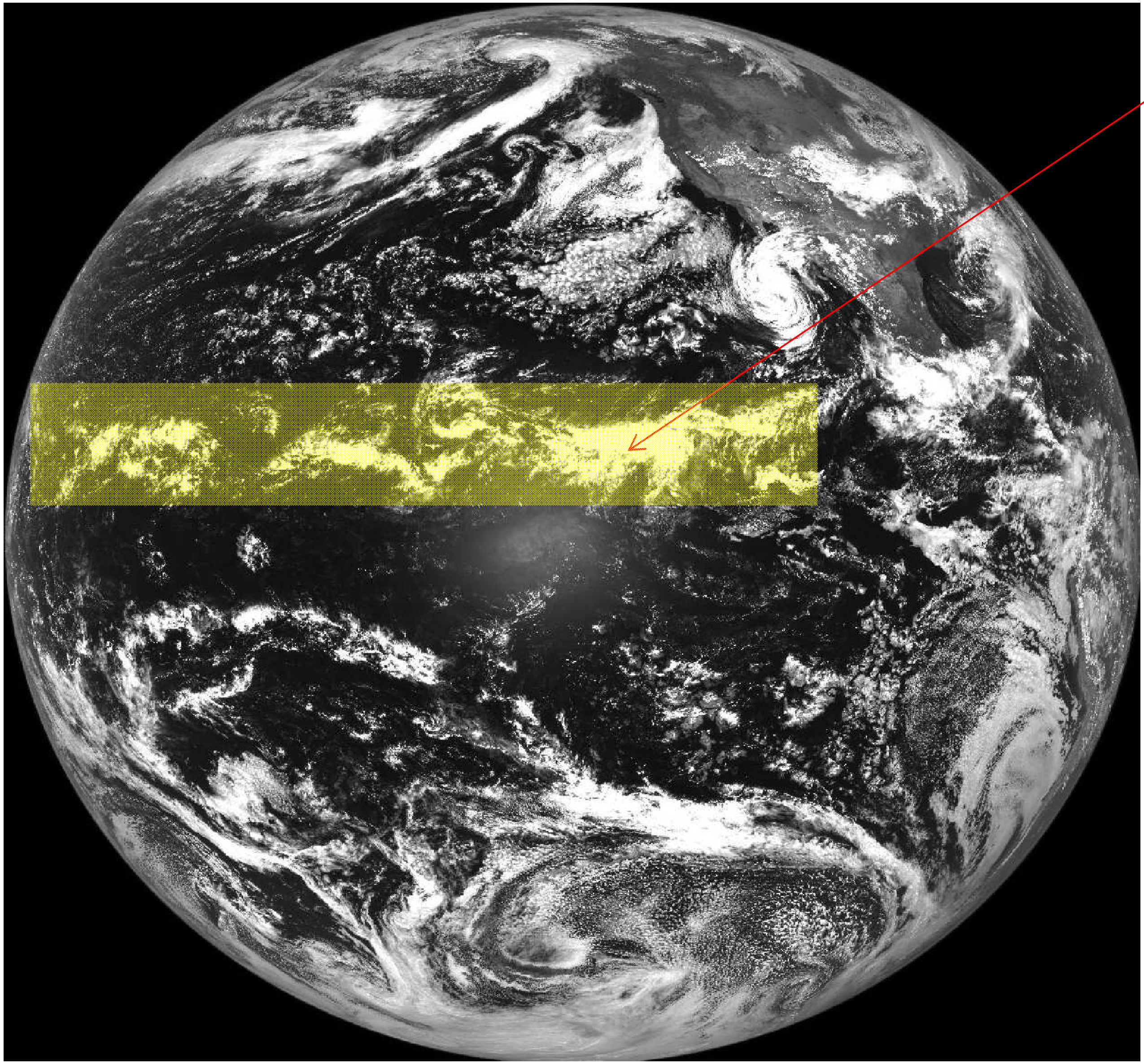





Maximum North – 25°
Tropic of Cancer
Tropic of Capricorn
Maximum South – 20°
ITCZ January
ITCZ July

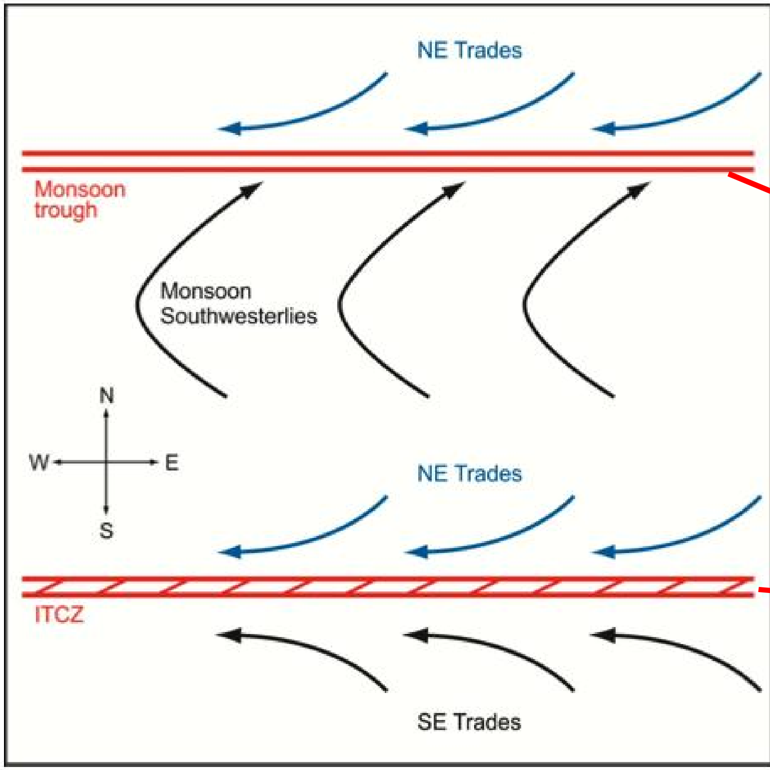

Summer
Easterly Trade Winds
NITCZ
Westerly Trade Winds
Easterly Trade Winds
Winter
Easterly Trade Winds
Westerly Trade Winds
SITCZ
Easterly Trade Winds

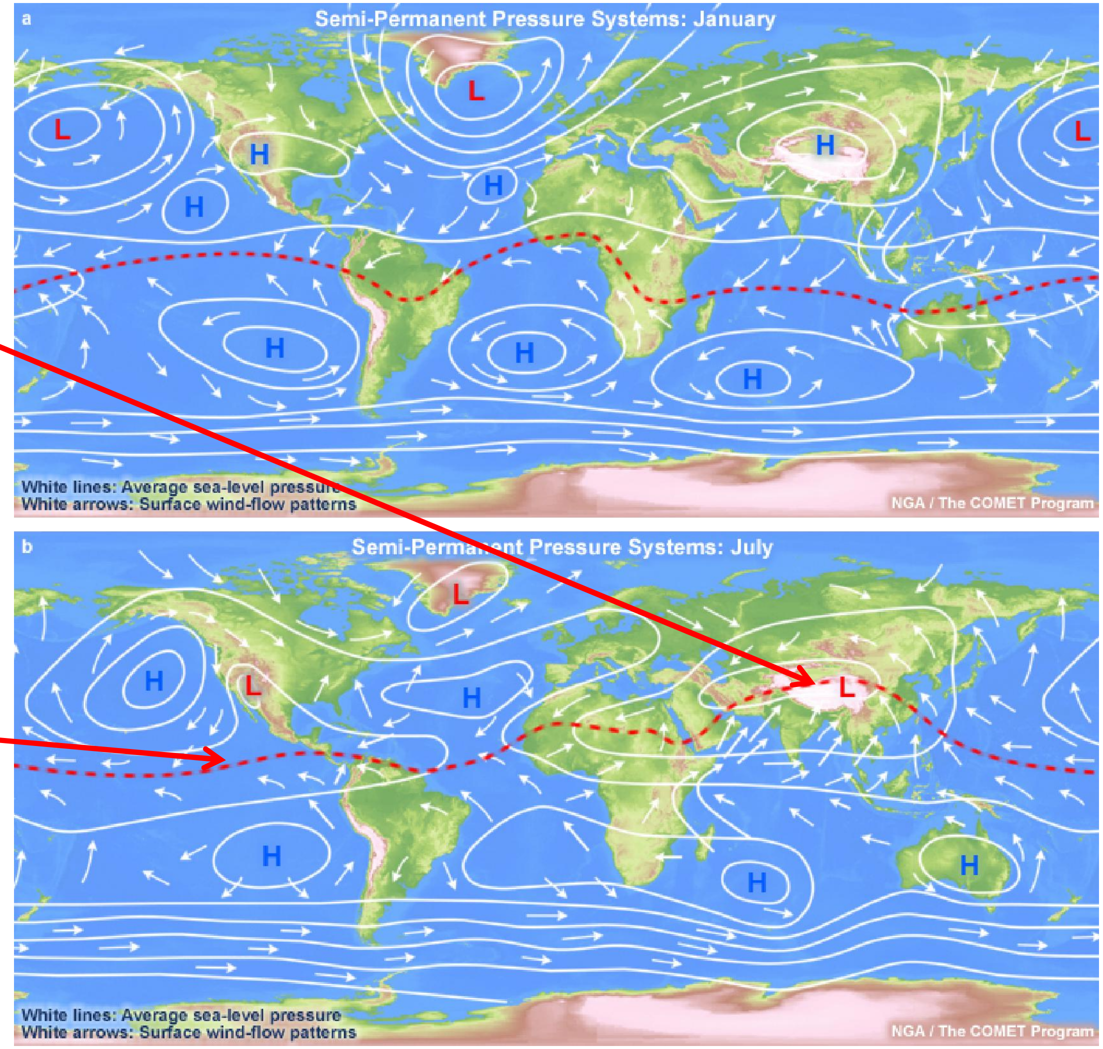
Inter-tropical convergence zone (ITCZ)



- Visible-wavelength image of Earth from GOES geostationary weather satellite.
- The Intertropical Convergence Zone (ITCZ) can be seen as a zonal band of clouds north of the equator.
- This is the rising branch of the Hadley cell where thunderstorm activity is prevalent.

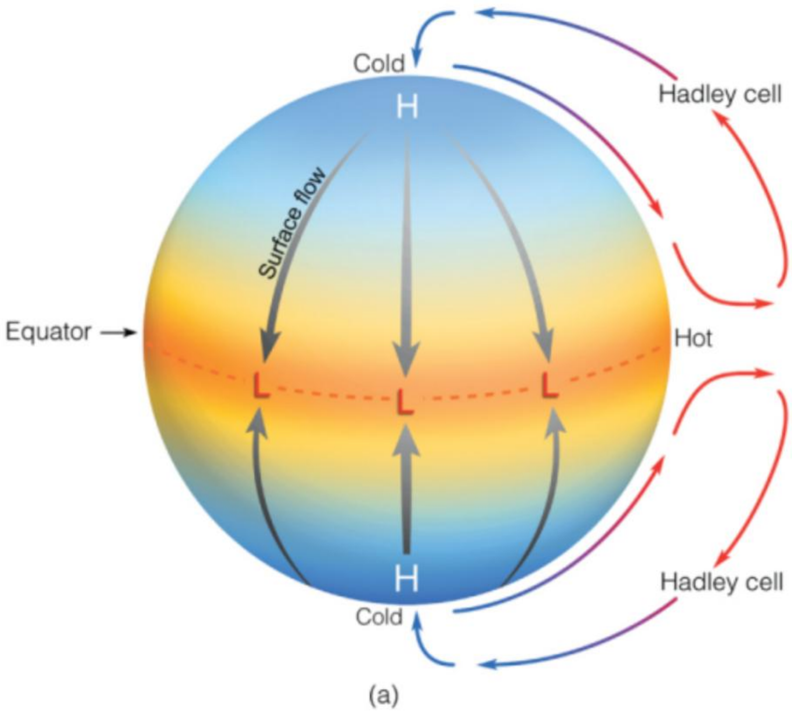
Difference in the calling Monsoon trough and ITCZ



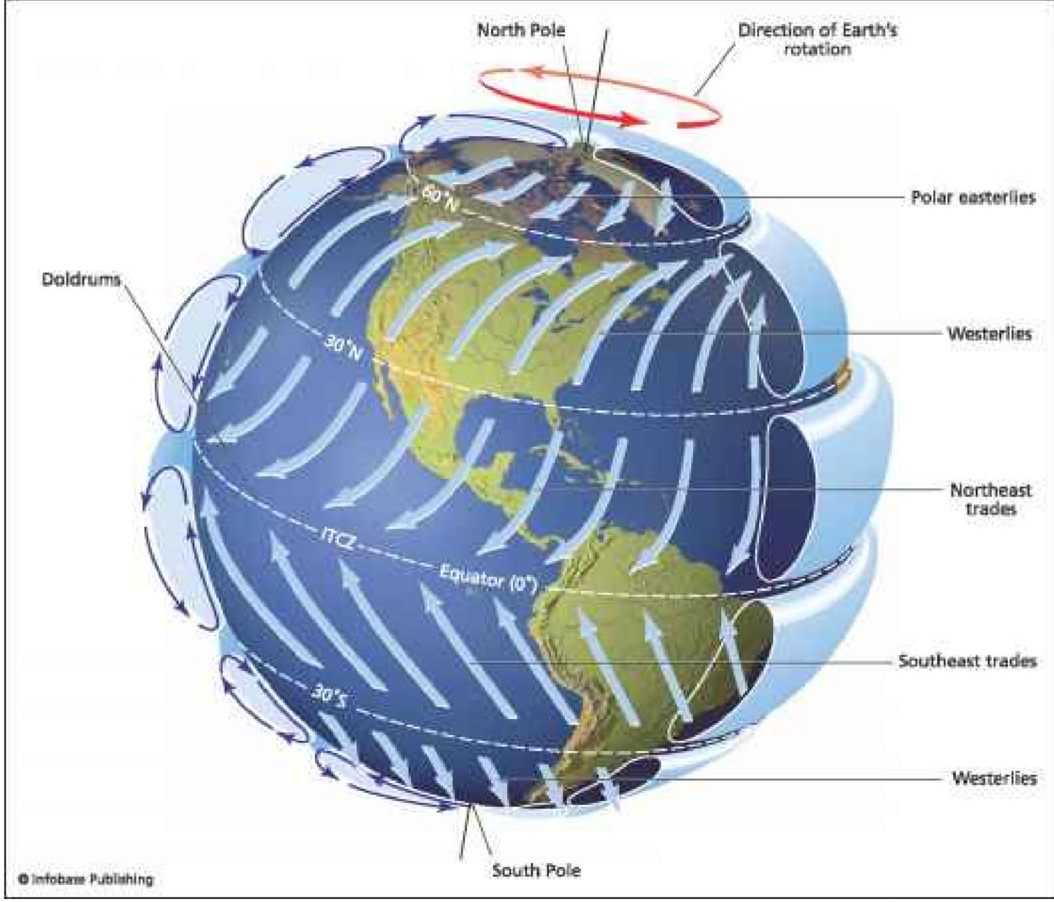


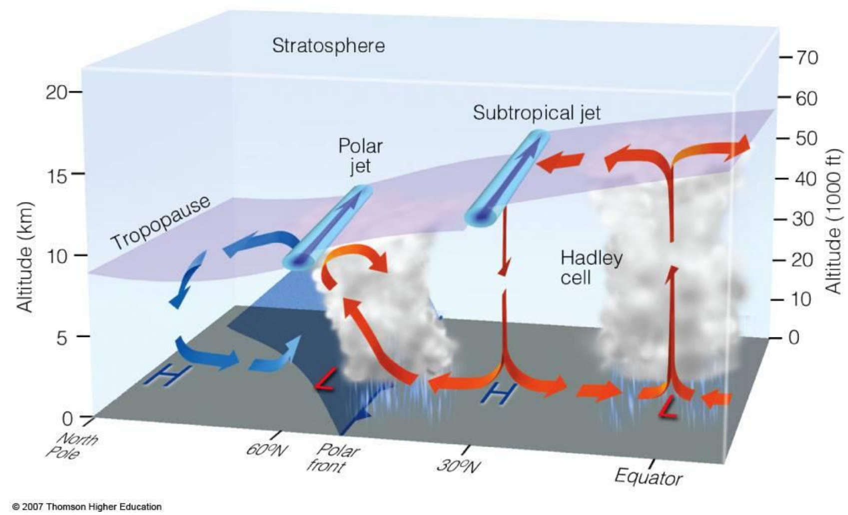
Why do we call monsoon trough and ITCZ differently?

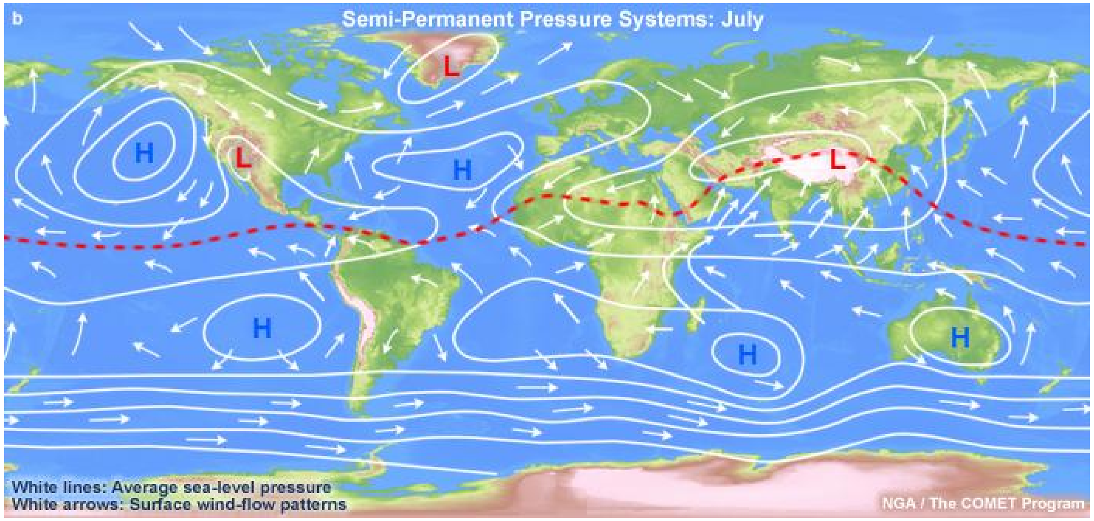
If the Earth were not rotating

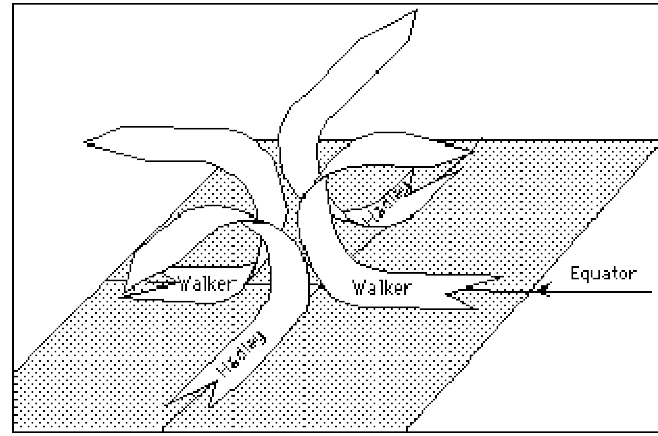


Single cell



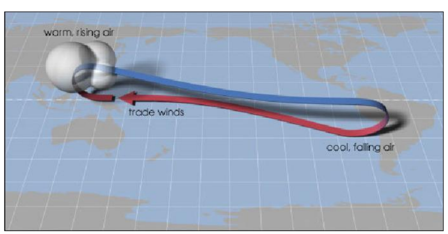






Hadley and Walker cells reveal a pattern in the atmosphere's response to differential heating

- ***In summer (June-September) the Tibetan plateau acts as an elevated heat source. The ascending air above the source gradually spreads southwards to join a descending limb over the north Indian Ocean near Mascarenes (High). The southwesterly winds at the surface form the return current to complete the Hadley cell. In addition, there is an east-west Walker cell that appears to influence the summer monsoon. Stronger ascending branch of the Walker cell is located over the semi-arid regions of northwest India, Pakistan and the middle East.***



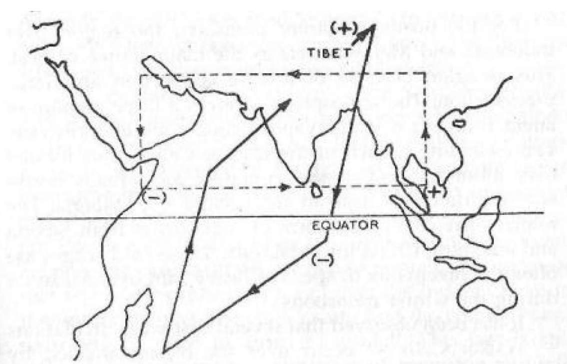
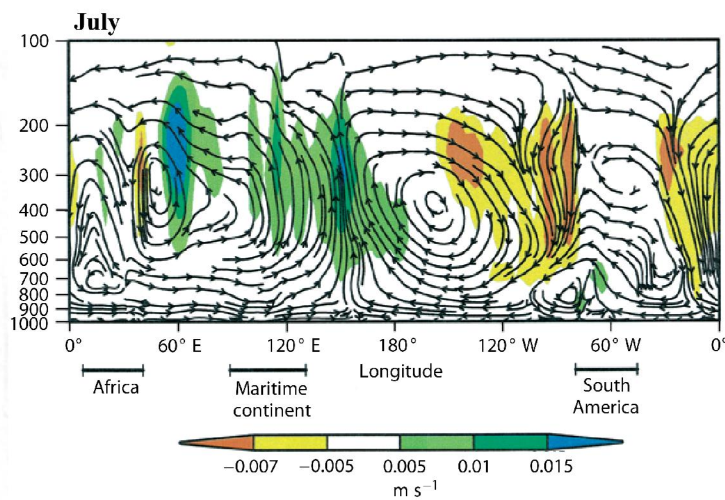
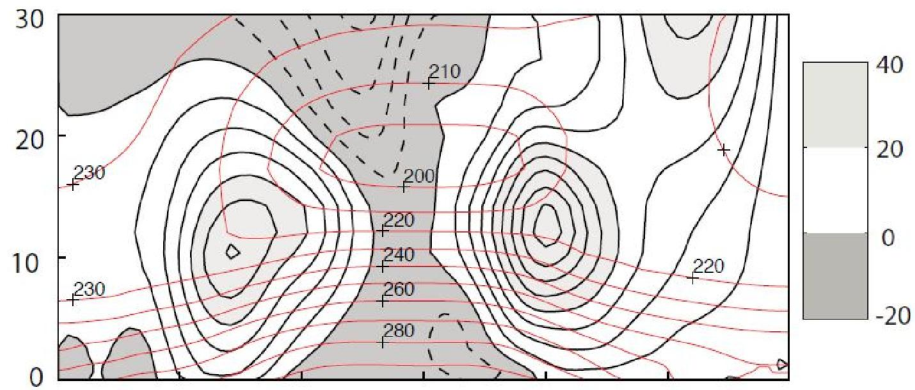


Figure 2.7. Summer Monsoon Hadley Cell. (Broken line represents the walker cell) Ascending limbs are marked (+) while (–) denotes descending branch.

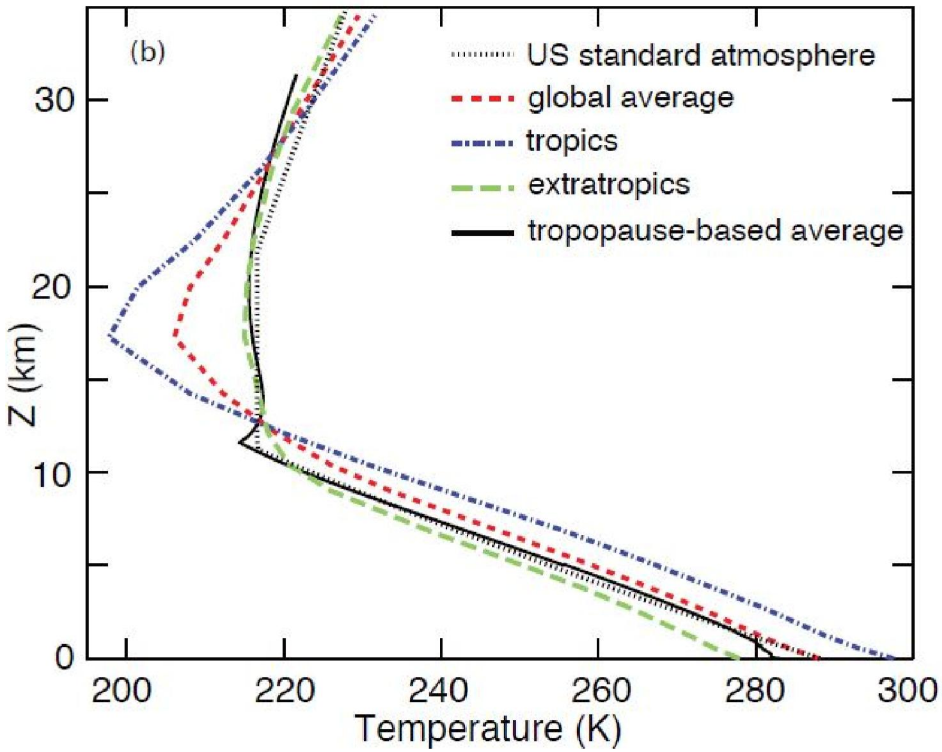


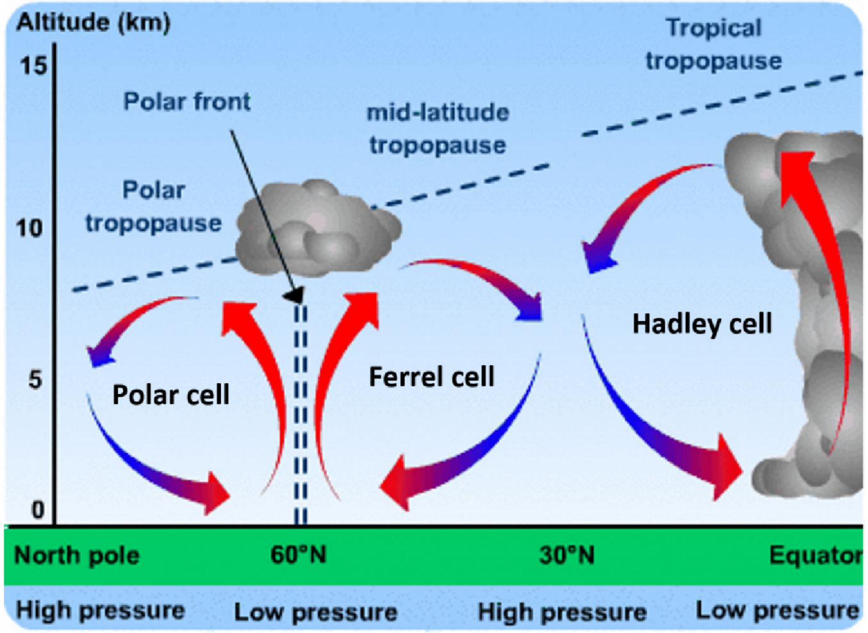
A "direct-Hadley cell", with warm air rising near the equator and sinking in the subtropics.

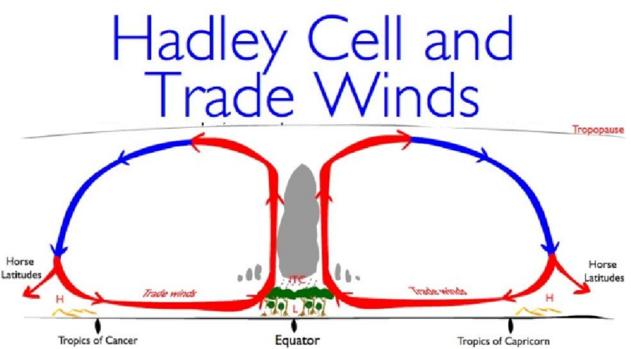
The winter Hadley cell is much stronger and has greater latitudinal extent than the summer one



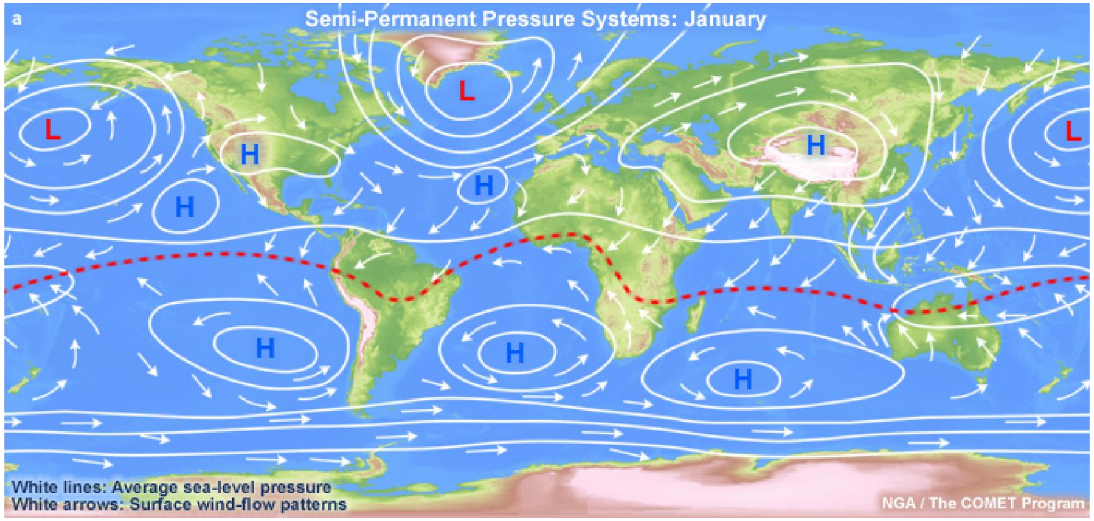
Zonally-averaged zonal wind (heavy contours and shading) and the zonally-averaged temperature (red, thinner contours) for the northern hemisphere winter (DJF).

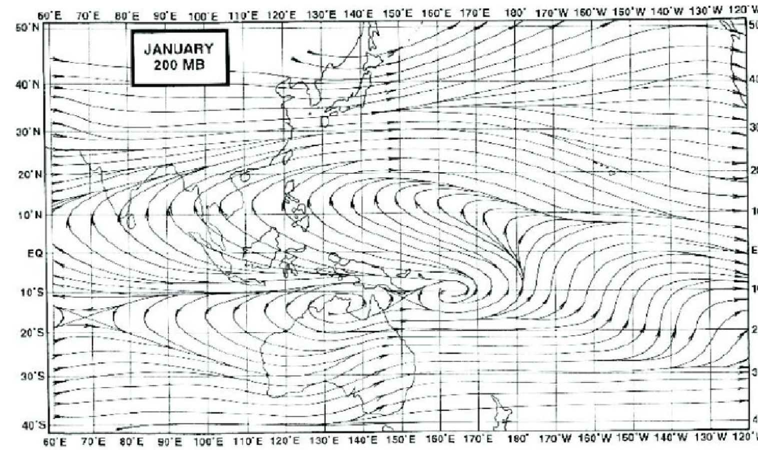




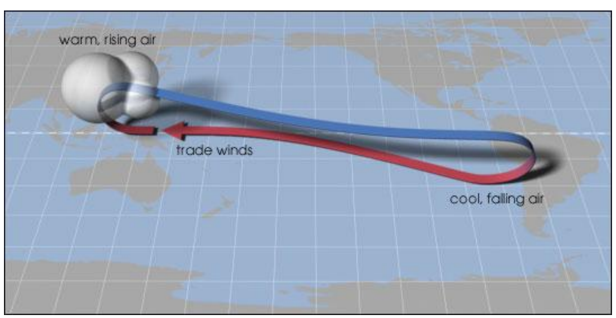


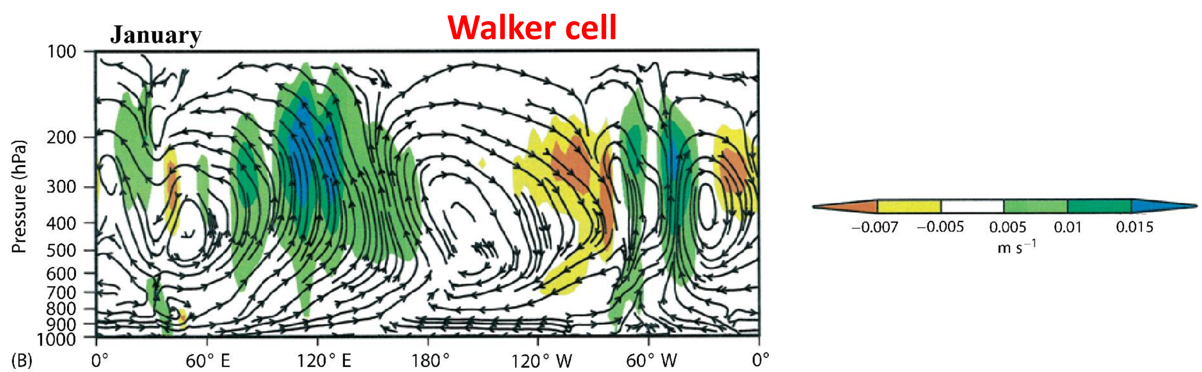
Both the Walker and Hadley cells are the result of thermal contrast and they transport moist static energy. Ferrel cells are indirect cells driven by transient baroclinic eddies and transport heat and momentum poleward





- *In winter (June-September), regions over Indonesia and Malaysia acts as the main source of heat. The ascending branch of the Hadley cell is located over Indonesia. As the ascending air spreads northwards , it descends near an anticyclone over Siberia. The return current is in the form of cold surges from Siberia and adjoining China into Malaysia.*





- *Good monsoons appear to be associated with more intense Hadley circulations and relatively weak Walker cells while poor monsoons occur when the Walker cell is strong and the Hadley cell is weak. The dynamics of this type of cellular convection on a planetary scale is often intimately linked with inter-annual variability of monsoons.*

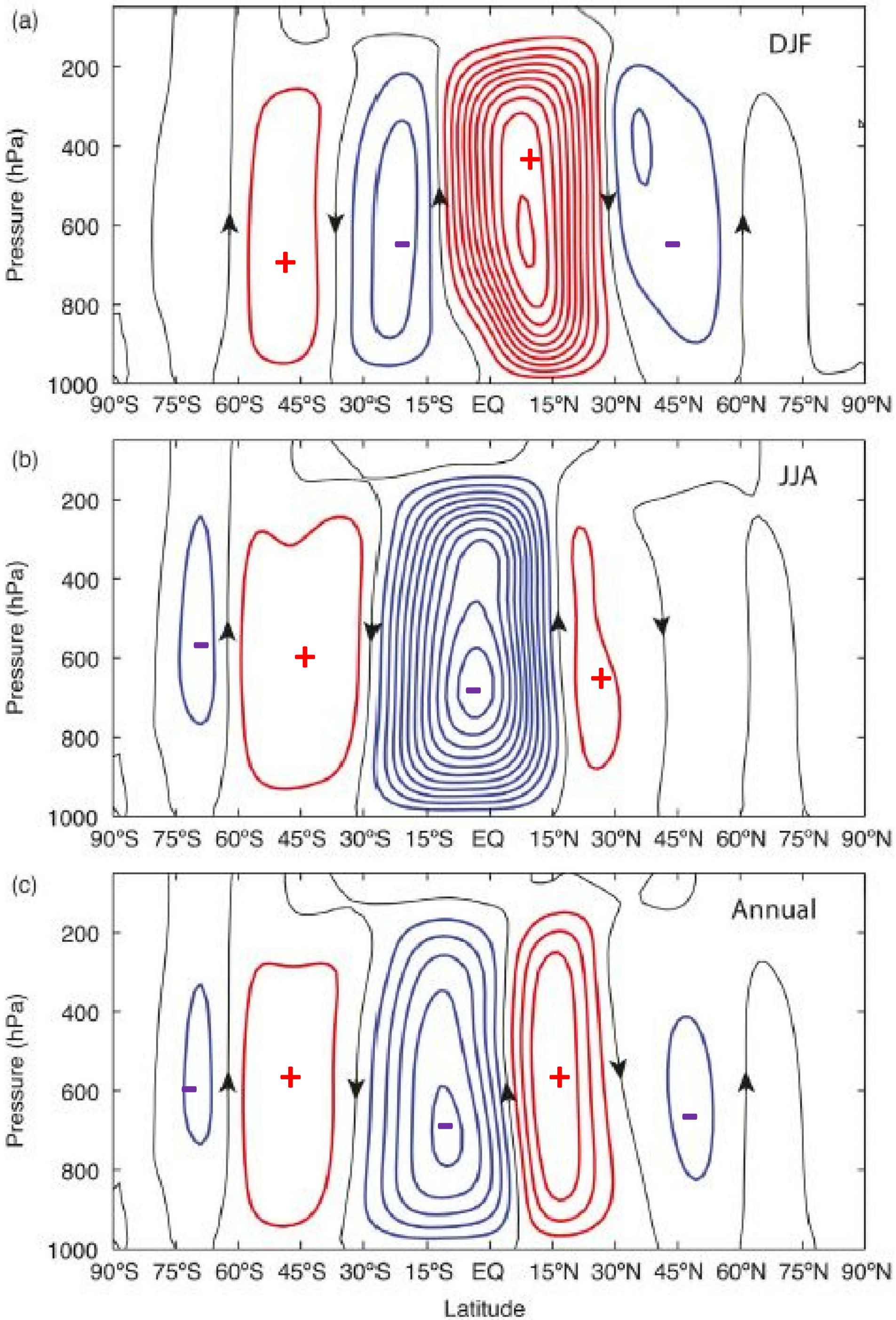
The zonal-average meridional and vertical components of wind are much weaker than the zonal wind.

$\Rightarrow$ Maximum mean meridional winds are only about 1 m s^{-1}, and mean vertical wind speeds are typically a hundred times smaller than the mean meridional wind.

The mean meridional circulation (MMC), which is composed of the zonal mean meridional and vertical velocities, can be described by a mass stream function (Ψ), which is defined by calculating the northward mass flux above a particular pressure level, p.

$$\boxed{\Psi_M \equiv \frac{2\pi a \cos\varphi}{g}\int_0^p [v]dp \quad \begin{cases} [v] = \dfrac{g}{2\pi a \cos\varphi}\dfrac{\partial \Psi_M}{\partial p} \\[2ex] [\omega] = -\dfrac{g}{2\pi a^2 \cos\varphi}\dfrac{\partial \Psi_M}{\partial \varphi} \end{cases}}$$

The mass flow between any two streamlines of the mean meridional stream function is equal to the difference in the stream function values.



Latitude–pressure cross-sections of the mean meridional mass stream function for the (a) DJF, (b) JJA, and (c) annual mean

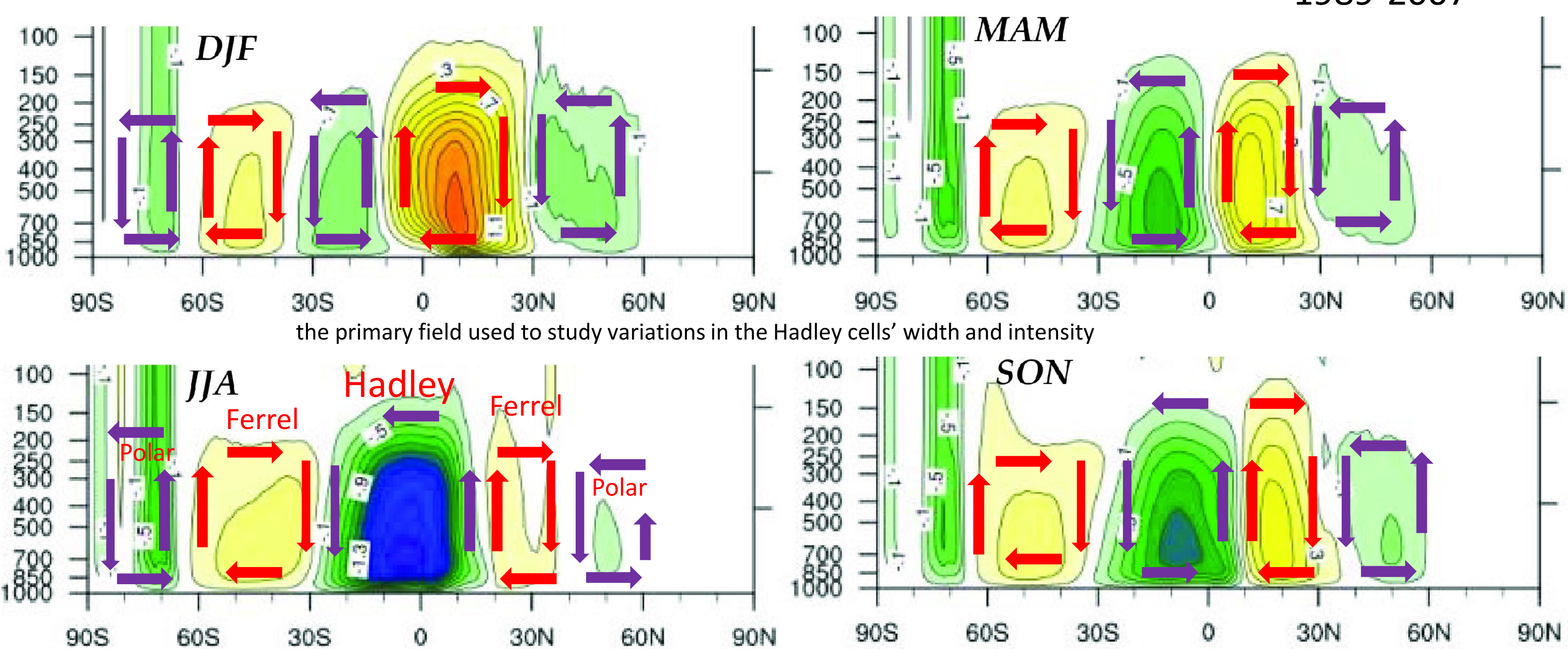
$$\Psi_M \equiv \frac{2\pi a \cos\varphi}{g} \int_0^p [v] dp$$

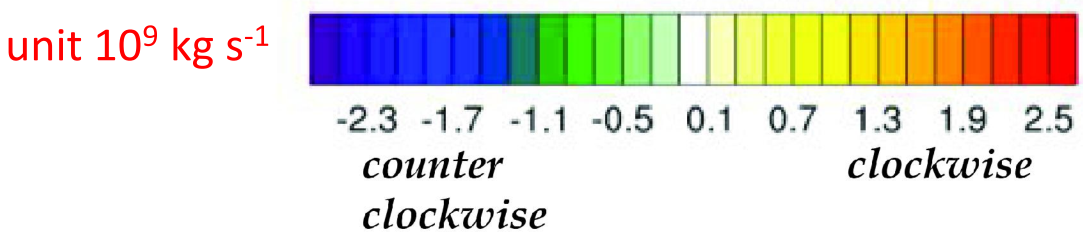
- Hadley cell: single circulation cell in which air rises near the equator, flows toward the winter hemisphere at upper levels, and sinks in the subtropical latitudes of the winter hemisphere

- In mid-latitudes, weaker cells called *Ferrel cells* circulate in the opposite direction to the Hadley cell. In these mid-latitude mean meridional circulation cells, rising occurs in cold air and sinking in warmer air.

- In midlatitudes, eddies transport energy so efficiently that the mean meridional circulation is thermally indirect, with rising motion in cold air and sinking motion in warm air.

1989-2007





Mass streamfunction is commonly known as meridional overturning circulation

Mass flux streamfunction

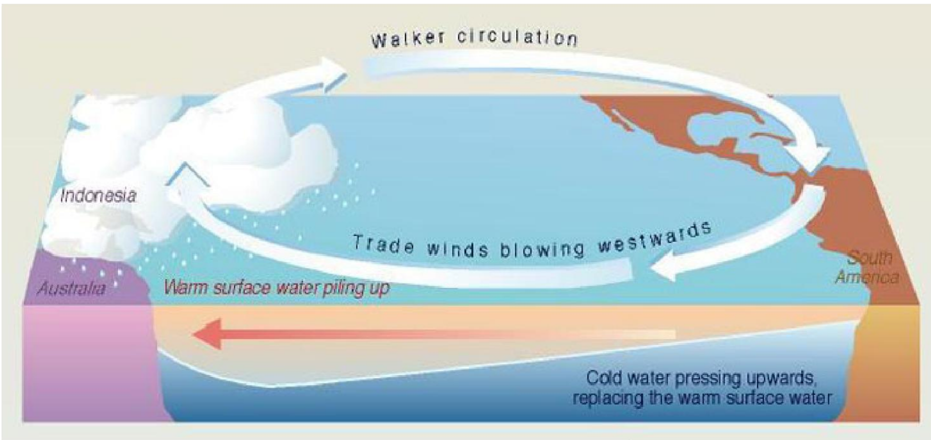
vertically integrated northward mass flux at latitude φ from pressure level p to the top of the atmosphere

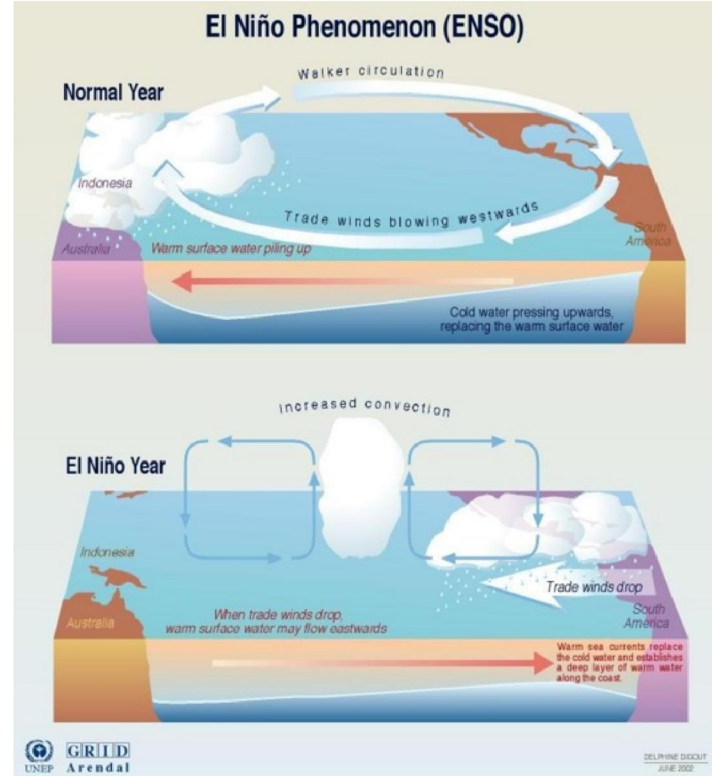
$$\Psi(p,\varphi) = \frac{2\pi a\cos\varphi}{g}\int_p^0 \langle v\rangle dp$$

The positive (negative) values denote clockwise (anticlockwise) rotation

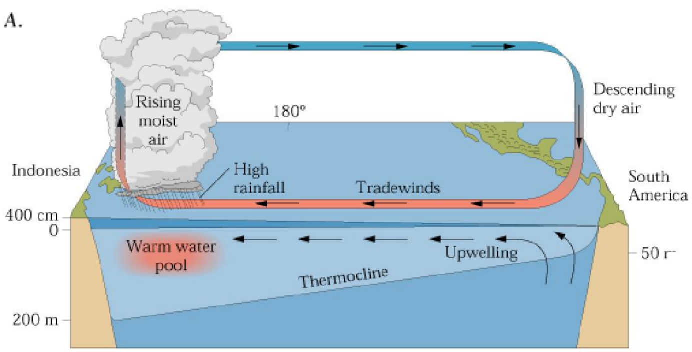
The positive (negative) values denote the direct (indirect) circulation

Hadley and Walker cells reveal a pattern in the atmosphere's response to differential heating

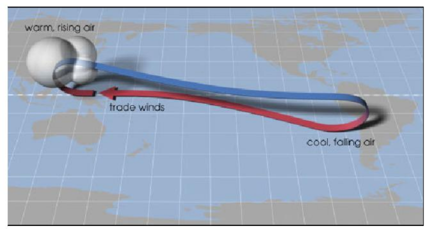




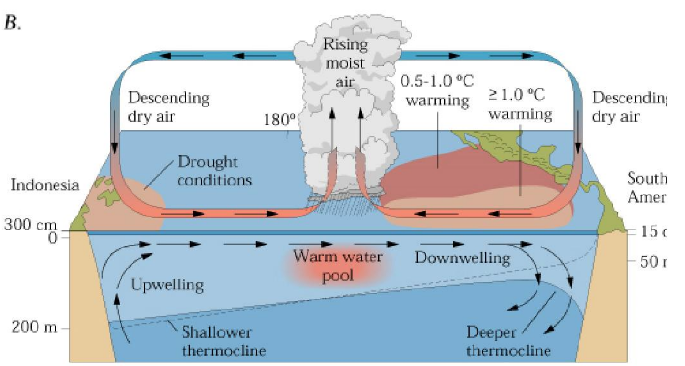
Sources: Climate Prediction Center-NCEP; NOAA.



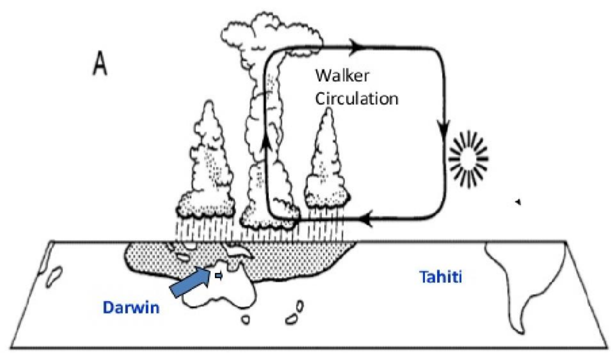
"Normal" conditions in the tropical Pacific



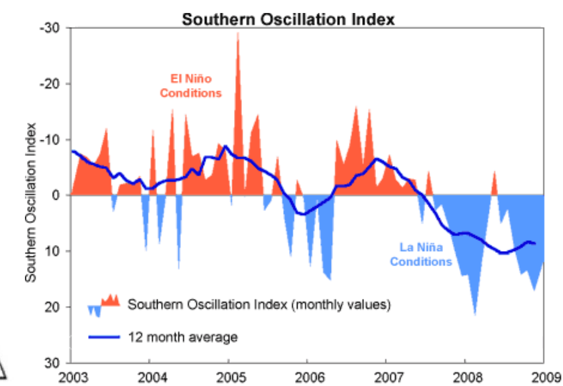
Walker Circulation & Southern Oscillation

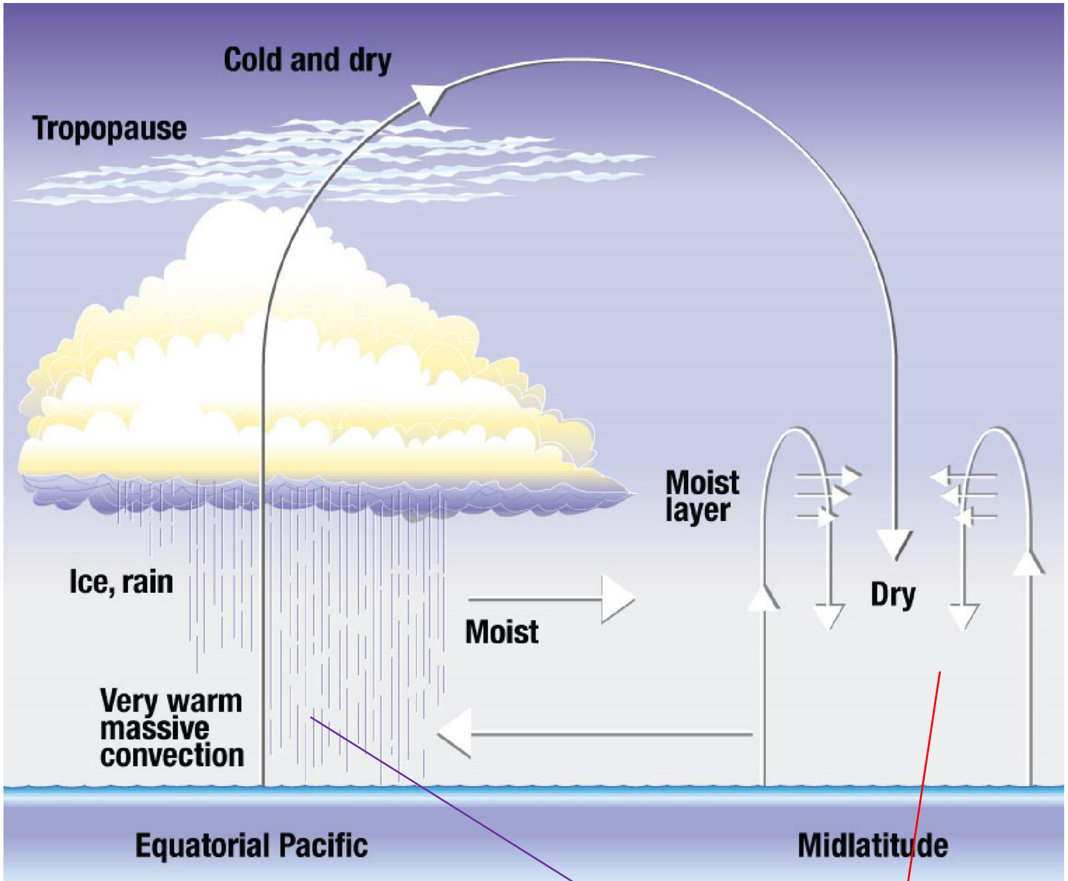


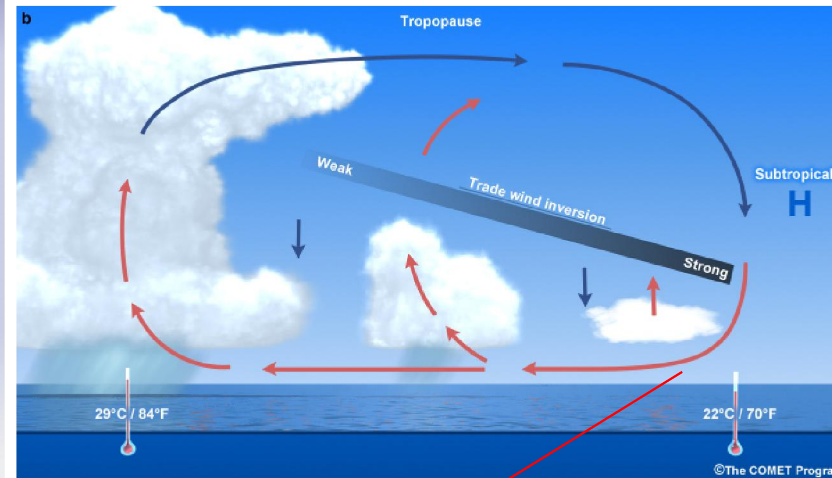
El Niño conditions in the tropical Pacific

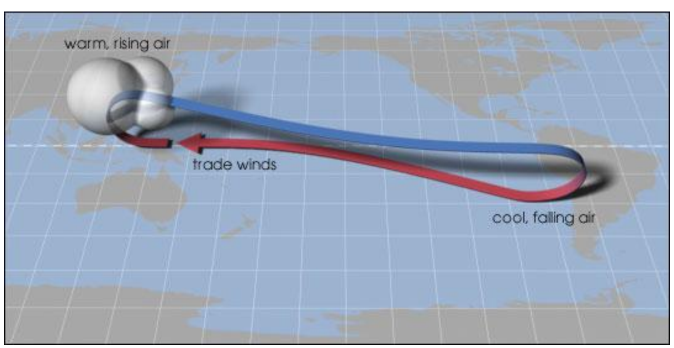


Southern Oscillation: fluctuations in the surface air pressure between Tahiti (east) and Darwin (west) – an indication of the strength of Walker Circulation

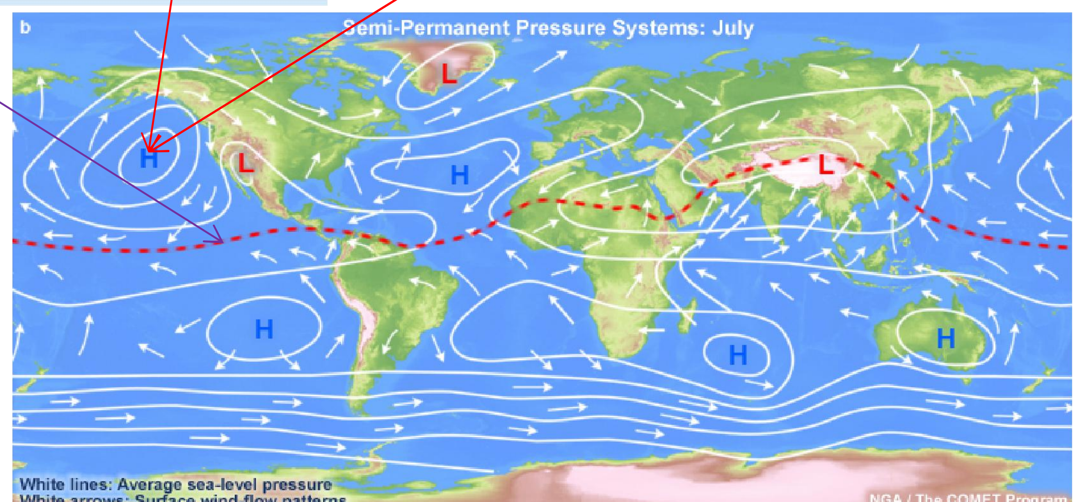


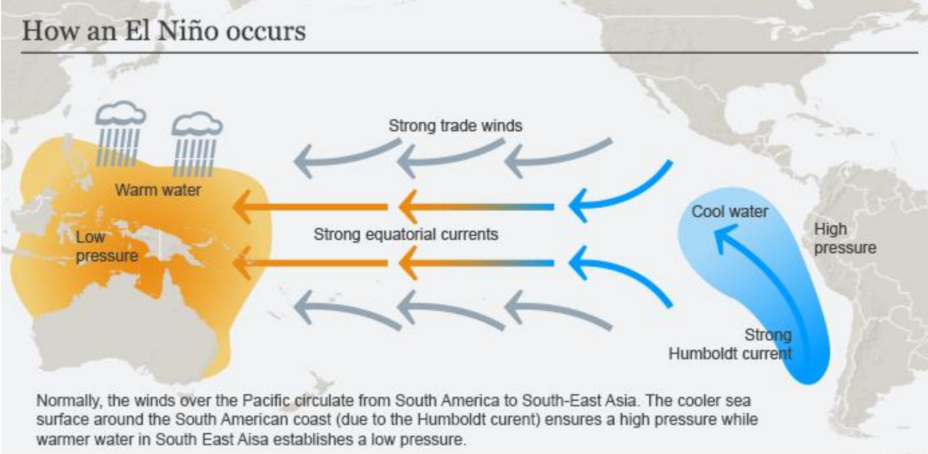

Cold and dry
Tropopause
Moist
layer
Ice, rain
Dry
Moist
Very warm
massive
convection
Equatorial Pacific
Midlatitude

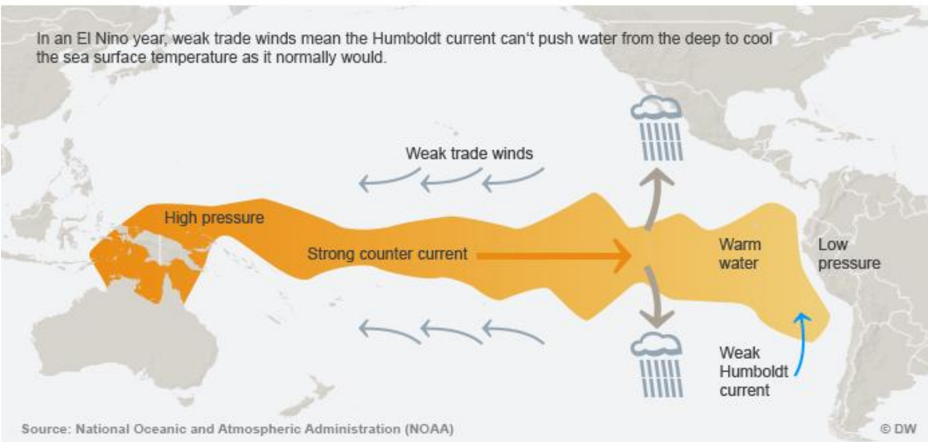

b
Tropopause
Weak
Trade wind inversion
Strong
Subtropical
H
29°C / 84°F
22°C / 70°F
©The COMET Program

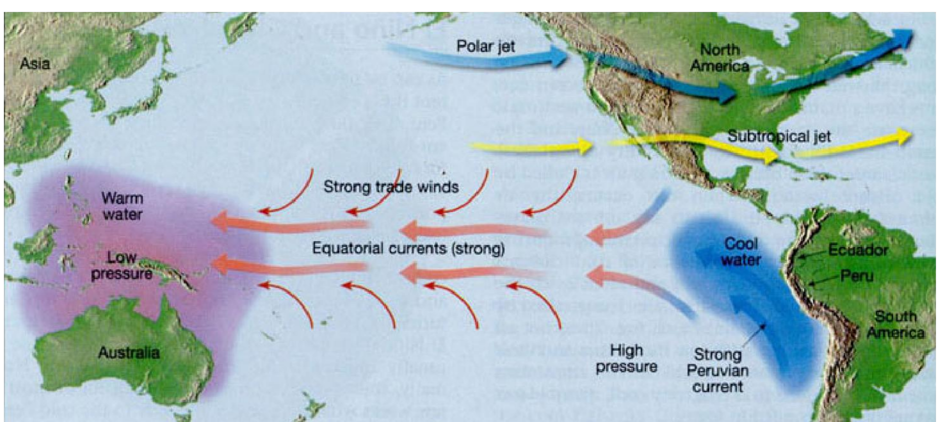

warm, rising air
trade winds
cool, falling air

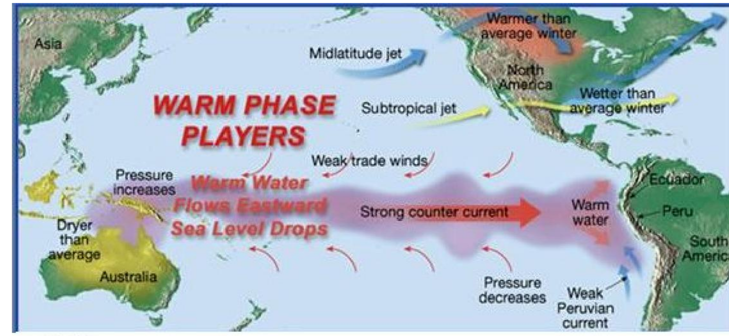
Walker cell


b
Semi-Permanent Pressure Systems: July
L
H
L
H
L
H
H
H
White lines: Average sea-level pressure
White arrows: Surface wind-flow patterns
NGA / The COMET Program

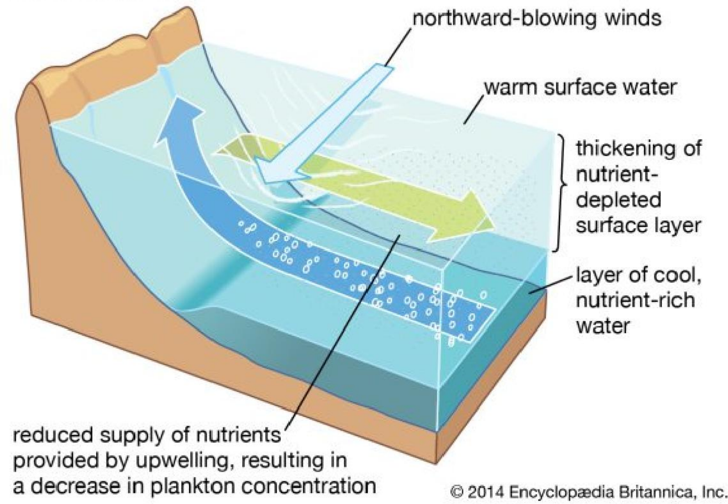


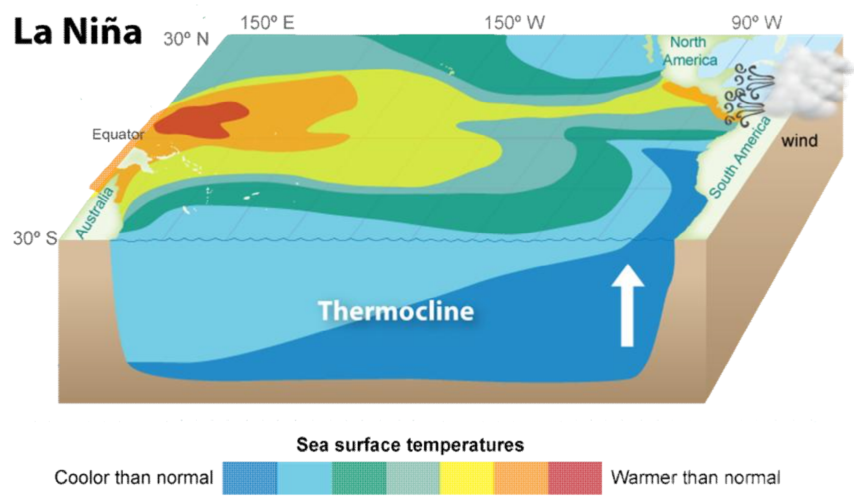




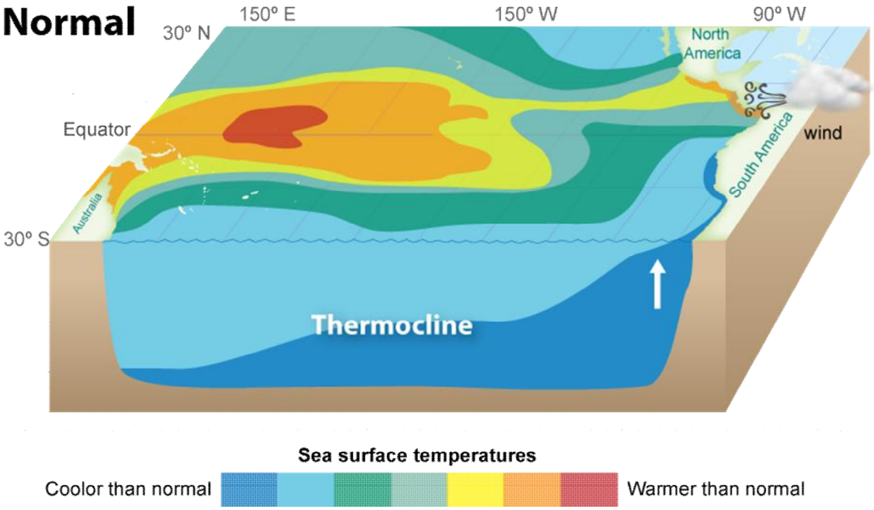


El Niño event



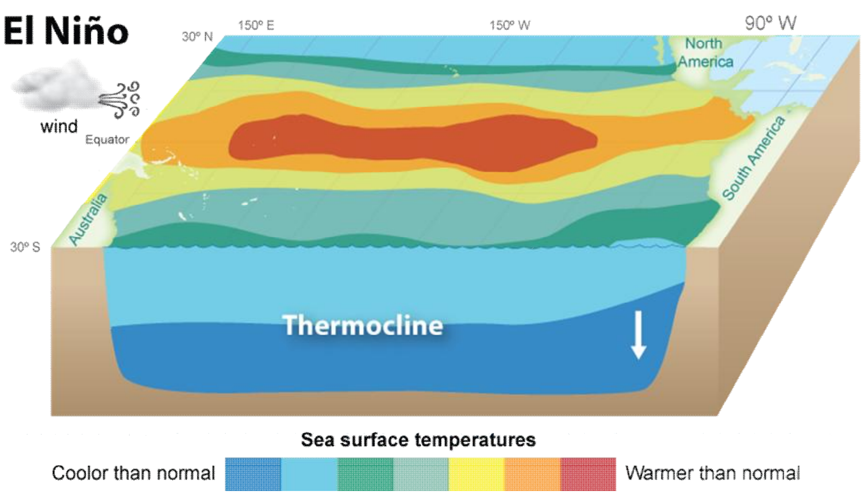


Normal

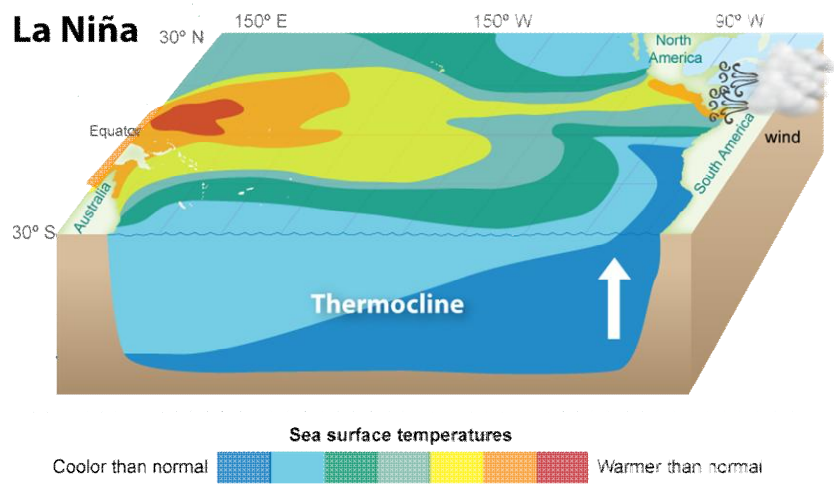


Remember!

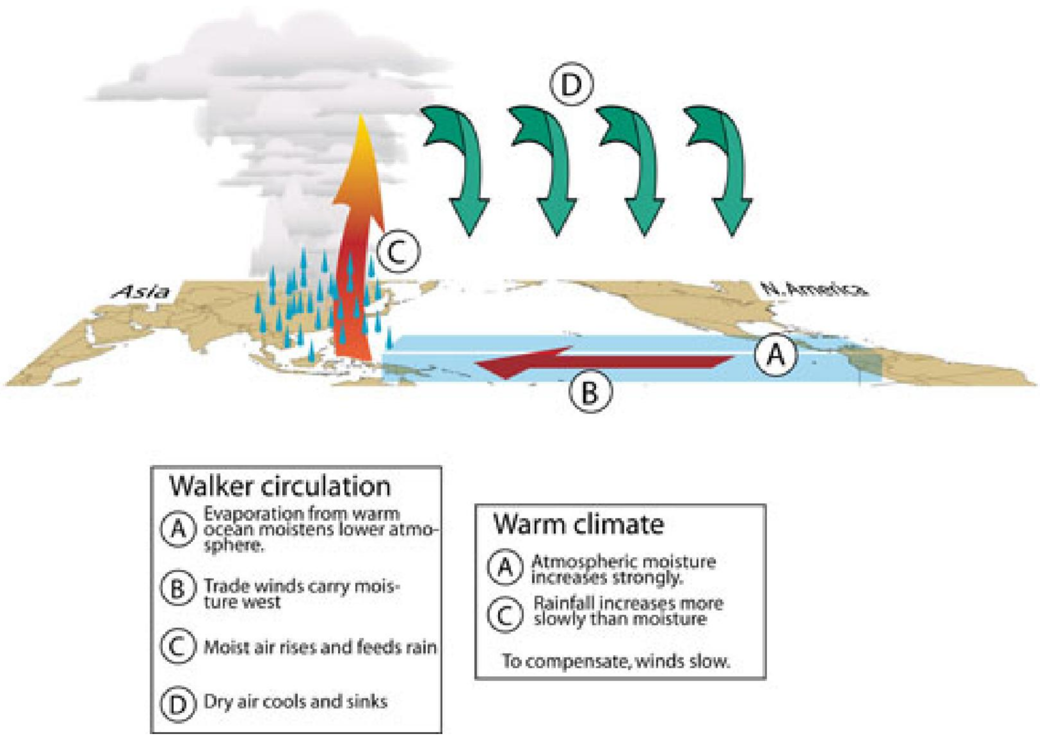
El Niño

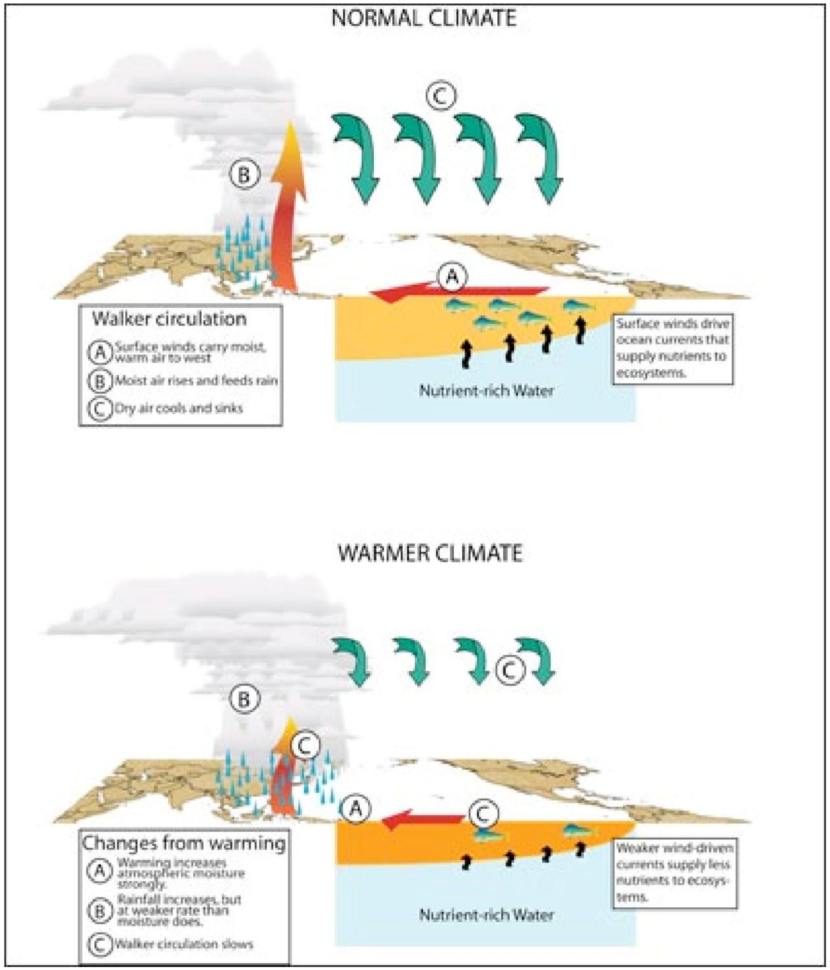


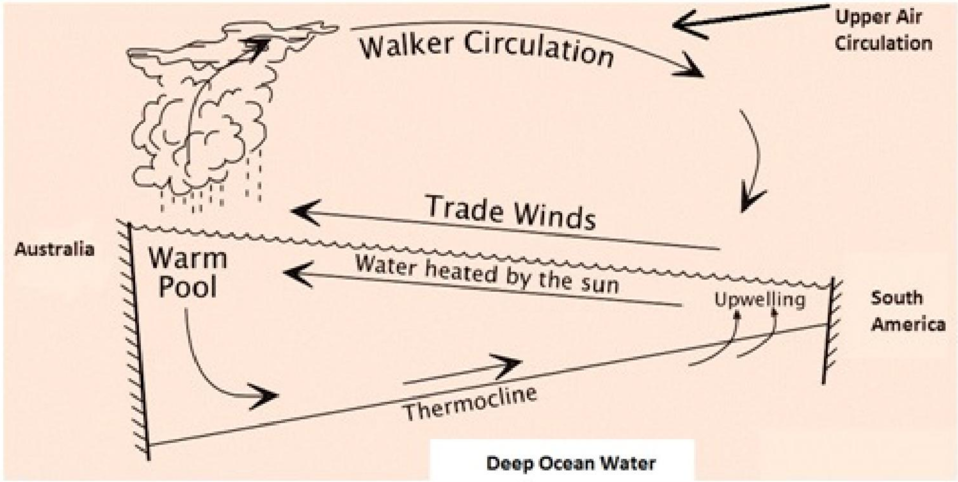
La Niña

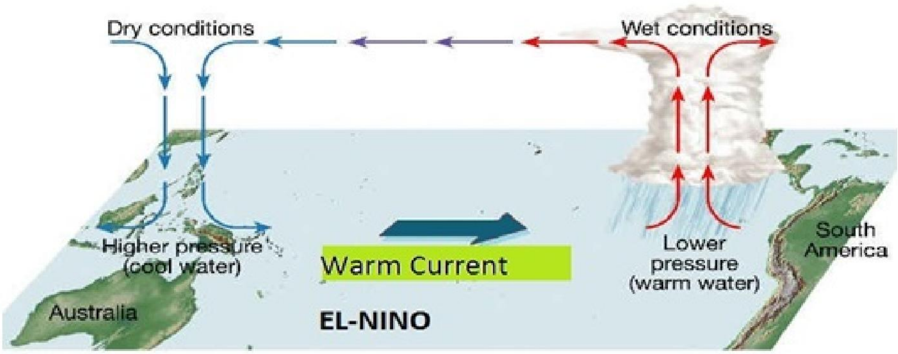


During warmer climate

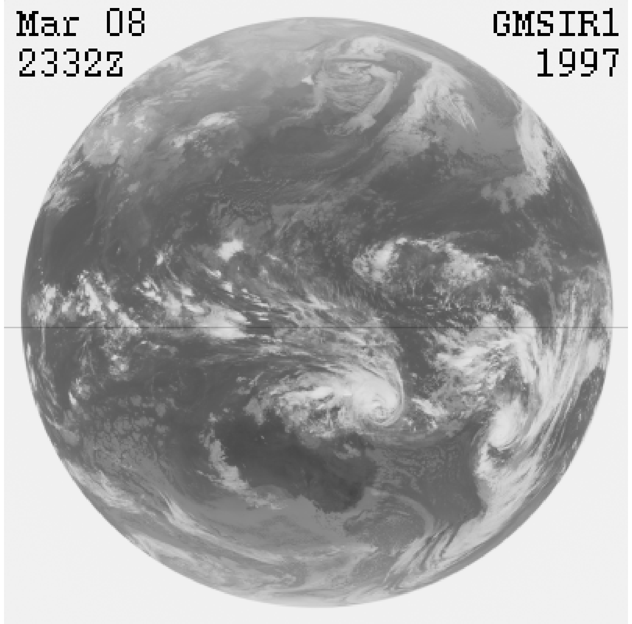








General circulation of the atmosphere



- ***Represents the average air flow around the globe***
- ***It is created by unequal heating at earth's surface***
- ***On global scale, earth is in radiative equilibrium: energy in equals energy out***
- ***General circulation's function is to transport heat poleward***
- ***The atmosphere of the earth is being moved by the energy of the sun. The atmosphere heated at the equator is then cooled at the poles, forming a kind of thermal convection.***
- ***By looking at global movement of clouds, we can see a prominent east-west tendency in the wind, i.e. easterly winds at low latitudes, and westerly winds at middle Latitudes.***

Components of general circulation

- Subtropical Highs
- Trade Winds
- Monsoons
- Intertropical Convergence Zone
- The Westerlies
- Polar Highs
- Polar Easterlies
- Subpolar Lows

Low vs. High Pressure

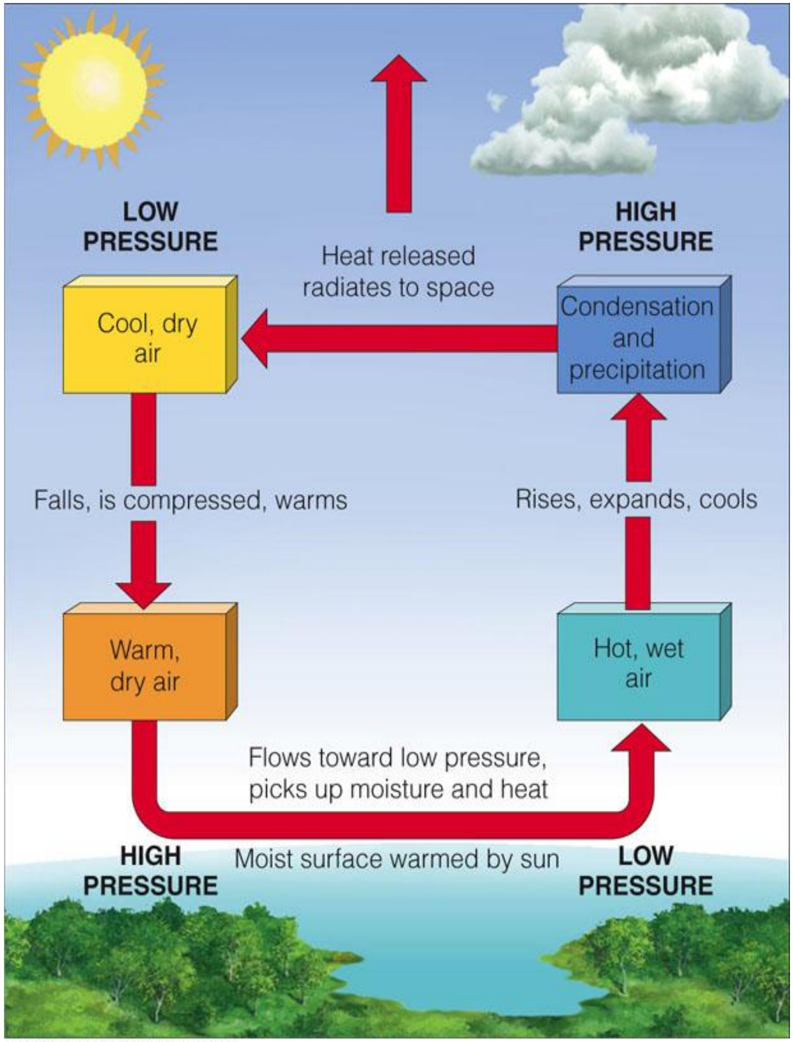
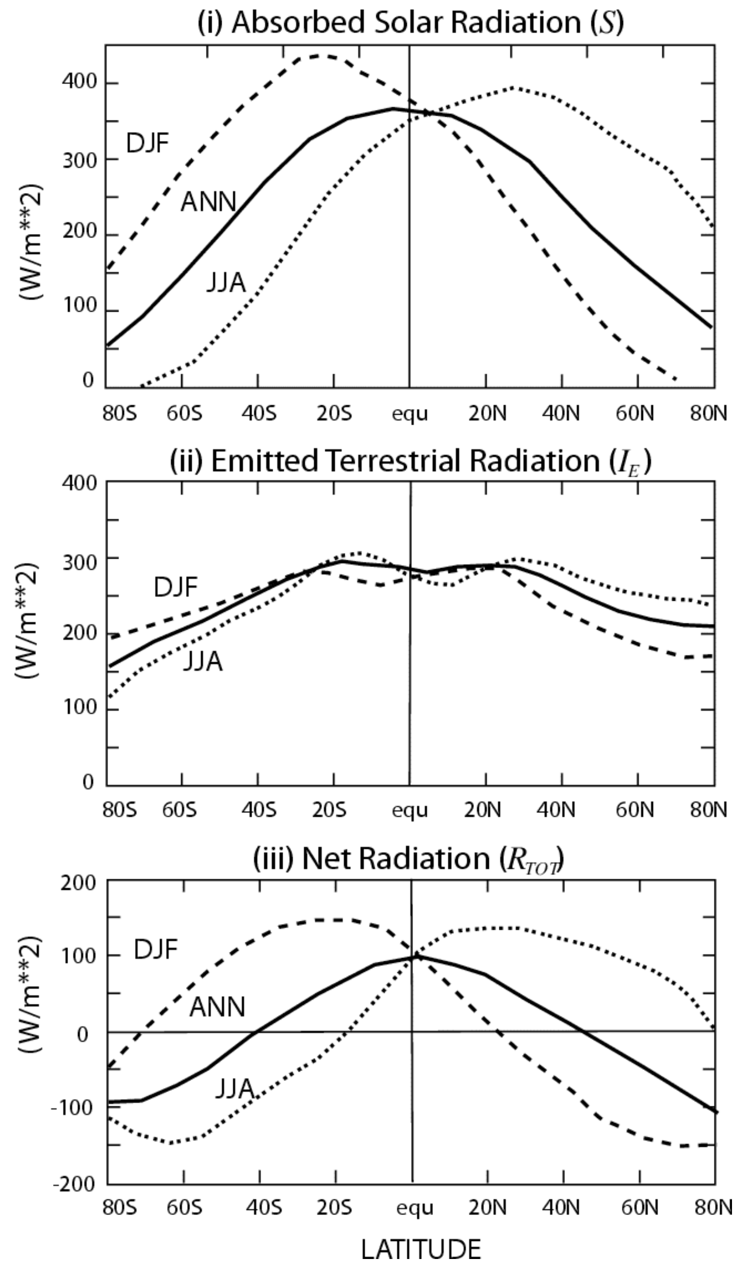


Figure shows the zonally averaged solar radiation absorbed at the surface of the planet (S, top panel), the long-wave radiation emitted to space by the planet (I_E, middle panel), and the net columnar radiation (R_{TOT}, defined as $S - I_E$; bottom panel)



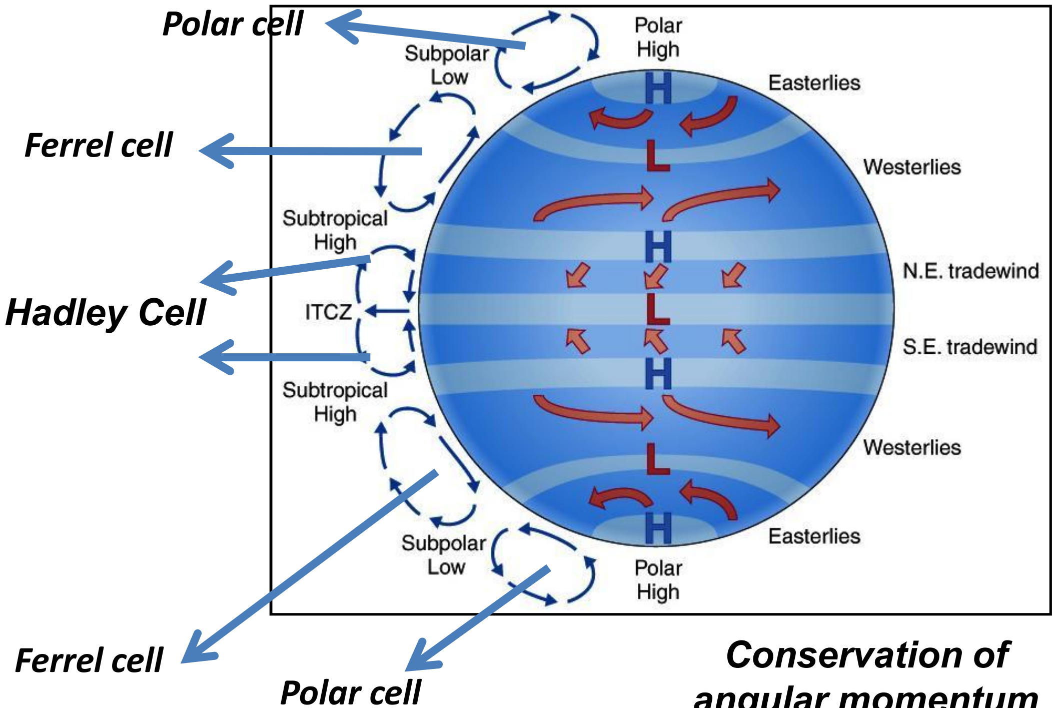
The absorbed solar radiation possesses an extremely strong seasonal variability, with maximum values in the summer subtropics. Emitted longwave radiation (I_E), which is relatively constant in the tropics and subtropics but shows substantial seasonal changes at high latitudes.

Overall, at all times of the year, there is net heating and substantial cooling at higher latitudes, especially in winter hemispheres.

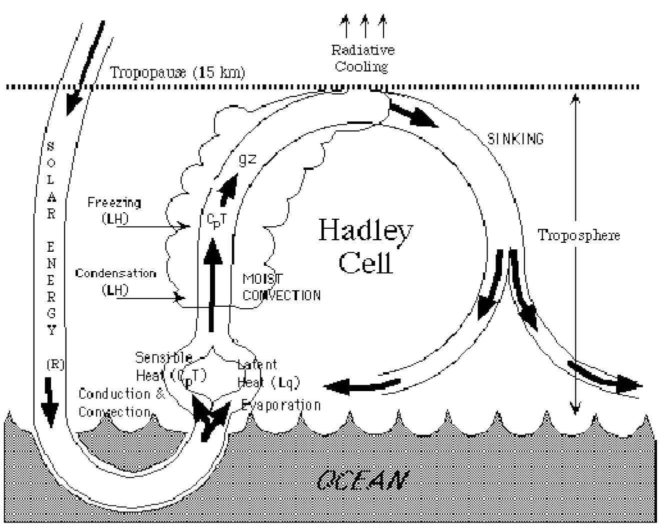
In general summer hemispheres show net heating between equator and the poles and possess a smaller equator-to-pole radiational heating gradient than the winter hemispheres.

It is important to note that while there exists net heating in the tropics and net cooling at higher latitudes, the long-term seasonal average temperature distribution remains relatively constant. Therefore, it is clear that there must be a net transport of heat between tropics and higher latitudes and can only be accomplished by fluid motions in the atmosphere and the ocean forced by pressure-gradient forces resulting from the radiational heating imbalances.

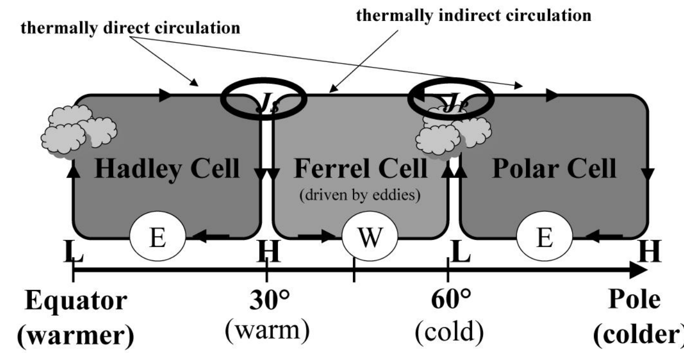
Sketch of the global circulation



Conservation of angular momentum argument



Properties of the Three Cells



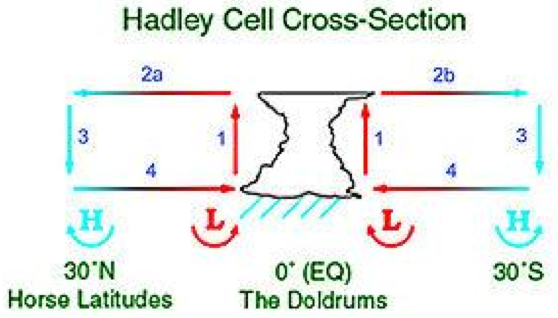
Thermally Direct/Indirect Cells

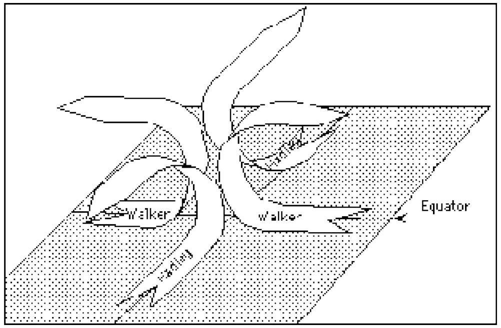
- **Thermally Direct Cells (Hadley and Polar Cells)**
  Both cells have their rising branches over warm temperature zones and sinking braches over the cold temperature zone. Both cells directly convert thermal energy to kinetic energy.

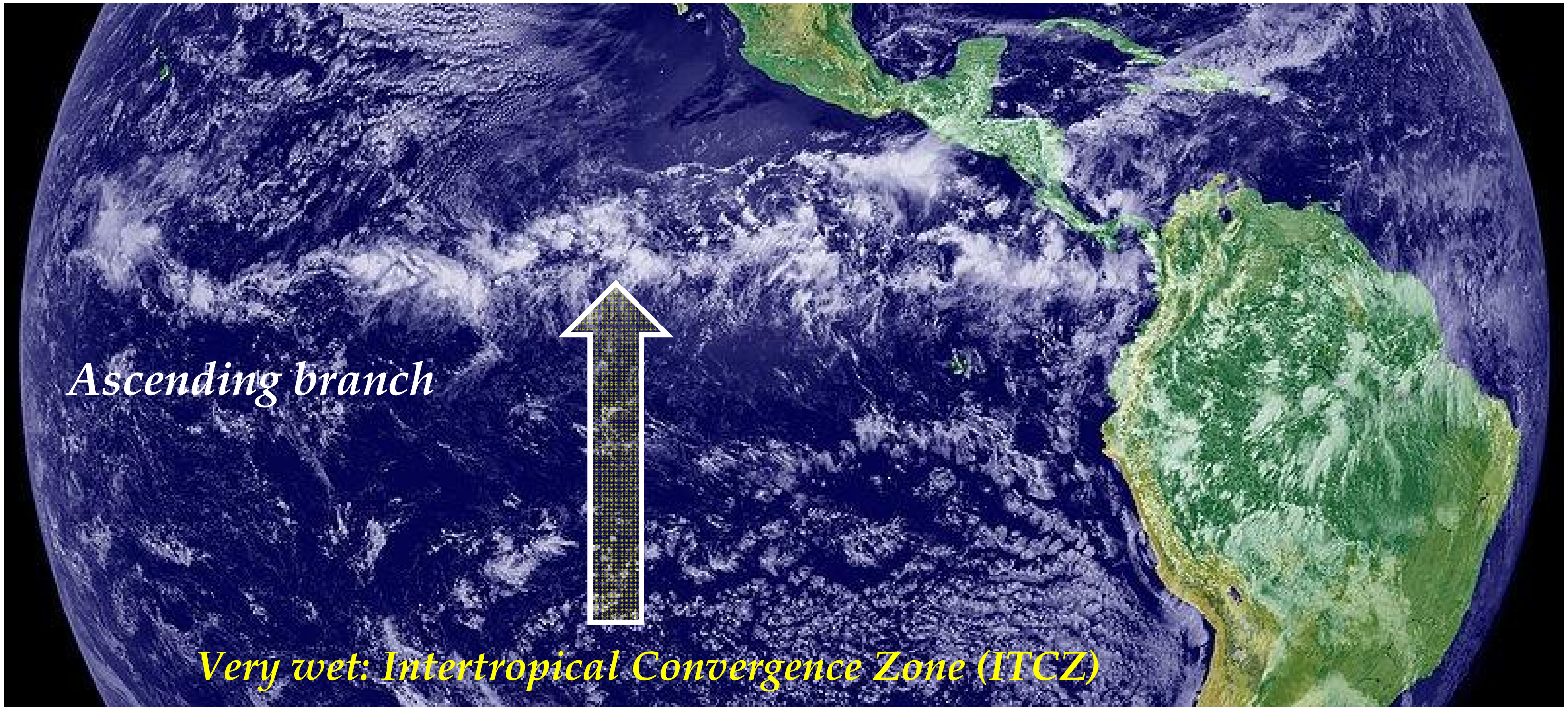
- **Thermally Indirect Cell (Ferrel Cell)**
  This cell rises over cold temperature zone and sinks over warm temperature zone. The cell is not driven by thermal forcing but driven by eddy (weather systems) forcing.

Characteristics of Hadley circulation

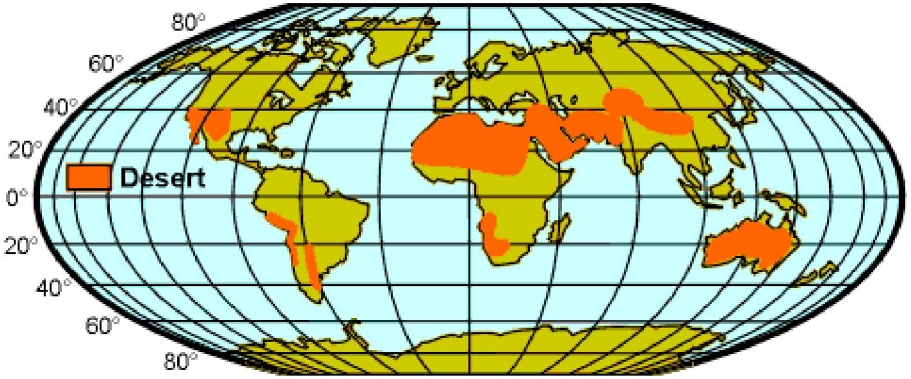
- *The Hadley circulation is a meridional circulation with an ascending branch in the extreme low-latitudes and a sinking branch in the subtropics.*
- *If the earth were not rotating the Hadley circulation would be expected to reach all the way to the poles.*
- *The ascending branch is associated with the zone of maximum solar heating, and migrates with the seasons.*
- *If the earth's surface was uniform, the mean position of the ascending branch would be at the Equator. Due to the asymmetric distribution of land between the Northern and Southern Hemispheres, and the very different thermal properties of land versus water, the mean position of the ascending branch of the Hadley cell is at about 5ºN (5ºN is often referred to as the Meteorological Equator).*
- *The ascending branch varies from about 5ºS to 15ºN over the course of the year.*
- *In the ascending branch, heat (primarily latent) is transported from the surface to the upper troposphere, where it is then transported poleward.*

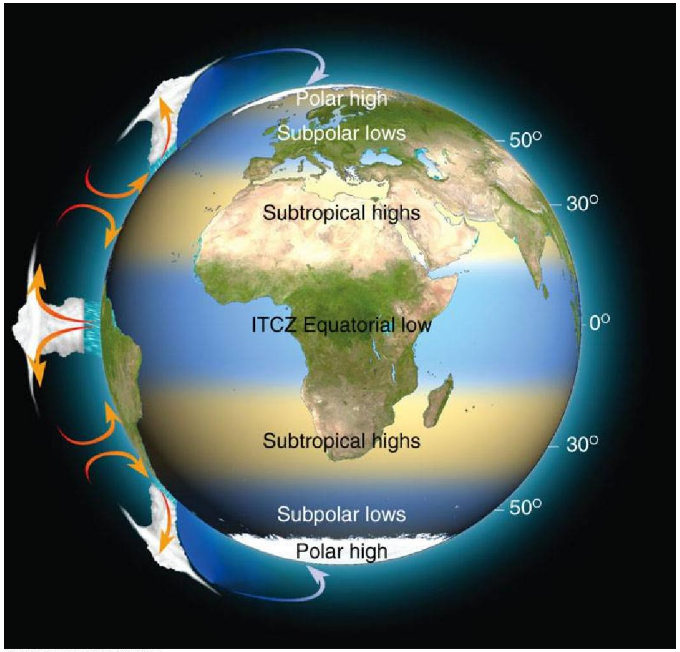




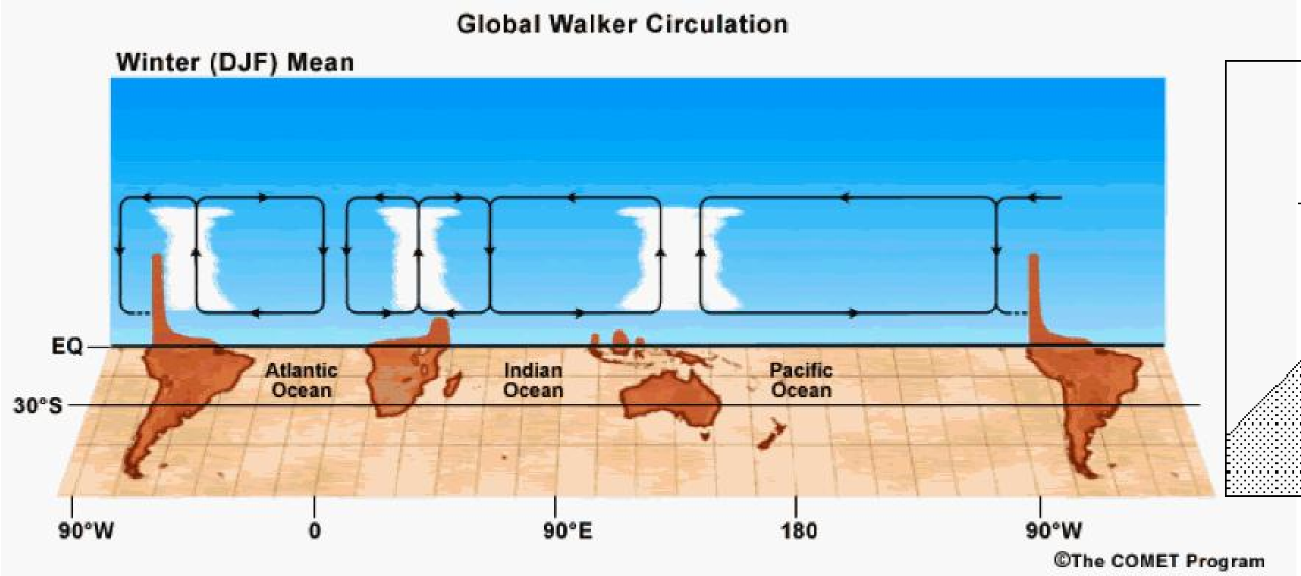


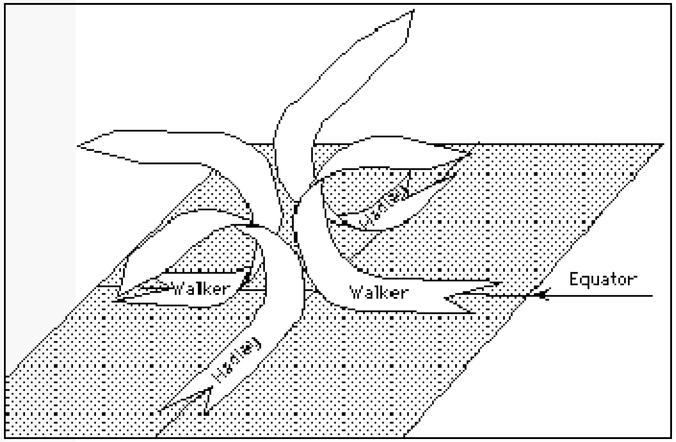
Descending branch





Walker circulation



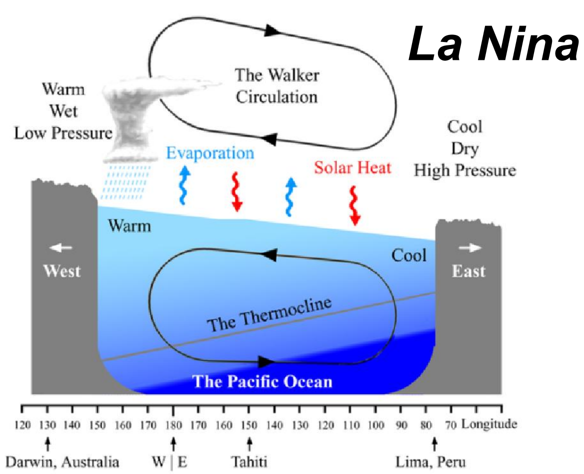


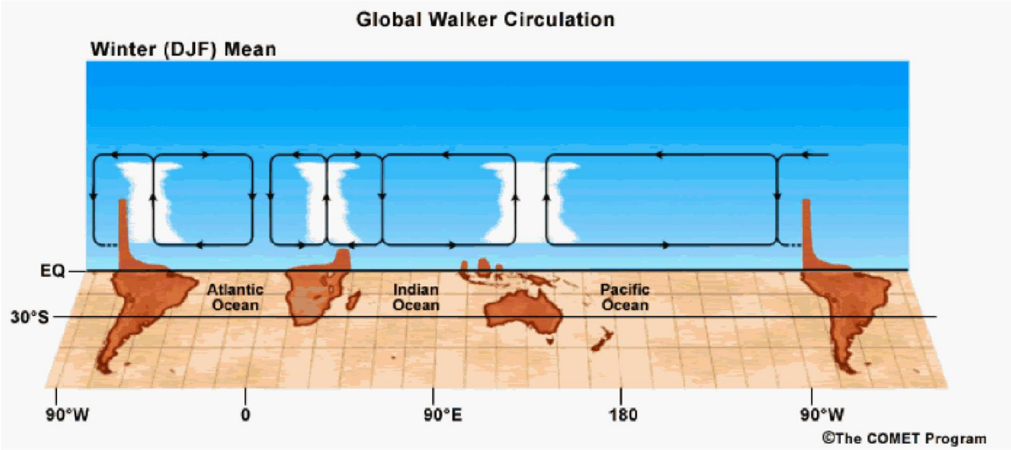
The Walker circulation is a 2D circulation (<u>large-scale zonal circulation</u>) along the equator in the longitude-height plane.

This circulation consists of cells comprising rising motions in major centres of equatorial convection (the Amazon, Africa, western Pacific) and sinking motions over adjacent ocean basins.

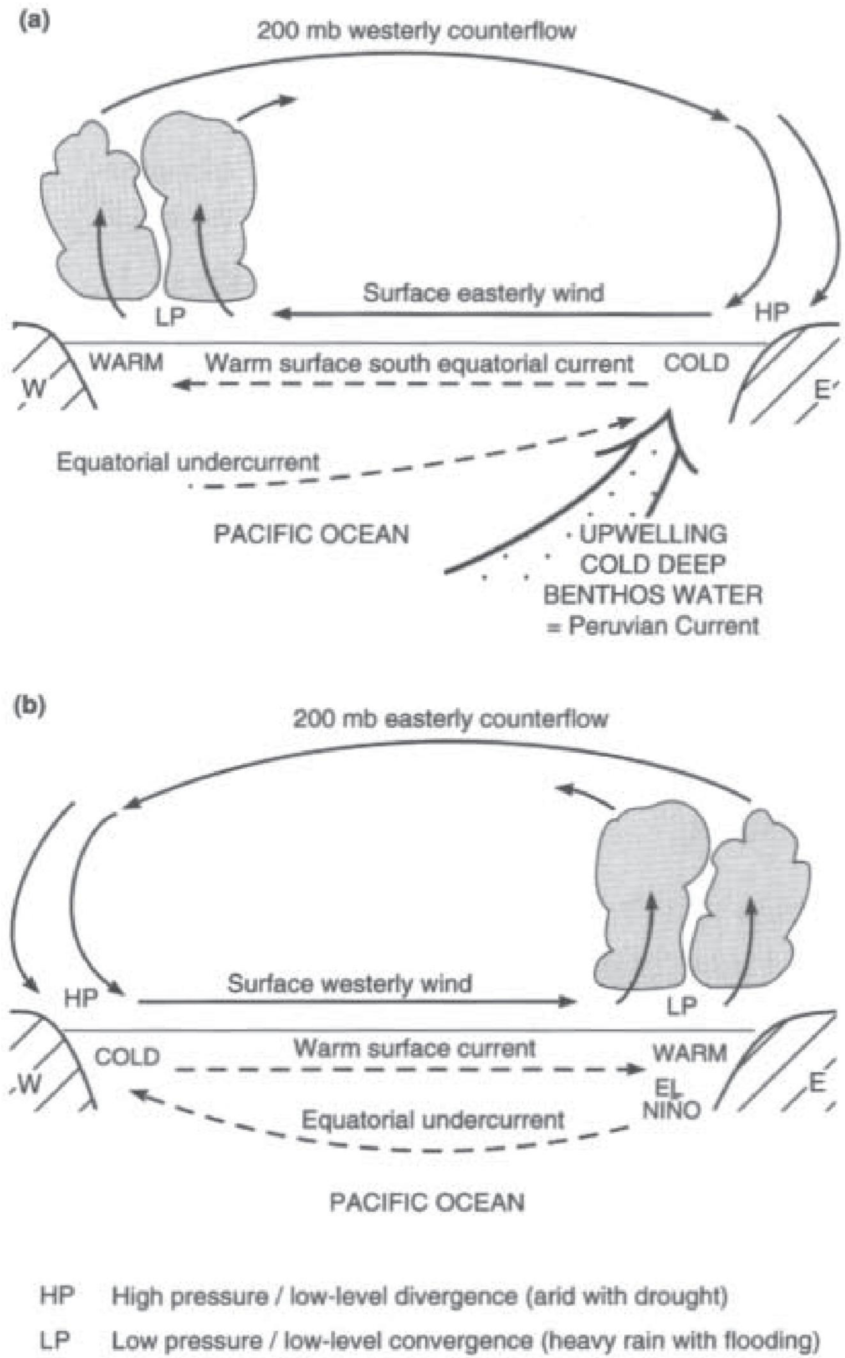
Walker circulation

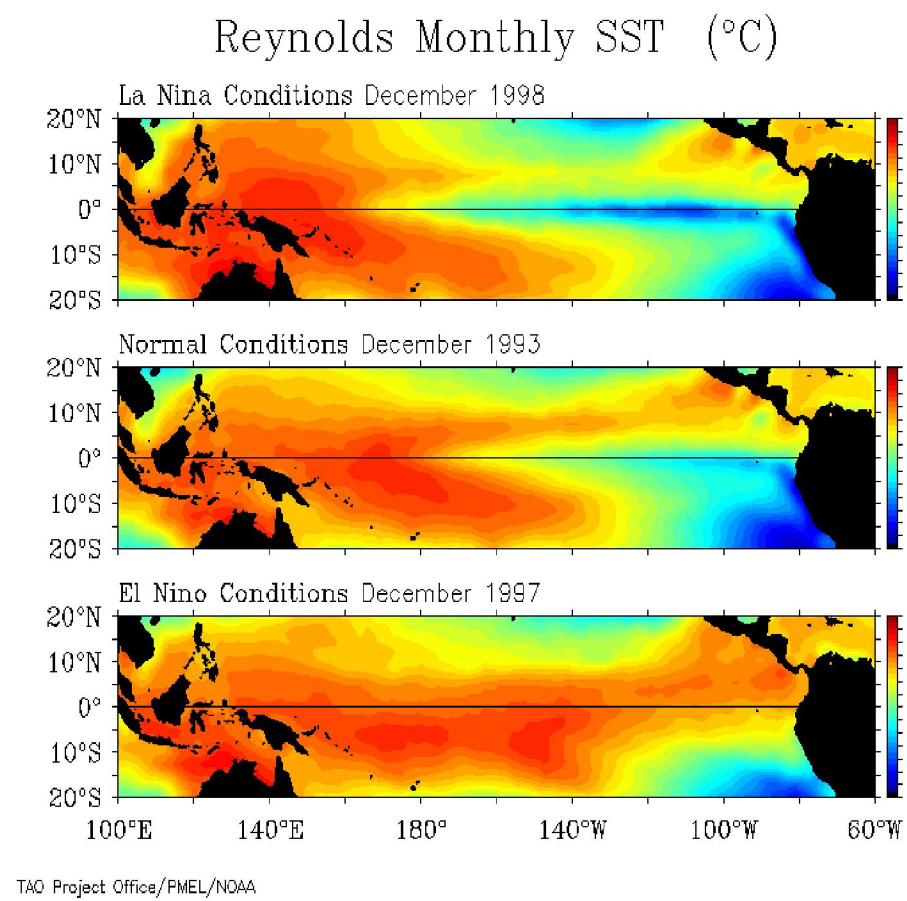
- *The Walker circulation is the result of a difference in surface pressure and temperature (is caused by differences in heat distribution between ocean and land) over the western and eastern tropical Pacific Ocean. A pressure gradient from east to west and causes surface air to from high pressure in the eastern Pacific to low pressure in the western Pacific. Higher up in the atmosphere, west-to-east winds complete the circulation.*
- *The Walker circulation is caused by the pressure gradient force that results from a high pressure system over the eastern Pacific ocean, and a low pressure system over Indonesia. When the Walker circulation weakens or reverses, an El Niño results, causing the ocean surface to be warmer than average, as upwelling of cold water occurs less or not at all. An especially strong Walker circulation causes a La Niña, resulting in cooler ocean temperatures due to increased upwelling.*
- *Walker circulation has been slowing since the mid-19th Century due to global warming*





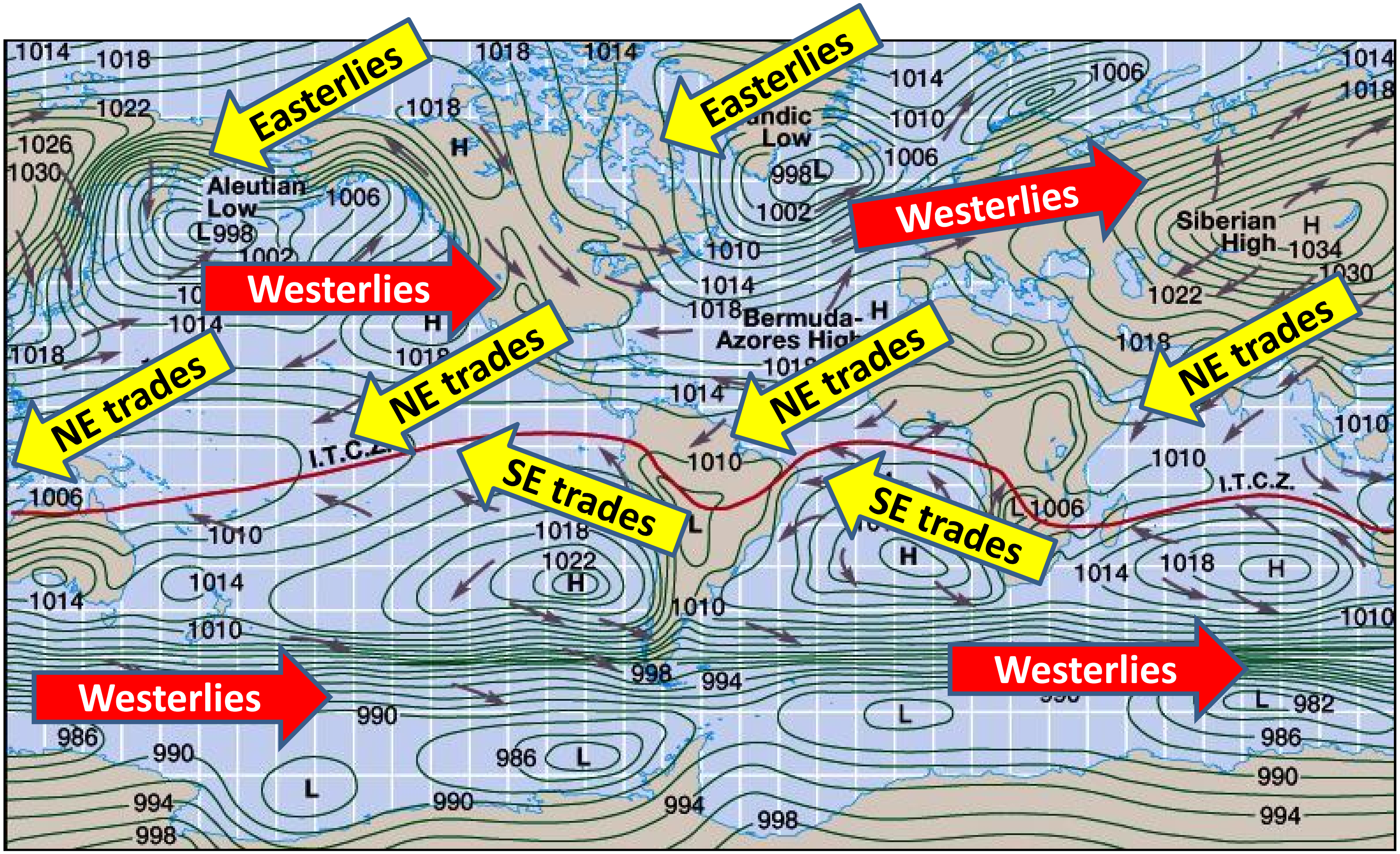
ENSO circulations: (a) normal Walker circulation and (b) El Niño circulation/reversal.





Equatorial Pacific: Sea Surface Temperature (SST)

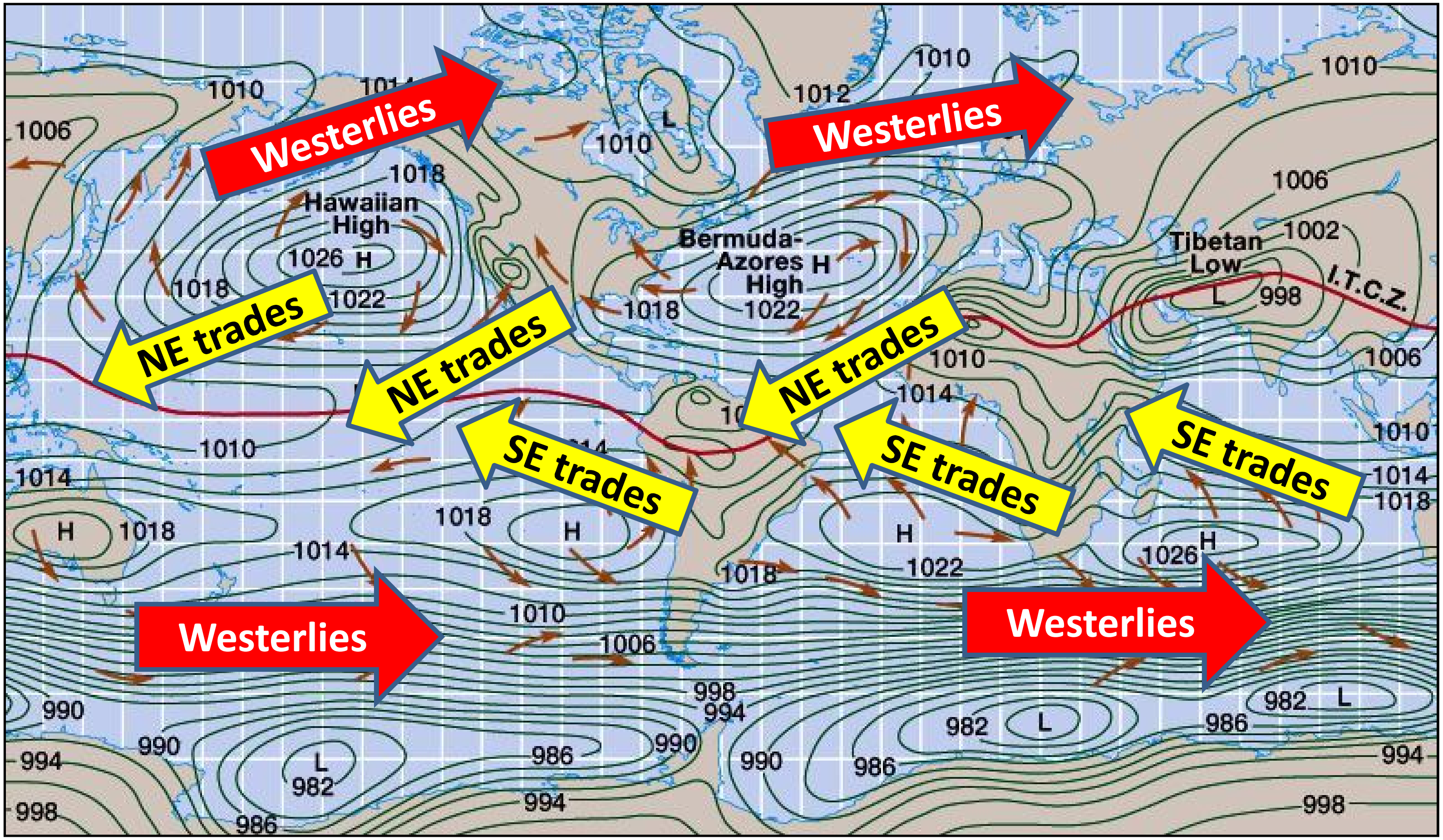
Circulation in a Global Context

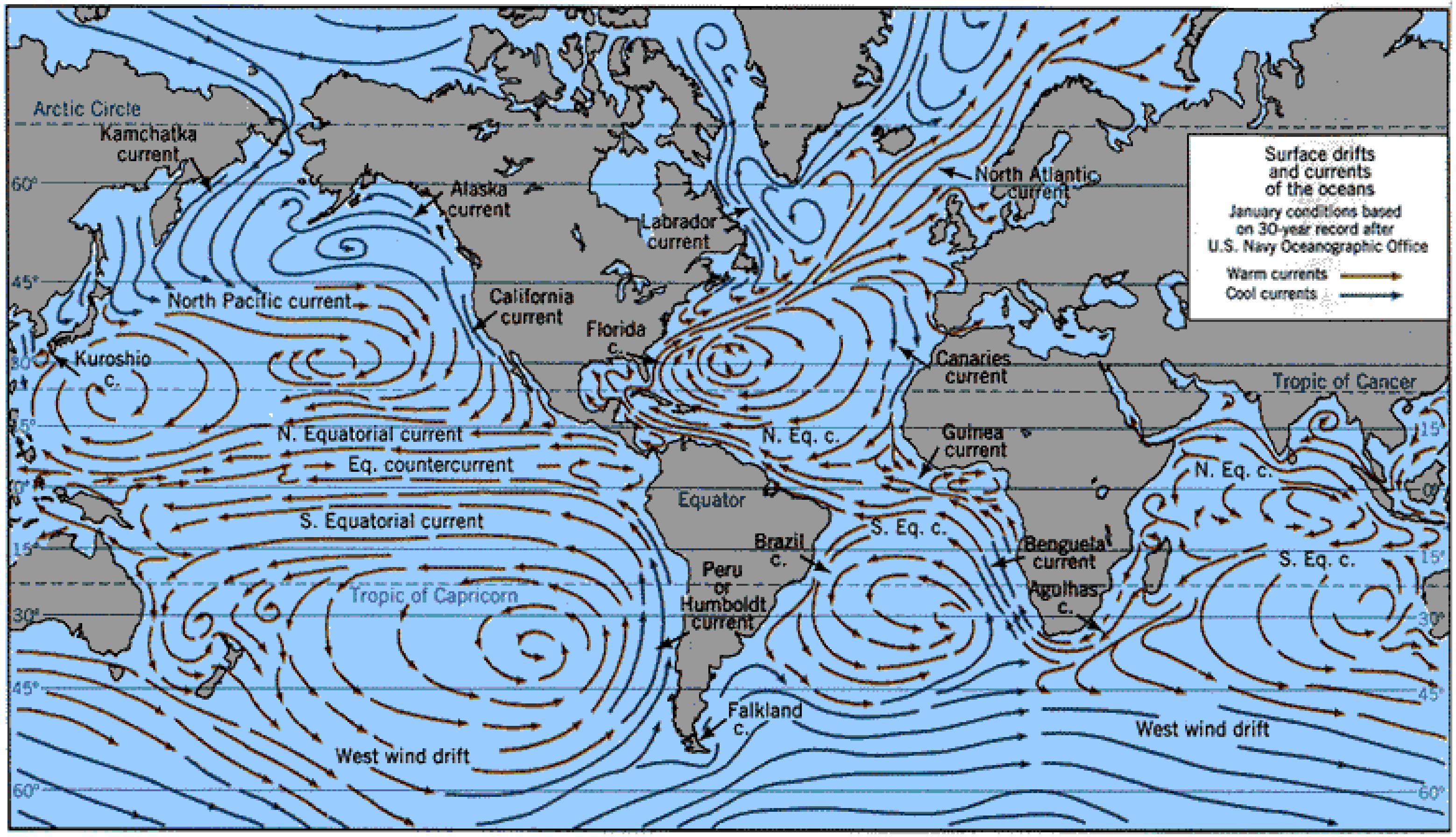


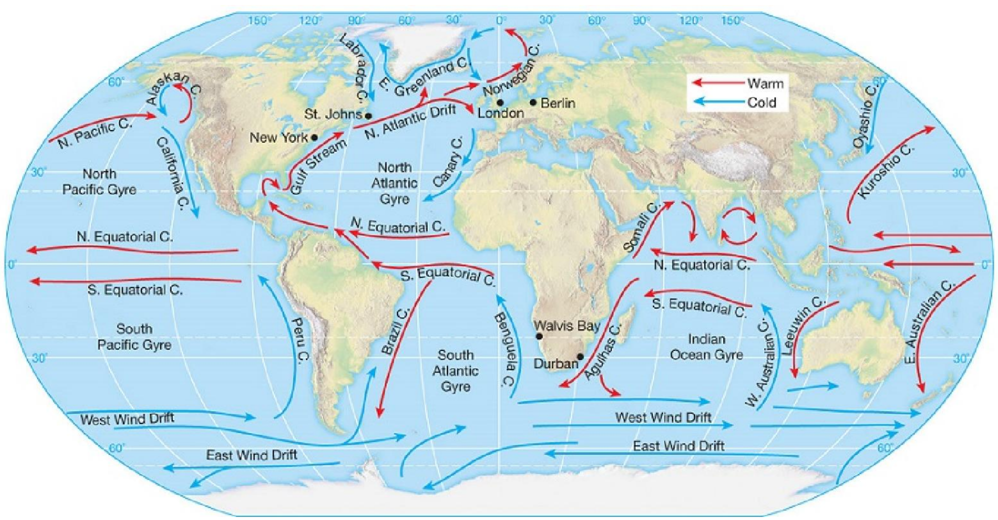
Mean surface pressure and winds during DJF (winter)

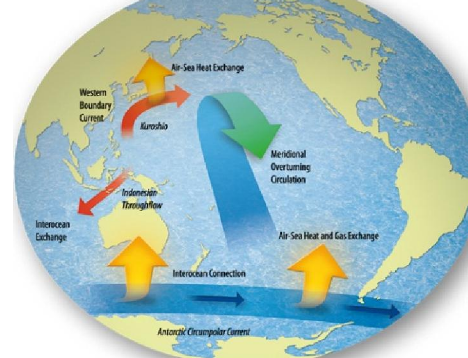
Mean surface pressure and winds during JJA (summer)

TRADE WINDS ARE EASTERLY WINDS



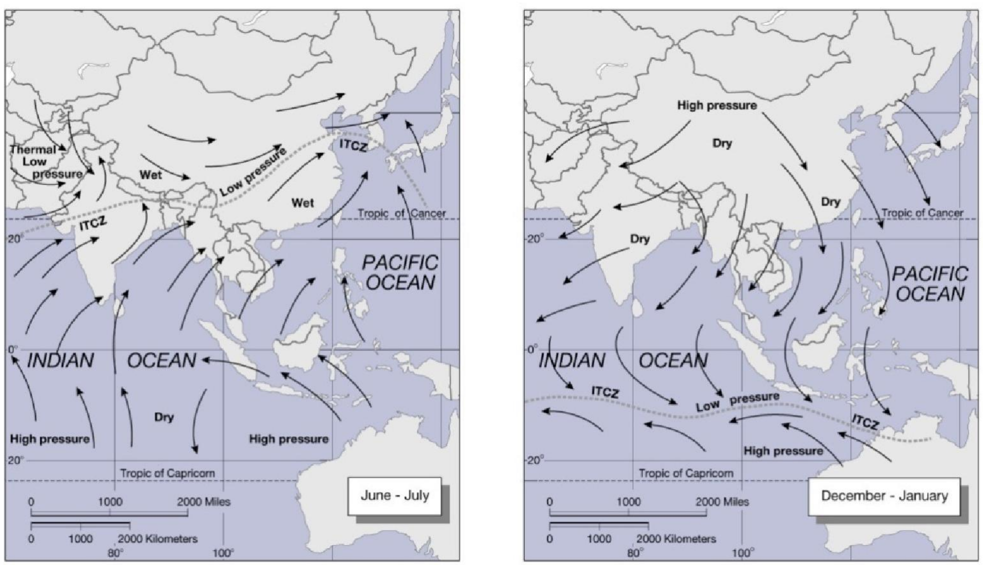

Surface drifts and currents of the oceans
January conditions based on 30-year record after U.S. Navy Oceanographic Office
Warm currents
Cool currents
Arctic Circle
Kamchatka current
Alaska current
Labrador current
North Atlantic current
North Pacific current
California current
Florida c.
Kuroshio c.
Canaries current
Tropic of Cancer
N. Equatorial current
N. Eq. c.
Guinea current
Eq. countercurrent
Equator
S. Equatorial current
S. Eq. c.
Brazil c.
Benguela current
Peru or Humboldt current
Agulhas c.
Tropic of Capricorn
Falkland c.
West wind drift
60°
45°
30°
15°
0°


Warm
Cold
Labrador C.
E. Greenland C.
Norwegian C.
Alaskan C.
N. Pacific C.
St. Johns
New York
London
Berlin
N. Atlantic Drift
Gulf Stream
California C.
North Pacific Gyre
North Atlantic Gyre
Canary C.
Oyashio C.
Kuroshio C.
N. Equatorial C.
Somali C.
S. Equatorial C.
Peru C.
Brazil C.
Benguela C.
South Pacific Gyre
South Atlantic Gyre
Walvis Bay
Durban
Agulhas C.
Indian Ocean Gyre
W. Australian C.
Leeuwin C.
E. Australian C.
West Wind Drift
East Wind Drift


Air-Sea Heat Exchange
Western Boundary Current
Kuroshio
Meridional Overturning Circulation
Indonesian Throughflow
Interocean Exchange
Air-Sea Heat and Gas Exchange
Interocean Connection
Antarctic Circumpolar Current

Driving mechanisms of monsoons

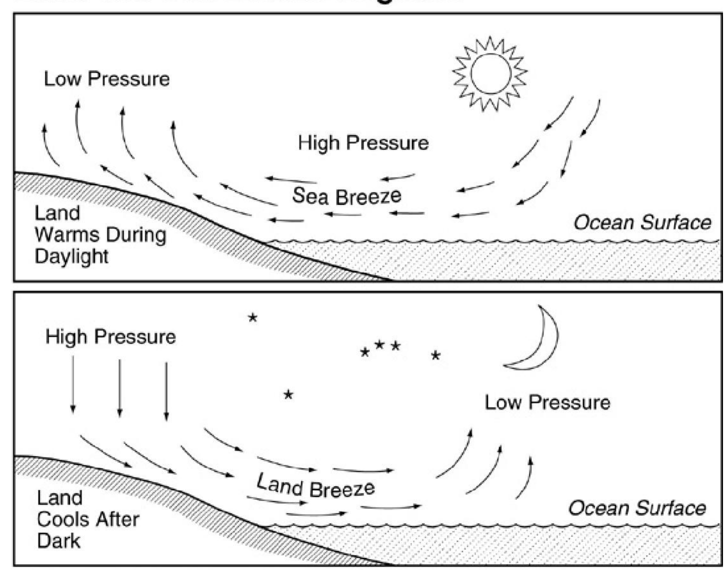
- *Differential heating of land and ocean*
- *Moist processes*
- *Rotation of the Earth*



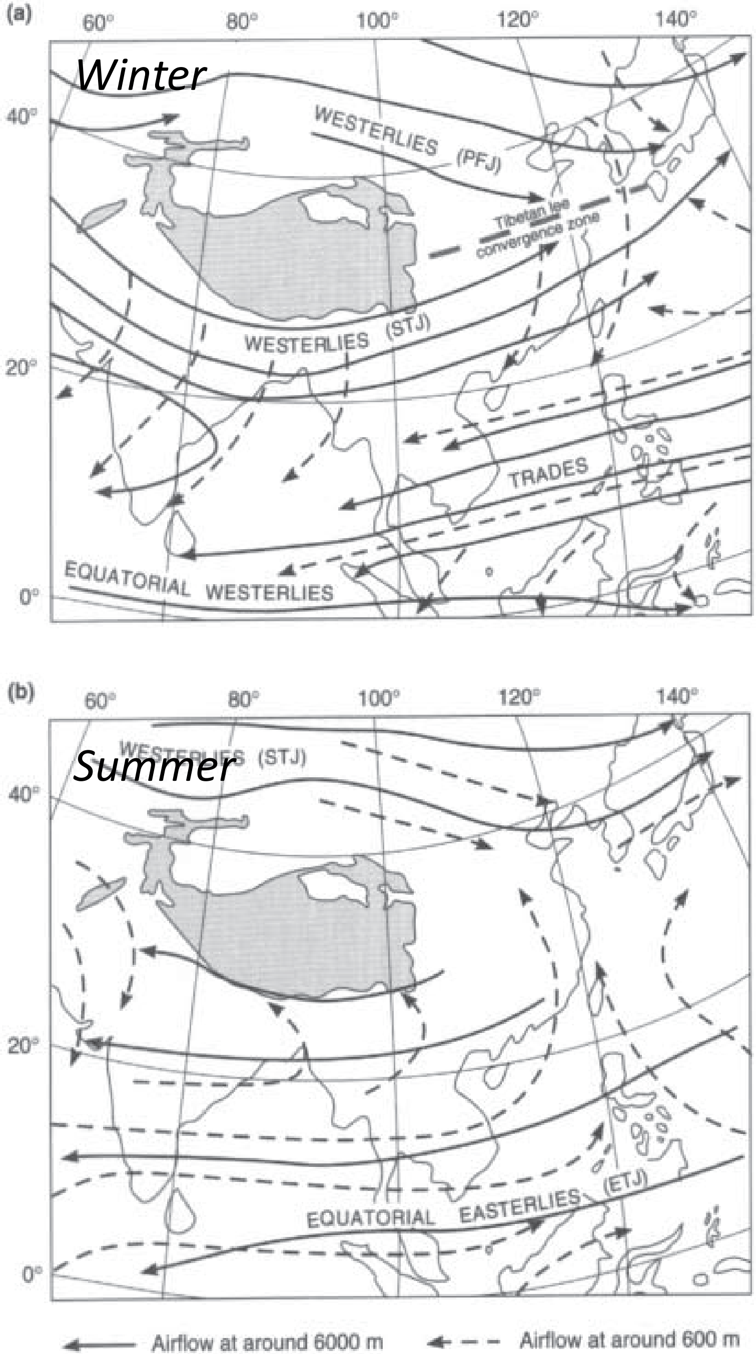
(a) (b)

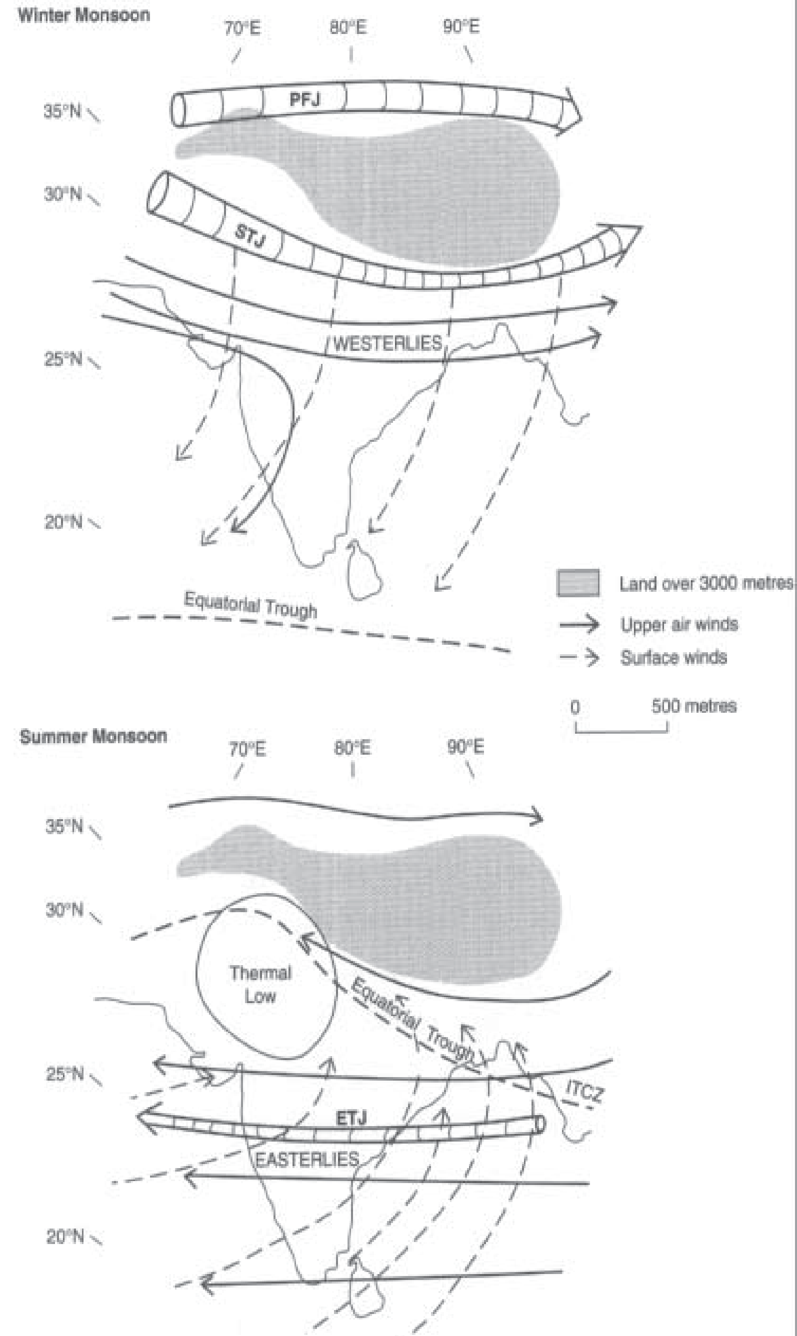
Figure 14

Land and Sea Breeze Regimes



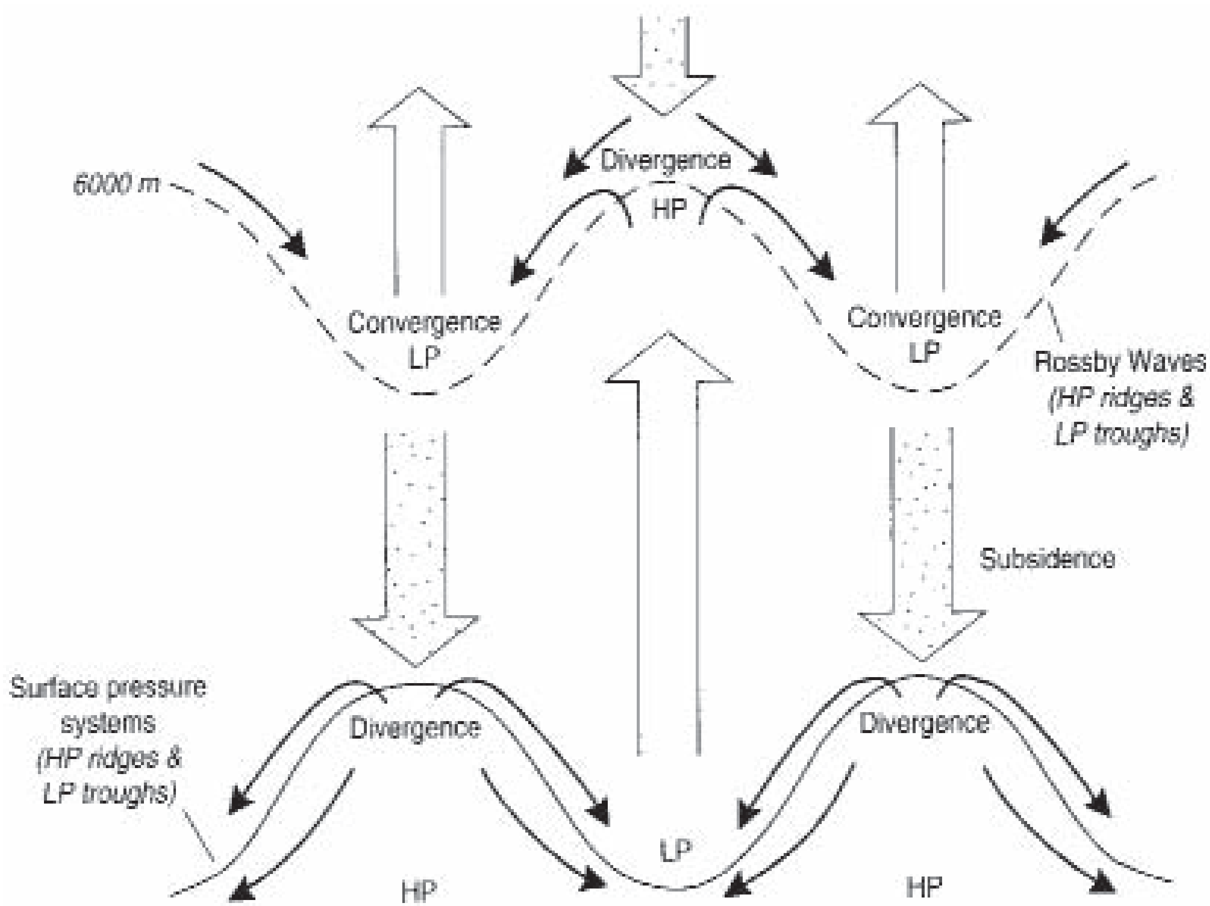
Adapted from William L. Donn, *Meteorology with Marine Applications.*





Upper air circulation during monsoon

Schematic cross-sectional representation of the coupling of upper-air Rossby waves and surface pressure systems.



Monsoons: DIFFERENTIAL HEATING OF LAND AND OCEAN

- *The specific heat of water is much larger than that of dry soil. Effective heat capacity difference is even larger, because mass of ocean is much larger.*
- *Only the upper most few centimetres of land are heated, due to slow molecular transfer of heat vertically. In oceans, heat is effectively mixed downward tens of meters via turbulent mixing.*
- *The difference in heat capacities, rather than specific heats themselves, is most important.*
- *Moist soil has higher specific heat than dry soil. Saturated soil behaves more like "ocean" than land.*

- *Differential heating sets up a horizontal pressure gradient (similar to land/sea breeze only on much larger scale.)*

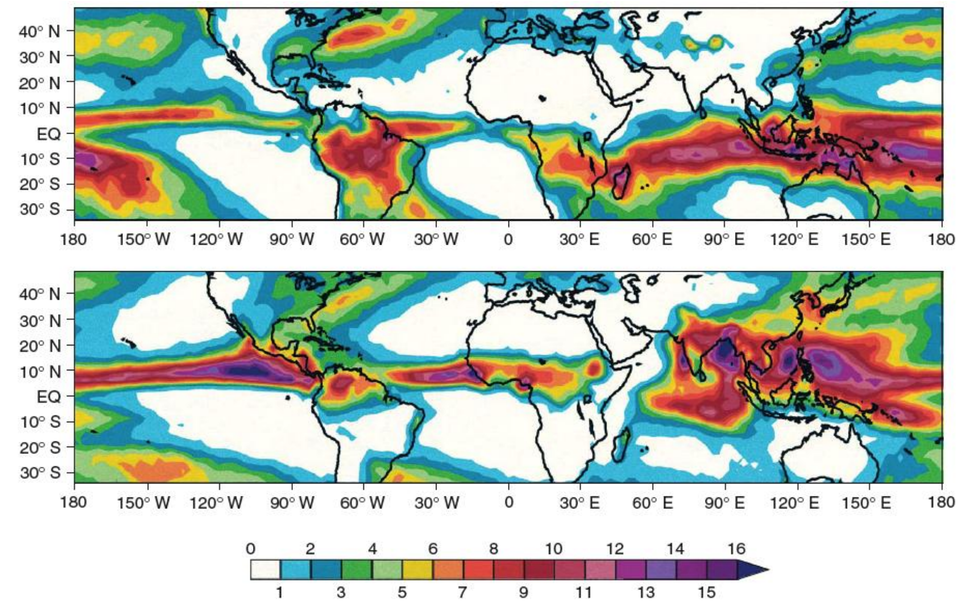
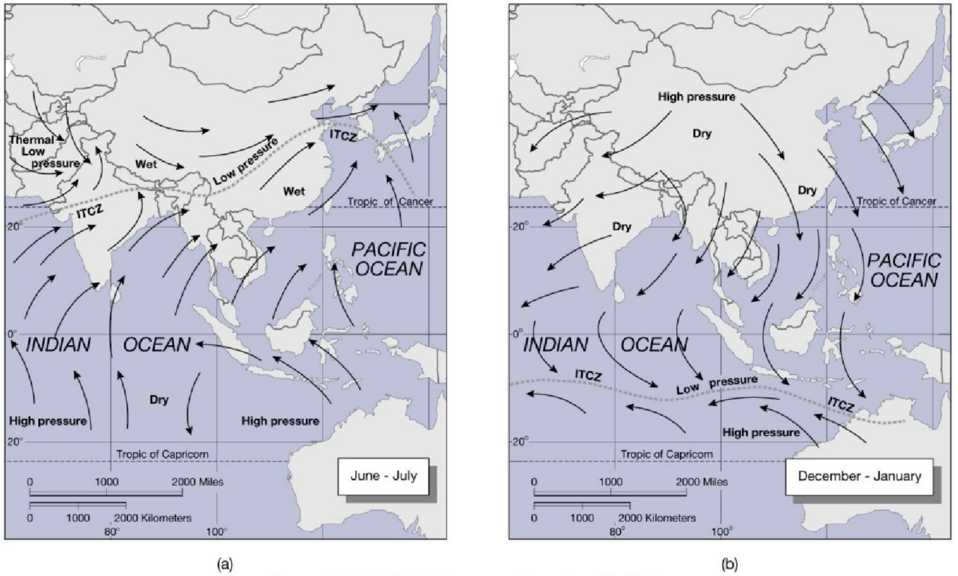


Figure 1 Mean precipitation distributions for northern winter (January–February; upper panel) and northern summer (July–August; lower panel) at the height of the monsoon season (units: mm day^{-1}). (Data source: Global Precipitation Climatology Project.)



(a) (b)

Monsoons: ROLE OF MOIST PROCESSES

- *Differential heating is not enough to explain the strength and extent of monsoon circulations.*

- *Moisture acts as "stored energy" through latent heat release.*

- *Evaporation occurs over the oceans, and then moisture is transported over the land, where it is released through condensation. This essentially "focuses" the effects of the solar heating collected over the ocean onto the land areas. This process is often referred to as the "solar collector."*

- *Latent heating results in a more intense monsoon flow, and also a vertically deeper monsoon flow. A moist monsoon has a depth on the order of the troposphere. A dry monsoon is much shallower, extending only to the mid-troposphere.*

- *Moisture also changes the character of the heating of the land.*

- *Moist land acts more like ocean.*

- *If land is dry, rising motion will occur closer to the coast, since the land will be very warm.*

- *As land becomes wet from precipitation, the rising motion will move inland over drier land.*

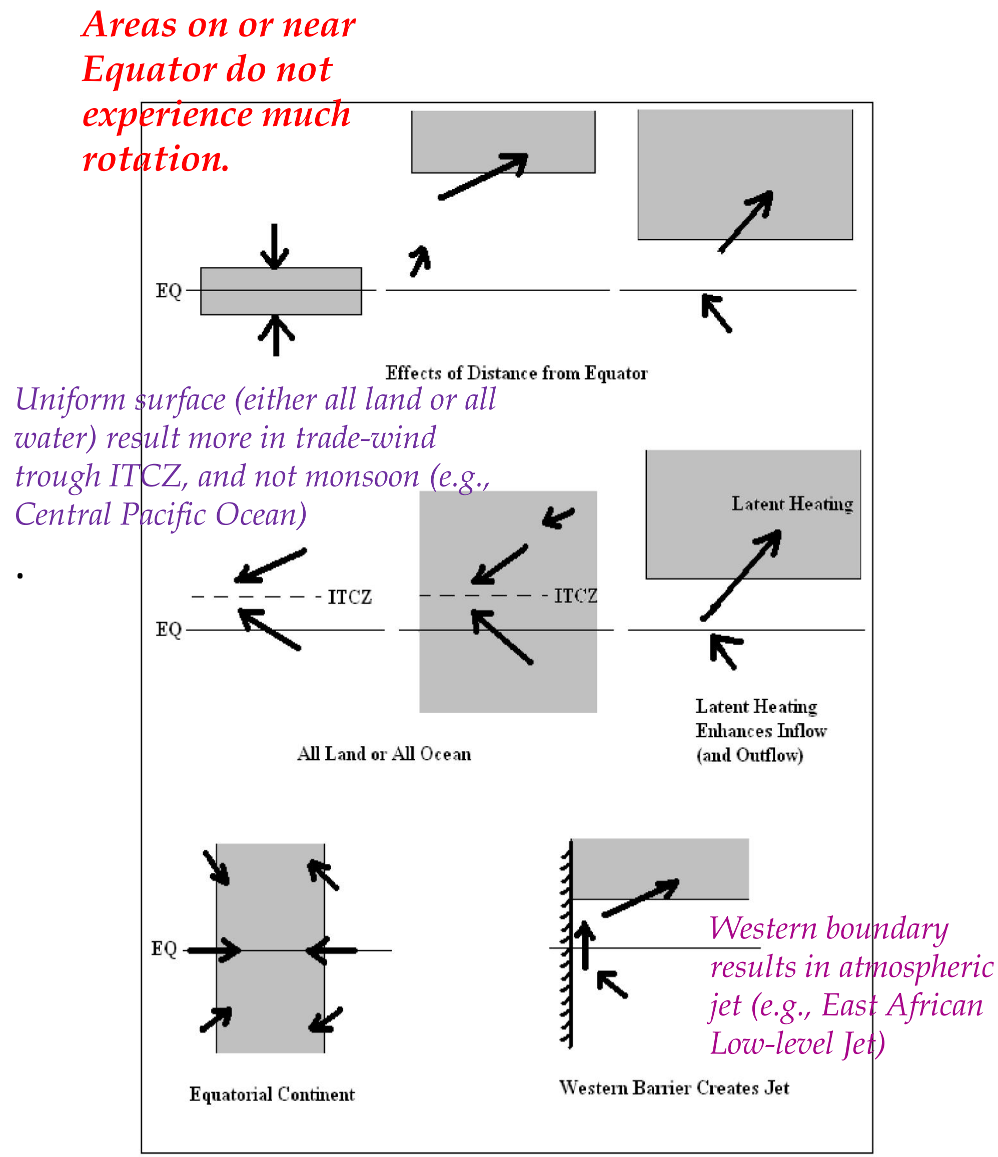
- *Precipitation will progress inland, allowing coastal area to dry out. Cycle will then repeat itself.*

- *This is one factor in monsoon variability and monsoon "breaks"*

Monsoons: ROTATIONAL AND FRICTIONAL EFFECTS

- *The Coriolis effect causes the air to "swirl" into the monsoon rather then flow directly in. It results in cyclonic inflow at the surface anticyclonic outflow aloft*

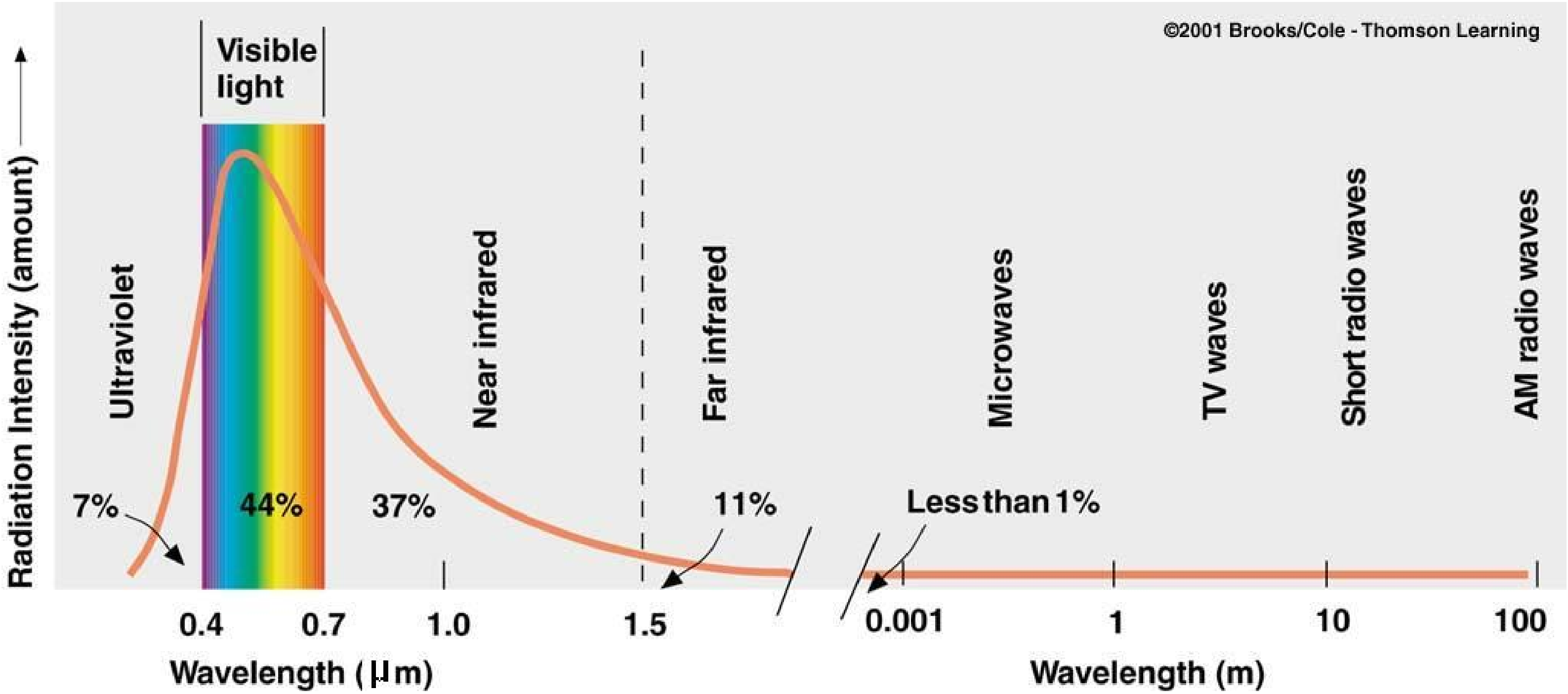
- *The longitudinal extent of the low-level, versus upper-level circulations are influenced by friction. There is more cross-isobaric flow at the surface than aloft, so surface circulation has less of a longitudinal extent than does the upper-level outflow.*



After "Physics of Monsoons: The Current View," J.L . Young, in Monsoons(Fein, ed)

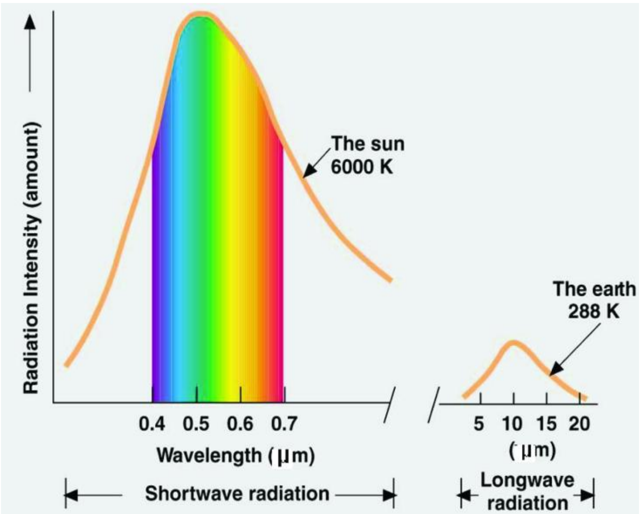
"Tropical Climatology", McGregor and Nieuwolt
"The Elementary Monsoon," Webster, in Monsoons, Fein (Ed.)

Solar Radiation (Sunlight)



- *Sunlight is primarily made up of the following:*
  - ***Visible Light (44%)***
  - ***Infrared Radiation (48%)***
  - ***Ultraviolet Radiation (7%)***

Reading material:
Earth's global energy Budget – Trenberth et al. (2009) – Bulletin of American Meteorological Society.

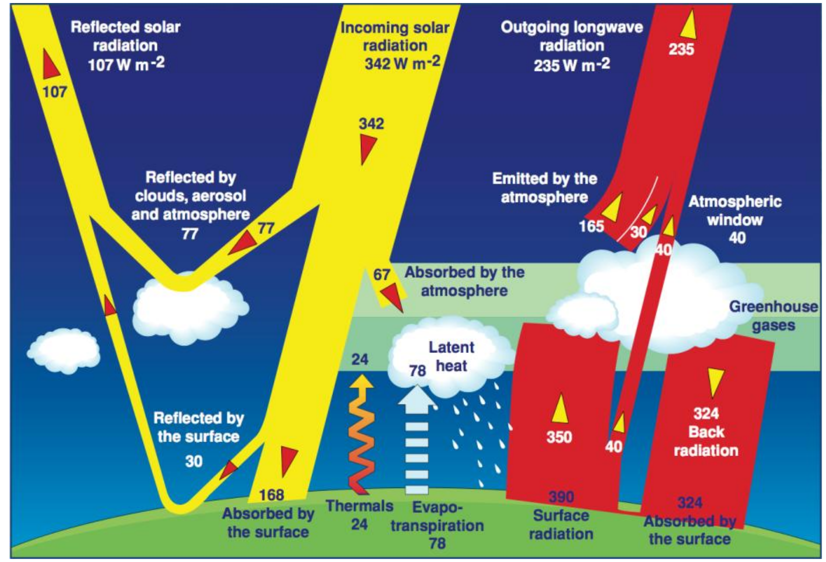


Wien's law

short-wave $\Leftarrow$ $\boxed{\lambda_{\max}(\mu m) = \dfrac{2898}{T(^{o}\mathrm{K})}}$ $\Rightarrow$ long-wave

(From the space into the atmosphere = 342 W m^{-2})

At TOA, 342 = 107 (30% from SW) + 235 (70% from LW)



At the surface; $\underbrace{168 + 324}_{\text{Absorbed}} = (\underbrace{24 + 78 + 350 + 40}_{\text{Emitted}})$

$T = 15^{o}\mathrm{C},\ E = \sigma T^{4} \Rightarrow 390\ \mathrm{W\ m^{-2}}$

(from the earth into the atmosphere)

Earth's energy balance (CONSERVATION OF ENERGY)

Energy entering at the top of the atmosphere (TOA) = Energy leaving TOA

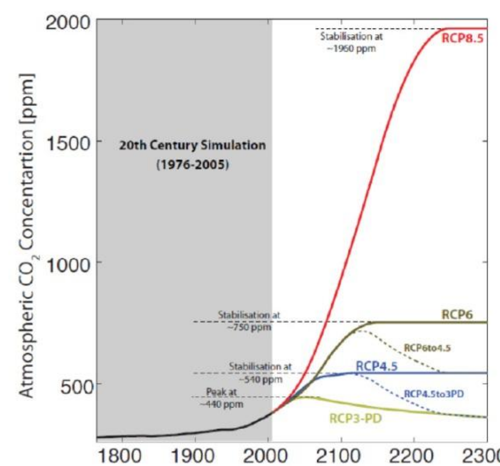
Energy entering the earth's surface = Energy leaving the Earth's surface

A small imbalance of difference, about few a watts per square meter, leads to global warming or cooling.

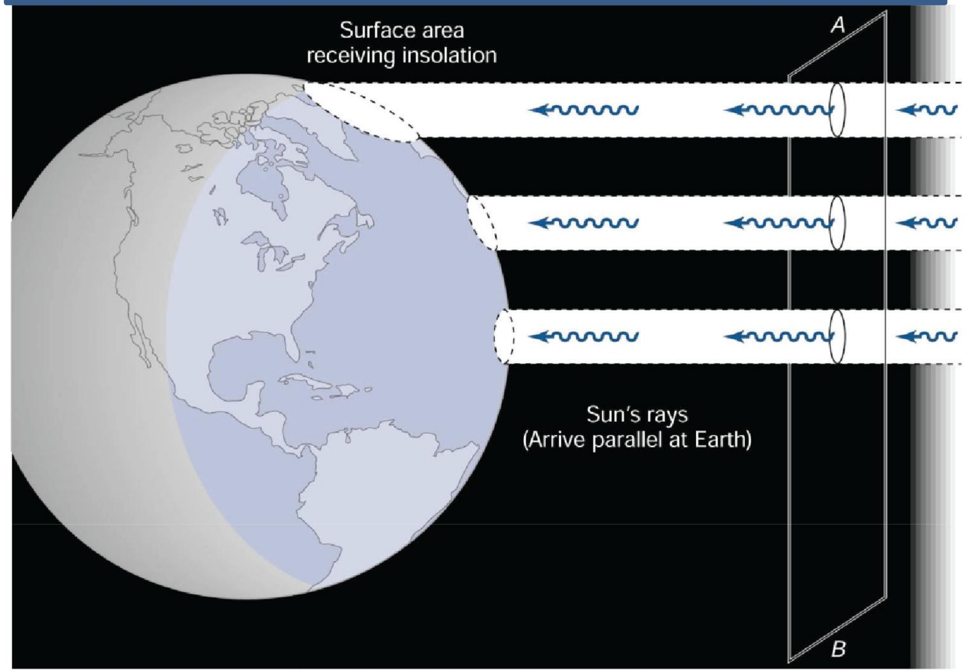
Radiative forcing (TOA) = incoming − outgoing (+ ve = warming; − ve = cooling)

Representative Concentration Pathways (RCPs) - IPCC Emission scenarios

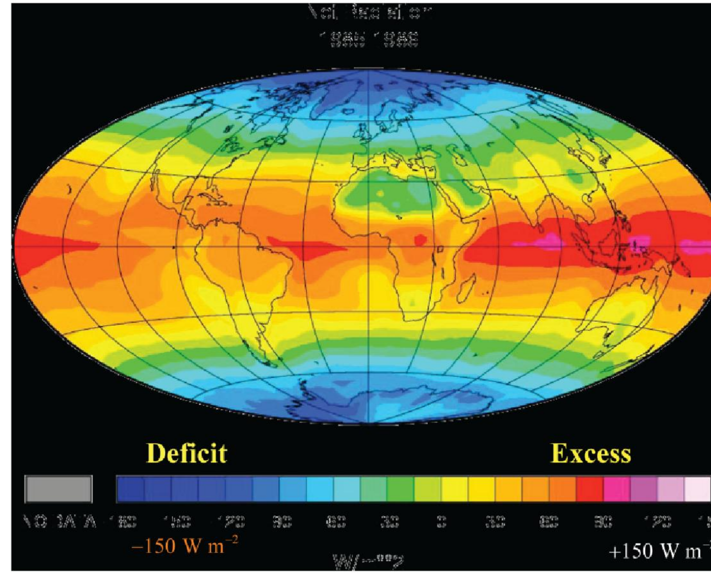
e.g., RCP 8.5 = Rising radiative forcing pathway to 8.5 W m^{-2} by 2100.



Why are poles colder than tropics?
Amount of sunshine falls per unit area (poles) < over the equatorial region

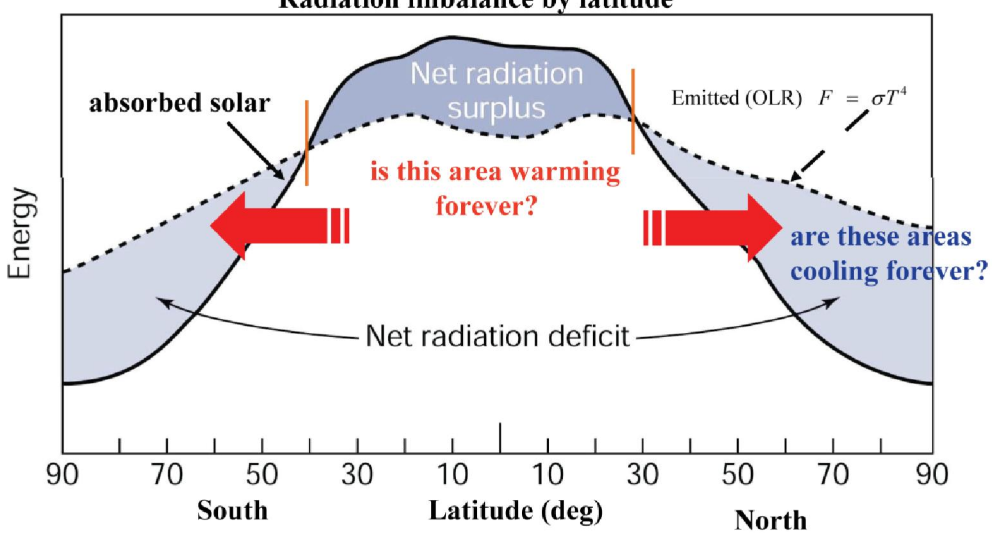


TOA Net radiation (incoming-terrestrial)



Is this radiation balanced locally?

Radiation imbalance by latitude



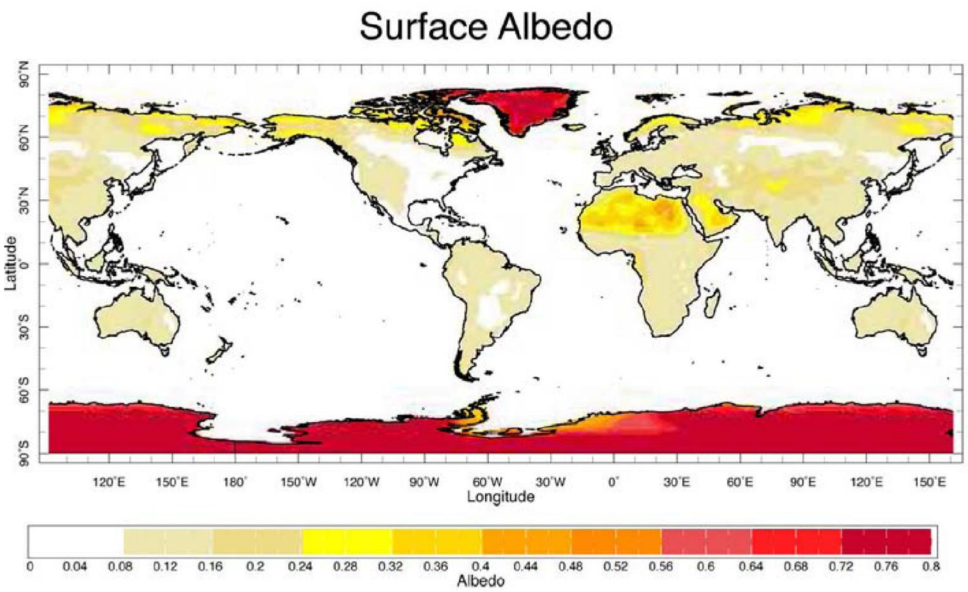
There must be a poleward transport of energy (for equilibrium)

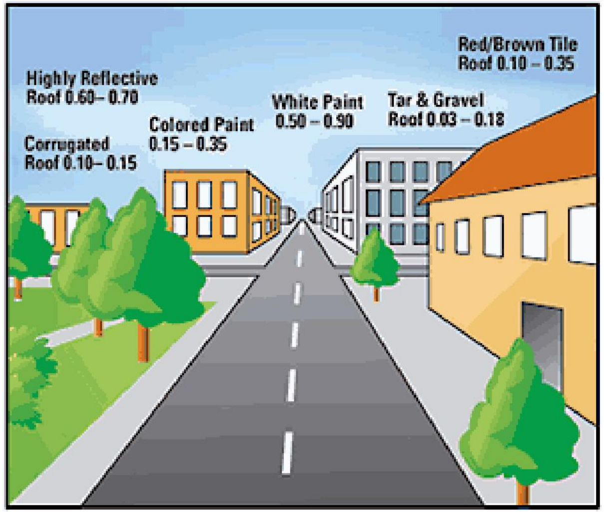
The transport is largely from atmospheric and oceanic motions driven by gradients of heat and pressure

Albedos of different surfaces

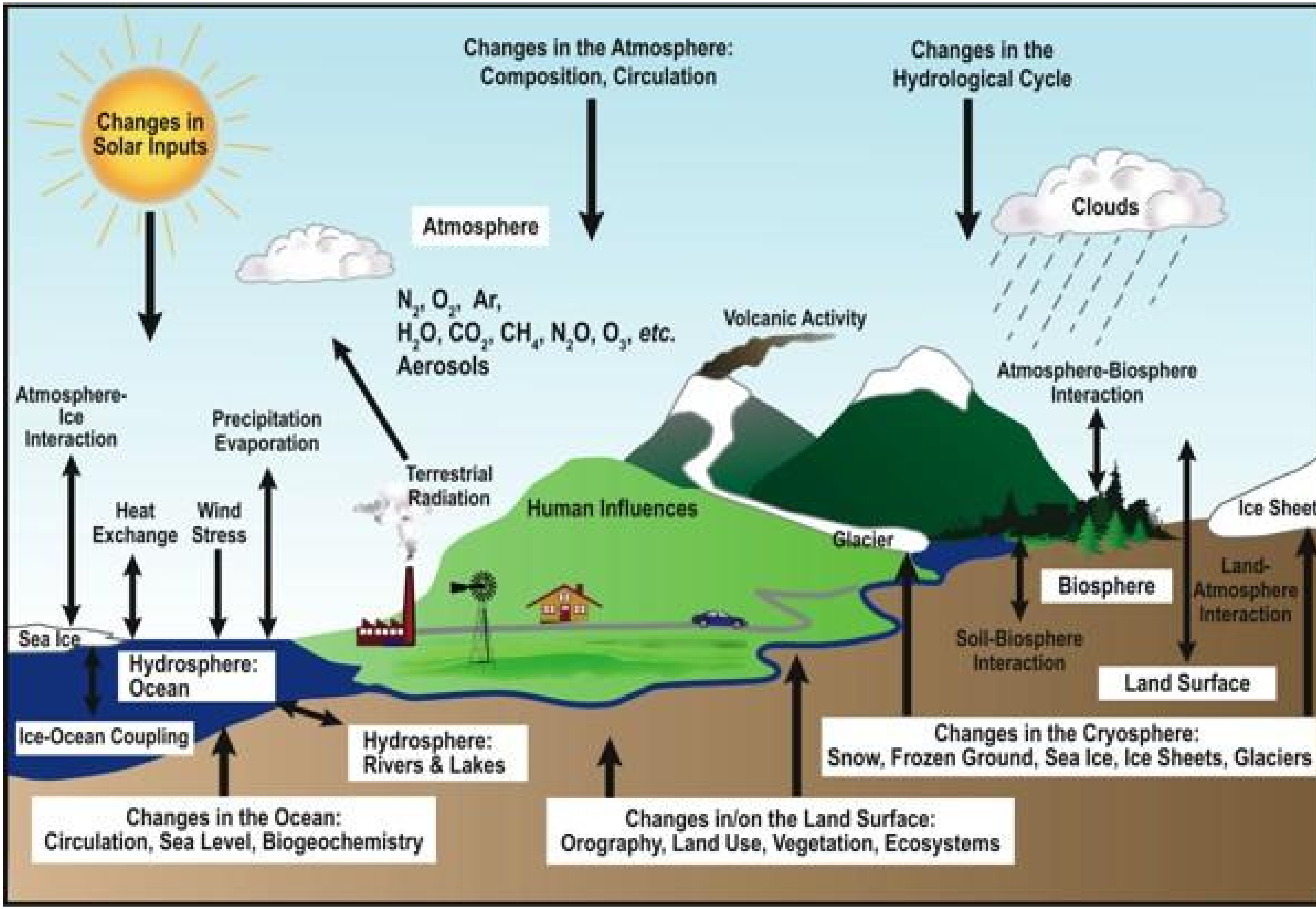
Type of surface	*Albedo/reflectivity (%)*
Ocean	*2-10*
Forest	*6-18*
Cities	*14-18*
Grass	*7-25*
Soil	*10-20*
Grassland	*16-20*
Desert (sand)	*35-45*
Ice	*20-70*
Cloud (thin, thick stratus)	*30, 60-70*
Snow (old)	*40-60*
Snow (fresh)	*75-95*

Note that the albedo of clouds is highly variable and depend on the type and form.





Albedo in the urban areas



Is the story of general circulation that simple??
No!!!, it is complicated!

Atmosphere – poor heat engine

- *Latitudinal variation in the net radiation flux at the top of the atmosphere results in an overall heat transport from equatorial to polar regions. In effect, the atmosphere operates like a heat engine, whereby a portion of the absorbed radiation (heat source) is converted into kinetic energy (work).*

- *The efficiency of the atmospheric heat engine is low, because of strong irreversibility in the system arising primarily from a highly irreversible heat transfer of solar radiation to the earth. Finally, the global hydrological cycle modulates the earth's energy and entropy budgets through the radiative and latent heating.*

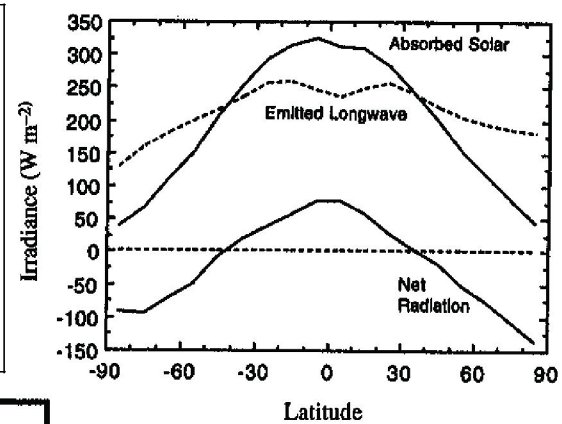
The strength of the thermal circulation depends on the efficiency of the heat engine.

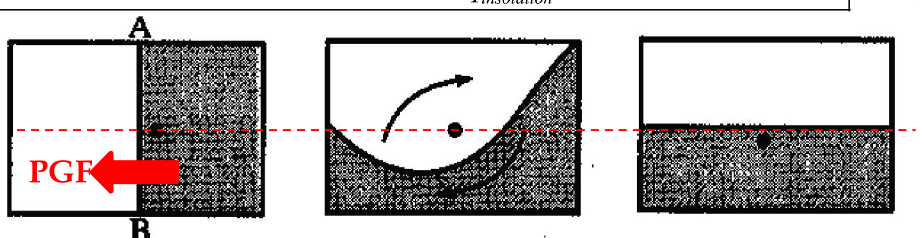
For a reversible Carnot engine using an ideal gas as a working fluid,

the efficiency $\xi = 1 - \frac{T_2 \text{ (poles)}}{T_1 \text{ (tropical)}} = 1 - \frac{200}{300} = 33\%$

Since Earth's climate system is irreversible, the actual efficiency of the Earth as a heat engine is much smaller.

A meaningful estimate of the efficiency of the earth's system is $\xi = \frac{W(work)}{q_{insolation}} = \frac{2 \text{ W m}^{-2}}{238 \text{ W m}^{-2}} \approx 0.8\%$



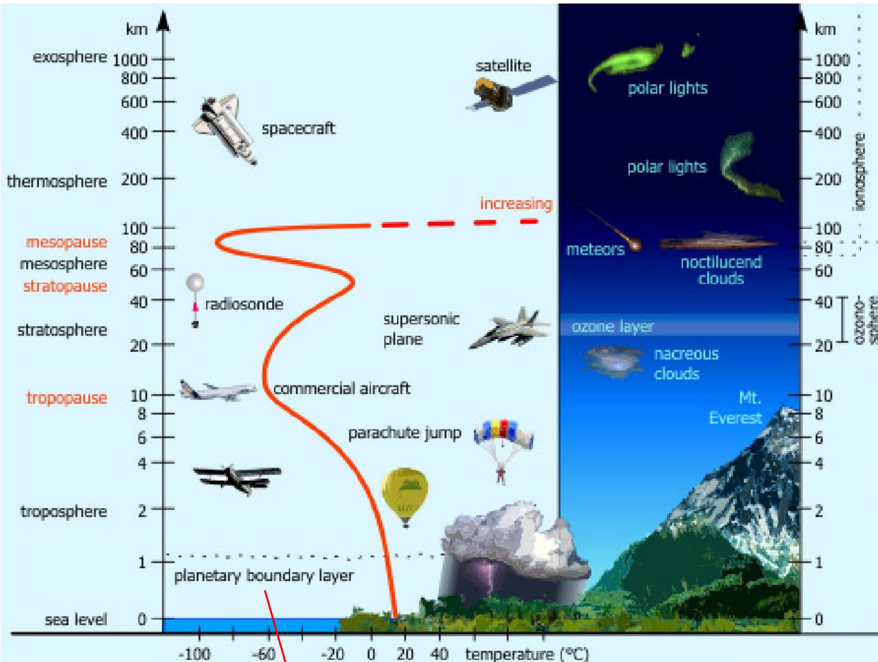


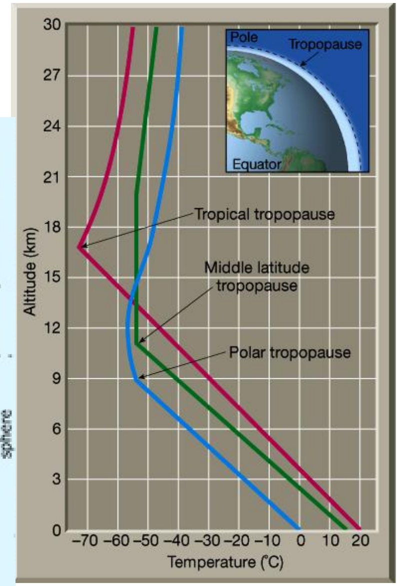
Heavier/denser (shaded) and lighter/rarer fluids are separated by a movable partition AB.
The dot represents the centre of gravity.
Fluids in motion following the removal of partition.
Equilibrium configuration of fluids after the motion has dissipated (PE is converted to KE of the fluid motions)

How best can we describe the atmosphere?

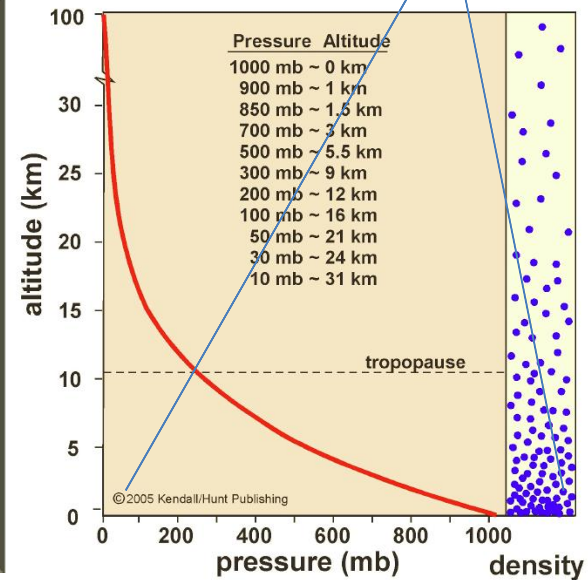
50% of air lies below 7 km

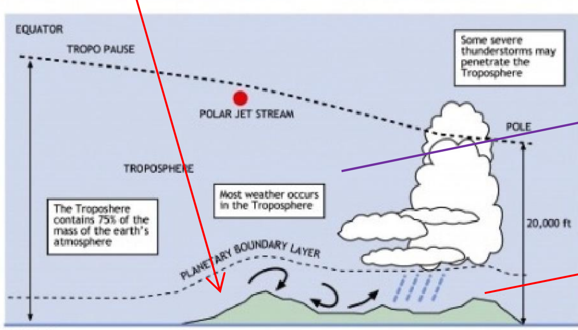
Most of the atmospheric mass is confined in the lowest 100 km above the sea level. (75% in troposphere)

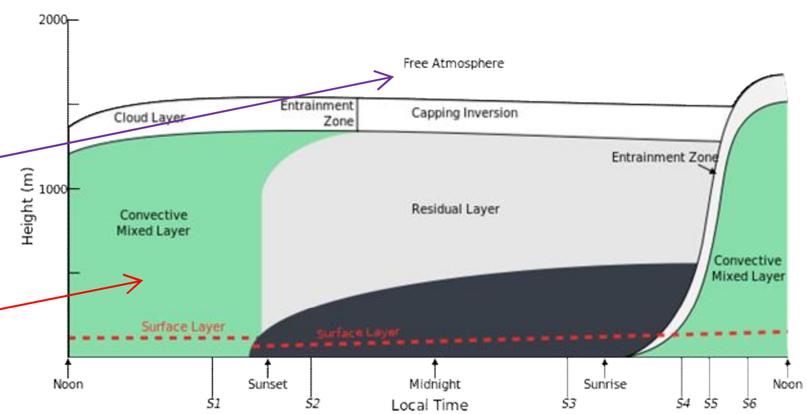




Tropopause is higher (lower) in warmer (colder) regions





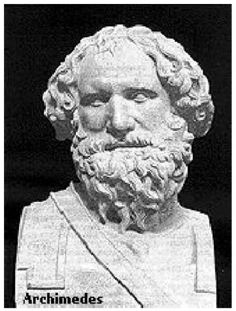


Because of the shallowness of the atmosphere, its motions over large areas are primarily horizontal. Typically, horizontal wind speeds are a thousands time greater than vertical wind speeds.

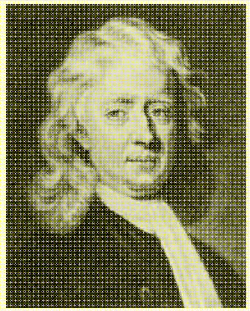
- ***Geophysical fluid dynamics (GFD) is the study of the dynamics of the fluid systems of earth and planets. The principal fluid systems we are interested are the atmosphere and oceans. Geophysicists are often concerned with a rotating frame of reference.***

Inviscid fluid dynamics

Buoyancy



Archimedes
(C. 287-212 BC)

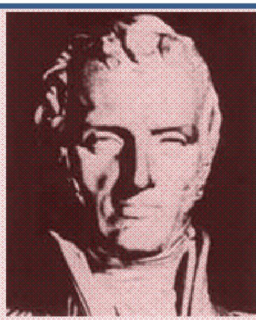


Newton
(1642-1727)

Leibniz
(1646-1716)

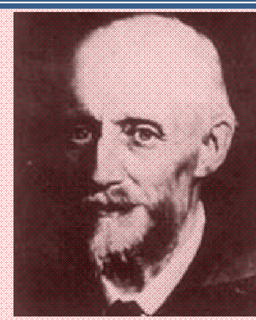
Bernoulli
(1667-1748)

Euler
(1707-1783)



Navier
(1785-1836)

Stokes
(1819-1903)



Reynolds
(1842-1912)

Prandtl
(1875-1953)

Taylor
(1886-1975)

Viscous fluid dynamics

Geophysical applications
Rotating flows

History: Faces of fluid dynamics

Historical development

Name	Dates	Topics
I. Newton	1700s	Mathematics, viscosity concept; Law of Motion for a particle
L. Euler	1750s	(Law of Motion applied to fluids)
D. Bernoulli		Equations for inviscid flow
L.M. Navier	1827	Equations for viscous fluid flow
G.G. Stokes	1845	
Boussinesq	1877	Turbulent mixing; eddy viscosity
O. Reynolds	1880–1890	Transition to turbulence
Rayleigh	1887–1913	Instability theories
G.I. Taylor	1915–1970	Geophysical applications; rotating flows

- ***The domains in atmospheric problems are very diverse. They can include the realm of a cloud, a planetary boundary layer (PBL), a storm with a diameter from tens of kilometres to 1000 km, or any region of the globe up to an entire planetary atmosphere. The time scales must cover from microseconds, for small-scale turbulence analysis, to billions of years for studies in climatology.***

Continuous Media

To describe the motion of a fluid, obviously we cannot (and do not wish to!) describe the motion of all its molecules or atoms individually. We are only interested in their mean motion. This means replacing the set of atoms or molecules which constitutes the fluid by a medium that behaves as this mean motion. Such an assumption is valid when the scale L, which we are interested in, is large compared to the mean free path ℓ of atoms or molecules. The ensuing approximation is measured by the $\boxed{\text{Knudsen no. } Kn = \frac{\ell}{L}}$ which needs to be small compared to unity.

The cases where $Kn \geq 1$ is the subject of the dynamics of rarefied gases based on the kinetic theory of gases. In general, it is not included in fluid mechanics.

Kn is always less than 0.01 $\Rightarrow$ and it is usual to say that the fluid is a continuum
Usually when Kn > 0.01, the concept of continuum does not hold good.

In continuum approach, fluid properties such as density, viscosity, temperature, thermal conductivity, etc. can be expressed as continuous functions of space and time.

Liquids and gases (Continuum hypothesis)

- ***A fluid is a collection of atoms or molecules in liquid or gaseous form. In continuum mechanics, a fluid is a system that flows. The central property is the fluid velocity. Both liquids and gases fall within the scope of the theory of fluid motion.***
- *Liquids and gases are made up of molecules. In a liquid, the molecules are in contact as they slide past each other, and overall act like a uniform fluid material at macroscopic scales. Liquids are fluids characterized by random motions of molecules on the scale of 10^{-7} to 10^{-8} cm, and by a **substantial resistance to compression**. In a gas, the molecules are not in immediate contact. Gases consist of molecules moving over larger distances, with mean free paths of the order of 10^{-3} cm, and **are readily compressed**.*
  - ***Continuum hypothesis: If the characteristic length, or size of the flow system is much larger than the mean free path of the molecules, the fluid can be considered as a continuous medium.***
- ***For example, in a standard atmosphere the molecular mean free path is 10^{-8} m, but in the upper atmosphere the mean free path is of the order of 1 m.***
  - ***Mean free path is inversely proportional to density!***
  - ***Air density = 1 kg m^{-3} ; Density of water = 1000 kg m^{-3}***

Continuum hypothesis

In the continuum model of fluids, physical quantities are considered to be varying continuously in space, for example, we may speak of velocity field $\vec{\mathbf{V}}(\vec{\mathbf{x}},t)$ or a temperature field $\mathrm{T}(\vec{\mathbf{x}},t)$. The "local" values of such quantities at a single point P in space should be understood as average values over a small region of size $L_{phenomenon}$ about P. This averaging procedure is only meaningful if the region is large enough to contain many molecules and yet small when compared to the length scale of the (macrospic) phenomena under consideration.

For any real fluid, there are three natural length scales,

$\mathrm{L}_{molecular}$ = molecular scale characterized by the mean free path

$\mathrm{L}_{phenomenon}$ = fluid element or fluid parcel

L_{fluid} = Scale of the container the fluid is in

Incompressible flow implies that the density remains constant within a parcel of fluid which moves the fluid velocity

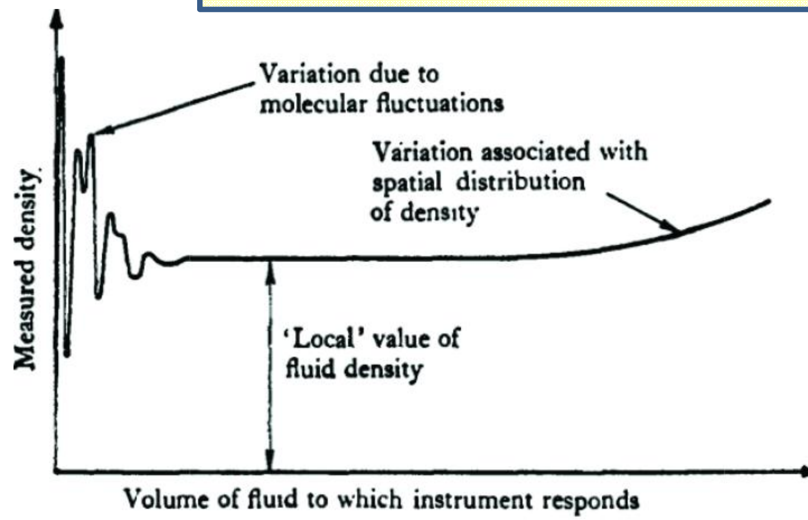
Continuum assumption: $\mathbf{L}_{\mathbf{molecular}} < \mathbf{L}_{\mathbf{phenomena}} < \mathbf{L}_{\mathbf{fluid}}$

Volume of the fluid element under consideration > Mean free path of the molecules, in order that there is little variation in physical and dynamical properties within the element.

For all practical purposes, fluids are incompressible. Under extremley high pressures, the volume of a fluid can be decreased, however, the decrease is minimal that it is considered to be negligible.

In Engineering terms, density changes in a flow is negligible, if the Mach number of the flow is small

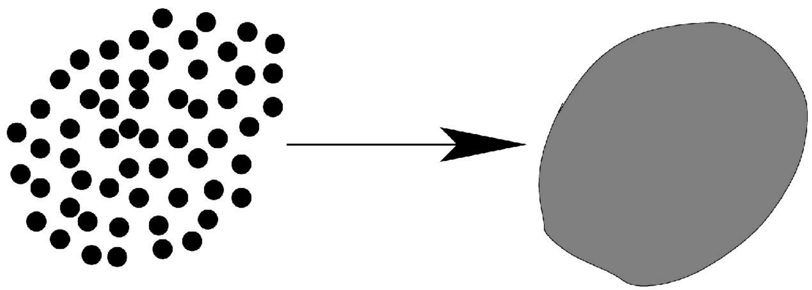
Air flow will be incompressible at velocities upto 102 m s^{-1}



The continuum hypothesis – Introduction to Fluid dynamics (Batchelor)

Read: Fluid mechanics of the atmosphere, Brown (1991)

Continuum hypothesis



A small parcel of water, say on the order 10^{-9}cm^3, is comprised of a huge number ofi nteracting molecules (roughly 3×10^{19}), schematically drawn in the left figure. For purposes of geophysical fluid dynamics, it is safe to ignore details of the individual molecules and approximate the collection of molecules as a continuum, as drawn in the right figure. This constitutes the continuum hypothesis .

Continuum assumption: $\mathbf{L_{molecular}} < \mathbf{L_{phenomena}} < \mathbf{L_{fluid}}$

Volume of the fluid element under consideration > Mean free path of the molecules, in order that there is little variation in physical and dynamical properties within the element.

Inviscid fluids

An inviscid fluid is one where the internal friction force is negligible in comparison to the other forces. All fluids have some internal friction that provides a resistance to motion. When a force is applied to a fluid, it continuously deforms. The fluid nearest to the force accelerates the most, and internal friction drags along adjacent fluid. However, the acceleration cannot continue indefinitely, and eventually the drag of the liquid reaches a point where it balances the applied force.

Therefore, the degree to which a fluid behaves without frictional effects depends on the speed of flow and the effectiveness of the fluid in transmitting the internal force to adjacent fluid. Faster flows, and fluids with small internal stress, behave inviscidly. The relative behaviour of some common fluids is given below:

Viscous = How sticky the fluid is?