Atmospheric Waves
Chapter 6

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Part 4: Tropical Dynamics

Tropical Dynamics

Question: What are some of the key features of the tropical atmosphere?

- Intertropical Convergence Zone (ITCZ)
- Tropical Monsoon
- Walker circulation
- El Niño and the Southern Oscillation
- Madden-Julian Oscillation
- Equatorial waves: Kelvin waves, Rossby waves, mixed Rossby-Gravity waves, inertia-gravity waves

Tropical Dynamics

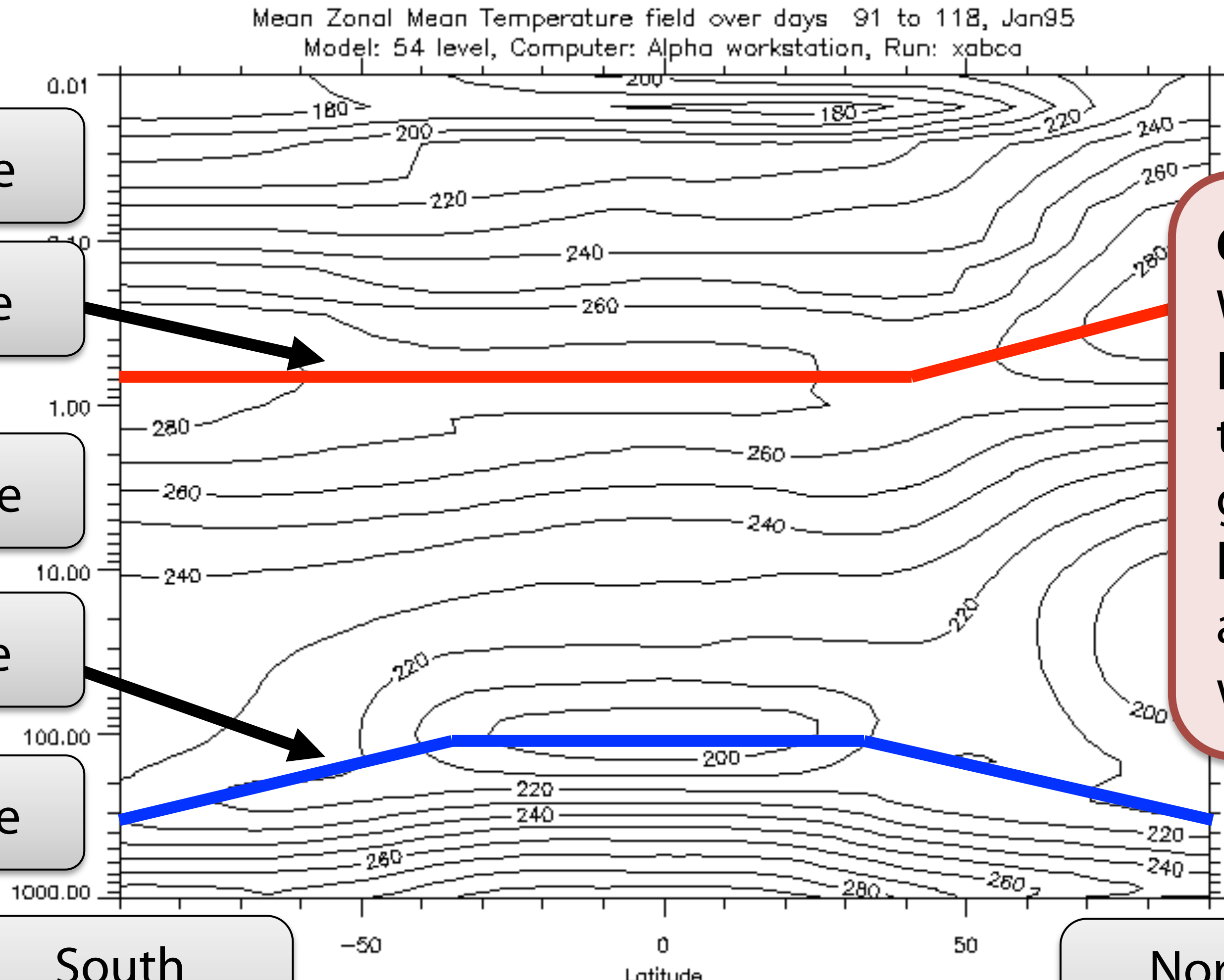
Question: What are the differences between the tropics and the midlatitudes of the Earth?

- The **tropics**, generally considered to be between 30S and 30N latitude, is half of the whole Earth's surface area.

- Alternatively, one can say the tropics is between 20S and 20N latitude, and subtropics are between 20 and 30 degrees of latitude in both hemispheres.

- **Most notable difference:** Coriolis goes to zero at the equator, and so geostrophic balance falls apart.

January Mean Temperature



Mesosphere

Stratopause

Stratosphere

Tropopause

Troposphere

South Summer

North Winter

Question: Where are horizontal temperature gradients large? Where are they weak?

Tropical Dynamics

Question: What are the differences between the tropics and the midlatitudes of the Earth?

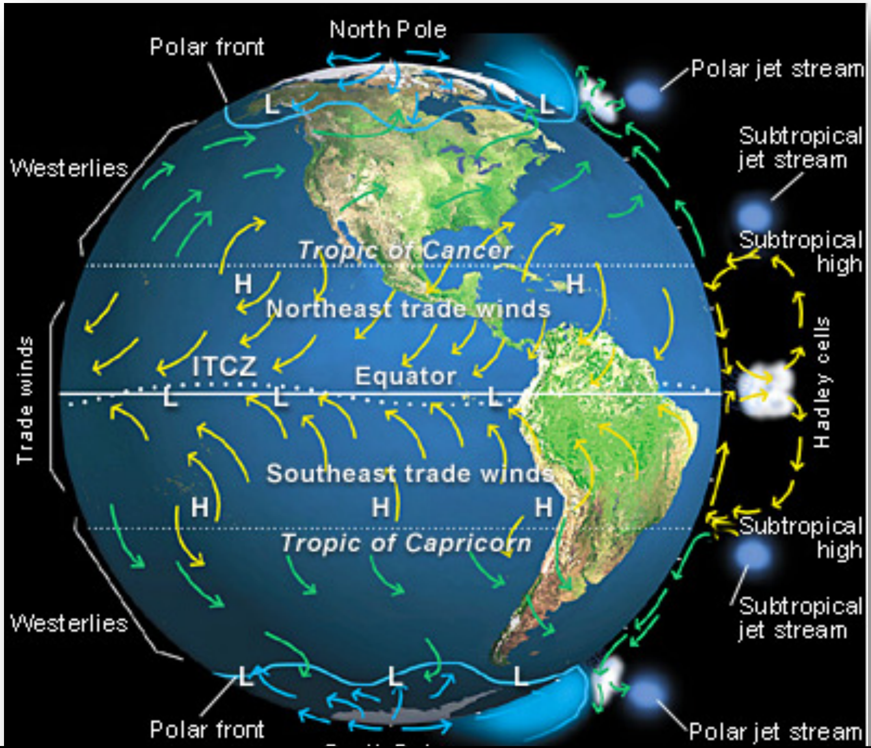
- In middle latitudes the waves grow from the energy available in the **baroclinic atmosphere**, driven by horizontal temperature gradients.
- In the tropics the horizontal scale is large, with latent heat release on scales small compared to scale for baroclinicity. Consequently, horizontal temperature gradients are small.
- Baroclinicity is less important in the tropics: Latent heat release is generally more important.

Intertropical Convergence Zone (ITCZ)

- Narrow zonal band of vigorous cumulus convection
- Many distinct cloud clusters, with scales of the order of a few hundred km, separated by clear sky regions
- Strength of ITCZ quite variable in space and time

Intertropical Convergence Zone (ITCZ)

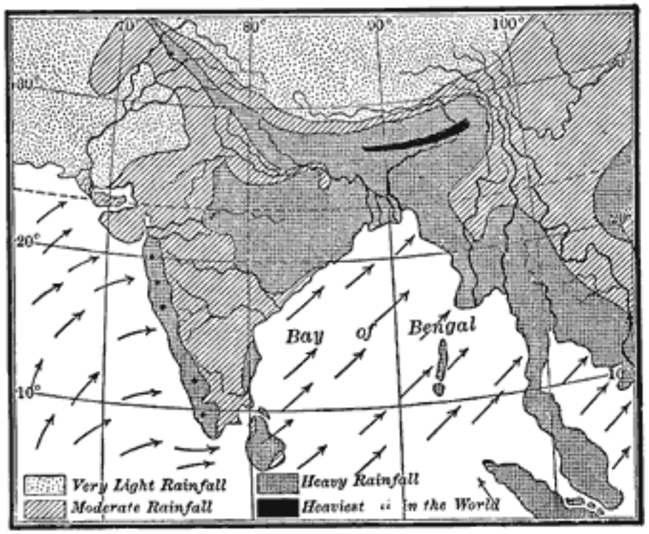
- ITCZ and large-scale overturning circulation (Hadley cell) are not as regular as typical schematic figures (below) suggest.
- ITCZ is persistent and well-defined over the Pacific and Atlantic between 5º-10º N
- Occasionally appears in the western Pacific between 5º-10º S
- Within ITCZ, precipitation greatly exceeds the moisture supplied by evaporation over the ocean surface below
- **Thus:** Much of the water vapor in the ITCZ supplied by converging trade winds



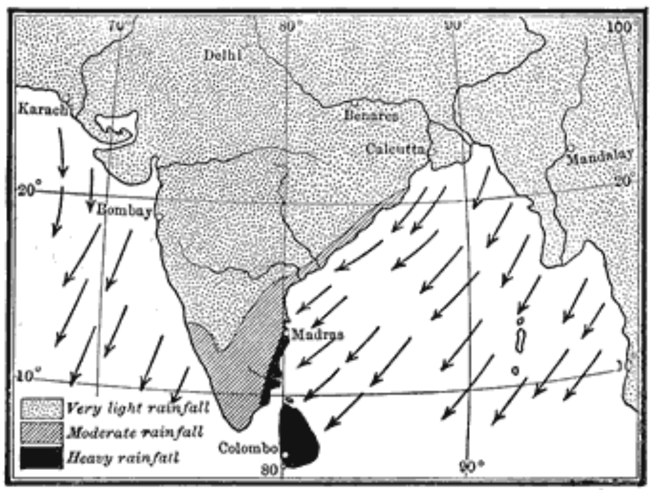
Monsoon Circulation

- Monsoon circulation is determined by the different heat capacity characteristics of continents and oceans.
- Similar to a sea/land breeze, except that is occurs over a much larger area.
- **In summer**, the winds usually flow from the water to the land, causing heavy rains inland.
- **In winter**, the winds usually reverse, and the flow from the land to the sea results in dry conditions.
- The word "monsoon" has arabic origin and means season: refers solely to a seasonal wind shift, and not to precipitation.

Monsoon Circulation



SUMMER MONSOON WINDS



WINTER MONSOON WINDS

- Heat capacity of the upper ocean layer larger than heat capacity of a thin layer of soil.
- In the summer, absorption of solar radiation raises the surface temperature over land much more rapidly than over the ocean.
- 1000-200 hPa thickness larger over land, pressure gradient force at upper levels drives circulation.

Asian Monsoon

Most extensive monsoon circulation is the Asian Monsoon. This monsoon dominates India's climate.

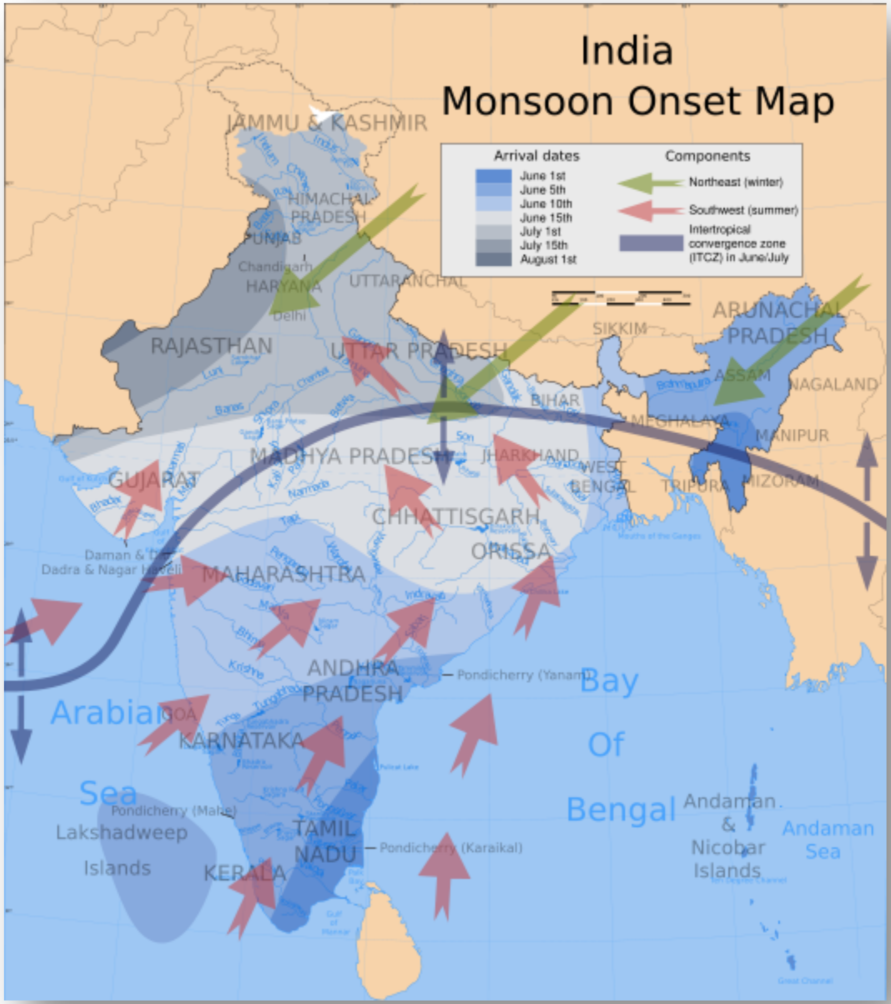
Figure: Mumbai in July 2007

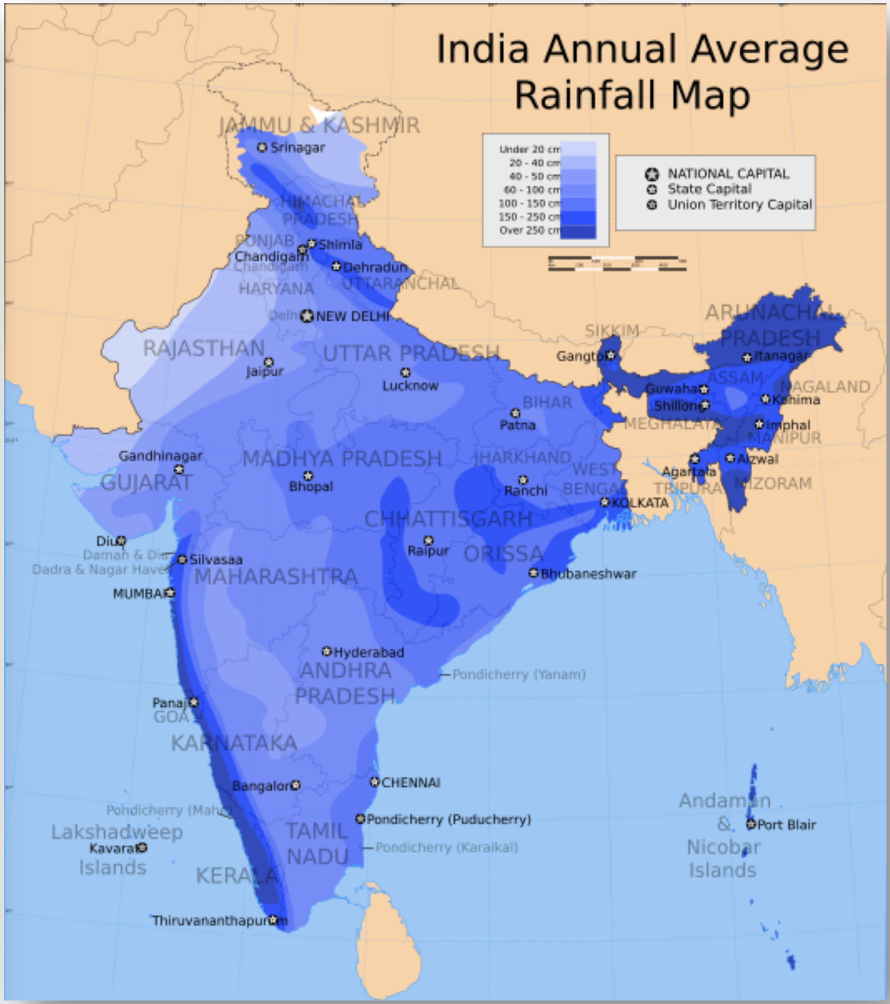
Figure: Monsoon that is two weeks late

Asian Monsoon

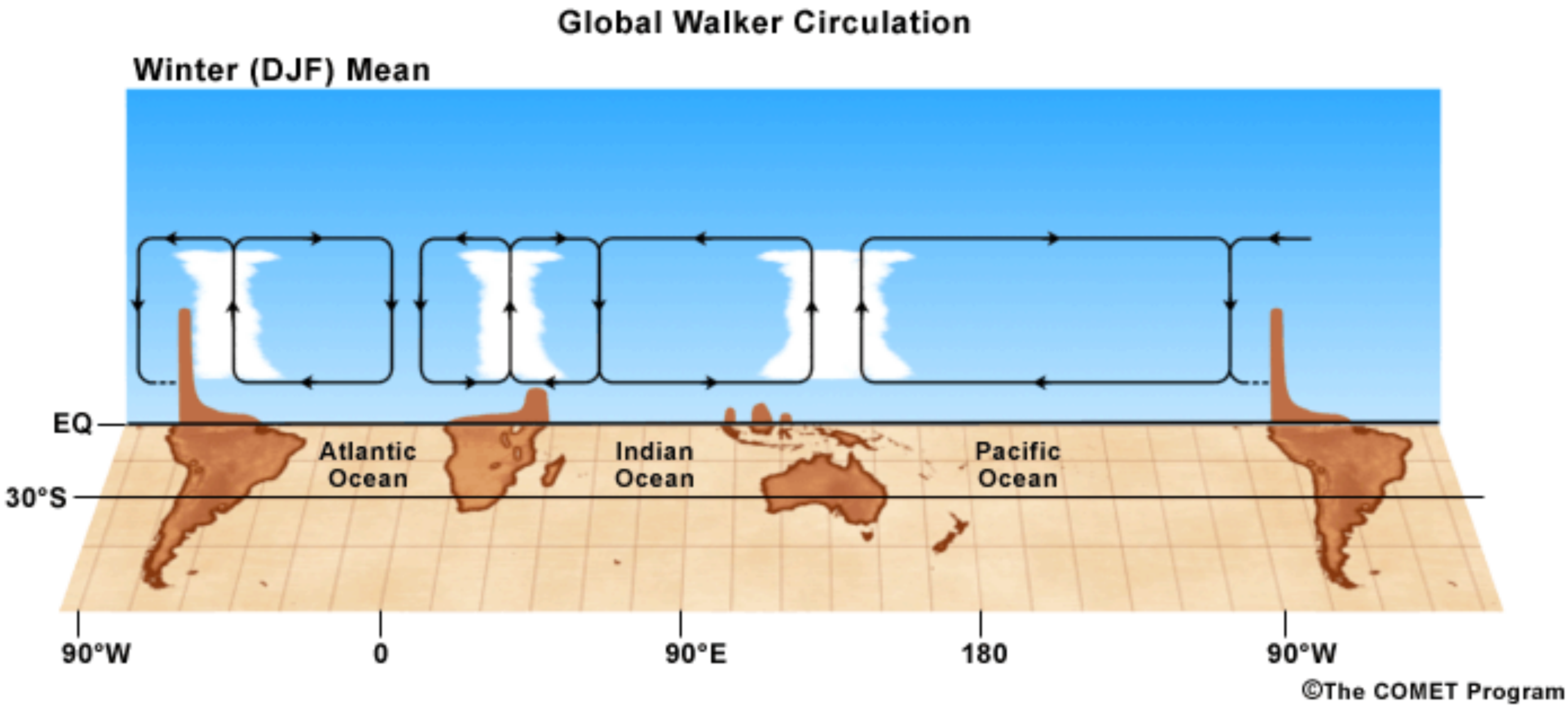
Figure: Sudden onset of the monsoon, here in India

Asian Monsoon





Walker Circulation



Walker Circulation: Equatorial circulation differences due to temperature differences over land and the ocean. Flow generally tends to be easterly, but since Coriolis force is negligible, surface temperature plays a greater role in determining motion.

Walker Circulation

- **Recall:** In the tropics geostrophic balance does not hold, and so other forcing mechanisms become dominant.
- **Definition:** The **Walker Circulation** is a conceptual model of air flow in the tropics caused by differences in heat distribution between ocean and land.
- Is in addition to the Hadley circulation which describes meridional motions.
- Connection with the ocean?

La Niña

"Normal" Conditions

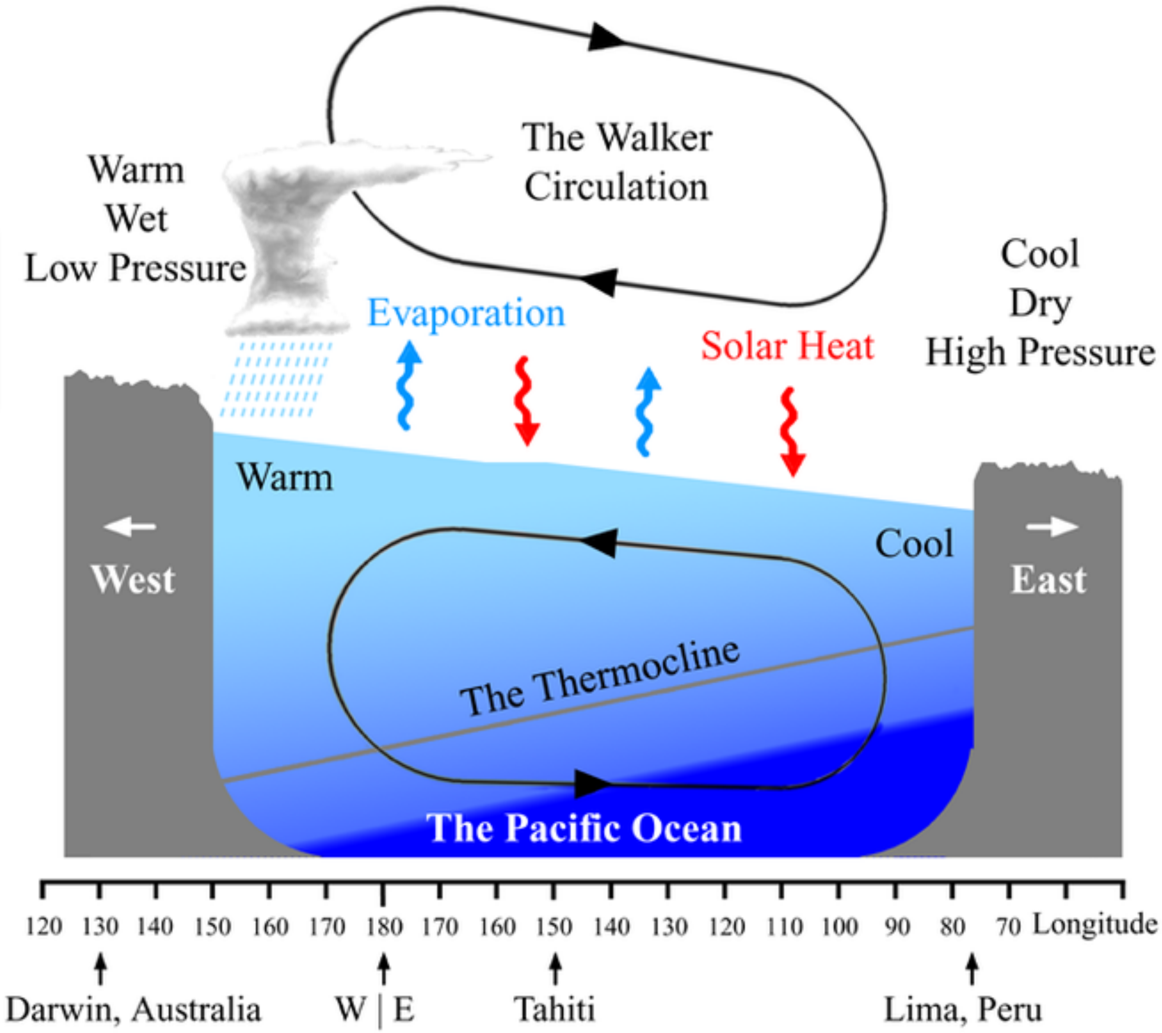


Figure: Schematic diagram of the quasi-equilibrium and La Niña phase of the southern oscillation. (Source: Wikipedia)

La Niña

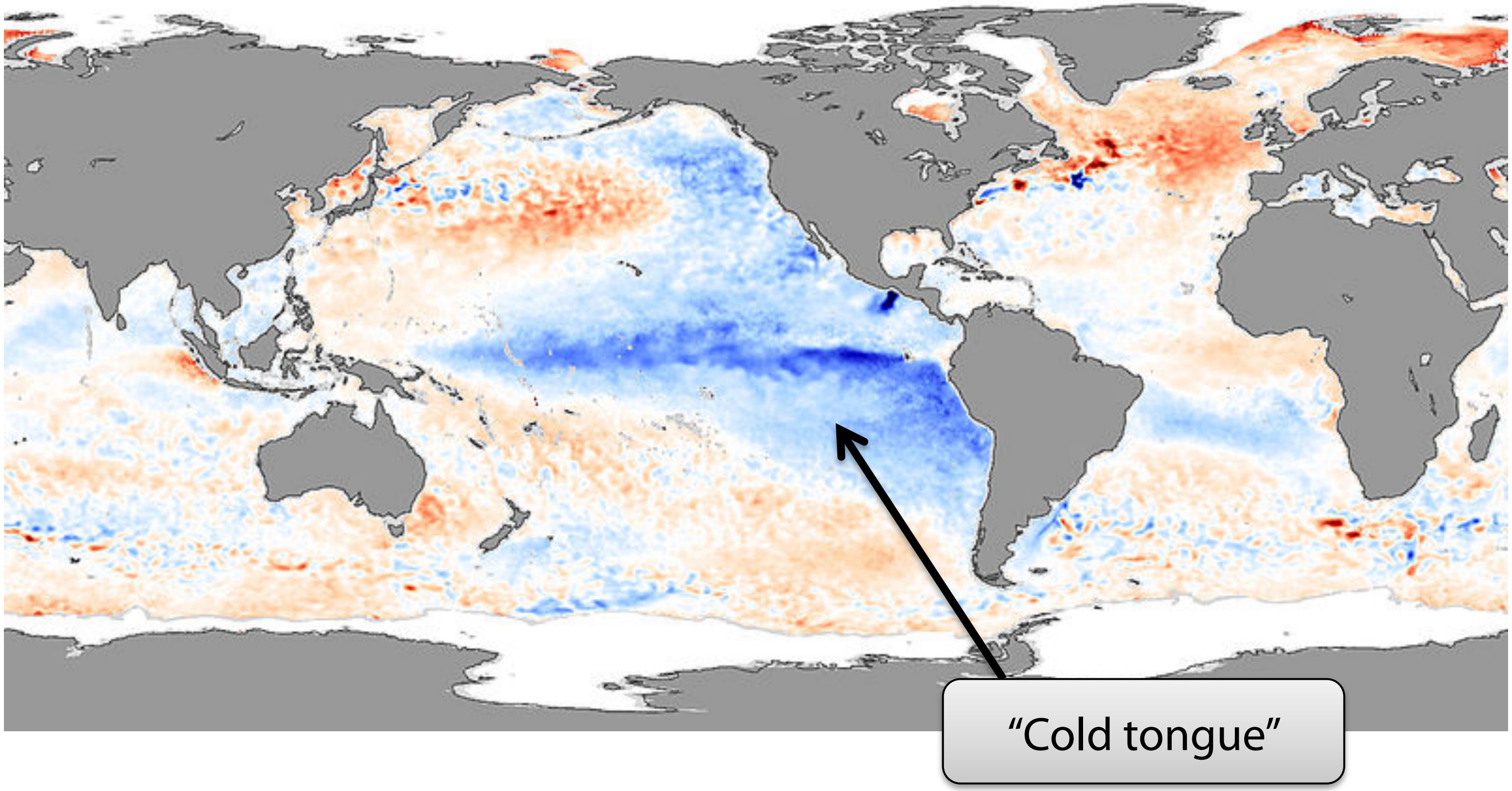


Figure: Sea surface temperature anomaly under "normal" conditions. The sea surface in the eastern Pacific is enhanced by upwelling of cold ocean waters.

El Niño / La Niña

- El Niño and La Niña are officially defined as sustained sea surface temperature anomalies of magnitude greater than 0.5°C across the central tropical Pacific Ocean.

- When the condition is met for a period of less than five months, it is classified as El Niño or La Niña conditions.

- If the anomaly persists for five months or longer, it is classified as an El Niño or La Niña episode.

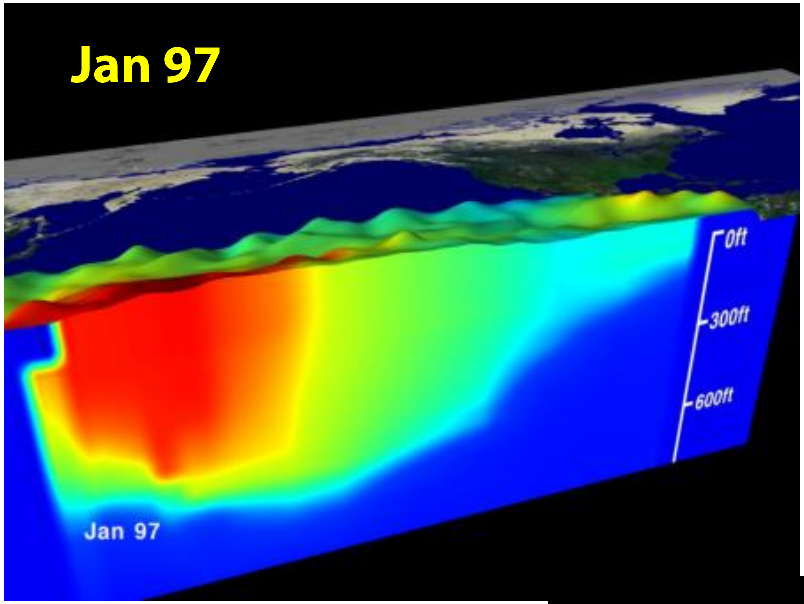
- Historically, it has occurred at irregular intervals of 2-7 years and has usually lasted one or two years.

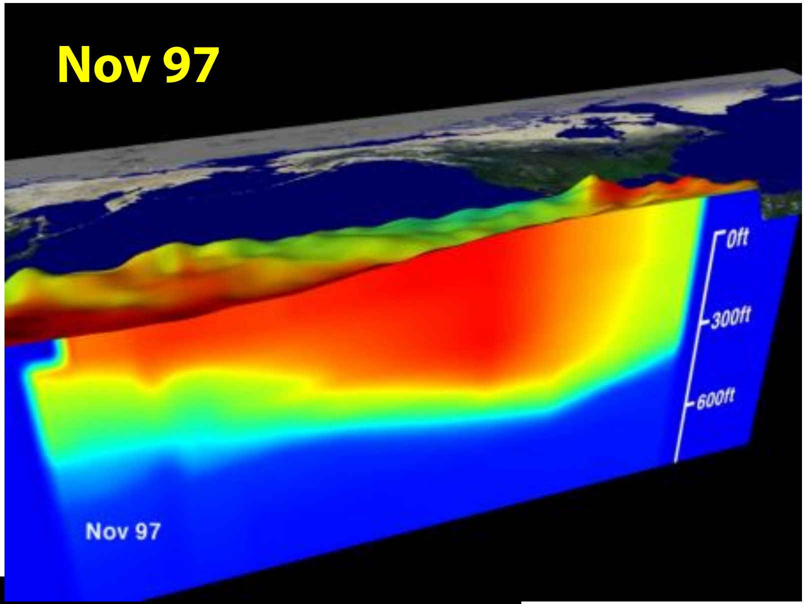
El Niño Southern Oscillation

The first signs of an El Nino are:

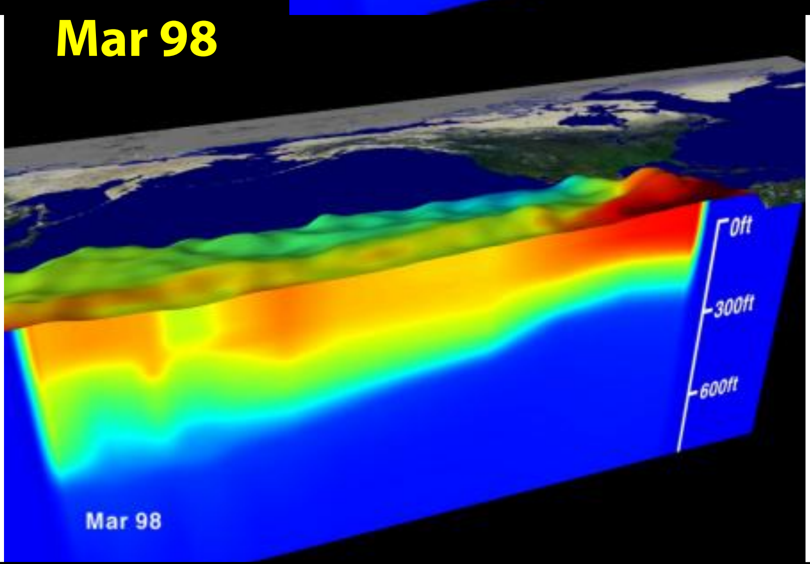
1. Rise in air pressure over the Indian Ocean, Indonesia, and Australia
2. Fall in air pressure over Tahiti and the rest of the central and eastern Pacific Ocean
3. Trade winds in the south Pacific weaken or head east
4. Warm air rises near Peru, causing rain in the deserts there
5. Warm water spreads from the west Pacific and the Indian Ocean to the east Pacific. It takes the rain with it, causing rainfall in normally dry areas and extensive drought in eastern areas.

El Niño SST Profile





Normal



El Niño

Madden Julian Oscillation

- The **Madden Julian Oscillation (MJO)** is also referred to as the 30-60 day or 40-50 day oscillation

- It is the main intra-annual fluctuation that explains weather variations in the tropics.

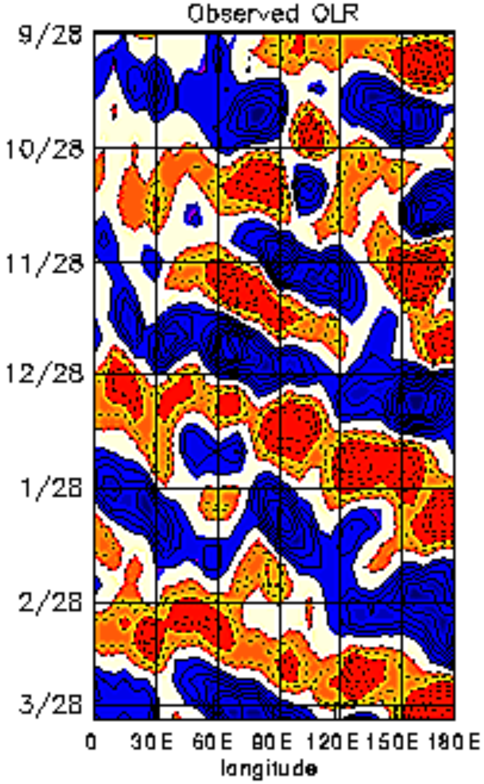
- The MJO affects the entire tropical troposphere but is most evident in the Indian and western Pacific Oceans.

- The MJO involves variations in wind, sea surface temperature (SST), cloudiness, and rainfall.

- Most tropical rainfall is convective, and convective cloud tops are very cold (emitting little longwave radiation), the MJO is most obvious in the variation of outgoing longwave radiation (OLR).

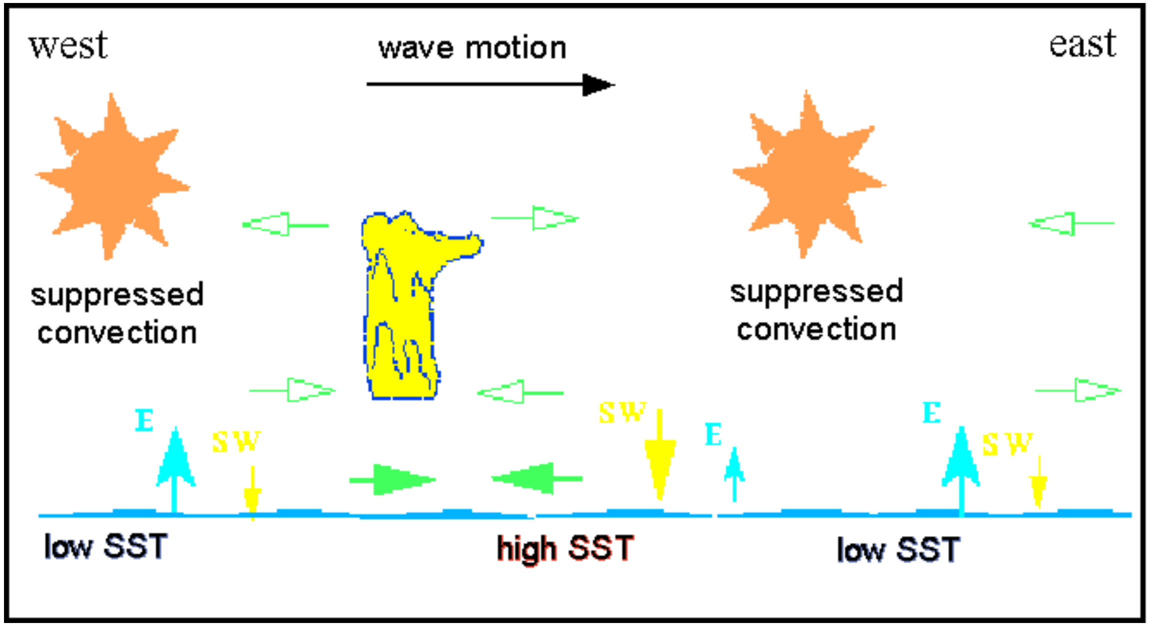
Madden Julian Oscillation

- Infrared satellite observations reveal OLR anomalies propagating to the east at ≈ 5 m s^{-1} (see Hovmoeller diagram).
- Recurrence interval for the OLR anomalies is about 30 to 60 days.
- The OLR signal west of the dateline is weaker.
- Mechanisms for Madden-Julian Oscillation not well-understood
- It appears that near the dateline a weak Kelvin wave propagates eastward and poleward at a speed exceeding 10 m/s.



Madden Julian Oscillation

- Eastward progression of large regions of both enhanced and suppressed tropical rainfall, observed mainly over the Indian Ocean and Pacific Ocean.
- MJO appears as a wavenumber 1-2 signal in Wheeler-Kiladis wavenumber-frequency diagrams



Equatorial Waves

- Equatorial waves are important class of eastward and westward propagating disturbances
- Present in atmosphere and ocean
- Trapped about the equator (they decay away from the equator)
- Types of waves:
  - **Equatorial Kelvin** waves
  - **Equatorial Rossby** (ER), **Mixed Rossby-Gravity** (MRG), **inertia-gravity** waves
- Atmospheric equatorial waves excited by diabatic heating by organized tropical convection
- Oceanic equatorial waves excited by wind stresses
- Waves communicate effects of convective storms over large longitudinal distances

Kelvin Waves

- Kelvin waves are trapped gravity waves
- A trapped wave is one that decays exponentially in some direction
- Kelvin waves need a boundary to exist
- Observed in the ocean and the atmosphere
  - Equatorial Kelvin waves in the ocean and atmosphere
  - Coastal Kelvin waves

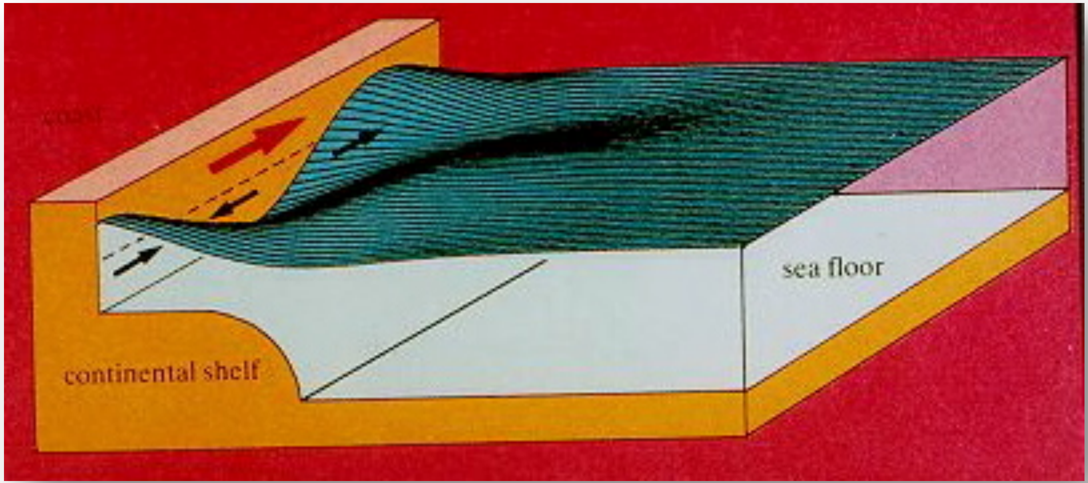
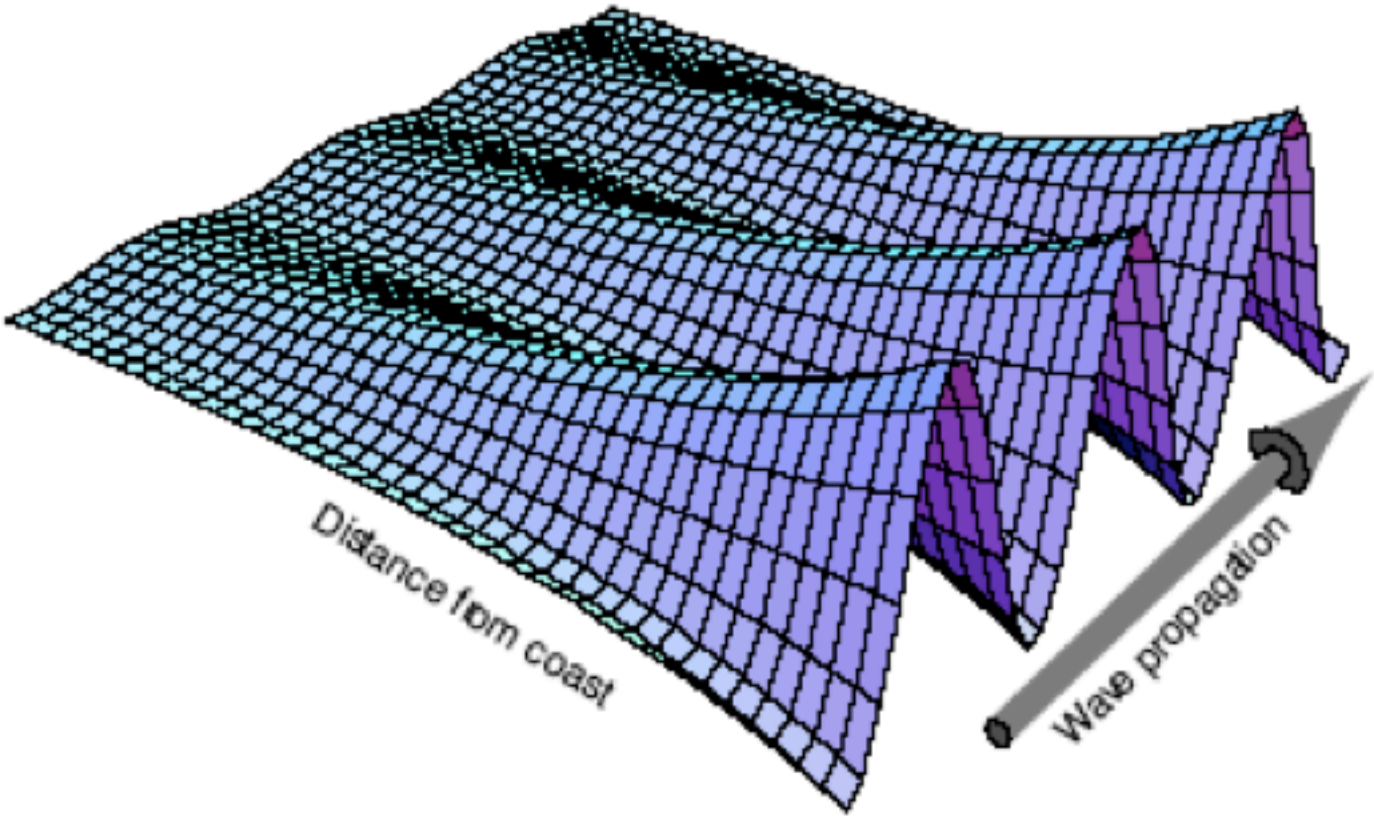


Figure: Diagram of a coastal Kelvin wave

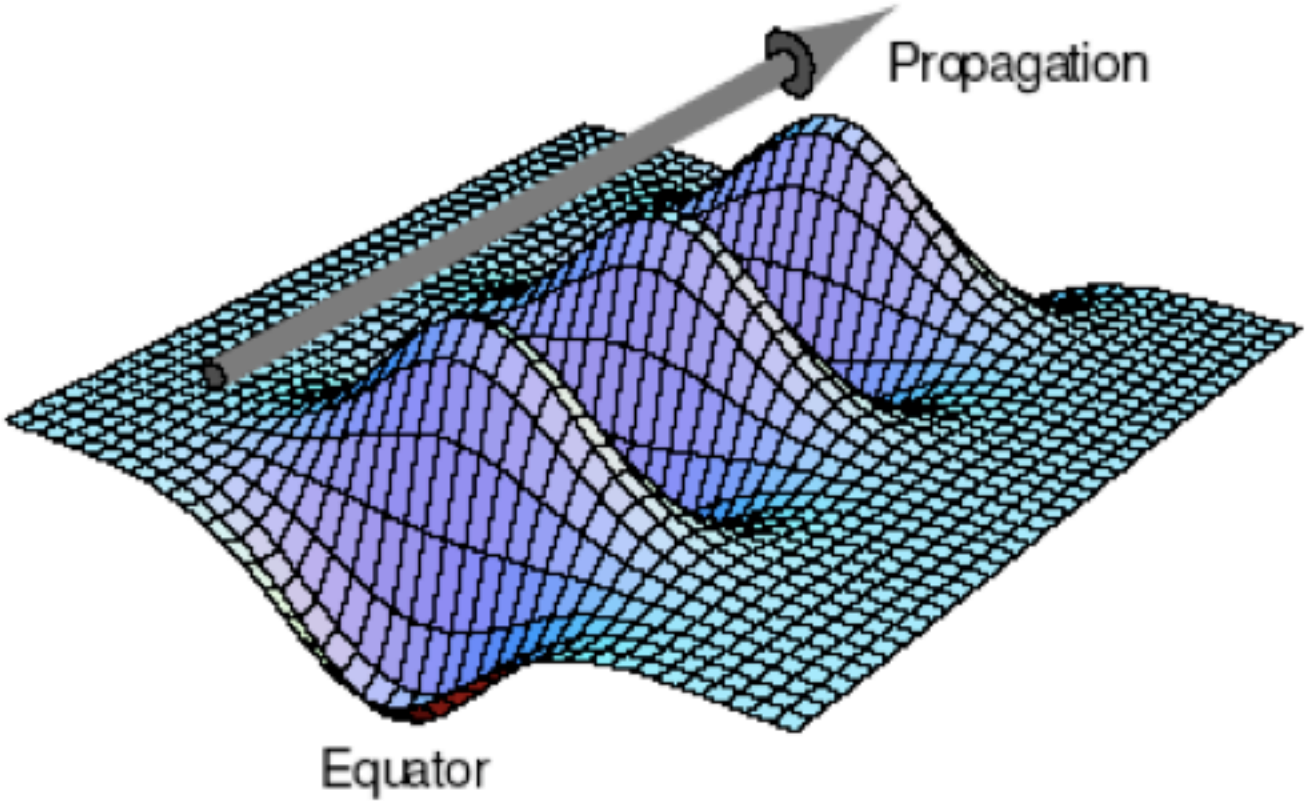
Coastal Kelvin Waves

Amplitudes decay away from the boundary (coastline)



Equatorial Kelvin Waves

Amplitudes decay away from the “boundary” (equator)



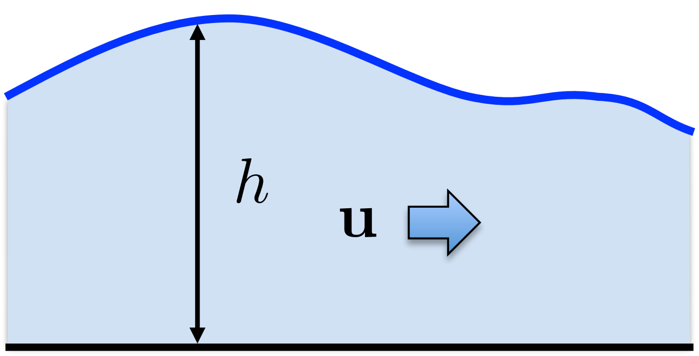
Equatorial Kelvin Waves

Start from: Shallow water equations

$$\frac{Du}{Dt} - fv + g\frac{\partial h}{\partial x} = 0$$

$$\frac{Dv}{Dt} + fu + g\frac{\partial h}{\partial y} = 0$$

$$\frac{Dh}{Dt} + h\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0$$



Equatorial Kelvin Waves

For equatorial Kelvin waves assume:

- Coriolis parameter at the equator is approximated by equatorial β-plane:

$$f = f_0 + \beta y, \quad f_0 = 0, \quad \beta = 2\Omega/a$$

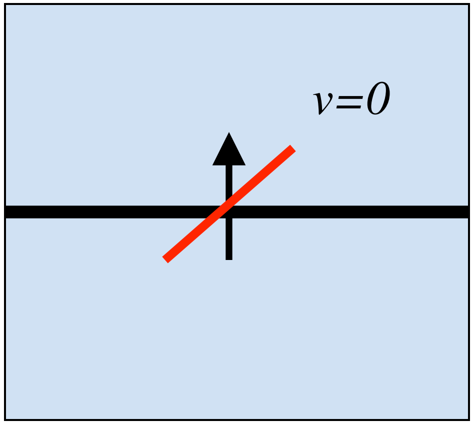
- Meridional velocity vanishes: $v = 0$ (everywhere)

- Shallow water equations become:

$$\frac{Du}{Dt} + g\frac{\partial h}{\partial x} = 0$$

$$\beta y u + g\frac{\partial h}{\partial y} = 0$$

$$\frac{Dh}{Dt} + h\frac{\partial u}{\partial x} = 0$$



Equator

Equatorial Kelvin Waves

Linearize shallow water equations about
a state at rest with mean height H:

$$\frac{\partial u'}{\partial t} + g\frac{\partial h'}{\partial x} = 0 \qquad (1)$$

$$\beta y u' + g\frac{\partial h'}{\partial y} = 0 \qquad (2)$$

$$\frac{\partial h'}{\partial t} + H\frac{\partial u'}{\partial x} = 0 \qquad (3)$$

Then compute…

$$\frac{\partial(1)}{\partial t} - g\frac{\partial(3)}{\partial x}$$

Yields

Wave Equation

$$\frac{\partial^2 u'}{\partial t^2} = c^2\frac{\partial^2 u'}{\partial x^2}$$

Phase Speed

$$c = \left(\frac{\nu}{k}\right) = \sqrt{gH}$$

Equatorial Kelvin Waves

Seek wave solutions (in x) and allow amplitude to vary in y:

$$(u', h') = \left(\hat{u}(y), \hat{h}(y)\right) \exp(i(kx - \nu t))$$

Yields the system:

$$-i\nu\hat{u} + ikg\hat{h} = 0 \qquad (1)$$

$$\beta y\hat{u} + g\frac{\partial\hat{h}}{\partial y} = 0 \qquad (2)$$

$$-i\nu\hat{h} + Hik\hat{u} = 0 \qquad (3)$$

Rearrange (1):

$$\hat{h} = \frac{\nu}{kg}\hat{u} = \frac{c}{g}\hat{u} \qquad (4)$$

Plug (4) into (2):

$$\beta y\hat{u} = -c\frac{\partial\hat{u}}{\partial y} \qquad (5)$$

Equatorial Kelvin Waves

Amplitude function for equatorial Kelvin waves (with u_0 amplitude of the perturbation at the equator)

$$\hat{u}(y) = u_0 \exp\left(\frac{-\beta y^2}{2c}\right) = u_0 \exp\left(\frac{-y^2}{2R_{eq}^2}\right)$$

Solutions decaying away from the equator exist only for c > 0 with

$$c = +\sqrt{gH}$$

Therefore: Kelvin waves always **propagate eastward**

Their zonal velocity and geopotential vary in latitude as Gaussian functions centered at the equator

Definition: The **Equatorial Rossby Radius of Deformation** is the radius at which rotational effects become important for equatorial waves.

$$R_{eq} = \sqrt{\frac{c}{\beta}}$$

Equatorial Kelvin Waves

Amplitude of the height perturbations using (3)

$$\hat{h}(y) = \hat{u}_0 \sqrt{\frac{H}{g}} \exp\left(\frac{-\beta y^2}{2c}\right)$$

The physical solutions are

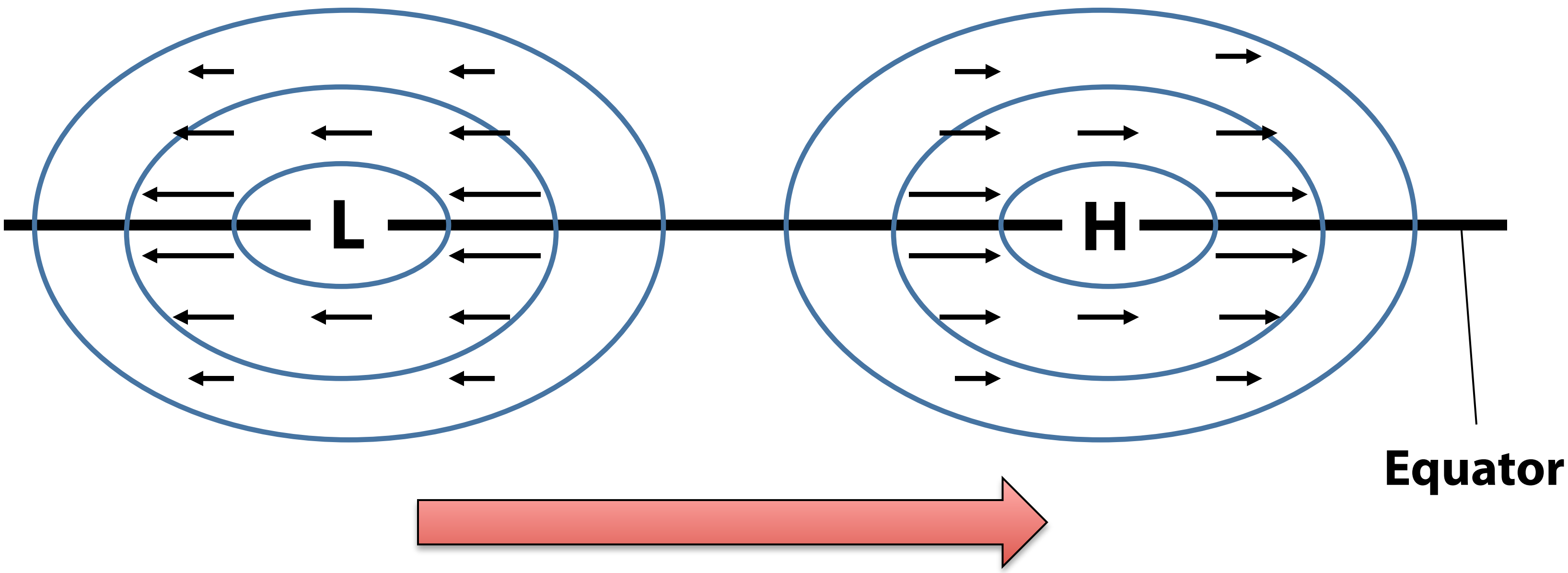
$$\begin{aligned} u = u' &= \mathrm{Re}\left[\hat{u}(y)\exp(i(kx - \nu t))\right] \\ &= \hat{u}_0 \exp\left(\frac{-\beta y^2}{2c}\right)\cos\left[k\left(x - \sqrt{gH}t\right)\right] \\ v = v' &= 0 \\ h = H + h' &= H + \mathrm{Re}\left[\hat{h}(y)\exp(i(kx - \nu t))\right] \\ &= H + \hat{u}_0 \sqrt{\frac{H}{g}} \exp\left(\frac{-\beta y^2}{2c}\right)\cos\left[k\left(x - \sqrt{gH}t\right)\right] \end{aligned}$$

Equatorial Kelvin Waves

Velocity and Height Perturbations

The e-folding decay width is $Y_k = \sqrt{\frac{2c}{\beta}}$

For example, for $c = 30$ m/s, we have $Y_k = 1600$ km



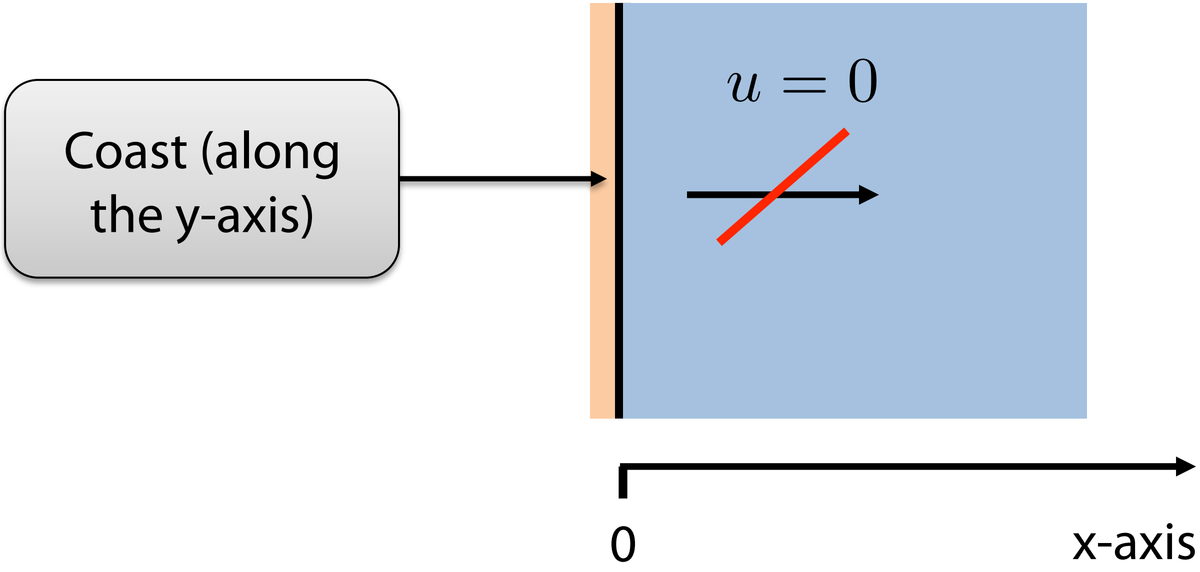
Kelvin wave animation:
http://www.ems.psu.edu/%7Ebannon/mpegs/eqkel.mpg

Coastal Kelvin Waves

Derivation

For coastal Kelvin waves assume:

- Flat bottom topography
- Constant Coriolis parameter f_0
- Coastline is parallel to the y-axis
- Zonal velocity (normal to the coast): $u=0$ (everywhere)



Coastal Kelvin Waves

Derivation

- Linearize shallow water equations about a state at rest with mean height H
- Derive the dispersion relationship.
- Seek wave solutions (in y) with **varying amplitude in x**: Solution technique analogous to equatorial Kelvin waves.
- Exponential decay away from coast: Trapped wave

Coastal Kelvin Waves

Example: Decay of Kelvin wave amplitude away from the coast manifested in the English Channel:

- North Atlantic Tide enters Channel from the west, tide assumes the character of a Kelvin wave

- Kelvin wave leans against the coast on its right (France), explains higher tides in France

Coastal Kelvin Waves

In the English Channel Atlantic tides enter from the west. Higher tide amplitudes are observed in France due to Kelvin waves