MET 361: Tropical Meteorology

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https://github.com/jeffjay88/MET361-TROPICAL_METEOROLOGY_LECTURE_SERIES

LECTURE 5

Recommended Links and Materials

https://www.researchgate.net/publication/268400435_Tropical_Meteorology_Equatorial_Waves
https://www.youtube.com/watch?v=YZ6wwynTiZ8
https://www.youtube.com/watch?v=7-v75_2IAzM
https://www.youtube.com/watch?v=jdqVfFk-jXQ
https://www.youtube.com/watch?v=jdqVfFk-jXQ
https://www.youtube.com/watch?v=jSWmhkcPsHw
https://www.youtube.com/watch?v=MzW5Isbv2A0

Equatorial Waves

In the 1980s and 1990s, technology finally enabled us to detect these waves in our atmosphere:

Hovmöller diagrams constructed from infrared satellite imagery reveal well defined bands of cloudiness associated with westward moving disturbances in the equatorial region (~10°S-10°N) and Selective filtering of precipitable water and infrared satellite data, aimed at identifying these waves, was successful.

Some equatorial waves are observed to be coupled to convection while other waves are not, and waves that are not coupled propagate much more quickly than coupled waves.

Recent analyses of satellite data have linked equatorial waves on the scale of 3,000–4,000 km, period range of 4–5 days, moving with speeds of ~8–10 m s^{-1} to initiation of tropical cyclones.

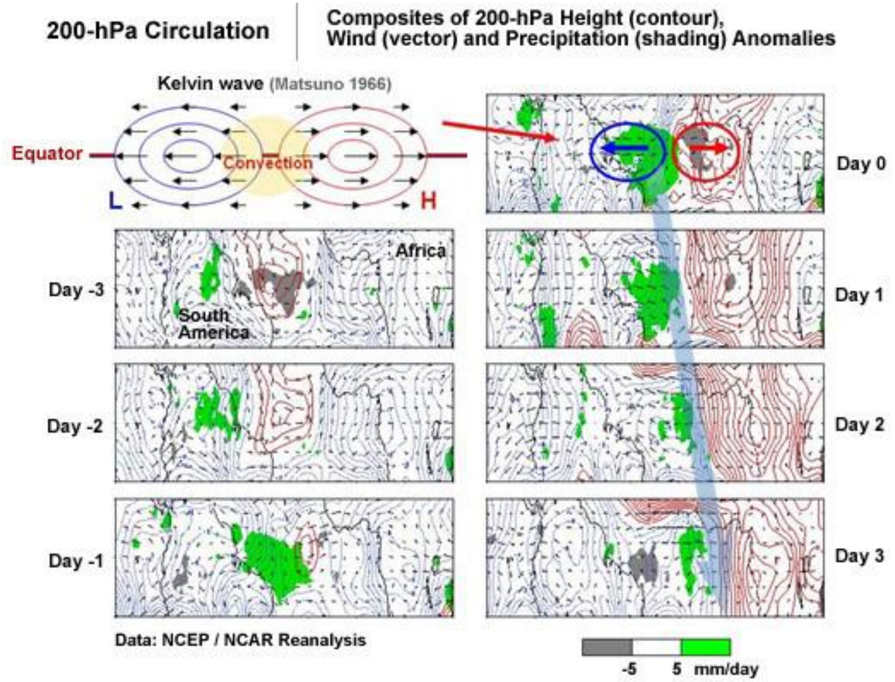
All waves result from a disturbance or instability that creates a perturbation on an initially balanced flow. Overshooting of the restoring force acting to eliminate the perturbation creates the wave oscillation.

Kelvin Waves

- Kelvin waves are large-scale waves whose structure "traps" them so that they propagate along a physical boundary such as a mountain range in the atmosphere or a coastline in the ocean.

- In the tropics, each hemisphere can act as the barrier for a Kelvin wave in the opposite atmosphere, resulting in "equatorially-trapped" Kelvin waves.

- Kelvin waves are thought to be important for initiation of the El Niño Southern Oscillation (ENSO) phenomenon and for maintenance of the MJO.



Composite of 200 hPa height (contour), wind (vector) and *precipitation* (shading) anomalies. Top left shows the theoretical Kelvin wave derived by Matsuno (1966). Light blue arrow shows the eastward movement of the wave.

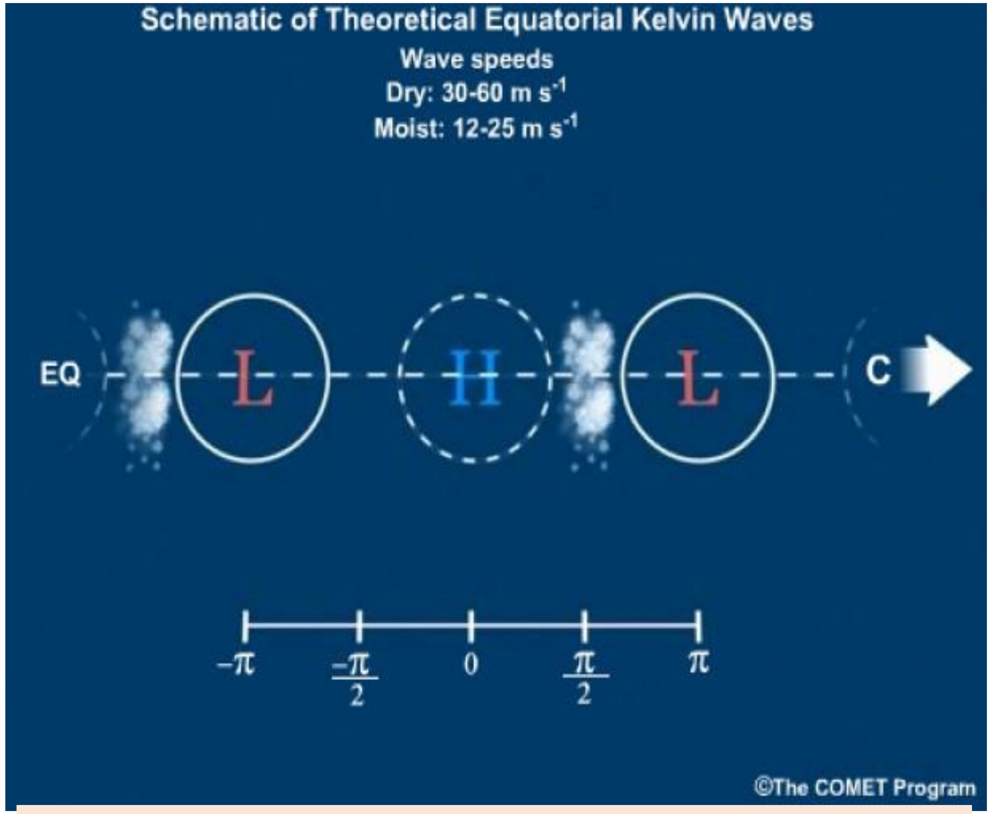
- Convectively-coupled atmospheric Kelvin waves have a typical period of **6–7 days**, when measured at a fixed point, and phase speeds of **12–25 ms^{-1}**, while dry Kelvin waves in the lower stratosphere have phase speed of **30-60 ms^{-1}**.

- Kelvin waves over the Indian Ocean generally propagate more slowly (**12–15 ms^{-1}**) than other regions. Kelvin waves can be thought of as large-scale gravity waves trapped at the equator.

Wave propagation

- With the low to the west of the high, have mass divergence between them (to the east of the low) leading to pressure falls on the equator. This means falling pressure to the west of the high (east of the low), so the wave moves towards the east.

- With the high to the west of the low, have mass convergence between them (to the east of the high) leading to pressure rises on the equator. This means rising pressure to the east of the high (west of the low), so the wave moves towards the east.



Schematic depiction of the theoretical solution for an equatorial Kelvin wave in a dry, incompressible atmosphere. Only a few pressure centers are shown.

- Both of these thought experiments give *eastward propagating Kelvin waves*. Moist Kelvin wave have moist convergence to the west of the low, leading to deep convection. Since the convection is to the west of an eastward moving low, and convection will generate cyclonic low level PV, the moist convection slows the wave propagation.

The Kelvin Wave (Summary)

The Kelvin wave is the simplest solution to the shallow water equations because it does not have a meridional wind component.

Special Properties: no meridional wind, must be *trapped* by something. In the real world Kelvin waves can be trapped by coastlines, mountains, or the equator.

Propagation Characteristics: Equatorially trapped convectively coupled Kelvin waves travel eastward at phase speeds of 15-20 m/s over the West Pacific and 12-15 m/s over the Indian Ocean because they tend to be more strongly coupled to convection. They are nondispersive, so their group speed is equal to their phase speed.

Horizontal Structure: Kelvin waves have their strongest zonal wind parallel to the equator which tapers off following a Gaussian function off the equator. They have a classic "in, up and out" structure with easterlies in front and westerlies in back. The area of zonal convergence in between is where the convection tends to occur. The area of convergence(associated with convection) is the "active" phase and the area of divergence (associated with suppressed vertical movement) is called the "inactive" phase.

Class Discussion

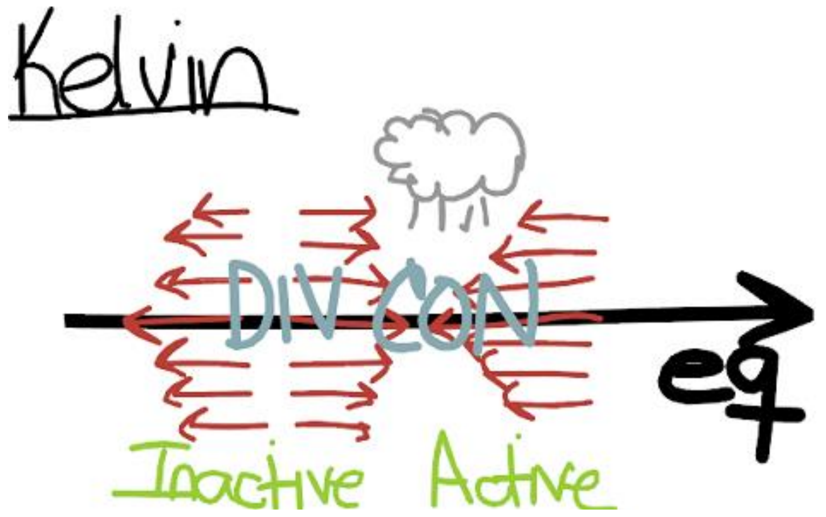
The Kelvin wave is the simplest solution to the shallow water equations because it does not have a meridional wind component. **Discuss**

Important Effects

- Outflow from their convection can cause Rossby wave trains to develop.

- The westerly wind phase (back) of the Kelvin wave can be associated with westerly wind bursts (WWBs). These WWBs create stress on the ocean which can move warm water from the warm pool in the Pacific to the east, which is important for El Nino development.

- Kelvin waves can provide favourable conditions for TCs to develop: convection, low-level vorticity, vertical shear and mid-level moisture.



The Equatorial Rossby Wave (ER)

Special Properties: twin cyclones, equatorial symmetry, convection is displaced off the equator, can come in different “flavors”.

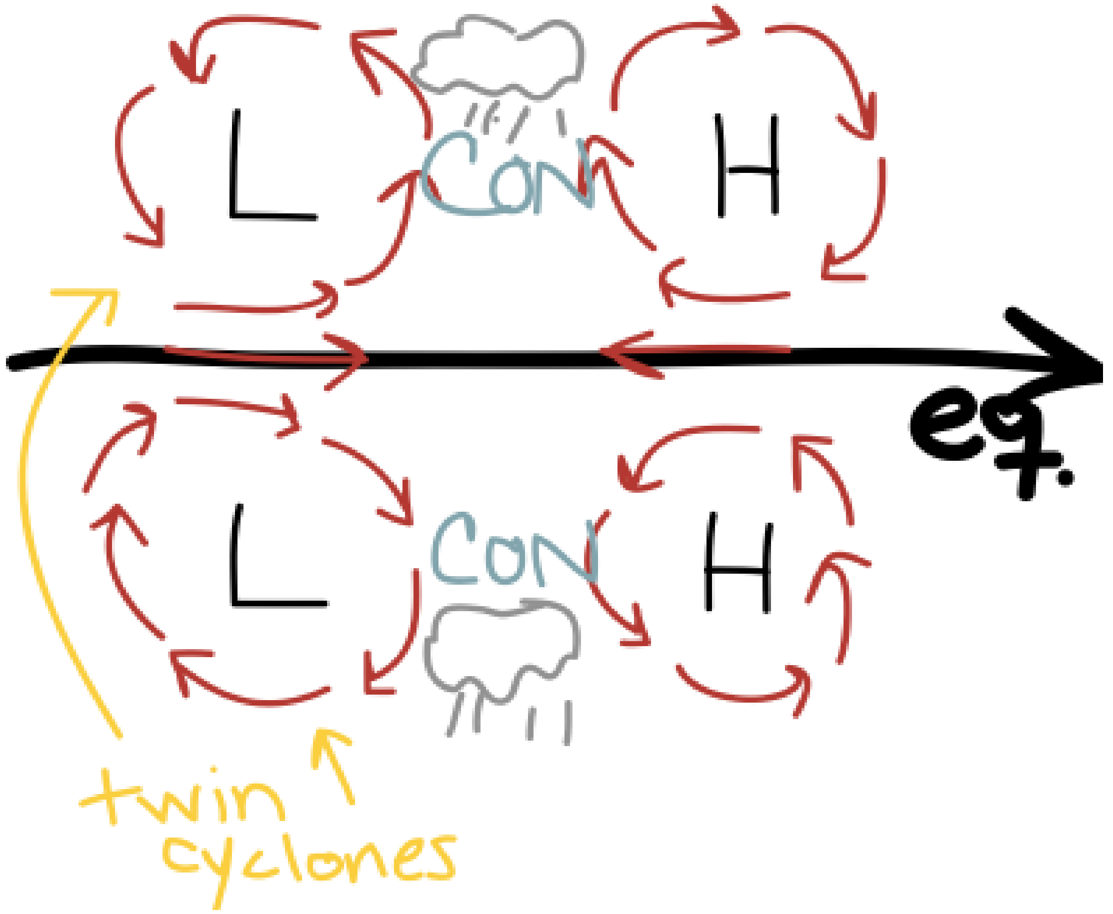
Propagation Characteristics: Travel westward at roughly 5 m/s.

Horizontal Structure: The twin cyclones are one of the key aspects, as well as the location of the convection.

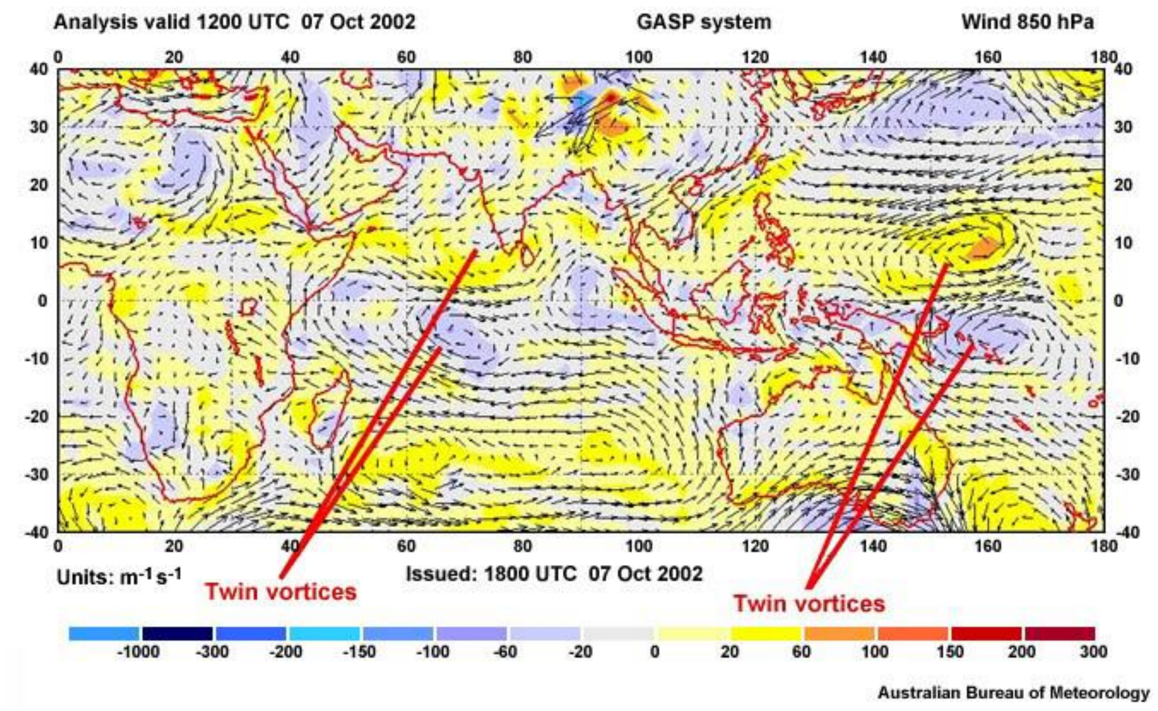
Important Effects:

- Outflow from their convection can cause Rossby wave trains to develop, similar to Kelvin Waves. ER waves are much more closely tied to midlatitude wave trains.
- The westerlies can be associated with westerly wind bursts, just like in the Kelvin wave.
- Twin cyclones can spin off and become tropical depressions. The vorticity associated with the convection can lead to TC genesis.

ER (n=1)



Rossby waves were first identified by Carl Gustaf Rossby in 193959 to describe large scale quasi-geostrophic motions in the midlatitudes. These waves explain the essential elements of the evolution and spatial scales of the dominant weather systems at these higher latitudes.



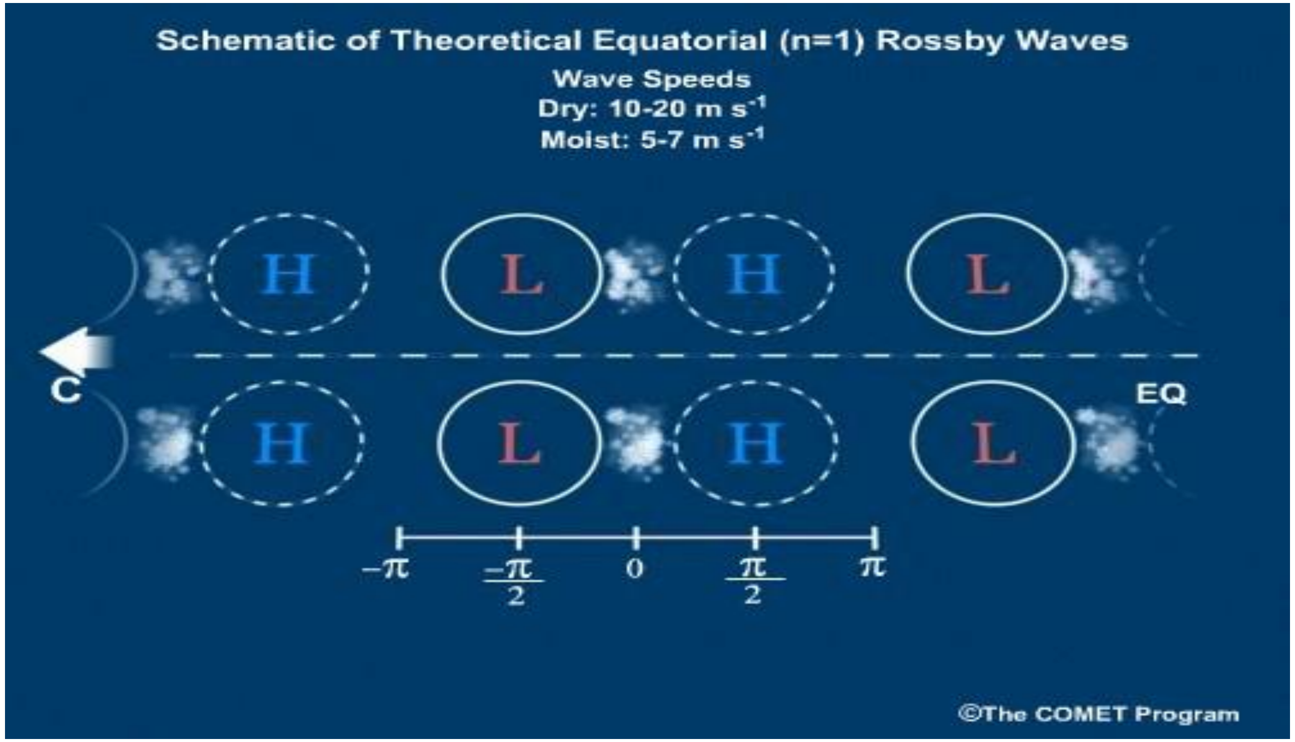
Evidence of equatorial Rossby (ER) waves in the Australian Bureau of Meteorology (BOM) 850 hPa tropical wind analysis for 1200 UTC 7 October 2002. An equatorial Rossby wave can be identified in the 850 hPa

Equatorial Rossby waves are observed to have a long lifetime, on the order of days to weeks.

The large waves of interest to us propagate westward with speeds on the order of 10–20 m s-1 for dry atmospheric Rossby waves, 5–7 m s-1 for convectively-coupled Rossby waves (and ~1 m s-1 for oceanic Rossby waves).

Given that the equatorial Pacific is about 17,760 km across, an atmospheric Rossby wave would cross the Pacific in roughly 18 days and an oceanic Rossby wave would take approximately 210 days.

Note that Rossby waves have the same sense of vorticity (opposite sense of rotation) either side of the equator. This results in maxima in the wind field on the equator and maxima in the mass field off-equator, so we are interested in the off-equator mass tendencies.



Schematic depiction of the theoretical solution for an equatorial Rossby wave in a dry, incompressible atmosphere.

a. With high to the west of the low, mass is advected poleward, leading to pressure drops, so the low moves westward.

b. With low to the west of the high, mass is advected into the region leading to pressure rises, so the high moves westward.

Shallow Water Theory

Imagine that the Earth is covered in only a layer of water with a homogeneous density under hydrostatic balance.

Let's assume that the Coriolis force varies linearly (still zero at the Equator) instead of sinusoidally. Let's call the depth of the water the ***equivalent depth***. When the momentum equations are simplified to fit this ideal scenario and solved, an important set of solutions comes out which we call **equatorial waves**.

Details: [*https://www.youtube.com/watch?v=tbJ3QCHAzI0*](https://www.youtube.com/watch?v=tbJ3QCHAzI0)

Although the real world is very different from the ideal world of shallow water theory, it is a decent approximation in the tropics and we see examples of equatorial waves all around us. These same wave modes can exist in the ocean as well.

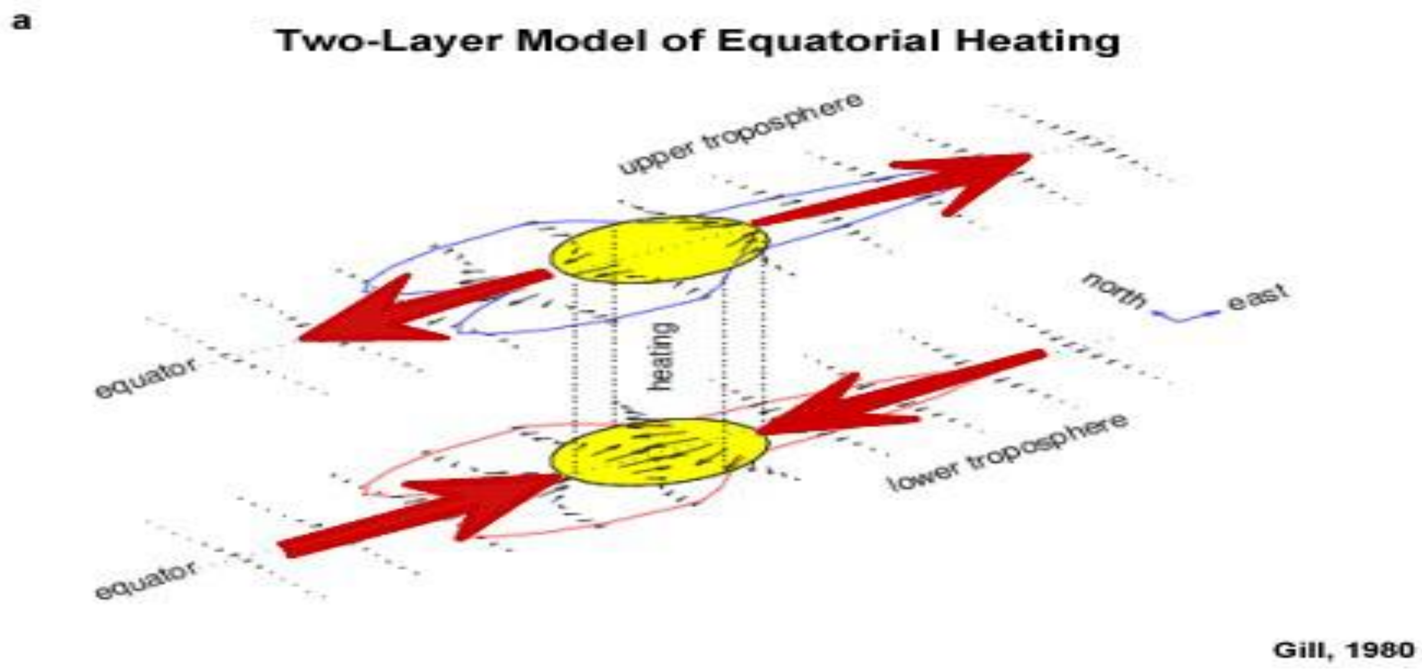
Note, also, that the shallow water equations are non-convective (“dry”). In the real world, we tend to focus on **convectively coupled equatorial waves (CCEW)** which are nothing more than the shallow water waves coupled to atmospheric convection.

Convectively coupled waves move more slowly than dry waves.

Convectively coupled equatorial waves can be thought of as large scale areas that are especially conducive for convection.

The presence of a CCEW does not necessarily imply convection and convection does not necessarily imply the presence of a CCEW.

The dynamical response of the atmosphere to imposed heating at the equator was modelled by several scientists, most notably, Matsuno (1966) and Gill (1980). They found significant zonally asymmetric components to the tropical circulation. Using the Shallow Water Equations, they calculated wave solutions that were later confirmed by observations.



(a) Two-layer model of the atmosphere showing heating source on the equator and the atmospheric response

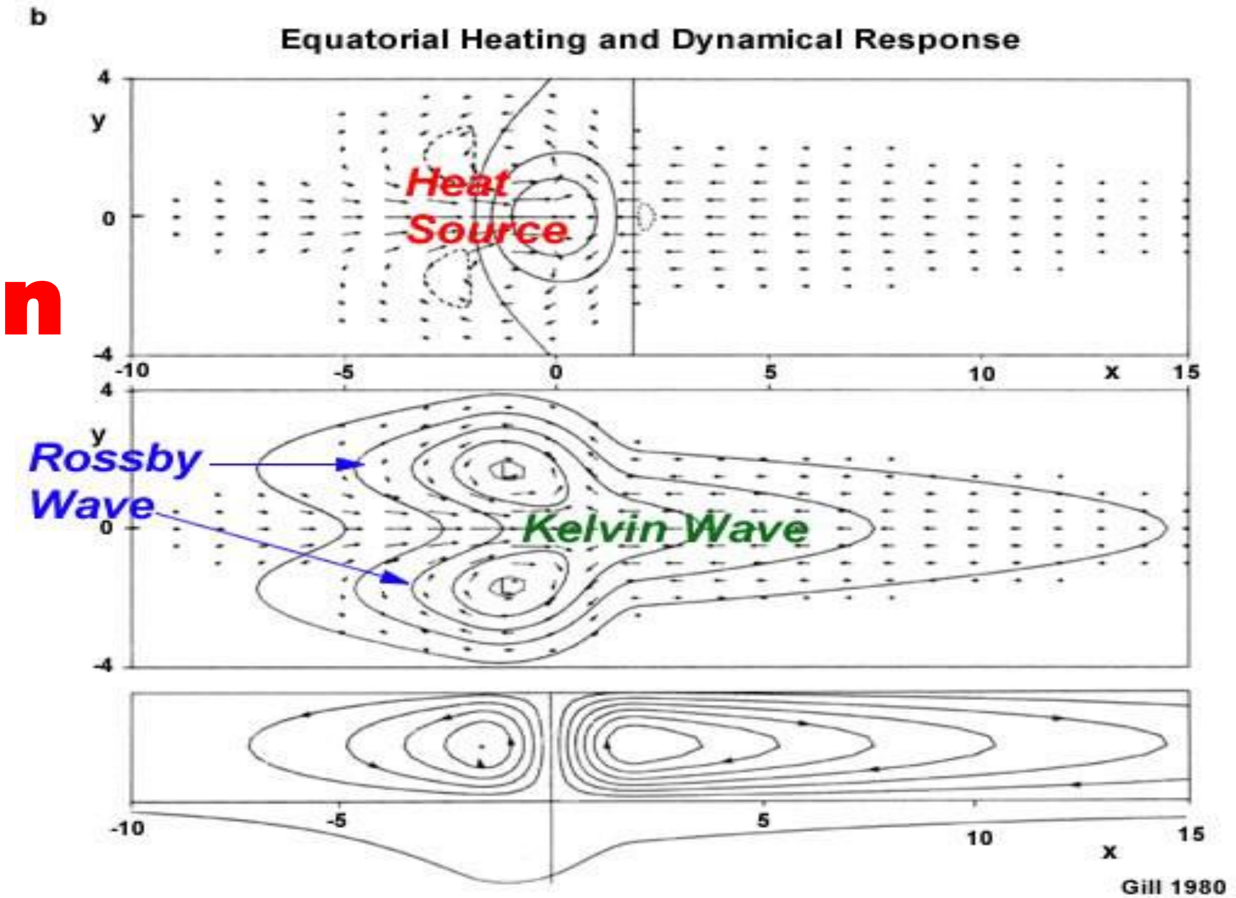
Effects of moisture (convection) on wave propagation

- The moist Kelvin wave has moist convergence to the west of the low, leading to deep convection. Since the convection is to the west of an eastward moving low, and convection generates cyclonic low-level PV, the moist convection slows the wave propagation.

- When moisture is added to the equatorial Rossby wave (e.g., the moist low–level convergence to the east of ("behind") the low center can force deep convection. Deep convection generates low–level cyclonic PV, and so slows down the wave.

- Equatorial waves contribute to tropical cyclogenesis especially over the Indian and west Pacific basins.

Effects of heating on equatorial wave propagation

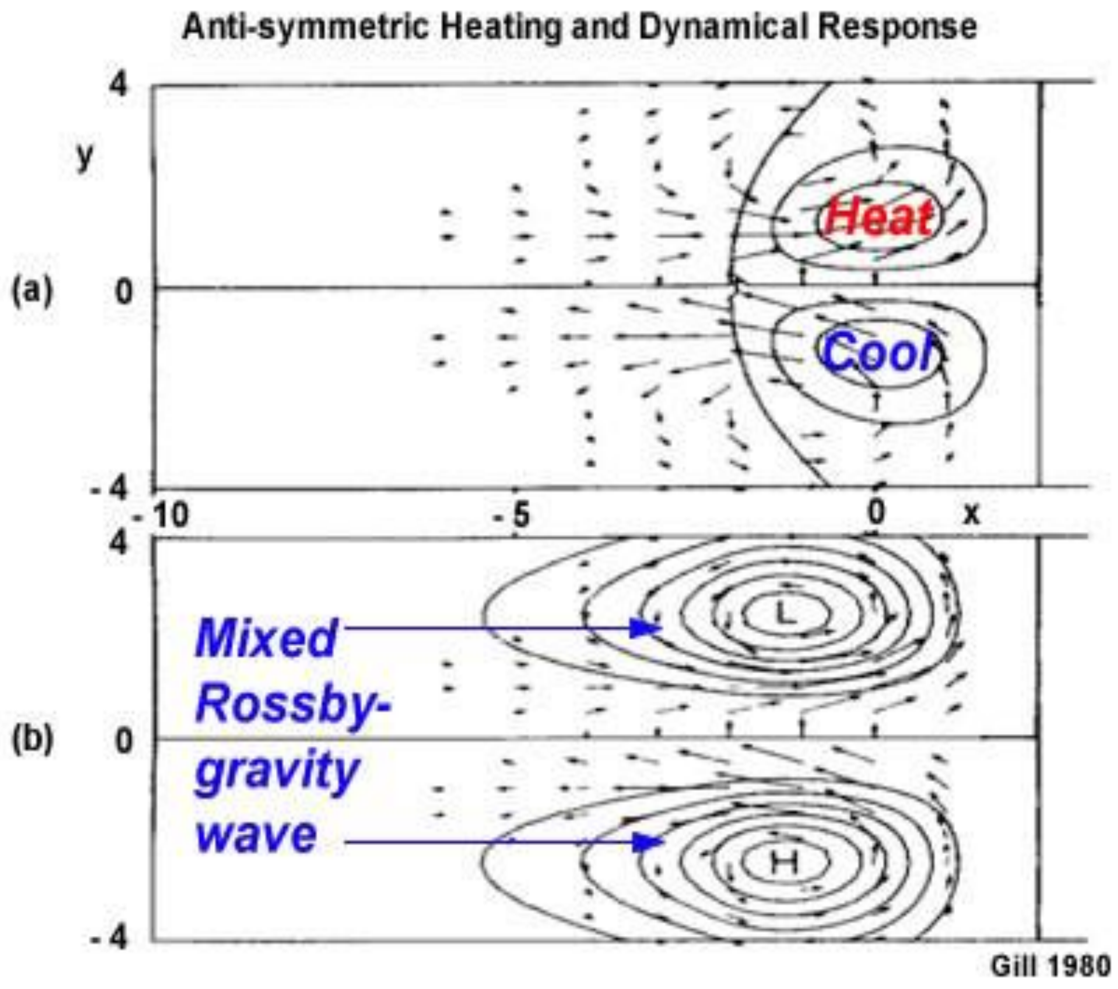


views of the circulations: horizontal wind vectors and vertical velocity contours; perturbation pressure contours overlaid on the same wind vectors; meridional integrated flow. The Rossby waves propagated westward and the Kelvin wave propagates eastward. Adapted from Gill (1980)

The solutions to their formulation were waves that propagated zonally along the equator and extended vertically to the upper troposphere and lower stratosphere

(a). The influence of heating extends farther to the east and then to the west but the amplitude of the response is greater to the west. The solution is confined much closer to the equator on the east than on the west. Some of these equatorially trapped waves propagated eastward and others westward.

The schematic in (b) shows the eastward-moving Kelvin wave and westward-moving Rossby waves that are generated in response to a heating source on the equator. These waves are sometimes coupled with strong convection, especially over the Indian and western Pacific oceans, where they can occasionally lead to tropical cyclone genesis.



Schematic of response to anti-symmetric heating off the equator (a) horizontal wind vectors and vertical velocity contours;
(b) perturbation pressure contours overlaid on the same wind vectors. A dominant anti-symmetric mode is a mixed Rossby-gravity wave that moves westward. Adapted from Gill (1980)

With the heat source distributed anti-symmetrically relative to the equator, the result is opposing high and low pressure across the equator. A long planetary wave develops to the west of the heating source. Rising motion and cyclone circulation are associated with the surplus heating and corresponding subsidence with the anticyclone. There is little response to the east. The dominant response is an anti-symmetric equatorial wave termed **a mixed Rossby-gravity wave**.

Tropical circulations result from a combination of symmetric and anti-symmetric heating. A result of the anti symmetric heating is the Hadley cell in July, which has a rising branch over the Northern Hemisphere surplus heating region and a sinking branch over the Southern Hemisphere cooling region.

One example of the response to symmetric heating component is the Pacific branch of the Walker Circulation, an east-west circulation, which has rising motion associated with the surplus heating over the warm western Pacific.


Questions?

RECAP OF LECTURE

- Equatorial Waves
  - Kelvin Waves
  - Rossby Waves
- Shallow Water Equations