

# The Atmospheric General Circulation

Lectures 14-15: Tropical Circulation

热带环流

- ✓ The Annual Mean Circulation of the Tropics
- ✓ The Seasons in the Tropics

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# 1. The Annual Mean Circulation of the Tropics

## 1.1 Rain rate, vertical velocity, and low clouds

- A disproportional fraction of the rain falls in the eastern hemisphere, dominated by the **Indo-Pacific warm pool**.
- the Pacific and Atlantic **ITCZs** Intertropical Convergence Zone
- The corresponding vertical velocity patterns at the 300 and 850 hPa levels, both resemble the rain rate pattern.
- The regions of ascent in the warm pool are more pronounced in  $\omega_{300}$ , whereas the ITCZs are in  $\omega_{850}$ .

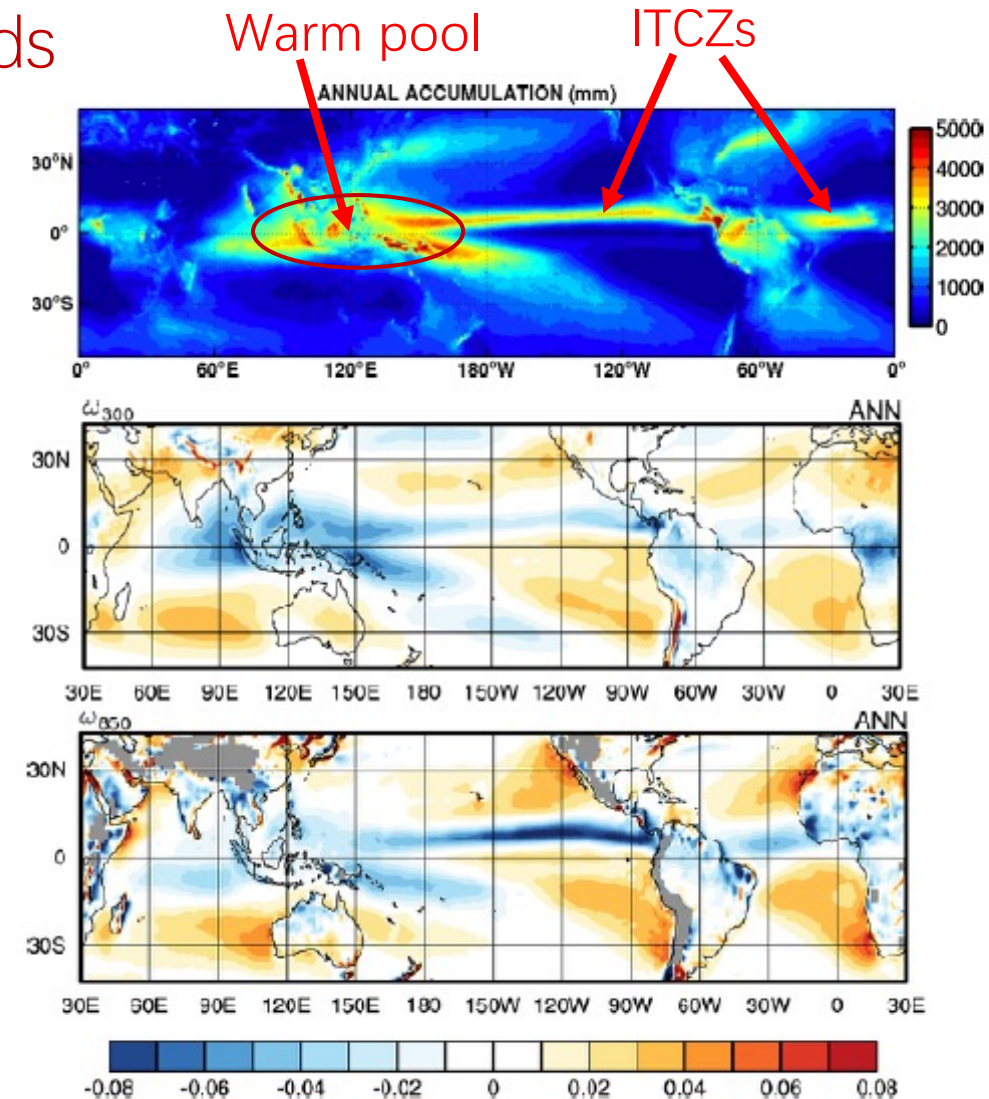


Figure 13.1: (Top panel) annual mean rainfall, Courtesy of V. Venugopal; (middle panel)  $\omega_{300}$ ; (bottom panel)  $\omega_{850}$ . Note that positive values of  $\omega$  indicate descent.

# 1. The Annual Mean Circulation of the Tropics

## 1.1 Rain rate, vertical velocity, and low clouds

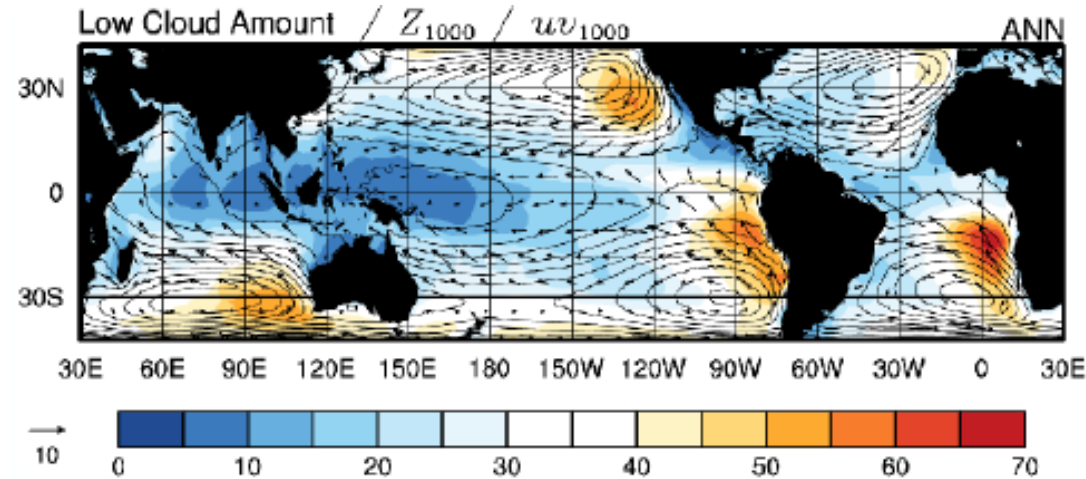


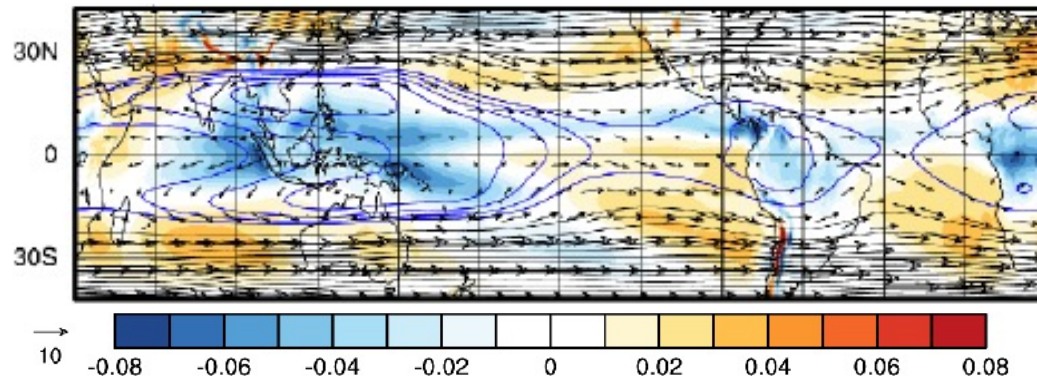
Figure 13.10: As in the bottom panel of Fig. 13.8, but here the shaded field is the percentage of the sky covered by low clouds. Based on data from the International Satellite Cloud Climatology Project (ISCCP).

- Low clouds form near the top of the boundary layer. The low clouds are much more extensive in the gold-shaded regions of descent than in the rain belts.

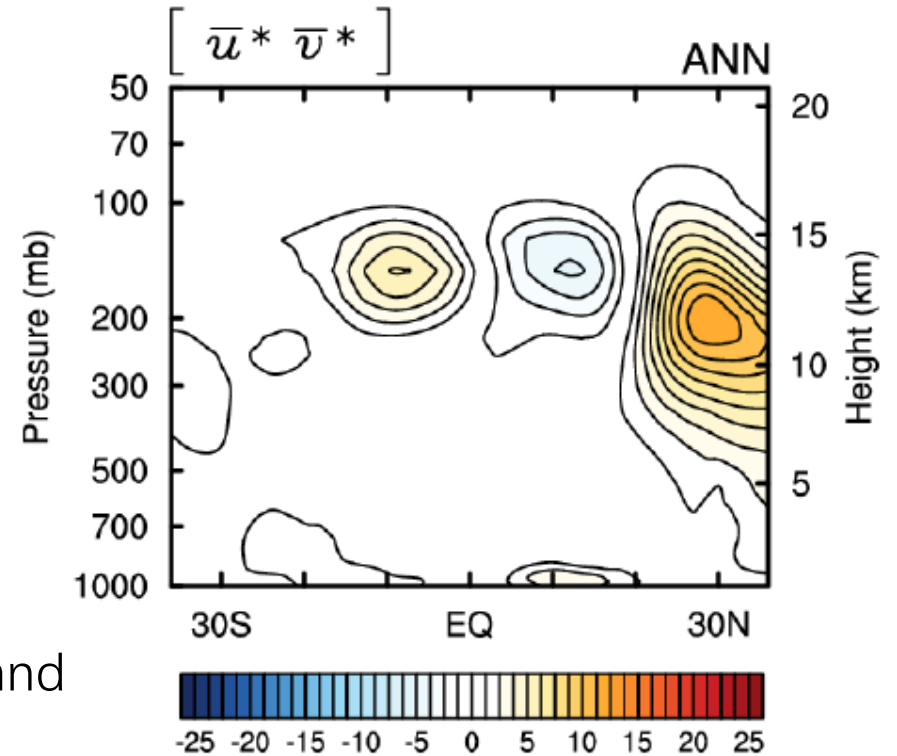
# 1. The Annual Mean Circulation of the Tropics

## 1.2 The upper tropospheric circulation

Annual mean  $\omega_{300}$  (color),  $Z_{150}$ ,  $V_{150}$



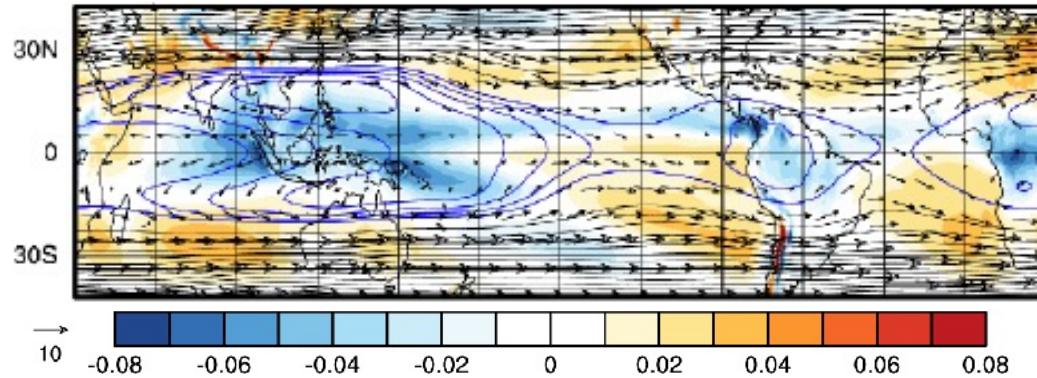
- The height field exhibits an equatorially focused and equatorially symmetric **wave pattern**
- **Ridge** from 90E to 150E and **troughs** over the Atlantic and eastern Pacific
- The off-equatorial features tilt with latitude in the sense indicative of a **meridional transport of westerly momentum** from the outer tropics into the equatorial belt.



# 1. The Annual Mean Circulation of the Tropics

## 1.2 The upper tropospheric circulation

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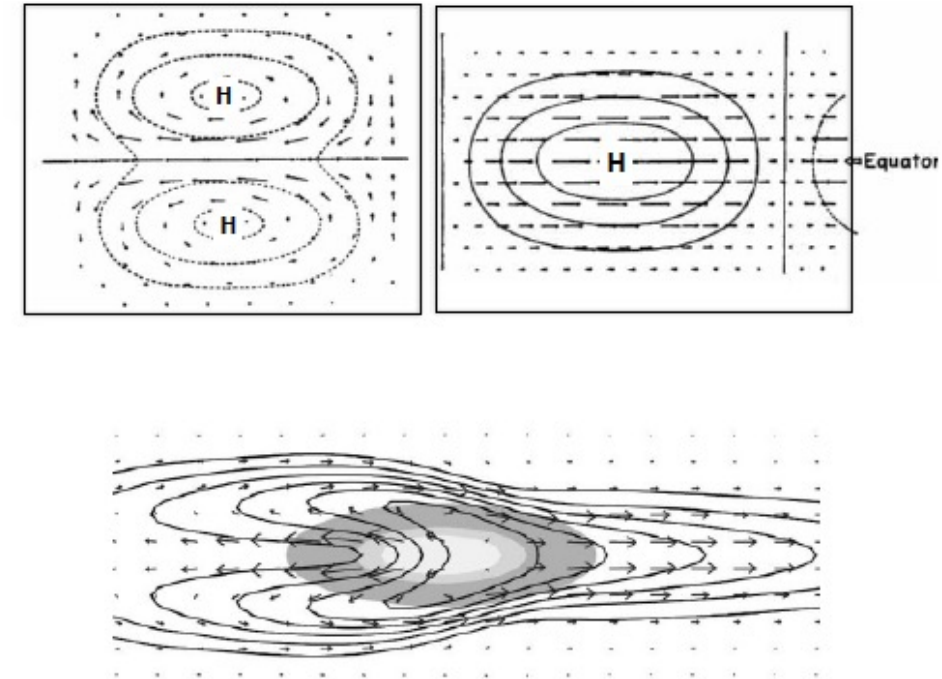
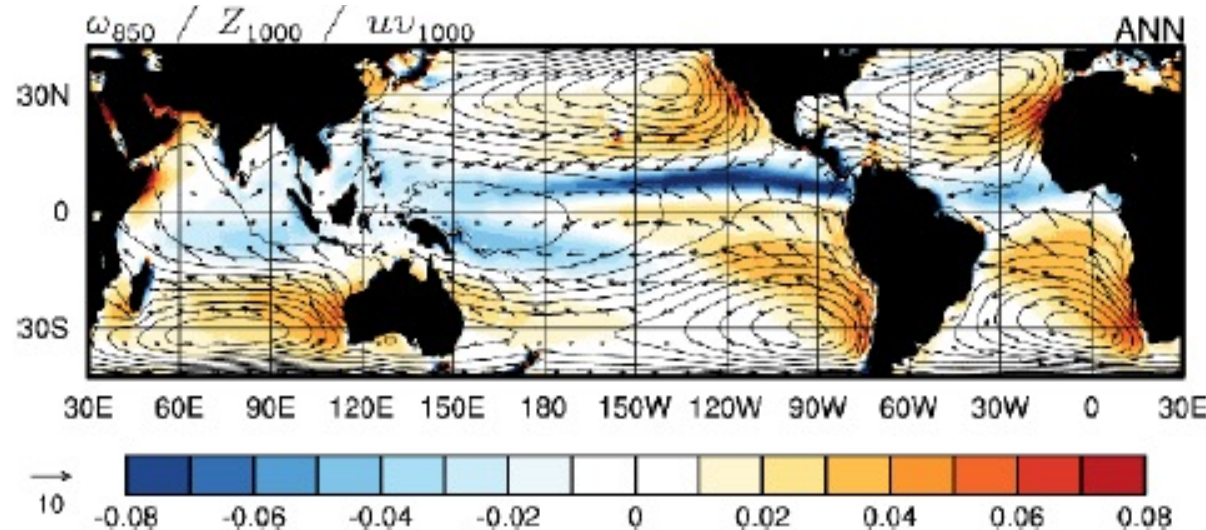


Figure 13.9: Top panels show Matsuno's 1966 solutions for waves on an equatorial  $\beta$ -plane: left, the Rossby wave and right, the Kelvin wave repeated from Fig. 13.3. The bottom panel shows Gill's 1980 solution for the response to an isolated heat source on the equator, indicated by the shading, which consists of a superposition of the wave solutions: the Rossby wave to the west of the heat source and the Kelvin wave to the east of it.

# 1. The Annual Mean Circulation of the Tropics

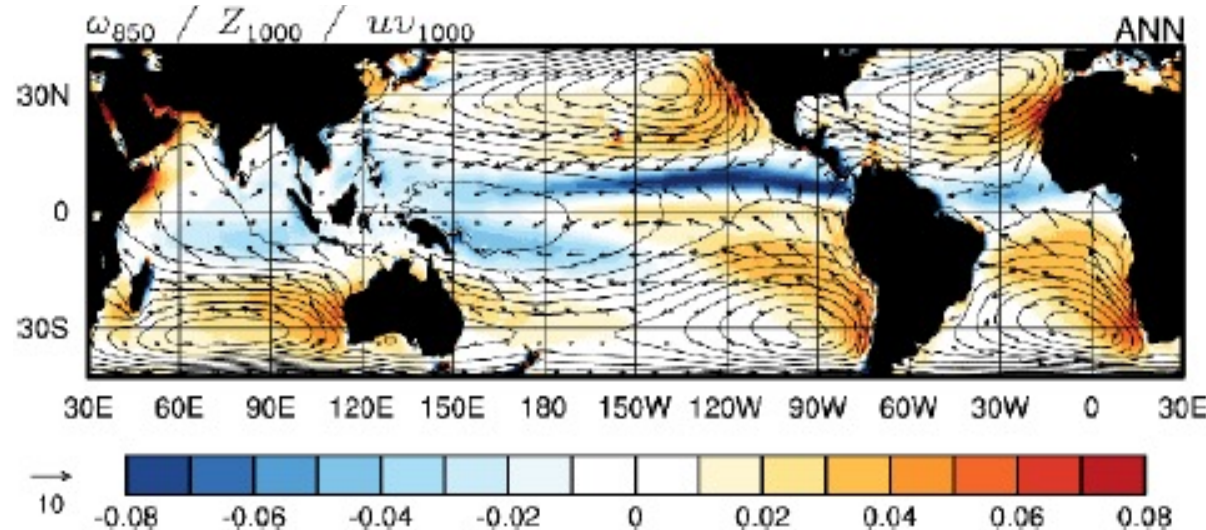
## 1.3 The lower tropospheric circulation



- The wind and height patterns are much different from their counterparts in the upper troposphere and not as amenable to a simple interpretation in terms of equatorially trapped planetary waves. One of the reasons is because frictional drag is of first order importance in the momentum balance.
- Other prominent features are the anticyclones over the subtropical eastern oceans, flanked on their eastern sides by **subtropical subsidence zones**.

# 1. The Annual Mean Circulation of the Tropics

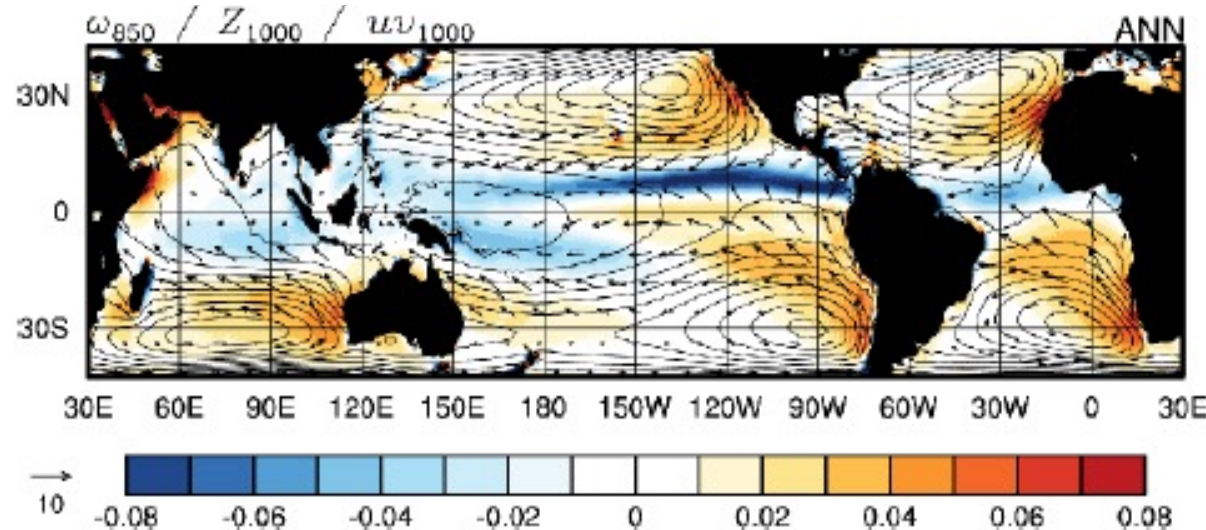
## 1.3 The lower tropospheric circulation



- In the heat balance, subsidence warming is balanced by cold advection and radiative cooling. Most of the subsidence in the sinking branch of the Hadley cell is concentrated within these zones and most of the equatorward flow is concentrated within them and in the trade-wind belts immediately downstream of them.
- The five prominent subtropical anticyclones can be viewed as Rossby wave responses to these injections of mass into the subtropical boundary layer from above in these zones.

# 1. The Annual Mean Circulation of the Tropics

## 1.3 The lower tropospheric circulation



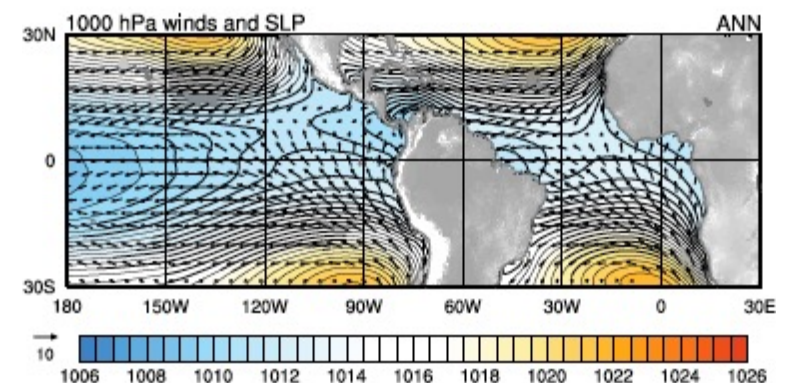
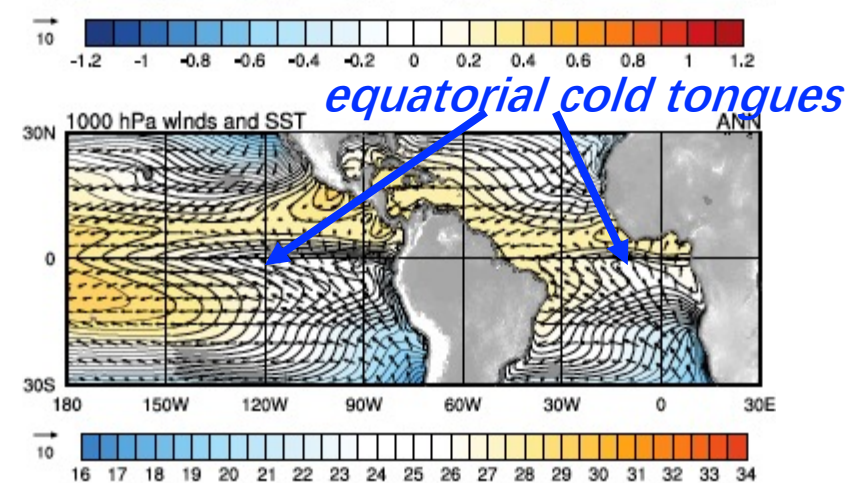
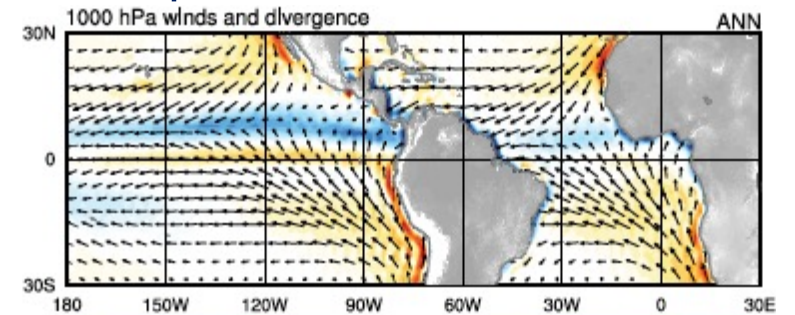
- The **subtropical subsidence zones** are thermally induced. In the tropics, the continents are warmer than the surrounding oceans at the top of the boundary layer (850 hPa) out to  $\sim 30^\circ\text{N/S}$  latitude, even during winter.
- The SLP pattern is, in large part, a hydrostatic response to the boundary forcing, with heat lows over then warm land and higher pressure over the cooler oceans. Why the highs are centered over the eastern oceans? Cold advection feedback

# 1. The Annual Mean Circulation of the Tropics

## 1.4 The ITCZ / cold tongue complexes

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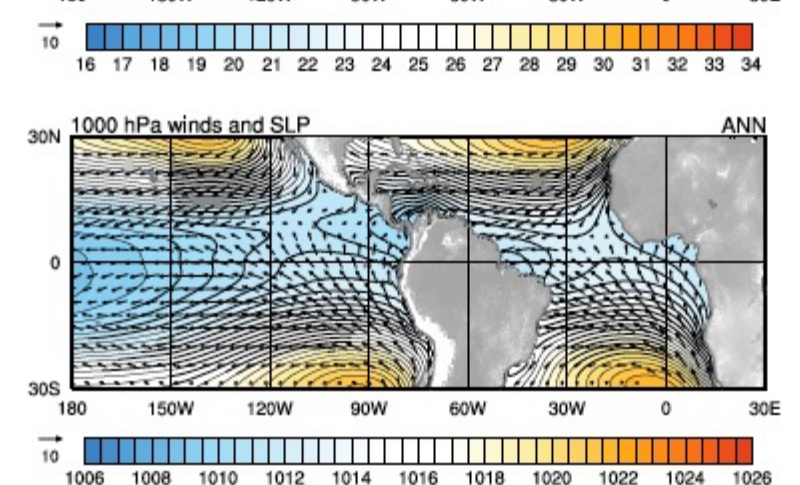
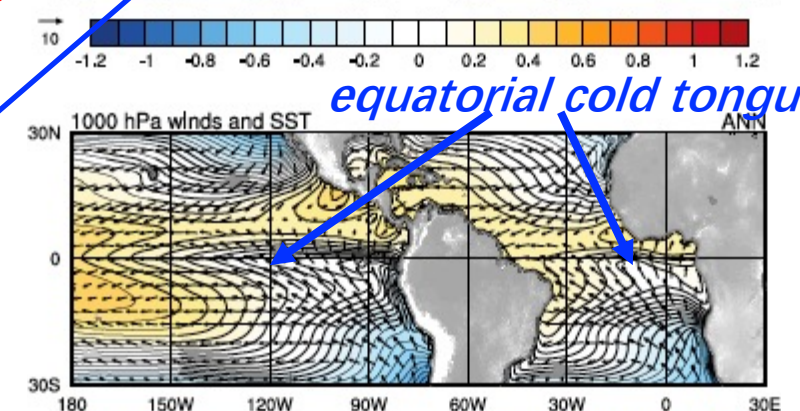
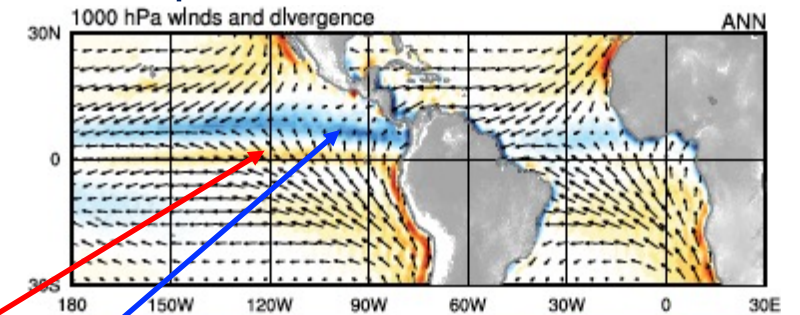
- An important oceanic feature, the so-called *equatorial cold tongues* on the eastern sides of the Pacific and Atlantic basins.
- They are a consequence of the easterly climatological mean surface winds along the equator.
- The westward drag force on the warm near-surface water deepens the thermocline on the western sides of the basins and raises it on the eastern sides, bringing cold water from below.
- Because of the shallowness of the equatorial thermocline on eastern side of the basins, the upwelled water is colder than it would be in the absence of the trade winds.



# 1. The Annual Mean Circulation of the Tropics

## 1.4 The ITCZ / cold tongue complexes

- The **northward flow across the equator** slows down as it passes over the cold tongue and speeds up again as it crosses the front, giving rise to a narrow band of **divergence along the front itself**.
- The northward wind stress drags the equatorial surface water northward, inducing upwelling to the south of the equator and downwelling to the north of, it giving rise to the observed equatorial asymmetry in the SST.
- The larger scale atmospheric asymmetries — the fact that the **ITCZ is in the Northern Hemisphere** and there is a strong **northward cross-equatorial flow year-round** — derive from the **asymmetries in the land-sea geometry and the orography**.

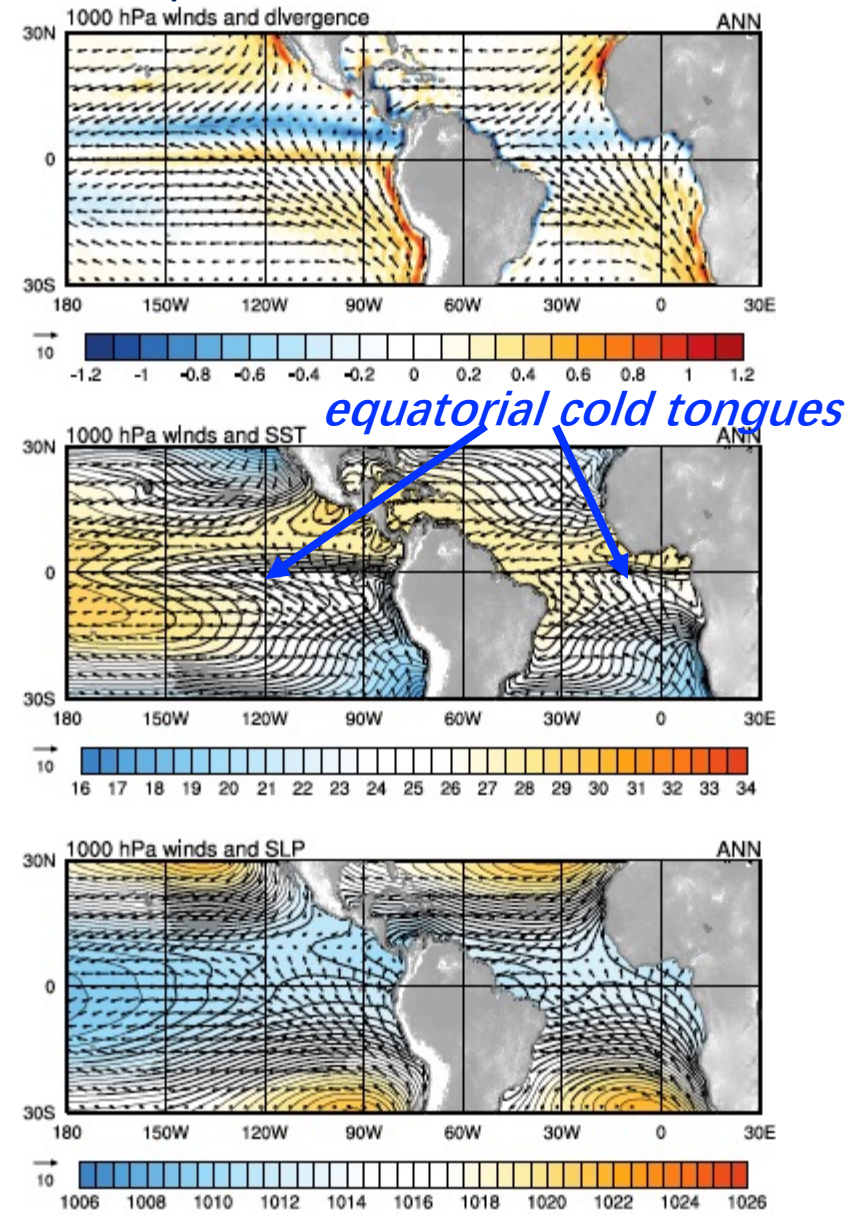


*equatorial cold tongues*

# 1. The Annual Mean Circulation of the Tropics

## 1.4 The ITCZ / cold tongue complexes

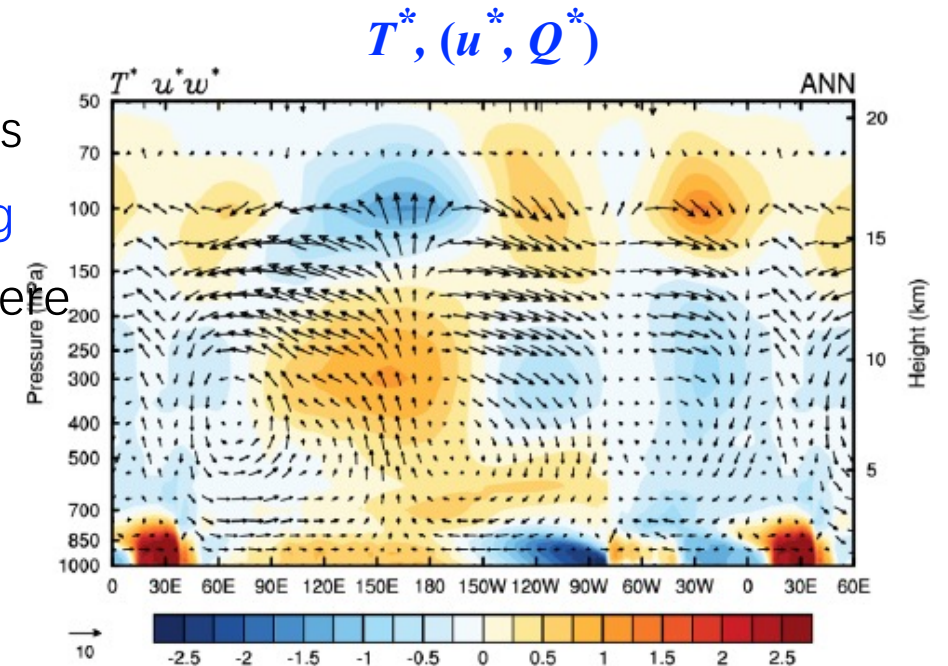
- The SLP field (**bottom panel**) is smoother than the SST field but it exhibits many of the same features with reversed sign, reflecting the strong influence of SST upon boundary layer temperature and, in turn, upon SLP by way of the hypsometric equation 压高方程.
- Almost everywhere within the equatorial belt ( $10^{\circ}\text{N}$ - $10^{\circ}\text{S}$ ) the surface wind blow down the horizontal pressure gradient, reflecting the prevalence of a two-way balance between the pressure gradient force and frictional drag. **The pervasive atmosphere-ocean coupling observed in the deep tropics affects the annual mean climatology, contributes to the seasonality, and plays a central role in ENSO physics.**



# 1. The Annual Mean Circulation of the Tropics

## 1.5 The equatorial stationary waves

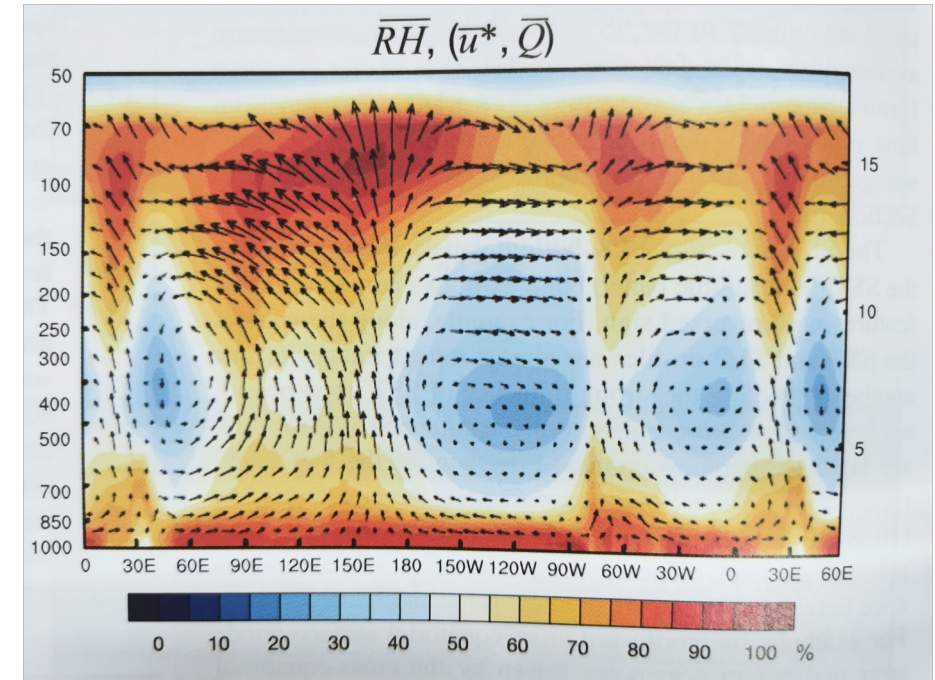
- Vertical structure of the equatorial stationary waves shows the most striking feature is the **plume of upward pointing arrows over the western Pacific**, extending into stratosphere.
- The overturning circulation is strongest around the 300 hPa level. It is **thermally direct**. Above 150 hPa level, the circulation is **thermally indirect**.
- In the lower troposphere, the overturning circulation is more complicated because it is influenced not only by the planetary waves, but also by the boundary forcing.



# 1. The Annual Mean Circulation of the Tropics

## 1.5 The equatorial stationary waves

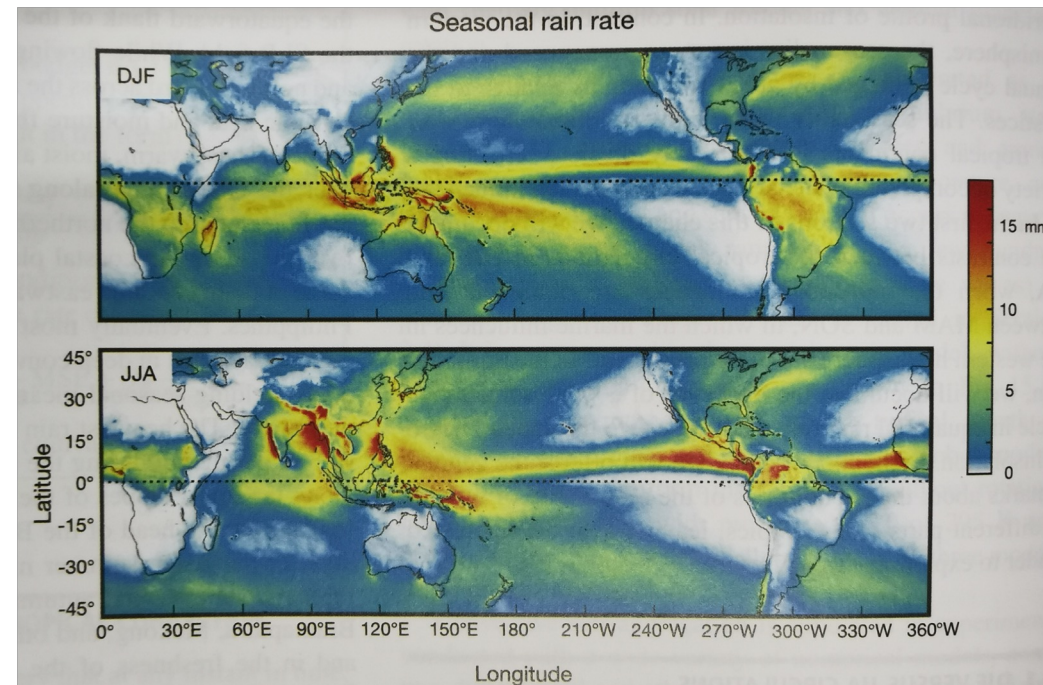
- The vertical arrows represent total vertical velocity ( $Q$ ). Ascent is evident over the warm pool, over Africa and South America. A strong correspondence between total vertical velocity ( $Q$ ) and relative humidity ( $RH$ ; colored shading)
- The air in the equatorial dry zones is remarkably dry, not only in the boundary layer, but throughout the entire depth of the troposphere. In fact, the strongest  $RH$  perturbations are observed in the mid-troposphere, where the  $Q$  in the equatorial planetary waves are strongest. The dryness of the mid-troposphere over the eastern tropical oceans tends to inhibit the occurrence of deep convection, even in the ITCZs.



## 2.The Seasons in the Tropics

### 2.1 DJF vs JJA circulations (zonally varying flow)

- The dominant features of the DJF and JJA climatological are the so-called *monsoon circulations*.
- A northward shift of the convection from DJF to JJA is evident at all longitudes — much greater over and near the continents than over the oceanic ITCZs.

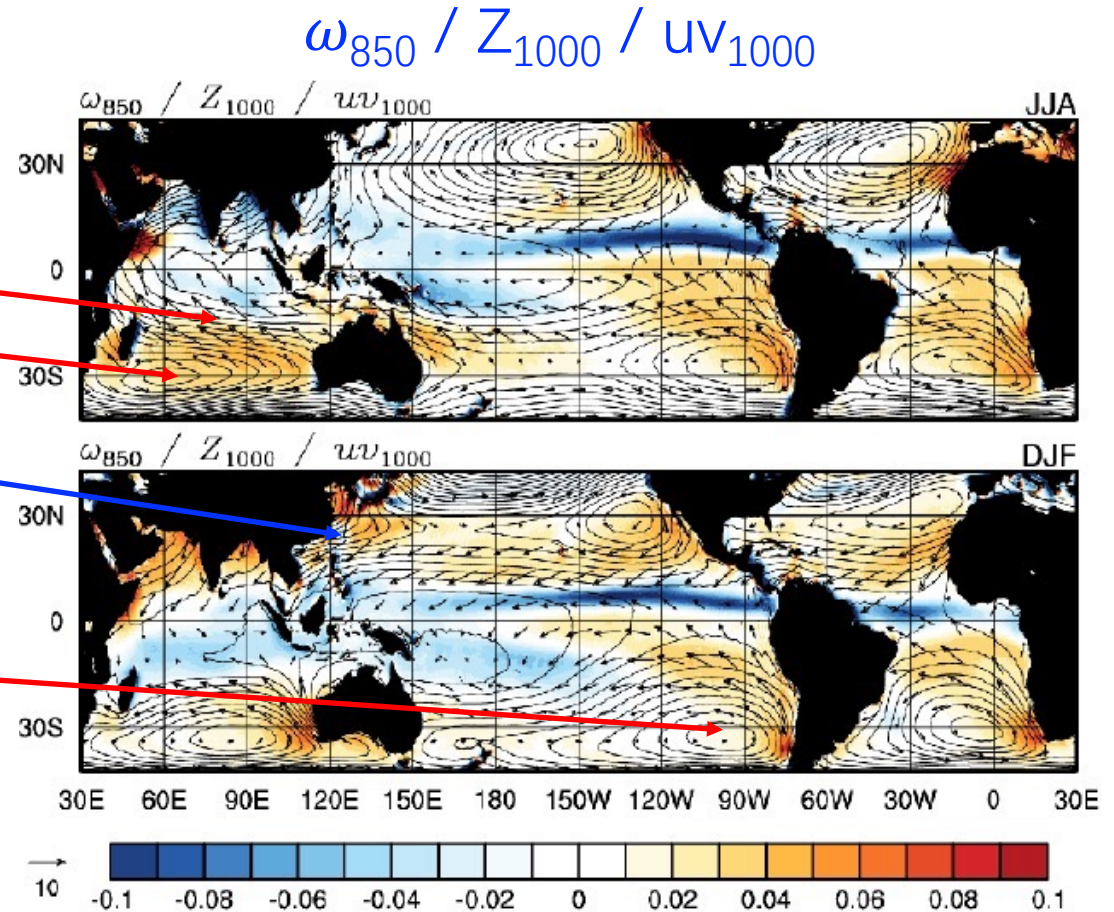


# 2.The Seasons in the Tropics

## 2.1 DJF vs JJA circulations (zonally varying flow)

The corresponding shift in the lower tropospheric circulation:

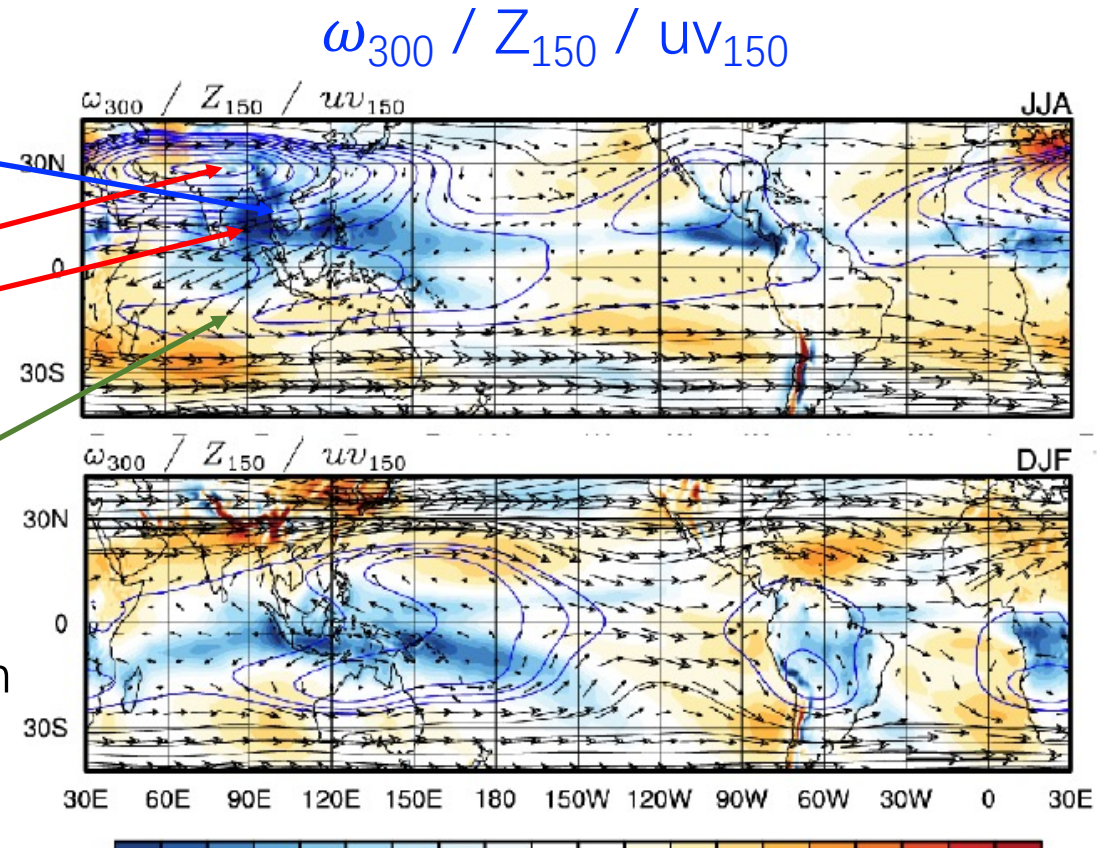
- JJA: Heavy rain in South Asia can be traced all the way back to the **southeasterly trade winds** in SH along the equatorward flank of the “**Mascarene high**”.
- DJF: Dry air in the **northeasterly flow** off East Asia crosses the equator and converges into rainband in SH tropics
- Four of the five subtropical subsiding equatorward jets and associated **subtropical anticyclones** on the eastern sides of the respective ocean basins are year-round features. That they are slightly stronger during summer than during winter suggests that the **thermal contrasts between the warm continents and cold oceans** plays a role in maintaining them.



# 2. The Seasons in the Tropics

## 2.1 DJF vs JJA circulations (zonally varying flow)

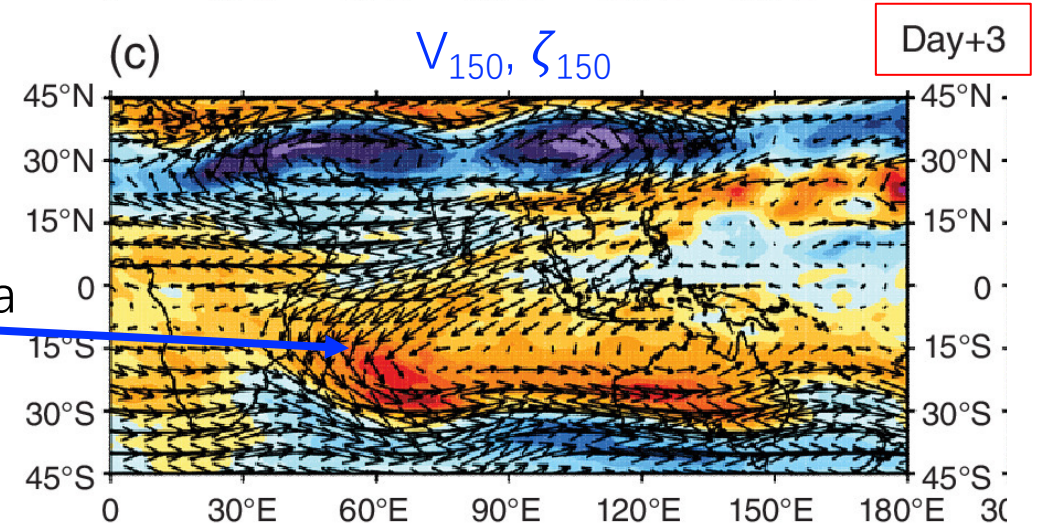
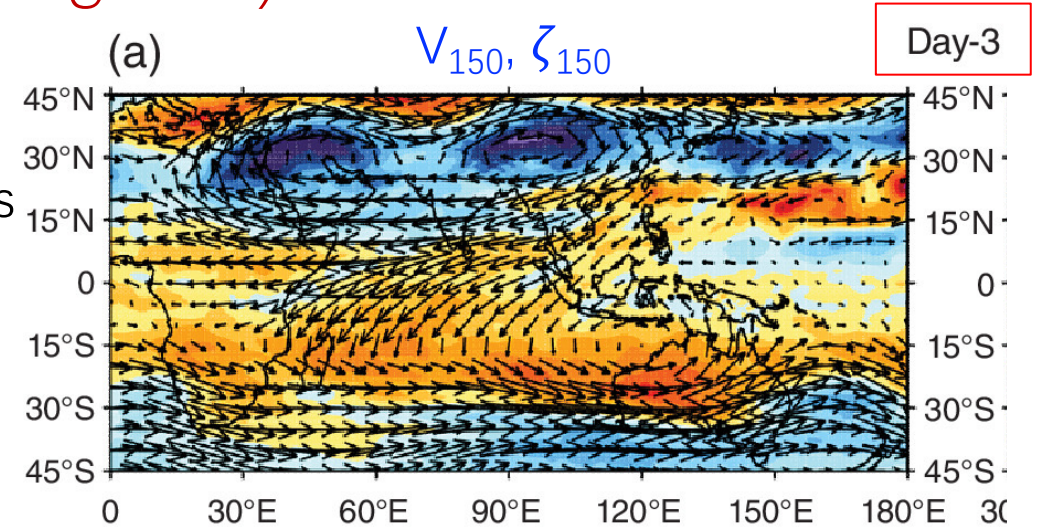
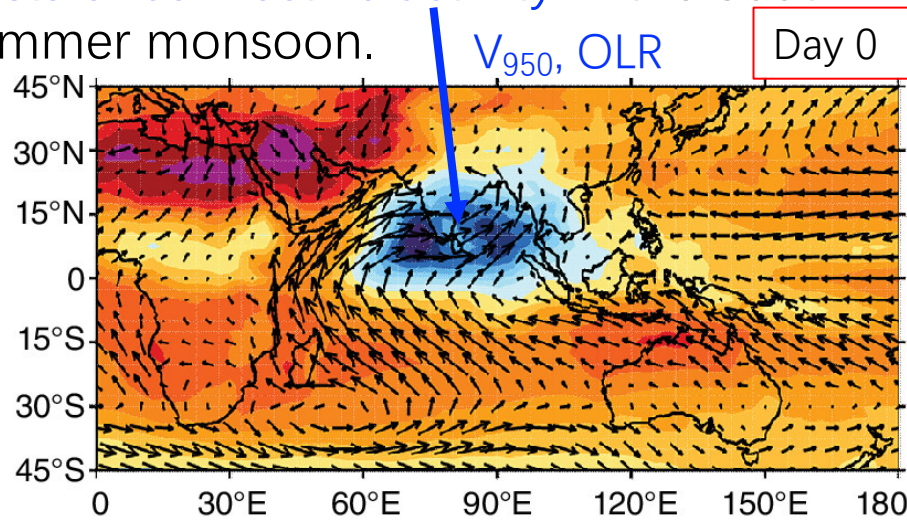
- At the 150 hPa level, divergent outflow from the tops of the **plumes of ascending air in the Asian summer monsoon** induces a planetary-scale Rossby wave response to the northwest, referred to as the **Tibetan anticyclone**.
- The so-called **tropical easterly jet** along its equatorward flank exhibits wind speeds  $> 30 \text{ m s}^{-1}$  as it crosses over the southern tip of India.
- A secondary feature in the JJA  $Z_{150}$  and  $\mathbf{V}_{150}$  patterns is an **anticyclone along  $14^\circ\text{S}$  in the Indian Ocean sector**, which is induced by the conservation of vorticity in the southward cross-equatorial flow. **A heat source in one hemisphere induces a Rossby wave response in the other.**



# 2. The Seasons in the Tropics

## 2.1 DJF vs JJA circulations (zonally varying flow)

- Further evidence of the cross-equatorial coupling
- Composites of daily data 3 days before and 3 days after bursts of convective activity in the South Asian summer monsoon.



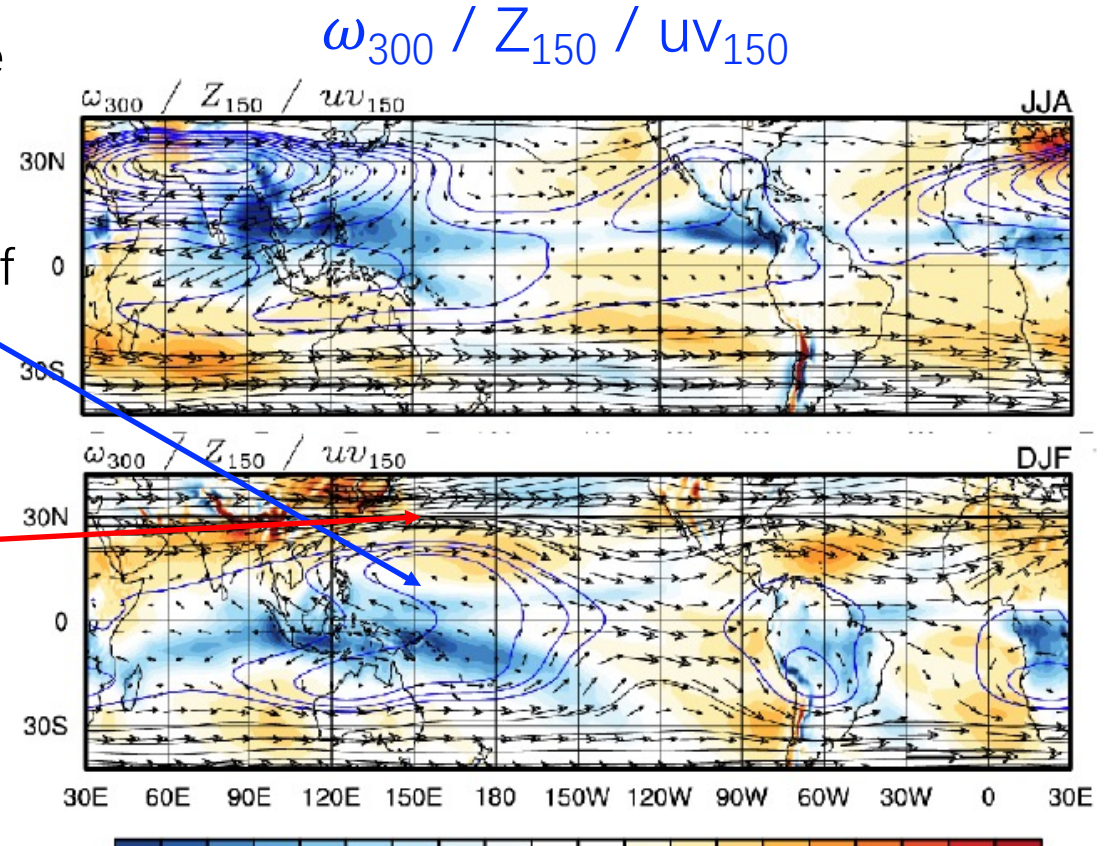
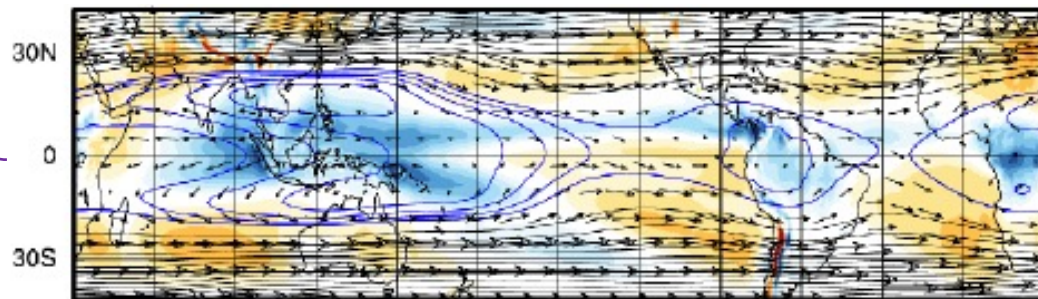
- A strengthening of the cross-equatorial flow and a strengthening of the downstream anticyclone in the southwest Indian Ocean. Much of the flow in the upper branch of the Hadley Cell take places in association with such bursts of deep convection.

# 2.The Seasons in the Tropics

## 2.1 DJF vs JJA circulations (zonally varying flow)

- DJF flow pattern is nearly equatorially symmetric. Like the **annual mean flow**, it bears a strong resemblance to the idealized response to an equatorial heat source, except that the **Rossby wave couplet is shifted toward the east** of the heating rather than toward the west of it.
- The anticyclonic flow around the Rossby wave couplet in the western Pacific contributes to the strength of the **climatological mean westerly jet stream** along 30°N.

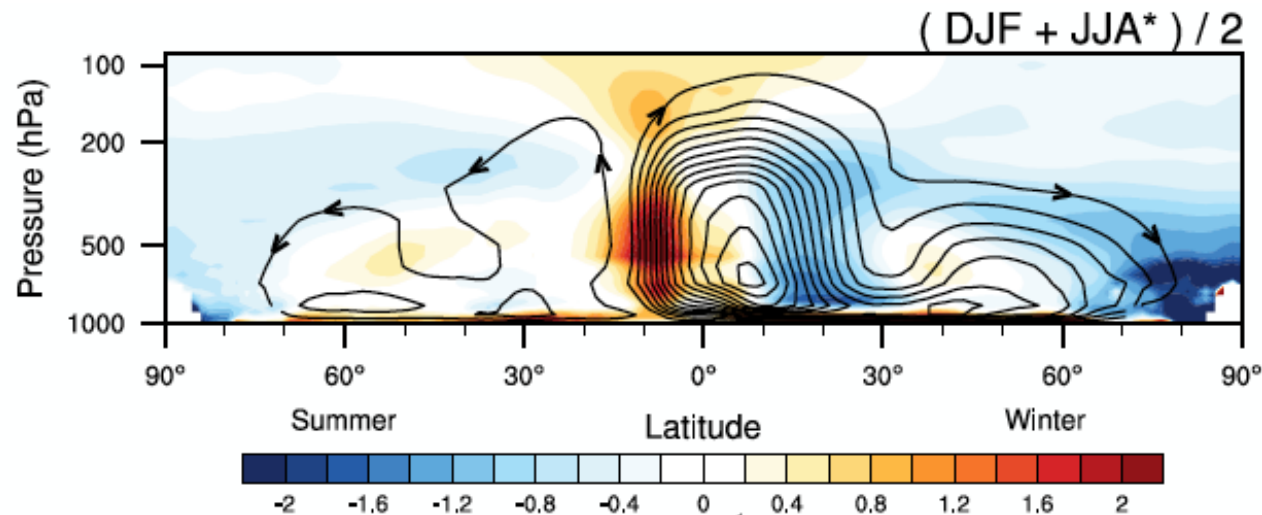
Annual mean  $w_{300}$ ,  $Z_{150}$ ,  $V_{150}$



## 2.The Seasons in the Tropics

### 2.1 DJF vs JJA circulations (zonally symmetric flow)

- The JJA and DJF circulation cells, straddle the equator, with rising branches in the summer hemisphere, sinking branches in the winter hemisphere, and flow from the summer hemisphere into the winter hemisphere in the upper branches centered ~150 hPa.
- They are represented by a **single cell**, which was constructed by transposing the JJA section left-to-right and averaging it with the DJF section.

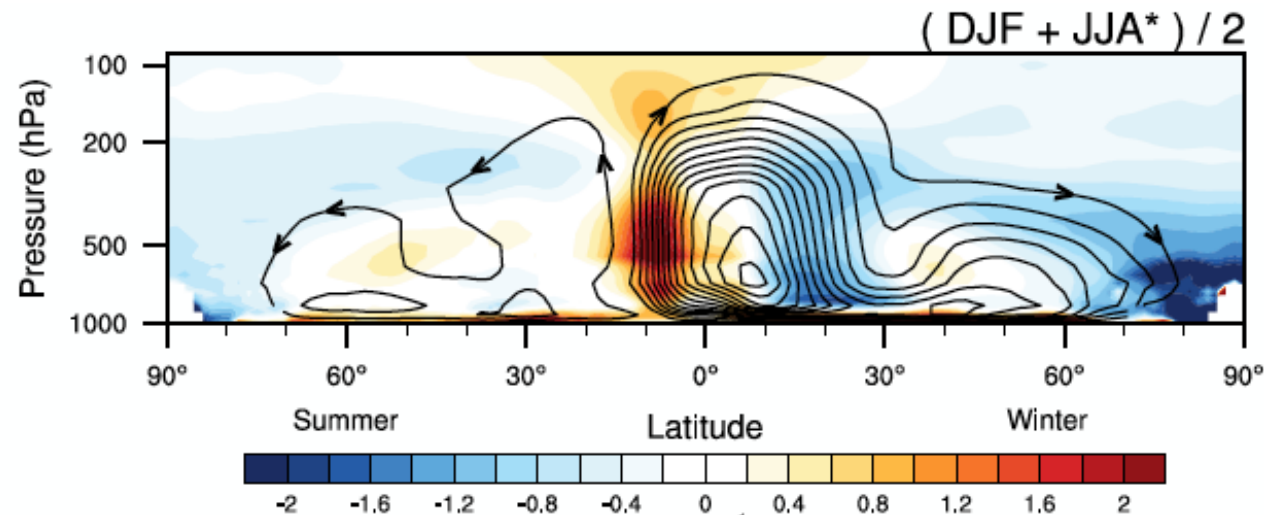


TEM meridional circulation and diabatic heating rate

## 2.The Seasons in the Tropics

### 2.1 DJF vs JJA circulations (zonally symmetric flow)

- The ascending branch of the cell is within  $15^\circ$  of the equator in the summer hemisphere and the descending branch is between  $15$  and  $30^\circ$  in the winter hemisphere.
- The cell is thermally direct, transporting dry static energy from the summer hemisphere to winter hemisphere. The moisture transport, which is in the same sense as the lower branches of the cell, is in the opposite direction.



## 2.The Seasons in the Tropics

### 2.1 DJF vs JJA circulations (zonally symmetric flow)

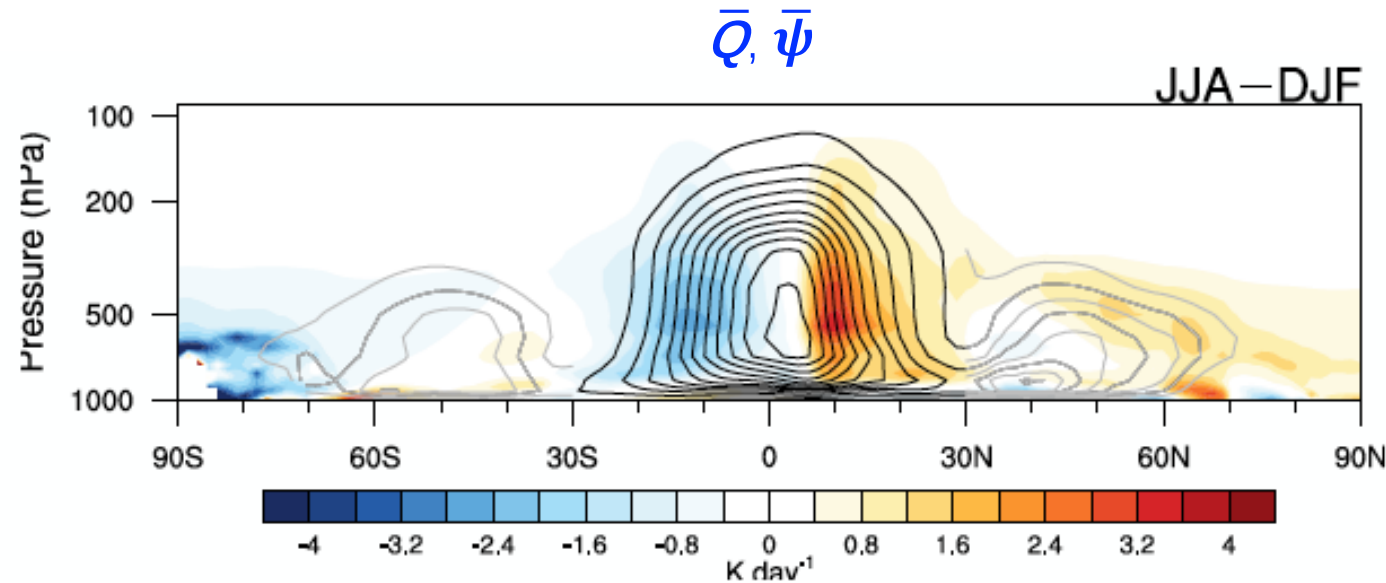
- To interpret the cross-equatorial transport of westerly momentum by this cell requires consideration of the **angular momentum balance**. The Coriolis torque acting on the low-level flow from the winter hemisphere feeding into the belt of heaviest rain rates in the tropics of the summer hemisphere is **balanced by frictional drag**, but the balance in the return flow in the upper troposphere requires consideration of the **eddy transports**.
- The cross-equatorial mass flux (from SH to NH) in the upper troposphere and the momentum transports should not be viewed as separate entities with the transports “driving” the mean meridional circulation: they are both manifestations of the same (zonally and time-varying) circulation.

## 2.The Seasons in the Tropics

### 2.1 DJF vs JJA circulations (zonally symmetric flow)

JJA–DJF cell:

- The  $Q$  and  $\omega$  at ITCZs and in the rain belts of boreal summer monsoons are enhanced in JJA relative to DJF and vice versa for the SPCZ and the rain belts of the austral summer monsoons.



# 2.The Seasons in the Tropics

## 2.2 SON vs NAM circulations

- A “marine monsoon” resembling a north-south seesaw with the same nodal line at  $\sim 7^\circ\text{N}$ , with greater emphasis on the Pacific and Atlantic ITCZs, dominates the NAM to SON difference patterns.
- During SON the northward flow associated with the observed Northern Hemisphere “oceanic monsoon” is a prominent feature of the circulation.
- The ITCZ/cold tongue complexes come closest to being equatorially symmetric in the boreal spring NAM. The Pacific ITCZ is located just a few degrees of latitude north of the equator and there is often a much weaker secondary ITCZ at comparable latitudes of the SH.

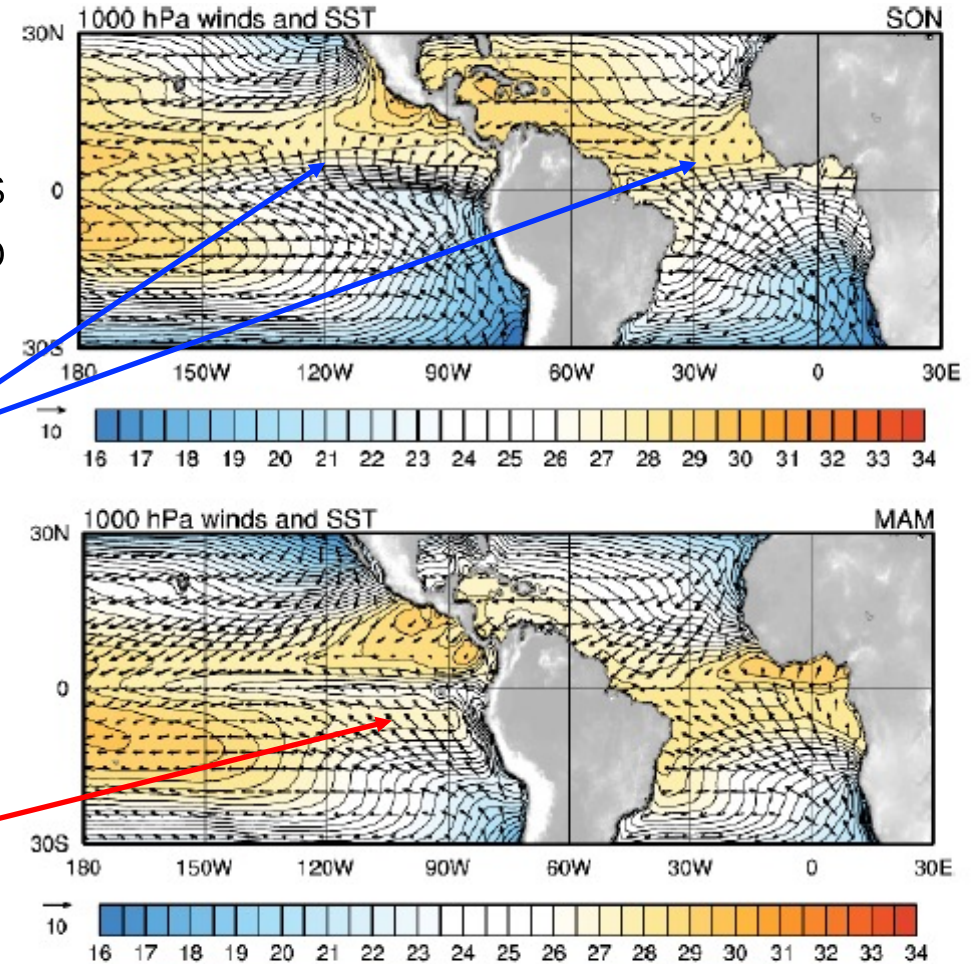


Figure 13.22:  $V_{1000}$ , in  $\text{m s}^{-1}$ , scale at bottom, superimposed upon sea surface temperature: (top) SON; (bottom) MAM.

# 2. The Seasons in the Tropics

## 2.2 SON vs NAM circulations

- Consistent with the northward shift in the belts of heavy rain rates, the boundary between the NH and SH Hadley cells shifts northward from NAM to SON. The diff pattern is dominated by a circulation cell centered on the latitude of the ITCZ, with ascent to the north and descent to the south. The diff cell is much narrower than its JJA–DJF counterpart.

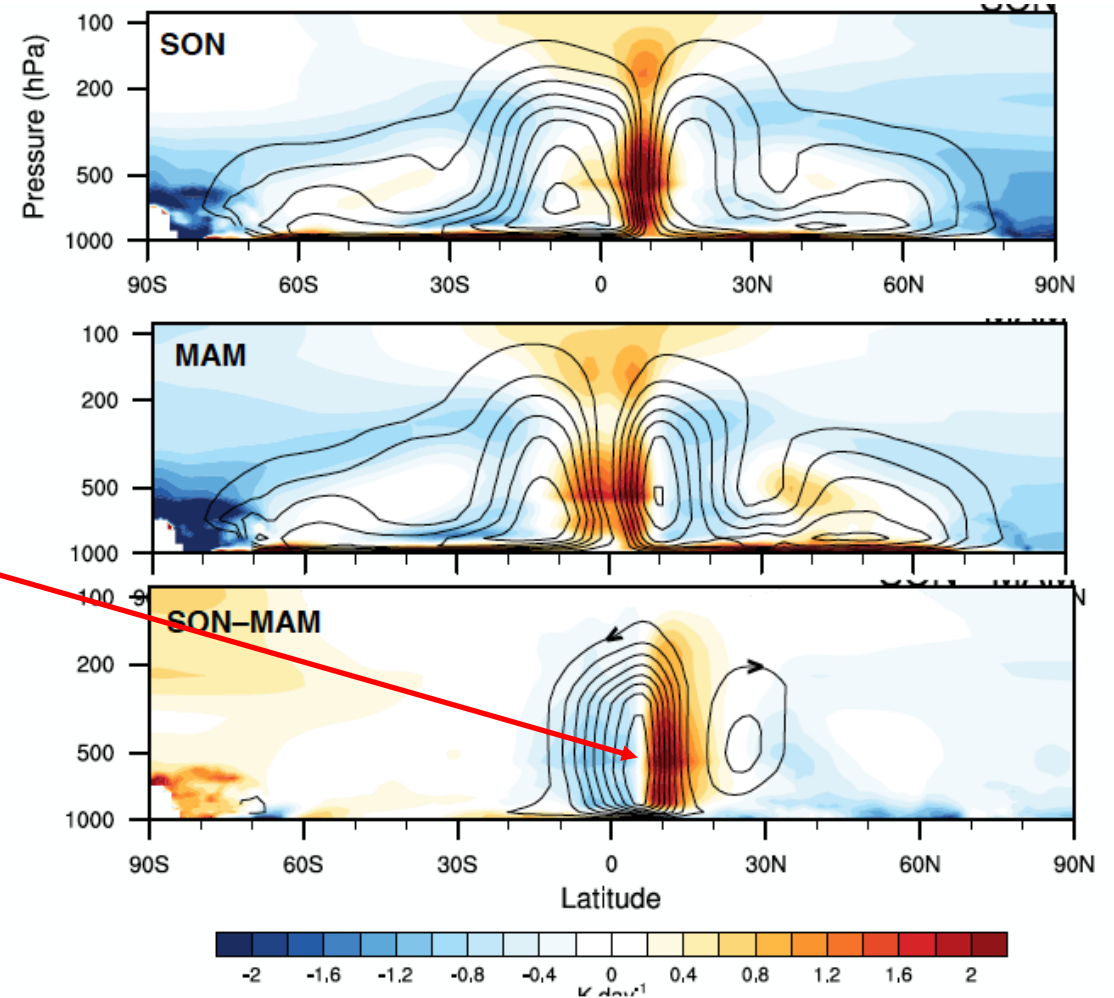
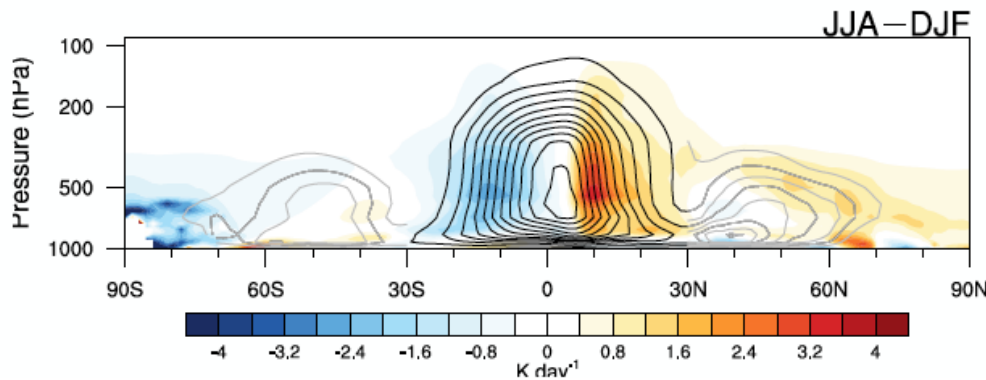


Figure 13.24: TEM mean meridional motions, contour interval ?? superimposed upon diabatic heating, colored shading: (top panel) MAM; (middle panel) SON and (bottom panel) SON minus MAM.

## 2.The Seasons in the Tropics

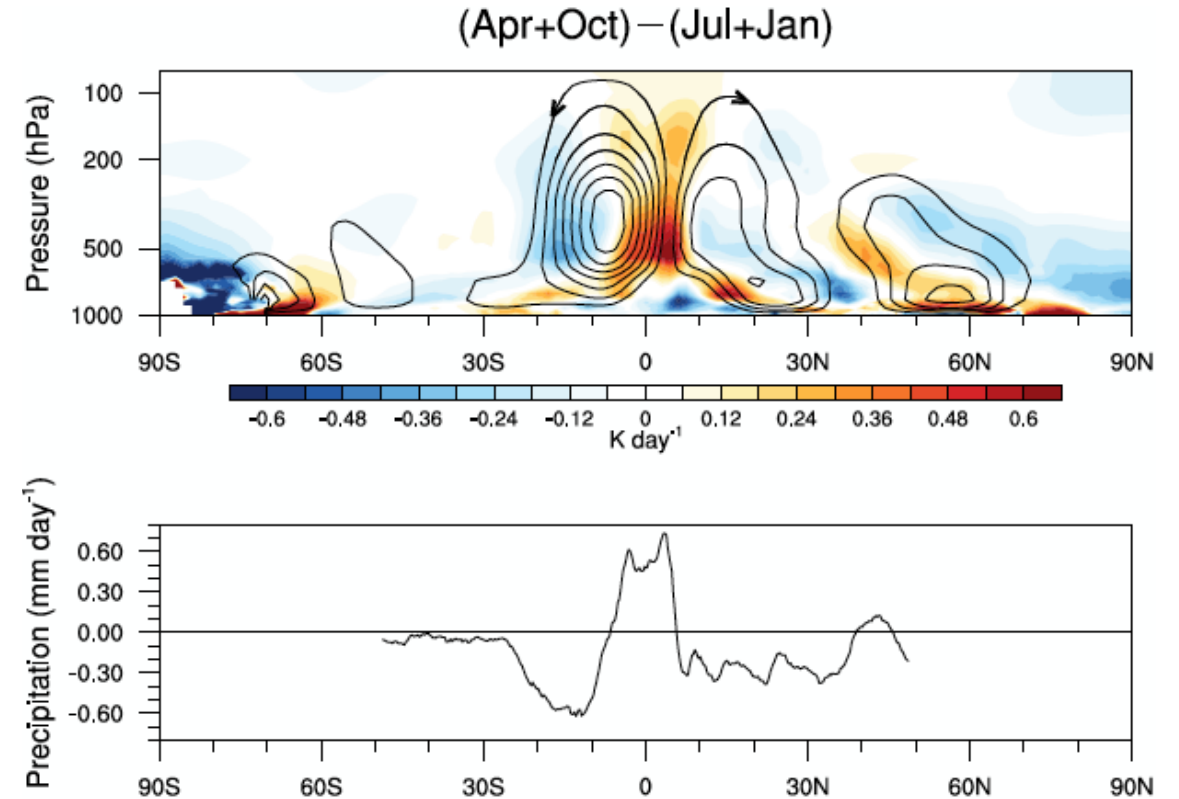
### 2.3 Why is the ITCZ in the Northern Hemisphere?

- The discovery that the trade winds converge, not at the equator but on average at  $\sim 7^\circ\text{N}$  was a major paradigm shift. The **double ITCZ** in the eastern Pacific during FMAM was first noticed in the observations and emerged in many simulations with coupled models.
- The models have tended to exaggerate the strength of the equatorial Pacific cold tongue and the secondary ITCZ in the SH, such that the overall configuration is more equatorially symmetric than observed. These **biases** vary substantially from model to model. There has been very little progress in reducing these biases.
- The observed bias of the ITCZ toward the NH can only be due to **two factors**:
  - Africa and the Americas extend farther westward in the NH than in the SH, forcing monsoon circulations in JJA that have no counterparts in DJF. Once established, these circulations, with northward low-level flow across the equator, tend to persist into SON because of positive wind-evaporation and cloud feedbacks.
  - The Andes protrude into the strong westerly flow beneath the jet stream at subtropical latitudes, deflecting some of it equatorward and downward into the subtropical subsidence zone (SSZ) on their upwind side along the coast of Chile. The direct dynamical response to this orographic enhancement of the SSZ, augmented by wind-evaporation and cloud feedbacks, renders the entire Southeast Trades stronger than the Northern Trades year-round (Takahashi and Battisti 2007).

## 2.The Seasons in the Tropics

### 2.4 The equatorial semiannual cycle

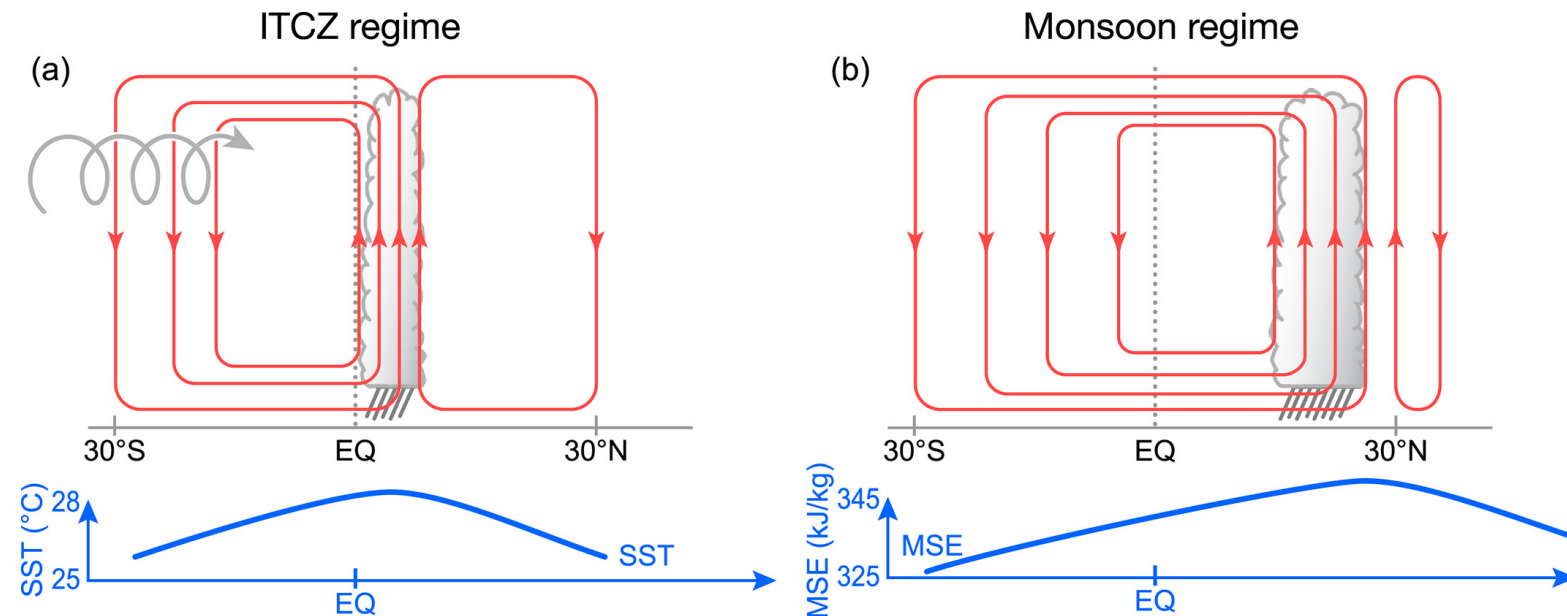
- Over the equator, insolation is  $\sim 8\%$  stronger at the times of the equinoxes than at the times of the solstices. In response to this forcing, rain rate in the equatorial belt exhibits a weak semiannual cycle with maxima about a month after the equinoxes.
- Rain rate is indeed heavier (bottom) and the semiannual cycle is also evident in diabatic heating rate and the MMC (top).



## 2. The Seasons in the Tropics

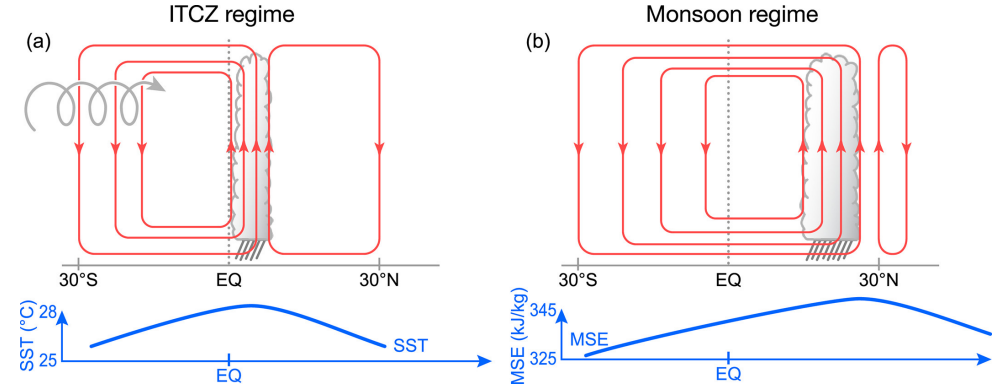
### 2.5 Abrupt seasonal transitions

- The ITCZs, in which precipitation is concentrated, undergo a **gentle latitudinal migration** in response to the seasonal cycle in meridional gradient in insolation.
- In the Indian Ocean and over South Africa and Central America, summer monsoon-related precipitation exhibits a **rather abrupt onset around the time of the summer solstice** and it extends poleward as far as  $\sim 20^\circ\text{N/S}$ .



## 2.The Seasons in the Tropics

### 2.5 Abrupt seasonal transitions



- The strength of the **ITCZ** precipitation and meridional overturning circulation is primarily governed by the amplitude of the **eddy transport of westerly momentum** out of the deep tropics associated with midlatitude baroclinic eddies. The strength of the precipitation and meridional circulation in these **monsoon** systems is largely determined by the amplitude of the near-surface **MSE maximum**.
- The dynamics that govern the ITCZ and the monsoons have been illuminated using atmospheric general circulation models coupled to a **slab ocean 平板海洋**, the so-called **aquaplanet 水球模式**, forced by the observed seasonal cycle in insolation.
- The timing of the **intraseasonal oscillation**'s impacts on the abrupt “regime shift” of Indian summer monsoon and the onset of “North American monsoon”.
- East Asian summer monsoon seasonality is a result of the **orographically induced wave response** to the tropospheric jet stream's shifting to the north of the Tibetan Plateau (Chiang et al. 2020).