Re-evaluate Hadley Circulation

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Abstract

Hadley cell is well accepted in meteorology to explain the primary meridional circulation at equatorial and subtropical regions. Look at the circulation closer, it can be seen that there are still few issues such as how energy is transported to high latitude, how a narrow ITCZ can provide enough energy for the whole atmosphere circulation.

We will apply the state equation and dynamic equation together to form a new dynamic equation, and from this new equation, a new method is used to separate weather/climate systems. Based on what kind of systems ITCZ and subtropical are, we can understand the meridional circulation better, and therefor proposed a new concept of the meridional circulation.

Introduction

Figure 1 is an image which illustrates the meridional circulation, where Hadley cells are the two at each side of the equator, and it is also stated that "Hadley Cells are the low-latitude overturning circulations that have air rising at the equator and air sinking at roughly 30° latitude. They are responsible for the trade winds in the Tropics and control low-latitude weather patterns. ...". Look at the Hadley cells in Figure 1 closer, there are something puzzled us to fully understand this picture:

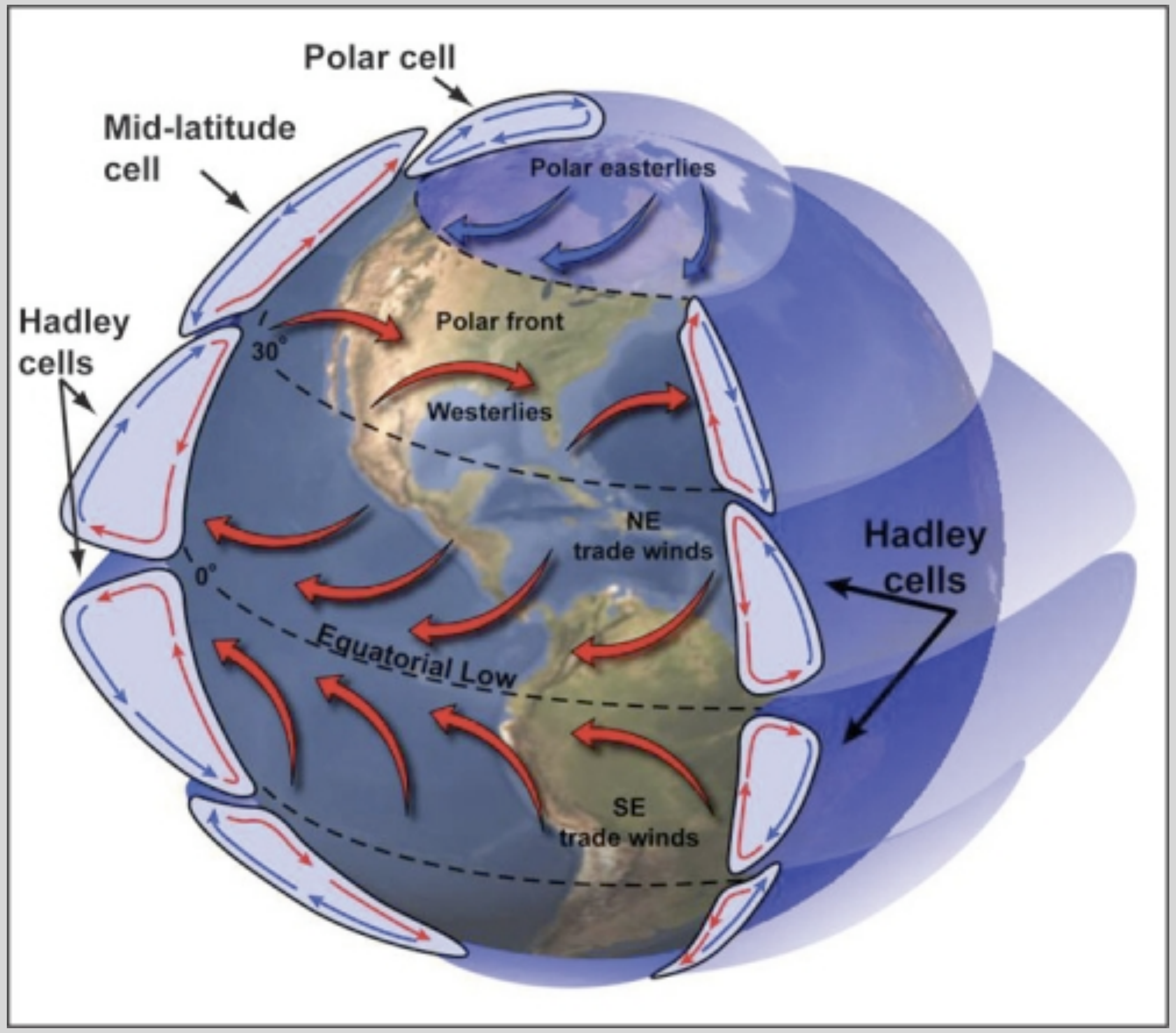

Figure 1. Hadley Cells in the meridional circulation
downloaded from: http://www.seas.harvard.edu/climate/eli/research/equable/hadley.html

- The Energy is originated at equatorial surface, then carry upward to upper level, and transported poleward, descending at subtropical high, and flow equatorward at surface. So it has to be carried a very long way.
- The energy is generated/collected from a very narrow region, but has to be provided to a much broad area. As 30S-30N is half the area of the sphere, and the Inter-Tropical Convergence Zone (ITCZ) is much less than half of the region of 30S to 30N. Which means that the energy generated/collected in less than a quarter of the sphere has to provide energy to more than 3 quarters of the sphere.
- The ITCZ is (frequently, if not always) cloud covered, so there is less solar radiation could reach the ground to generate enough moisture, considering the precipitation, the rain-water is much colder than the Sea Surface Temperature (SST), which cools down the sea surface when there is rain.

Therefor, we feel there is a need to re-evaluate this circulation from a different angle.

First, let us re-check what is really happening in the equator and sub-tropical region. Figure 2 at left shows the Satellite image at 12Z on January 12, 2016 overlaid with wind barb and temperature field over Pacific Ocean. ITCZ is clear and near equator, but we can see that it is quite narrower compare with the clear sky region.

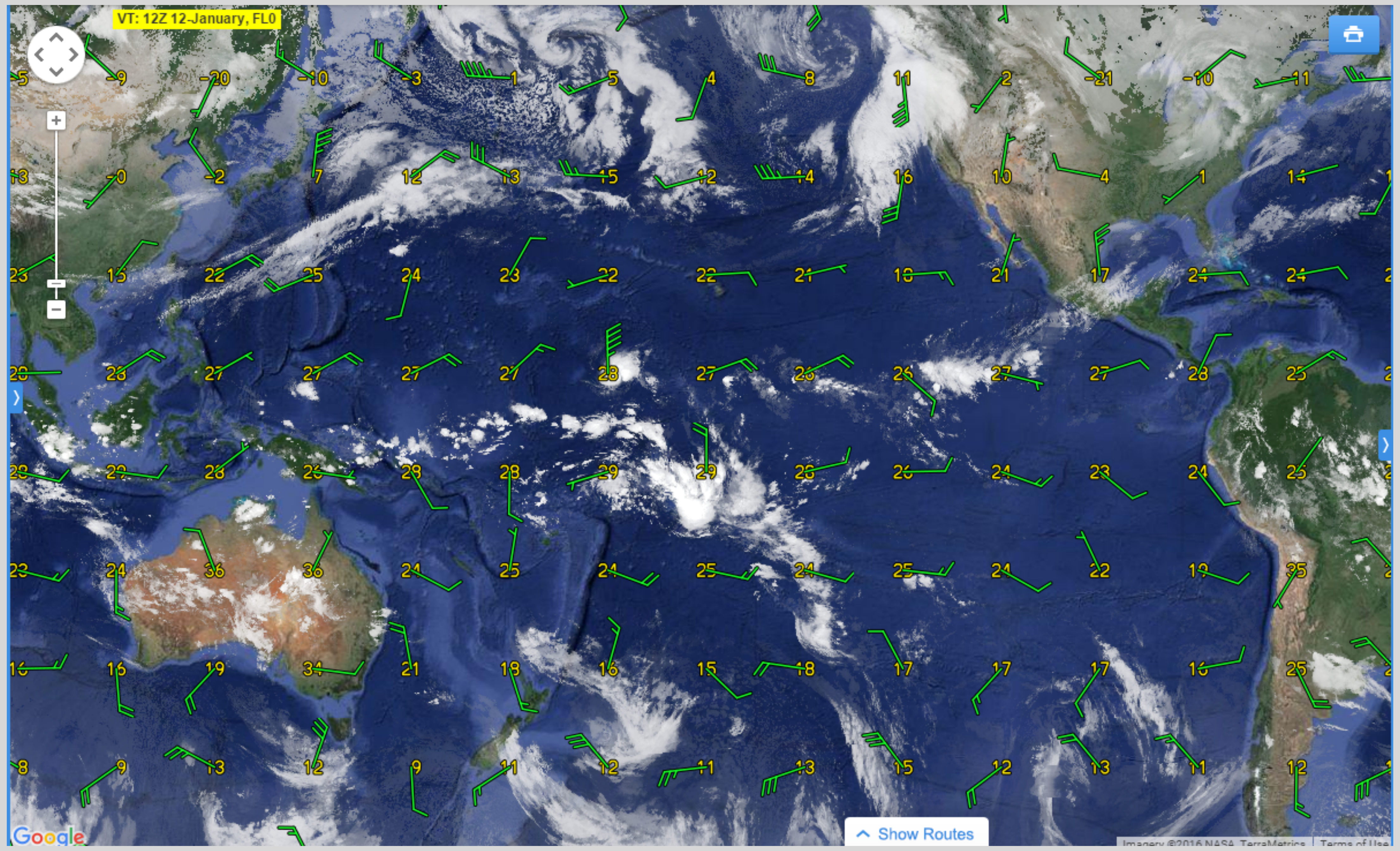

Figure 2 Satellite image at Pacific overlaid with surface wind and temperature
Copied from Universal Weather and Aviation web-site

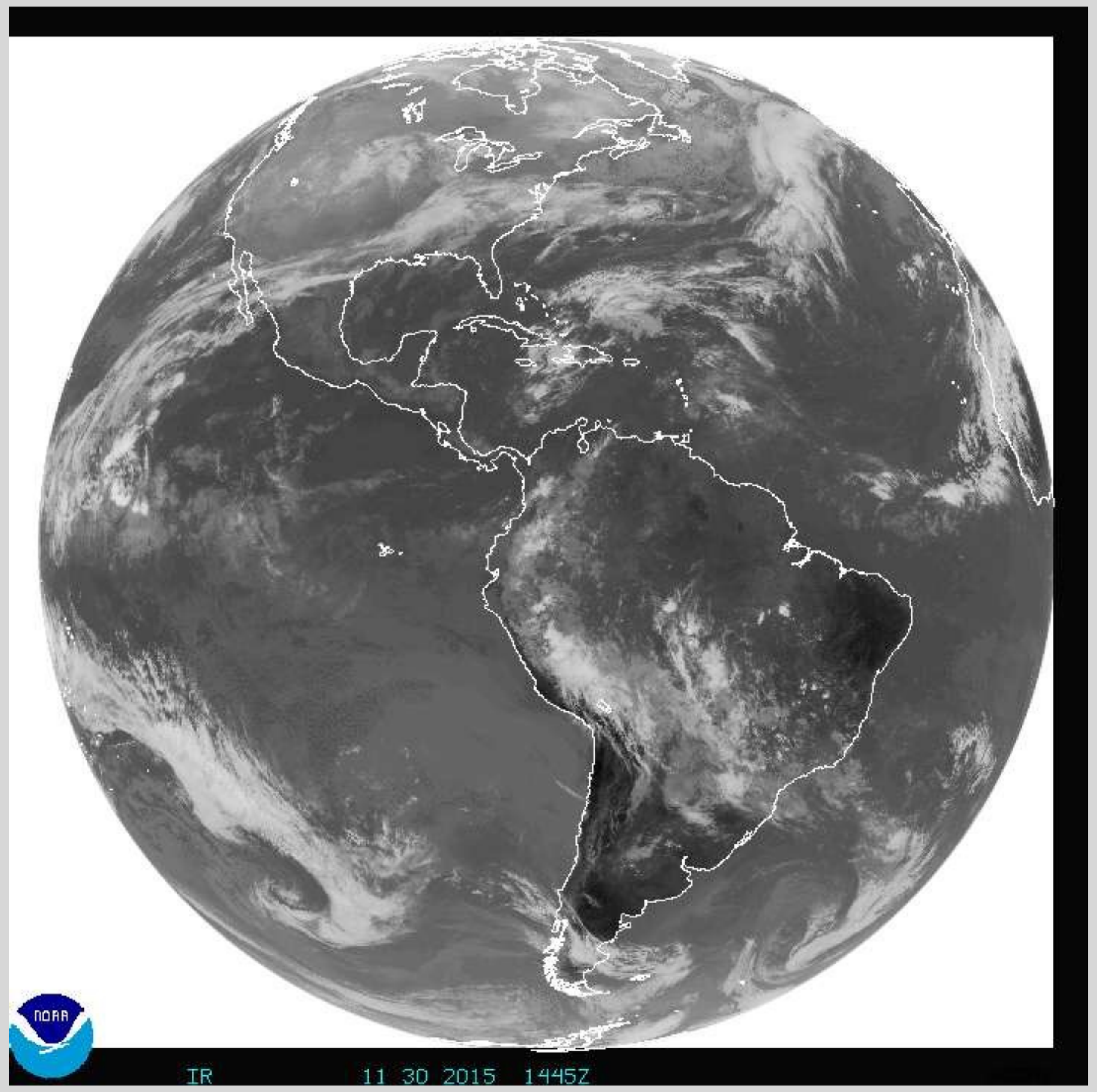

Figure 3 GOES East satellite image

Figure 3 below is a GOES East satellite image, which shows very little cloud at east pacific equatorial region, and there is cloud in the equatorial area over Atlantic, but majority of lower latitude is clear. There may have times that more cloud in the equatorial region, but certainly not always.

Definition of Weather Systems

Based on the dynamic equation:

$$\frac{d\vec{V}}{dt} + 2\Omega\times\vec{V} = -\frac{1}{\rho}\nabla P \qquad (1)$$

Apply the state equation:

$$P = \rho R T \qquad (2)$$

to the right side of dynamic equation, and we can get a new form of dynamic equations:

$$\frac{d\vec{V}}{dt} + 2\Omega\times\vec{V} = -R\nabla T - RT\nabla \ln \rho \qquad (3)$$

The right hand side of the equation 3 has two terms now, where the first term is related to temperature field, and the second one is more related to density field. Based on which term is the primary term, we can define the weather system into to types:

1. **Thermal System:** Where the temperature field is the primary factor, and the atmosphere motion is more dominated by thermal effects. Such weather systems are warm highs, or cold lows. Ignore the second term of right-hand side of Eq. 3, we have gravity wave.
2. **Dynamic System:** Which the density field in the dominate factor, and air motion is mainly controlled by the density fields. Such weather systems are warm lows, and cold highs. Ignore first term of Eq. 3 right-hand side, we get acoustic wave.

Based on the definition above, we can see that:

1. Sub-tropical high is a thermal system, which means higher temperature in the center, will results stronger of this sub-tropical high.
2. ITCZ is a dynamic system, a higher temperature in the ITCZ zone will not make the ITCZ stronger, but needs a lower density to make ITCZ stronger.

Now we can clearly feel that the definition above is very different to the Hadley cells illustrated in Figure 1. So, let us re-check the temperature and density field at subtropical and tropical region. Let us begin with the sub-tropical high.

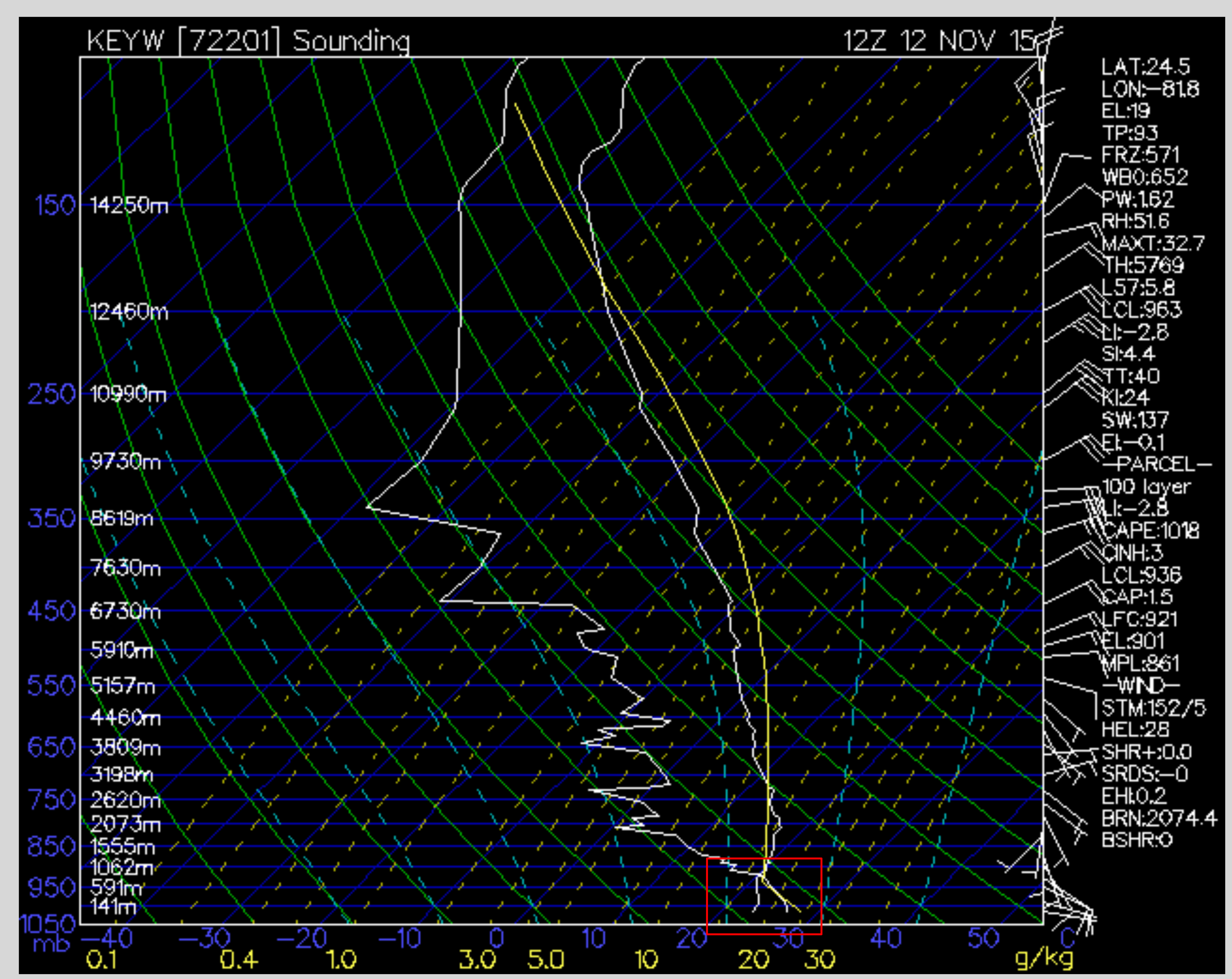

Figure 4 Skew-T on Key West (72201) at 12Z 12 Nov, 2015

Adiabatic Process in Sub-tropical High

In the sub-tropical high, most people believe that the warmer temperature here is (at least partially) by the warming effects from the downward motion of the atmosphere. The reason is that from adiabatic equation:

$$\frac{d\theta}{dt} = 0 \qquad (4)$$

We can further get:

$$\frac{\partial T}{\partial t} = (\gamma - \gamma_d)w \qquad (5)$$

In Eq. 5, we usually have: ($\gamma < \gamma_d$). Where γ is temperature lapse rate which in standard air it is 0.65 degree per hundred meter, and γ_d is dry air temperature lase rate which is 0.98 degree per hundred meter, so in the standard atmosphere, downward motion will have a warm effects. But look at the temperature profile within the red square in Figure 4, we can see that at near surface, the lapse rate is close to dry lapse rate, where the descending motion won't generating any warming.

Temperature and Density Field

In the original Hadley circulation theory, where the warmer SST at equatorial region is the reason that generates ITCZ. Figure 5 shows the annual mean surface wind and SST (where the data are from NCEP reanalysis).

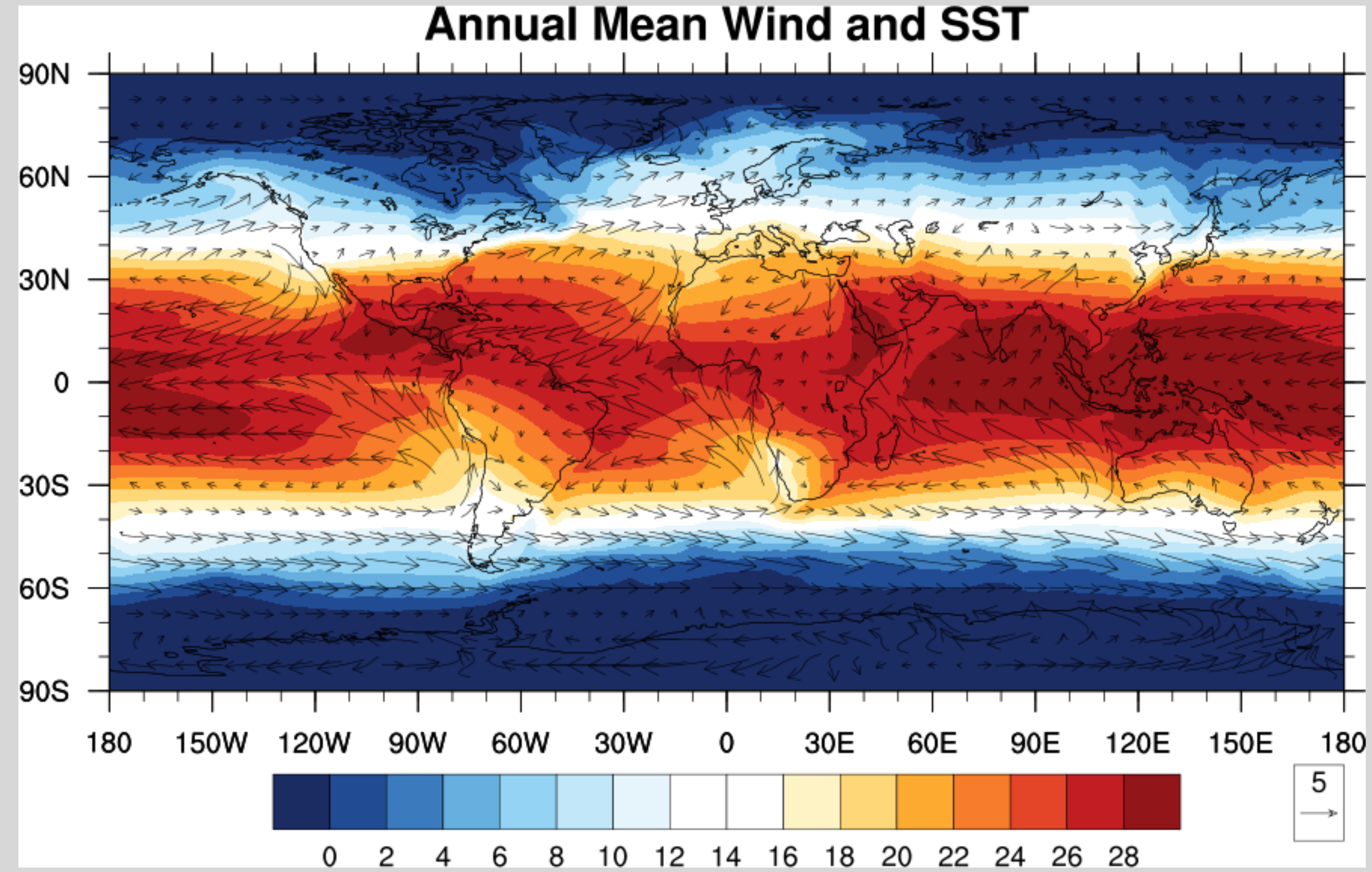

Figure 5 Annual mean surface wind, and SST

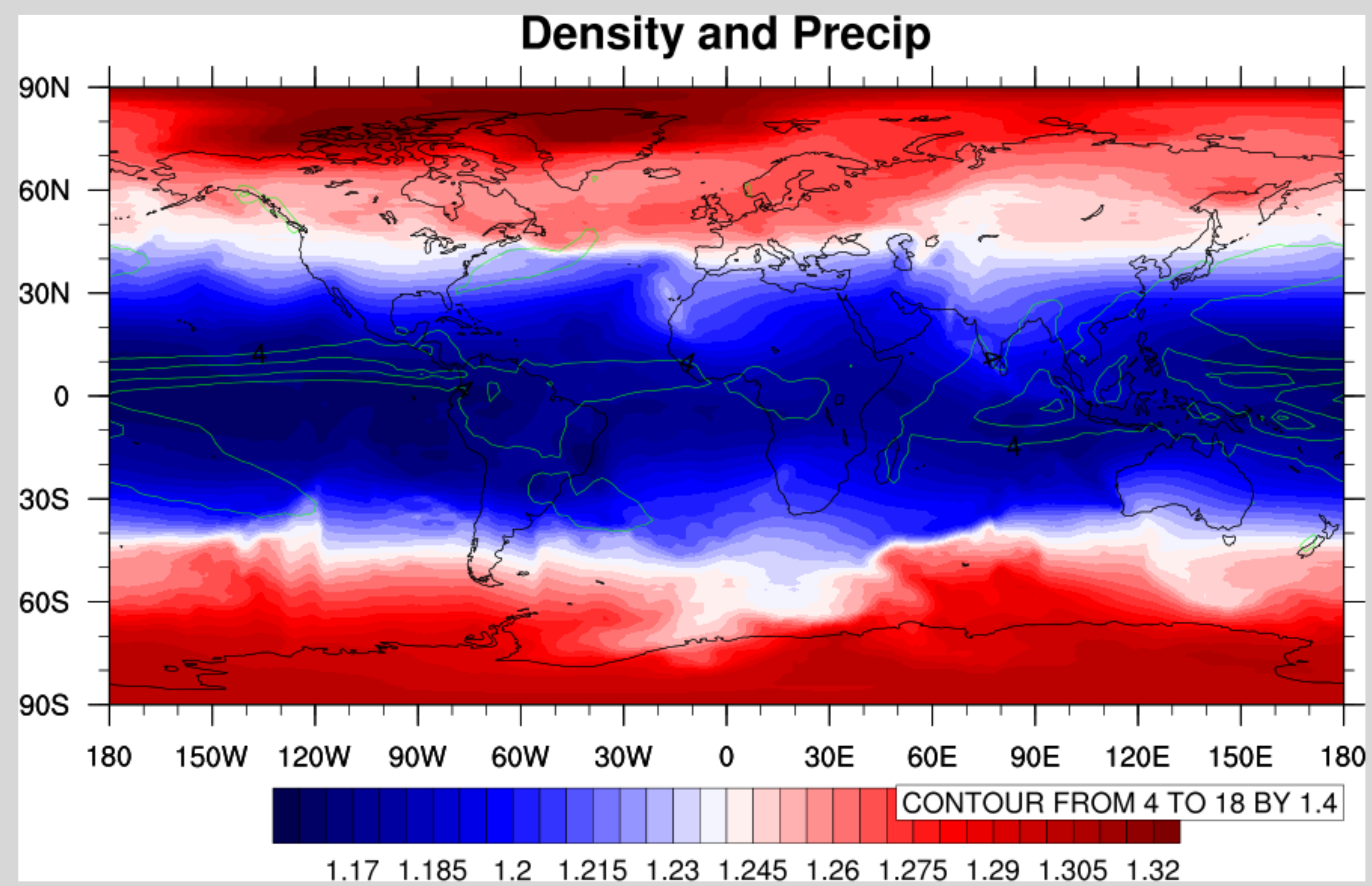

Figure 6 Annual mean surface density, and precipitation

Figure 6 shows the annual mean surface density, and annual precipitation, which shows the high precipitation zone is located where the low density is along equator. This confirms what we have discussed above, where the ITCZ is a dynamic system. Compare Fig. 5 and Fig. 6, we'd believe that ITCZ and precipitation zone are the results of lower density, rather than warmer SST.

New Concept of Meridional Cells at Equator

From the discussion above, we see that the Hadley circulation has lots of limits: a) ITCZ is not directly or sensitive to temperature at equatorial zone, b) but rather highly related to density field, c) descending motion did not warm the air near surface at sub-tropical high. To overcome there limits, we propose a new meridional cells at Equator as in Figure 7.

In the new cells, the solar heats the equatorial area, which cause divergence at lower near surface region, and flow to higher latitude. The air converge at high latitude and arise there. The divergent flow at equatorial surface also causes a descending motion in above. In the up level, air flow towards equator, as a result of higher latitude ascending motions, also served as the results of downward motion at the equator.

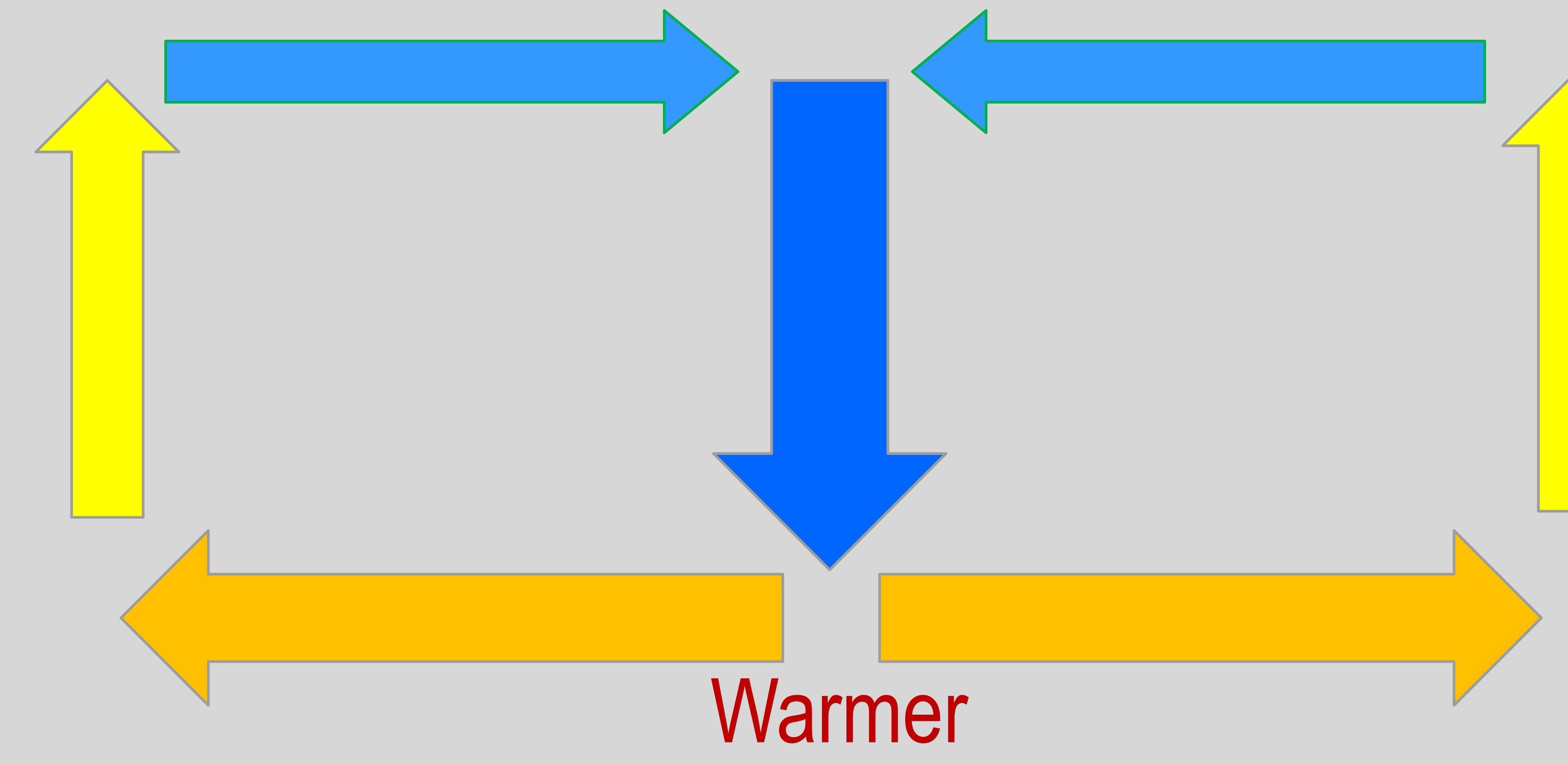

Figure 7 New Meridional Cells at the Equator

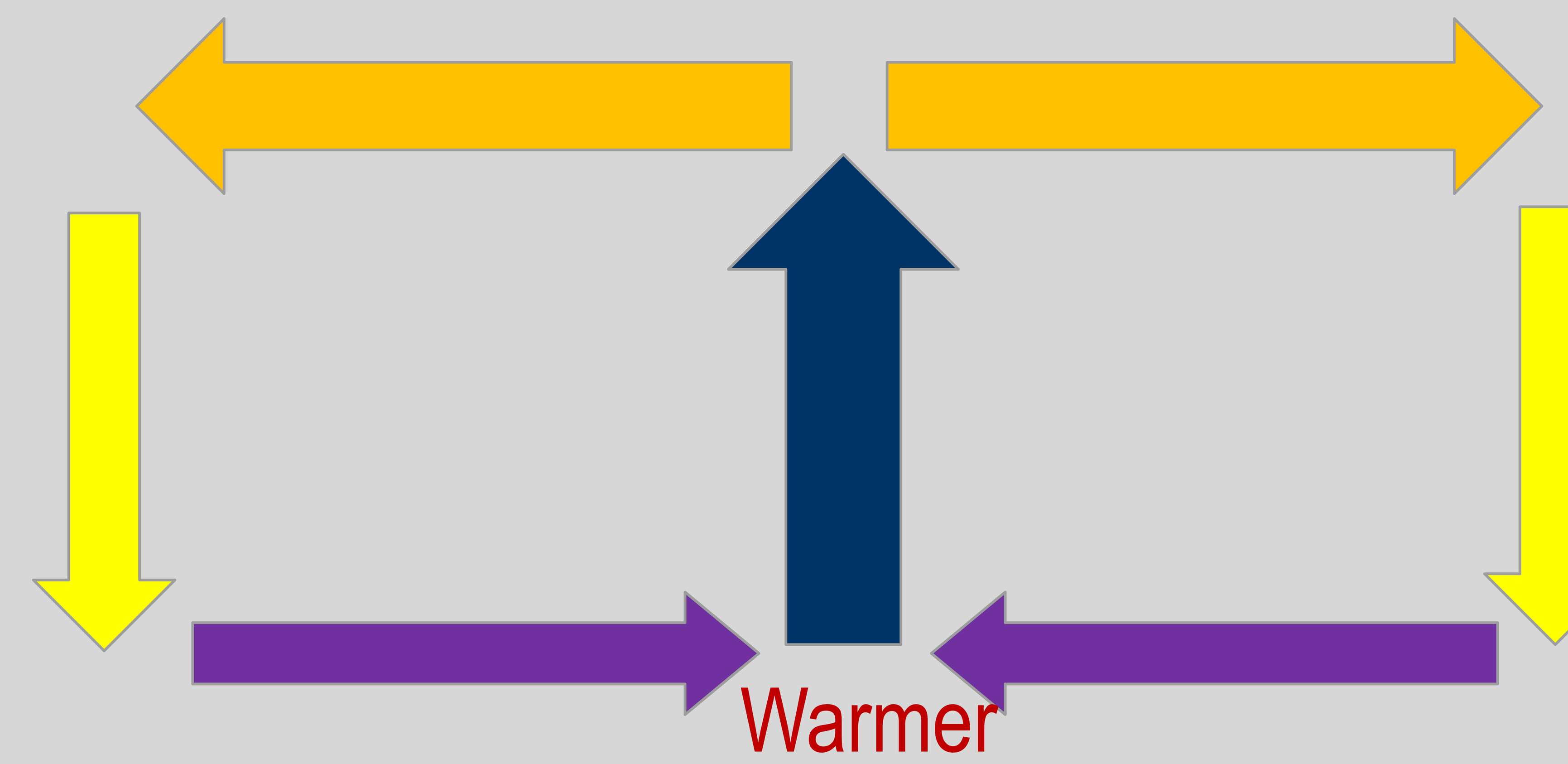

Figure 8 Original Meridional Cells at the Equator

The original widely accepted single cell Hadley circulation can be illustrated in Figure 8. Below are the comparison of these two single meridional cells.

New Meridional Cell

- Shortest path to pole
- Clear Sky Equator
- Cloudy/Rainy Pole
- More solar energy transported to pole
- A more efficient engine

Old Meridional Cell

- Longest path to pole
- Cloudy/Rainy Equator
- Clear sky Pole
- Less solar energy transported to pole
- A less efficient engine

The new meridional theory says that surface subtropical divergent flow are related to solar heating, but Fig. 5 clearly shows that where the high SST zone is along the equator, where the equatorial zone is the ITCZ. How the high/warm temperature field can be connected to the subtropical divergent flow?

First, let us check the solar radiation. Figure 9 shows the average rate of solar radiation reached the top of the atmosphere. At solstices, the maximum daily averaged maximum is at 35 degree. In the south hemisphere solstice, the maximum heating zone is 35S, which is the latitude of sub-tropical high's center of southern hemisphere summer. In the north hemisphere solstice, the heating zone is also the sub-tropical high center of northern hemisphere summer, located at 35N.

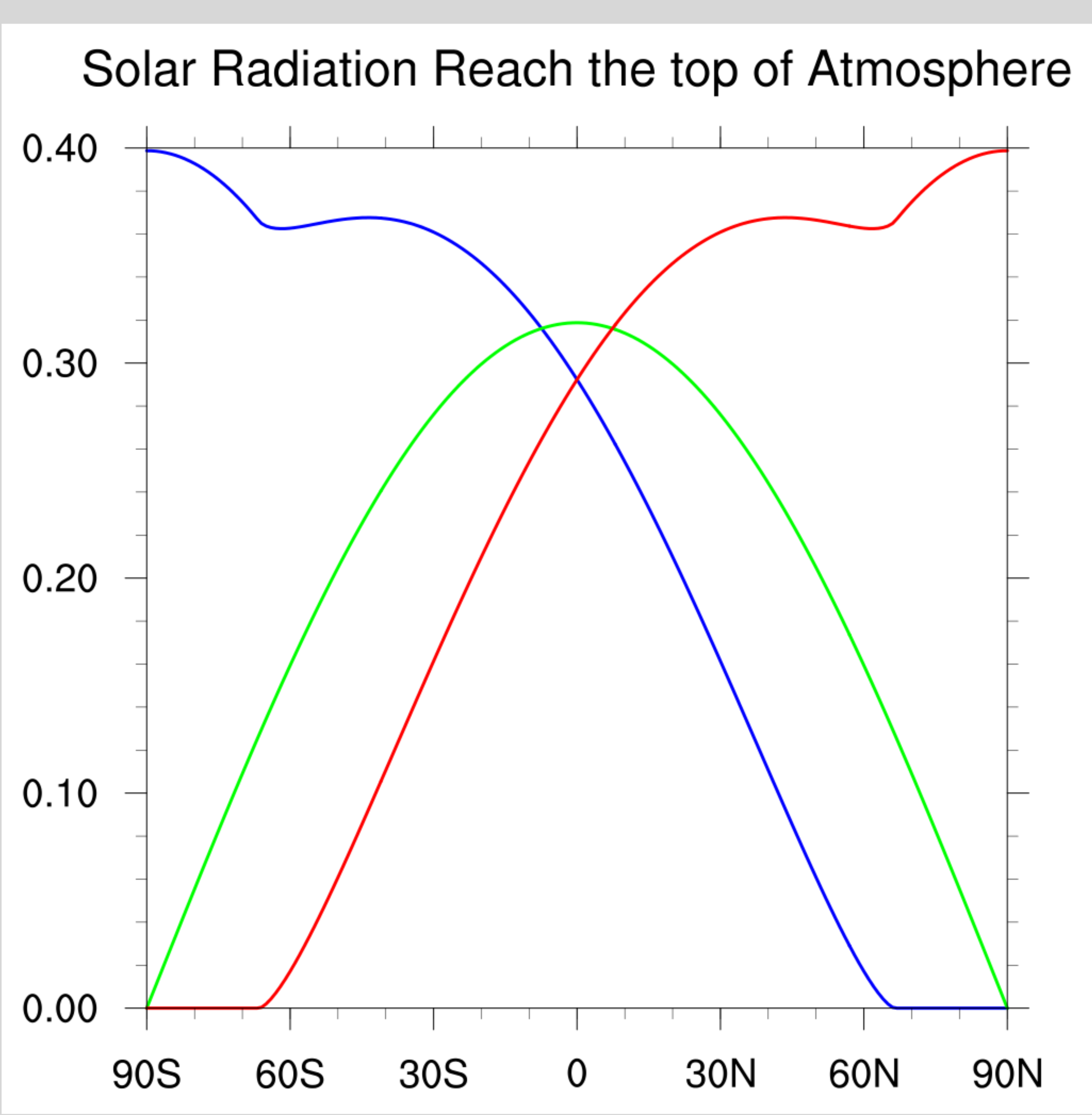

Figure 9 Day-averaged Solar Radiation Reached the Top of Atmosphere (%)

Blue: Southern Solstice;
Green: Equinox;
Red: Northern Solstice

Now, check the picture of SST and wind field at summer. If we plot the SST directly, obviously there will be high SST along equator, which is certainly not the central position of subtropical high at this season. In order to see the seasonal character more clearly, we can draw the difference of the monthly averaged SST to annual mean SST, and the monthly mean surface wind field. This difference will show the seasonal heating as we have taken out the annual changes. We want to use the whole wind field as wind field changes are more closer to the seasonal variation of temperature field.

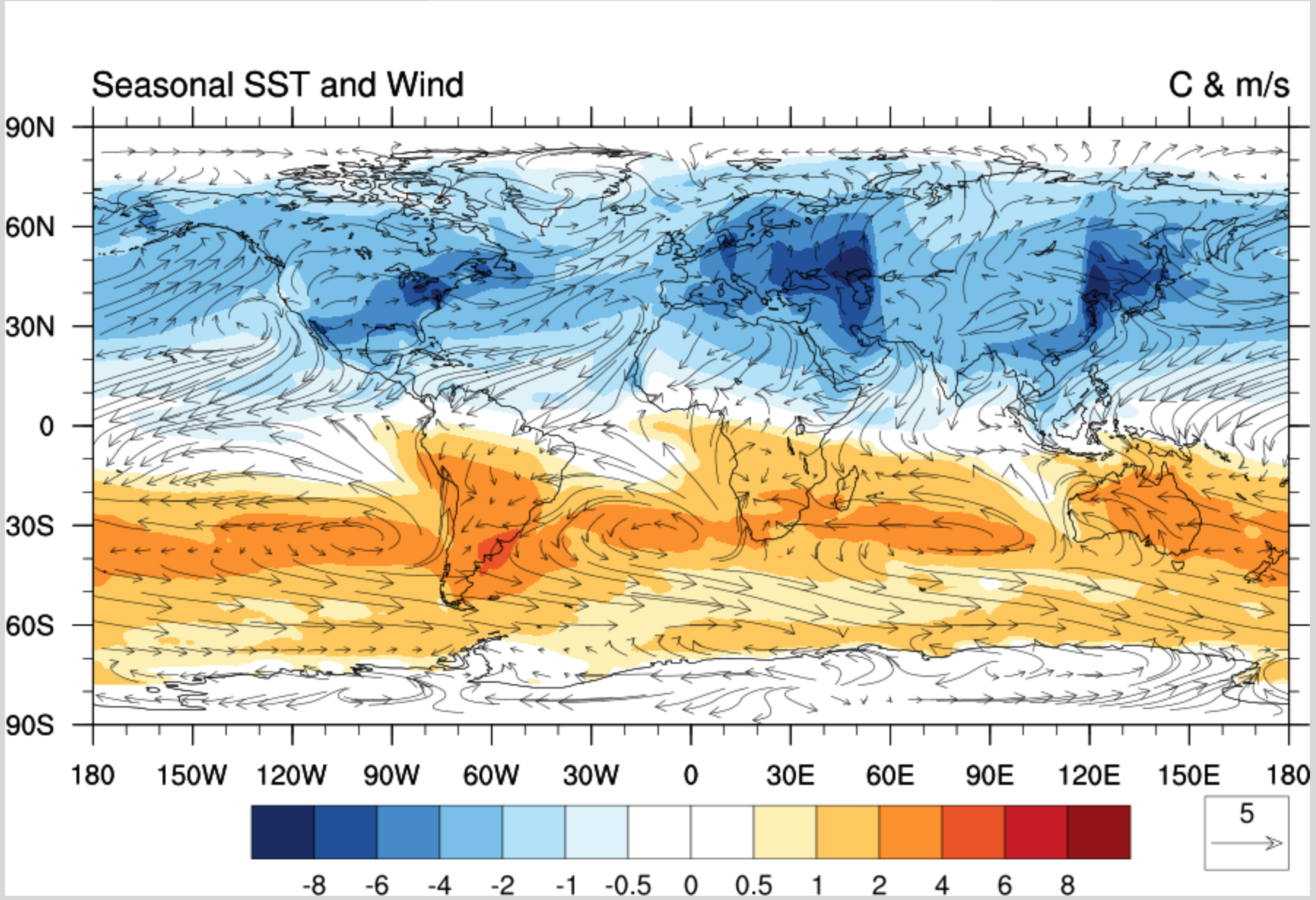

Figure 10 a) Averaged February SST and surface wind

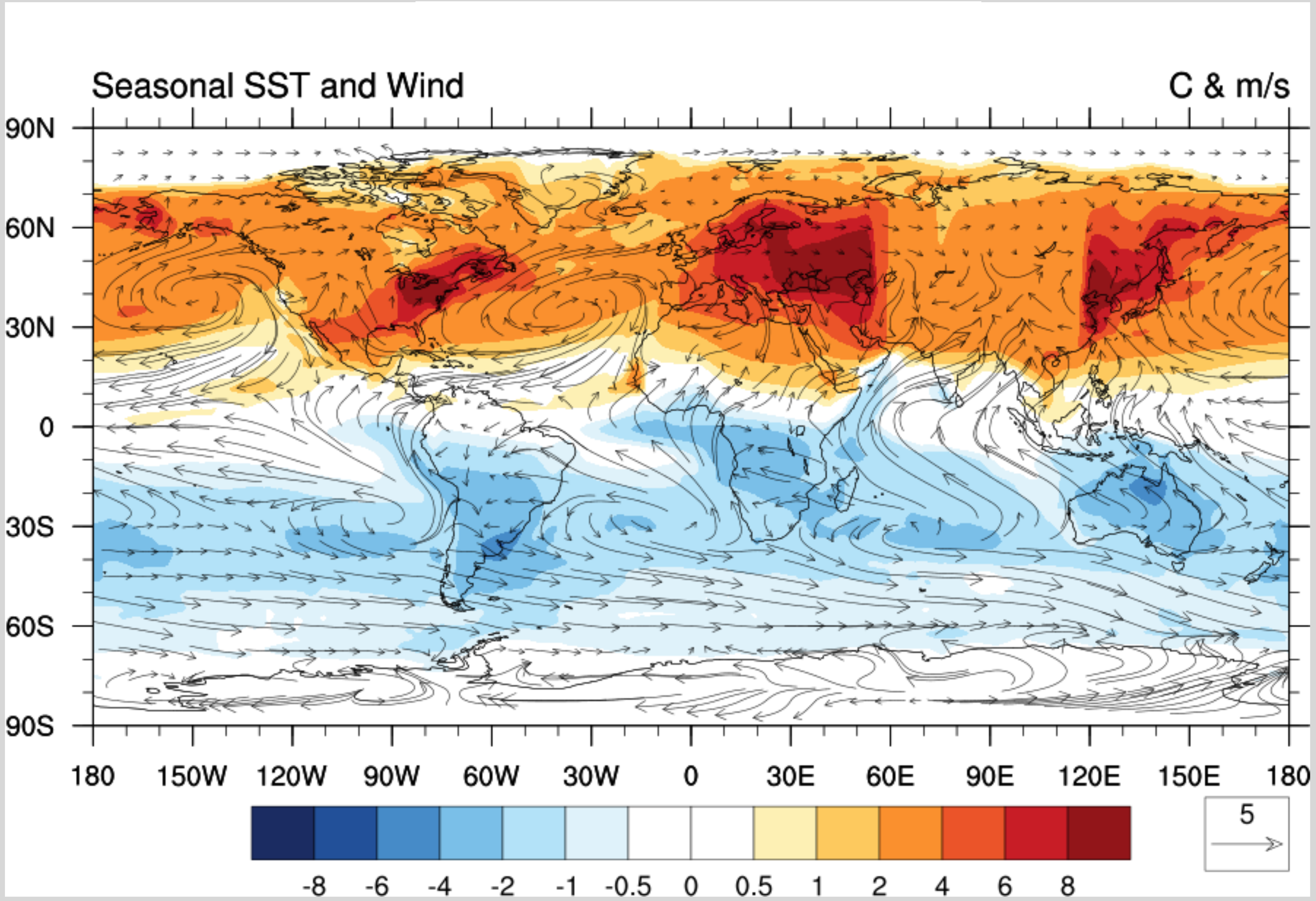

Figure 10 b) Averaged August SST and surface wind

Figure 10 a) shows difference of February SST to annual mean and February wind vectors. There is a high SST zone along 35 degree at southern hemisphere (as this is its summer), and divergent wind flow is centered right along with the high SST zone. This zone is also consistent with what we see from Fig. 9, where the maximum solar radiation at southern hemisphere solstice is right at 35 degree south. There are cold centers at northern hemisphere (which we are not interested for now), and ITCZ is between equator and south 10 degree (which we will discuss in Poster 44).

Figure 10 b) which shows the difference of August SST to annual mean SST, and annual mean surface wind of August. Over the oceans, the divergent flow is centered along 35 degrees north, where the SST is also a positive (local) maximum. But over land, the warm center is further north. Also check with Figure 9, we see that the solar radiation's maximum is at 35 degree north at northern hemisphere summer. There are divergent center and cold centers in south hemisphere, which are beyond the discussion of this Poster.

Since Figure 10 show the difference of monthly SST to annual SST, so we can think these SST difference as seasonal changes, which we can conclude that the divergent surface flow is created from the seasonal solar heating (as we believe the warmer centers are formed as the results of solar radiation). Here we can get the conclusion that the sub-tropical high is the energy source, instead of energy sink from traditional Hadley theory. Figure 11 is from Trenberth and Stepaniak (2003), which clearly described the roles of subtropical high, it serves well as the source of moisture and other types of heat. But unfortunately, they thought the surface energy is provided by ocean heat transport, instead of directly from solar radiation. But their work proved that the subtropical is an energy source of the atmosphere circulation.

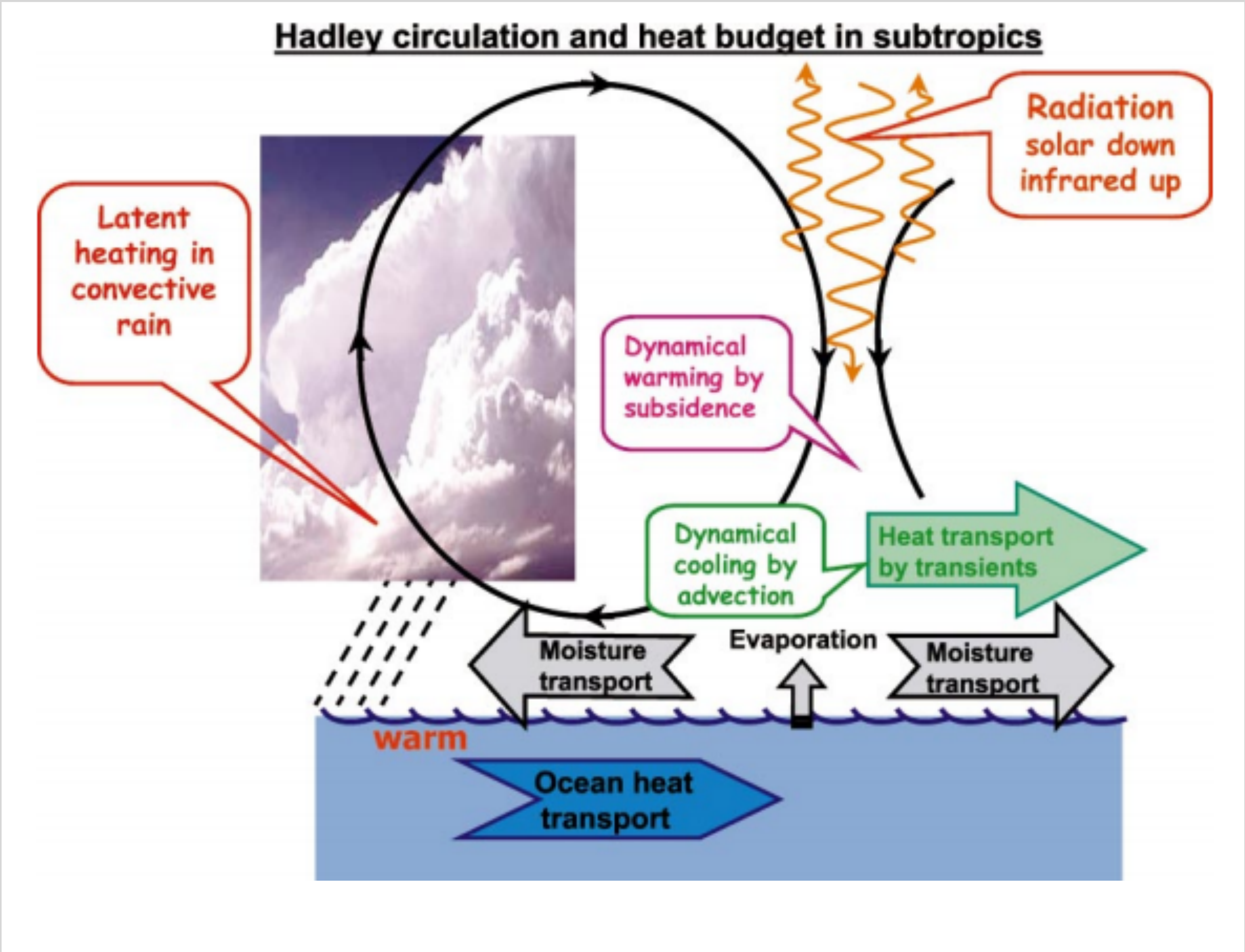

Figure 11 Atmospheric energy transports from the Hadley Circulation from Trenberth, and Stepaniak (2003)

Our theory above described the situation in summer hemisphere, where the solar radiation maximum is at 35 degree, which is where the subtropical high located. But in Spring and Fall, the maximum heat region is at equator, as shown in Figure 5 and Figure 6, which is the region where ITCZ is located, and certainly it is a low pressure region. We will explain how ITCZ and trade wind is formed at Equinox (Spring and Fall) in Poster 44.

Conclusion

By re-examine the dynamic equation, we have developed new way to define weather systems into two types: Thermal systems, and dynamic systems. By study the characteristics of ITCZ and sub-tropical high, we figured that ITCZ belongs to dynamic systems, therefor it is not a direct response to temperature field, but sub-tropical high is, as it is a thermal system, here we proposed a new circulation model as shown in Fig. 7.

The new cells can not explain how ITCZ and trade wind is generated during equinox. To see how ITCZ and trade wind are created, please check out my poster at 44.

Reference

Trenberth, K. E., and D. P. Stepaniak: Seamless poleward atmospheric energy transports and implications for the Hadley circulation. (2003) J. Climate, 16, 3706-3722

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