Re-think ITCZ and Trade Wind

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Abstract

Trade wind is considered as the surface flow of the Hadley cells. Intertropical convergence zone (ITCZ) is the result of trade wind converging at equator. But as we have pointed out that the meridional circulation is different (see Poster 51) now, we have to figure out how the trade wind is generated.

The new meridional circulation is built on the base where the temperature is from averaged solar radiation, but never count the earth's rotation, therefor the diurnal cycle is left behind the scene. Here we will examine the effects of diurnal cycle and figure out how trade wind is generated, and therefor how ITCZ is formed.

Introduction

Figure 1 at right illustrates the Trade Wind, which we see north-easterly at north hemisphere, and south-easterly at south hemisphere in the low latitude. From Figure 6 in Poster 51, we see that there is a maximum heating at equator, and it seems we should have a circulation like Figure 5 (in poster 51). Figure 5 only has considered the general temperature field, but has ignored an important feather of the earth, the self-rotation. Now let us check the impacts of diurnal cycle.

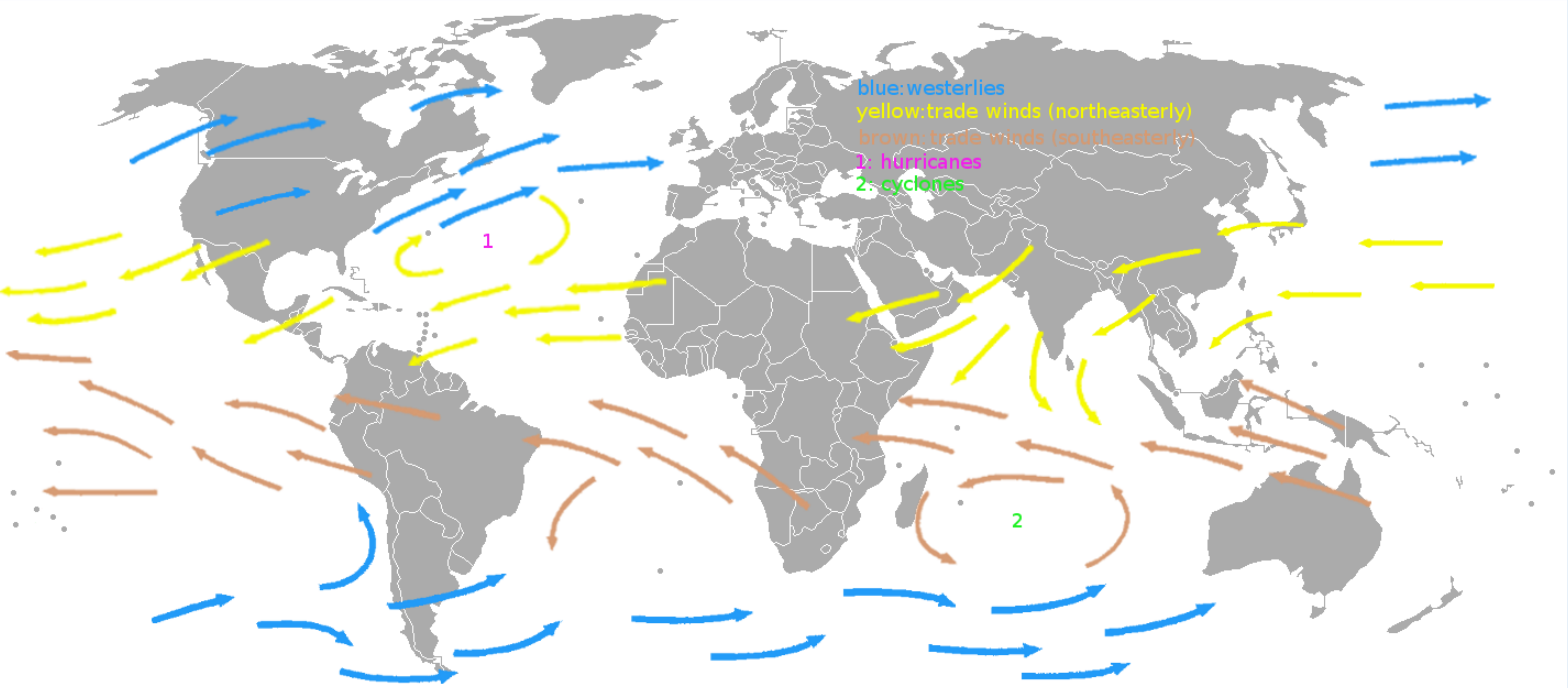

Figure 1 Illustrate of Trade Wind
Image downloaded from: https://en.wikipedia.org/wiki/Trade_winds

Similar to Figure 10 of Poster 52, we can check the difference of SST at Equinox to the annual mean SST, and the wind field, which is shown in Figure 2, where the Equinox mean was the average of May and November. We do see a weak warm zone along equator, but difference to Figure 10, here the wind is a convergent flow, which means the weather system here is not a thermal system, but dynamic system. Therefore, we should see a lower density zone.

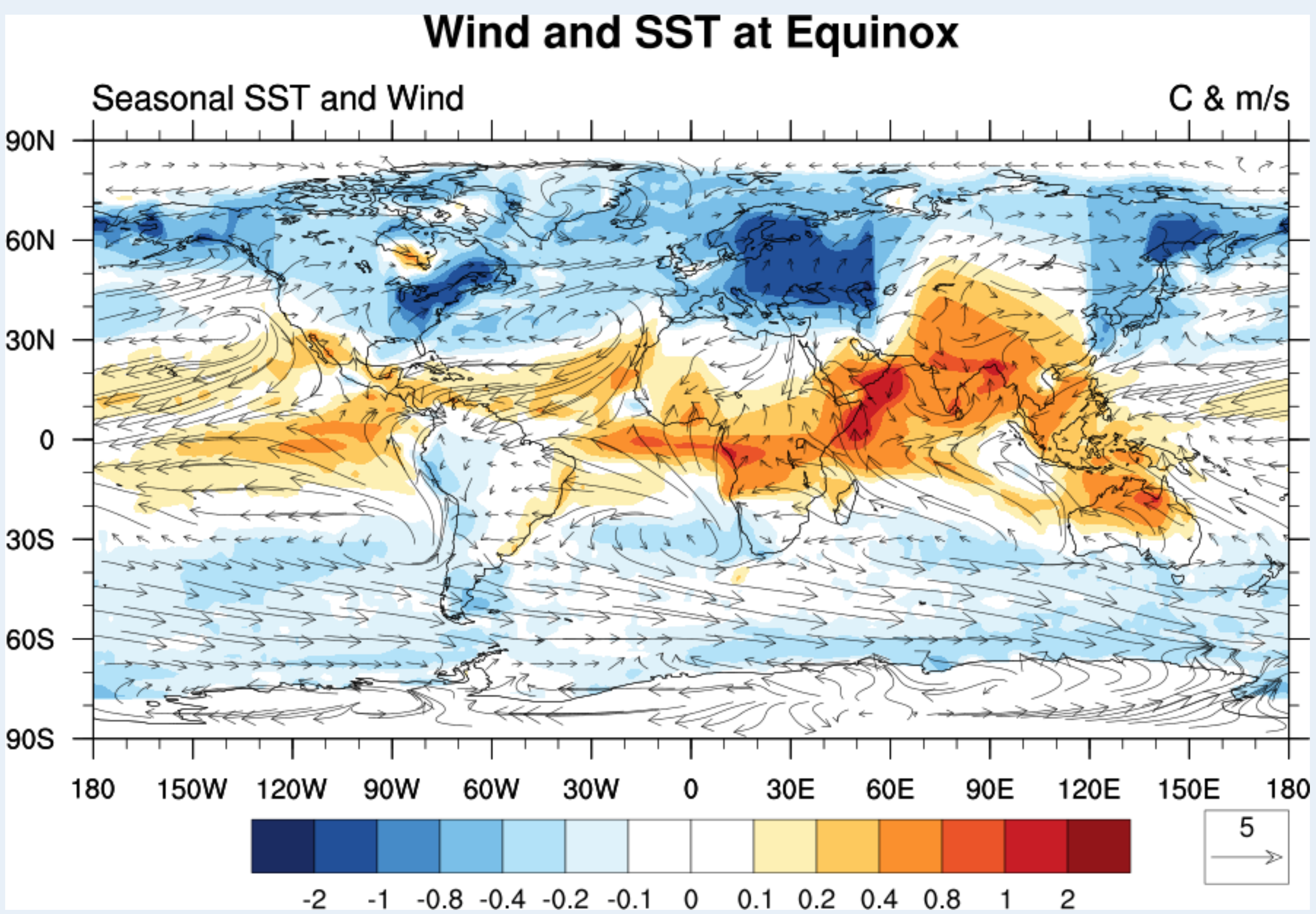

Figure 2 difference of SST at Equinox to Annual And surface wind at Equinox

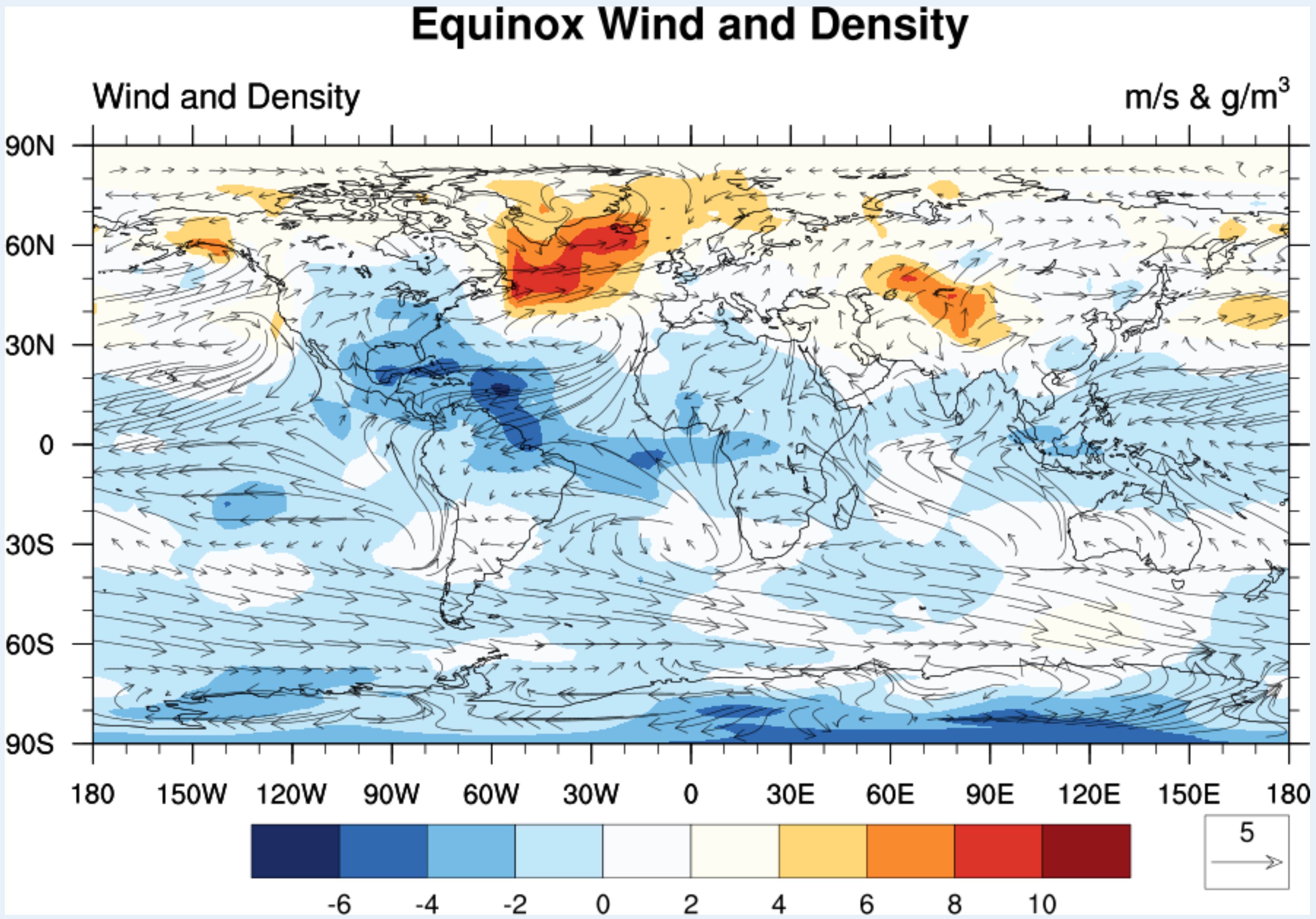

Figure 3 difference of density at Equinox to Annual And surface wind at Equinox

Figure 3 shows the difference of density at Equinox to the annual mean density, and the surface wind vector. Clearly, there is lower density zone along equator, and we can see the wind vector converges to the lower density center.

Here arise a question, why in the summer the warmer center generates a divergent flow, but in the equinox (spring or fall) season, the warmer center creates a convergent flow?

The Generation of Trade Wind

Back to the new dynamic equation (as see in Poster 52):

$$\frac{d\vec{V}}{dt} + 2\boldsymbol{\Omega}\times\vec{V} = - R\nabla T - RT\nabla \ln \rho \qquad (1)$$

The solar radiation which reach the top of the atmosphere can be written as:

$$I = I_0 \cos(\varphi - \varphi_0)\cos(\omega t + \lambda) \qquad (2)$$

Where I_0 is solar constant, φ is latitude, φ_0 the earth's tilt angle, ω is earth's angular speed, and λ is longitude. With the earth rotating, the solar radiation reach the ground will have a diurnal cycle, and we can image that temperature will have a diurnal cycle which can be expressed like:

$$\Delta T = \Delta T_0 \cos(\varphi - \varphi_0)\cos(\omega t + \lambda) \qquad (3)$$

With such temperature diurnal cycle, which the wind field will have a response to it, and from Equation 1, we can derive a wind field as:

$$U = -U_0 \cos(\varphi - \varphi_0)\cos(\omega t + \lambda) \qquad (4)$$

Here U_0 is a positive number. Such a wind response is an easterly. With temperature diurnal cycle at the amplitude of 10 K, we can estimate that the easterly speed will be around 6 meters per second. This easterly, we believe is truly the Trade Wind at Equinox time. So here we can conclude that the Trade Wind is generated from temperature's diurnal cycle, or the diurnal cycle of the solar radiation.

This is very different to the original Hadley theory which it stated that the heating in the equator generated convergent flow, and the Coriolis force turned the convergent flow into easterly (trade wind). We all know that Coriolis is weak near equator, so it could have problem to force the convergent flow into easterly. Now as the trade wind is generated from diurnal cycle, we need to re-think the meridional cells at the Equinox time.

New Meridional Circulation with Trade Wind

At Equinox time, we first think the meridional circulation should be like Figure 7 in Poster 52, which has descending motion at the equator, and divergent flow at surface. With the diurnal impact, now the trade wind is generated at surface (as the diurnal cycle should be strongest near surface) along the equator, which will split the warmer high

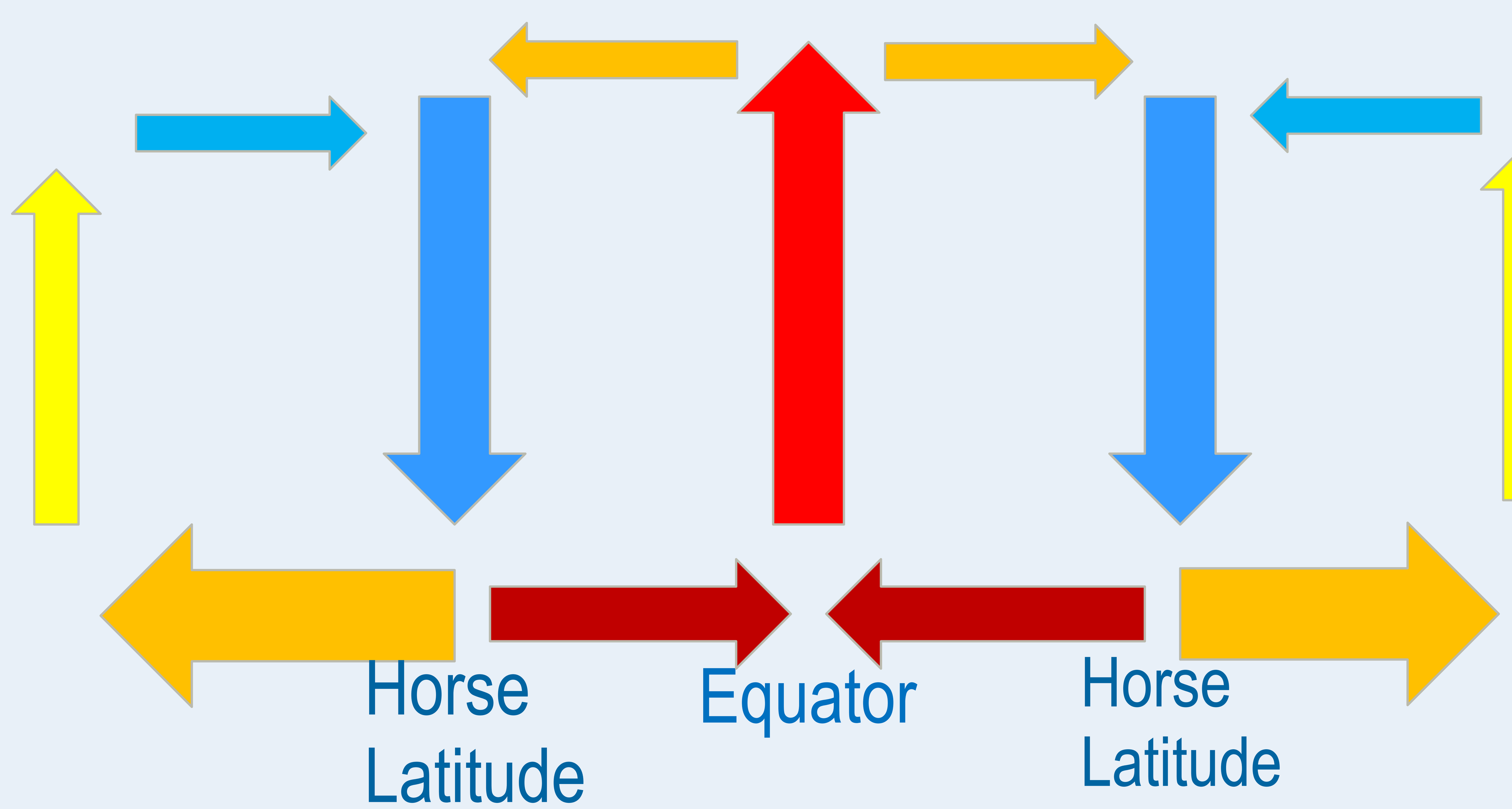

Figure 4 New Meridional Circulation

into two, one in the southern hemisphere, and one in the northern hemisphere. As the high centers move away, then a lower center will be created, and then a convergent flow following, and the strongest convergence is at equator, which is the position of Inter-Tropical Convergence Zone (ITCZ). With surface convergent at surface, and moisture air (if over the ocean) will pile up and gradually convection will happen, and produce precipitation in equatorial region. The convection bring heat to the upper level, and then creates divergent flow there. The divergent flow converge and then descending at the sub-tropical highs. Figure 4 illustrated the new meridional circulation.

People may say that the new meridional circulation in Figure 4 looks just like Hadley cell plus mid-latitude cell from Figure 1 of Poster 52, but we say now the meanings are very different. Table 1 compares the new meridional circulation and the original Hadley cells for Equinox time. We also want to emphasize that the subtropical polar-ward flow is a direct way to transport energy polar-ward, and it is a short path to move energy from subtropical to polar region. The equatorial ward energy transport will keep the equatorial region warm even though it could be cloud covered, the moisture air piled in ITCZ is why we see lots of convections happened there, and also it is why the equatorial region can stay warm.

	New Meridional Circulation	**Original Hadley Cell**
Sub-tropical high	Energy source Energy from solar radiation Provide energy for ITCZ Transport energy polar ward Cleary sky to absorb more solar energy	Energy sink Energy from descending adiabatic heating Still provide energy to ITCZ? Does it have enough energy polar ward? Clear sky won’t benefit anything.
ITCZ	Energy source at upper level Energy sink at lower level Strength not impacted by cloudy sky	Energy source at upper level Energy source at lower level Cloudy sky blocks solar, and weaken system
Trade Wind	Generated from diurnal cycle Do not depend on Coriolis	Convergent equator-ward flow changed to easterly forced by Coriolis

Table 1 Comparison of New Meridional Circulation and Original Hadley Cell

We have talked about trade wind in Equinox time, then how about in the summer (we will not discuss winter here). Similar to Equinox time, in the northern hemisphere summer, as the earth tilted, the sun is at the latitude of Tropical of Cancer, so the trade wind will be strong at 23.5 degree. As we have discussed in Poster 52, at this time, the maximum heating zone is not at this latitude, but further north to 35 degree, so the center of sub-tropical high is at 35 degree, and the equator-ward flow will become north-easterly under the influence of Coriolis, which will overlap with the trade wind generated by diurnal cycle to form a much stronger easterly at 23.5 degree. The north-easterly become easterly at 23.5 degree and forms the convergent zone, which is the so-called ITCZ at northern hemisphere summer. As the new convergent zone generated at 23.5 degree, the air between equator and 23.5 degree will flow towards 23.5, and forms south-easterly. The strong easterly also serves a role to prevent the energy transport from north of 23.5 to south side as it acts as a barrier, which is very important to the ocean overturning circulation, and therefor to the winter time circulation. We will discuss more of its roles in a talk “The Oceanic Overturning Circulation under New Atmospheric Meridional Circulation and Water Vapor’s Role” (send to AMS meeting: Joint 21st Satellite Meteorology, Oceanography and Climatology Conference and 20th Conference on Air-Sea Interaction).

Trade Wind's Impact to Tropical Cyclone Genesis

In tropical meteorology, one of the most important topics is tropical cyclone. In the above discussion, we see that trade wind is very important in the form of meridional circulation, here we want to check its impact on tropical cyclone genesis. From Equation 4, we can derive a relative vertical vorticity from trade wind:

$$\zeta = -\zeta_0 \sin(\varphi - \varphi_0)\cos(\omega t + \lambda) \qquad (5)$$

Here ζ_0 is positive. From Equation 5, we see that in equinox φ_0=0, so the relative vorticity is negative at northern hemisphere, which is (partially) why we see an anti-cyclone north of equator at spring and fall. But in (north hemisphere) summer φ_0=23.5, we will see a positive relative vertical vorticity between equator and 23.5 degree. As the air flow is strongly affected by Coriolis force, by multiple Coriolis force with Equation 5, we can get picture as Figure 5.

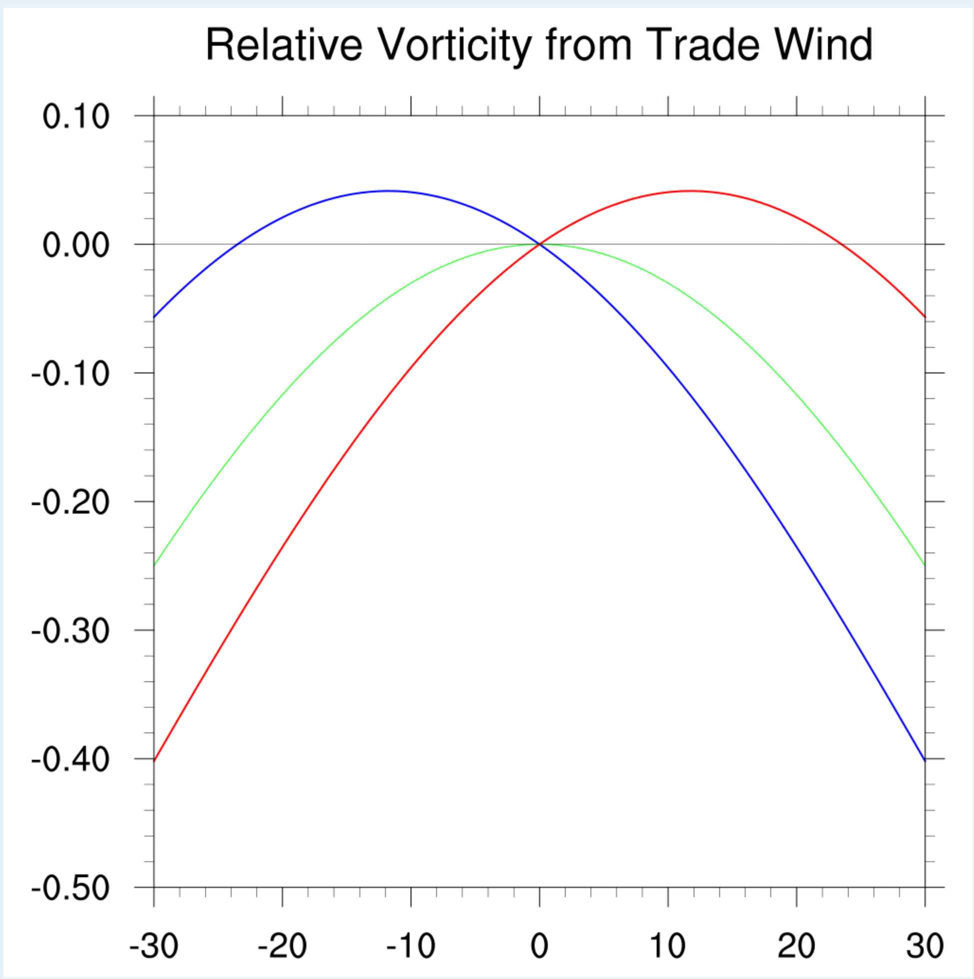

Figure 5 Tropical Cyclone Genesis Function

Blue: Southern Summer
Green: Equinox
Red: Northern Summer

If we believe that Figure 5 can be used as the tropical cyclone genesis function, we can see that at southern hemisphere summer, the tropical cyclone is going to be within equator and 23.5 degree south, and the most likely hood of tropical cyclone is between 10 to 15 degree south. In the Equinox season, there is no genesis value larger than 0, therefor no tropical cyclones at these two seasons. In the northern hemisphere summer, as shown in red, there is a higher possibility that the tropical cyclone will generated between 10 to 15 degree north.

If you think that we use Equation 5 for tropical cyclone genesis had gone to far, but al least we can think that it represents a wave, since the wind is easterly, we can it east wave. The meteorologists in Guangdong Province, China, have used this for their weather forecast. Actually, this is similar to all of us to use west wave to predict weather in mid-latitude at the times when weather maps were widely used.

Numerical Model Results of Diurnal Cycle

We have discussed the impacts of the diurnal cycle in theory, with modern technology, the best way to check it is to assimilate it on computer from a numerical weather forecast model.

The numerical weather model we choose is the Model for Predication Across Scale (MPAS, details can find it at: https://mpas-dev.github.io/). MPAS uses polygons (most of them are hexagons) to cover the sphere, as Figure 6.

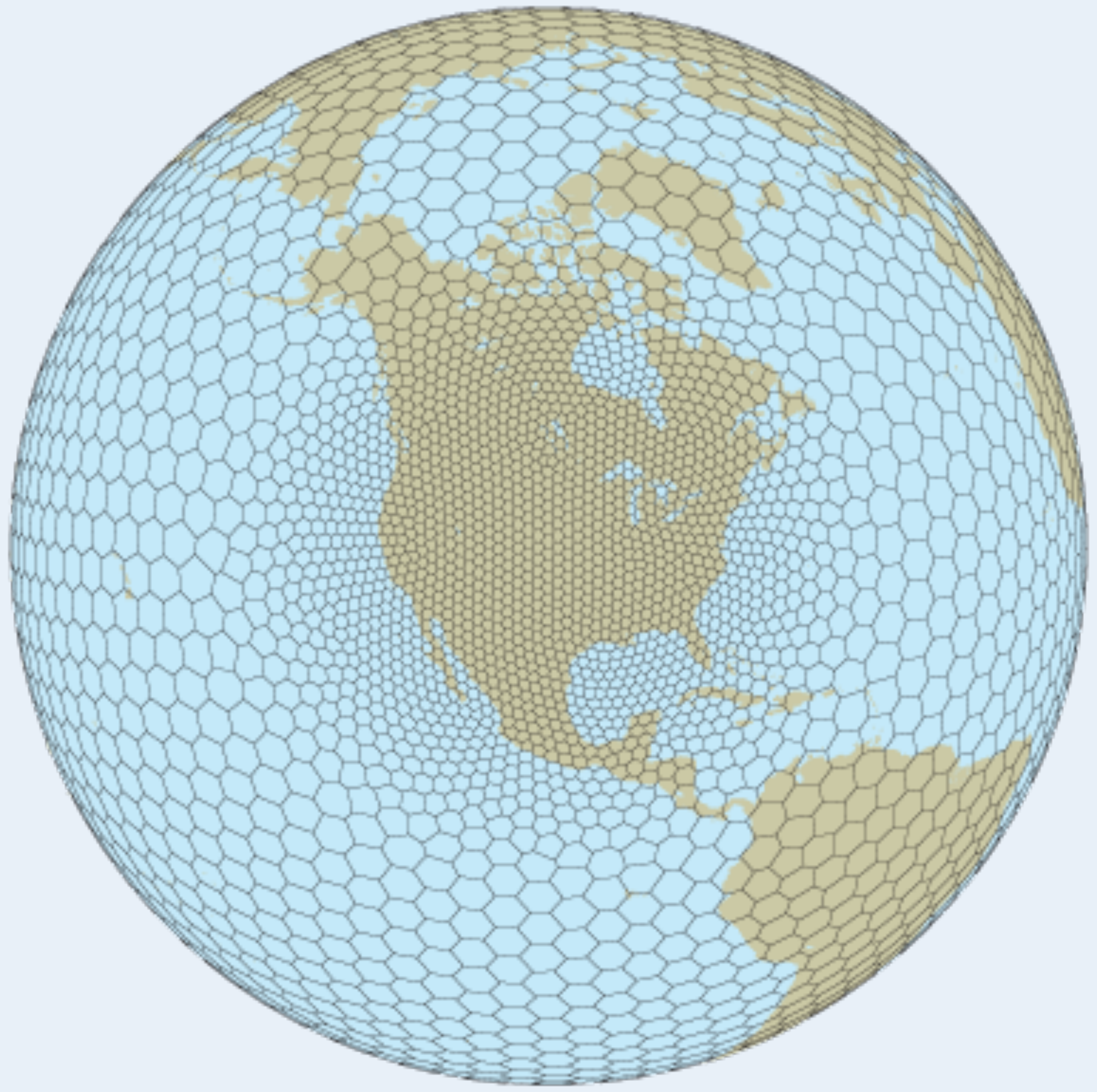

Figure 6
A variable resolution MPAS Voronoi mesh

The model itself has full physics packages, therefore diurnal cycle is (automatically) included. So, we need to design a scheme which somehow still has solar radiation included, but do not have the diurnal cycle. From Eq. 2, we know that the incoming solar radiation is a function of time, if we integrate the incoming solar radiation for 24 hours, and then take the average, then we can get a mean solar radiation (reached the top of the atmosphere), but now it does not have the daily changes.

Certainly we have to bear in mind that this experiment can only partially examine the diurnal cycle impacts as we have only make changes in atmospheric model. In the real world, the ocean will play very important role to affect the atmospheric circulation.

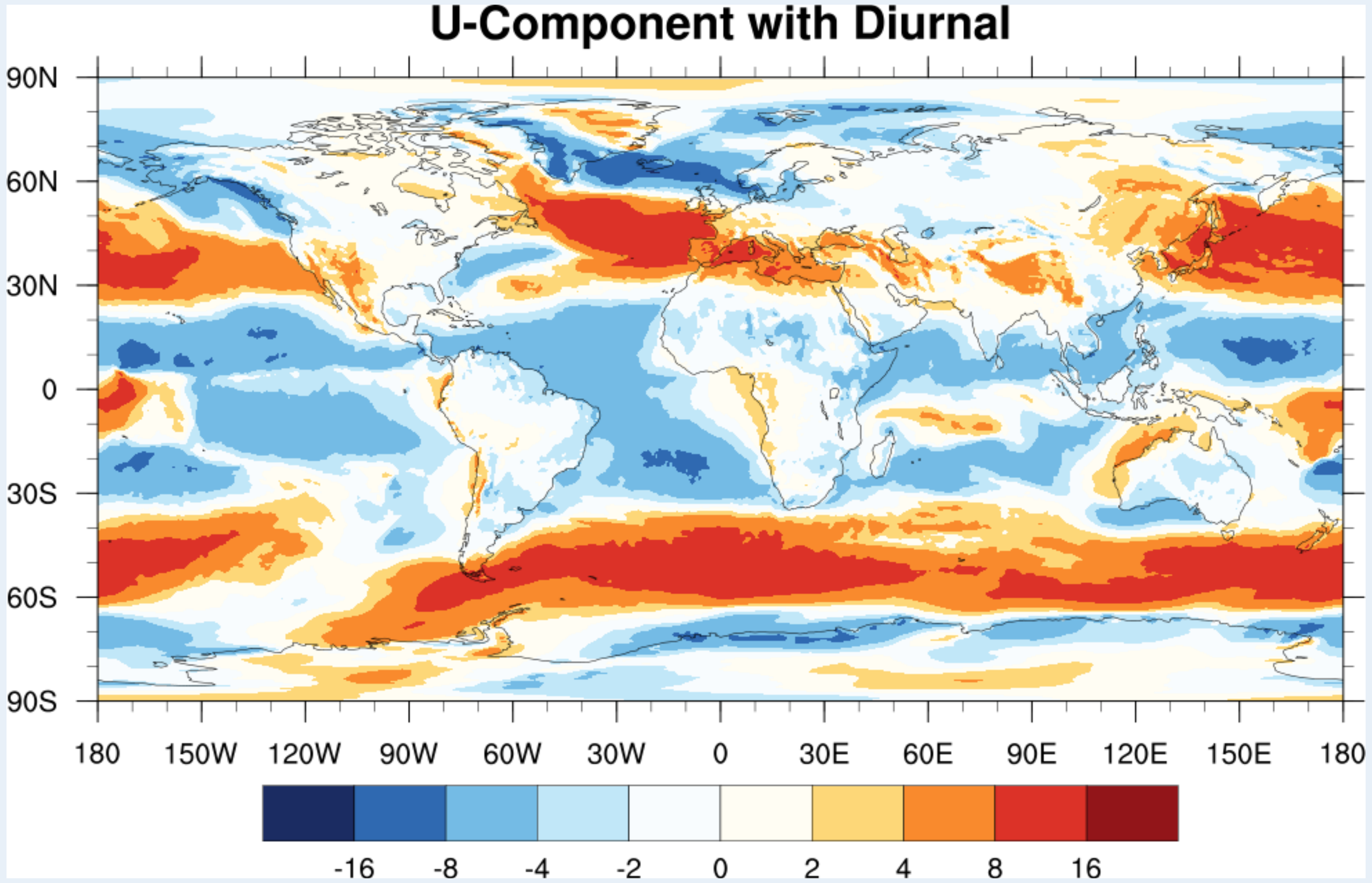

Figure 7 MPAS Zonal Wind with Diurnal Cycle

We run MPAS model from January 6 to 11, 2016 for two cases, one is the original model, which include the diurnal cycle, and the other one with modified solar zenith angle to eliminate the diurnal cycle. Figure 7 shows the averaged 5 days run zonal wind (at the lowest model level) with diurnal cycle, and Figure 8 the 5 days mean zonal wind without diurnal cycle. With original Hadley circulation theory, these two runs should not have big

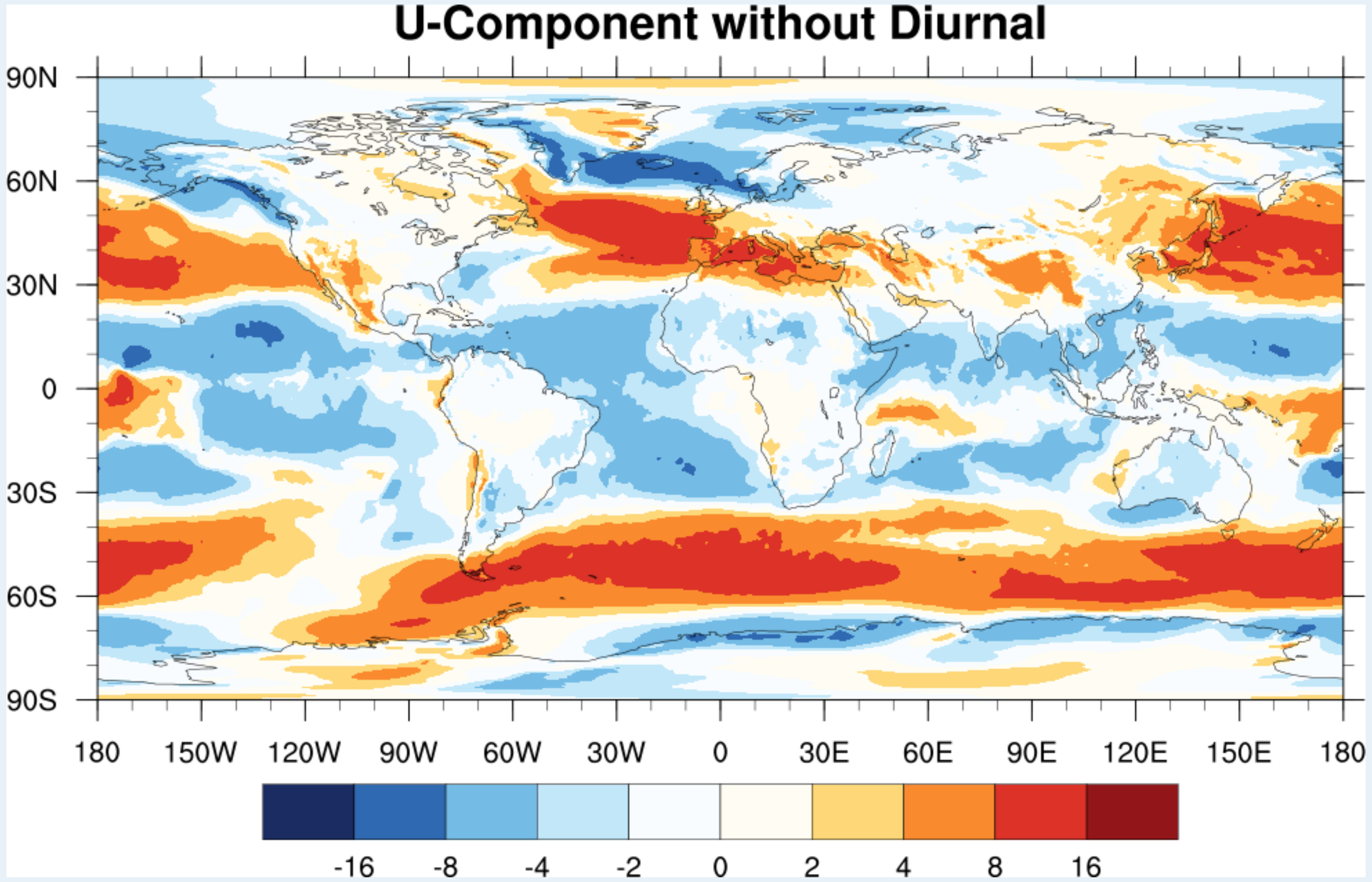

Figure 8 MPAS Zonal Wind without Diurnal Cycle

difference, as we have tried to keep the total amount of solar radiation (reached the top of the atmosphere) the same. With our new meridional circulation theory, we are expected to see the difference in trade wind, as we believe the trade wind is generated from diurnal cycle. Comparing Figure 7 and Figure 8, and focus on the values along 20 degree south (as this is the time of southern summer, the trade wind is strong near 20 degree south), we see difference in east Pacific ocean, and middle of Atlantis ocean. Other significant difference is west of Pacific ocean near east 160 degree, and north 10 degree

Figure 9 shows the difference of zonal wind with and without diurnal cycle. Significant difference are shown around (20S, 150W), equatorial Atlantis ocean, west equatorial Indian ocean, and west equatorial Pacific ocean. Figure 10 shows the difference of convective rain. As we can expect, with diurnal cycle produce more precipitation, than without.

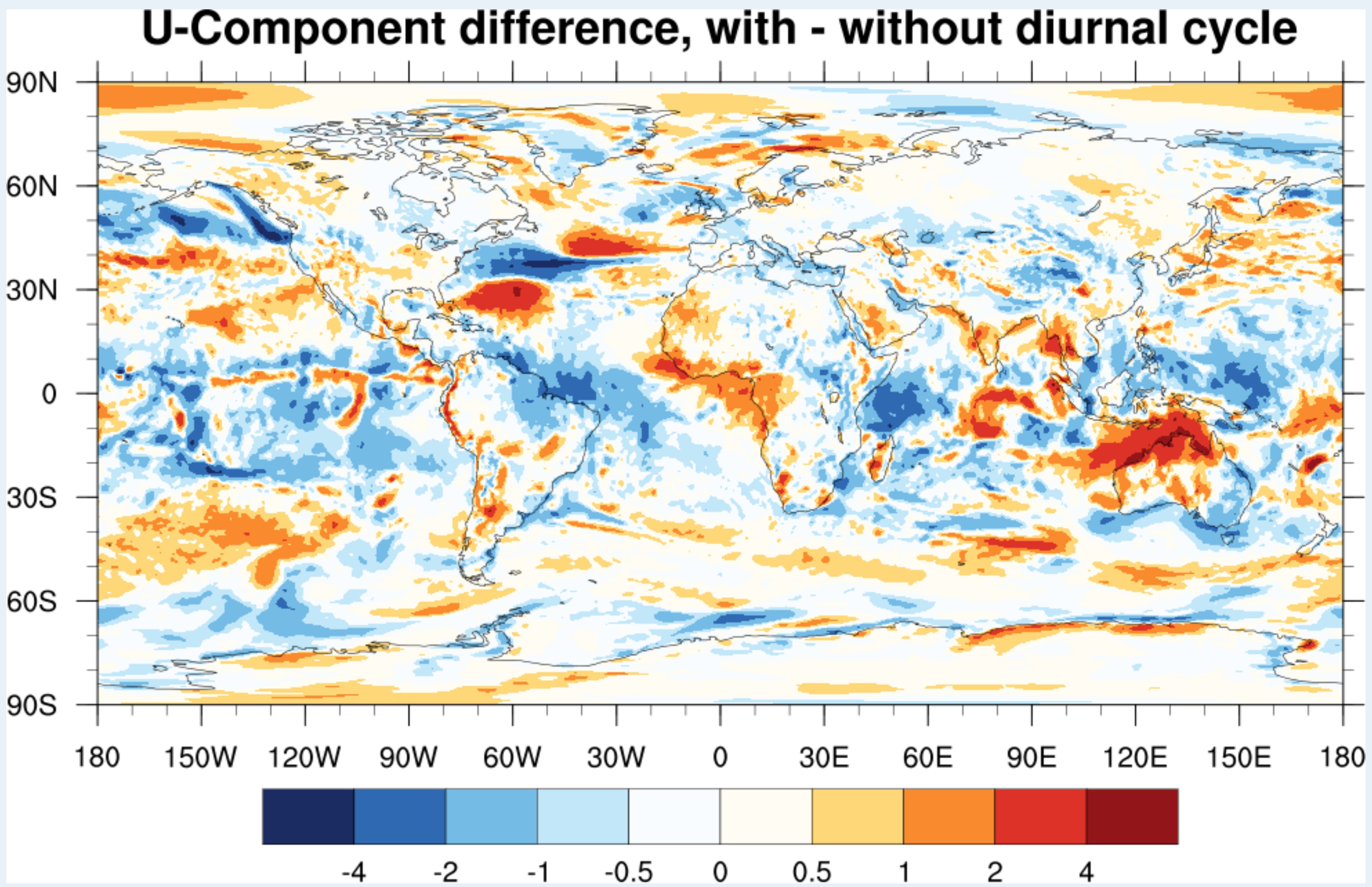

Figure 9 MPAS Zonal Wind with – without Diurnal Cycle

Conclusion

By re-examine the dynamic equation, and diurnal changes of the solar radiation, we have found that the trade wind is the result of diurnal cycles, and ITCZ is formed as the result of trade wind.

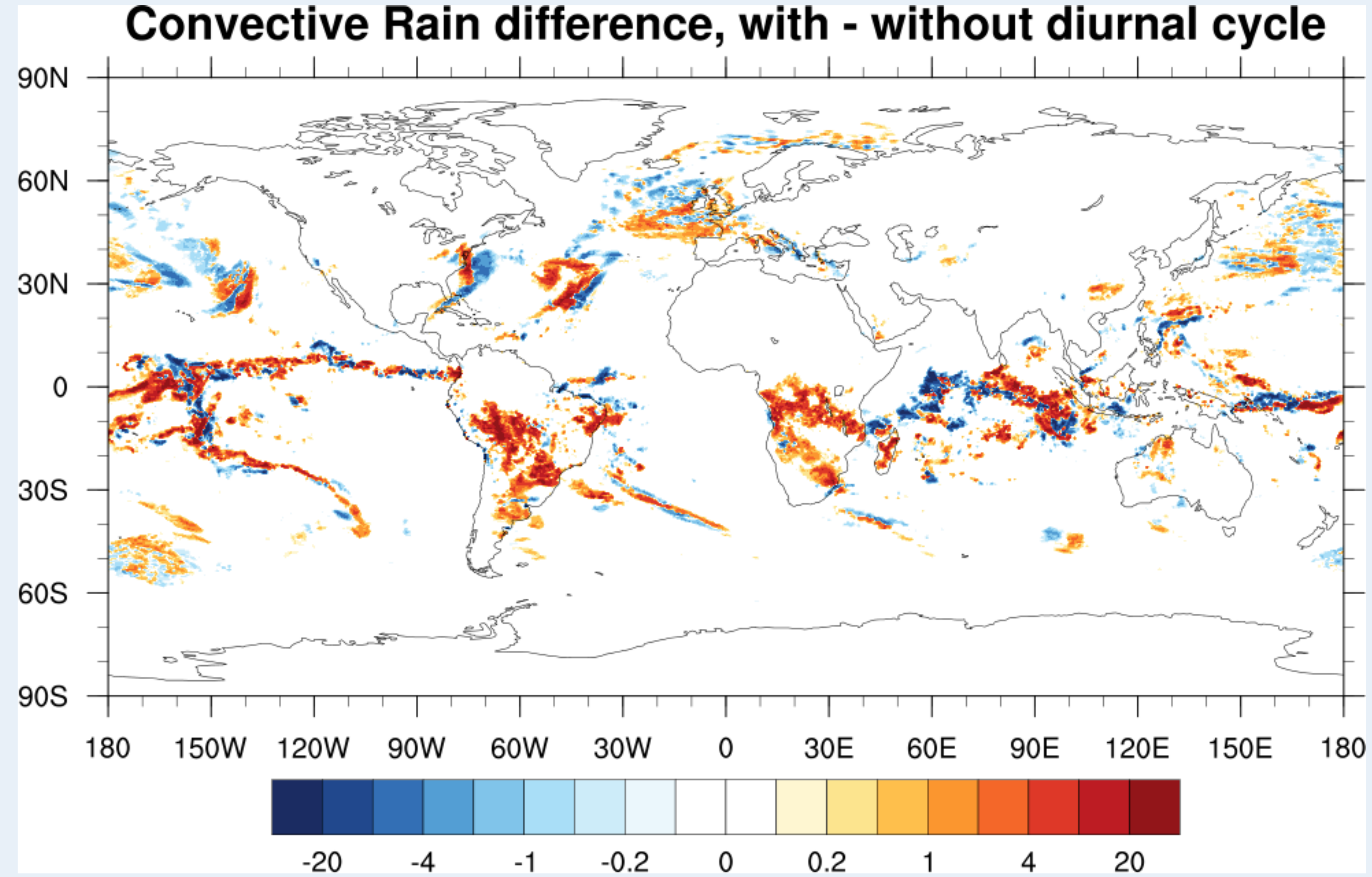

Figure 10 Convective Rain with/without Diurnal Cycle

We also examined the trade wind at summer, and pointed out that the trade wind can create a tropical storm genesis zone between equator and ITCZ with a maximum between 9-12 degree.

Numerical results from MPAS confirms that diurnal cycle creates the trade wind, or at least, strengthen easterly beneath the sun/

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