Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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Lecture- 36

ATMOSPHERIC CIRCULATION SYSTEMS - BASIC CONCEPTS

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. In the previous week, we completed our discussion regarding the temperature gradients we expect in the atmosphere due to the transmission and absorption of radiation by the various absorbing gases. And we evaluated simple analytical relations by which under radiative equilibrium how that vertical temperature gradients of the atmosphere can be evaluated. However, till now we have mostly neglected the horizontal components of atmospheric transport. We have mentioned them but we have not covered them in a lot of detail. However, horizontal transport of mass and energy through wind and oceanic circulation system is a major aspect of climate and of course it is the one thing that we experience most directly in our lives.

The horizontal transport of energy at the surface through winds and the ocean currents affect the weather and the climate that we experience the most. Hence, we have to have a good understanding of the atmospheric as well as the oceanic circulation systems in order to understand how the climate is regulated in the planet and what is the cause of climatic variabilities between various geographic locations. So, in the next, this week and probably I will keep it in the next week, we will change gears somewhat and we will discuss primarily the transport of mass, momentum and energy in what is called the zonal and the meridional direction. The zonal direction is nothing but the west to east direction and the meridional direction is nothing but the south to north direction.

So, first we will discuss the atmospheric circulation systems that is the wind circulation systems. As we have alluded to earlier, there occurs large scale horizontal transport of energy in terms of heat transfer, mass transfer and momentum transfer through winds in the atmosphere. These winds may be surface level winds or high level winds towards the top of the troposphere. In this map, just to get a flavor of the things, this is a contour map of the general wind circulation patterns in our planet during the, so for example, this part initially is the December, January, February. So, this figure is the wind circulation system in the December, January and February months, averaged over these three months.

And the bottom figure is the wind circulation system in the June, July, August months. So, one is in the northern hemisphere winter and one is in the southern hemisphere winter. The arrow gives you the direction and the strength of the wind circulation. So, these are 10, the arrows are in meters per second, okay. And the wind circulation has been shown at the surface level, that is 10 meters above the ground.

So, bigger the arrows, stronger is the wind circulation in that specific direction. Smaller the arrows, weaker is the wind circulation system in that specific direction at that level. Superimposed on this is the pressure contour. again at the sea level conditions in hectopascals. So, for example, 1020 hectopascals is this one here.

Remember, 1 hectopascal is 100 pascals. 1020 hectopascals is 102 kilopascals. Remember, 101.325 is the mean sea level pressure of the earth. So, the mean sea level is kind of yellow.

The orange and the red are at pressures higher than the mean sea level pressure, while the green, blue and green and blue are pressures lower than the mean sea level pressure. So, first let us look at the northern hemisphere winter season that is December, January and February. The first thing you will notice is that, so this is the direction of a 10 meter per second wind, this is the strength of the, the average winds are usually lower than that. The first thing you will notice is that in the oceans the winds are significantly stronger, particularly in the southern ocean, it is near Antarctica, so the ocean surrounding the Antarctic has the one of the strongest wind circulation systems and is going in general from west to east. In winter, in the northern hemisphere winter, in the southern hemisphere summer and we see that the ocean above the Antarctic continent has extremely low pressures along the entire zonal direction, west to east direction, one of the lowest pressure 985 to 990 hectopascals. And we see a striped pattern if you go from south to north. So, the oceans near the Antarctic continent have a low pressure, then we go to a high pressure region, Just above, so off the coast of South Africa, off the coast of Australia and off the coast of Latin America, in the southern tip, you have a region of high pressure. Then, in the subtropical and the tropical regions, you get a region of relatively low pressure over the Indian Ocean, Southern Pacific and Southern Atlantic Ocean. Then if you go now to the northern hemisphere subtropical region, you get a region of high pressure which is extending from the Pacific to the Atlantic and then again in the northern Atlantic high latitude regions, you get a region of low pressure just as you would get in the southern latitude above the Antarctic continent. So low pressure, high pressure, low pressure, high pressure, low pressure. So you get this striated structure particularly in the oceans which are along the oriented in the west to east direction. All right. Note however that this striated structure gets disturbed as we move towards the continents.

So what we see here is over Asia particularly in the inner Asian region, so inner Mongolia, inner China region, you have a very strong high pressure region, one of the highest pressure regions that are present in the world during the winter period in the northern hemisphere. Similarly, the low pressure region of the tropics and the subtropics of the Southern Hemisphere gets extended downwards and extends throughout the Southern Africa, the Australian landmass and the Latin American landmass. Just as the high pressure region extends in the Northern Hemisphere continents, the low pressure regions extend in the Southern Hemisphere continents. And the reason is, and this high pressure region is also present as you see in the entire North American continent. So, the reason for this is that the land masses are strongly affected by seasonal temperature variation.

So, northern hemisphere winter the land masses are particularly cold and snow covered making the air above it also cold and dense. So, you would expect the land masses to have particularly high pressure regions in the winter hemisphere as we see here. Similarly, the southern hemisphere summer will be hot and humid and hence the pressure of air above the landmass will be low and hence the low pressure regions will extend throughout the southern hemisphere continents during the southern hemisphere summer. The ocean temperature does not change as much. As a result, you get a more evenly distributed striated pattern of high pressure and low pressure zone in the winter and the summer hemisphere.

We will discuss later in maybe in the next class the reason for this striated pattern of low-high, low-high. And this is basically related to the the three major convection cells that are present in the atmospheric system. We will discuss that in detail later. Now, the question is how does the wind looks like beyond the Antarctic Ocean? So, you will also see a strong oceanic wind circulation pattern around between the 20 degree north and the 20 degree south latitude going towards the equator. So, there is a strong wind pattern moving towards the equator from the subtropical zone which is converging towards the equator.

So, the equatorial region is a low pressure belt and so a significant wind driven circulation is happening from the high pressure belt surrounding the subtropics towards the equator. This is primarily the trade wind that we will discuss later. We also see a strong wind pattern moving from the cold interior of the Asian continent towards both the equator and a small amount of wind pattern also going towards the lows in the higher latitude. And this is the northeast monsoon that we will again discuss significantly later in the classes. Similar patterns are also seen in the Atlantic Ocean and in the Indian Ocean.

Now let us look at the reverse season, that is when it is northern hemisphere summer. Now here we see that the Southern Ocean does not change significantly apart from the fact that the low pressure region and the high pressure region is shifted somewhat upwards. So, once again the ocean surrounding the Antarctic continent is a very low pressure region with high, large values of west to east beams. So, the Antarctic Peninsula, the Antarctic continent is not affected significantly by the seasonal variable. Above it, we again see the high pressure region, but it is much more thinner than before and the low pressure region has now shifted further downwards, away from the equator.

So, the low pressure region has now shifted, sorry, there is a significant broad low pressure region that is extending from the Antarctic Ocean up to the equatorial region. So, here there is a difference. Before you see here there is a.

The primarily high pressure region was extending only up to the edge of the southern continents, so in the mid latitudes. Now, the high pressure region is extending much further upwards towards the equator in the southern hemisphere. And the reason is that right now in the June, July and August is the southern hemisphere winter.

So the land masses in the southern hemisphere are significantly colder and you have a broad and strong high pressure region extending throughout the mid-latitudes and the subtropics. And the low pressure region kind of moves therefore upwards towards the northern hemisphere. And you see that the largest low pressure region is now centered in the Indian subcontinent as well as parts of Arabia. And hence a strong wing pattern develops from the high pressure region of the southern hemisphere mid-latitudes towards the low pressure region in the northern hemisphere low latitudes. the Indian subcontinent and the southern edges of Asia.

And this is the cause of the southwest monsoon that we see in the June, July, August, June. In other places also we have low pressure regions, but they are not as pronounced. So, we have lower values of winds, but still similar kind of wind patterns are happening. Then we have a high pressure region now stationed in the northern Pacific and the northern Atlantic Ocean where there was a low pressure region before. This is again because of the shifting of the various circulation systems because it is now northern hemisphere winter and hence Northern Hemisphere summer, so what has been, had been the low pressure region of the Northern Hemisphere, Northern Ocean have become high pressure regions here, whereas the low pressure is now extending throughout the Asian and the continental North America.

So, we see a significant shift in wind patterns in many regions of the world. So, for example, in the Southern Indian Ocean, the winds are moving now from south-east to north-west and then shifting to going from south-west to north-east. Whereas, in the winter month, you would see the winds are moving in the opposite direction between the

Indian subcontinent and the equator. Similarly, other places also the wind patterns have changed significantly. So, for example, in the Northern Pacific and Northern Atlantic, the wind circulation system has reversed itself because it was a high pressure, low pressure region in the winter months.

Now, it is a high pressure region in the summer months. So, we will discuss the seasonal shifts of wind variability in detail as we move along and why these things happen. But as you can see very clearly that the seasonal shifts have much to do in determining the climatic changes that happen in the continents and in the oceans over a period of a year. Now, we will then now look at Before we discuss qualitatively the wind circulation patterns in detail, we will discuss quantitatively what are the forces that govern the wind velocity and the wind direction. the main forces that drive the atmospheric wind circulation includes the Coriolis force, we will discuss what the Coriolis force is very soon, the pressure gradient force which is far more easier to understand, it's the change in the pressure as we move in any direction and wind is typically moves from a high pressure region towards a low pressure region.

The gravitational force which is not very significant in the horizontal directions, but the vertical convection cells are dependent on the gravitational force through buoyancy induced effects. And finally, frictional force which is the surface drag that is very important in transporting the momentum of the winds to oceanic currents and also slowing down the wind circulation near the surface. So, the frictional force While not very important, in the overall wind circulation system away from the surface, near the surface they play a very important role in the transport of momentum from the atmosphere to the oceans. We can define the wind velocity vector as made up of three components. One component is in the west to east direction.

We call this component u and it is called the zonal component of velocity. So, the zonal direction, so just remember the word, the zonal direction is the west to east direction. So, a wind moving from the west to east is a zonal wind with a certain velocity u. Then we have vj, this is the meridional direction, so a wind moving from north, south to north. So, moving from the south direction towards the north direction with the velocity v, it is called the meridional direction.

And then the vertical direction is w, that is going from the ground to up in the atmosphere is the vertical component of the wind. So we have the zonal, the meridional and the vertical. So a wind typically can have all three components and together the wind velocity can be something like this. So it can have a zonal direction, a meridional direction component and a vertical component. and the wind velocity is determined by the momentum equations in these three directions.

The x momentum equation is the zonal momentum equation, the y momentum equation is the meridional momentum equation and the z momentum equation is the vertical momentum equation. The momentum equations primarily is basically force is equals to mass into acceleration and acceleration is the total derivative of velocity with respect to time. So, dv dt, right? So, we can write the x momentum equation as du dt, d is the total derivative of the zonal velocity u equal to 1 by m, the mass of a parcel of wind into the forces that are contributing towards the change in the wind velocity. And what are these forces? The Coriolis force, the zonal component of Coriolis force, the zonal component of pressure force and the zonal component of frictional force. Zonal component is along the latitudes, west to east direction.

So, it is a latitudinal direction. Similarly, dv dt, the change in the meridional velocity component is 1 by m into the y component of Coriolis force or the meridional component of Coriolis force, the meridional component of pressure force and the meridional component of frictional force. Similarly, the vertical momentum equation, the change in the vertical velocity component w with time is 1 by m, the vertical component of Coriolis force, the vertical component of pressure force, the vertical component of frictional force plus the vertical component of gravitational force because gravity is one force which is present in the vertical direction but not present in the x or y direction. And the total derivative is a partial derivative with respect to time plus the advection components that is the derivative with respect to space, how the u, v and w are changing with x with y and with z. It is given by u into del del x, b into del del y plus w into del del z. This gives the total derivative of the velocity.

So, du dt is basically del u del t plus u del u del x plus v del del u del y plus w del u del z. Basically, it is b dot del. This is the advection constant. So now, what we will do in this class and the next few classes is to understand these three components of forces. The Coriolis force, Fx Coriolis, Fy Coriolis and Fz Coriolis, what is the expression for it? The pressure force, what are the expressions of x, y and z components of pressure force? And what is the expression for the x, y and z components of the frictional force? First, we will look at the Coriolis force.

X (zonal) momentum equation:

$$\frac{Du}{Dt} = \frac{1}{m}\left(F_{Cor}^{x} + F_{P}^{x} + F_{f}^{x}\right) \quad ($$

Y (meridional) momentum equation:

$$\frac{Dv}{Dt} = \frac{1}{m}\left(F_{Cor}^{y} + F_{P}^{y} + F_{f}^{y}\right) \quad ($$

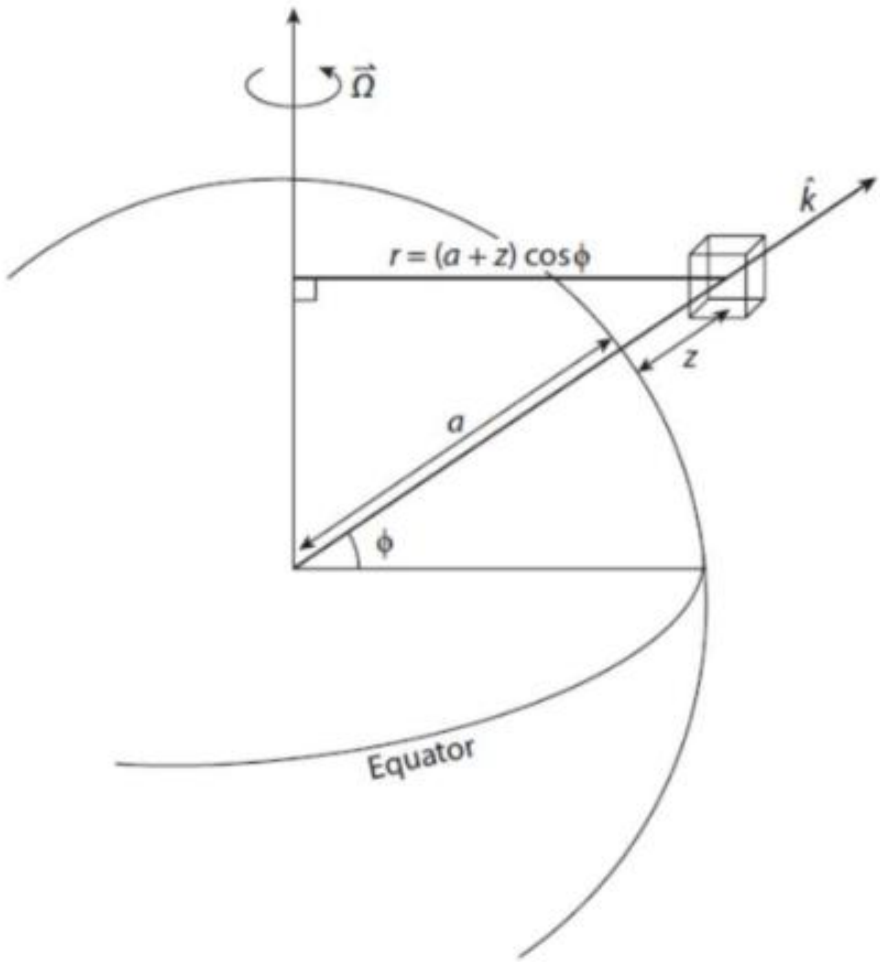
Z (vertical) momentum equation:

$$\frac{Dw}{Dt} = \frac{1}{m}\left(F_{Cor}^{z} + F_{P}^{z} + F_{f}^{z} + F_{G}^{z}\right)$$

Where

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

What is the Coriolis force? The Coriolis force is the apparent force or the pseudo force that arises when the force balance for a parcel of air in the atmosphere is done with respect to the non-inertial frame of a rotating earth. So what does this mean? Newton's laws of motion work only for inertial frames. These frames which are either at absolute rest or at constant uniform velocities. However, this is not true for earth. Earth is rotating along, around this axis, so it has an angular motion which makes it a non-inertial frame of reference.



When you try to do the force balance in a non-inertial frame of reference, additional forces come into play which are called apparent forces or feudal forces that would not have been there if the frame was an inertial reference. And these apparent or feudal forces in the case of using earth as a frame of reference are called Coriolis forces. It has two major sources. One is due to the conservation of angular momentum in a rotating earth. Angular momentum has to be conserved. This conservation principle gives one component of core distribution. The other is the presence of the outward directed centrifugal pseudo force due to the rotation of the earth. Because the earth is rotating, there is a centrifugal pseudo force that is also a second aspect of the Coriolis force vector. So, first we will discuss the component of force that arises due to conservation of angular momentum.

We will start this in the next class. Thank you for listening and we will continue next time.