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

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ATMOSPHERIC CIRCULATION SYSTEMS

- FRICTIONAL FORCES AND SURFACE LEVEL WINDS

Good morning class. In the previous lecture, we had discussed about the pressure force and before that on the Coriolis force. The third and the final force that is of importance are the frictional forces. These are primarily important flows to the surface where it helps to decelerate the air due to frictional drag effects and it also helps transfer momentum to the ocean and hence start the oceanic circulation system. The presence of friction reduces wind speed due to frictional drag effect which in turn reduces the Coriolis force as it is proportional to the wind speed. Note that the pressure gradient force is not proportional to the wind speed but the Coriolis forces.

We can show this here. Here the pressure gradient force is just proportional to the geopotential gradients. But the Coriolis force is basically F_v and F_u. which are proportional to the velocity components.

So, if the friction is decelerating the winds near the surface, that means the oriolis force is weakening and the geostrophic balance is broken. So, friction makes it possible for the pressure gradients to become stronger and the wind accelerates down the local pressure gradients. This is why surface-level winds tend to follow the pressure gradient that is moving along the gradient of P from the high-pressure to the low-pressure $-\Delta P/\Delta x$, correct? That way moves from high-pressure to the low-pressure while the high-level winds are usually in geostrophic balance. Hence, in a cyclone for example, the winds near the surface are slowed by friction and hence deviate from the geostrophic direction and begin to spiral inwards towards the low-pressure center. So, while the upper section of the cyclone, the winds are always rotating tangentially, in the lower section, because the Coriolis force is no longer strong enough to balance the pressure force, the winds start to flow along the gradient and spiral inwards towards the low-pressure center.

The cyclonic winds near the surface are not strictly circular but converges into the low-pressure center while anti-cyclonic winds diverge outwards. Mass accumulating in the low-pressure center of a cyclone is forced to move vertically upwards. Because mass is accumulating near the bottom of the cyclone, that excess mass has to move upwards to preserve mass balance, setting up a convection cell that creates condensation, cloud formation and precipitation. So, this is also very important. Without the deceleration and the accumulation of the mass in the low-pressure center, this mass of air would not be rising upwards due to this accumulation, and only when the mass is moving upwards do we have condensation, cloud formation and precipitation events which are associated with the cyclone.

So, it is this deceleration caused accumulation of mass and the rising of mass that creates a convection cell in a cyclone which generates the clouds and the precipitation events. So, this can be seen here. So, near the eye, the winds kind of circle inwards and then it moves upwards and creates this cloud formation and convection cells. Okay. Also, near the equator, the core release forces are substantially weaker. Hence, the balance is between the friction and the pressure force and the wind direction is generally directly down the pressure gradients. So, near the equator, Coriolis forces are much weaker. So, in low-pressure regions, the winds flow directly into the low-pressure region and directly away from the high-pressure regions and have weaker tangential components. Hence, cyclonic and anticyclonic circulations are weaker near the equator due to rapid convergence and divergence of mass. The lows and the highs of pressure are also substantially weaker.

Because mass is quickly being transported to the center of the low-pressure or transported away from the high-pressure, the pressure gradients quickly balance each other due to direct transport of mass near the equator and hence the low-pressure and the high-pressure zones are substantially weaker and the cyclonic and the anti-cyclonic circulations are also weaker. This is why Cyclonic circulations in the temperate regions and in the high latitudes are far stronger than in the tropical region, where you just have depressions basically.

$$\frac{Du}{Dt} = \frac{1}{m}\left(fv - \frac{1}{\rho}\frac{\partial p}{\partial x} + F_f^x\right)$$

So, with this view in context, the final simplified form of the momentum equations is $\frac{Du}{Dt}$, x component zonal is $\frac{1}{m}fv$ which is the zonal correlates force $-\frac{1}{\rho}\frac{\partial p}{\partial x}$. This we can also replace by the geopotential gradient plus the frictional force in the x direction.

$$\frac{Dv}{Dt} = \frac{1}{m}\left(-fu - \frac{1}{\rho}\frac{\partial p}{\partial y} + F_f^y\right)$$

The y component in the momentum equation in the meridional direction is $\frac{Dv}{Dt}$ equals to $\frac{1}{m}\left(-fu - \frac{1}{\rho}\frac{\partial p}{\partial y} + F_f^y\right)$, the frictional force.

$$\frac{Dw}{Dt} = \frac{1}{m}\left(-g - \frac{1}{\rho}\frac{\partial p}{\partial z} + F_f^z\right)$$

$$\text{Where, } \frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} \text{ and, } f = 2\Omega sin\phi$$

And the vertical component, $\frac{Dw}{Dt}$, here it is just the gravitational force, the force is negligible. $\frac{1}{\rho}\frac{\partial p}{\partial y}$, the gradient of pressure in the y direction and F_f^z, the frictional force in the z direction, where $\frac{D}{Dt}$ is this total derivative and $f = 2\Omega sin\phi$. We see that in the x and y direction, geostrophic flow occurs when these two terms go to 0 and these two terms go to 0. So, that is clear. In the z direction, hydrostatic balance is valid when again this term goes to 0 and frictional term goes to 0.

So, $\frac{g}{m}$ is equals to $\frac{1}{\rho}\frac{\partial p}{\partial y}$. This is not $\frac{\partial p}{\partial y}$, sorry about that. This is $\frac{\partial p}{\partial z}$. Now, these are the instantaneous zonal, meridional and vertical velocities. In climatology, we prefer working with means and they may be temporal means or spatial means.

So, what do we mean by this? So a time averaged velocity component we can write as $\bar{u} = \frac{1}{\Delta t}\int_0^t udt$. This can be v bar, w bar as well. So these are the time averaged velocity components. It can be over a day, over a month, over a season or over a year. The time averaged velocity component at any given location. This is location dependent but averaged over time. The other option is space averaged velocity. There may be various ways to do space averaged velocity. The most common is over an entire longitude or at a particular latitude circle. So, average over all the longitudes for a particular latitude circle.

So, you are averaging over the entire latitude circle for all the meridional angles, longitudinal angles. Remember the longitudinal angle is starting from the Greenwich 0 to 180, 0 to minus 180 or it is 0 to 360 at a given latitude angle. This is also often done along an isopressure surface level. So, at a given latitude angle over all meridians and along the constant pressure surface. This is usually the common practice.

Such an integration is called the zonal average because you are averaging over an entire latitude circle. And it is given by $[u] = \frac{1}{2\pi}\int_0^{2\pi} ud\lambda$. Lambda is the latitude, longitude angle. Now, this is averaged over space at a given instant of time. This is averaged over time at a given space.

We can do a dual average now. We are integrating both over time, say over a day and along a latitude circle. So, this is $\bar{u}$ within brackets. This is the integration of $\bar{u}$, the mean over say an entire day, over an entire latitude circle. So, this is $\bar{u}$ within brackets.

$$[\bar{u}] = \frac{1}{2\pi}\int_0^{2\pi} \bar{u}d\lambda$$

This kind of double integration integrates both over a certain period of time as well as over an entire latitude circle. This we can call as the zonal average of the time mean of a quantity.

You can have V bar, W bar, whatever. Such mean quantities and their variations over long periods are important variables for climate modeling purposes. So, this class is not climate modeling, but how to get the mean equation from the instantaneous equations is an important aspect of the climatological fluid dynamics problem.

So, with this kind of analytical introduction, now let us look at the description of how these wind distributions actually look like. And we will start from simple and then we will go more and more complex. So, what we are looking at the patterns of atmospheric circulation, alright. This is a simplified form of what are the surface level patterns. There are three types of circulation systems based on where the lows and the highs are situated.

The equator is a low-pressure belt. So, we are calling it an equatorial low. Now, at 30 degree north and 30 degree south, we have a high-pressure belt which is called the subtropical high. Then, at 60 degree north and 60 degree south, we have a low-pressure belt which is called the subpolar low and then at 90 degree north and south we have a high-pressure belt which is called the polar high. Winds tend to move from the high-pressure belt to the low-pressure belt and it gets deflected by the Coriolis force.

This understanding you have explains all the wind directions we are seeing at the surface here. Wind is moving from the subtropical high to the equatorial low from north to south. So, B is negative. As B is negative, F, Coriolis force is positive. So, we have a negative zonal acceleration term. Hence, winds are deflected westwards. So, you have the northeast trade winds. Why it is northeast? Because it is coming from north and east and northeast trade winds are moving in the westward direction. Similarly, we have the south east trade winds because winds are moving from the subtropical high northwards where F is negative. So, once again the zonal acceleration is negative. So, wind will be accelerated towards the west. So, it will be a again a west moving wind from the subtropical high of southern hemisphere to the equatorial low. So, we have southeast trade winds. Similarly, from the subtropical highs, winds will be moving to subpolar loads. It is moving in the north direction. And F is positive in the northern hemisphere, so it is strongly deflected in the western direction. It is strongly deflected because the latitudes are higher, so the Coriolis force is stronger. So, it is almost a west moving wind. And hence, these are called mid-latitude westerlies. They are primarily moving westwards because of the strong Coriolis force with a small component in the northward direction.

Similarly, we have mid-latitude westerlies between the subtropical high and the subpolar low. And finally, from the polar high-pressure belt, things are moving southwards in the northern hemisphere and is getting deflected westward as a result. So, you have polar easterlies, winds coming from east to west. Similarly, polar easterlies in the southern hemisphere, winds coming from east to west. So, this is the entire wind circulation system and this wind circulation system is governed by this low-pressure, high-pressure, low-pressure, high-pressure structure.

And this structure is created by convection cells. So, there is one strong convection cell where a lot of the winds near the tropics is moving upwards in the high altitudes. Then spreading out and moving northward and southwards towards the high latitudes and finally dropping at 30 degrees north and 30 degrees south latitudes to come back again as surface winds as northeast and southeast trade winds and is moving towards equator where it rises again. This is called the Hadley circulation system which is the strongest circulation system on earth. Similarly, you have a very strong high-pressure region at the top of the poles.

So, winds are descending there and is then moving towards the subpolar lows where the wind has warmed enough that it rises up and creates a second convection structure which are called the polar cells which results in the polar easterlies. Part of this high-pressure high winds descending to subtropical highs will also move towards the sub polar lows. Here also in the southern hemisphere and these are leading to the neat latitude westerlies we have discussed earlier. Now, why the Hadley circulation or the convection driven circulation in the equator so strong? Because the Coriolis parameter is low and hence wind flow is primarily dominated by pressure gradients caused by differential thermal heating. So differential thermal heating causes pressure gradients and because Coriolis force is low, wind flows directly from the high-pressure to low-pressure.

Such circulations are called thermally direct circulation systems. They arise in association with differences in surface temperature and therefore low level geopotential gradients or pressure gradients. Large scale thermally direct circulations like the Hadley circulation that I just described, this one, covers the full depth of the troposphere between 30 degree north and 30 degree south. And the reason is simple, there is a lot of solar insulation in the tropics creating strong solar heating and strong conversion evaporation of water. So, warm humid winds generate over the tropics and move upwards and because the conditions are warm and humid it is a conditionally unstable system.

So, the system becomes unstable and strong tropical convection circulations are generated which is the driving force within the Hadley circulation system. Two such cells exist, one in the northern hemisphere and one in the southern hemisphere. They can be plotted as a combination of zonally averaged annual mean meridional velocity. So, zonally averaged along the entire latitude circle, annual mean averaged over the entire year of meridional velocity, not south moving velocity and zonally averaged annual mean vertical velocity.

These are shown here. These gray lines are basically the meridional wind velocity contours and these lines are the vertical wind velocity contours. So, vertical winds are moving like this, rising up in the equator and going down, while the horizontal winds are especially strong at the bottom. And at the top where they are spreading outwards or going inwards. And these are the contours for the horizontal wind.

These are the contours for the vertical wind. And this creates the Hadley circulation system. These surface level winds are partially deflected to the right in the northern hemisphere and southern hemisphere by the weak Coriolis force as we discussed. So these are called the northeast trade winds in the northern hemisphere and southeast trade winds in the southern hemisphere. These surface level winds meet near the equator to produce the intertropical convergence ITCZ. Now, we have done these components in the vertical direction and the zonal direction or the meridional direction.

We can combine these to create a stream function. Remember, U and V together can create a stream function from fluid mechanics. So, similarly, here we can create a mass stream function contours by combining the zonally averaged annual mean velocity in the vertical direction and in the meridional direction. The strength of the Hadley circulation will be proportional to the gradient of this mass stream function contours. And when we plot this mass stream function contours, the strength of these cells become much clearer. This is the mass stream function contours for the various convection cells.

These two are the Hadley cells, the northern Hadley cell and the southern Hadley cell, sorry the northern Hadley cell this one and the southern Hadley cell in the December, January, February. This is the polar cell here and the mid-latitude cell here which are both of which are significantly weaker than the Hadley circulation system which is governed by strong differential heating and weak Coriolis forces. Furthermore, the winter hemisphere Hadley circulation system is far stronger. You can see in December, January, February northern hemisphere circulation system is stronger. In June, July, August the southern hemisphere circulation system is stronger.

And the reason is there is a larger gradient of heating in the southern hemisphere in winter and northern hemisphere in winter even in the equator to the subtropical region which has now moved away from the sun. Because of the gradient in the differential heating you have a strong Hadley circulation system especially in the winter hemisphere and this extends into the equator for both. So, the northern Hadley circulation cell is strongest during December, January, February, while southern Hadley circulation cell is strongest during June, July, August. This is because the winter hemisphere has stronger temperature gradients and the effective equator where insulation is maximum has moved to the summer hemisphere. Note that part of air descending down in the subtropics moves towards the poles and contribute to the transport of heat from low to high temperatures.

So, this moves a bit towards the poles to the second cells and this contribute to the transport of heat. Now, the polar region or the sub polar region 60 to 90 degree is extremely cold due to low insulation. As a result, air near the poles cool and sink down towards surface creating a polar high-pressure zone. On reaching surface the cold winds move towards the equator and at the 60 degree north and south latitude collides with the forward moving surface winds from the subtropical high-pressure zone and is forced to rise. So part of the Hadley circulation as it moves down is moving towards the 60 degree north and 60 degree south winds.

And the polar winds descend at 60 degree north and south and these two heat together. And heating causing a rise in the air at this point. So, the polar wind moving towards the 60 degree north and the Hadley wind moving towards 60 degree north, these two converters are forced to rise up. Thus, a subpolar low-pressure belt forms at 60 degree north and south because of the collision of these winds coming from the tropics and coming from the polar. And here you have a very strong $\frac{dT}{dy}$ gradient as well because of this convergence issue.

So, a very strong westerly get generated in the 60 degree north and the 60 degree south magnitudes because the $\frac{dT}{dy}$ gradient is very strong. The rising air moves back towards the poles creating the polar convection cell. So, this you can see here, the polar convection cells moving up, this air moving going here heating going up creating the polar convection cell. The surface level meridional wind is from the poles towards the 60 degree latitude. They are strongly deflected to the right in the northern hemisphere and to the left in the southern hemisphere and hence are called the polar easterlies because they are moving from east to west and hence they are polar easterlies.

In the mid latitudes, we have a weak convection cell. Which is there basically to balance the mass and the momentum constraints created by the polar and the Hadley circulation system. Because what we are seeing here is at 60 degree north winds are ascending, at 30 degree north winds are descending. Clearly wind at 30 degree north is warmer than wind at 60 degree north. So, in terms of the polar of the mid-latitude cell, which is called the ferrule cell, it's the hot air that is going downwards and the cold air that is moving upwards. So, it's an indirect circulation system, which is dry, which is against the thermally driven circulation systems of the Hadley and the polar cell.

And they exist primarily to preserve mass and momentum value. Hence, the Ferrel cell is particularly weak. Clearly, it also transports winds from the subtropical high to the subpolar low and is deflected by the Coriolis force in the westward direction and hence you have the westerlies. These are called the mid latitude westerlies. So, the main surface level winds are the polar easterlies 90 to 60 degrees that flow from east to west, the mid-latitude westerlies 60 to 30 that flow from west to east and northeast trade winds in northern hemisphere and southeast trade winds in the southern hemisphere.

So, we will stop here. In the next class, we will discuss the high-level winds, winds near the top of the troposphere and how they look. Thank you for listening and see you in the next class.