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

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IMPORTANCE OF MIXING LAYER AND WIND DRIVEN SURFACE CURRENT

Good morning class and welcome to our continuing lectures on climate modeling, climate dynamics and climate variability. We are continuing our discussion on oceanic circulation systems. And in the last class we started discussing about the mixed layer which is the well-mixed relatively shallow surface layer of the ocean where the wind and the wave actions are sufficient to vigorously mix the water, so that the temperature and the salinity gradients are uniform with temperature. We also saw that the mixed layer is the region where most of the solar heat is getting absorbed and it is also the region where ocean uses heat to the atmosphere through surface processes like evaporation of water, convection based cooling by the wind and radiation losses. We also saw that in the equatorial region the mixed layer has significantly high values of salinity, making it thin and warm, whereas in the high latitudes, especially in the winter, the mixed layer is thick due to vigorous buoyancy driven convection currents that exist within it. Hence, the depth of the mixed layer is larger in the winter hemisphere, particularly in the high latitude oceans.

Whereas it is thinner in the summer hemisphere, particularly in the subtropics. When we discuss climate modeling and we are looking at timescales of a year or up to a decade, it's the mix layer which is the most important part of the ocean. Much of the short and medium term climatic influence of the ocean is confined to processes occurring in the mix layer. Storage and removal of heat from the ocean on the time scales of less than a year are confined entirely to the mix layer only.

The mix layer responds fairly quickly to changes in the surface wind and surface temperature whereas oceans below the mix layer does not. Here we are showing the potential temperature contours of the mix layer in the month of January which is northern hemisphere winter and in the month of July which is northern hemisphere summer. We see that in the equator and the subtropical belts the temperatures do not vary significantly between January and July. There is some increase in temperature in the temperate regions in the mixed layer during summer months compared to the winter months though it is not significant. In general, the ocean's mixed layer temperature, potential temperature, does not vary significantly from one season to the next.

The thermal capacity of the mixed layer can be considered to be the effective heat capacity of the ocean on the timescales of years to a decade and is approximately 30 times the heat capacity of the atmosphere. These are important considerations when we are looking at climate modeling on what part of the ocean is of relevance when it comes to the span over which we are determining the climatic variations. Now, we have said that wind driven surface currents are an important part of the mixed layer of the ocean. So the mix layer is the region where you have large surface level currents of the ocean and these are driven by the wind systems or the atmospheric wind circulation systems near the surface. In the past, these ocean currents were very important for travel of the ships.

So these ocean currents have been carefully mapped. before the advent of mechanized ships. How do the ocean currents form? They form due to the transfer of momentum from the winds to the ocean through frictional drag forces. So the uppermost layer of the ocean are dragged by wind driven frictional acceleration which in turn drags the layers below. So, we will have an interesting point here and I will just note this down before we discuss this in detail.

The topmost layer, the sea surface is dragged by the wind and the topmost layer therefore circulates in the direction of the wind. However, the layers below still within the mixed layer but not the topmost layer. There the movement of the ocean currents will be different than the wind direction and this happens due to the presence of Coriolis forces which affect the ocean current as well. So the uppermost layers of the oceans are dragged by wind driven frictional acceleration which in turn drags the layers below. However, this frictional acceleration weakens with depth and the base of the mixed layer is the location where the frictional acceleration effect decays to zero.

So, the bottom of the mixed layer is also the location where the impact of the frictional drag force caused by the wind decays to zero. So, the mixed layer has many simultaneous definitions. It's the region where the temperature and the salinity are constant due to vigorous mixing. It's the region where solar heating is happening. It's also the region where the frictional drag force of the wind is confined to. The depth over which wind-driven surface currents are generated is also called the Ekman layer. After V.W. Ekman who developed the essential physics describing how the ocean currents form. So we also call this the Ekman layer.

And here we are getting the impact of the Coriolis force on how the currents are oriented as we go deeper and deeper into the weak space. If you remember the Coriolis force is given by this expression here.

$$\overrightarrow{F_{Cor}} \cong mf(v\hat{\imath} - u\hat{\imath});\ where, f = 2\Omega sin\Phi\ is\ the\ Coriolis\ parameter$$

The force is mass, here it will be the mass of the water in question into the Coriolis parameter which is $2\Omega sin\Phi$, where omega is the earth's rotation in radians per second and phi is the latitude angle, positive in northern hemisphere and negative in southern hemisphere. mf into now the zonal component of the Coriolis force which is determined by the meridional velocity v minus the meridional component of Coriolis force which is determined by the negative of the zonal velocity v $(v\hat{\imath} - u\hat{\imath})$. Remember the Coriolis force parameter is positive in the northern hemisphere where $sin\Phi$ is positive and negative in the southern hemisphere where $sin\Phi$ is negative.

So, if the ocean current is moving in the plus u direction that is west to east direction, then you have plus u here which means you will have a minus mfu as the Coriolis course in the j direction of the north-south direction. Hence that ocean current will feel an acceleration in the north to south direction. As a result, the ocean current will be diverted from directly going from west to east to going towards the south. So, it will be diverted towards its right. This means that the current will be deflected southwards to its right. In the southern hemisphere, the Coriolis force parameter is negative and hence the force will be south to north and hence the current will be deflected northwards. So, if the current was flowing from west to east, in the southern hemisphere it will be deflected towards its left, that is northwards. And this is what we see in this figure here. The initial frictional force is from west to east. In the northern hemisphere, the Coriolis force is affecting and the actual direction is shifting rightwards. Coriolis force in the north to south direction and hence the actual current is shifting rightwards. Similarly, in the southern hemisphere, the actual current is shifting leftwards. Now, this surface current drags the water immediately below it as well. So, there is a cascading effect of the frictional force. The surface, the water moving along the surface will have a frictional effect on the water layer directly below it and it will drag it in the same direction as the surface current is moving.

But again, due to the Coriolis force, because now the layer below the surface also has this direction, it will find a Coriolis force that will shift back towards the further rightward in the northern hemisphere and further leftward in the southern hemisphere. But once again, the Coriolis force acts on the second layer whereby the flow of the second layer is deflected to the right of the first layer. So, the first layer is here, the direction. Because the Coriolis force is once again acting on the second layer, the flow of the second layer is deflected to the right and moves further to the right. Similarly, here also it moves further to the left and goes in this direction.

And this process of moving continuously rightward and moving continuously leftward happens as we move further and further down until the point where we reach the bottom of the mixed layer where the frictional force tends to zero. So, what we have is a clockwise spiraling current with depth in the northern hemisphere. In the northern hemisphere, we have a clockwise spiral with depth. In the southern hemisphere, we have an anticlockwise spiraling current with depth in the southern hemisphere. This is called the Ekman spiral.

So, you can see this here. The wind direction here is from south to north. So, you have a zonal acceleration from west to east causing the current to move, shift rightwards to 45 degrees. This is the surface current. The current below it shifts further right, the current below it shifts further right, so on and so forth and you are getting kind of a spiral motion till you reach the bottom of the mixed layer where the frictional force goes away completely and the velocities continue to decay as the frictional force weakens and weakens.

So, as we go in depth the current moves rightwards of the immediately preceding surface layer and decreases in magnitude. In the southern hemisphere, the current moves leftwards of the immediately preceding layer and decreases in magnitude. So, you have a clockwise decaying spiral in the northern hemisphere and an anticlockwise decaying spiral in the southern hemisphere. Now, you can integrate all of these velocities together and find the net volumetric transport of this current. And what we will see is the net transport of water because of the combined impact of all of these spirals is a transport 90 degrees of the wind direction.

So, paradoxically, the surface current is 45 degrees or it may be more, it kind of depends on the strength of the Coriolis force. So, near the equator the deflection is lower, in the high latitudes the deflection is far higher and as a result you will have a surface current which is deviating at a certain angle with respect to the wind direction. But the net water transport will be always be perpendicular to the direction of the wind by the combined integration of these spiraling currents. So, whichever way the wind is blowing, the ocean current is transporting water 90 degrees against it.

Okay. And this is 90 degrees to the right in the northern hemisphere, 90 degrees to the left in the southern hemisphere. So, if this south to north moving wind was in the southern hemisphere, the transport would be in this direction, in the leftward direction. And we can show this explicitly in an analytical expression. So let us see how this works and we will use a very similar kind of an idea as a geostrophic balance. There the balance was between the pressure force and the Coriolis force.

Here the pressure forces are negligible. So you have a balance between the frictional force and the Coriolis force. And we can assume steady state condition, so the net effect of the total derivative $\frac{Du}{Dt} = \frac{Dv}{Dt} = 0$.

$$0 = fv_E + F_F^x \text{ and } 0 = -fu_E + F_F^y$$

Neglecting the pressure force, you get the zonal component as fv_E, the Ekman velocity, the meridional component of the Ekman Ocean current velocity into the Coriolis parameter F, this is the first term here, plus the frictional force in the zonal direction. Similarly, the negative Fue, negative Coriolis parameter into the zonal Ekman velocity u_E, this parameter here, plus the frictional drag force in the y direction caused by the wind current.

So, F_F^x and F_F^y are the zonal and the meridional components of the frictional forces per unit mass. u_E and v_E are the zonal and the meridian components of the Ekman velocity for that parcel of water. Here we have equated the Coriolis force with the frictional drag force. Now what is the frictional drag force? We need an explicit expression for the frictional drag force. Remember water can be viewed as an incompressible liquid.

So, the net frictional drag force experienced by a parcel of water in the x or the zonal direction is proportional to the difference between the x component of shear stress between its top and bottom surface. So, suppose you have a parcel of water oriented in the vertical direction. There is a shear stress acting in the x direction on its top surface and a shear stress acting in the negative x direction say or a smaller amount of shear stress acting in the negative x direction in the bottom surface. The difference between these two shear stresses is a net fictional drag force that is acting on this volume of water. Hence, the zonal component of the frictional drag force is proportional to the vertical gradient of the zonal shear stress tau x.

So, the zonal shear stress tau x will have a vertical component. So, $\frac{\partial \tau_x}{\partial z}$, the vertical gradient, how the shear stress is decreasing with depth. That gradient is going to be proportional to the frictional drag force and the exact proportionality constant by unit balance is the density of water.

$$F_F^x = \frac{1}{\rho_w}\frac{\partial \tau_x}{\partial z} \; and, F_F^y = \frac{1}{\rho_w}\frac{\partial \tau_y}{\partial z}$$

So, frictional force in the x or the zonal direction per unit mass is equal to the gradient of the zonal component of the frictional drag divided by the density of water. Similarly, the meridional component of the frictional force is equal per unit mass is the gradient of the meridional shear stress with depth and the density of water.

So, we can put these expressions directly here. So, we get the Ekman velocity is $\frac{1}{\rho_w}$ into the gradient of the meridional shear stress the meridional Ekman velocity is minus 1 by rho wa into the gradient of the zonal shear stress. So, notice that the zonal velocity is determined by the gradient of the meridional shear stress and the meridional velocity is determined by the negative of the gradient of the zonal shear stress. Now the vertical height is kept at z equal to 0 at sea level and is negative downwards. Assuming that the density of water is constant throughout the mixed layer, so we take ρ_w to be a constant, then we integrate from the top of the ocean surface where z is 0, the sharp surface shear stress values are τ_x^S and τ_y^S, the components at the surface and we integrate from there to the bottom of the mix layer which has a certain depth h and at the bottom of the mix layer there is no shear stress left.

So, τ_x and τ_y are 0. So, we start from τ_x^S , τ_y^S and get to 0. If we do that, then we can integrate this and get the vertically integrated Ekman velocity. Vertically integrated Ekman velocity flux. Since, we are integrating with respect to the depth, the unit of this is meter square per second. So, that is why it is called a velocity flux.

$$\begin{aligned}\vec{V} &= U\hat{\imath} + V\hat{\jmath} = \int_{-h}^{0} u_E dz\hat{\imath} + \int_{-h}^{0} v_E dz\hat{\jmath} \\ &= \frac{\tau_y^S}{\rho_w f}\hat{\imath} - \frac{\tau_x^S}{\rho_w f}\hat{\jmath} = \frac{1}{\rho_w f}\left(\tau_y^S\hat{\imath} - \tau_x^S\hat{\jmath}\right) \\ &= -\frac{\widehat{k} \times \overrightarrow{\tau_S}}{\rho_w f}\end{aligned}$$

So, the velocity flux V is capital $U\hat{\imath} + V\hat{\jmath}$ integral of 0 to minus h $u_E dz$ plus integral of minus h to 0 $v_E dz$ or integral of these two terms. And because we are integrating a gradient, you get back the shear stress at the surface. At h, the shear stress goes to 0. So, you get the surface meridional shear stress by density of water into the Coriolis parameter as the zonal Ekman velocity plus and minus the zonal shear stress at the surface density of water at Coriolis parameter as the meridional Ekman velocity plus. In terms of vector product, it is basically the vertical component cross product of the vertical direction with the surface shear stress at the sea level, at the sea surface divided by density into the Coriolis parameter.

This is the expression. So, now you can see the surface shear stress along the wind direction, correct. So, because you are doing a vertical direction across the surface shear stress, the direction of this Ekman velocity flux is perpendicular to the surface shear stress in the rightward direction. So, it is k cross that, so in this direction for the northern hemisphere. Whereas, if you are in the southern hemisphere, then it is the opposite, it is the opposite direction. Hence, the velocity flux associated with the Ekman transport is perpendicular to the direction of the wind. If we multiply the flux with a suitable length scale L, which may be associated with the width of the current, then we will get the net volumetric transport rate of water. There is one correction, this will be negative. So, k cross i is j. So this is a negative term. So just remember that. I will put it in the correct forms. This is negative of the k cross the surface shear stress $\rho_w f$. Now you have the correct direction. So k cross tau s is this direction.

Negative of this is this direction. So in the northern hemisphere, it is going rightwards. And in the southern hemisphere, it is the opposite. So it is going in the leftward direction. Hence the velocity flux associated with Ekman transport is perpendicular to the wind direction. If we multiply the flux with the suitable length scale L, which may be the width of the total ocean current, then we will get the net volumetric transport rate of water in meter cube per second.

This is called the Ekman transport and is also perpendicular to the wind direction. Obviously, you are basically multiplying the meter square per second along with the length scale which is usually the width of the current over which you want to see the volumetric transport. The common unit of volumetric transport by surface currents is swear drup. S-W-E-R-D-R-U-P, SWERDRUP, the unit is S_V, and one SWERDRUP is 10 to the power 6 meter cube per second. Clearly, a lot of, a significant volume of water is getting transported by this wind current driven Ekman circulation system, and hence the unit is basically a million-meter cube per second, which is one SWERDRUP.

Note that wind shear is along the direction of the wind, hence Ekman transfer is perpendicular to the wind direction. Now what does it mean? You will see, so for example consider the case of a cyclonic and an anti-cyclonic circulation over the northern hemisphere, wind circulation. So we have the cyclonic circulation of the northern hemisphere, we have anti-clockwise direction. So the winds are moving in this way over the surface. Now, because of the Ekman spiral effect the direction of water transport is perpendicular to the wind direction.

So, it will be in the radially outward direction because the currents are to the right of the direction of the wind. So, you will get a radially outward moving flow of water from the low pressure center. So, you will get kind of water is moving away from the low pressure towards the side and you have a divergence and you will have upwelling of deeper layers near the center of the low pressure. So, the surface waters will move away and there will be upwelling of colder water from the deep near the low pressure center. On the opposite hand, if you have a high-pressure zone, of course, the winds will be moving in the clockwise direction.

So, here the right moving is inside towards the high-pressure center and so there will be a convergence of surface waters from the extremities of this anti-cycling circulation towards the center and then this water will try to move downwards. So, there will be a downwelling from the high pressure center. Note in the southern hemisphere the low pressures will be clockwise direction. So, in southern hemisphere low pressure it will be in the clockwise direction, but the Ekman direction is also going to switch. So, in the southern hemisphere the surface currents are going to the left of the ocean currents.

The water transport is going to the left of the wind. So, because it is going this way and you are looking at the left direction, again you will have a divergence. Similarly, at the high pressure zone, you will have a convergence. So, the same effect in the southern hemisphere because both the direction of the Coriolis force and the direction of the wind force is, wind direction is changing. So, the net effect remains the same. In both northern and southern hemisphere, you will see a divergence from the lows and a convergence on the highs.

Near the equator, this is not correct. So, near the equator, because the Coriolis force is weak, you will have the water transport along the wind direction exactly at the equator. Further away from the equator the Coriolis force will become stronger and stronger and by 10 degree north latitudes you are getting the full effect of the Ekman spiral and you get transport of water perpendicular to the direction of wind. In the southern hemisphere it will be towards the left of the wind, in the northern hemisphere to the right of the wind. Suppose you have a east to west moving wind, this will be the vector structure of the water transport around the equator. What this means is an east to west moving wind will cause a net divergence of the ocean surface level water from the equator creating an upwelling.

Similarly, a west to east moving wind will have the opposite effect, a convergence of ocean waters from the outside and it will cause a downwelling. And this is important because if you remember, the northeast and southeast trade winds are going from west to east. So, you will expect that the ocean current, there will be a convergence of waters from the say 10 degree north and 10 degree south towards the equator causing a local downwelling at the equatorial reach. Now, at the surface level you will have at the at the extreme top surface the ocean currents broadly follow the wind circulation patterns with certain deviations and because large subtropical high pressure centers exist on the oceans between 20 degree and 30 degree latitudes corresponding to the descending branch of the Hadley circulation system. These high pressure belts lead to formation of large subtropical anticyclonic circulation in the winds, which we have seen before, right? You have anticyclonic circulation in the subtropical regions.

And these anticyclonic circulations drive a clockwise wind circulation system between the low and the mid latitudes in the northern hemisphere and an anticlockwise wind circulation system at the low and the mid latitude in the southern hemisphere. The equatorial easterlies and the mid-latitude westerlies are the lower and the upper arms of this anti-cyclonic circulation system in the oceans. This causes the near surface waters, waters close to the surface, not the entire mixed layer, at these regions to also generally move in a clockwise pattern in the northern hemisphere and in the anticlockwise pattern in the southern hemisphere. And these circulating water flows are called gyres.

You will see this effect here. So, near the equator you have the movement like this. So you have winds, northeast trade winds and southeast trade winds which are moving winds from east to west direction as a result the ocean currents also typically move in the east to west direction but because of the coldest force is diverging towards the right so you will have this kind of a structure. Similarly in the southern hemisphere you will have the wind moving from in the from the southeast trade winds you are moving like this And the ocean currents also have a divergence like this. And in the mid-latitudes, you have the westerlies, west moving strong winds in the mid-latitudes here and here, which is causing the ocean currents to move back towards the east from the west direction. So, overall, you will have a clockwise circulation system around the subtropical high pressure zones. These are called the North Atlantic Gyre and the North Pacific Gyre where this bottom layer is driven by the trade winds and the top layer is driven by the westerlies.

Similarly, in the Southern Ocean, you have the South Atlantic Gyre, Indian Ocean Gyre and South Pacific Gyre which are moving in the anticlockwise direction along the trade winds near the equator and along the westerlies near the temperate regions. These circulation systems are important because remember the mixed layer is quite warm near the subtropical region. So, this warm water travels upwards along the eastern coast of the continents as you can see here. here and here so eastern coast of Australia eastern coast of Asia eastern coast of North America and eastern coast of Brazil. So the warm tropical waters move along these gyres, along the eastern coast of the continents, making the eastern coast of the continents relatively warm and wet, because these waters are quite warm and wet, sorry, quite warm, they have a stronger evaporation rates, creating climatic instabilities.

So, the eastern coast of the continents have greater chances of storms and precipitation events happening because of the presence of these warm waters along its coastlines. In contrast, as these waters move in the temperate region, driven by the westerlies, they slowly cool down and by the time they are moving downwards again along the western coast of the continents, they have become quite cold. Remember the mixed layer has become quite cold in the temperate regions because of the high loss of heat due to radiation, due to evaporation and due to wind driven convection. So, this current become quite cold. So, you will see that cold currents are moving along the western coasts of the continent, western South Africa, western coast of North America, western coast of USA, western coast of Brazil.

Similarly, western coast of Australia. Because the oceans along these coasts are very cold, the amount of evaporation is also very low and you will get cold, dry climates along the western coast of the continent. So, in general, the eastern coasts are warm and humid, with a lot of rainfall. the western coasts are cold and dry. As a result, you will see desert-like conditions or arid conditions prevailing in the western coasts of the continents compared to the eastern coasts of the continents.

So, for example, East Australia is extremely warm with lots of forest. Western Australia is arid. Southern African continent is quite wet and humid. The Kalahari deserts and other desert regions are along the western coast of both South Africa, Southern Africa and western coast of North Africa where you have the big Sahara desert. Similarly, the California region and the Mexican western coast is quite arid, the regions around Peru is quite arid, whereas the eastern coast Brazil and Argentina are quite humid. So, this is how this ocean currents control the climates of these continental coastlines.

I will discuss these things further in the next class. Thank you for listening and we will continue this lecture.