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

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Week- 08

Lecture- 43

OCEAN SALINITY AND MIXING LAYER

Good morning class and welcome to our continuing discussions on climate dynamics, climate variability and climate monitoring. In the previous lecture we started our discussion on global ocean systems and oceanic circulation system and we discussed two important properties temperature and salinity which are very important in determining the oceanic movement of oceanic waters due to density gradients. As we saw the density of high temperature water is lower than the density of colder oceanic waters also at a given temperature more saline water is denser than less saline water. Temperature gradients and salinity gradients together determine the flow that oceanic systems will have, especially in the deeper layers where wind driven circulation systems are not active. In the previous class, we looked at the salinity gradients as well as the temperature gradients with seasons and in different latitudes of the Atlantic and at the Pacific Ocean. Today we will combine all of that information in creating contour maps, in looking at the contour maps of potential density, potential temperature and salinity.

If you recall potential density and potential temperature are the densities and the temperature that are certain mass of water at a given depth Z will have if it were adiabatically brought to sea level pressure of 1 bar. We are looking at the potential density and potential temperature because it eliminates the compressibility effects which will distort the effective density and temperature differences otherwise. Now the contour maps have been plotted with respect to pressures in decibar. Now 1 decibar is basically 0.1 bar. So, in the x-axis we are plotting the salinity or potential temperature or potential density, while in the y-axis we are plotting the decibar, the increase in the pressure as we as we go further and further down from the sea level in terms of decibars, ok. So, potential density delta has been plotted which is the density at a given altitude given depth minus 1000 kg per meter cube which is the density of seawater at one bar. So, this is the density deviation above the 1000 kg per meter cube which is the standard density of water at a at standard temperatures and pressures. Now, why we are plotting using pressure in decibar instead of depth? Actually, pressure in decibar is a good proxy for depth as 1 decibar increase in pressure corresponds to increase in depth of about 1 meter.

So, there is a reasonable correspondence between the increase in pressure with depth with the increase in the actual depth of the ocean from the sea level. So, if a location has 100 decibar pressure above 1 bar, then that location is 100 meters below the sea level. So, let us look at the contours first and then we will discuss the basic features one by one. First, we are looking at the potential temperature contours. in the Atlantic Ocean and in the Pacific Ocean and these are the mean contours which is mean over the entire year.

Here is the latitude values in the x axis. So, this is equator 20 degree north, 40 degree north, 60 degree north, 80 degree north then the north pole. This is the south pole minus 20 degree, minus 40 degree, minus 60 degree etcetera. Here it is ending at minus 80 because the 80 to 90 degrees you have the Antarctic continent, so there is no sea there. In the y-axis, we are starting at the sea level which is 0 decibels.

So, this is the basically what is the gauge pressure, pressure above the sea level. So, this is sea level pressure. This is 500 decibels above the sea level pressure, 1000 decibels above the sea level pressure, 1500 decibels above the sea level pressure. So, again we are measuring up to say 1500 meters only approximately. And we are plotting the potential temperature contour in degree centigrade.

The values of the potential temperatures are also being given. So, this is the 2 degree centigrade contour. This is 12 degree centigrade contour. This is 6 degree centigrade contour. And if you go above, this will go up to say, so this is 14, 16, 17, 18, 20, 22, 24, up to 24 degree centigrade contour.

Similarly, in the Pacific Ocean. So now what you can see is that The equatorial and the subtropical regions of both the Pacific and the Atlantic Ocean is very hot near the surface. So, the first say 100 meters or 100 decibels which is associated with the mixed layer of the ocean is quite warm both in the equatorial region and the subtropical regions between say 0 to 30 degree north and south latitudes. Beyond that, the mixed layer temperature decreases very quickly and goes down to say 0 degree centigrade by the time you reach minus 70 or plus 70, 70 degree north or 70 degree south latitudes. And this is true also for the Pacific Ocean as well.

If you go down you have a very steep temperature gradient, a decrease in temperature at the equator. So, the thermocline region is extremely steep in the equatorial region for both the Pacific Ocean and the Atlantic Ocean. And it remains reasonably steep also in the subtropical belts as well. Though you can see that in the subtropical belts the hot water extends further down. So, you have this kind of a lobe structure that you are getting hotter waters more deeper into the as we go down towards those.

However, by around 1000 meters you are seeing that the thermocline leveling out. over the entire equatorial and the subtropical belt and you are getting around 4 degree to 6 degree centigrade by 1000 meters. Beyond the equatorial region, so beyond say 40 degree north and 40 degree south, you are seeing the thermocline region, the surface water also significantly cold, as a result the thermocline becomes less and less steep. So, by the time you reach the sub polar regions of 60 degree or 70 degree north and south, you are getting colder waters extending throughout from the depths of the ocean to the top of the mix layer. And in extremely high latitudes, you may get waters that are colder on the surface than at the oceanic depths.

So, steep thermocline regions in the equator and reasonably steep thermocline regions in the subtropics, the thermocline kind of decays in gradient as we go to higher and higher latitudes as the mix layer also becomes colder and colder and it is almost non-existent in the high latitude ocean. Now let us look at the salinity gradients. So, here the values are also you can see 34.4 grams per kg, 34.8 grams per kg, 35.2 grams per kg and so it is written like this. Again in terms of 0.2 grams per kg gradients of salinity. Here we see a marked difference between the Atlantic and the Pacific Ocean. we see that the salinity values are much lower in the Pacific Ocean than in the Atlantic Ocean.

So, you are getting up to 37, 37.5 salinity values in the mixed layer of the subtropical regions of the Atlantic, whereas in the Pacific you are getting much lower values of around 34.5, 34.8 in the same regions. So, this goes up to say 36, 37 here.

So, this is 35.2, 35.4, 6, 8, 36, 36.2, so up to say 36.5 you are getting salinity values in the subtropical regions of the mixed layer. And in the Atlantic, in some regions, especially in the South Atlantic subtropical region, in the North Atlantic subtropical region, the salinity is quite high, even up to 1500 meter depth. So, even at the bottom of the thermocline, salinity is reasonably large.

This is not true in the Southern Atlantic, which is a little bit more open, where the salinity drops reasonably quickly as we go down. As we go in the passive, however, the salinity is high in the mixed layer but drops off very quickly as we go to below say 500 meters or 500 decibels at the ocean bottom from the surface. Now as we go into the high latitude regions, the mixed layer becomes noticeably fresher than the deep layers. So the salinity gradient is reversed in the mid latitudes and in the high latitudes. So from say 40 degrees south and around 50 degree north in the Atlantic Ocean and around 40 degree south and around 30 degree north in the Pacific Ocean, we are seeing that the surface layers are fresher than the deeper layers.

So, you are getting much lower salinity at the top surface than in the deep waters. So, the reason for this is also discussed before. So, I will just reiterate it. The subtropical oceans have high evaporation and low precipitation. As a result, salinities are high, whereas the subpolar and the mid-latitude oceans have high precipitation and low evaporation.

Hence, it is freshened. than the deep layers also. So, this point becomes important when

we are discussing the potential density gradients. So, what we see here is that the subtropical ocean, upper layers of the subtropical ocean have high salinity as well as high temperature, all right, compared to the deeper layers. Whereas in the higher latitudes, you have lower salinity and almost the same temperature as compared to the deeper layers. What does this mean? As we said, since the temperature gradients are reasonably small, you will be getting more salinity driven circulation in the high latitudes, whereas since the temperature gradients are much larger in the subtropical regions, you will be getting more temperature driven circulation in the subtropical oceans.

And we see this effect in the potential density contours which is the last of the contour plots. So, here you see The red has lower density and the blue has higher density. So, bluer it is, higher is the density. Redder it is, lower is the density. And the density is in kg per meter cube minus 1000, the potential density delta.

How much is the density compared to 1000 kg per meter cube? Okay. So, this is basically 1026 kg per meter cube, this is 1027 kg per meter cube, this is 1027.75 kg per meter. So, we are removing the 1000, so we are getting the density deltas. So what you can see both in the Pacific and the Atlantic Ocean, the equatorial and the subtropical oceanic layers have a high gradient of density.

You have less dense, significantly less dense waters in the mixed layer and the density decreases as we go down in a monotonic fashion. What this means is denser water is at the bottom and less dense water is at the top Hence, there is very little chance of vertical circulation due to density effects. There is no buoyancy driven circulation at all because less dense water is at the top, more dense water is at the bottom. As a result, there is very upwelling and downwelling of oceanic waters does not occur in the equatorial and the subtropical regions at all. Because of the nearly uniform temperature gradients as well as salinity gradients in the high latitude regions, there you will see that the density gradients are substantially weaker.

So, you will see here there is very little density gradient between the deep layers and the top layers in both the, at around 70 degree south or 70 degree, 70 or 80 degree north So here there is a significantly greater chance of upwelling and downwelling of ocean currents. oceanic waters from the deep layers move up to the top layers only at the high latitudes and only at the high latitudes also top layer waters go down. So, the entire mixing of the deep layers with the upper layers of the oceans only happen in the high latitude regions near the north and the south pole. So, this is these are the main things that we have to be mindful of. that upwelling and downwelling of deep layer waters primarily happen in the subpolar region between 70 to 80 degree latitudes.

We will see this effect when we discuss the ocean currents more. Now, let us look at little bit more into the base different types of layers particularly the mixed layer which is very important determining the climate of the world. So, the mixed layer is the uppermost layer of the ocean and is defined as the region where temperature and salinity values are nearly constant with depth due to efficient mixing by the winds and the waves. This is the region where winds and the waves are strong enough to agitate the oceanic waters. As a result, temperature and salinity values are nearly constant.

The primary heat source of the ocean is solar radiation. So how do oceans heat up? By absorbing solar radiation. And the mixed layer is the region where this solar radiation is getting absorbed. So all the energy flux in the sun is also absorbed within the mixed layer.

So there are two things. First criteria. strong mixing by winds and the waves causing nearly uniform temperature and salinity gradients. This is also the region where all the solar radiation is getting absorbed. The solar flux decreases exponentially with depth and the heating rate decreases to about 50% of the surface value within 1 meter depth of the surface. So, as soon as the sun heats the water, water is a strong absorber of sunlight, ok, unlike the atmosphere. So, within the top 1 meter, 50% of the solar radiation has been absorbed, ok.

However, significant heating may extend up to 100 meters which is near the bottom of the mix layer depending on the amount of suspended matter present within the mix layer. So, if the ocean is very clear, there is very little suspended matter in the ocean, then the sunlight can reach deeper into the oceanic water and you can have significant heating till about 100 meters deep. So, there is a kind of a volumetric heating of the top 100 meters which is the mixed layer of the ocean. How does the ocean lose heat? The ocean lose heat at the surface to the atmosphere. It is gaining heat by absorbing sunlight in the top 100 meters and it is losing heat to the atmosphere from the top of its surface.

So, heat loss is a surface phenomenon, heat absorption is a volumetric phenomenon. And how does it lose heat? To phenomena like evaporation of water. As water evaporates from the surface, it absorbs latent heat of evaporation from the water around it which cools the surface, the rest of the surface of the water and also sensible and radiative heat losses. So, as ocean heats up, it radiates heat. So, that is a loss to the atmosphere and also sensible heat.

So, it is also cooled by convection from the wind flowing on top of it. In contrast, heat is absorbed by the ocean from the solar radiation over a depth of several tens of meters. Hence, you have a net upward flux of energy from the bottom to the top of the mixed layer in order to satisfy the energy balance. Let us understand this using this very simple kind of graphic. This is the solar radiation and where the solar heat is getting absorbed.

It's an exponentially decaying curve. So, most of the heat is getting absorbed here, but there is still sufficient heat absorbed up to say 100 meters here. So, this entire is the heating rate of the oceanic layer. The heat flux going out is from the surface. So, evaporative cooling. and also sensible and radiative heat loss is happening from the surface.

So, if you do an energy balance of the surface, there must be heat transport from the depths of the mix layer to the surface to have an energy balance here. So, if the surface water is at a certain constant temperature, it is at a constant temperature because the energy loss from the surface through radiation, evaporation etcetera is balanced by energy coming through the mix layer from the bottom of the mix layer. So, there is a net transport of heat from the near, from the bottom of the mix layer towards the top. This heat flux, how does this heat flux get transported? By turbulent mixing. So, because you have a strong turbulent mixing effect caused by the waves and the winds, that mixes the hotter waters at near the center of the mix layer to the colder water at the surface that is being cooled by radiation and evaporation effects.

You can also have convective overturning. So, this water as it cools due to radiation and evaporation becomes denser and can go down whereas relatively hotter water near the center of the mix layer can come up. So, you can have convective overturning within the mix layer as well. And mean vertical motion which is called the upwelling or downwelling in the ocean. This is all, this can also happen. Entrainment of cold water coming from below the mix layer can also be an effective means of transporting water to the top.

So, all of these processes can transport heat towards the surface where it is lost through radiation, evaporation, convection, etc. Now, the turbulent mixing process, which is one of the main ways by the water heat transport is happening, is driven by the supply of kinetic energy from the winds and their interaction with the waves on the surface of the water. So, that is a complicated process. The winds are creating the waves that you see in the ocean. So, the turbulence that is caused by the joint impact of the winds and the waves is causing the turbulent mixing.

And these processes are very efficient and are particularly strong in regions of high winds and waves. In the high latitudes the ocean surface is cooled very strongly creating cold dense water near the surface and generated buoyancy forces drive convective overturning with the sinking of the cold water and rise of the warm water in the mixed layer. So, here what we are discussing is where which process is stronger. So, in the regions where we have very strong winds clearly turbulent mixing processes will be stronger because strong waves and wind driven turbulence will be generated. Further in the high latitudes to the subpolar regions, you will have a lot of cooling, but not sufficient thermal radiation coming to the, coming on the surface.

So, there will be strong cooling because the atmosphere is quite cold. So, the surface water will be very cold because it will lose heat very quickly to the cold atmosphere and hence it will come down. quickly towards the bottom of the mix layer and water from the bottom of the mix layer will go up. So, the buoyancy driven convection forces will be very strong in the high latitudes. So, mix layers in the high latitudes and in the winters are usually thicker.

So, this is something that we have seen before. So, we have seen in the previous class that we when we looked at the mix layer depths in the winter time the mix layers are significantly deeper and this is because the buoyancy driven convective overturning mixing the waters is stronger so the mix layer width thickens because mix layer by definition is where you have a significant mixing process working so as the mixing process increases in strength the mix layer also increases in depth and this is true in the high latitude winters At low latitudes and in the summer, the ocean surface is cooled very weakly because the atmosphere is also quite hot and may be warm by strong surface absorption of radiation. So, because the solar insulation is so strong that you will have significant heat absorption near the surface as well, whereas the cooling is relatively muted. So, the surface waters remain relatively warm, depressing the effect of convective overturning. Therefore, buoyancy driven overturning does not happen. So, the mixed layers in the low latitudes or during summer are usually warm and thin.

So, cold and thick mixed layers in the high latitudes and in winters, warm and thin mixed layers in low latitudes and in summers. because of this completing forces the depth of the mixed layer can be quite variable from region to region its average depth is 70 meters but in some regions it may be as low as 20 30 meters near the equator And in some regions, especially in the high latitudes where there is strong upwelling and downwelling of ocean currents, it can be more than 500 meters deep. And this fact can be seen in the mixed layer depth values over the globe. So, here we have the contours, say in the northern hemisphere winter in January, and And red regions are thin regions, blue regions and white regions are very thick regions. So here the contours are at 30 decibar intervals with the reddest contours with layers, depth layers less than 30 bars.

And the deep blue regions are where you have very deep mixed layers because of the large scale downwelling of surface level waters and upwelling of deep waters. So, you see a significant region, you have mixed layer depth of 30, then you have mixed layer depth of 60. So, because this is summer in July, you have warm and thin mixed layers over the entire northern hemisphere. Whereas, most of the southern hemisphere the mixed layers are thicker because they are colder and you have stronger buoyancy driven circulations. So, throughout the southern hemisphere the mixed layers go from 60 to 90 to 120 to 150 to 200, 150, 180, 210, 230.

So, especially in the winter hemisphere the mixed layers are thicker. near the high latitudes close to the Atlantic, Antarctic peninsula, you have extremely deep mixed layers where the, there is strong upwelling and downwelling of surface level water with the deep, deep level waters. The situation is reversed in the northern hemisphere winter, here now you can see that the entire southern hemisphere the mix layer is shallow and warm even in the southern oceans, whereas in the winter hemisphere the mix layers increase in depth and especially in the near the top of the Antarctic, Atlantic and Pacific Ocean you have deep mix layers because you have strong upwelling and downwelling of the surface level waters. So, what you see here is that in the winter hemisphere at high latitudes there is significant mixing of the deep oceanic layers with the surface level waters. And this is the reason why deep oceanic layer waters are so cold because they are sourcing their water from the cold mixed layer waters of the southern hemisphere high latitude winter regions or southern hemisphere, northern hemisphere, high latitude winter regions. So why is the mix layer so important? Much of the short and medium term climatic influences of the ocean are constrained by processes occurring within the mix layer only. The storage and removal of heat from the ocean on the timescales of less than a year are confined to the mix layer. The mix layer is the part of the ocean that responds fairly quickly to change in surface wind and surface temperatures. So, the yearly or even decadal climate is constrained by how the mix layer reacts to changes in these constraints.

So, we will discuss that more in the next class. Thank you for listening and see you again.