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

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OCEAN CIRCULATION AND DEEP OCEANIC THERMOHALINE CIRCULATION

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. In the previous class, we were starting our discussion on the ocean currents that are present on the surface layers of our oceans. What we said was there were large anti-cyclonic high pressure systems that exist around the 20 degrees to 30 degrees north and south latitudes, creating clockwise and anti-clockwise circulation systems in the northern hemisphere and the southern hemisphere surface level winds over the oceans. These circulation systems drag the surface waters along with them, creating what are called oceanic gyres over North Atlantic, South Atlantic, North Pacific, South Pacific and Indian Oceans. These gyres are responsible for transporting warm waters that are near the equator up along the eastern coasts of the continents and then as these ocean currents cool in the mid-latitudes, transporting these cold waters that are in the mid-latitudes down towards the equator along the western coasts of the continents. As a result, eastern coasts of the major continents like Australia, Asia, Africa, the Americas have warm ocean currents flowing along their coastlines creating warm humid conditions and precipitation events.

So these regions are usually warmer and more humid than what is expected along their latitudes. In contrast, the western coasts of the continents have colder ocean currents coming from the high latitudes creating high pressure air regions which cool because of the presence of these colder ocean currents, low evaporation rates and hence cold and dry conditions. So, the western coasts of the continents are associated with the presence of deserts or arid conditions like the Atacama desert in Peru, the Mexican desert in the coasts of Mexico, the Saharan desert and the Namib desert in the north and southern western coasts of Africa and the Australian desert in the western coasts of Australia. The other important point to note is that these anticyclonic circulations create an effective transport of water towards their centers.

As we have noted, anticyclonic highs create a convergence of water from the edges of that high pressure belt towards the center. Hence, when we look at the entire Ekman transport. Hence, when you look at these gyres, the net effect is transport of mixed layer oceanic water from the edges of these continents towards the center of these gyres. Both in North Atlantic, South Atlantic, Indian Ocean, North Pacific and South Pacific. As a result, water is being dragged away from the coastlines causing upwelling of deep layer or thermocline layer waters towards the surface along the coasts of these continents.

This is particularly true when the continental margin is in the meridional or the north-south direction. For example, western coast of South Africa is oriented approximately in the north-south or the meridional direction causing significant strengthening of the Ekman transport from the coast towards the center of the South Pacific Gyre creating large upwelling of cold deep layer waters along these regions. This further cools because deep layer waters are colder than surface layer waters. These upwelling events further cool the ocean surface waters, create deep cold mixed layers and more arid conditions. Particularly true in the South American western coasts and the South African western coasts which are located in the oriented in the north-south direction.

So, these are the major regions of upwelling of the cold oceanic waters in the deep layers. As you can see the western coasts of the continents are the primary regions where this happens. One other location where this sort of upwelling is occurring is near the equator along the eastern coast of Africa in the Somalian Peninsula. The reason why this happens here and as well as in the eastern coast of Central America is because of the presence of northeast and southeast trade winds. These trade winds are dragging the water near the equator from the east to west direction.

Because of that, water is moving away from these coasts towards the western coast towards from away from the eastern coast of Africa towards the western coast of Indonesia. Here, so the trade winds are moving in this direction from west to east so water also in the equatorial regions particularly are moving in this direction. Creating upwelling, localized upwelling near the equator, particularly in the east coast of Africa. So, this effect is happening because Coriolis effect is absent near the equator and hence the easterly trade winds drive surface currents westwards. As they travel along the surface, these equatorial currents warm up by absorbing strong equatorial solar radiation, especially in the Pacific where the ocean basin is wide.

These warm equatorial waters arrive on the coast of Indonesia and northeast Australia, where they promote evaporation and formation of atmospheric instability. So, these northeast and southeast trade winds that are moving from the east to west direction, particularly over the Pacific, are creating these effects. Next up, we will look away from the mixed layer. Till now our discussion has been focused primarily on the mixed layer circulation systems and the mixed layer currents. Now we will go from the mixed layer to the deeper ocean and the circulation system in the deep ocean.

This is called the deep oceanic thermohaline circulation. Thermohaline because it is related to temperature and salinity gradients. Haline is basically representing salinity, thermo is of course temperature. So, thermohaline circulation is defined as that part of the oceanic circulation that is driven by water density variations caused by gradients in temperature and salinity. These circulations cannot be usually detected directly because they are extremely slow.

What we do, what scientists do is they use proxies to understand how these circulation systems are happening. One of the proxies is the amount of oxygen that is present in the water. Near surface water has a large amount of oxygen dissolved in the water because oxygen is coming from the atmosphere and is dissolving in the surface layers through wave and wind action. Further, the photosynthetic microorganisms like the plankton are generating a lot of oxygen on the surface waters as they photosynthesize using sunlight and nutrients. So, in general surface level waters have the highest oxygen concentration.

As these waters sink down, the photosynthetic activity is gone because beyond the mixed layer there is no sunlight, so no autotrophs can exist. However, this oxygen is still being consumed by all the heterotrophic microorganisms, organisms that are breathing in oxygen but not generating in oxygen through photosynthesis. So, as the oceanic water spends more and more time away from the surface, its oxygen concentration decreases. So, by noting the amount of oxygen concentration at different levels of water in the ocean, we can know how long that water has spent away from the surface relative to the surface level waters today. So, if a certain water coming from a certain depth of the ocean has very low oxygen concentration compared to that on the surface, we would know that these oceanic waters have spent a lot of time away from the surface.

So, oxygen concentration deviation from surface level values is a proxy for how long ago a parcel of water has last been at the surface. Here, we are plotting the oxygen concentration. Let me see what is the units. I think it is ppm. I am not entirely sure.

The units are in parts per million, I think. Or it's in the percentage terms. It's primarily as a relative percentage. So the surface level water is 100. So that is considered the base and deeper waters have oxygen concentration as a fraction of the surface level oxygen concentration. So if the surface level is kept as 100 and somewhere else it is 40, then that water has only 40 percent as much oxygen as the surface level water. So that is how this is done. So this is the oxygen concentration in the Atlantic contour along the depth and along the latitude. So, this is the northern hemisphere, this is the southern hemisphere, this is at the surface, this is the deepest part of the Atlantic, it is 5000 meters. What is interesting to note is that the most oxygen depleted water is not at the deep ocean at all, but it's the intermediate layers in the thermocline region of the subtropics and the equatorial region.

So, the subtropical thermocline region between 200 meters to 1000 meters in the North Atlantic and the South Atlantic, have the most oxygen depleted water among the entire Atlantic Ocean, showing that these waters have not been to the surface for a very, very long time. However, if you see the contours, you see that the deep oceans have fairly large oxygen concentrations. And there is a significant continuous gradient of high oxygen concentration coming from the North Atlantic at high latitude North Atlantic Ocean, 60 degrees and 80 degree north, which is almost continuous to the depths up to the bottom of the Atlantic Ocean in the north. And then as we move from the high latitudes of North Atlantic Ocean in the deep layers below the thermoplane, slowly we move southwards, the oxygen concentration depletes. So it seems there is a downwelling of waters from the high latitudes, subpolar regions of the North Atlantic Ocean to the depths of the Atlantic Ocean and then a slow southward moving motion of this downwelling water towards the South Atlantic Ocean.

So, the oxygen concentration slowly depletes and then it depletes, here the oxygen concentration is, so this is the kind of the motion that is happening and then another upwelling is occurring in the 60 degree south latitude. So you have a subduction of the oceanic waters in the high latitude North Atlantic Ocean and then an upwelling of these deep oceanic waters in the 60 degree to 70 degree south latitudes. So, an up downwelling North Atlantic high latitude and an upwelling in the South Atlantic high latitude. We also see a continuous gradient just along the coast of the Antarctic continent and so there is another downwelling just close to the coastline of the Antarctic continent. This is caused as we will see in the discussion that the Antarctic continent contains a lot of land ice as well as sea ice.

Particularly in winter, a lot of the surface water freezes to ice. As the surface water freezes to ice, the salt separates out of the water and increases the salinity of the water that has not frozen. So this cold saline water becomes dense and starts to descend along the coastlines of the Antarctic continent. So, there is another downwelling at 80 degree south latitude which is bringing these waters which have just recently moved up back down into the deep ocean. So, we have a large scale north to south deep level thermohaline circulation in the Atlantic and then a upwelling and then a sharp downwelling near the coastlines of the Antarctic.

Whereas, thermocline region of the equatorial and the subtropical regions is generally isolated from this structure, ok. If you see the situation in the Pacific, you are seeing a significantly large concentration of extremely cold waters in the North Pacific region that is extending from say around 10 degree south latitudes to almost 60 degree north latitudes and is extending up to 4000 meters in depth. So a large region of the North Pacific Ocean water is extremely old and has not reached the surface for many, many centuries. Why is this the case? Why is this not the case in the Atlantic Ocean? But this is the case in the Pacific Ocean. Remember the Pacific Ocean surface water is significantly less saline that is fresher than the Atlantic Ocean surface water because the Pacific Ocean has significantly lower runoff and higher precipitation.

As a result, the surface level waters are significantly lower in density for the Pacific Ocean than in the Atlantic Ocean, suppressing the possibility of downwelling in the Pacific Ocean. As a result, large density gradients exist between the surface level less dense water to the more dense water in the deep level. Hence, the thermocline and the deep waters particularly in the South Pacific does not mix with the rest of the oceanic system. Hence, in the North Pacific, equatorial, subtropical and the temperate regions, we see extremely cold water that has not reached the surface for a very long period of time. The only region where significant down wellings occurring in the Pacific is once again at the 80 degree south latitude close to the continent of Antarctica.

So, throughout the southern ocean close to the coast of Antarctica you have a down welling of the mixed layer waters. The other point to notice, beyond the 70 degree north latitude in the Pacific and in the Antarctic to some extent, you have the Arctic, Pacific and in the

Atlantic to some extent, you have the Arctic Ocean which is quite well mixed from the top to the bottom due to once again thermohaline circulation driven by salinity gradients. The Arctic Ocean is extremely cold and especially during the winter times it becomes saline as a lot of sea ice forms at the top and hence these waters go down all the way and hence you have a very well mixed sea in the Arctic Ocean itself. So what are these main points? In the North Atlantic large volumes of the surface water sink at these high latitudes in the North Atlantic and these then spread outwards to lower latitudes and the Southern Atlantic Ocean at depths below 2000 meters. It's only between 20 degree South and 20 degree North latitudes of the Atlantic Ocean in the thermocline region that you are getting very depleted oxygen concentration.

The situation is different in North Pacific where oxygen depleted waters extend from 20 degree south to 60 degree north up to 3000 meters in depth. Thus there is very little turnover of waters in the North Pacific. Oxygen gradients decrease at 40 degree south and 50 degree south latitudes up to an intermediate depth of 1000 meters indicating a downwelling of South Pacific surface waters up to the bottom of the thermocline. So this region here. because this water is colder, so it has a somewhat a downwelling that is happening to intermediate layers only.

Overall, Pacific Ocean receives higher precipitation and its surface waters are relatively fresher than the Atlantic Ocean and hence large vertical overturning up to the deep layers are suppressed. Hence, the combination of high salinity and low temperatures in the upper North Atlantic leads to large-scale downwelling and most of the deep waters in the world oceans originate from the subpolar North Atlantic surface waters. So, this is the key point, all the waters in the deep layers of the world ocean is coming from downwelling of subpolar North Atlantic surface waters. Apart from North Atlantic, it is only in the Southern Ocean around the Antarctica where surface waters move all the way down very quickly because of the salinity gradients caused by the creation of sea ice. This is also true for the Arctic Ocean, though it is relatively cut up from the rest of the oceanic system.

Deep waters subducted from North Atlantic and Southern Ocean tend to rise upward along the 60 to 70 degree south latitudes both in the Pacific and the Atlantic Ocean. So, the deep waters here again tend to rise up in the 60 degree and 70 degree latitude. So, this gradient in the Pacific and this gradient in the Atlantic is the same. So the deep waters here are coming from the North Atlantic and flowing into the Pacific and are then moving upwards. The upwelling is still happening in the 60 degree south and 70 degree south latitudes both in the Pacific and the Atlantic oceans, up to the base of the mixed layer.

Thus, the intermediate ocean layers in these latitudes are characterized by low oxygen saturation and the oxygen depleted deep waters migrate upwards. So, if you now average out the entire Pacific, Atlantic and the Indian Ocean, and look at the salinity gradients 100 to 0, what do you see? You see a large amount of oxygen saturation content. You see a large oxygen depleted zone extending from around 500 meters to around 2500 meters in the from around 15 degree south to 40 degree north latitude. This is contributed mostly by the Pacific Ocean intermediate layer which is not mixing. What you are seeing here, however, is in the North Atlantic specifically you have a significant downwelling of the surface level waters that are moving from the North Atlantic southwards spreading through the deep layers of both the Atlantic and the Pacific Oceans and are then rising up at 60 to 70 degree south latitudes.

Then this water that has risen up has two movements, because water is moving down, in the north latitude there is a net movement of surface level waters from 60 degree south towards 60 degree north to maintain mass continuity and the rest of the upwelling water goes down of the coast of Antarctica to the extremely deep layers and then mix with the layer coming from the North Atlantic region, ok. You can see the density contours also overlaid here. So, these are lower density, these are higher density, and this is the oxygen saturation content as well. So, there are two regions of very large importance when it comes to deep ocean circulation. The North Atlantic region where the most of the deep waters originate and in the South Atlantic region, south southern ocean region from 60 degree south onwards.

At 80 degree south you have a downwelling of surface waters and at 60 to 70 degree south you have a upwelling of the deep oceanic waters. So the Southern Ocean is a region where both water is coming up and water is going down. A mean flow of surface waters also exists. The Southern Ocean therefore is a key region where there is both upwelling of deep water that originally sunk in North Atlantic and a downwelling of surface water due to ice formation close to the coast. Now, what does this imply? The usual turnover time for the replacement of deep water is around 1000 years.

That is it takes about 1000 years for water that is sunk down to the deep layers to rise back up to the surface. So, this water going down, if it rises back up here, this entire process takes around 1000 years. That's how slow this process is actually. Thus, the Antarctic continent is surrounded by surface waters that have spent a thousand years at the ocean bottom. The upwelling is causing and that is creating the surface waters around the Antarctic continent.

So, deep waters that spend the thousand years at the ocean bottom are rising up off the coast of Antarctica and then going back down again. This makes the currents around Antarctica extremely cold and climatologically isolated from the decadal and century scale perturbations that happen in the other places of the world. So, Antarctic is unique case because the ocean currents circulating has waters that are thousand years old coming from the deep parts of the ocean that have been isolated from what has been going on in the atmosphere or on the planet for the last thousand years. Hence, any climatological change that is happening in the rest of the world will not affect Antarctica to that great of an extent. Antarctic is significantly delayed, so Antarctica is affected significantly later due to climatological changes than other parts of the world because of this old ocean water surrounding it.

This is one of the key reasons while the Antarctic continent has not warmed as much as say Greenland or other parts of the world. Where you have surface level waters that are reacting much more quickly to climatological changes.

So, we will stop here today. In the next class, we will look at one of the important climatological variability that are present in the climate which is the El Nino La Lina Southern Oscillation event which is called the ENSO, where the climate, the atmosphere and the oceans coupled together to create this internal variability over a 5 or 10 year range scale. Thank you for listening.