Transcript from Epic of Evolution: Life, the Earth and the Cosmos (BEP 210A)
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I'm going to talk for this week about water in a variety of different forms but primarily water from a geological point of view. Water is everything to us as well as the fact that we are mostly water ourselves, as are most life forms. We need water vitally as animals and as a culture. For instance, one of the fastest growing fields is for legal environmental issues. For instance, many of the Western states are locked in a court battle that will probably run forever as to who owns the water of the Colorado River. For example, not a single drop at times of the Colorado River makes it to the ocean. It all gets sucked up for agriculture and human use before it gets there and so by the time this at one point quite mighty river gets to the ocean all the water has been used up and this is becoming more and more common. And there are places such as the Great Valley and the Midwest where much of the crops that we grow to feed us and others is grown from water that's actually in the ground and we are pumping up and out water that took tens of thousands of years to get down there. And we can think of this as a nonrenewable source because over our lifetimes there's no way that the water can get back down there fast enough to replace the water that we're pumping out. So the issues of water are very important to us but we call geologically the whole process by which water moves around the hydrologic cycle. And I will explain in a moment what this is but it involves every form that water is in. That's the atmospheres, the oceans, rivers, streams, glaciers, groundwater, the biosphere, us -- everything, all the places that water travels through. Now, way back when we didn't have an atmosphere. I mentioned that early on right after the T-Tauri phase of the sun Earth was devoid of an atmosphere. The blast of the sun as it essentially ignited so to speak would have stripped us of our atmosphere and probably most of our oceans if not all of our oceans. And so we would have been a fairly hot cinder floating around in space. We would have been hot for two reasons -- the Earth was much hotter back then but the sun was also giving off less heat. We would have felt the sun as being cooler at that time and that has to do with the history of how the sun has burned its fuel. However, very quickly Earth began to get an atmosphere and an ocean back and this atmosphere came about through two things. One is a process called degassing and the second is the arrival of comets. The first one we understand pretty well, the second one is still very highly speculative. Look at any volcanic eruption, what do you see? You see a lot of stuff blowing up into the atmosphere. Well, volcanic eruptions have been going on throughout the history of the Earth and in fact were much more violent and frequent early on. And essentially volcanoes are a way of getting gas up and out into the atmosphere because the gases are much lighter than the rock and so they're going to preferentially move up to the surface. So we began to grow our atmosphere back and the stuff was primarily carbon dioxide, water, nitrogen. Comets, now, there was someone who recently claimed that the Earth is constantly being bombarded by small, little pieces of comet. Unlike asteroids or meteors which are rock, comets are ice and they are water ice, methane ice, ammonia ice, carbon dioxide ice, a variety of gases that are frozen. That doesn't quite seem to hold up but nonetheless throughout Earth's history we've been bombarded by foreign objects -- meteorites as well as pieces of comet that float around, little junk left over after the creation of the solar system. And we constantly accumulate, you know the Earth is still sweeping up any little pieces or fragments that exist in our solar system and some of it comes in the form of gases as well. So we've grown our atmosphere through the accumulation of these objects as well. At some point we had enough, the density was great enough that it would begin to rain out as liquid rain and begin to form oceans and at that point (more than 4.3 billion years ago) we would have begun a hydrologic cycle on the surface of the Earth, which essentially is the process of rain, evaporation, rain, evaporation and a cycle of water between the surface and the ground of the Earth and the atmosphere. And I'll show this is generally what it looks like. Okay.

There's an important note that I have to add here and that is the atmosphere that we have is totally different than the atmosphere that we had once the hydrologic cycle began. Our early atmosphere and I'm not talking about the previous atmosphere that got blown away by the T-Tauri phase of the sun, but the atmosphere as it began to come back was almost entirely carbon dioxide. It's what you exhale through your process of respiration. Mars and Venus both have atmospheres and they're almost exclusively (97-98 percent) carbon dioxide. As I mentioned in the first class that I gave, carbon dioxide is less than a thousandth of one percent on the Earth so why is this? Where did all that carbon dioxide go? Well, we owe a big tribute to life for that and in particular the development of plant life, in particular one-celled plant life like early algae. The development of the complexity of life where early cells developed a symbiotic relationship with chloroplasts (which perform photosynthesis) was one of the most significant events geologically in the surface of the Earth. Because once you had early plant life and for billions of years it was just one-celled algae and life forms of that sort, you began to absorb the carbon dioxide and plant life has essentially just sucked that carbon dioxide right out of the atmosphere. Now, the carbon cycle is a little more complex and there is also carbon that goes in the oceans and it goes on carbonate rocks that form but essentially you had early life removing carbon dioxide from the atmosphere and then producing oxygen. And we all know that plants produce oxygen. This is remarkably significant because early on we had no free oxygen in our atmosphere. We know this because we see deposits of iron put down that's not rusted. And oxygen is very reactive and if there was any metal like iron around it would react to it and oxidize it and it didn't. We have rocks as late as 2½ billion years that show no presence of free oxygen in the atmosphere. But over time that life has essentially allowed for a cycle that keeps oxygen in the atmosphere. Ursula, you have a question?

[I just wanted to add a biologic asterisk here and that is that there are many, many single-celled bacteria as well as algae that absorb CO_2]

Right, I just didn't want to get into any of the names, and we have an even more important geological aspect in the fact that we have oxygen in the atmosphere because oxygen does something very significant, and that is if you have oxygen which normally exists in an O_2 molecule and you zap it with a little bit of solar radiation you form an equilibrium with a molecule that has three atoms of oxygen and this is known as ozone. We often think of ozone as a bad thing because it's part of urban smog, you get a lot of ozone buildup in cities. So Los Angeles will have ozone alert as well as other alert days, where and when the levels of ozone are high and that's not good. But ozone does something that's wonderful and that is it blocks out further ultraviolet radiation. So we have ozone that is essentially a shield from solar ultraviolet radiation. And this is why people are all worried about for instance the big ozone hole that seems to be developing over Antarctica on a yearly basis. And that is ozone is fairly delicate and there are certain materials like chlorofluorocarbons that we've used in refrigerators and deodorants and sprays that will break down the ozone, and if you break down the ozone then essentially you let the ultraviolet radiation in which is very harmful to life. This presence of this ozone was vital because it allowed for the development of further complexity in life. You can't maintain this complex genetic code that Ursula was talking about if you're constantly zapping it with high levels of ultraviolet radiation. So the development of the oxygen in the atmosphere has essentially allowed for a further complexity of that whole life cycle to continue. Okay.

This is how the basic hydrologic cycle looks and it's fairly obvious in its just basic appearance. Okay, there's nothing of any surprise here. We have rain that either comes in the form of snow or sleet or liquid rain. And if it's snow it may become a glacier but that glacier will eventually melt and run off in a series of streams and work its way back into the ocean. Or it will go directly into rain that will run into the ocean, though some of it will seep into the ground and travel underwater as groundwater. But the basic rule of the hydrologic cycle is that water flows downhill except when it flows uphill, and that's what happens in the oceans and that is for all the water that's coming down we have a balance of water coming back up again. And in the oceans and rivers and the surface of the Earth we get a continuous process of evaporation where we turn liquid back into water vapor and put that back up into the atmosphere. People have understood this part for a long time. Here's a quote from Ecclesiastics in the Bible: "All of the rivers run to the sea yet the sea is not full. Unto the place from whence the rivers came thither they return again." Okay, they noticed that the sea was not filling up. All these rivers are flowing into the sea but the level of the ocean isn't rising so thither they return again. Somehow the water is going from here back up to the streams and the ice to flow down the surface again. But they didn't think about the rain being enough to replace that. Let me give you another quote from Leonardo da Vinci in the late 1400s: "Once we may conclude that the water goes from the rivers to the sea and from the sea to the rivers thus constantly circulating and returning and that all the sea and rivers have passed through the mouth of the Nile an infinite number of times." So da Vinci was of the opinion that this cycle has just gone on and on and on and any drop of water has actually flowed through the mouth of any given river an infinite number of times. He goes on to say, "The conclusion is that the saltiness of the sea must proceed from the many springs of water which as they penetrate the Earth find mines of salt and these they dissolve in part and carry with them to the ocean and other seas, whence the clouds, the begetters of rivers, never carry it back up." Okay, this is a very smart guy. He realized that rain is not salty. Okay, go out and stick your tongue out when it rains. It's not saltwater that's falling down on you, whereas streams have a considerable amount of salt in them. If you take a big bucket of stream water and let the water evaporate off you'll get a nice deposit of salt at the bottom because the streams are essentially washing all the salts from the continents. So the streams are washing the salt into the ocean but when the water evaporates again you don't get the salt rising back up, so you just keep bringing the salt into the ocean. Well, people tried to use that actually to date the age of the Earth. In fact, there were some people in the late 1800s who took the salinity of the ocean and the volume of the ocean and the salinity of rivers and the volume of rivers and came up with an age of the Earth and the number they came up was usually on the order of about 100 million years, which gave geologists and evolutionary biologists like Darwin heart attacks because there's no way you can create the Earth and create life in such a short amount of time. They were wrong obviously. The Earth is 4½ billion years old but the reason is that quite simple as any chemist could tell you and that is water can only hold a certain amount of salt in it before you begin to precipitate salt out the bottom. So as the sea gets more and more salt it doesn't become saltier. If you look at the bottom of the ocean there are these layers of salt that are being deposited at the bottom and so there is a certain maximum saturation of this salt. Okay.

The whole process of the water cycle, the hydrologic cycle, begins right here, begins with evaporation. And evaporation is a remarkable thing when you think about the fact that you are lifting an enormous amount of water several kilometers up into the air and in terms of just the amount of energy required this is actually quite a feat. Where does this energy come from? I'm saying that rhetorically but if anybody, you know what drives the whole hydrologic cycle? A guess? The whole process of circulation of water at the surface is driven by the sun -- not the whole process -- gravity plays a big part pulling it back down. But the sun pumps a tremendous amount of energy into the surface of the Earth and this comes in the form of heat, of wind and evaporation in particular. What happens at the surface of the ocean is that you know you go to the beach and it's pretty hot there. That heat which is in the form of radiation from the sun hits the top layer of water there and if the molecules of water absorb enough energy essentially they are able to make a quantum leap in energy that will break the weak bonds that hold the water molecules together as a liquid. And once you break those bonds you essentially free those water molecules and they just fly off into the atmosphere. And then we have active convection cycles within the atmosphere where we have the hot, warm water at the surface that rises up in exactly the same way that I talked about convection within the Earth. And the heat from the sun turns the liquid into gas (that's evaporation) and then lifts it up through convection, so the sun drives that whole process. Now, I talked a little bit awhile back about the marvels of water. I mentioned how it's one of these freaky materials that expands when you freeze it. It's one of the few things that does that. Water also is very important because it has a very stabilizing thermal effect and this is due to the fact that it has a very high heat capacity and I'll explain what this term means in a moment. This first thing anyone who has been to both the Midwest or lived in both the Midwest and the East or West Coast knows intuitively, and that is here in the Midwest it can 20 degrees in the morning and it can be 90 degrees by the late afternoon. The temperature can swing wildly all over the place. Go to the coast or better yet go to a place like Hawaii. I remember when I was in Hawaii for a meeting and I saw the news and it said that the total range in temperature on that day had been 69 to 82 so over 100 years of recording the temperature on that day had never varied above or below that range. Okay, the water is this huge inertial thermal buffer and the reason is that this high heat capacity means it takes a lot of energy to raise the temperature of water which is why it takes so long to cook spaghetti. You put your pot on the stove and you just have to wait and wait and wait because it takes a lot of heat to raise the temperature of that water and then it takes a tremendous more, greater amount of heat to turn that water into steam. And as a result water has a tremendous buffering effect. Here in the Midwest we don't have any big oceans, we don't have any big bodies of water and so the temperature can swing about wildly and rock has a much lower heat capacity than water does. Okay.

Okay, if this were the only thing involved then we would have two big cycles of air circulation within our atmosphere. We would have all of this, a tremendous amount of evaporation occurring at the equator, which is where the sun hits most directly. And we would have it sinking this air, sinking back down at the Poles but this is not what happens. We in fact have six major independent cells of convection and we call these Hadley cells after one of the people who invented it. The basic idea is that the sun causes a tremendous amount of evaporation in an equatorial region and that air comes up and it's moisture laden and as it goes to higher atmospheres it rains out. So you get a tremendous amount of rain along the equator as the moisture just gets sucked right up out of the oceans and then as it's going up and beginning to move away it rains back down again. However, as the air moves northward or southward it actually rotates and this is due to the rotation of the Earth. And so we have our air, or I'll say atmospheric circulation, is a combination of convection driven by the sun and rotation. The number of cells is entirely dependent on the rate upon which the planet revolves. So for instance, Jupiter which goes much faster than us and is very large is broken up into lots of bands and there are lots of different Hadley cells. Venus hardly rotates at all and so it only has two cells in the northern hemisphere and in the southern hemisphere. If the Earth were to spin a little bit faster we'd go from three cells to four or five in each of the northern and southern hemispheres. The result is very interesting though and that is we end up with a real general division of the Earth by latitude and that is we have the tropics which tend to be very moist. This is where water comes up but then the air comes back down again on average at 30 degrees north and 30 degrees south. By the time this air comes down however it's totally devoid of moisture and acts like a sponge and it just soaks the water right out of the air and that's why deserts tend to be very dry, because in general the large circulation is of the air coming down at 30 degrees north and south and as this air comes down it absorbs moisture and it's very dry. We have a second pattern though and that is we also have air coming up at about 60 degrees south and 60 degrees north and it both comes back down at 30 degrees and comes down at the Pole again. So let me go back to this picture here. Here's this top little circulation pattern. At about 60 degrees north we have air come up and some of that comes back down at 30 degrees and some of it goes and comes down at the Pole. The result is that generally 50 to 60 or 70 degrees north tends to be very rich in vegetation and this is both north and in the southern hemisphere. But as this dry air comes down at the Poles it acts like a sponge and absorbs moisture as well and technically the North and South Poles are deserts. And we don't normally think of a desert as being all ice like in Antarctica but it's a desert because there's almost no precipitation. It snows very little. There's just very little moisture that comes down there and so considering the amount of moisture that comes down it's technically a desert. We see this pattern in the biosphere. If we look at a picture of vegetation on land and also the amount of biomass, largely things like plankton and algae in the oceans which go from very low here with this purple to very high which is the red here along the coasts, we can see that banding as well. Here's the band across the equator here so we get very rich vegetation in Africa at the equator right across here, in Ecuador, Galapagos again is right at the equator here. So we get the Amazon jungles but then as you move south or north we get into this zone of desert and you get the deserts of the southern part of South Africa and the Sahara Desert and the Middle East. And this is all at about 30 degrees north here, the very dry deserts of Mexico and southeast U.S. Australia is also in that desert zone. Much of the Outback of Australia is desert. It's very dry but as you go north again there are places up in Canada for instance, it's very green, it's very lush. And then we go to the Poles and we get to desert area as well. This pattern we see throughout time. In fact, if you go back 250 million years ago to when all the continents were together at Pangea and we look at the geological record in the rocks we see exactly the same thing. Here we see a band of essentially tropics here at the equator and all of these blackouts are places where we have a lot of coal from that time. And remember coal is essentially fossilized swamp so we had swamp lands in here, including Ethiopia and Sudan which we think of as being desert now but they were much more equatorial at that point. And as you move away on north and south we have these areas of deserts that would have been most of Canada and where the Amazon is now in South America, and then as you move away you get to the Poles, and Australia and India show tremendous amounts of glaciers, glaciation at that time because they were at the South Pole before the continents split up. So we've seen this happening for a long time.

This picture leads into a third interesting factor and I have to put an asterisk here and that is the shape and distribution of the continents plays a very strong, vital role in confining our whole pattern of atmospheric circulation and the whole water cycle. One reason is that in general it's very hard for clouds with water in them to go more than about 1,000 miles over land. Usually by that time they've lost all of their moisture as rain which is why places like China, the Gobi Desert, are not at 30 degrees north, they're more north than that but they're so far away from the ocean and again the weather in the northern hemisphere, the air circulation generally comes from the west, that by the time the air gets to the Gobi Desert it's lost all its moisture and so we end up essentially having a very dry area. That would have been tremendously important with a supercontinent like Pangea because it would have meant that essentially the whole interior of that supercontinent would have been tremendously arid and very dry because it's very hard to get that moisture to go a very far distance across land. However, the continents -- and another very obvious aspect is that of ocean circulations and I'll talk about that in a little bit, but there's essentially a wall from Alaska to the Straits of Magellan here that prevents any water circulation from occurring and this has incredibly significant impacts upon our whole climate and weather cycle. We're just learning now things like El Nino and the whole method by which the whole weather patterns oscillate are very driven by this ocean circulation pattern. And it wasn't so long ago that North and South America were not attached and the water could have flowed straight through here. That would have led to a very different global climate. So the climate we get is also a function of just where the continents happen to be randomly placed but we don't see those effects over short time periods. What we see are the effects of the convection and the rotation in the air circulation and only very long geologic times do we see the effect that the placement of the continents have. Okay.

If we want to talk about the whole process of the hydrologic cycle we need to know three things. We need to know the volumes of water that are in different parts of the system, we need to know the residence time, and we need to know the paths of motion. Residence time is just that. It's the time that the water is in residence in one of these systems. And I'll go through the different components but again we essentially have oceans, glaciers, groundwater, lakes, rivers, the atmosphere, we also have the biosphere, as the major components of this hydrologic cycle. Now, if you look at a picture of -- this is a schematic of course, water is never actually piled up entirely just on the United States of America but if you could take all the water in the hydrologic system and lay it out evenly across the U.S. you would get a layer of water about 150 kilometers thick. Okay, so it gives you some sense for how much water is involved in our hydrologic cycle. The oceans carry 97½ percent of all the water. Okay, so almost all the water is in the oceans. This is no surprise. There are some surprises but this isn't one of them. Okay, and if you go and take all the rest of the water (the remaining 2½ percent) you see that most of it's in the form of glaciers. The rest of it's in the form of groundwater and a trivial amount is in the form of rivers, lakes and atmosphere, and the biosphere doesn't even rank on this picture. That's not to say that those aren't important as I'll mention in a little bit. In fact, they're absolutely vital it turns out because their residence time is very fast. But most of the water is not in streams, atmosphere and life. Now, the oceans as I said have 97½ percent of the total and the other thing that's important though is the residence time. The average residence time in the ocean is about 3,000 years. Okay, that means if you have a molecule of water in the ocean on average it'll sit there for 3,000 years before it gets evaporated. Of course it varies widely. Deep ocean water can sit down there for a million years, and water right at the surface where streams come in can be there for minutes before they get evaporated so there's a whole range, but this is the average. So in general water is in the ocean for a long time but not a ridiculously large amount of time. And in terms of this other thing I talked about (the paths of motion) water leaves the ocean by evaporation and it primarily comes back into it through precipitation. I mean after all, the oceans are 70 percent of the world so most of the world's rain falls back in the oceans and streams and groundwater which flow back into the ocean. So we understand pretty well the circulation pattern there as well. Let's go to this remaining -- actually let me just add one bit about the ocean. The study of the ocean currents is actually a remarkably complex subject. Here's a very rough draft and it's a very bizarre map projection actually. Here's Europe and Africa, here's the Atlantic Ocean, here's North America, Florida is here but then they've wrapped the Earth around Antarctica here to be able to show the full currents unbroken and so actually here's North America here upside down and then Alaska and then Japan and Asia along here. But just notice how we get all these gyres of water circulating in a variety of different ways. This pattern is still largely misunderstood or poorly understood, and in fact we often use sort of freak opportunities to find out about circulation. There was a case where an ocean liner -- a cargo ship in the Pacific carrying millions of sneakers sank and all of these sneakers just washed out of the boat into the ocean but it was a wonderful example because for months people found sneakers all the way from Southern California to Alaska and judging on when the sneakers arrived where they were actually able to determine quite a bit about the ocean circulation patterns in the northeastern Pacific Ocean which we currently had no real, very little understanding of. But again the pattern is largely constrained by where you get your continents to deposit it. Okay.

Let me go to the second case and actually we normally look at it this way even though the word Antarctica is sideways there. This is Antarctica and of the remaining water 80 percent of the remaining total (2 percent of the total) is in the form of glaciers and almost all of that's in Antarctica with a nice big chunk in Greenland as well and other little bits of ice scattered in alpine glaciers around the world. It wasn't so long ago as I'll mention at the end of this week, that much of the continents looked like this. In fact, the leading edge of the most recent glacier came down Route 70 that runs right through town here. That was the edge of the glacier so if you could have stood up on top of Brookings and looked north you would have seen the leading edge of this several kilometer thick ice sheet with ice pouring down -- I mean pouring inches a day -- pouring down from the north. And we still see this process here in Antarctica. We have several kilometers worth of ice and the glaciers are a very active dynamic system that the ice doesn't just sit there. We have some interesting features. This whole area here is the Ross Ice Shelf and there is some volcanic activity under here and there's been some worry. You may have heard it in the news recently that if you were to suddenly break off this ice sheet and have it flow into the ocean you would raise global sea levels by 10 or 15 feet or whatever. Which doesn't sound like a lot but most cities or a large part of the population lives right at sea level and it would be fairly catastrophic. And this is another large ice sheet up here, and the continent is actually fairly narrow right here. But the ice is constantly flowing into the ocean and being replenished and this is the basic structure of a glacier. You have a region of accumulation where you have snow falling and you have that snow turning, being compressed into ice. I mean think about a snowball. A snowball tends to be unless you get really great conditions, fairly fluffy. But sometimes you get just the right conditions for snowballs and you can pack it really tightly and heavy. The process of glaciation takes snow and essentially squeezes out all the air and turns it into dense ice and that's what a glacier is. But even when the front of a glacier is standing still the glacier is constantly flowing out and the whole bottom half of the glacier you're losing ice and you do it by three processes. You sublimate the ice, and sublimate is the same as evaporate but for ice. So if you take ice some of the ice when the solar radiation hits it will convert right into gas. It skips the water phase. It goes straight from a solid to a gas. And then of course you melt the leading edge of the glacier and also you break off large pieces that will float away as icebergs. We've just discovered a 1,000-kilometer long iceberg that's in the process of breaking off, a long edge of Antarctica. All the ocean ships in the southern hemisphere are on alert for this long, big wedge of ice that's just recently broken off. Okay.

The residence time for glaciers is much longer. It's generally about 10,000 years or so. It's interesting, we actually have a lot people in our department who go down to Antarctica a lot. We don't have anybody who studies Antarctica here -- actually we have one person who does. These people study meteorites. It turns out that glaciers are one of the best places to find meteors because here you have this snow that comes down and travels along and then the snow melts but what else might fall down on there on the snow? Well, there's not a lot if you're just out in the middle of a big ice field but any meteorites that fall in here are going to be essentially preserved and when you melt off the ice you're left with this sort of rocky rubble that often contains large amounts of meteorite. So people will go to the fronts of these large glacial sheets to pick up meteorites that have fallen in on them. The glaciers have been totally gone at times. There have been warm periods and I'll talk about climate at the end. But there have been times when Antarctica and everywhere else had no ice on top of them. If you were to do that right now today, if you were to take all of the ice and melt it (again which has happened) the sea level would raise up on the order of about 300 feet. Okay, now, we are currently here in St. Louis at an elevation of only about 450 feet so we're talking about the sea level rising a full two-thirds of the way up to where we are, and we think of ourselves as totally removed from the sea. But the mouth of the Mississippi would come right up into Illinois if the glaciers were to melt and much of the inner part of the continent would be flooded. The opposite effect has also happened though. Ten to fifteen thousand years ago there was so much water on ice that the global sea level was about 100 feet lower and there are places that we think of as oceans that are actually continents. For example, the whole Bering Strait between Alaska and Siberia is all just slightly submerged continent and very few places that are more than about 100 kilometers deep. And that was all above land and it's thought that this is how the Native Americans settled North America and then South America. They essentially walked across or moved in fishing boats from village to village along all the land that rimmed the northern part of the Pacific. Much of Southeast Asia and Australia is reachable by land if you drop the sea level by 100 feet and so it's thought that people that are now on separate islands there were all part of one large land mass 20,000 years ago. So the ice has obviously had a very large impact on humans in the past and can do so again. Okay, I will pick up with the rest of this on Wednesday.