Dr. Josh Willis:
A Brief History of Ocean Altimetry and Why It's the Most Important Mission Ever!
June 08, 2017

Coordinator: Good afternoon and thank you for standing by. As a reminder, today's conference call is being recorded. If you have any objections, you may disconnect at this time. I would now like to turn today's conference over to Amelia Chapman. Thank you. You may begin.

Amelia Chapman: All right. Well thank you and welcome officially everybody. This is Amelia., and thank you for joining us today on World Ocean Day for a Museum Alliance Professional Development Conversation, "Ocean Altimetry and Why It's the Most Important Mission Ever". So, you came to the right place.

First, a few reminders again -- make sure that your phone is on mute, not just on hold. And the slides for today's presentation can be found on the Museum Alliance and Solar System Ambassador site. If you have any problems, contact Kay Ferrari or myself.

I'd like to introduce our speaker today, Dr. Josh Willis, a NASA Climate scientist and Project Scientist for the Jason Missions to measure sea levels from space. He's also the Principal Investigator for the Oceans Melting Greenland (OMG) Airborne Mission. He studies ocean warming and Greenland ice loss and enjoys communicating so much, that he went back to school to get a degree in comedy from the Second City Improv School here in Hollywood, California. So, I think he's going to be a good speaker. And hopefully he's had a chance to get his breath caught from running back from the meeting.

So once again, we're going to turn it over to Josh. And he has indicated he's happy to take questions as we go. Josh, everybody is muted so it does take them a moment to unmute and ask those questions, so if you could have a little wait time, that's appreciated.

Josh Willis: Awesome. Thank you, Amelia and thank you everybody for having me. I'm really excited. As Amelia said, I just ran all the way across the JPL campus, which turns out I'm told is bigger than Disneyland. So, imagine that I just ran all the way across Disneyland, went up three flights of stairs, and here I am -- ready to talk to you guys.

I am also happy to take questions anytime, so keep your fingers on the mute buttons and pull the trigger when you're ready.

As Amelia said, I'm Josh Willis. I'm a climate scientist here at NASA's Jet Propulsion Laboratory. And for the last -- I looked it up today -- it's been eight years I've been working on the Jason series of satellites. These are satellites that measure the height of the ocean surface from space. They're quite incredible. They can measure the height of the ocean with an accuracy of about one inch from 800 miles up. So, it's a pretty amazing technological feat. We've been doing it since the early 90s and what I want to give you today is a little bit of a history and background of what we're doing and a glimpse of the future and along the way hopefully convey why I think this is the most important mission ever.

So like I said, feel free to jump in if you have questions. Right now if you've downloaded the slides, I'm on slide one. It's the one with our beautiful-looking image model of the next Jason mission, which will begin flying in 2020. We're actually building two of these. They're called Jason CS. They have another name, which you may hear in different places at different times -

- Sentinel Six. It’s called Sentinel Six because it’s part of European Space Agency’s Sentinel series of satellites.

But this particular one is dedicated to satellite altimetry and so its other name is Jason CS, which stands for “continuity of service”. And the reason we’re calling it that is because we’re actually building two of these things at the same time. There’s a Jason CS-A and a Jason CS-B. The plan is to launch the first one in 2020, put the second one in a shoebox or something equivalent for about five years and launch it in 2025 and build another ten years onto the record of sea level change that was started in the early 90s by TOPEX/Poseidon.

So anyway, it’s a very exciting time to be working on these missions. And without further ado, we’ll plug away and see some of what they do.

So if you’re on the slides, I’m going to slide two now. This is a little bit of an overview of the different kinds of science that we do. The measurement of the height of the ocean surface is important for a whole bunch of reasons. We use it to - if you average the height of the oceans all over the planet, then you can see the global rise in sea levels, which is the direct result of human-caused warming of the climate or global warming. And I’ll come back to that a whole bunch of times throughout the talk, so don’t worry -- we’re going to talk plenty about global warming.

But what you can see right there in the center is a time series of the increasing height of the average oceans -- essentially the increase in the volume of the oceans -- from 1992 all the way through I think this one goes to about 2016, early or mid-2016. And, there’s an overall rise. You can see an up and a down that has to do with the exchange every year of water between the land and the oceans.

But apart from that, the most obvious thing in this record -- this is the plot with the red, blue, and green dots right in the middle of slide two -- is the rise of about three millimeters per year of global sea levels. And this is a direct result of climate change, because the water is both warming up and expanding and the amount of water in the ocean is increasing as the ice in places like Greenland and Antarctica melt.

But another reason that we like to measure the height of the oceans is because it tells us about ocean currents. These satellites give us information about real-time ocean or near real-time ocean currents. That can be important for trying to predict things like debris fields and oil slicks, where things are going to flow. In the upper right, you can see the Gulf of Mexico and the oil spill, the oil slick from the Deep Water Horizon oil platform which exploded in 2010 and caused a massive leak of oil into the Gulf of Mexico. Satellite altimeters were actually key to measuring the currents in that region, which pushed this debris field around to the Gulf of Mexico.

Satellite measurements of the height of the ocean are also important because they tell us about where the heat is in the oceans. On the lower left, there's a plot showing the sea surface height in the Gulf of Mexico again just before Katrina made landfall in Louisiana.

And this is important because warm water stands taller. Because water that's warm takes up more space, when you see a high in sea level, it's usually associated not just with a surface temperature that's warm, but water temperatures down deep all the way through the water column are also warm. And in fact, the inclusion of sea surface height data from this series of satellites is one of the main improvements in predicting the intensity of hurricanes and how that changes over time that we’ve seen in the last couple decades.

So, satellite data help us improve hurricane forecasts. But they also help us watch things evolve like the El Niños in the Pacific Ocean. These are movements of heat across the Equator in the Pacific Ocean that affect sea surface height, which is directly measured by the satellites.

And so, we’re really able to keep an eye on the entire Pacific Ocean and watch how it’s changing in near real time and learn about how El Niños and La Niñas in the Pacific Ocean evolve. And those of course have big implications for weather all across North America and in some cases throughout the world.

So moving on to slide three, this is just a little bit of a diagram about how these satellites work. The Jason missions measure how tall the ocean is and they do it in a pretty simple way. There’s a big dish right on the bottom which has a radar. It bounces a radar wave off the surface of the ocean and it times how long it takes to go down and come back up. That very simple measurement of round trip travel time gives you an estimate of the distance between the satellite and the surface of the ocean.

Now, you have to correct that number for a few different things -- the radio wave passes through the ionosphere and through the atmosphere and as it encounters different amounts of ions and different amounts of water vapor and other things, it slows down. And so you have to measure that independently and correct the travel time for those things. But when you do that, you get an accuracy of about a centimeter or two with which we can tell the distance between the satellite and the surface of the ocean.

Now, that’s not the whole story because in order to know the height of the ocean above -- for example, the center of mass of the earth -- we need to know *where* the satellite is. So, there’s three different positioning systems on these satellites that give us information about the location of the satellite.

There are GPS satellites -- it uses a GPS just like the one in your car. There are also DORIS stations, which are sort of like reverse GPS. You can think of them as stations that are attached to the land that broadcast upward. And so satellites see the signals from those and they can interpret their location and speed. And then there’s Laser Ranging, where you essentially have a fixed station on the ground and you bounce the laser off of the satellite and measure its position very accurately that way.

So with these three different systems, we can tell where the satellite is all the time very, very accurately. And those two pieces of information tell us the height of the ocean. So the distance from between the satellite and the surface and the location of the satellite, essentially you subtract those two and they tell you how tall the ocean is.

So there’s a few bells and whistles here, a few things, a few technical details. But overall, it’s really a pretty simple measurement. And that’s one of the reasons it has become such a powerful tool for measuring the climate and how the oceans are changing.

So I’m going to move on to slide four. There’s an interesting history of altimeters measuring the ocean height. Turns out the very first altimeter to get stuck on anything in orbit was Skylab in 1973. This had an altimeter. The space station had an altimeter that looked down at the oceans, and the land as well, and made some of the very first measurements of the shape of the surface of the earth. It wasn’t super accurate, but it was the first one.

Then, moving on to slide five, there was GEOS-3 which was essentially a satellite designed to measure more about the oceans -- particularly the geoid, which I'll explain a little later. And SeaSat in 1978. Now, SeaSat was really the first satellite altimeter that was designed to try and do oceanography. The idea was to measure the height of the ocean accurately enough to get an idea of where the currents were and how they were changing. That's important because it's really one of the fundamental reasons that we began flying the TOPEX and Jason missions in the early 90s and eventually 2000s.

You can look up - actually there's pretty good histories of all these satellites on Wikipedia. If you're interested, you can go learn more about what they did and how they did it. I'll talk a little more about their accuracy in a second.

So on slide six I want to just take a minute and explain why oceanographers are so interested in measuring the surface of the ocean. It turns out that when currents in the ocean travel for more than a couple of days and over a distance of more than a few kilometers, they start to feel the forces of rotation of the Earth.

The Coriolis force is a major player in terms of the forces that ocean currents feel. And it winds up that whenever you have a current in the ocean -- especially at the surface -- it tends to tilt the sea surface. So if you're in the northern hemisphere and you have a current that's going from the front of the page through the back of the page -- like you can see on slide six here -- then it implies that there is a high in sea level to the right of the current and a low to the left of the current.

That's just to do with the physics that currents eventually feel from the Coriolis force in the Earth. As the Earth rotates, then the currents feel those forces and essentially this pressure gradient -- the difference between the high pressure from the high sea level and the low pressure on the low sea level -- wind up balancing. That’s a balance that just the physics work out that winds up being true for all ocean currents in the world that last longer than a day or two and travel more than a few kilometers.

So we have this sort of tool -- if we can measure sea level everywhere -- for inferring the ocean currents. And if we move on to slide seven, then you can see sort of what the ocean currents look like. That difference in height as you move around on the ocean surface is called the dynamic topography – “topography” meaning the shape of the surface and “dynamic” because it has to do with the fact that the currents are what really set this shape.

So you can see right in the center of slide seven there’s this huge high off the south of Japan. This is called the North Pacific Subtropical Gyre. This high is circled by lines of constant height that go around clockwise. And the northern and western boundary of it form the Kuroshio which is a major current, just like the Gulf Stream, which runs from southwest to northeast up the coast of North America.

So just over to the right you can see the United States. You can see Florida. And there’s a high sea level just off the coastline and a whole bunch of lines very tightly packed together that make up the Gulf Stream, which is the huge current that carries warm water from around the southern tip of Florida up into the north Atlantic Ocean.

So this height map is really telling us about the currents of the ocean. There’s all kinds of interesting things in this map. I could spend a long time talking about it. But we’ll move on. If you guys have questions, hit your mute button.

So, it turns out that ocean currents are not the only things that affect the height of the ocean. If you go on to slide eight, you'll see that the ocean surface is also shaped by the land itself. Now, this image is like a cutaway through the land and the ocean. There's an island right in the middle of it popping up out of the water.

What happens is that that island, the pull of gravity from the rock that makes up that island, actually pulls the water towards the island. You can see the blue surface there kind of piling up toward the island. This effect is essentially called the geoid. So, the geoid is the shape of the ocean surface that's caused by the pull of gravity of the rocks and the land underneath it.

So, the geoid actually also shapes the sea surface. So, when oceanographers look at data from the Jason mission, one of the first things we do is take a mean over time and subtract that out and look at the changes in the ocean surface.

The reason that we do that is because it allows us to separate this signal from the signal in the image right before it. The rocks and the islands don't move around, so if we see an ocean slope changing, then we infer that that is caused by currents in the ocean that are changing as opposed to underwater sea mountains scurrying around like cockroaches -- because they don't do that.

The gravity field shapes the surface of the ocean and currents shape the surface of the ocean. And one of the main jobs of altimeters, of satellite missions that measure the height of the ocean, is to separate these two signals out.

And that brings us to slide nine, which is a picture of GEOSAT. So GEOSAT launched in 1985, was launched by the US Navy. And it was launched specifically to measure the geoid -- the idea being that the pull of gravity caused by the changing shape of the surface was important if you wanted to launch and guide cruise missiles and ICBMs. So in fact, the geoid and its shape was a military secret for at least through most of the 80s.

Eventually, other satellites got launched and took data and released it to the public of the sufficient accuracy that you could figure out the geoid using the public data and the GEOSAT data was eventually declassified and became part of the science record. But anyway, it’s an interesting story that it wasn’t always oceanographers measuring the height of the ocean surface using these satellites.

Slide ten, I kind of already mentioned the geoid. This is what it looks like. The highs and lows here denote in the upper left-hand corner of the graph on slide ten show the kind of large-scale changes, and these have to do with differences in the crust thickness and the mantle and so forth.

And then in a smaller scale if you zoom in really close, like in the lower right-hand corner, you can see that the underwater shape of the ocean is really shaping the geoid in a large sense. In fact, one of the early uses of altimeter data was to make maps of the sea floor. It’s still one of the uses of the altimeter data, and we’re still learning about the shape of the sea floor whenever we have an altimeter that moves off onto a track that’s not been occupied a whole bunch of times.

Anyway, moving on to slide 11, in 1991 ERS-1 was launched and -- excuse me, sorry -- ERS-1 was launched. This is a European satellite that had an altimeter on board. I think it had a whole bunch of other stuff as well. But it was one of the first ones that was of sufficient accuracy that you could begin to do oceanography. Now ERS-1 by itself really didn't quite have a good enough system for doing really accurate measurements of the sea surface.

If you go on to slide 12, you can see I made a little table here of the accuracy of all of the different altimeters that flew -- the ones that we talked about -- historically. So starting with Skylab, the accuracy was about one meter. GEOS-3 it was a quarter of a meter. By SeaSat, it was five centimeters and GeoSat were four centimeters. But actually at the time, they couldn't quite get that good an accuracy because they didn't quite know the orbits and the geoid all that well.

ERS-1 had a really highly accurate altimeter. It could do - it had an accuracy of about three centimeters. But it wasn't quite good enough at doing orbits. It wasn't until the Jason mission launched -- no, the TOPEX/Poseidon launch in 1992, as you can see in slide 13. There's a picture of it, and then going on to slide 14 -- that the accuracy all the systems needed to get a really accurate measurement were finally put in place. The other thing you'll notice about TOPEX/Poseidon is that it was at a much higher altitude.

That's important because at that very high altitude, the atmospheric drag is almost zero. So, the satellite tends to fly in a very circular, very stable orbit that's easy to measure and easier to define. And so, the position of the satellite was finally very, very accurately defined.

Because it flew at the same time as ERS-1, you can use the places where both satellites fly over the same place at nearly the same time to improve the accuracy of ERS-1. So that three-centimeter accuracy on ERS-1 kind of has an asterisk because it wasn't until TOPEX flew that they were really able to do quite that well.

So anyway, that’s kind of it for the history of altimetry -- well not totally it.

Once we get into the TOPEX/Poseidon era in 1992, these satellites became extremely accurate. Two or three-centimeter accuracy for measurements of the sea surface height is plenty for doing all kinds of oceanography. And as we’ll talk about a little later, it’s also good enough to measure globally average sea level. And that’s when really the golden era of oceanography from space began.

You can see in slide 15 that scientists really love this data. This is the number of publications using satellite altimeter data on slide 15 from the early 90s through today. And you can see that about 200 papers per year get published every year, even now, using data from these satellites. So, they’re extremely well used. There’s over 4,300 peer-reviewed science articles and they really pick up in the early 90s with the launch of TOPEX.

So, these are - I don’t know which is “respoinstibel”? Anyway, there’s a weird typo in this slide. I don’t know what I was going after there. But anyway, these are extremely accurate missions and they’re used for all kinds of really amazing science.

Which brings us on slide 16 to the successor mission for TOPEX/Poseidon which was Jason 1. This was the first one where we decided hey, we might like to do these in succession one after the other and maintain this record of sea level change that was started by TOPEX/Poseidon. And it was really during the life of TOPEX that we realized the satellites were accurate enough to not just measure the shape of the sea surface so we could do oceanography, but the globally average surface and how it evolved over time. So, we could really do climate science as well.

So TOPEX was launched into exactly the same – sorry – Jason 1 was launched into the exact same orbit as TOPEX/Poseidon. They flew one right after the other about 80 seconds apart for six months or so and measured the same ocean and the same atmosphere at almost the same time. And using that cross calibration, we began to build a long-term record that was really solid for how the sea levels have changed.

Then on slide 17, that kind of brings us to the modern era of altimetry. You can see TOPEX/Poseidon there in the middle followed by Jason 1, Jason 2 which is still flying, Jason 3 which launched in 2016, and eventually Jason CS in 2020 and the second one in 2025.

So we're at about 25 years, the record of sea level rise from these missions and it's really a remarkable climate science achievement. We launched Jason 3 in 2016. Did somebody have a question? I heard shuffling. I can pause for a second if anybody wants to ask questions so far.

(Jeff): Actually Josh, yes. Hi. This is Jeff with Museum Alliance. Why does Jason CS look so much different than all the other Jasons?

Josh Willis: That's a great question. Jason 1, 2, and 3 were all built by CNES -- the French Space Agency -- using the same satellite bus. It was called a Proteus bus. Jason 3 was actually the last one manufactured by the company Thales which CNES uses to build its spacecraft.

Jason CS is being launched by ESA. So, the lead agency and the agency that's actually building the satellite changed for Jason CS. And they're using a different model. This is the same actual satellite bus which was used for GRACE -- which is a gravity mission -- also for CryoSat, which is an altimeter designed specifically for looking at ice.

And so, it's a completely different satellite bus and a completely new agency that's building it. So, it's a total redesign.

1, 2 and 3 were all built to be nearly identical. And that's good for maintaining the long-term continuity of the records. So, every time we overlapped Jason 1 and 2 and Jason 2 and 3, they lined up really well. We'll have a little longer overlap between Jason 3 and Jason CS because it's a total redesign, but we expect it to be as accurate or slightly more accurate than the Jason missions. So that's the short answer.

Jeff: That's fine, thanks.

Josh Willis: You bet. Any other questions? So, in 2016 last January? February? Anyway, we launched Jason 3. So, moving on to slide 18. This is my fun image for Jason 3. Jason Part 3. It's been quite a remarkable achievement. You know, the Jason Friday the 13th horror movies were incredibly successful in some degree because they made, I don't know, 13 of them? I can't remember.

But we've been incredibly lucky with our Jason missions because we've been able to link them together one after the other in order to make this continuous record. And so, we hope to continue that with Jason CS. But this one's good for a joke or two.

Slide 19 is just an image of Jason 3. Always good for sort of introducing this subject. I think you guys all have these slides, so you're welcome to use them.

Slide 20 is a little bit of fun for me. That's me - this is actually a video. I'm going to hit the play button. You may hear the sound in the background. If you are going to use this -- and you are all welcome to use it -- I highly recommend plugging in some sound because the audio of the rocket taking off is really quite spectacular.

As you can see in the cut about halfway through the sound from the rocket was so loud that it scared a herd of cows which fled the scene, running away from the rocket. Probably the smartest animals on the property that day.

But anyway, the launch in 2016 of Jason 3 was fogged in, so we weren’t actually able to see the rocket, but we were able to hear it -- as was the livestock.

Twenty-one is just a nice picture of the launch from Jason 2. It actually was lucky enough to launch on an extremely clear day. And this photographer took a long exposure of the launch. I got this really nice trace of it taking off from Vandenberg and heading up into the sky.

So, there’s a few fun pretty pictures for you if you are doing a talk on the Jason missions. Another one that I like to use to introduce the idea of El Niño -- which is a key thing that the Jason missions measure -- is slide 22 which you guys may remember if you’re old like me. Back in 1998, that’s Chris Farley playing the part of El Niño, the storm to end all other storms.

El Niño is not really a giant, doughy comedian named Chris Farley but in fact it is a major climate impact. And it’s one of the main reasons the Jason missions became such a huge - it really in a way scientifically put the Jason missions on the map, because it was such a worldwide phenomenon in 1998.

Slide 23 is a slide from someone who latched onto the name Godzilla El Niño. You guys may have heard this term thrown around a couple of years ago when we had a repeat. We had another El Niño that was as big as the 1998 El Niño, as I'll show you in just a minute, but didn't have quite the same impact in southern California so unfortunately, we didn't have comedians doing Saturday Night Live sketches about the Godzilla El Niño. But it was still a worldwide event, as I'll talk about in a little bit.

Man: Question.

Josh Willis: Yes. Go for it.

Man: What location was the launch on slide 20 where the cows are running?

Josh Willis: That's Vandenberg. Both that one, 20 and 21, were Vandenberg launches. I believe Jason 1 was also a Vandenberg launch. So that's up the coast here in Southern California.

Man: Thanks.

Josh Willis: You bet. I don't know where Chris Farley did that, but I assume it was New York.

So let's talk about El Niño for a minute. I kind of talked up how important these missions are for studying El Niño.

On slide 24, there's a little animated slide just kind of explaining what an El Niño is. So, you remember the earlier slide showing the height of the ocean surface based on the currents. Well, that also relates to how the warm water moves around in the ocean. So, high sea levels are not only associated with currents on the side of the current, but high sea level is associated with warm water. This is also true and important for hurricane forecasting.

So, in the Pacific Ocean, you have this situation where most of the time the warmest water on the planet sits in the Western Pacific Warm Pool. This is an area that goes from a little west of the date line over to Indonesia or so and many 10 or 20 degrees of the equator. This was an area which contains like I said the warmest water anywhere on the planet, and it tends to be associated with convections.

So, when you have a warm patch on the ocean, then it tends to warm the atmosphere from below. That warm atmosphere rises. Since it's over the ocean, it's easy to collect water so it tends to be very wet. As that atmosphere rises, then the water condenses out of it, releasing more heat into the atmosphere and causing more convection and rain, which is associated with these convective regions. So, this big warm patch is sort of a source region for an atmospheric change in circulation that extends all the way across the Pacific Ocean.

So, this interaction between the warm water and the atmosphere typically starts off over the warm pool when the warm pool is all the way locked against Indonesia in the western part of the Pacific Ocean.

Now the trade winds, which blow from east to west across the equator, typically are kind of pushing that warm pool toward the west. Occasionally, those trade winds relax and the warm pool begins to move from west to east. It expands across the Pacific Ocean and it takes that area of convection with it. So, the convection area begins to move and this rearranges the atmospheric circulation in a way that kind of wreaks havoc with typical weather patterns across the planet. So that's what's happening in these two images on slide 24.

If we go on to slide 25, we can look a little bit at the impacts of what's happening here. So, this is just a sort of little graphic design to show where the warm pool is -- where it says Pacific Ocean, that big white blob. As it extends out to the east, then the jet stream, which typically brings storms across the United States out of the Pacific, can wind up strengthening and moving a little bit south.

This tends to make the southern half of the United States wet and warm throughout the winter, in which an El Niño peaks. It also tends to dry out the far northern United States and Canada. So, on the Pacific coast, we tend to have wet winters in El Niño in southern California and dry El Niño winters in Northern California, Oregon, and Washington.

So that's the typical pattern for an El Niño. And in 2015 and 2016, on slide 27, you can see that we had another giant El Niño. I think this one's – I'm trying to remember if this one's an animation - yes. If you actually click on slide 26 and you make it full screen, this is actually an animated GIF that will play through a comparison of the 1997-98 El Niño -- which I'm going to call the Chris Farley El Niño -- and the 2015-2016 El Niño -- which we'll call the Godzilla El Niño.

Now, this GIF is a little bit old. You can download an updated version from the web address right there at the bottom -- sealevel.jpl.nasa.gov. Just click on the El Niño Watch and it should take you to a place where you can actually download this animated GIF and update it all the way through the end of 2016.

And what it shows is that the two El Niños are actually very different. The 97-98 El Niño, which brought huge rainfall to southern California and wound up putting Chris Farley on Saturday Night Live wearing a wrestler's outfit. And in 2015 we also had a huge El Niño, but if you remember -- especially if you were here in Southern California -- we did not get that much rainfall. In fact, Southern California kind of got passed by during the 2015-16 El Niño in terms of rainfall. Northern California, Oregon, and Washington got tons of rain that year. But we really didn't end our decade-long drought here in Southern California, which was what really everybody hoped for, with the big 2015-2016 El Niño.

So, this is a nice one to use. And like I said, check out that sea level site for an updated version.

So, another way in which we use these satellite data is to average them all over the globe. And when you average sea surface height everywhere in the globe, you're essentially measuring the volume of the oceans. And that's a key impact and indicator of human-caused climate change.

So slide 27 is a slide that I usually use to introduce this topic. It's one that I really feel like drives home the point of just how important this mission and set of missions is. This is the slide that I use to justify the "Most Important Mission Ever" title that we saw that at the very beginning.

The curve there on the left is the rise in atmospheric CO2, now measured by NOAA and started by the Scripps Institution of Oceanography, the famous Keeling Curve. This is the rise in CO2 from Mauna Loa in Hawaii. And it goes back to the mid-1950s, I guess. And it charts the rise and it's really showing - because CO2 is well mixed in the atmosphere, if you measure it at one point high up in the atmosphere, you get a good estimate of what the total atmospheric CO2 is like.

It's been rising, as we all know. As we burn fossil fuels, we add CO2 to the atmosphere and it traps heat and causes the climate to warm. One of the effects of that climate warming is the rising seas. And in fact, the oceans absorb over 90% of the heat trapped by these greenhouse gases. So, they're really a primary indicator for how much change we've caused in terms of the planet.

Another slide that I like to use that's occasionally fun is to ask people, you know, so you've seen this slide. What causes global warming? And usually, two or three people in the audience yell out CO2 and then I flip to slide 28 and say no, it's actually Democrats. That joke may not be as funny anymore to you, but I still get a laugh out of it every now and then. But anyway, it's not really Al Gore, of course -- although some people say he can breathe fire in real life. I've never verified that myself. But in fact, CO2 is what's causing climate warming.

On slide 29 you can see some of the evidence for human-caused climate warming if you look at the poles. This is an older image in the early 2000s this massive shelf or floating sheet of ice in Antarctica -- the Larsen B Ice Shelf -- collapsed. It was about the size of Rhode Island. They went back afterwards and drilled into the sediment below where the shelf used to be and they found that the shelf had been there for more than 10,000 years. That means that it extended all the way back to the last Ice Age and it wasn't until the recent warming that it got warm enough to collapse.

And by the way, since then several other ice shelfs have collapsed along this peninsula. There's clearly something happening now in the last 100 years that hasn't happened any time in many thousands of years.

Slide 30 is kind of a basic global warming slide. This is how global warming works -- we trap heat in the atmosphere when we change the composition and more heat winds up staying on the planet.

Slide 31 is an indicator of what happens to that heat. I mentioned this in an earlier slide, but over 90% of the heat trapped by global warming is actually warming the oceans. That means that even though we live in the atmosphere and we care about surface warming, really almost all of the action for global warming and human-caused climate change is happening in the oceans. And that's why these satellite altimeters are so important.

I think I'll skip ahead a little bit, since we're running a little late on time and I want to give you guys plenty of time to ask me questions. If you skip down to slide 33, again this is the global rise in sea level. In this plot I've removed the seasonal cycle, which you saw that has to do with the exchange of water between atmosphere and oceans just through the atmosphere and runoff.

This again is the long-term rise in sea level that's an indicator of that warming ocean and the warming glaciers and ice sheets around the planet which contribute to sea level rise as well. That's important because worldwide 200 million people or more live in land that will be regularly flooded by sea level by 2100. And each -- this is a little bit older study -- each year we seem to be finding more and more evidence that ice sheets are warming faster and melting faster. Estimates of sea level rise throughout the next century keep being revised upward. So as we learn more and more, we're seeing that the rising oceans are really our primary indicator for how we're impacting the climate.

I think I'm going to end on slide 34 here and then you guys are welcome to ask me questions. And you guys are also welcome to use any of the later slides down here. There's a few more animations of the El Niño and some other things that I've kind of talked a little bit about, but you guys can use these slides for your own purposes.

The future rise in sea level is really one of the main questions for climate scientists today. The fact is that we’re pretty good at projecting future temperatures of the planet -- at least globally averaged temperatures. We can’t tell you the temperature and rainfall change in your backyard, but we have a pretty good idea of how the global temperature is going to change in the next hundred years given a certain amount of CO2 in the atmosphere.

We can’t really say the same thing for sea level rise. We really just don’t have enough information and enough knowledge to predict future sea level rise very well. And so, the altimeters are kind of our fingers on the pulse of this climate change into the future. Since we don’t have a very good idea of how to predict it, the next best thing we can do is measure it and watch carefully how it’s changing.

This slide 34 is an older projection. There are some higher projections now even more recently. But it’s a projection of future sea level rise out to 2100 and there are different scenarios. This particular study didn’t assign any likelihood to those scenarios. We just really don’t know which one is the most likely.

But, our satellite altimeters are suggesting that we’re on sort of a moderate to higher path -- at least so far. My comment at the beginning about this being the most important mission ever, I really think our ability to measure our changing climate is key to helping us better respond to the climate that we’re building for ourselves in the future. And that’s why I make that claim.

I think since we’re getting close to 2:00 I’m going to stop talking. There’s more slides, but you guys ask me some questions and I’m happy to answer anything you want.

Earl: Yes, question?

Josh Willis: Go for it.

Earle: Yes. This is Earle Kyle, Solar System Ambassador. Since methane is a more powerful greenhouse gas than carbon dioxide, with this potential flooding with the ocean rising causing a lot of rotting vegetation, is that going to be a positive feedback loop? Anybody taken that into consideration for modeling this?

Josh Willis: That’s a good question. Changes in land use are estimated. I think that places like tundra thawing out are expected to be bigger sources of potential methane. Of course, methane is a powerful greenhouse gas, but it doesn’t stay in the atmosphere. It breaks down into CO2. But it’s a more short-lived greenhouse gas.

But nevertheless, you’re exactly right -- huge sources of methane could be feedback. And right now, we really just don’t have a handle on feedbacks. We think that they are these kind of tripwires in the climate system and if we cross one, then we could unleash warming a lot more quickly. We might unleash sea level rise a lot more quickly. But the fact is we just really - those are still big unknowns.

Land use at the coast is an issue -- not just because of sea level rise, but also mainly because of development. So as we turn former salt marshes and other things into golf courses and housing developments, that has an impact on sources for methane and CO2 as well.

But I think those things are all important but of course, the biggest factor right now still is fossil fuel use and CO2 production.

Earle: Thanks.

Josh Willis: You bet.

Adrienne: Hi, Josh. This is Adrienne Provenzano. I'm a Solar System Ambassador. And I'm wondering if there are any other altimetry experiments being done on other satellites. And if there's any use of the cube satellites for this kind research.

Josh Willis: That's a great question. I'm not aware of CubeSat altimeters. But there are other altimeters on other satellite missions. There's a satellite called Altica which was a joint French-Indian satellite. There's other Sentinel missions, Sentinel 3. Folks tend to put other altimeters on kind of big flagship missions that have all kind of everything and the kitchen sink. These tend to fly in sun synchronous orbits because they have a lot of stuff on them and they need a lot of power. And that's great for supplementing the Jason missions.

It has some issues because if you're in a sun synchronous orbit, then you're aliasing the tide into the mean, which can be troublesome. But they still use data from those and in combination with missions like the Jason missions, they make a very powerful platform for seeing the smaller scale stuff. So, the Jason missions kind of look down at a single ten-kilometer footprint and move around the Earth sweeping out a kind of ball of yarn pattern. As you have more and more satellites in different orbits, then you fill in those missing diamonds and get higher and higher resolution.

Further into the future in 2020, there is development of a mission called SWOT which stands for Surface Water and Ocean Topography, which is actually an interferometer. So, this will measure a swath of heights across the ocean instead of just a single kind of nadir pencil beam looking down on the ocean. It will sweep out a whole map as it goes. And that will sort of revolutionize the oceanography we can we can do with satellite altimetry out in the future.

Some people I think are looking at CubeSats but I don't know of any that - I don't know anybody who's flown a CubeSat altimeter yet.

Adrienne: And then, is there any connection with the ISS on any of this research?

Josh Willis: The Space Station has been talked about for a platform. One of the issues with it is that it doesn't go to very high altitudes. So, we have kind of a lot of altimeters in the medium to lower altitudes. The place where we need more altimeters is kind of at the poles.

So right now, there's not a plan that I'm aware of to put one on the Space Station, but who knows? We wouldn't say no to it.

Adrienne: All right. Thank you.

Josh Willis: Sure.

Man: I have a question on slide 35.

Josh Willis: You bet.

Man: Let's see. I've seen this upper left slide before. I didn't quite understand the point about what ice melt as accelerated since ice melt, if it's polar cap, if it's already in the water, it doesn't change the sea surface. So, I guess that refers to the ice sheaths or the glaciers?

Josh Willis: Right. From other satellites, we know Greenland and Antarctica have accelerating ice loss.

Man: Okay. The lower left and especially the right hand one I'd appreciate if you could explain in some detail. They're kind of new to me.

Josh Willis: Yes, so this is from a paper that - this whole slide probably deserves a little more explanation. This is from a paper that's kind of looking at the 25-year record of global mean sea level change and asking the question when should we begin to see that this record is curved, that it has an acceleration.

We expect an acceleration because we're adding more CO2 to the atmosphere, the temperature is rising faster and faster. And as we just mentioned, two of the contributors to sea level rise -- Greenland and Antarctica melt -- are both accelerating. So where is the acceleration in global mean sea level?

And so, this paper looked at a couple things. One are these kind of bumps and wiggles that you can see. So, in 1997 and 98 during the big El Niño, there was a bump in sea level. Turns out this had to do with rain that normally falls over land staying over the ocean and extra runoff filing up the ocean a little bit during the 97-98 El Niño.

The opposite happens during La Niñas, which you can see just after 2010 and in 2011 the orange curve dips down a little below the kind of straight line. And that has to do with again exchange of water. That time, there was more rain over land -- particularly Australia -- and a lot of that water stayed for six months or a year. And as it slowly ran off, then sea level kind of came back to where it was.

So we know there are these natural bumps and wiggles in the sea level curve. It's not perfectly straight with global warming. And down below, is an attempt to estimate one that we think might have happened right at the beginning of the launch of TOPEX/Poseidon.

So in 1992 -- I guess it was 91 -- Mount Pinatubo erupted, and this blew aerosols into the stratosphere and actually blotted out a little bit of sun, caused extra reflection at the upper levels of the atmosphere and cooled the Earth a little bit. And as the Earth cools, you expect a little bit less energy to go into the ocean, and so sea levels to fall just a little bit.

So, this lower left-hand corner is a model result that is an attempt to estimate how much sea levels should have fallen because of the Mount Pinatubo eruption. And they get a millimeter or two is kind of the answer.

And so, this is an attempt to kind of explain why the early part of the record is not quite as flat as you might expect. Probably honestly that's a little bit of a red herring. If I was remaking this slide, I would leave off that lower left-hand thing. You can check out the paper if you want, but it's kind of an attempt to explain why there's no acceleration detected yet.

But really, the real reason is the record is just not quite long enough. We needed a couple more years of increasing sea level rise rates in order to distinguish a curvature in this record from the kind of bumps and wiggles that you expect from an El Niño. And that's what's shown on the figure on the right. So, this is an estimate of acceleration and how well you can measure an acceleration. So, the gray is kind of an error bound based on a guess of what the acceleration is and an estimate of how big those bumps and wiggles are.

And what it’s kind of telling us is that by 2020 or 2025, we should be able to distinguish the acceleration of sea level rise from the kind of long-term trend. So that’s when we kind of expect it to become statistically significant relative to these kind of expected bumps and wiggles. Does that make sense?

Man: Yes. Let me see if I do understand the difference between acceleration and rise. If I understand, the historical has been like 0.25 millimeter until the 20th century or so and then it kicked up and by the end of the 20th century, it was more in the range of 3 millimeters -- the slope, the rise.

Josh Willis: Right.

Man: And now it’s turned the corner slightly again a couple times to 3.3 or 3.4 if I’ve read the literature right. Is this saying at stabilizing on the order of 0.1 to 0.12 millimeters a year acceleration, we expect it to go to, you know, 3.5 to 3.6 to 3.7 and so on and just would be climbing like that? Is that the point of this, that the slope will keep moving upward?

Josh Willis: Yes, that’s right. This is really if you look really carefully, it’s millimeters per year per year. It’s millimeters per year squared.

Man: Right.

Josh Willis: So, 0.1 means every year it goes up by 0.1 millimeters. So if it’s 3.4 in 2015 then it will be 3.5 in 2016, 3.6 in 2017 and so on. So, it’s the…

Man: So, in 30 years, 35 years it’s going to double the rate of rise.

Josh Willis: That's right. Now, this is an assumed acceleration. So, they kind of took a guess at the acceleration and said this is what we think it should be. And if this is what it is, then this is how long it would take for us to detect it.

Man: So that's going to be interesting to see if that plays out, because that's pretty scary if the slope keeps changing like that.

Josh Willis: It certainly is. And we certainly expect it to. The ways that Greenland and Antarctica are reacting to the warming climate are not strictly linear, so we do expect that the rate of rise will definitely increase throughout the 21st century. Whether it increases this fast or not is still kind of anybody's guess.

Amelia Chapman: Josh, I know we're right up against 2:00. Do you still have a few more minutes to answer more questions?

Josh Willis: Absolutely.

Amelia Chapman: Okay, great.

Peter: I have a question. Josh, this is Peter Falcon. I've heard the term tipping point quite often. Could you explain what a tipping point is and if we're there at this point?

Josh Willis: Right. A tipping point is a place where if you're changing the climate by forcing it -- think of this as let's say you had a marble in the bottom of a cereal bowl. If the marble is kind of the climate, then as we force it, as we push the marble up the side of the bowl, we're forcing the climate into a new regime.

A tipping point would be something like the edge of the bowl, where you push the marble up to the top of the edge and if you push it just over the edge, then whether you keep pushing or not, the marble is going to roll out of the bowl.

Tipping points in the climate are just like this. They are things that we're - forcing climate into a new regime and if we reach a tipping point, then the climate would continue to change on its own even if we weren't forcing it anymore.

The answer to whether or not we've reached tipping points yet is I don't really know. It's hard to kind of say before you get to the tipping point. There is some suggestion that in Antarctica at least, we've reached a tipping point with melt in some of the places. Some of the more threatened huge glaciers in Antarctica, the ice actually - the ground underneath the ice actually slopes downward as you move away from the ocean. That means that water can actually creep in underneath the ice and eat away at it from below.

There is some suggestion that that process has begun and it may be a runway process that even if we stopped climate warming now, that that would continue. But it's going to take a little while before we're really sure.

I don't think anyone has suggested yet that we've reached the kinds of tipping points we talked about earlier like methane release, but we may be getting close.

So, the short answer is we don't really know how close we are to tipping points. We'll kind of only know that we passed them when we see the major results take off without our help.

Peter: Yes.

Man: I have a question. On slide 31, I don’t quite understand how global warming warms the ocean more than the atmosphere. Can you elaborate on that, please?

Josh Willis: Absolutely. So, if you think about the ocean and the atmosphere, water is very heavy and it takes a huge amount of energy to change the temperature of water relative to the temperature of air. So the ocean has a heat capacity that’s about 1,000 times bigger than the atmosphere’s. So, to change the temperature of the ocean by one degree takes 1,000 times more energy than to change the atmosphere by one degree.

The other thing to remember is that the oceans cover two-thirds of the planet’s surface. So really as we watch the planet warm, even surface temperature if you’re just looking at the record of surface temperature over time, two-thirds of that reflects what’s going on in the oceans.

So, the oceans are really a huge player here and it’s all of those things together that wind up kind of conspiring to make these numbers so drastic. In fact, in a very real sense, we shouldn’t be worried about atmosphere warming. We should be worried about ocean warming because that’s really where all the action is.

Man: Right. And that affects the global weather patterns overall -- hurricanes, et cetera.

Josh Willis: Absolutely. As the heat gets into the ocean, it’s there for thousands of years -- sort of like your in-laws at dinner, right? When the heat gets into the ocean layers below just right at the surface, then it goes on this long circuit throughout the ocean called the global conveyer belt or the ocean conveyer belt. And the time scale for the conveyer belt is thousands of years.

So really, we’re watching the oceans change because it’s kind of the most complete and comprehensive indicator of just how much we’re changing the climate.

Man: Thank you.

Josh Willis: You bet.

Amelia Chapman: This is Amelia. I had sort of a minor question. Back on slide eight…

Josh Willis: Yes.

Amelia Chapman: …with the island, just what are the numbers that are on that slide in yellow?

Josh Willis: Slide eight. Okay. This was a more elaborate discussion of what all these different sectors were. I grabbed this from something, and I forget. But I can tell you what the lines are. Like 5 is the geoid. That’s the sort of level surface where you would say gravity points perpendicular to this surface everywhere. That’s the strict definition of the geoid and it pushes up around the island through the island because the pull of gravity is from the island is tilting it that direction.

The green thing is kind of the sphere but not quite sphere that the Earth would be if it was perfectly smooth like a marble.

Amelia Chapman: Okay. Thank you.

Josh Willis: You bet. 4 is land, 1 is water. I can tell you that. That's all I know.

Amelia Chapman: And did we have any more questions from the crowd?

Josh Willis: Well, I just wanted to say thanks everybody. I really enjoyed this and I hope it was informative and you're always welcome to email me with questions, too.

Woman: I did have a question really quick if that's okay.

Josh Willis: Sure. Yes, you bet.

Woman: I was just wondering what agencies are using this data to prepare for sea level rise.

Josh Willis: All kinds. NASA and NOAA both house the data here in the United States. It's used by the Navy. It's publicly available as well. And we have users kind of all over the world. A lot of them are scientists, but fisheries also use the data for things like looking for ocean currents. I think agencies who are looking for, you know - different agencies take the information from things like sea level rise as well as information from the rest of the literature about what the future sea level rise is going to be and try and put them together in reports. Actually, California just put out a pretty recent report on sea level rise in the last couple of months and uses a lot of data from these missions - and all sorts of other sources - to kind of make suggestions about how decision making should happen in this environment.

Woman: Thanks.

Josh Willis: You bet.

Amelia Chapman: All right. Well we’re going to go ahead and let you go. And I wanted to thank again Dr. Josh Willis for speaking with us today and to thank all of you for joining us.

I’d like to remind you that tomorrow you’re welcome to join us again for the conversation at 11:00. In honor of this week, it’s Pacific Time. We’ll have “Exploring Ocean Worlds: Prebiotic and Astrobiology Implications” with astrobiologist Dr. Morgan Cable talking about oceans on other worlds.

So once again thank you so much to Dr. Willis and all of you for joining us.

John Willis: Thanks.

Group: Thank you.

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