THE ENDLESS VOYAGE

"Ebb and Flow" Episode 115

Many ancient cultures, going back thousands of years, wondered and theorized about the origin of the tides. One of the interesting ideas that was considered was the fact that the earth was considered to be a living organism, and the breathing of that organism, the inhaling and the exhaling, was the thing that caused the tides to go up and down.

The tides do contain a lot of energy, and there's a lot of energy in this earth/moon system. If we can harvest it nicely, we'd have a good source of power.

We're just at the beginning of this hypothesis that the tides are important in mixing the oceans, and that has a profound sequence of consequences in determining the ocean circulation and determining the ocean's impact on climate.

NARRATOR:
WITH ALMOST MECHANICAL PRECISION, THE TIDES COME AND GO LIKE CLOCKWORK, RISING AND FALLING ON A PREDICTABLY REGULAR BASIS. THEY'VE BEEN A SUBJECT OF SIGNIFICANT INTEREST FOR COUNTLESS MARINERS SINCE THE BEGINNINGS OF OCEAN EXPLORATION, AS WELL AS A SOURCE OF ENDLESS WONDER FOR EVERY CHILD WHO HAS VENTURED TO THE EDGE OF THE SEASHORE WITH A SHOVEL AND BUCKET. THE DAILY EBB AND FLOW OF THE TIDES IS SOMETHING THAT SIMPLY IS, LIKE BREATHING OR THE CHANGE OF SEASONS. AND YET BENEATH THE SURFACE OF THIS APPARENTLY SIMPLE PROCESS IS A DYNAMIC WEB OF INTERACTIONS THAT IS SURPRISINGLY COMPLEX.

JAMES IRISH, Ph.D., Woods Hole Oceanographic Institution:
It just keeps coming and going again every day, like the sun comes up every day, in a periodic sort of way. So, tides is, essentially, the rise and fall of sea level, and it's really caused by the gravitational attraction of the sun and moon.

REINHARD FLICK, Ph.D., Scripps Institution of Oceanography, UCSD:
That's on the surface a very simple concept. The earth and the moon and the sun have mutual gravitational attraction. And the fact that the waters of the earth in some sense are loose on the earth, they can move around—the small differences in the gravitational forces, because of the relative motion of the earth, the moon and the sun, can make those waters shift, and the results are the twice and once per day ups and downs of the tides.

NARRATOR:
IN THE 17^{TH} CENTURY, THE INTERACTION OF THE EARTH, THE SUN AND THE MOON AS REFLECTED IN THE DAILY TIDES WAS A SUBJECT OF CONSIDERABLE INTEREST TO, AMONG OTHERS, SIR ISAAC NEWTON.

FLICK:
Being arguably one of the best physicists that ever lived, wrestled with this problem as part of his fundamental understanding of motion—the laws of motion—for quite a number of decades before he came up with the theory of gravitation. And in fact, the tides was one of the fundamental aspects of physics and astronomy that he considered, and he thought was very important to explain in his development of the theory of gravitation. Before Newton came up with the idea of gravity, it just was not understandable to people how a distant celestial object like the moon could influence the waters of the earth. It took Newton and the description of gravitational attraction to really make that connection and take it away from the so called occult.

NARRATOR:
THE ROLE OF THE SUN AND THE MOON HAS LONG SINCE BEEN RECOGNIZED AS A PIVOTAL ASPECT OF TIDAL PROCESSES.

DOUGLAS LUTHER, Ph.D., University of Hawaii at Manoa:
The moon, even though it is very small even compared to the earth—it's so much closer to the earth than the sun that at the surface of the earth, the gravitational perturbations due to the sun are only about half the strength of the gravitational perturbations due to the moon. And it's all due to proximity.

ROGER BLANDFORD, Ph.D., California Institute of Technology:
So what you see in practice is a compromise between the tidal pull of the moon and the tidal pull of the sun. And when they're pointed in the same direction, then the tides are rather strong, and we sometime call these spring tides. And when they're pointed in perpendicular directions, the tides are less strong and we call them neap tides.

NARRATOR:
WHILE GRAVITATIONAL ATTRACTION IS LARGELY RESPONSIBLE FOR THE TIDES, THE FULL STORY IS MUCH MORE COMPLEX THAN WHAT HAS COME TO BE CALLED THE EQUILIBRIUM THEORY.

LIBE WASHBURN, Ph.D., University of California, Santa Barbara:
The equilibrium theory makes a number of assumptions that are not true and this was realized by the people who developed the theory. But if the earth were a uniformly covered sphere, and it was uniformly covered with water that was very deep, then the equilibrium theory would predict that underneath the moon and opposite the moon on the earth, the water would bulge outward and the tides would change through the day as the earth rotated within these bulges that were aligned with the moon. And this would correctly predict the frequency of the tides, which is about two cycles per day.

LUTHER:
There's really not much to say about the equilibrium tide other than that. If there was no dynamics, no fluid flow problems, if we didn't have to worry about the fact that there were continents, if we didn't have to worry about the fact that the water is rubbing along

the bottom and is being held back from moving where it wants to go, then you'd get this equilibrium tide.

The equilibrium theory of the tide can't really work. I mea,n it's an interesting concept to describe the fact that—why there are two bulges, but those two bulges cannot make their way around the world fast enough, or keep up essentially with the rotation of the earth, because the waves—if we describe these water motions as waves—have their own physics that they have to adhere to. Specifically, the waves cannot keep up because the ocean isn't deep enough for those waves to be able to move fast enough to get around twice a day. So they can't keep up. And the second thing is very simple—that you can't have two bulges of water on the earth because these inconvenient continents would get in the way of these two bulges. In fact, the earth is not covered completely by an ocean.

NARRATOR:
WHILE THE EQUILIBRIUM THEORY IS BASED ON A SET OF GEOGRAPHIC CONDITIONS THAT DO NOT EXIST, THE DYNAMIC THEORY OF THE TIDES IS DERIVED FROM REAL WORLD PHYSICAL CONDITIONS.

LUTHER:
The dynamic theory of the tides is based on the fact that the ocean is water. It has to obey the laws of fluid mechanics. These laws say that you have a certain acceleration due to the gravitational attraction of the moon and the sun, but you also have forces holding back the water motion. You'll have drag on the bottom, like a gravity wave hitting the shoreline, like surf hitting the shoreline, the tides are a gravity wave. That is their dynamics. That is the dynamical theory, basically, is that tides are gravity waves. They're affected by rotation more than your surf hitting the shore, but they are gravity waves.

One useful way to describe the tides is as a progressive wave—that is, a wave that has a crest and a trough, a crest being the high part and the trough being the low part—and this wave progressively moves around—actually a series of waves progressively move around the ocean basin in a circular fashion, so that we have a continuous succession of increasing elevations and decreasing elevations with highs and lows in between as the day goes by.

NARRATOR:
PART OF THE CHALLENGE OF PREDICTING TIDES IS THAT EVERY LOCALE HAS ITS OWN UNIQUE SET OF TOPOGRAPHIC CONDITIONS.

FLICK:
At first thought you might think that cities, for example, at the same latitude would have essentially the same tides, but nothing could be further from the truth, because the tidal forcing is really only half of the answer to what it is that makes tides in a specific location. The second part of that answer is the local ocean response to that specific tidal forcing.

And in some places around the world, we find that tides have a diurnal component that is very strong, and this means that we have one high tide and one low tide per day. This occurs often on the east coast of the United States. In other areas, such as here in Santa Barbara, we have what's called a mixed tide, where both the diurnal or daily tidal components, and the semi diurnal tidal components—these are twice-a-day tides—are both strong enough that we have two high tides and two low tides per day.

NARRATOR:
TIDAL CURRENTS, WHICH ARE MOVEMENTS OF WATER RELATED TO THE TIDES, ALSO VARY ACCORDING TO LOCATION.

FLICK:
If we think of the tidal motions—the up and down motions—as a phenomenon related to the wave nature of tides, there is also a motion of water associated with that. In short, tidal currents occur everywhere and all the time wherever you have a tide. Tidal currents can be very important in constricted passages. One of those examples, even where the tide is small, was in Aristotle's consternation in trying to figure out what the tidal currents were through the Greek Isles. Because of the constrictions, even though the tides aren't very large, we can have significant currents. On the other hand, in areas like the ocean off of California, we have relatively weak tidal currents because there's really no constriction.

LUTHER:
The tide is slow—a cycle per day, two cycles per day. And the flow of water is not constricted, so you get currents of a few centimeters a second at most of the open ocean. But as soon as you run it up into a continental shelf and then on into estuaries or harbors or channels, then it has to speed up.

REINHARD FLICK, Ph.D., Scripps Institution of Oceanography, UCSD:
Tidal currents in constrictions are important. They are important and they are regularly mapped and used by mariners in entrances—bay entrances. New York Harbor, San Diego Bay, San Francisco Bay, the Straits of Juan de Fuca in Seattle—tidal currents are a very important phenomenon in those constrictions, and they're important for shipping still today.

WALTER MUNK, Ph.D., Scripps Institution of Oceanography, UCSD:
When you live near the ocean and you want to take a boat out of some harbors, you're limited by tidal currents. If I were in Woods Hole at spring tide—the current velocity through the so-called "hole" gets up to seven knots. You may have a problem manipulating it so that, in that sense, tidal currents are a factor in coastal areas and may dictate how you can get in and out of harbors. That certainly is a major consideration.

NARRATOR:
WHILE THE EFFECTS OF THE TIDES WITHIN HARBORS AND OTHER CONSTRICTED AREAS HAVE LONG BEEN RECOGNIZED, THE IMPACT OF

TIDAL PROCESSES EXTENDS TO MANY OTHER AREAS WITHIN THE MARINE ENVIRONMENT.

FLICK:
For example, during storm activity, if high waves and storm impact on coastlines occurs, especially on the west coast, during the time of very high tides, then coastal erosion and coastal flooding can be much more of a problem than if those same storms occur during either periods of low tide or during periods of lower tidal range.

NARRATOR:
PERHAPS NOWHERE IS THE IMPACT OF THE TIDES MORE SIGNIFICANT THAN AT THE APPROPRIATELY NAMED INTERTIDAL ZONE.

JUDITH McDOWELL, Ph.D., Woods Hold Oceanographic Institution:
The Intertidal Zone is that area of the shoreline that is exposed during the tides. The area along this beach will be submerged by water part of the day, and exposed to the air part of the day. The actual features of the Intertidal Zones will change as the tides change—daily within the lunar cycle. As the tides are influenced by both the gravity pull on the earth's surface by the moon and the sun, the exact position of high tide and low tide will change within that lunar cycle. If you were an organism living within the Intertidal Zone, you have the complications of being exposed to air, in the summer time extreme heat, in the winter time, extreme cold.

DOUGLAS LUTHER, Ph.D., University of Hawaii at Manoa:
The marine organisms, both the fauna and the flora, have to have evolved survival mechanisms such that at one part of the day they're snuggly, wrapped in the warm water of the surface, and they're getting nutrients, they're getting the oxygen they need. And then, all of a sudden, the water goes away, and now they're exposed to the drying effects of air, to the stronger effects of sunlight. And so they have had to evolve mechanisms to survive these, essentially, daily droughts that occur in their life cycle. So the tides have made a big impact on creatures in the coastal zone.

NARRATOR:
FOR SOME ORGANISMS IN THE INTERTIDAL ZONE, THE ROLE PLAYED BY TIDAL CURRENTS IS EVEN MORE DIRECT.

LUTHER:
They move out the eggs of the critters that live in the coastal zone, take them out to sea where they develop, and then bring them back into the coastal zone where they settle down again. The tides also remove pollutants. All these plants and animals in the coastal zone are generating waste products, and the currents come in and wash those away, bringing them fresh water with more nutrients.

NARRATOR:
IN SOME COASTAL REGIONS, THE TIDES AFFECT NOT ONLY THE ORGANISMS WHICH RESIDE THERE, BUT THE SHAPE AND DIMENSIONS OF THE ENTIRE AREA.

ANTONY ORME, Ph.D., University of California, Los Angeles:
For example, some tidally dominant estuaries, such as those on the north coast of Australia, are characterized by significant tidal ranges, and by sediment moving into and out of them with each tide, and being shaped essentially as almost funnel-shaped estuaries by that tidal regime. The Thames estuary in Southeast England is essentially a tidally dominated estuary, because you have a tidal range there of five to eight meters or so, and this pushes the tidal bore into the river mouth a considerable distance upstream and then, of course, it returns seaward a few hours later. This creates a very distinctive type of river mouth.

NARRATOR:
TIDAL MOTIONS ARE SOMETIMES VIEWED FROM A VERY DIFFERENT PERSPECTIVE, AS WHEN SATELLITES LIKE THE TOPEX/POSEIDON COLLECT OCEAN SURFACE DATA HIGH ABOVE PLANET EARTH.

LEE-LEUNG FU, Ph.D., Jet Propulsion Laboratory:
One of the goals was to measure the ocean tides in unprecedented accuracy and coverage. The interesting thing is that the ocean topography mission like TOPEX/Poseidon, was not necessarily interesting tides. But we have to understand tides to remove that as a noise, otherwise, the sea surface topography measure is going to be dominated by tidal motions. So you have to remove that before you see smaller signals like El Niño and the Gulf Stream and things like that.

One of the big problems in trying to sort out trends in past sea level changes—global sea level changes—has been the inability to measure sea level at lots of places over the ocean. Almost all of the sea level measurements that we rely on to talk about global change, you know, global sea level increases, come from the tide gauge networks that are located on coastlines and on a very few mid-ocean islands, like Hawaii, for example. So there has been a renewed interest in a very old subject—namely the study of tides as a necessity to remove this tidal signal, open ocean tidal signal, from these satellite measurements.

NARRATOR:
ANOTHER LINK BETWEEN TIDES AND GLOBAL CLIMATE IS A FUNCTION OF TIDAL FRICTION.

LIBE WASHBURN, Ph.D., University of California, Santa Barbara:
Tidal friction arises from the interaction of the water movements caused by the tides with the bottom.

A very important aspect of this tidal friction is in understanding how the ocean is stratified, what maintains the thermal stratification of the deep ocean. You know, if you didn't have this—if you didn't have that mixing, the deep oceans would, over a few thousand years, fill up with very cold water. This has very profound climate indications, because at the poles—the surface ocean gives up its heat to the atmosphere, produces very cold water which then sinks to the bottom, and flows throughout the oceans. Now if you didn't have mixing in the subtropics and tropics of the warm, surface water downward, eventually that production of cold water would fill up the entire oceans beneath the thermocline. And then you wouldn't have any further convection. Once the deep ocean is filled with cold water, you'll no longer get cold water convecting at the high latitudes. And then the currents, which move pole-ward with warm water, would stop, and there wouldn't be as much heat brought to the high latitudes. Europe would freeze. You know, there could be immense climate implications for how much mixing occurs in the deep ocean. Now the tides is a key player in this, we believe. So that's one aspect of where tidal friction is important. More directly, tidal friction is very strongly interlinked with the evolution of the earth-moon system.

WALTER MUNK, Ph.D., Scripps Institution of Oceanography, UCSD:
At this moment of geologic history, the moon and the sun are almost equally strong—not quite, the moon is stronger, but they both are significant. Tidal friction, the same phenomena responsible for deep-ocean mixing, is also responsible for changing the orbit of the moon. And you can show that the amount of tidal friction we have would be responsible for having the moon move away from the earth at about an inch per year. That doesn't sound very much, but over a billion years, that's a lot. And my statement that the moon now is stronger than the sun, but will eventually be weaker, is based on the fact that if you extrapolate that one inch per year for a billion years the moon will be that much further from the earth, and the tides will be that much lower.

NARRATOR:
PART OF MODERN SCIENTIFIC INTEREST IN THE TIDES FOCUSES ON THE UTILIZATION OF TIDAL ENERGY AS A SOURCE OF POWER.

It's something that many people have looked at because it's free, it's there. It would be a non-polluting, renewable resource if we could harness the energy that's in this daily motion of the sea level.

FLICK:
Tidal power is a very realistic source of power. The north coast of France, for example, in Brittany—there are working tidal electricity generating plants. The tides there are in the range of 30 or 40 feet.

DOUGLAS LUTHER, Ph.D. University of Hawaii at Manoa:
So that's a good tide range you can harness. So what they did was they built a dam, and they hooked up turbines in their spillway. So on the rising tide, they'd close the dam, they let the water rise on the outside of the dam to a certain point, then they open up the flume. The water flows through the turbines as it comes into the estuary, generating

power on the flood tide. Then at roughly around high tide they close the dam again, wait for the water level to drop on the outside of the dam, open it up, and the water flows out on the ebb tide, generating electricity. So you have these two cycles. You can actually generate electricity as the water comes in and goes out, and that's been very successful.

REINHARD FLICK, Ph.D., Scripps Institution of Oceanography, UCSD:
You have to have the right kind of coastal features in order to make the construction of these dams feasible, as well as an appreciable range of tide. The Bay of Fundy on the east coast of Canada has been suggested as another area with 40 foot tides that could be harnessed for tidal energy.

MUNK:
Calculations are, that you could get the same amount of energy out as you get from a major nuclear plant. A thousand megawatts is sort of what you can generate with a major nuclear plant. Apparently you could get two thousand megawatts of power out of the Bay of Fundy, which is unique because of its high power.

Locations for tidal generation should be areas where there is a strong tidal flow that frequently occurs, because the power is extracted from the energy of movement of the sea water. So it requires a region where there is a steady, predictable flow and a strong tidal flow, and a sufficiently large volume of water that a large amount of energy can be generated.

NARRATOR:
BUT WHILE THE GENERATION OF TIDAL POWER CERTAINLY IS TECHNICALLY FEASIBLE, THERE ARE POTENTIAL PROBLEMS. FOR EXAMPLE, THERE MAY WELL BE AN ADVERSE IMPACT ON ANIMALS LIVING IN AN ESTUARY IN WHICH A DAM IS BUILT.

Every estuary, every bay has a normal mode of resonance. If the particular normal mode of the estuary that has the high tides matches the period of the tide, then as the tide wave comes into this harbor, it can force this normal mode, and you get this resonance, you get this really strong sloshing. That's what happens in the Bay of Fundy, for instance. Well, now you put a dam across it, and you're changing dynamically the character, the structure of your bay, of your estuary, that can change the normal mode character, and you may not get the same size tides after the dam is in. The tide range may not be what it was before the dam was there. Now even worse—or I shouldn't say worse, but even more intriguing is once you've changed the normal mode character of your estuary, that change will affect the tides in the neighboring domain.

JAMES IRISH, Ph.D., Woods Hole Oceanographic Institution:
They were going to block off a good section of the Bay of Fundy, but the Bay of Fundy is sort of a resonance basin. And the geometry of the basin is a resonance just below the tidal frequency. And by blocking off the northern end of it slightly, they detuned it. And one of the consequences of tuning it is moving it slightly towards the tidal frequencies,

which means you should get a bigger tide. And the implication of that is like, Boston and might have a six inch higher tide.

Can you imagine the litigation that would occur from the increased shoreline erosion if the Canadians put a dam in the Bay of Fundy, and then you get stronger erosion in Boston? So there are some pitfalls to doing it.

NARRATOR:
WHETHER OR NOT THE TIDES CAN BE UTILIZED AS A RELIABLE WIDESPREAD SOURCE OF ENERGY REMAINS UNCLEAR. BUT MOST SCIENTISTS BELIEVE THAT THE DISSIPATION OF TIDAL ENERGY IS PERHAPS THE SINGLE MOST IMPORTANT ASPECT OF THE ENTIRE TIDAL PROCESS.

One of the most important questions in modern tidal study is the question of where the energy goes. That is an important question, because of the uncertainty in the mixing of the transport of heat through the ocean. And all of this is related to the question of climate change and the impacts of warming—future warming—and how that warming is distributed.

LUTHER:
The potential is huge for the importance of tides in these other processes. And we're just at the beginning of looking at that. We're asking basic questions now. What are the processes? What are the mechanisms of internal tide generation? How much energy is really flowing from the main sea level rise and fall of the tides? What we call the Barotropic tides.

FLICK:
One of the important questions is how the ocean mixes, and intimately related with that is how the tidal energy gets dissipated, and where that energy ultimately goes, what the mechanisms are for that transfer from the surface motions into internal motions, and ultimately dissipation to heat. So that's one of the aspects that has reinvigorated this very, very old question—very old study and interest in tides.

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