Oceans in Motion: The Tides

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Key Concepts

1. Tides influence virtually all human activities in the near-shore environment.

2. Tides are a result of the differential gravitational attraction of the moon and the sun on different parts of the fluid ocean.

3. One must have a clear understanding of the changing positions of the earth, moon, and sun in order to predict tides.

4. There are many factors which influence the behavior of tides. Most of these are cyclical and predictable. A few are random and unpredictable.

Background

"The best that can be hoped for is that a tide chart will be reasonably accurate on a calm day when atmospheric pressure is close to standard."

There are two things one must understand before teaching about tides:

1.Only about 1% of the population has any idea how tides occur.

2.There are no students in this 1% and very few teachers.

The biggest problem in teaching about tides is that so many students come armed with a host of firmly held misconceptions. The challenge we face as teachers is to de-program the misconceptions and replace them with cogent explanations . The trick is to avoid becoming so embroiled in the physics of tides that we lose track of our objectives. It may be necessary to give students a little "misinformation" in order to help them build an understanding of the tides. Just be sure to identify the "misinformation" for what it is.

Test yourself. Try this true-false test, and then check your answers against the explanations given below. No peeking!!

True or False?

1. The center of the moon is in orbit around the center of the earth.
2. The moon's orbit lies directly above the earth's Equator.
3. The tides will be much greater at new moon, when the moon and sun are on the same side of the earth, than they will at full moon, when the moon and sun are on opposite sides of the earth.

4. Except for variations in height (amplitude), tides display much the same daily pattern in all parts of the ocean.
5. Although the sun is very much more massive than the moon, the moon is closer to the earth, and so exerts a greater gravitational attraction on the ocean.
6. The tide on the side of the earth nearest the moon is caused by gravity. The tide on the side away from the moon is caused by centrifugal force.

Answers:

1. False. The earth and moon both orbit about a common center of mass. This center of mass is located on a straight line between the center of the earth and the center of the moon and is found about 800 miles below the earth's surface. It is the center of mass for the earth-moon system which orbits the sun.
2. False. The moon's orbit has a **declination** of 5° 8" to the earth's Equator. This means that the moon spends half of each "month" in the northern hemisphere and half in the southern hemisphere.
3. False. Since the moon and sun each operate to form theoretically equal and opposite tides on opposite sides of the earth, the combined solar and lunar tides will be the same at full and new moon. It is at first and last quarter that the tide range is significantly reduced. This assumes that the distances between earth and moon and earth-moon and sun remain constant, which of course they don't. If you knew all that, you can give yourself credit for a "True".
4. False. The shape of ocean basins and the local topography cause a wide variety of tidal cycles throughout the world. These are generally divided into three major categories: diurnal, semi-diurnal and mixed. Most locations lie somewhere along a continuum between purely diurnal and purely semi-diurnal qualities.
5. False. If the gravitational attraction is computed using the universal gravitation equation, the sun is found to have a much greater gravitational effect. The moon <u>is</u> a more effective tide producing body than is the sun, but not because of stronger gravitational attraction. (See explanation of "differential gravitational attraction" below.)
6. False. There is no such thing as "centrifugal force". It is a fictitious force. The only force involved in the creation of tides is the force of gravity. The "indirect tide" found on the side away from the moon is there because, at the greater distance from the moon, the gravitational attraction is less than it is for the "direct tide" which lies below the moon. The angular momentum caused by the motion of the various bodies is an important component. This is one of those topics better left alone than taught incorrectly. Use your judgement, but try to avoid "centrifugal force".

How did you do? Are you more confused now than when you started? Good! That means you are ready to learn. Read this short introduction to tides. Read the Oregon State University Sea Grant bulletin titled “Understanding Tides”. Read two or three good resources about tides, and then dive in. Students will ask questions you won’t be able to answer. Do not let that scare you. After all, you will be modeling that learning is an ongoing process!

“It is better to be approximately correct and understandable than to be academically accurate and unintelligible.” - Anonymous, 1971

Introduction to Tides

The earth and the moon both rotate around their common center of mass once in approximately 27 1/3 days. Where and how this motion originated are questions for a course in cosmology. The fact is that the **inertia** of these two bodies, their tendency to keep moving in a straight line, is balanced by the gravitational attraction between them, and they are in orbit around the center of mass.

Similarly, the earth-moon system and the sun are in orbit around their common center of gravity which is **very** close to the center of the sun. When some student asks if this means that the orbital motion of the earth and moon are the result of the mass of the sun warping the local space-time continuum, smile, say, “Yes”, and move quickly and calmly to the next topic.

One key to visualizing how tides work is to think of the earth as a huge ball of liquid water. The fluid part of the earth generally acts as if it were a part of a large liquid sphere, and the elimination of the solid portion of the earth often makes it easier to understand the behavior of the liquid. In point of fact, the solid portions of the earth behave in an analogous fashion and the continents experience earth tides twice each day.

The liquid sphere has inertia. This means that it is in motion and will stay in motion in a straight line unless acted upon by an outside force. Consider just the earth and moon. The outside force that acts on the earth is the moon’s gravitational attraction for the earth. This force of gravity exactly balances the inertia of the earth-moon system and keeps the two bodies in mutual orbit around their common center of mass.

On the side of the earth nearest the moon, the gravitational attraction is slightly greater than the inertia, so the water is displaced toward the moon causing the **direct** high tide. On the side of the earth opposite the moon, the gravitational attraction of the moon is attenuated by greater distance and the gravitational attraction is slightly less than inertia. The result is the <u>indirect</u> high tide. If you and your students wish to pursue the mathematics, you can demonstrate that these two tides will be of similar magnitude.

In order to predict tides, observations of the time and height of each tide must be recorded over a long period of time. Surprisingly, tides depend nearly as much on local topography as they do on the position of the moon and sun.

The data collected at tide gauging stations are used to establish local sea level and reveal patterns created by local conditions. These data become the basis for making long term predictions of tidal activity. It should be noted that 0.0 feet on local tide gauges is not “sea level”. In fact 0.0 ft. is located at the average position of the lower of each day’s two low tides. It is known officially as “mean lower low water-(MLLW)”, and it varies from place to place, dependent on local tidal data. 0.0 feet in Seattle, Washington is not necessarily the same elevation as 0.0 ft. in Port Aransas, Texas or South Portland, Maine.

Tides influence all organisms living in the coastal region. This includes human beings. The lives of many coastal residents are in part controlled by the coming and going of the water. Fishers, sea captains, and marine ecologists all must pay attention to the behavior of the tides. The organisms that inhabit the intertidal region live in the most dynamic of marine environments. In addition to avoiding predators from both the land and the sea, these organisms must be adapted to deal with the incredible pounding force of waves and the drying effects of wind and sun. It is likely that organisms migrated from the sea through this transition zone to occupy the land. Poorly adapted species certainly could not have survived. Today we find a wide variety of organisms living on the edge utilizing a unique variety of strategies for survival.

The Oregon State University Extension Marine Advisory Program publication “Understanding Tides” is included in this background to provide additional information to help you in teaching this unit. This material is appropriate for students if you choose to use it with them. This is where you need to identify the “misinformation”. Despite overall excellence, this publication does explain the indirect high tide in terms of “centrifugal force” which we have already said does not really exist. The idea of a force that creates the second tide has helped many students to begin understanding tidal dynamics, but you need to let students know that the terminology is not precisely correct.

Materials

For the class:

- the largest rotating globe available
- a plywood mock-up of tidal bulges which will fit over the globe (see below)
- an appropriately sized sphere to represent the moon for your globe

Students have real problems visualizing the relationships you will be describing. These demonstration materials will save a great deal of time and anguish.

Teaching Hints

Duplicate the text pages. One set is recommended for each student. Remember that tides are somewhat confusing to human beings. Go slowly and keep your objectives in mind. Some students will build castles in the sky while others will only lay a few bricks. Just be sure the bricks are straight and level. Check with your local film distribution center to see what films are available on tides. Most are basic and the visuals can be very useful. Many general oceanography films, such as “The Boundless Seas”, contain segments on tides.

Before students do the “Oceans in Motion” reading, use the globe and cutout of tides to demonstrate that the tides do not come in and go out. It is the earth’s rotation on its axis that causes tides to appear to come and go while in fact they remain lined up with the moon.

Clear the deck and get kids up playing the parts of moon and earth in demonstrating any aspect of planetary motion. Two students of equal size can “revolve” around each other by joining hands and spinning. Note that the center of mass is located half way between them. A large student paired with a small one produces a lot of motion for the smaller person, and moves the center of mass closer to the large student. This is what happens with the earth and moon.

Depending on the size of the tide mock-up, place a student inside the mock-up and have the student rotate through the tide cycle to see that it is the earth that moves, not the tides. Have a student take the part of the moon and move about 12° along the orbit to show why the tides are 52 minutes later each day. A similar demonstration can show why the lunar month (29 1/2 days) and the sidereal month (27 1/3) days do not coincide.

A very helpful resource is Harold V. Thurman’s *Introduction to Oceanography*, Charles Merrill Publishing. Chapter 10 contains an excellent explanation of many of the concepts presented in this unit. Any good general oceanography reference will be helpful, and several very readable books devoted solely to the tides have been published.

Another helpful book is James Trefil’s *Scientist at the Seashore*, published by Charles Scribner and Sons. There are a plethora of books out there with fair to poor explanations of tides. Get one of the good ones.

Key Words

center of mass - the point at which the total mass of an object or group of objects appears to reside

centrifugal force - a fictional force, sometimes employed to explain the apparent force tending to move an object away from a center of rotation

ebb tide - a tide which is receding from a high toward a low

flood tide - a tide which is advancing from a low toward a high

force - any push or pull on a mass

gravitational attraction - the attraction of one object for another based directly upon the masses of the two bodies and inversely upon the square of the distance between them. The gravitational attraction = $\mathbf{G(m_1m_2 / r^2)}$ where **G** is the universal gravitational constant, **m** is the mass of the two objects, and **r** is the distance between the center of mass of each object

inertia - the tendency of a body at rest to remain at rest or a body in motion to remain in motion unless acted upon by an outside force

mean lower low water - the average level of the lower of the two low tides each day, used to establish 0.0 feet on the tidal gauge and as the basis for marine charts

neap tide - tides of lower than average range which occur at first and last quarter of the moon

nodal point - sometimes called an **amphidromic point**, a no-tide point around which the tidal crest rotates each tidal cycle

range - the vertical change in water level between a high tide and the next low tide, or between a low tide and the next high tide

spring tide - higher than average tidal range which occurs at new or full moon

varies directly - shows the same kind of change as another parameter; e.g. the bigger an object is, the bigger its tide producing force

varies indirectly - shows the opposite change as another parameter; e.g. the larger the distance between objects, the smaller the gravitational attraction between them

Extensions

1. Have students devise or research other demonstrations which show the effects of forces upon an inertial mass. Ask them to present the results of their work to the class.
2. Have students research the "pre-computer" machines used to calculate predicted tide levels

Answer Key

1. The rhythmic rise and fall of water level along a coastline is called the tide.
2. Answers will vary. Jobs that might depend on knowledge of tides include fishing and lifeguarding. Sea captains, river pilots and marine biologists need to know about tides as well.
3. Answers will vary.
4. Inertia is the tendency of a body in motion to remain in motion unless acted upon by an outside force.
5. The two tide bulges are caused by the differences between inertia and the force of gravity where each bulge is produced.
6. The tides occur 52 minutes later each day because the moon moves ahead in its orbit during the 24 hours that the earth rotates on its axis. The earth then has to rotate another 52 minutes until the original point is back underneath the moon.
7. The tidal range would be 10.0 ft. for this tide.

8. Spring tides are caused by the addition of tide producing forces when the earth, moon, and sun form a nearly straight line in space. This occurs twice each lunar cycle, at new moon and at full moon.
9. Neap tides are caused by the sun and moon applying their tide producing forces in opposite directions when earth, moon, and sun form right angles in space. This occurs twice each lunar cycle, at first and last quarter of the moon.
10. Each ocean reacts independently to the tide producing forces. Differences in the topography of the basins accounts for the wide variations observed in the tides.
11. Tidelands are those areas that are covered and uncovered during each tidal cycle. Tide pools are areas within the tidelands that retain their water during low tide.

One Step Further: OK, So Who's Tougher, the Sun or the Moon??

1a. The tide producing force of the sun due to mass is 27,000,000 times greater than that of the moon

b. The tide producing force of the sun due to distance is $\frac{1}{(389)^3}$ or

$$\left(\frac{1}{389} \times \frac{1}{389} \times \frac{1}{389}\right) \text{ which equals}$$

$\frac{1}{58,863,869}$ times the force of the moon.

"[The] tide producing forces vary inversely as the **cube** of the distance from the center of the earth to the center of the tide-generating object, instead of varying inversely to the square of the distance as does the gravitational attraction. This simply tells us that the tide-generating force, although it is derived from the force of gravitational attraction, is not proportional to it. Distance becomes a more highly weighted variable when we consider the tide-generating forces than it is in the determination of gravitational attraction force. Although the gravitational attraction between the earth and sun is over 177 times that between the earth and moon, the moon dominates the tides." Thurman, 1978

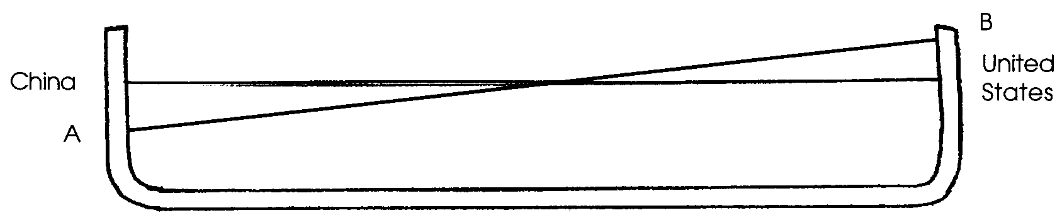
c. The combined forces equal:

$$27,000,000 \times \frac{1}{58,863,869} = \frac{27,000,000}{58,863,869} = .46$$

The tide producing force of the sun is .46 or 46% of the tide producing force of the moon. In other words, the moon plays more than twice the role of the sun in producing the earth's tides.

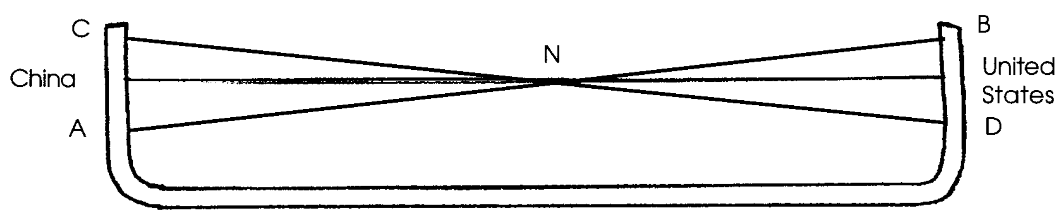
d. The sun's tide producing force is .46 times that of the moon.
e. The moon is the heavenly body most responsible for the tides.

More One Step Further: Tides are Standing Waves



1.

2a. The United States is having a high tide.
b. High tides would be occurring all the way from B to **N**
c. China is having a low tide.
d. Low tides would be occurring all the way from A to **N**
e. The water level at N remains the same, it does not change.



3.

a. China is having a high tide.
b. High tides would be occurring all the way from C toN
c. The United States is having a low tide.
d. Low tides would be occurring all the way from D to N
e. The water level at N remains the same, it does not change.

4. A nodal line is a line along which there is no (or little) tide change.

Oceans In Motion: The Tides

Behavior of Tides

Anyone who has been to the ocean beaches is familiar with the daily comings and goings of the water we call the tides. If you have gone on field trips, you may have noticed your teachers checking the ocean and their watches on a regular basis. Teachers do not want to have their students trapped in the tide pools by the rising waters of the incoming flood tide.

As you study this unit you will begin to understand what causes tides, and you will see how your teachers decide on a day and time to go into the tide pools. More importantly you will see how they decide what time to <u>leave</u> the tide pools.

History

From ancient times, people who live along the ocean shores have watched the rise and fall of the tides. The regular rhythm of the rising and falling of the water was said to represent the breathing of the earth. People noticed that there were **high** tides (the peak of the flooding stage) and low tides (the low point of the ebb) **every day**. By watching the tides for long periods of time and recording the heights, people were able to predict the tides. Many people depend on these tide predictions in their daily work as well as in their recreation.

1. What is the tide?

2. What kinds of jobs, in addition to teaching oceanography, might require an understanding of how tides behave?

What else did people notice about the rising and falling of the tides? From their records they soon discovered that there were two exceptional high tides and two exceptional low tides every **29 1/2 days**. Not only were the changes regular, they also followed the changes seen in the phases, or light and dark patterns, of the **moon**. People began to wonder “Did the moon cause the tides?”

3. People who lived along the coasts noticed several things about the tides. List three of their observations.
    a.

    b.

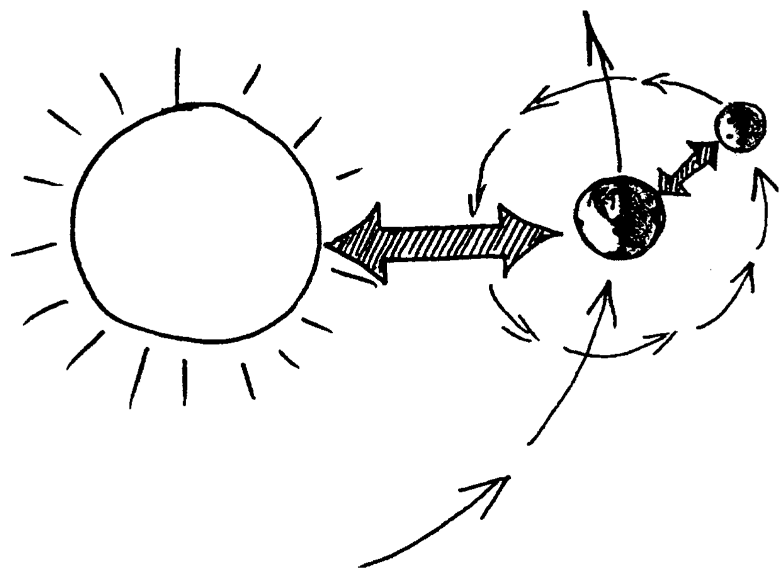
    c.

What Causes the Tides?

About 1700, Sir Isaac Newton gave us the theory that would eventually explain the tides. In what has since come to be known as the Law of Gravity, Newton stated that everything (large or small,) in the universe, exerts a pull on everything else. How does this help explain the tides?

If the earth were not being influenced by the gravity of the sun and moon, it would be moving in a straight line through space. The earth is said to have **inertia**. Inertia is the tendency of a body in motion to stay in motion, in a straight line, unless acted on by some outside force. A car skidding on ice travels in a straight line unless it either hits something or its tires regain traction. Tires and trees qualify as “outside forces”. We wear seat belts because inertia can do bad things to human bodies. Though a car stops in a crash, the driver continues to move until outside forces, say a seat belt and an air bag, stop the driver’s movement.

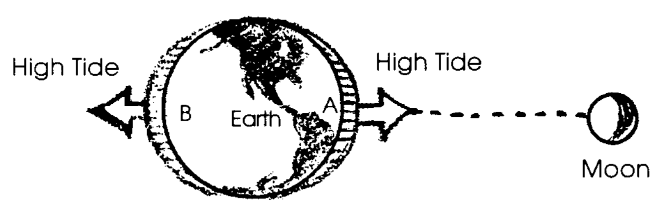
Gravity is the outside force that acts on the earth. The earth would keep traveling in a straight line if the sun's and moon's gravity didn't pull on the earth. It is the balance between the earth's inertia and this gravitational attraction that creates the planetary orbit and creates the tides.



4. What is inertia?

The closer an object is, the greater its gravitational attraction. In figure 1, the high tide at point A is caused because the moon is closer to that part of the ocean, and the pull of gravity is just a little stronger than the inertia. At point B the opposite is true. Point B is 8000 miles farther from the moon, and the pull of gravity is less than the inertia, so the water bulges slightly in the opposite direction. These two tides will be the same size.

Figure 1.



5. What causes the two tide bulges seen in figure 1?

The moon appears over the horizon later each day. Because the moon is constantly moving ahead in its orbit each day, it takes a point on the earth about 52 additional minutes to catch up with the moon and its tidal bulges each day. As a result, a given tide happens about 52 minutes later each day.

Keep in mind that there are no simple tide bulges in the oceans. All of this works very well on a water-covered planet, but add continents and you have tidal trouble right here in Ocean City. Fortunately the “trouble” is predictable, and we can still trust our tide charts . . . usually.

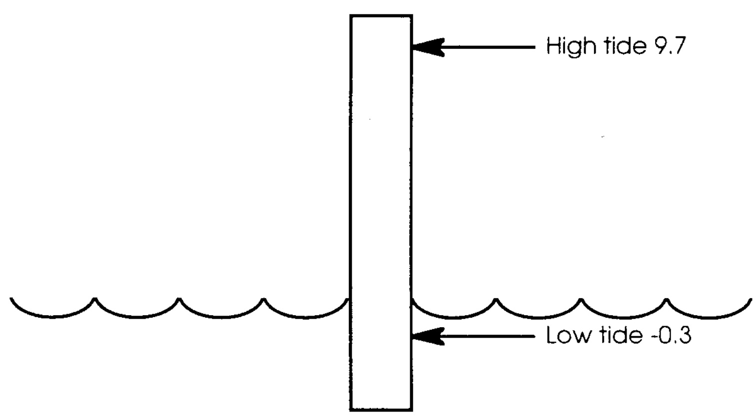
6. Why do tides occur 52 minutes later each day?

The Sun Also Plays a Role

Although the sun is much farther away than the moon, its much greater mass allows it to play a role in the tides. The sun’s gravitational pull also tends to create two tidal bulges in the same way that the moon does. The earth’s inertia and the sun’s gravity are in balance. One tidal bulge is under the sun and the other is on the opposite side of the world. These bulges are smaller than those caused by the moon. Remember, the moon is only about 200,000 miles away in space. The sun is 93,000,000 miles away. Its ability to produce tides is greatly reduced by its distance, as we shall see. Ordinarily the solar (sun) tides do not have a separate effect. Instead, they increase or decrease the lunar (moon) tide.

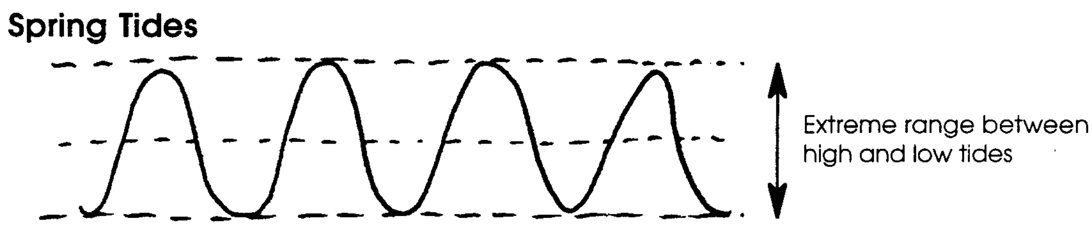
Let’s look at the sun’s effect. The difference between successive high and low tides is called the **tidal range**. The tidal range changes as a result of the changing positions of the sun and the moon with respect to the earth. As the earth and moon rotate around their center of gravity about once a month, the moon is in line with the sun twice a month and it is at right angles at two other times during the month.

7. If the high tide Monday is +9.7 feet and the low tide is -0.3 feet, what is the tidal range for Monday?



When the moon and sun are in line, the attractive forces are added together and the tide rises higher than the average. If the water is being pulled into higher than normal highs, the low tides must also be lower than normal. The tidal range is at the maximum. These tides are called **spring tides**. The name relates to the fact that the water seems to “spring” away from the earth. It has nothing to due with the time of the year. There are two spring tides **every** month. Figure 2 shows spring tides.

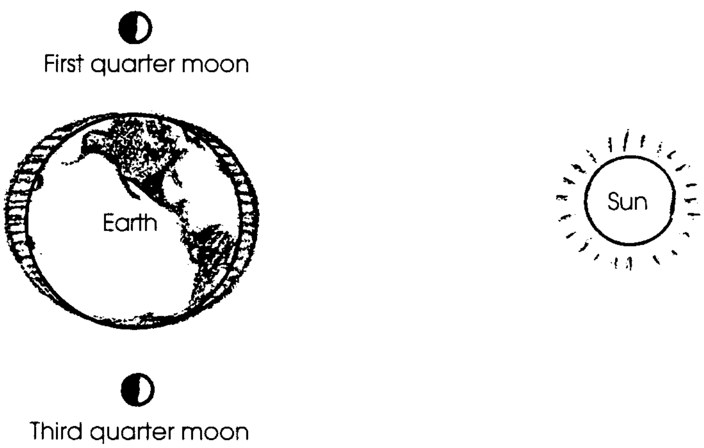
Figure 2.

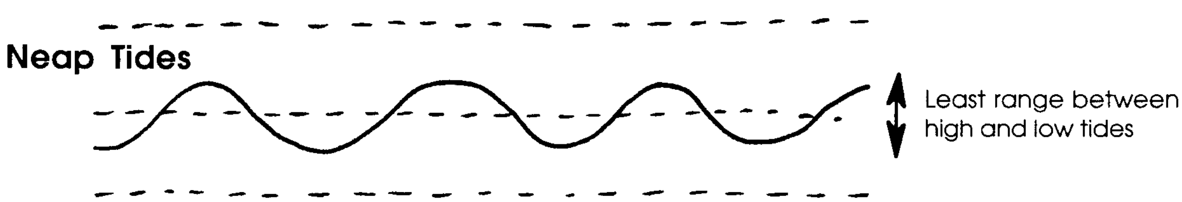


8. What causes the spring tide?

When the moon and the sun are at right angles with respect to the earth, the tide producing forces of the sun and the moon work against each other. At this time the tidal range is decreased. The tide rises and falls less than the average. We call these tides **neap tides**. The name comes from the fact that the water is lowered or “nipped”. Figure 3 shows neap tides.

Figure 3.





9. What causes the neap tide?

REAL Life

From what we have seen, there should be two high tides and two low tides in every place about every 24 hours and 52 minutes. Yet if we look around we find places with only one high and one low tide a day. We also see great variations in the height and duration of the tides. Why?

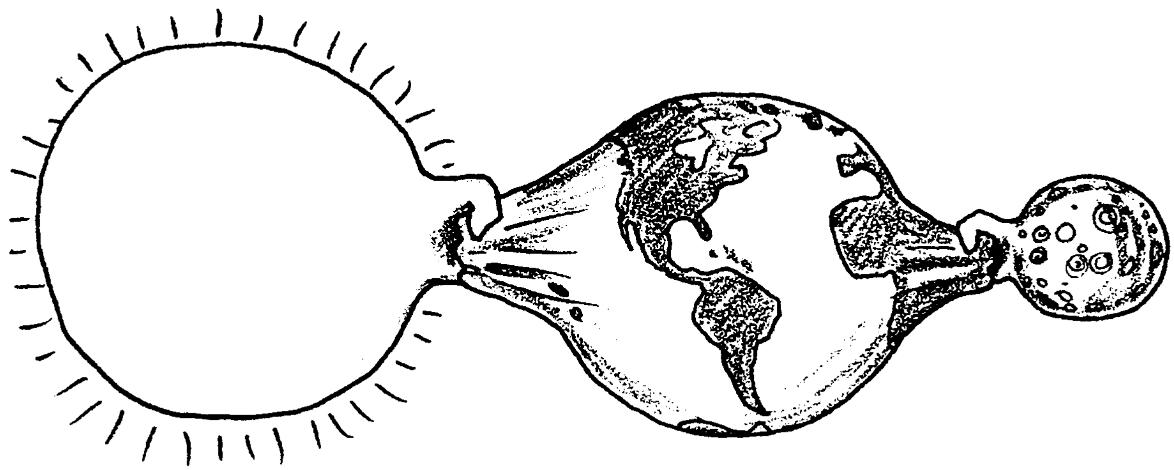
Scientists have discovered that the distribution of the oceans and land masses is irregular. This irregularity causes the oceanic basins of the world to respond to tide producing forces as individual closed basins. In spite of the fact that all of the oceans are connected, the oceans do not behave as a unified whole. Each ocean independently feels the effect of the moon and sun. In each of the natural basins, the water sloshes back and forth at a speed determined by the length and depth of the basin.

10. What causes variation we see in real life tides?

The Importance of Tides

How are tides important to us? Ships and boats watch the tides to avoid running aground when entering and leaving shallow harbors. Fishes watch the tides. The incoming tides bring new food supplies which attract fish. Fishing, then, is best on an incoming tide. People who gather shellfish watch for low tides. Tides are important in the lives of people. They are also important in the lives of all the seashore animals and plants that live on the shoreline.

11. From your reading what do you think the terms “tideland” and “tide pool” mean?



One Step Further:

Ok, So Who's Tougher, the Moon or the Sun??

1. We have seen that both the sun and the moon have an effect on the tides. Can we calculate the importance of each? Let's look at the tide producing forces of two imaginary suns, star A and star B. Star A has twice the mass of star B.

   a. The tide producing force of a heavenly body varies directly with its mass. In other words, star A which has twice the mass of star B would have twice the tide producing force.

      The earth's sun has a mass 27,000,000 times greater than that of our moon. As far as mass is concerned, how many times greater is the tide producing force of the sun compared to that of the moon?

   b. The tide producing force of a heavenly body also varies **inversely** with the cube of the distance to the earth. For example, if star A were twice as far from the earth as star B, its tide producing force would be (1/2)3 or (1/2 x 1/2 x 1/2 = 1/8) or one eighth of the tide producing force of star B.

      The sun is 389 times farther away from the earth than the moon. As far as distance is concerned, how many times less is the tide producing force of the sun compared to that of the moon? Show your work!

c. The tide producing force of a body is actually a combination of the forces due to mass and distance. For example, star A would have twice the force from mass times one-eighth the force from distance

Star A =(2 x 1/8)= 1/4

Star A then has one fourth the tide producing power of Star B.

Combine the forces due to mass and distance to calculate what the tide producing force of the sun is compared to the tide producing force of the moon. Show your work!

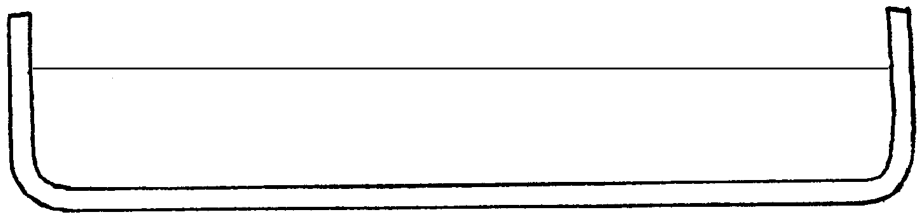
d. How much less is the sun's tide generating force?

e. Which heavenly body is most responsible for the tides?

More One Step Further:

Tides Are Standing Waves

We have seen that the irregularity in the distribution of the oceans and land masses causes the oceans to respond to the tide producing forces independently. The water in each basin sloshes back and forth at a rate of speed determined by the length and depth of the basin. Let's let the tank in figure 1 represent an ocean basin.



1. Use your imagination to tilt the ocean basin toward the United States. Draw a line that would show the new water surface. LABEL this line AB by writing an A at the China end and a B at the U.S. end.

2. Use an N to LABEL the point where line AB crosses the original water surface. Line AB represents a **stationary wave**. In the real oceans, water moves in stationary waves. The Tide-making forces of the moon and sun keep the waves moving.

   a. If AB represents the new water surface, which country is having a high tide?

   b. High tides would be occurring all the way from B to_______________

   c. Which country is having a low tide?

   d. Low tides would be occurring all the way from A to_______________?

   e. What happens to the water level at N?

3. Use your imagination to now tilt the ocean basin the same amount but in the opposite direction. Draw a second line through N that would show the new water surface. LABEL this line CD with C at the China end of your ocean basin.

a. If CD represents the new water surface, which country is having a high tide?

b. High tides would be occurring all the way from______to_____.

c. Which country is having a low tide?

d. Low tides would be occurring all the way from_____to_____

e. What happens to the water level at N?

N represents a **nodal line**. Any island located along line N would have very small tides since the water level at N remains the same whether it is high tide on the China coast or on the coast of the United States. For example, Tahiti is near a nodal line in the Pacific Ocean. The tides on Tahiti are small and are due to the sun's pull alone.

4. What is a nodal line?