Spring 2003 **Oceanography 1001** **Prof. Nof**

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A. First Set of Reviews

1. <u>Fractal structure of the coastline:</u> The length of the coastline is not a fixed measure but rather depends on the length of the segments used for the measurement. For example, consider the coastline shown in Fig. 1. Suppose that we use two different segments for the measurement of the coastline from A to B. One is relatively long (solid line) and the other is relatively short (broken line).

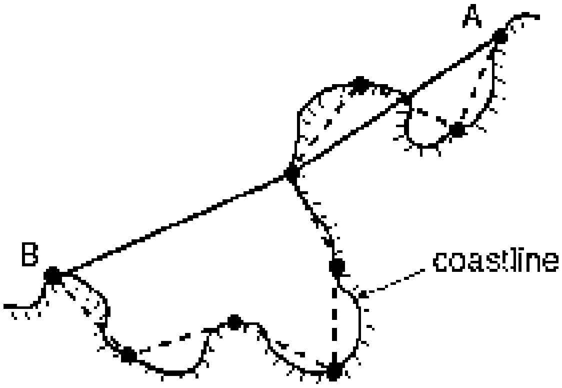


Fig. 1. Top view of a coast.

Clearly, when we use the large segment (solid line) we obtain a shorter coastline length than we would obtain using the short segment (broken line). Since there is no agreement in our society on what segment is to be used when we measure a coastline (i.e., a meter? kilometer?) the length is poorly defined.

From a mathematical point of view, the length of the coastline is infinite when the length of the segment used for the measurement is infinitesimal (i.e., as small as you can think). Despite this, the area confined by the coastline is finite. This cannot be easily seen but the so-called Kotch curve helps illustrate it. The Kotch curve is a curve obtained by considering a triangle on which new triangles are constructed by continuously dividing the sides into three equal segments as shown in Fig. 2.

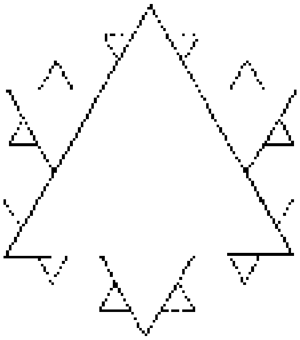


Fig. 2. The construction of a Kotch curve.

The Kotch curve is the circumference of the configuration shown in Fig. 2 when the number of new triangles being constructed is infinite. Although we have not done so in class, it can be shown mathematically that its length is infinite even though the area that it confines is finite.

2. <u>Pressure:</u> Pressure is the weight of the fluid (water or air) *directly* above divided by the area. It is measured in kilograms per centimeter square (or pounds per square inch).

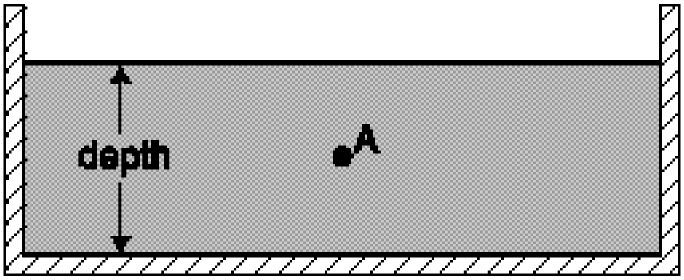


Fig. 3.

For example, the pressure on the *bottom* of the container shown in Fig. 3 is the weight of the water in the container divided by the area of the bottom. The pressure at, say, point A, which is at half the container depth, is the weight of the water directly above <u>A</u> divided by the area, i.e., it is half the pressure along the bottom. Since the pressure is the weight of the fluid above divided by the area, *it is proportional to the depth of the fluid directly above*. To understand this, recall that the weight of the fluid is just the volume (proportional to the area) times the density (weight per unit volume).

Because gravity acts directly downward, it is only the water directly above that counts. For instance, the pressure on the bottom of the two containers shown in Fig. 4 (which have identical depths) is identical even though their volumes are different. This is because the excess water in B is exerted on the side walls and not on the bottom.

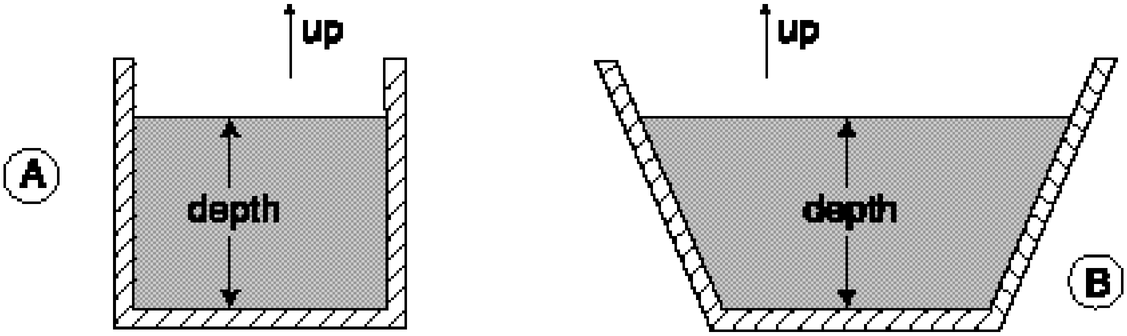


Fig. 4. Two containers with identical depths but different volumes.

Another example is that of a slanted container as shown in Fig. 5.

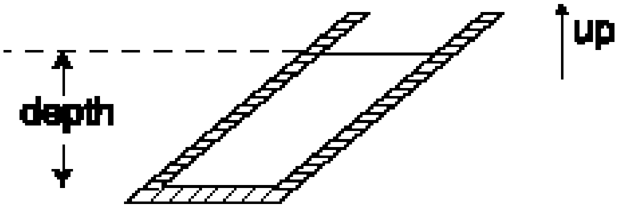


Fig. 5. A slanted container

Here, the pressure along the bottom is proportional to the depth shown which is measured directly upward from the bottom to the imaginary free surface above. The pressure along the bottom is not proportional to the actual length of the water in the container because some of this water exerts pressure on the side of the container and not the bottom/

At a given point (say, the solid dot shown in Fig. 6), the pressure acts uniformly in all directions (shown by the arrows).

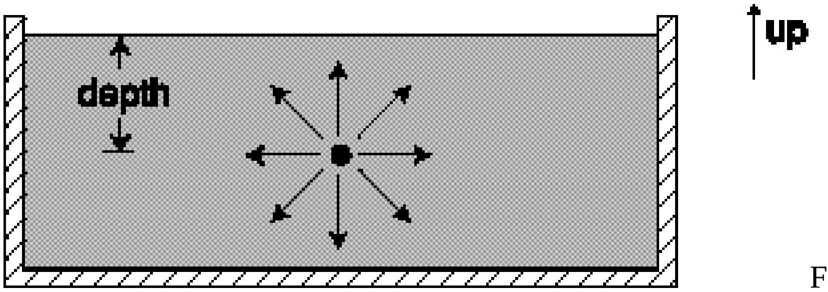


Fig. 6

This cannot be easily understood but we have demonstrated it by measuring the draining times through two different orifices (Fig. 7).

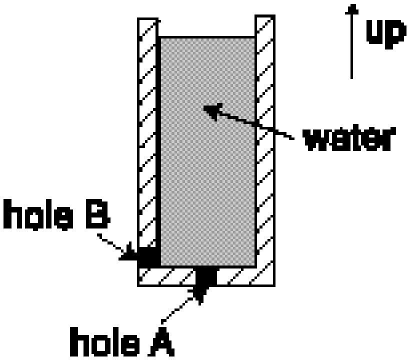


Fig. 7

The container shown in Fig. 7 has two identical holes, one along the bottom (hole A) and the other on the side as close to the bottom as possible (hole B). We have measured one draining period with hole B closed and hole A open and the other with B open and A closed. Since the pressure to the side (i.e., the pressure acting on B) is the same as the pressure downward (i.e., the pressure acting on A), the time required for draining is the same in both situations. (There is actually a minute difference in the two draining times because, due to mechanical limitations, hole B is slightly higher than hole A. However, there would have not been any difference at all in the draining times had the two holes been exactly at the same level.)

We have also demonstrated that objects float or sink depending on whether the upward pressure exerted on them exceeds their weight. For example, a drum situated in the middle of the water column (Fig. 8) will float when the difference between the total pressure from below (proportional to the "lower depth") and the total pressure from above (proportional to the "upper depth") exceeds its weight. (Note that by the "total pressure" we mean here the pressure times the area of the drum's bottom or the top.) Likewise, it will sink when the weight exceeds the difference in total pressures. Here, the first situation (floating objects) corresponds to objects whose density is less than that of the water whereas the second situation (sinking objects) corresponds to objects whose density is greater than that of the water.

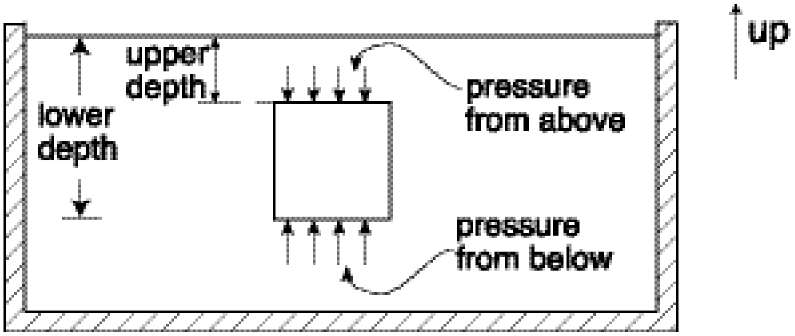


Fig. 8

Regardless of the object's weight, when it is situated next to the bottom in such a way that water cannot get under it (and push it upward) it will never float. We showed this using a floating drum (Fig. 9).

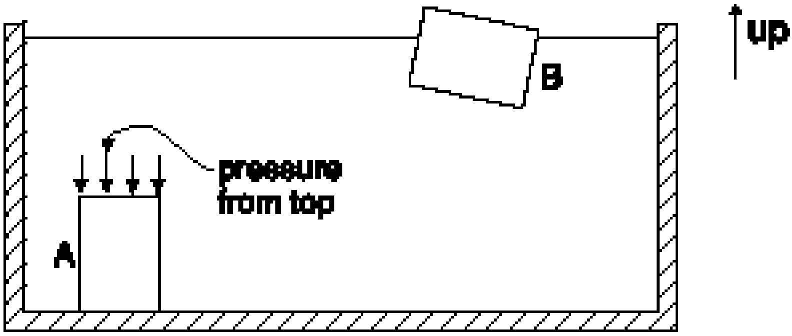


Fig. 9

When the object was placed next to the bottom, there was no water under it and, consequently, there was no pressure from below and, as a result, the drum stayed on the bottom (situation A, Fig. 9). When we forced some water under it by slightly tilting it a bit it floated to the top (situation B, Fig. 9).

We then proceeded and mentioned that, in most cases that we see every day, water flows from high to low pressure. Since the pressure is proportional to the depth of the water above and not to the depth of the water below, water may appear at times to be flowing uphill (as shown in Fig. 10a).

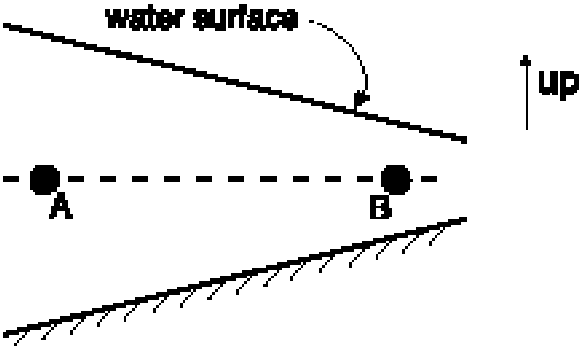


Fig. 10a

In the situation shown in Fig. 10a, the bottom is sloping *upward* (from left to right) whereas the surface of the water is sloping downward (from left to right). When we look at two points A and B (which are situated on the same level) we see that the pressure at A is higher than the pressure at B. As a result, water flows from left to right regardless of the bottom's shape. (We shall see later that the presence of Coriolis will alter this but, for the moment, we speak about a situation that does not sense the Coriolis force.)

To illustrate how dramatic the effects of pressure can be, the "can experiment" has been shown (Fig. 10b).

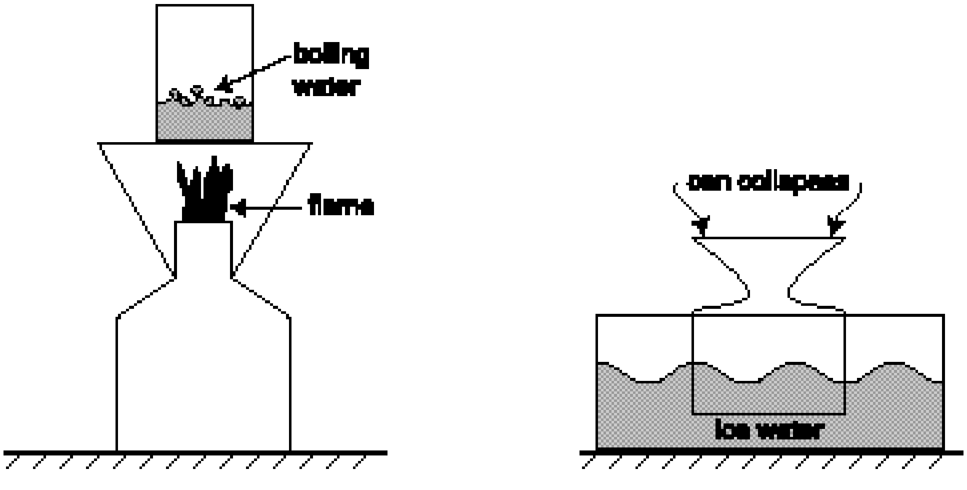


Fig. 10b

In this demonstration we first boiled some water in a coke can (left panel, Fig. 11). We then took the can with the boiling water and very quickly turned it upside down into the ice water (right panel, Fig. 11). The can collapsed and drew more water into it.

The collapse and suction of water into the can result from the fact that the pressure within the can has been reduced compared to the outside atmospheric pressure which remained, of course, constant. The reduction of pressure inside the can resulted from the condensation of vapor (created by the boiling water) inside the can. This condensation is just like the condensation of water vapor on a glass of cold water. In our case, condensation took place because the coke can which was submerged into the ice water is made out of aluminum which is a good heat conductor. The collapse and suction are most pronounced when the temperature difference between the water inside the can and the water in the container is the greatest. When the water in the can is not brought to a boil and water at room temperature rather than ice water is used for submergence, the effect is dramatically reduced.

3. Red Sea crossing: An example of a wind-driven flow is the Red Sea crossing. The diagrams below, the article on the following page (reprinted from the New York Times) and the three-dimensional picture (reproduced from the L.A. Times) describe the process in detail.

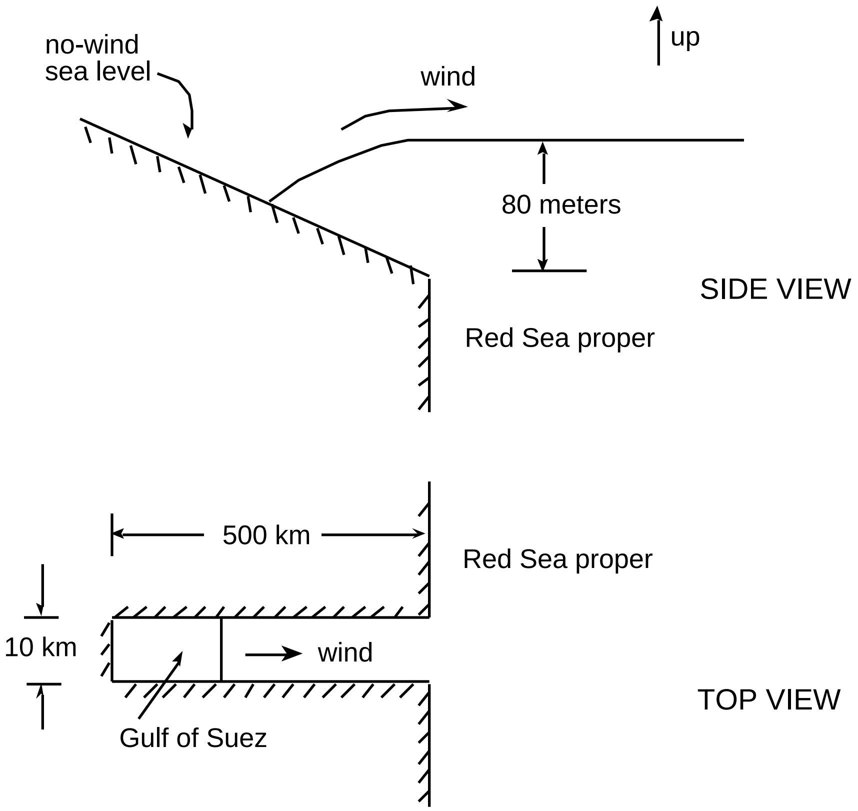


Fig. 11. A diagram of a gulf (connected to a large body of water) subject to wind action. The wind is dragging the water into the deep gulf.

The following article on page 7 is from the New York *Times*, Sunday, March 13, 1992:

Oceanographers Say Winds *__May Have Parted the Waters__*

By JOHN NOBLE WILFORD

Applying an expert knowledge of wind over water, two oceanographers have developed what they say is a plausible scientific explanation for the parting of the waters that enabled the Israelites to make their miraculous escape from Egypt in the biblical story of the Exodus.

The oceanographers calculated that strong winds blowing along the narrow, shallow Gulf of Suez, a northern extension of the Red Sea considered the likely site for the crossing, could account for the phenomenon. Steady winds of 40 knots could push enough water to the south to cause a 10-foot drop in sea level, exposing a large swath or sea floor over which the Israelites could have walked to safety.

And when the wind subsided, the scientists concluded, the parted waters could have spilled back into place in only four minutes The pursuing Egyptian army, without time to escape the flood, could thus have been drowned in mid-crossing, as described in the Bible.

Theory to Be Published

The theory was proposed by Dr. Doron Nof, a professor of oceanography at Florida State University in Tallahassee, and Dr. Nathan Paldor, an expert in atmospheric sciences at Hebrew University in Jerusalem and visiting scholar at the University of Rhode Island's Graduate School of Oceanography at Narragansett. They discuss their research in a report to be published this week in The Bulletin of the American Meteorological Society.

Since 1962 there have been biblical scholars who translate Hebrew texts of the book of Exodus as saying the Israelites crossed the Sea of Reeds, a marshy area at the northern end of the Gulf or Suez, not the Red Sea itself.

Dr. Nof and Dr Paldor say they are the first scientists to consider the question of the parting of waters during the Exodus as a physical oceanography problem. Another explanation, based more on archeological findings, involves vast waves, perhaps generated by a powerful volcanic eruption on the Greek island of Thera.

Biblical Account

In Exodus 14:21-22, it is written: "and the Lord caused the sea to go back by a strong east wind all that night, and made the sea dry land, and the waters were divided. And the children of Israel went into the midst of the sea upon the dry ground; and the waters were a wall unto the on their right hand, and on their left.”

When the Israelites had passed safely the other side, the Bible says that God to moses to stretch his hand over the sea aga “that the waters may come again upon t Egyptians, upon their chariots, and up their horsemen.” Moses obeyed, the pursui forces of Pharoah were destroyed and t Israelites began their 40 years of wanderi in the wilderness during which Moses ceived the Ten Commandments on Mt Sinai.

Dr. Paldor said the new research focus not on whether the crossing had actual occurred, but rather on providing a scienti explanation of how it could have occurr through a phenomenon created by stro winds.

“The Gulf of Suez provides an ide body of water for such a process because its unique geography,” Dr. Paldor said. Mo scholars say the northern part of the gulf the most likely crossing site, though som who favor theories of volcano-generated tid waves often place it at Lake Manzala, near t Mediterranean Sea.

40 Knot Winds

The Gulf of Suez is more than 200 mil long, 12 to 18 miles wide and fairly shallo at its northern end. Winds chan-nel between the mountains on each side of t gulf can exert a powerful force on the sea. T scientists’ study showed that a wind of knots, or 46 miles per hour, blowing for 1 12 hours, could push water a mile or two fro the original shoreline.

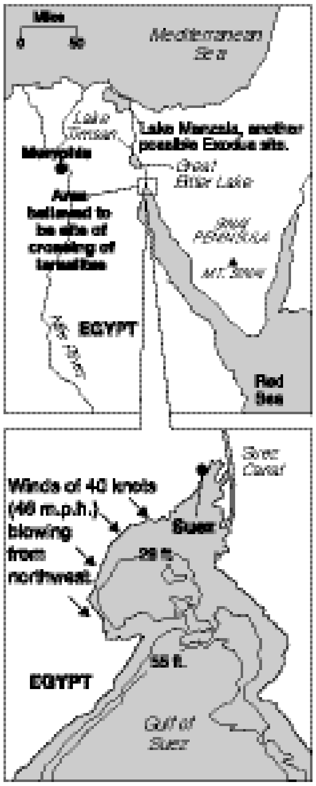
“Our physical and mathematical analys shows that both values for the drop in the s surface height and withdrawal distance f the water are more than sufficient to cause t calamity that befell the Egyptians,” I Paldor said.

The scientists noted that in the biblic account a strong wind is said to have blov for the entire night before the crossing by t Israelites. They also said the biblic description of the Israelites’ going “into t midst of the sea upon the dry ground” cou be explained by the presence of a natu ridge in the bottom of the gulf. The accou of a wall of water on either side, they sai supports the theory that the wind w pushing back the water.

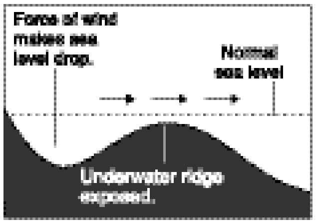
“Whether this theory explains t crossing or not,” Dr. Paldor said, “Nof and believe it should not affect the religio aspects of the Exodus. Believers can find t presence and existence of God in the ve creation of the wind with is particul properties, just as they find it in t establishment of a miracle. Some may ev find our proposed mechanism to be supportive argument for the original biblic description of this event.”

The Winds of Exodus?

A new theory explains how sustained strong winds and the shape of the seabed could have allowed the Israelites to cross while pursuing Egyptians drowned.



Scientists have shown that a strong wind blowing 10 to 12 hours could push water a mile or two from the original shoreline of the Gulf of Suez, a northern extension of the Red Sea. An exposed undersea ridge could have been a temporary bridge.



Source: Dr. Nathan Paldor

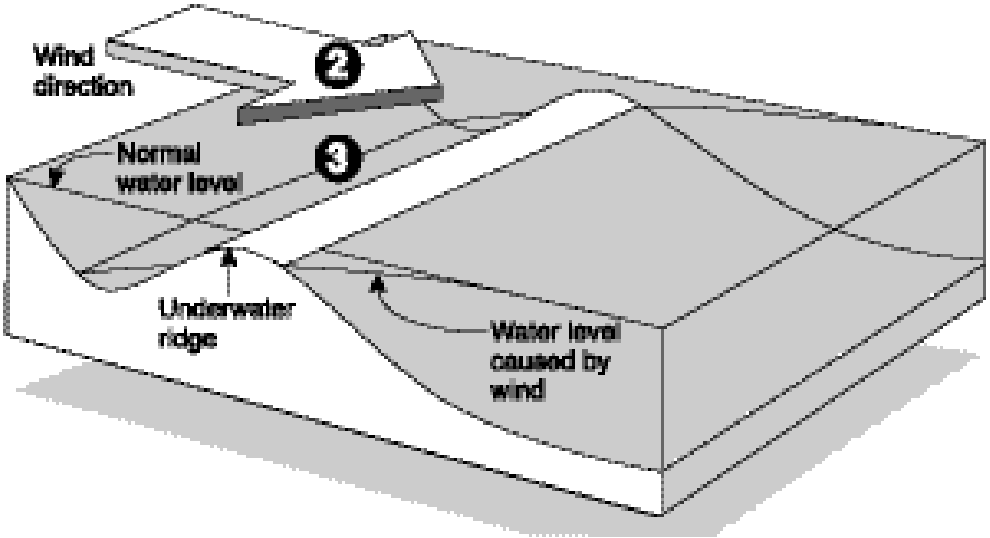
The Red Sea Crossing: A Theory

Sophisticated computer calculations indicate that the biblical parting of the Red Sea, said to have allowed the Israelites led by Moses to escape from Egypt, could have occurred precisely as the Bible describes it.

❶ Scientists believe the crossing probably occurred in the northern end of the Red Sea, in the Gulf of Suez.

❷ A moderate wind blowing in from the Mediterranean might cause the water to recede for about a mile because of the geography of the gulf –a long, narrow body of water connected to a larger sea. (The narrowness minimizes the amont of force necessary to move the water, while the large sea at the opposite end captures the water without any significant gains in height.)

❸ If the wind movement occurred in an area of shallow water, where a temporary undersea ridge was located, it could have provided a stretch of land for the Israelites to cross on.



SANDY KAY / Los Angeles *Times*

4. Coriolis: The Coriolis effect is the tendency of objects to drift from their appointed path – to the right in the northern hemisphere and the left in the southern hemisphere.

To understand this, we first need to note that even though the earth rotates in one sense it appears to an observer in the northern hemisphere to be rotating counterclockwise and clockwise to an observer in the southern hemisphere. (Use a globe that can be spinned to understand this.)

The Coriolis force results from the fact that the earth is spinning on its axis. Consider, for instance, a rocket that is fired toward, say Atlanta from the north pole. The rocket stays in space for, say, 10 hours and is proceeding in space along a *straight line*. However, while the rocket is progressing in space, the earth is turning underneath it. Consequently, the projection of the rocket on the earth is not a straight line but rather a curved line as shown in Fig. 12; path A is the path that the rocket follows in space (a straight solid line) and path B (broken line) is its projection on the turning earth. These paths show that while the rocket has been in space, the earth has turned from under it. As seen in Fig. 12, when the rocket is viewed as if it is progressing *away from you*, the Coriolis effect appears to be a deflection to the right in the northern hemisphere (and to the left in the southern). The Coriolis *force* is the force (to the right) which is required in order to produce the observed deflection.

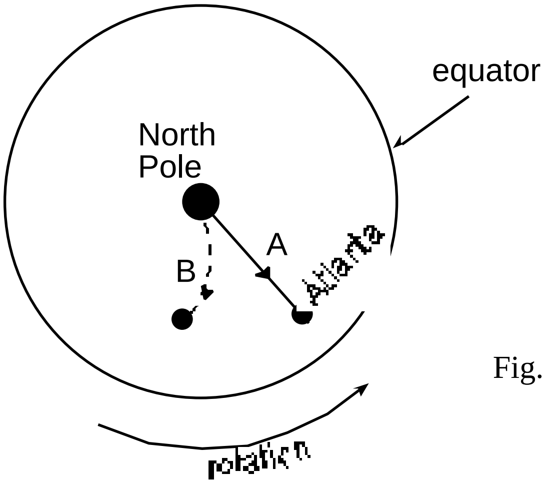


Fig. 12

The Coriolis effect is strongest in the poles and diminishes as one approaches the equator (where it is zero).

Even though it cannot be understood as easily as the North Pole-Atlanta situation shown in Fig. 12, the Coriolis effect and the resulting drifts to the right or left take place *regardless of the direction that the rocket is fired at* (Fig. 13).

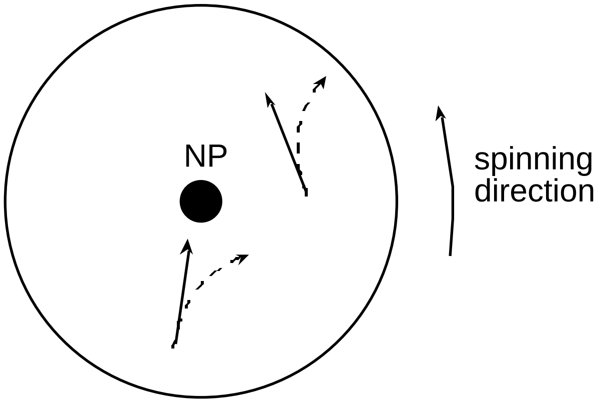


Fig. 13. Solid arrows denote the direction at which the rocket is aimed and broken arrows denote that actual orientation due to Coriolis.

The Coriolis effect is important whenever we speak about processes that last days, months or years. Processes that last only a short time compared to a day (the time that it takes the earth to complete one revolution) are not affected by the Coriolis force. Flows in swimming pools, small lakes, ponds, sinks etc. belong to this category. They do not last long enough for the Coriolis effect to be significant. Consequently, common statements about water draining in sinks following one direction in one hemisphere and another direction in the other hemisphere are not valid. Sinks may indeed drain in a preferred direction but this is due to the geometry of the sinks and not due to Coriolis.

We have also demonstrated the importance of the Coriolis force using a rotating pie-shaped ocean which can be thought of as representing the Atlantic Ocean (Fig. 14).

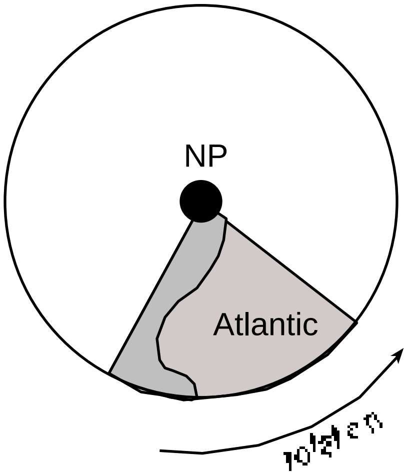


Fig. 14

We showed that water injected in the North Pole progressed away from the pole along the western boundary of the ocean (hatched area). Without the Coriolis effect the water would, of course, spread uniformly in all directions.

Finally, we illustrated the Coriolis force using the so-called “Foucault pendulum”. This is a pendulum that is so large that it can continuously swing for a few days. Because the pendulum swings along a straight line in space and the earth is turning under it, the projection of the pendulum on the ground rotates to the right in the northern hemisphere (as shown in Fig. 15).

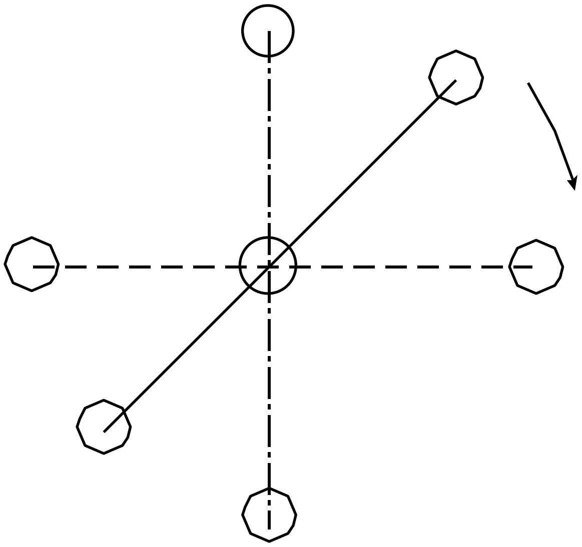


Fig. 15. The projection of a pendulum as time progresses.

This was first done by Foucault. In class we used a small pendulum and "speeded up" the turning of the earth by artificially turning the plastic sheet underneath. When the pendulum is viewed by someone on "earth" it appears to be rotating to the right, i.e., the dashed-dotted line represents the initial projection of the pendulum, the solid line a later projection and the dashed line a still later projection.

5. Ekman flows: Ekman flows are driven directly by the wind and occupy only the top 50 meters or so of the ocean. They were first noticed by Norwegian explorers of the North Pole who noticed that the ice did not drift in the direction of the wind but rather to the right of the wind. Ekman flows correspond to a balance between the force exerted on the water by the wind and the Coriolis force (i.e., the wind plays a role equivalent to that of the pressure gradient force in the geostrophic flow case). As shown in Fig. 16, the ocean surface is flat and there are no mounds or valleys. (It is mentioned here in passing that the detailed Ekman flow corresponds to a spiral with speeds decreasing away from the free surface. You might have seen this in your book. This detail is not important for our discussion.)

   When an Ekman flow is present next to a shoreline, there is either an upwelling or downwelling. For instance, in the case of the California coast, the wind is blowing from the north and is pushing surface water offshore. Deep and cold water (which is rich in nutrients) must rise to the surface to replace the water removed by the Ekman flow (Fig. 17). This upwelling is the cause of the fog common to the area. It is also the cause of the low water temperature compared to regions at the same latitude along the east coast. A similar process takes place along the coast of Peru. Here, as a result of the upwelling which contains a large among of nutrients, the area is biologically rich.

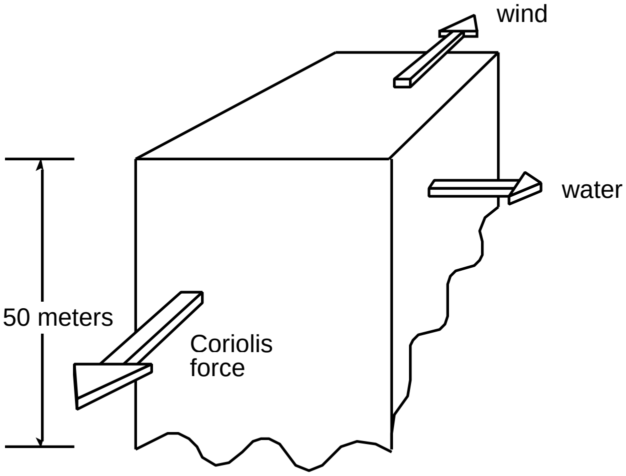


Fig. 16. The balance of forces associated with an Ekman flow in the northern hemisphere. The Coriolis force opposes the wind force exerted on the water. Since the Coriolis is always 90˚ to the right of the flow, the water must be flowing at 90˚ to the right of the wind.

6. Geostrophic flows: Geostrophic flow corresponds to a balance between the Coriolis force and the pressure gradient force. (Recall that all motions correspond to some sort of a balance. For instance, in a moving car there is a balance between the forward force produced by the engine and the backward frictional resistance resulting from the contact of the wheels with the road and the contact of other moving parts.) This means that, in contrast to the familiar kind of flow that proceeds from high to low pressure, the geostrophic flow is perpendicular to the pressure gradient as shown in Fig. 1a and Fig. 1b. Most flows in the ocean (and atmosphere) are geostrophic. How are such flows established will become clear later.

   This kind of flow is counter-intuitive and difficult to understand. If you don't understand the situation shown in Fig. 18, try to think about it in a different way. Suppose that there is an ocean with a slanted free surface. (How the slanting surface is established is presently not important. We shall discuss this later.) Initially, the water will "try" to flow downhill but the Coriolis force will deflect it to the right. This deflection continues until the flow is parallel to the lines of constant pressure, i.e., until the Coriolis force is opposing the pressure gradient force.

   Instead of considering a flat surface, consider now a "mound" or a "valley." Again, how the mound or valley is established is not important for the present analysis. We shall show later, however, that they can be created by wind or other processes. Incidentally, recall that the mounds and valleys in the ocean are minute in the sense that they correspond to sea-level variations of a few feet over distances of a few hundred or a few thousand miles. The geostrophic flows associated with mounds or valleys are shown in Fig. 19.

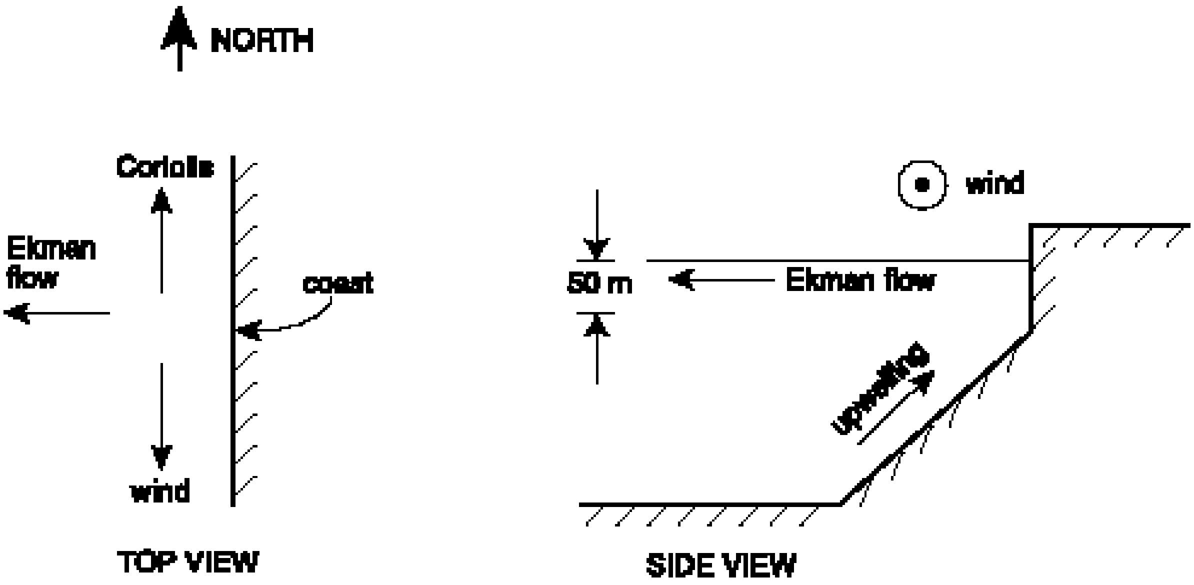


Fig. 17a. Upwelling resulting from the presence of a coast to the left of the wind (in the northern hemisphere). The Ekman flow is moving surface water (i.e., the water in the top 50 meters) offshore resulting in an upwelling. In other words, deep water must rise to replace the surface water that is moving away from the shore.

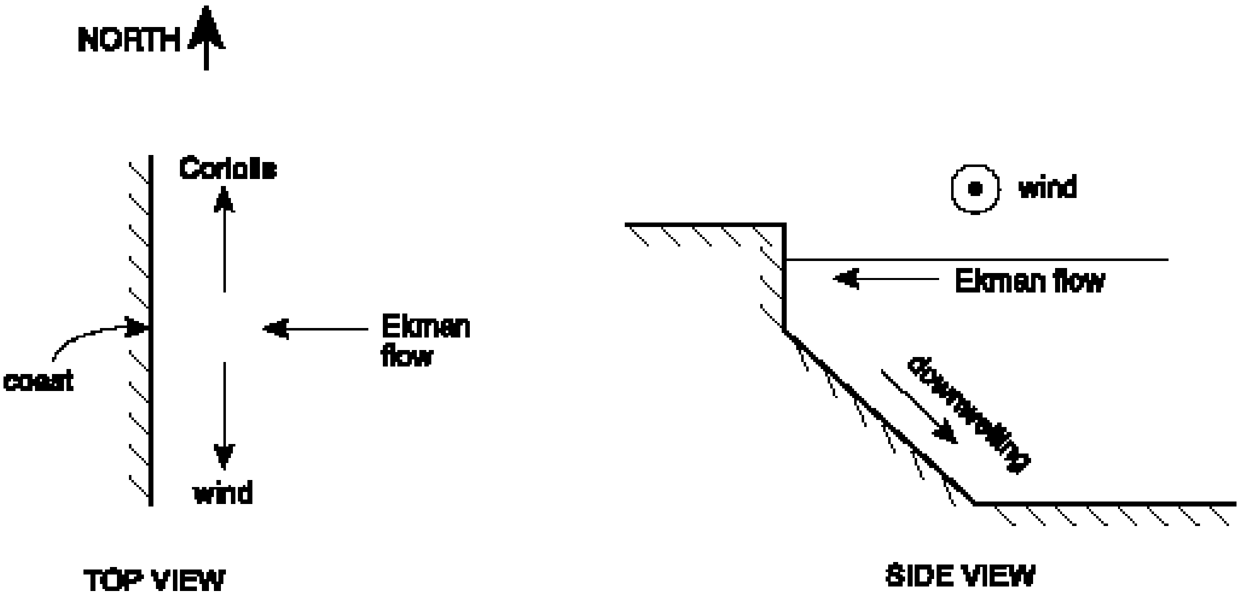


Fig. 17b. The same as in Fig. 17a, except that the coast is situated to the right of the wind implying a downwelling rather an upwelling.

Most of the flows in the ocean are geostrophic. They correspond to speeds ranging from one to a few hundred centimeters per second (i.e., from 1/12 of a inch to several feet per second). They are usually present from a depth of about 50 meters (the bottom of the Ekman flow which will be discussed shortly) to the bottom of the ocean (i.e., 4000 – 5000 meters). Namely, they occupy most of the water column. As mentioned, they are also very common in the atmosphere. The familiar hurricanes correspond to a valley (in the top of the atmosphere) and a counterclockwise flow.

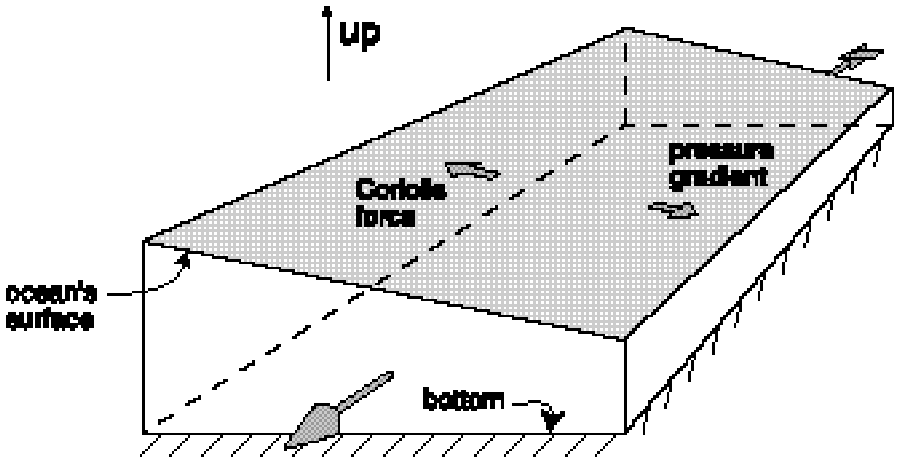


Fig. 18a. Schematic diagram of a geostrophic flow in the northern hemisphere. The three-dimensional view shows an imaginary "slice" of oceanic water extending from the free surface at the top to the bottom. The ocean surface is not flat but rather is sloping in one direction resulting in a pressure gradient. The pressure gradient is balanced by the Coriolis force. Since the Coriolis force is always at 90˚ to the right of the flow, the balance implies that, as shown, the geostrophic flow (shown with the three-dimensional arrow) is perpendicular to the pressure gradient.

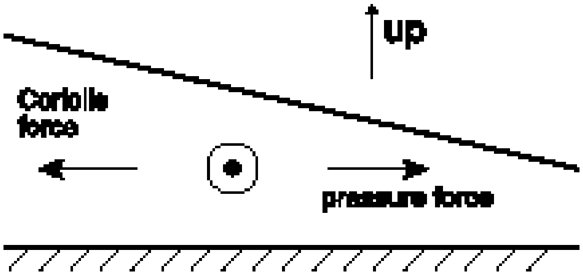


Fig. 18b. A side view of the geostrophic flow shown in Fig. 1a. The pressure gradient force is from left to right, the Coriolis force is from right to left, and the flow is coming to you (i.e., out of the pages).

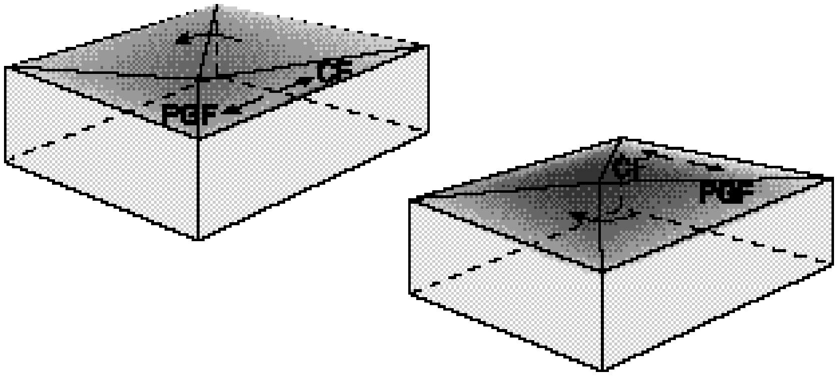


Fig. 19. Three-dimensional view of a “mound” (right panel” and a “valley” (left panel). In the mound case the pressure gradient force (PGF) is pointing away from the center. It is balanced by an opposite Coriolis force (CF) resulting in a clockwise geostrophic flow. In the valley case the opposite is true. The PGF is pointing toward the center and the CF away from the center. Consequently, the geostrophic flow is counterclockwise.

7. The general circulation of the ocean – Wind-driven circulation: The general circulation of the ocean corresponds to many years' average of the flows in the ocean. This average is analogous to the term "climate" which is frequently used for the atmosphere. (Recall that "weather" is the daily state of the atmosphere whereas "climate" is the state averaged over a few months.)

Surface waves which appear to many of us to be the most important aspect of oceanic flows are not important to the general flow in the ocean because of two reasons. First, they are active only in the top several meters of the ocean, and second, away from the coast, they correspond to a periodic back-and-forth motion which has no "average" importance.

There are *two kinds* of processes associated with the general oceanic circulation. The first is wind-driven flows (Fig. 20) and the second is the so-called thermohaline circulation (not shown in this stage). As the name suggests, wind-driven flows are currents resulting from the action of the wind. Thermohaline circulation, on the other hand, is the flow resulting from density differences (associated with temperature and salt) which come about through heat (or moisture) exchange with the atmosphere. Wind-driven flows are typical for the upper ocean and density driven flows are common in the deep ocean. We shall see that geostrophic and Ekman flows are the key ingredients of both of these processes. We shall begin by discussing the wind-driven circulation.

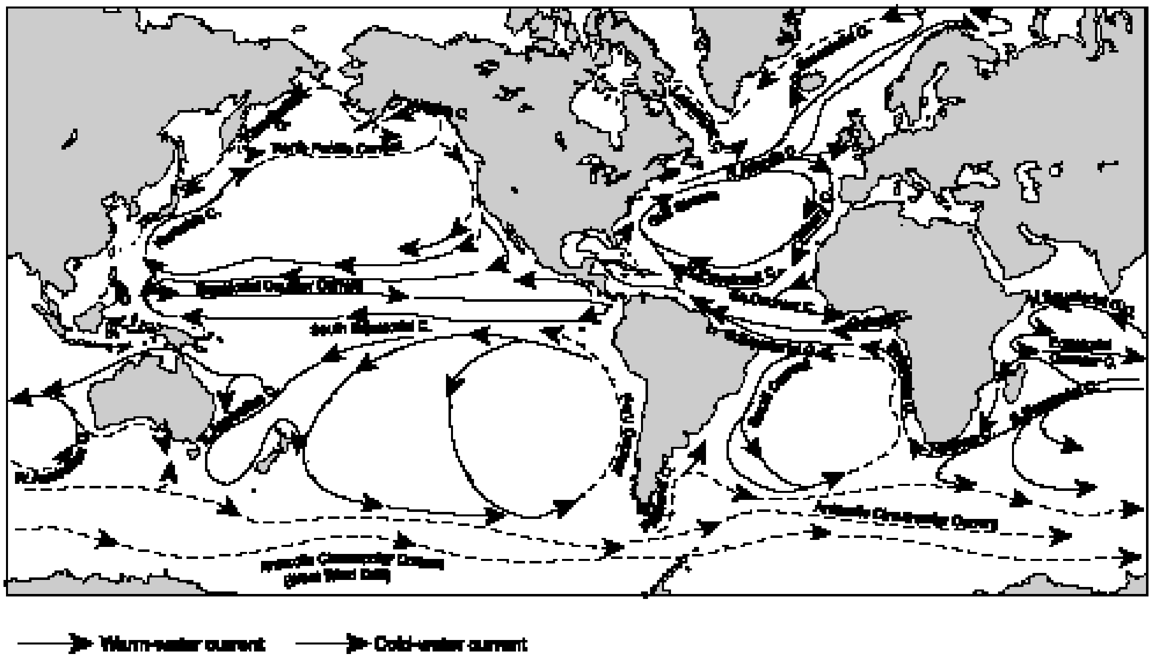


Fig. 20. The general wind-driven circulation of the world ocean.

Consider the box shown in Fig. 21 as a very simple model of the actual flow in the North Atlantic or the North Pacific (Fig. 20). Using the plastic box (which was placed on the overhead projector) and two hair dryers, we have shown in class that a basin subject to winds which reverse direction with latitude (in the manner shown in Fig. 21) always result in a clockwise circulation. (No circulation is established when the winds do not reverse direction with latitude.) This circulation pattern is similar to the actual circulation in the ocean (Fig. 20) even though the time of our experiment was very short compared to a day so that, of course, there was *no* Coriolis force.

It turns out that when rotation (i.e., Coriolis) is added to our model (Fig. 22), the general circulation pattern is not altered. (Because of mechanical limitations we could not do such a demonstration in class.) However, due to geostrophy, the sea level now corresponds to a "mound" with the highest level at the center. Also, in addition to the shown clockwise geostrophic flow which takes place over most of the water column (thick arrows), there is now an Ekman flow on top ("wiggly" arrows). Because the Ekman flow takes place over a very thin layer (top 50 meters) compared to the much thicker geostrophic flow (4000 – 5000 meters), its effect on the average circulation pattern is negligible. However, it is very important to the establishment of the pressure difference (which is responsible for the geostrophic flow)because it causes the accumulation of water in the center. Namely, the Ekman flow helps build the mound which, in turn, drives the geostrophic flow underneath. Note that the Ekman flow is present during all of the time and not only during the "beginning" of the circulation.

A three-dimensional view of the general (geostrophic) flow associated with Fig. 22 is shown in Fig. 23. The speed of the flow (ranging from a few centimeters per second to a few meters per second) decreases as one approaches the ocean floor but some flow is present even along the bottom. We have demonstrated this in class using balls in a circular container with a disk on top (Fig. 24).

Finally, recall that, in contrast to the (erroneous) statements made in some of the videos that you saw which attributed the direction of the circulation in the North Atlantic to the Coriolis force (which causes a deflection to the right), the direction of the circulation in the North and South Atlantic is a consequence of the boundaries (imposed by the continents) and the wind pattern rather than the Coriolis force. Otherwise, the circumpolar current which runs around Antarctica without interruption in a clockwise manner would have run counterclockwise (in accordance with the deflection to the left scenario).

When one looks at an "instantaneous" picture of the ocean, one does not encounter the general smooth pattern shown in Figs 20-23 but rather a variety of meandering currents which shed rings and eddies every few weeks (or months). For instance, Fig. 25 is a typical picture of the Gulf Stream on a given day. Clockwise rotating eddies which are called warm-core rings are present north of the Stream and counterclockwise eddies (called cold-core rings) are south of the Stream. Such rings detach from the Gulf Stream in the manner shown in Fig. 25.

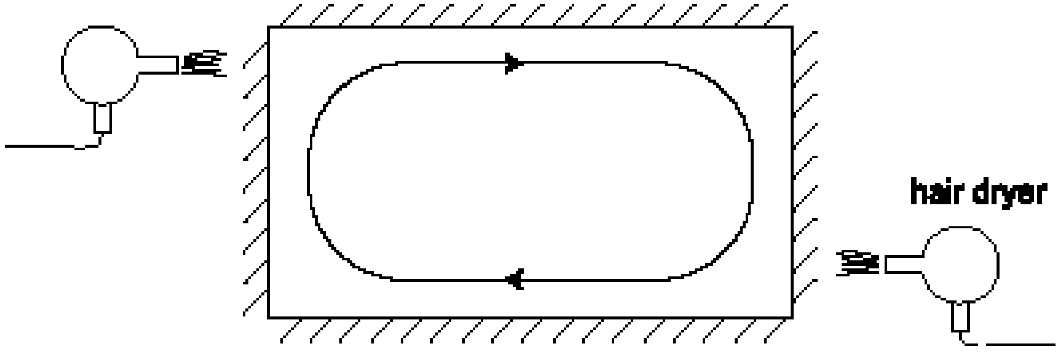


Fig. 21. A very simple model of the general circulation in the North Atlantic or North Pacific. The "winds" (i.e., hair dryers) change direction with latitute and, consequently, a clockwise flow is established.

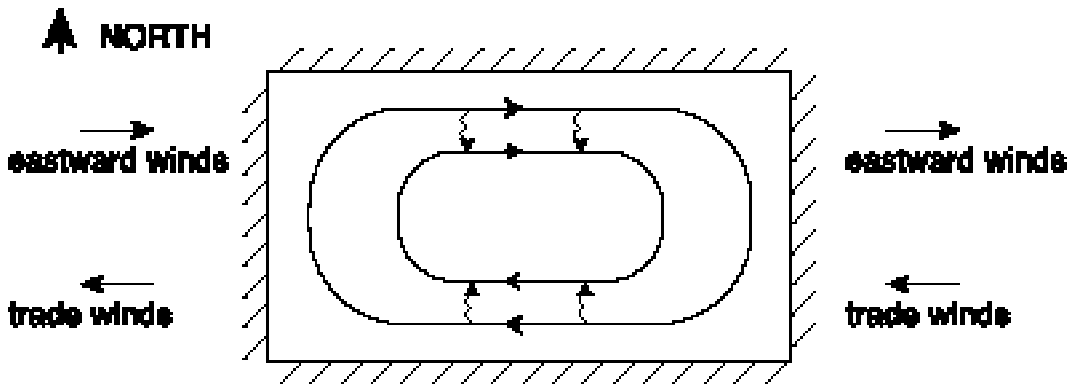


Fig. 22. A more realistic model of the wind-driven circulation in the North Atlantic or the North Pacific. As before, in low latitudes the trade winds are blowing toward the west (shown on the right and left-hand sides of the box) whereas in mid-latitude the wind is blowing toward the east. Again, the resulting clockwise circulation is a consequence of the wind pattern and the fact that the oceans are bounded by continents. However, in contrast to the model shown in Fig. 6, we now take into account the Coriolis force. As a result, the general flow structure is not altered, but the sea level is altered (see text). The thick arrows within the box show the geostrophic flow which takes place over most of the water column. The small "wiggly" arrows show the superimposed Ekman flow which is only active within the top 50 meters.

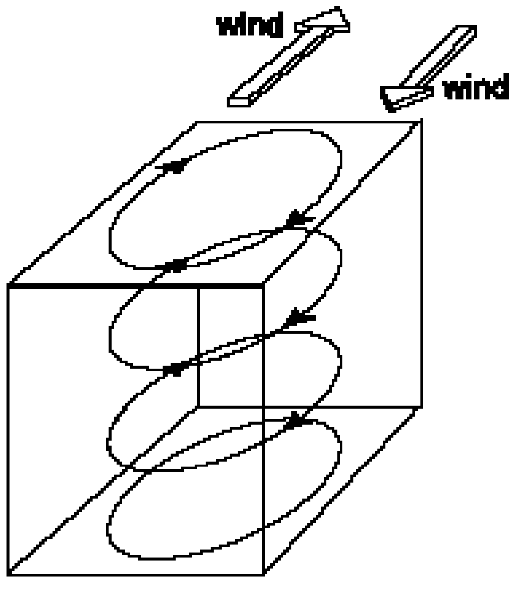


Fig. 23. A three-dimensional view of the general circulation pattern shown in Fig. 7. On the very top, Ekman flows which drive water to the center are present (not shown). Most of the flow, however, is geostrophic and decays gradually as one approaches the bottom.

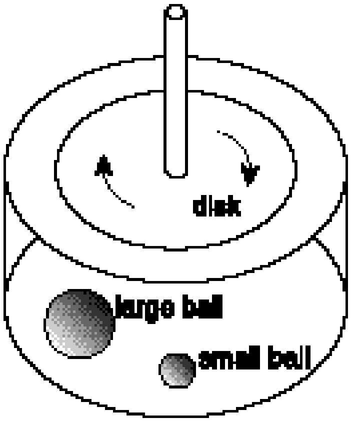


Fig. 24. A demonstration of the geostrophic speed decay as the bottom is approached. The container is filled with syrup and the turning disk simulates the wind action on the ocean's surface. The large ball moves (clockwise) faster than the small ball indicating that speed increases as one proceeds upward from the bottom.

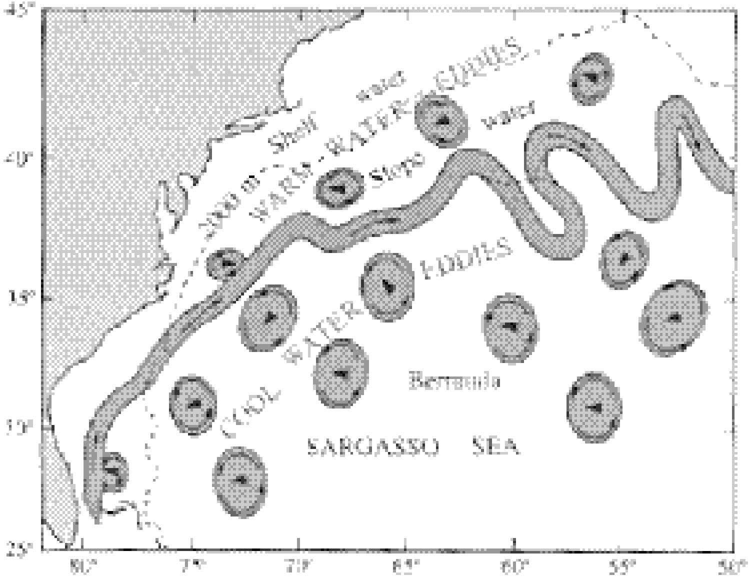


Fig. 25. An instantaneous picture of the Gulf Stream (drawn from satellite photographs).

B. Second Set of Reviews

We shall now continue to discuss ocean eddies and rings. The rings formation process is shown in Fig. 1a,b. Rings translate westward at a rate of about 1 km day^{-1} (due to the sphericity of the earth), i.e., they are like a frisbee in the sense that they rotate around a central axis and move forward (see Fig. 1c).Rings that spin in the same sense have a tendency to merge (if they bump into each other) but rings that rotate in the opposite direction do not have the tendency to do so. This is shown with the aid of the "figure 8" demonstration (Fig. 1d).

1. El Nino: An El Nino event is a non-periodic climatic fluctuation, centered in the Pacific, that occurs every 2–10 years. The event is a disturbance in both the ocean and the atmosphere. Its most obvious sign is the appearance of unusually warm water off the coast of Ecuador and Peru. This occurs within a few months of Christmas and the name “El Nino” – meaning the Christ Child – is simply the local name for the increase of water temperature. (Note that Coriolis is not very important here because of the proximity to the equator.)

As demonstrated with the example shown in Fig. 2, during normal non-El Nino years the trade winds drag the relatively warm water (lying on top of the Pacific) toward the west. The warm water is kept in the western part of the Pacific by the constantly blowing winds. Occasionally, for unknown reasons, the trade winds collapse and the warm water flows toward the eastern Pacific. We demonstrated this using a hair dryer acting on a two-layer ocean. Note that it takes the warm water 6–12 months to advance from the western to the eastern Pacific.

This movement of warm water has far reaching consequences to the climate over the entire globe. One of the these effects is on the local fishing industry off Peru. The waters off Peru are subject to upwelling due to equator-ward winds (which do not collapse with the collapse of the trade winds). As shown in the left panel of Fig. 3, during non-El Nino years the ocean along the eastern Pacific is not stratified and, consequently, the upwelling brings nutrients-rich water from the deep ocean. This upwelling is the main reason for the very rich fishing in the area. During El Nino, one the other hand, the upwelling does not reach the bottom (Fig. 3, right panel) and, as a result, the fishing industry collapses. We demonstrated the two corresponding situations using the conveyer belt experiment with homogeneous and stratified oceans (Fig. 4).

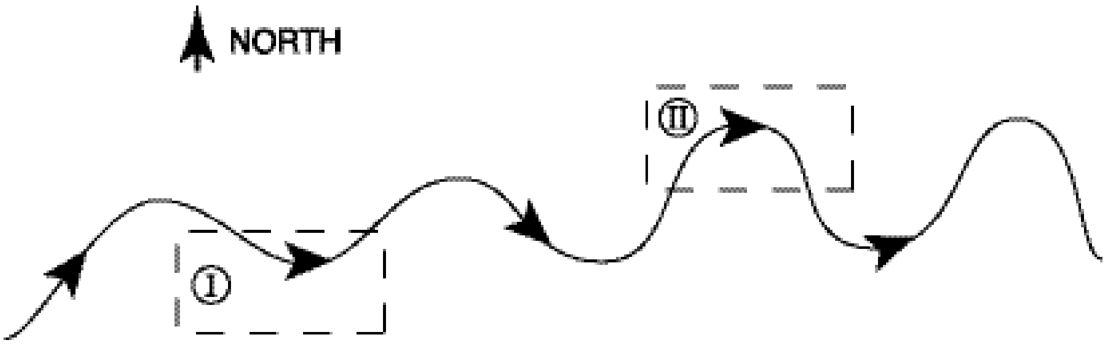


Fig. 1a. A schematic diagram of the instantaneous structure of the Gulf Stream. Regions I and II (the squares bounded by the dashed lines) are referred to in Fig. 9b.

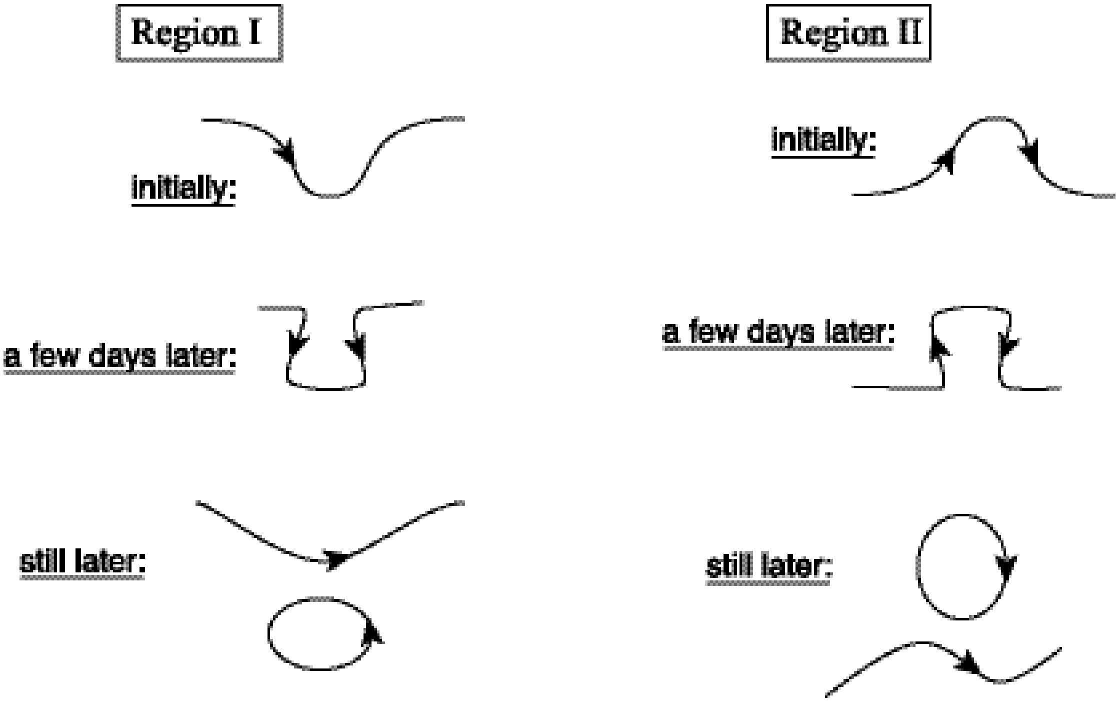


Fig. 1b. The establishment of counterclockwise and clockwise eddies south and north of the Gulf Stream. Regions I and II are shown in Fig. 9a.

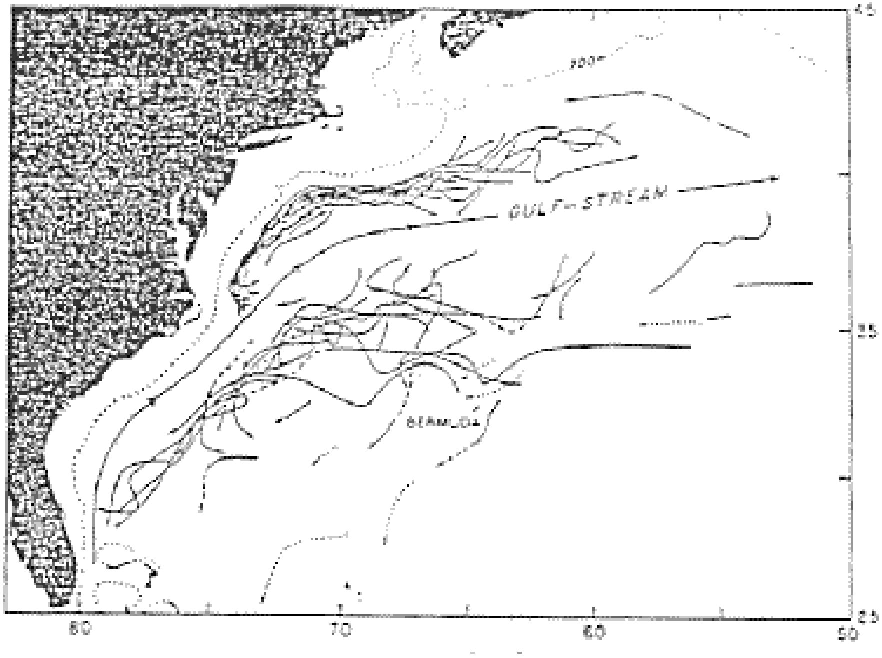


Fig. 1c. <u>Cold rings south of the Stream</u>. Some rings moved westward until they were close to the Stream, then they turned southwest and appeared to coalesce with the Stream near Florida. Other rings moved in a more a southward direction into the Sargasso Sea.

<u>Warm rings north of the Stream.</u> Movement of warm rings is westward; their mean track is confined between the continental slope and the Gulf Stream. Warm rings routinely coalesce with the Stream near Cape Hatteras, N.C.

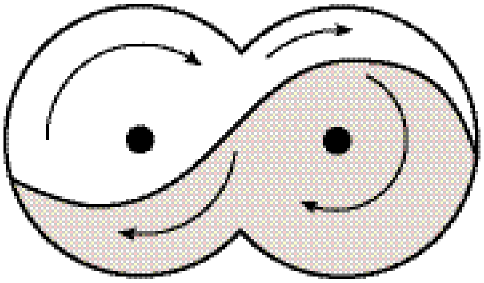
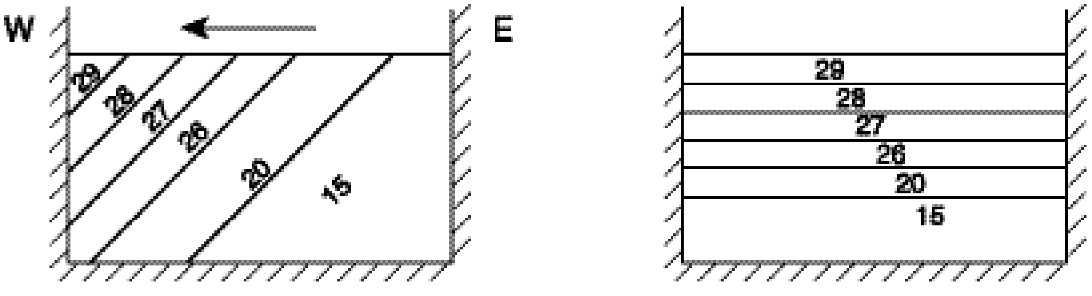


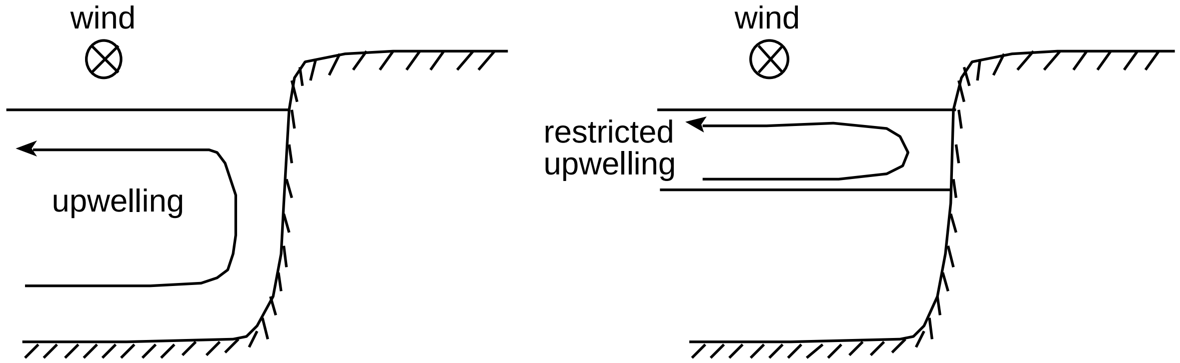
Fig. 1d. A schematic diagram of the demonstration used to illustrate the merging of two eddies spinning in the same sense. Each eddy draws the fluid of the other.



non-El Nino
trade winds

El Nino
(no wind)

Fig. 2. The temperature structure (in centigrade) associated with El Nino and non-El Nino years.



non-El Nino situation
(upwelling takes place
over the entire
water column)

El Nino situation
(upwelling is confined
to surface water due
to stratification)

Fig. 3

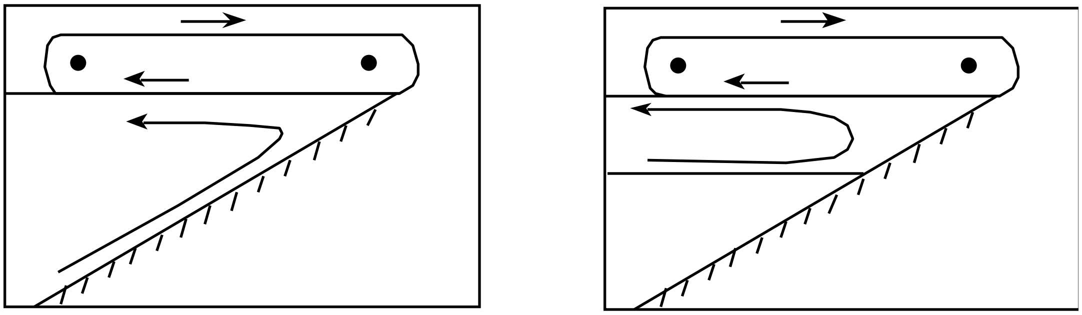
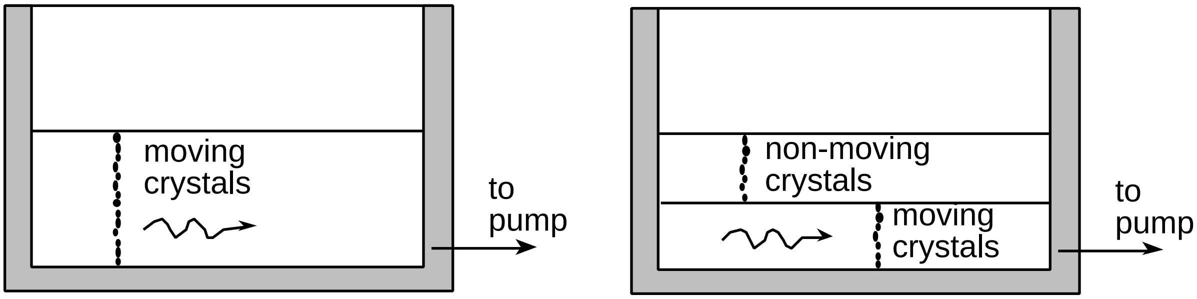

non-El Nino (homogeneous)   El Nino (stratified)

Fig. 4

The fact that water of one density can "slide" on top of water with slightly greater density was also demonstrated using the vacuum pump experiment (Fig. 5). When the fluid was homogenous, crystal at all levels were sucked out (Fig. 5, left panel) but when the fluid consisted of two layer (Fig. 5, right panel) only the lower fluid was sucked out.



El Nino (stratified)   El Nino (stratified)

Fig. 5

2. Density-driven flows: As mentioned, density-driven flows are not caused directly by the wind but rather by heat exchange or moisture exchange (i.e., evaporation and precipitation) with the atmosphere. We shall first discuss flows resulting from heat exchange with the atmosphere.

Because of the spherical shape of the earth, polar regions receive much less heat from the sun than equatorial regions. To see this, note that the surface of the earth is tilted (relative to the sun) in polar regions (Fig. 6). Recall that the popular (and erroneous) explanation for the difference in the amount of light received from the sun is that the equatorial regions are *closer* to the sun than the polar regions are. Although it is certainly true that the equatorial regions are indeed closer to the sun, the difference in the distances involved is minute and cannot explain the dramatic difference in the amounts of received sunlight.

Because of the small amount of heat that the polar regions receive, polar oceans contain regions where cold water is formed near the surface. Since cold water shrinks in volume, it becomes denser than water that is not cold. Consequently, it cascades along the continental rise (the "walls" of the ocean) and sinks to the bottom. We have demonstrated this process using dyed ice (Fig. 7ab). In the latter demonstration the water mixes and warms up as it proceeds along the bottom. It ultimately rises in the equatorial region because some water must obviously rise to replace the sinking water. Note that, due to the symmetry of the process, the rising must take place in the middle of the box (i.e., the "equator"). In reality, however, the continents are not symmetrical so the rising occurs off the equator.

Because of the earth’s rotation, this movement of cold water occurs along the western boundaries of the ocean. Both observations and demonstrations (Fig. 7b) show that this is the case. We have demonstrated this using a rotating pie-shaped ocean which can be thought of as representing the Atlantic ocean. We showed that cold and dense water injected in the North Pole progressed away from the pole along the western boundary of the ocean (hatched area). Without the Coriolis effect the water would, of course, spread uniformly in all directions.

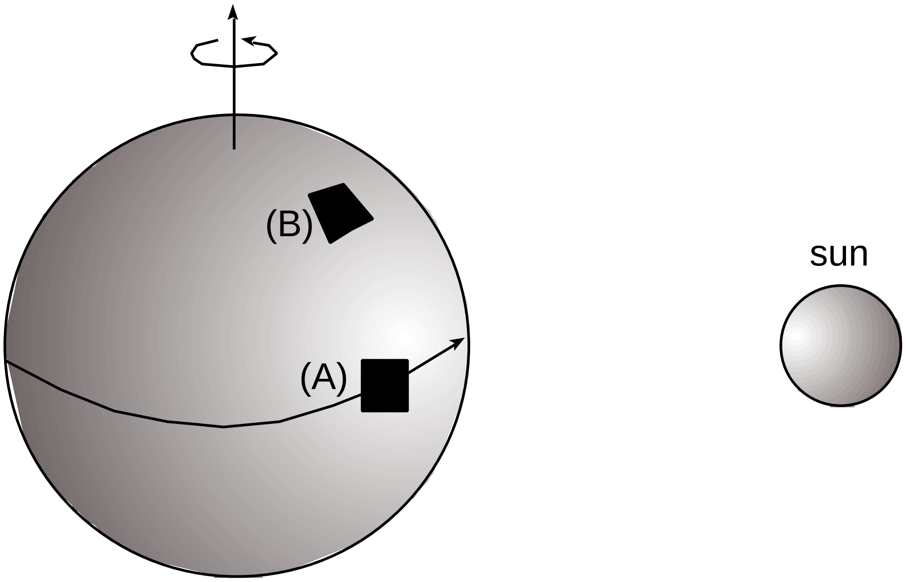


Fig. 6. The position of two equal areas on earth (black squares) relative to the sun. One is situated in an equatorial region (A) and the other in a polar region (B). The square in A receives more light from the sun than the square in B because the square in B is tilted relative to the sun.

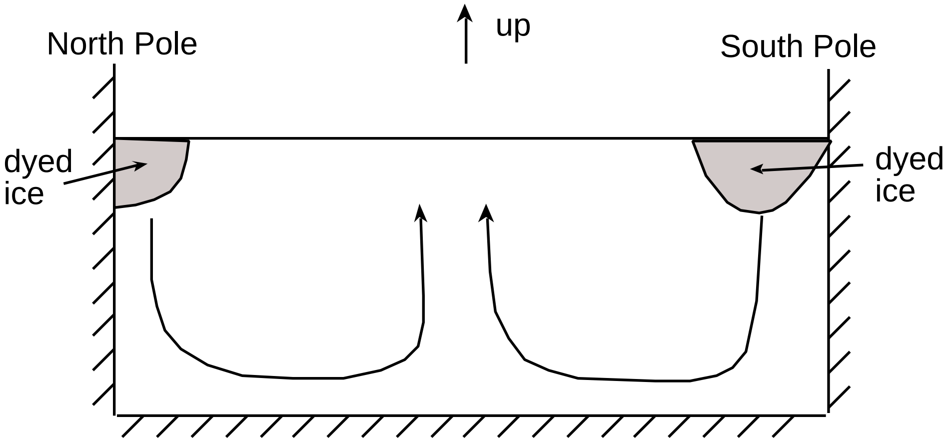


Fig. 7a. The demonstration used to illustrate the circulation pattern resulting from the sinking of cold water in polar regions.

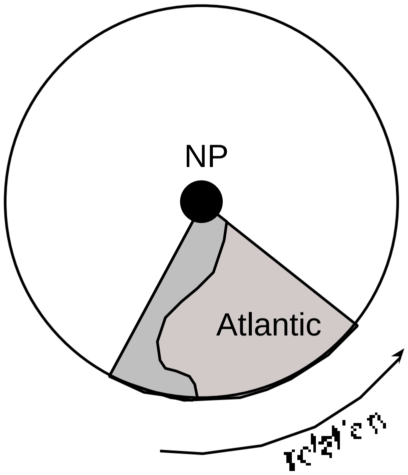


Fig. 7b

We shall now proceed and discuss density-driven flows where the density difference results from differences in salt concentration rather than differences in temperature discussed so far. Before doing so, however, recall that evaporation releases only *fresh* water to the atmosphere. Consequently, when oceanic water evaporates, its salt is left behind and the remaining water becomes denser than the initial water. To see this, consider the two containers which initially have the same concentration of salt as shown in Fig. 8. As a result of the evaporation, the density of the water in container A increased.

Armed with this information, it is now possible to analyze the flow associated with the exchange of water between the Atlantic and the Mediterranean Sea. Because of strong winds and a mostly arid climate, the eastern Mediterranean Sea is subject to an excess of evaporation over precipitation (~ 1 meter per year). As a result, dense water is formed in the eastern Mediterranean. This dense water sinks and flows toward the Atlantic along the bottom (Fig. 9). It ultimately crosses the Strait of Gibraltar (solid arrows) and penetrates into the Atlantic at mid-depth. Relatively light surface Atlantic water (broken arrow) must, of course, enter the Mediterranean Sea to replace the exiting water.

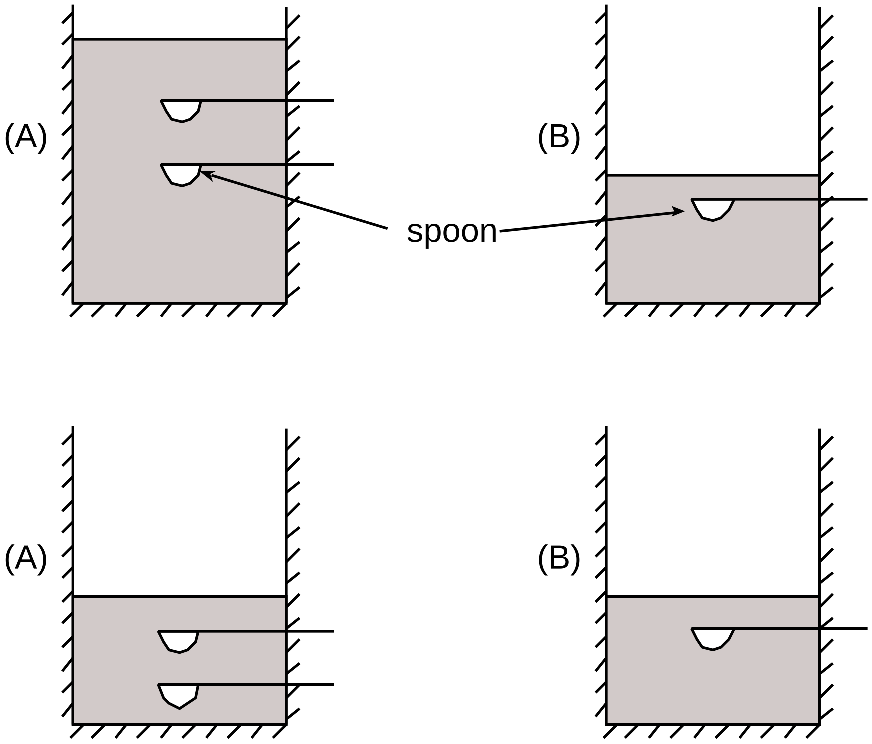


Fig. 8. The effect of evaporation on the density of sea water. In the upper panel, there are two containers A and B, each of which is filled with water of the same density. The spoons indicate the amount of dissolved salt. Container A has twice the volume as container B but it also has twice the amount of salt (two spoons). In the lower panel, half of the water in container A has evaporated resulting in water denser than that of the non-evaporated water in B.

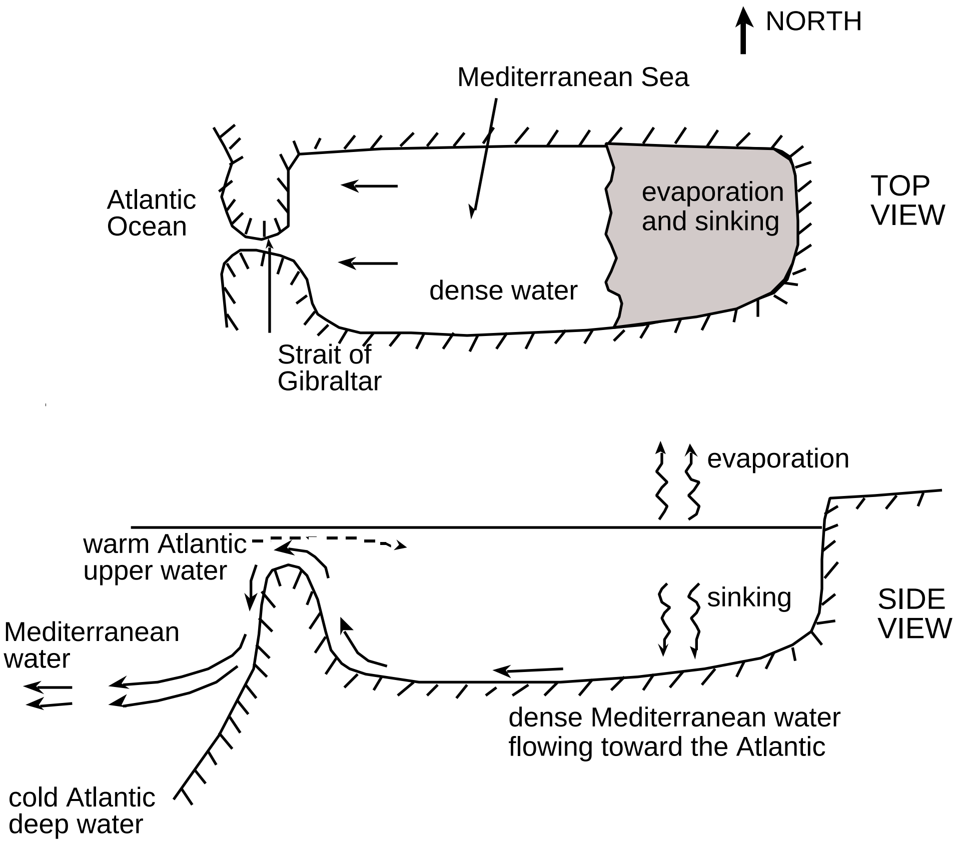


Fig. 9. The exchange of water between the Mediterranean Sea and the Atlantic ocean. Because of evaporation over the eastern Mediterranean, dense water is formed. This water sinks to the bottom and flows westward toward the Atlantic (solid arrows). It then crosses the Strait of Gibraltar and penetrates into the Atlantic at a depth of about 1000 meters. Surface Atlantic water must, of course, enter the Mediterranean (broken arrow) to replace the exiting dense water.

As shown in Fig. 10, the penetration of Mediterranean water into the Atlantic occurs at mid-depth (around 1000 meters) rather than the bottom (around 4000 meters) because it so happens that, although the dense Mediterranean water is heavier than the surface Atlantic water, it is lighter than the lower Atlantic water. Note that the density difference between the upper Atlantic water and the lower Atlantic water results from two processes. First, the upper Atlantic is exposed to the sun so that it becomes warmer (and lighter) and second, the water that sinks in the polar regions cools the lower Atlantic water. It is important to realize that this exchange between the Mediterranean and the Atlantic results from density differences associated with both salt and temperature differences.

Sometimes the outflow from the Mediterranean does not take place in a continuous manner. Occasionally, it twists and meanders around like the Gulf Stream and forms “Meddies.” We know that this is the case because floats that are embedded in the outflow occasionally form paths that indicate a migration superimposed on an orbital motion (Fig. 11). (To understand this, think of a point on a moving frisbee and the trajectory that it forms.)

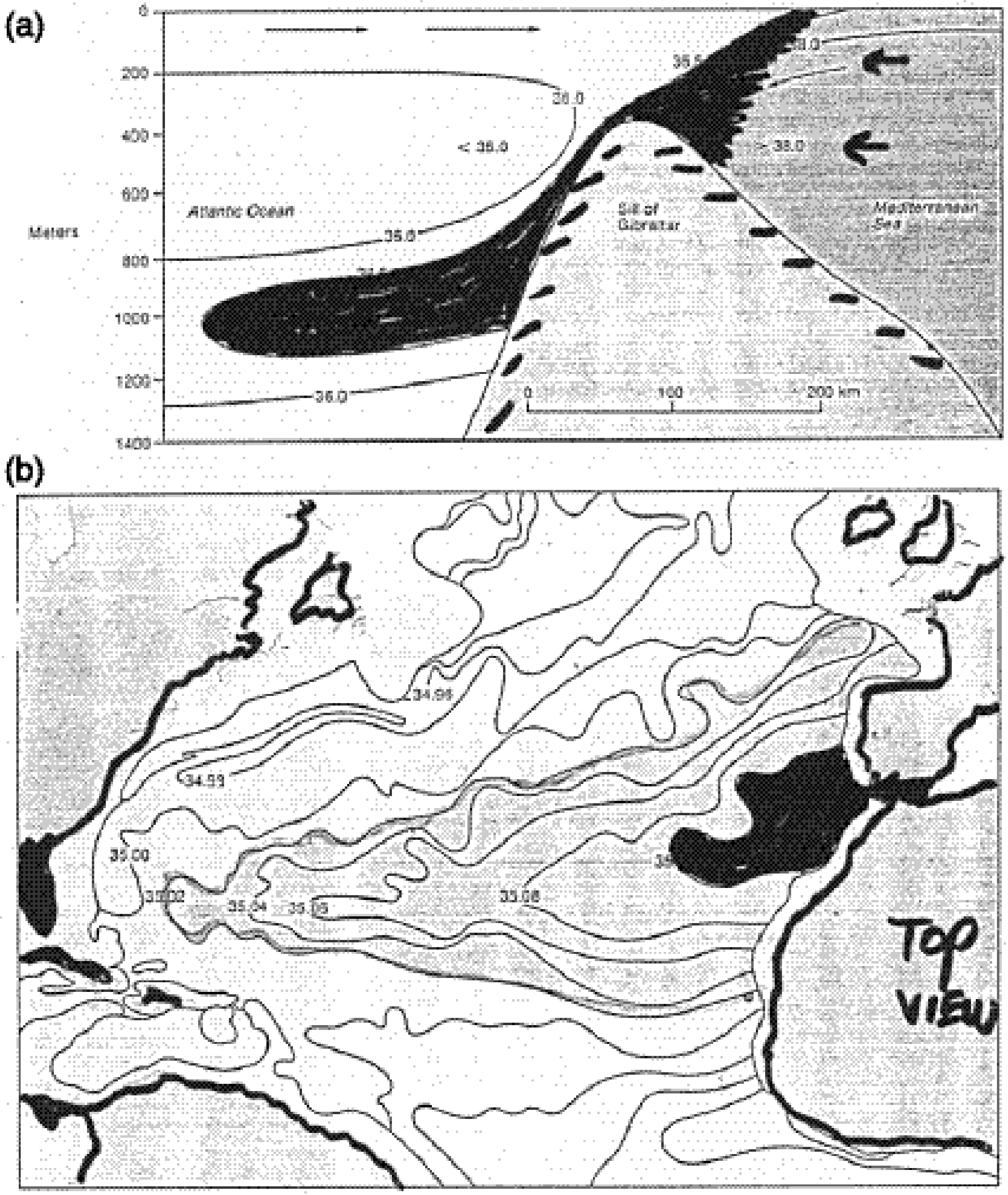


Fig. 10. Profile showing Mediterranean sea water entering the Atlantic Ocean over the Gibraltar Sill (a) with a tongue of salty water extending thousands of kilometers into the Atlantic (b). Numbers represent salt concentration in kilograms per tons of water. The profile is based on measurements.

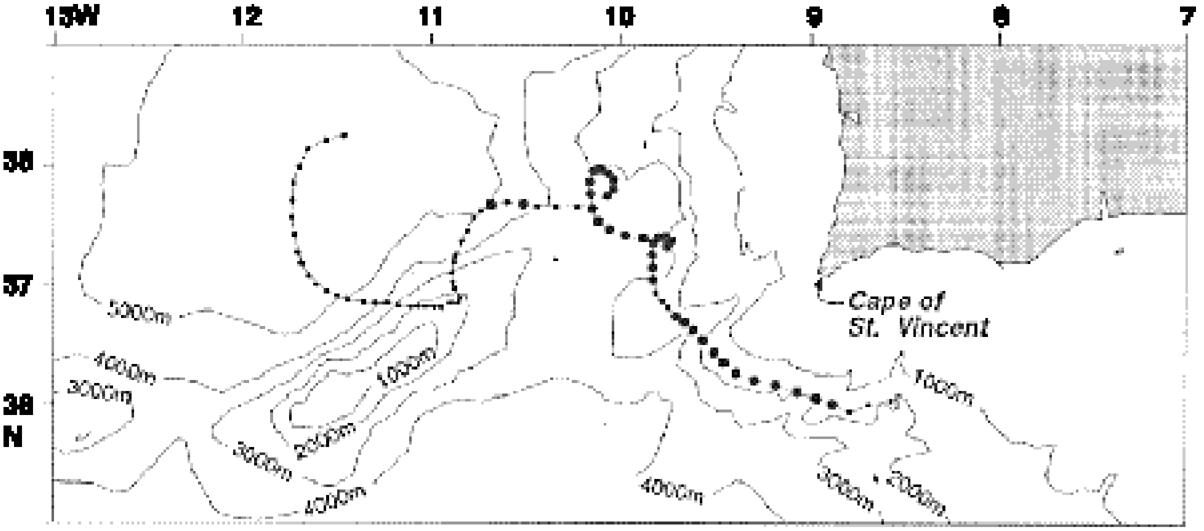


Fig. 11. Float trajectories associated with the Mediterranean outflow. The float represents the core of the outflow.

C. Third Set of Reviews

1. The 1929 Grand Banks Earthquake: In the early evening of November 18, 1929, an earthquake tremor shook the ocean floor to the South of Newfoundland, Canada. The event was notable in three respects. First, although seismicity is common in the North Atlantic, the shocks tend to be confined to the region of the Mid-Atlantic Ridge. By contrast, the epicenter of this event was located far from the ridge, originating on the continental slope in water depths between 2000 and 4000 m. Second, submarine earthquakes in the North Atlantic tend to be relatively weak in intensity, particularly compared to the powerful seismic tremors ravaging the Pacific islands. The Grand Banks earthquake of 1929, on the other hand, was quite severe, registering a magnitude of 7.2 on seismometers. Finally, submarine earthquakes in the North Atlantic usually disrupt only naturally occurring features, because the tremors occur far out at sea. This event was an exception; it disturbed a region where a dense network of transatlantic telegraph cables had been laid down on the ocean floor. Despite expensive damage to this equipment, this third aspect proved to be particularly noteworthy, because it revealed the presence of an important process in the deep sea that until that time had not been recognized – the turbidity current.

Two oceanographers, Bruce Heezen and Maurice Ewing, studied the time sequence of cable breaks, which had been recorded accurately by the disruption of communications between North America and Europe. The pattern was peculiarly interesting. Eight cables draped across the continental slope in close proximity to the epicenter broke simultaneously, presumably in response to massive sediment slides and slumps that accompanied the first ground motions of the tremor (Fig. 1a). Then, for 13 hours after the Grand Banks earthquake, telegraph cables to the south of the epicentral area broke sequentially from north to south. The farthest and last cable to break was located about 675 km from the Grand Banks (see Fig. 1b, 1c).

Heezen and Ewing postulated that large blocks of sediment, dislodged from the seabed of the continental slope by the earthquake, poured a voluminous mass of watery mud which flowed downslope as a density current snapping cables systematically from north to south (Fig. 2). Based on the break times of the cables and their spacing on the sea floor, the oceanographers estimated that the speed of the turbidity currents decreased with distance of travel from around 20 m/sec (40 knots!) near its source to 8 m/sec (12 knots) at the last cable break.

Subsequent surveys confirmed Heezen and Ewing’s analysis. Retrieval of the severed cabled revealed that they had all been buried by sediment after they broke. Also, numerous cores taken from the Deep-Sea area affected by the proposed turbidity flow contained many signs of rapid and turbulent transport, including gravel and sand layers overlying undisturbed mud, and scraped shells of shallow-water fossils.

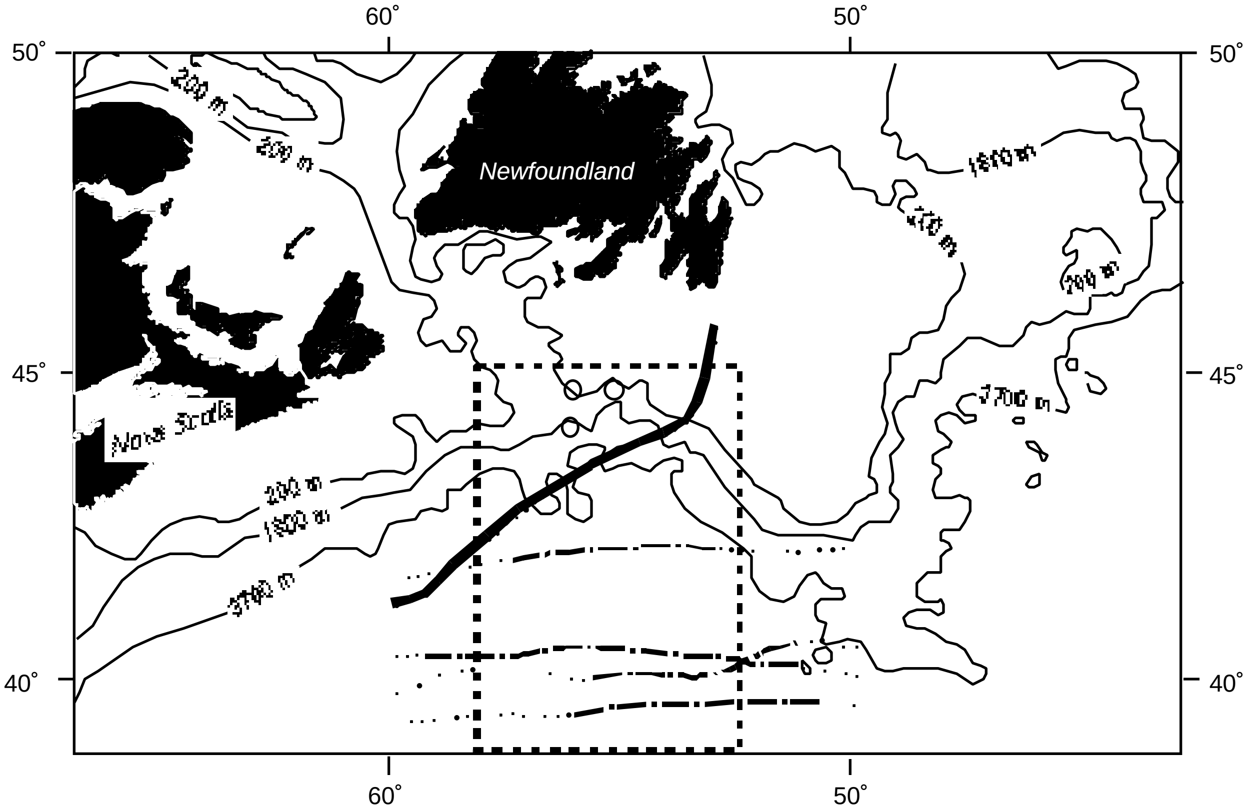


Fig. 1a. Bathymetric map of the western North Atlantic showing the epicenters of the 1929 quake (❍), the telegraph cables (dotted lines), and the areas of damaged cables (dash-dotted lines). A close-up of the region bounded by the dashed line is shown in Fig. 1b.

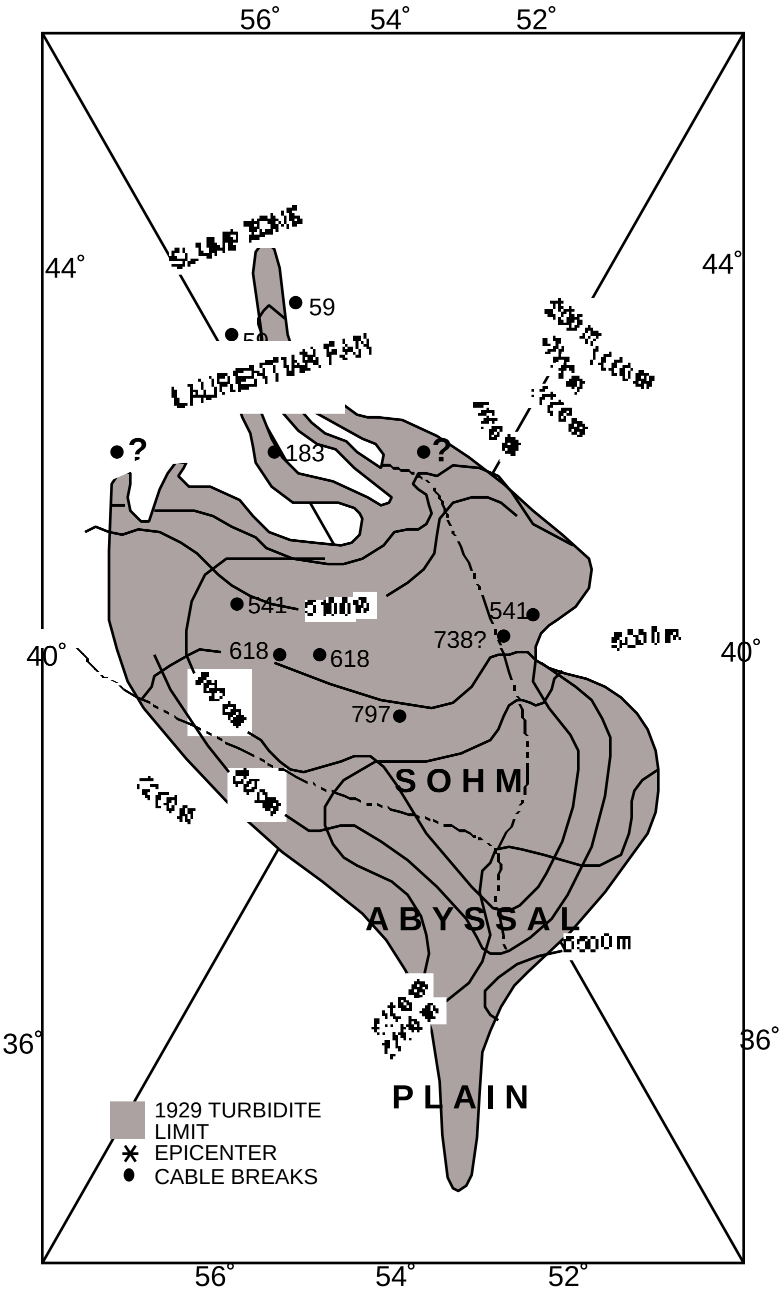


Fig. 1b. A close-up of the region bounded by the dashed line in Fig. 1a, showing the location of the 1929 turbidite relative to the topography. Times (in minutes) of cable breaks (solid dots) and the thicknesses of the turbidite deposits are also shown.

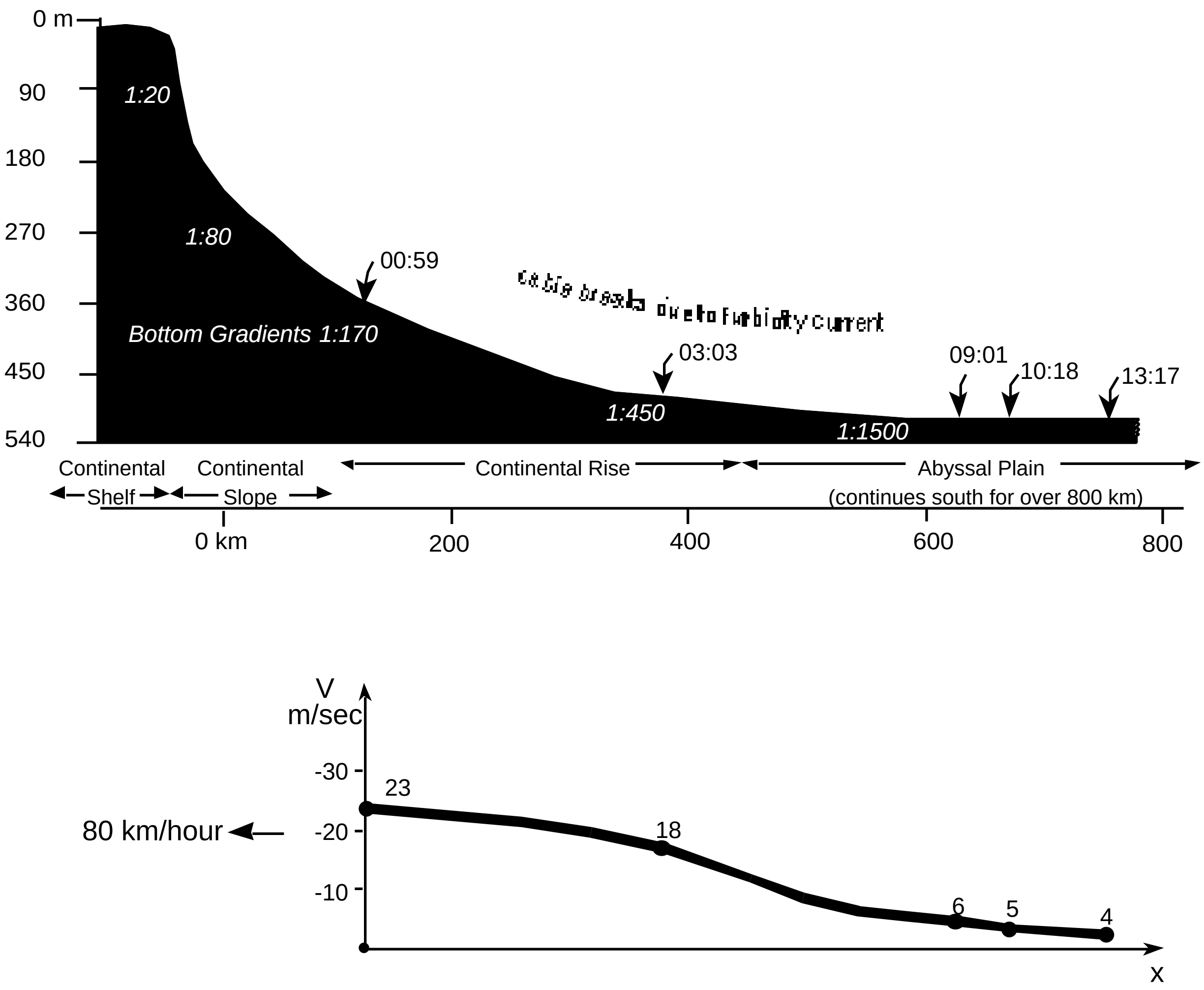


Fig. 1c. Topographic cross-section south of the 1929 Grand Banks earthquake, with superimposed downhill propagation rate profile as determined by the successive cable breaks.

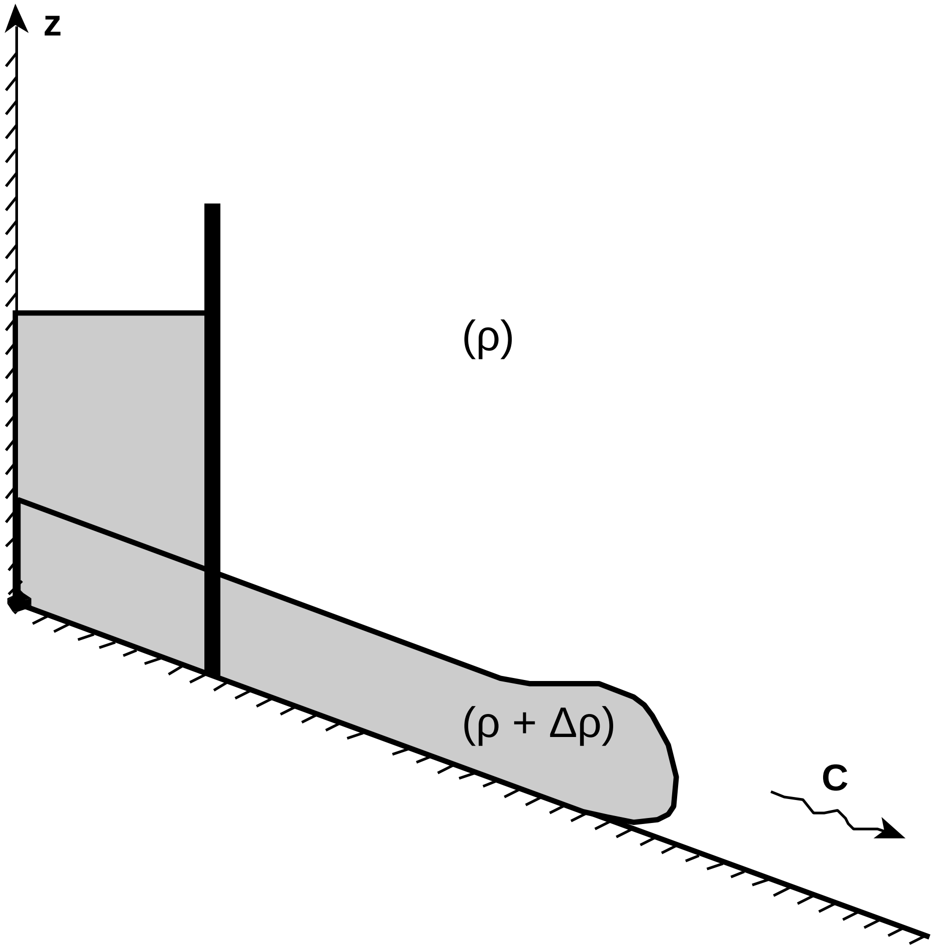


Fig. 2. A turbidity gravity current resulting from the removal of a lock. The current) whose density is $\rho + \Delta\rho$) underlies an infinitely deep layer (of density ρ) and advances to the right (at a speed C) due to the excess pressure behind the head. This situation is analogous to that occurring during the 1929 Grand Banks earthquake.

Recently, a survey of the epicenter region with a sidescan sonar revealed the presence of numerous slide and slump scars on Newfoundland's continental slope. Furthermore, large gravel waves 2–5 m high and 50–100 m long abound in a valley found at water depths between 1600 and 4500 m. Gravel waves are bedforms that form in response to the flow of a powerful current across loose sedimentary grains, in a manner roughly similar to the formation of sand dunes by wind currents. Theory suggests that these large gravel bedforms and the sizes of the particles required bottom flow velocities of at least 8–12 m/sec to move to their present positions – speeds that agree well with Heezen and Ewing's calculations.

2. Microstructure of the ocean: So far, we examined processes that take place on the oceanic basins scale (i.e., many thousands of kilometers), and the oceanic eddies scale (hundreds of kilometers). We shall focus now on processes with a very small scale of a few centimeters. Because of this small length scale and the associated short time scale, the Coriolis force is not important and can be ignored. The two most important processes which take place in phenomena with this length scale are mixing and stirring. *Mixing* is the reduction of variations by the action of molecular diffusion along gradients from regions of high temperature (or salt concentration) to regions of low temperature. Mixing rates depend on the steepness of the gradients and the coefficient of molecular diffusion. An example of a process which involves mixing alone is the diffusion of a teaspoon of sugar situated undisturbed on the bottom of a still teacup filled with hot water. *Stirring*, on the other hand, does not involve diffusion and is simply the creation of velocity differences by any process that imparts kinetic energy to the liquid. An example of stirring is, of course, the stirring of the sugar-water system. Note that there can be stirring without mixing (e.g., oil and water) but most of the time stirring is associated with mixing.

We shall now discuss the stability of solutions involving temperature and salt gradients. The microstructure of the ocean involves water rising or sinking (due to density variations) and it is important to understand how these processes come about. The most important issue to understand here is that heat diffuses a hundred times faster than salt. With this information we can now analyze the stability characteristics of three systems which frequently occur in the ocean.

The first is a system of warm and fresh water overlying a denser layer of cold and salty water (Fig. 3). To perform the stability analysis we proceed in the same manner that one examines the stability of a ball situated along the bottom of a channel. We imagine that we give the ball a push and then ask the question whether the ball will return to its original position. If it does, the system is said to be stable (Fig. 4, left panel) and if it does not (Fig. 4, right panel) the system is said to be unstable.

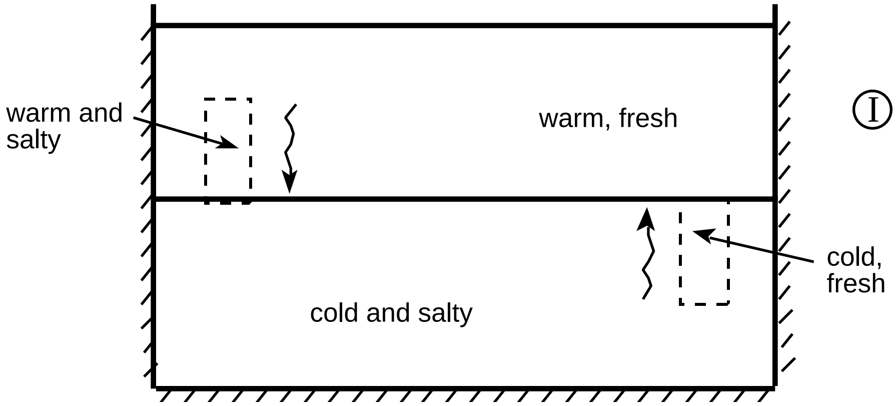


Fig. 3. A system of warm and fresh water overlying cold and salty water. This system is stable.

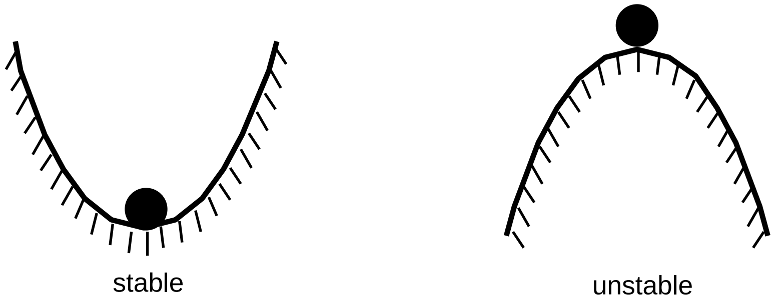


Fig. 4. Stable and unstable situations.

To apply these principles to the system shown in Fig. 3 we imagine that a small amount of cold and salty water (say, a "finger") is pushed into the upper (warm and fresh) fluid. This "finger" is shown with the dashed line on the left-hand side of Fig. 3. Since heat diffuses much faster than salt, the finger will accept its new environmental temperature right away but will retain its salt concentration for a long time. Hence, the finger (on the left) will become warm and salty. Since it is heavier than the upper layer it will fall down and stay in between the two layers. Similarly, the finger on the right will become cold and fresh very quickly. Cold and fresh is lighter than cold and salty and, therefore, the finger will float back to the interface. In view of these, the system shown in Fig. 3 is stable.

The next system that we will consider is shown in Fig. 5. Here, we have a layer of warm and salty water overlying cold and fresh water. Using the same principles that we applied before, we note that a hypothetical finger on the left will quickly become warm and fresh and that a finger on the right will quickly become cold and salty. In contrast to the earlier system (system I), the finger on the left is now lighter than its environmental fluid and, consequently, rises to the top. Similarly, the finger on the right sinks to the bottom. Because of these properties we say that this system is inherently unstable. As demonstrated in class, it produces salt-fingers within minutes (Fig. 5a).

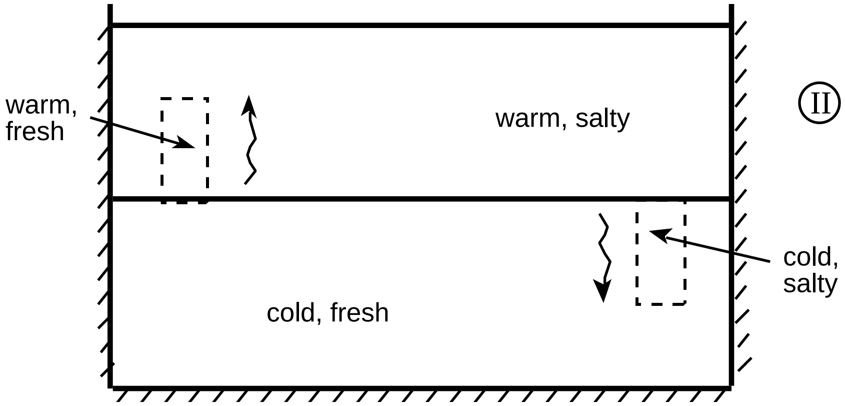


Fig. 5. A system of warm and salty water overlying cold and fresh water. This system is inherently unstable and produces “salt-fingers.”

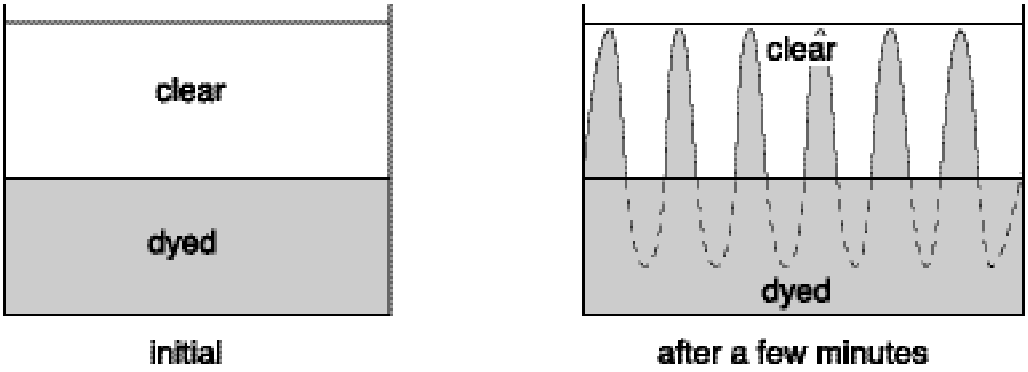


Fig. 5a. The salt-fingers demonstration. We used a system analogous to “warm, salty” above “cold, fresh” by using solutions with two salts each of which has a different diffusivity (In analogy to heat vs. salt, one of our salts diffuses much faster than the other.) Note that the dyed fingers were clearly visible but the light ones were not. This is because the clear fluid fingers were surrounded by dyed water.

The last system that we shall consider is shown in Fig. 6. Here we have cold and fresh water above warm and salty water. Again, using the same principles that we used before, we find that the finger on the left will become cold and salty which is heavier than the fluid from which it originated (warm, salty). It will therefore sink to the bottom of the lower layer. Similarly, the finger on the right will become warm and fresh which is lighter than the upper layer and, therefore, will rise to the top. Because of these motions across the layers we say that the system is stable and *convective*. Note that the first system that we considered (Fig. 3) was also stable but it was not *convective*. In that case, the fingers merely moved back to their original layer, i.e., they were not lighter or heavier than the fluid from which they originate.

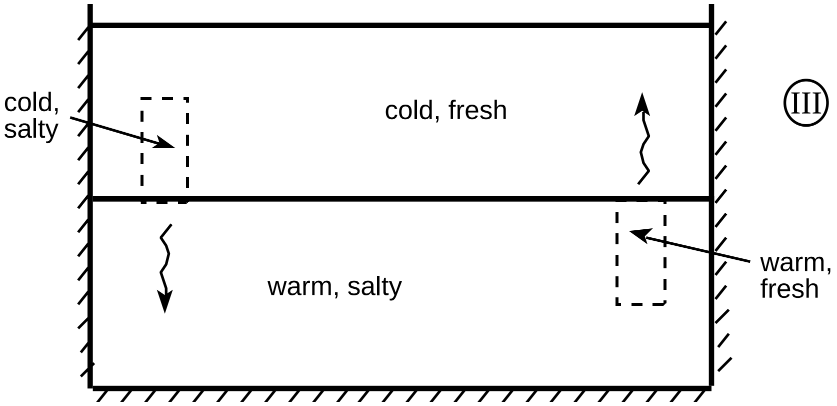


Fig. 6. A system of cold and fresh water overlying warm and salty water. This system is stable and convective.

3. Waves: Ocean surfaces are rarely still, with waves continually moving across them. The three most important wave generators are winds blowing across the ocean surface, the gravitational attraction of the sun and moon, and earthquakes. Winds generate most surface waves, ranging from ripples less than 1 cm high to giant, storm-generated waves more than 30 m high. Tides also behave like waves but are so large that their wavelike characteristics are easily missed. Seismic sea waves, caused by earthquakes, are still less common. At sea they are easily overlooked but damage coastal communities and cause catastrophic losses of life, especially in lands bordering the Pacific. In this section, we examine various types of waves and their behavior in the ocean.

(a) Ideal progressive waves

We begin by studying a series of waves. Progressive waves (in which the wave form moves) passing a fixed point show a regular succession of crests (highest points) and troughs (lowest points). Wave height (H) is the vertical distance from a crest to the next trough (Fig. 7a). Successive crests (or troughs) are separated by one wave length (L). The time required for successive crests (or troughs) to pass the fixed point is the wave period (T), commonly expressed in seconds. Wave periods are often used to classify waves.

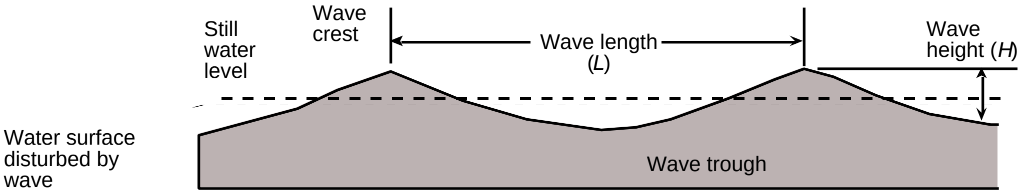


Fig. 7a. A simple wave and its parts. Note that the water surface changes as the wave passes.

Wave speed (V) is calculated by the simple ratio V = L/T. In simple words, this formula tells us that wave speed, wave length, and wave period are all directly related; knowing any two factors, we can calculate the third. Wave height (H) is unrelated to the other three factors and must be observed. Wave steepness, expressed as H/L, is the ratio of wave height to wave length.

A cork floating on a water surface moves forward as wave crests pass and backward as troughs pass. After each wave passes, the cork returns to its initial position. This shows that only the wave form moves, and that there is almost no net water movement associated with a wave's passage. (We shall see later, however, that shallow waters are moved by waves breaking on beaches.)

Movements of small floats at various depths in a tank show that water parcels below the surface move in nearly circular orbits as waves pass (Fig. 7b). At the surface, orbital diameter equals wave height. Beneath wave crests, particles move in the direction of wave motion; under wave troughs, particle motion is reversed. Below the surface, speed or orbital motion decreases and the orbits become smaller. At a depth of half a wave length (L/2), the wave-induced orbital motions vanish.

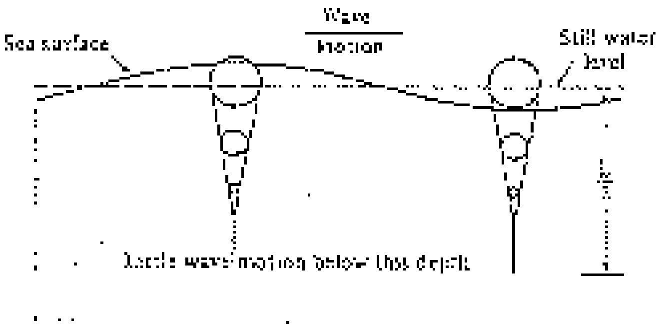


Fig. 7b. Wave profile and water-particle motions caused by a wave moving through deep water. Note the diminishing size of the orbits traced by water-particle movements with increasing depth below the water surface.

(b) *Shallow-water waves*

Where water depths are less than one-half wave length (L/2), waves interact with the bottom. Water particles near the bottom can move only horizontally and not vertically (Fig. 7c). Farther from the bottom, water particles move in flattened elliptical orbits that become flatter near the bottom and more circular near the surface.

When water depth exceeds one-half wave length, waves are unaffected by the bottom. Therefore, in the deep ocean, a wave’s speed is determined by its wave length and period; longer waves move faster than shorter ones. This implies that long waves from distant storms arrive first; they are followed by shorter waves.

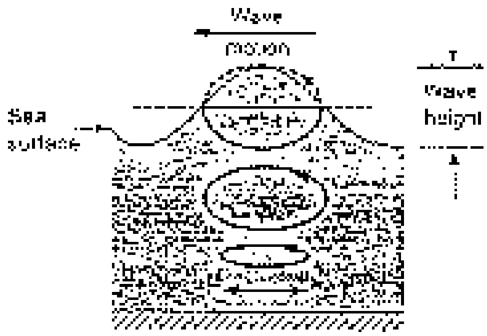


Fig. 7c. Motions of water particles caused by passage of shallow-water waves. Note that the orbits are influenced by the bottom in shallow waters.

In shallow water the depth controls wave speed. Where the water depth is less than one-half of the wave length the wave speed (V) is controlled by the average water depth (d) and can be calculated by the formula:

$$V = 3.1\sqrt{d} \ ,$$

where V is wave speed (velocity) in meters per second and d is depth in meters.

As waves move from deep water into shallow water, the wave speed, and the wave length change, but the wave period remains unaltered. Directions of wave advances are also deflected when waves encounter shallow or irregular bottoms; this is called *wave diffraction* (Fig. 7d).

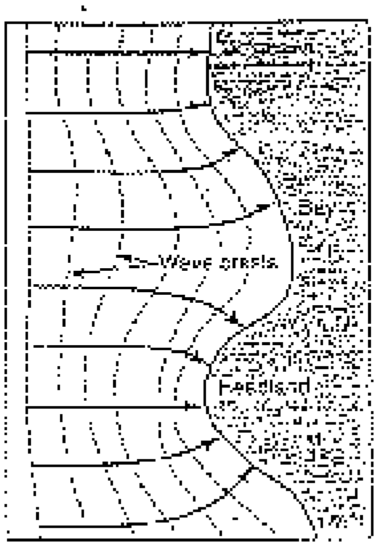


Fig. 7d. Waves approaching shores are diffracted by varying water depths, moving more slowly in shallow waters. In deeper waters of bays, wave crests are diffracted and their energy is spread over larger areas. Thus, wave energy is concentrated on headlands, increasing erosion there and depositing materials in bays where there is less wave energy to remove them.

As the waves approach beaches and the ocean depths decrease (becoming less than L/2) the orbital water-particle motions are flattened due to their interaction with the bottom. Although the wave period remains unchanged, the wave length is shortened. Consequently, the wave height increases and the wave crests become more peaked. When wave crests peak sharply, they become unstable and break (Fig. 7e). Waves usually break when water depth is about 1.3 times wave height.

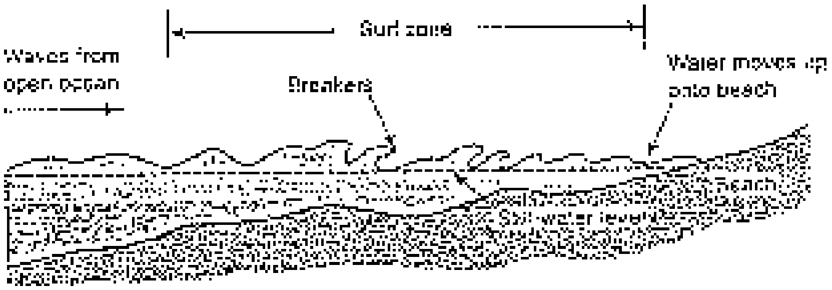


Fig. 7e. Waves peak upon entering shallow waters. At a depth of 1.3 times wave height, waves break, re-form, and break again. Finally the water moves up as a thin sheet onto the beach.

Breaking waves can form new, smaller waves, which also break as they reach shallower water. Thus, surf zones may have several sets of breakers, depending on wave conditions and bottom configurations.

When waves break, their energy is dissipated, primarily by conversion to heat. If heat from breaking waves were not thoroughly dissipated in large volumes of sea water, surf-zone temperatures would rise appreciably. Breaking waves also generate waves in the solid earth, which are detected (as noise) by seismographs.

(c) Seismic sea wave (tsunamis)

These large waves are generated by sudden movements of the ocean bottom, caused by earthquakes or explosions. These seismic sea waves, called “tsunamis” (a Japanese word meaning harbor waves; pronounced soo-NA-mhees), have wave lengths up to 200 km, periods of 10 – 20 min., and wave heights in the open ocean up to 0.5 meters. Although sometimes called tidal waves, they are unrelated to astronomical tides, which we will discuss later.

In the open sea, seismic sea waves are small and pass unnoticed by ships. When these waves encounter shallow bottom topography they can form enormous breakers. Large loss of life and extensive property damage have resulted from tsunamis. Pacific coastal and island locations are especially vulnerable to these waves. In the past 150 years, the Hawaiian Islands have averaged one seismic sea wave every four years. An international tsunami warning network operates, and warn vulnerable locations that a large earthquake (possibly one that might generate a tsunami) has occurred.

New seismographs installed on the sea floor near especially active earthquake zones will improve tsunami detection and predictions. Also, more powerful computers permit more accurate predictions of wave propagation across ocean basins. The problem is, of course, made worse as coastal populations continue to increase.

(d) Generation of wind waves

We shall address the production of the waves discussed in sections (a) and (b). Gentle winds blowing across a water surface first form small wavelets or ripples, less than 1 cm high with rounded crests and V-shaped troughs. Because the ripples are so small, surface tension, resulting form the mutual attraction of water molecules, influences their shape. These ripples (also called "capillary waves") move with the wind and last for only short periods of time, but they provide much of the wind's grip on water surfaces.

As wind speed increases, small gravity waves form from the ripples and travel in the same direction as the winds that formed them. Wave size depends on wind speed, the length of time it blows in one direction, and the distance (called the "fetch") it has blown across the water (Fig. 7f). In short, the size of wind waves generated depends on the amount of energy imparted by the wind to the water surface.

In a storm, a mixture of waves and ripples, known as a "sea," develops. These waves continue to grow and after the winds die, the waves move away from the generating area and become more regular. Long, regular waves are known as "swell" (Fig. 7f).

Wind waves are classified according to their periods. Ripples have periods of a fraction of a second. Wind waves in fully developed seas (i.e., seas with waves as large as the wind can possibly produce) have periods up to 15 seconds; swells have periods of 5 – 16 seconds. Unlike currents, wind waves are usually not affected by the Coriolis effect.

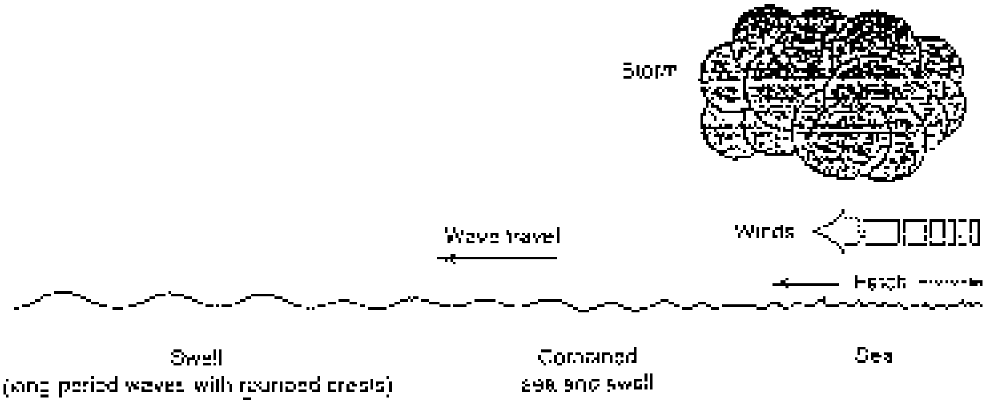


Fig. 7f. Winds in a storm first form areas of short, choppy waves, called seas. As the waves move away from the storm, they develop into waves with longer periods and smooth crests, called swell.

Waves move initially in the same direction as the winds that caused them. Winds from different directions can destroy earlier sets of waves and generate new ones. Little energy is lost by waves as they cross over the deep ocean. Thus, waves continue until they meet an obstacle where their energy is dissipated on a cliff, beach, or breakwater. Waves generated in Antarctic storms have been detected near the Aleutians off Alaska, nearly halfway around the earth.

(e) Stationary waves

In contrast to progressive waves, which move across water surfaces, stationary waves (in which wave forms do not move) occur widely in the ocean; they are also called “seiches” (pronounced say-shees; French for sloshes). They are easily generated in a full, round-bottomed coffee cup by tilting the cup and setting it down on a surface. Viewed from the side, the water surface tilts toward one side and then toward the other. This oscillation of water surfaces is caused by the standing wave you generated. When you spill coffee from a cup you are carrying, the culprit is often a standing wave.

Stationary waves are generated in enclosed water bodies (Fig. 7g) by sudden disturbances, such as storms or sudden changes in atmospheric pressure. Once set in motion, a body of water will oscillate with its period determined by the water depth and the basin length. Eventually, the seiches die out owing to loss of energy through friction of the waters moving along the basin’s edges. Lake Erie has a characteristic seiche with a period of 14.3 hours; that is, every 14.3 hours the lake surface returns to its original position. In Lake Michigan, the characteristic seiche has a period of 6 hours. Because of the earth’s rotation, wave crests in large lakes in the Northern Hemisphere move clockwise around the basins.

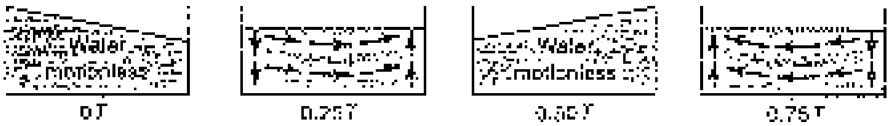


Fig. 7g. Water motions in a simple stationary wave, shown at quarter-period intervals. The cycle shown here repeats itself.

(f) Tides

Among ocean phenomena, tides (periodic rising and falling of sea surfaces) are easy to observe. A firmly anchored pole with marked heights can be used to measure relative heights of the sea surface at frequent intervals, and the rise and fall of the tide can be determined from such data. A simple tide gauge consists of a float connected to a pencil, which draws a tidal curve (a record of sea level over several days) on a paper-covered, clock-driven cylinder. Modern tide gauges measure water pressure at the bottom (this indicates water depths) and record the data for later analysis. Some gauges transmit tidal readings by satellite to a central facility, where the data are analyzed immediately to detect tsunamis.

Although partially understood since antiquity, the astronomic origin of the tides was first explained in detail by Sir Isaac Newton’s (1642-1727) law of gravitational attraction, which states that the attraction between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. In other words, the attraction between bodies increases as the masses of the bodies increase, and decreases as the distance between them increases.

To understand tides, we must consider the gravitational effects of the sun and moon. These two are most important to ocean tides because of the sun's large mass and the moon's nearness to the earth. Newton's theory of gravity can be used to develop and equilibrium tidal model for an idealized, water-covered earth without continents. First, we consider tidal effects caused by the moon alone.

Tides are caused primarily by gravitational attractions among earth, sun and moon. Ocean tides are caused by slight differences along the earth's surface in the gravitational attraction and centrifugal forces between the earth and the moon. The ocean's surface is deformed by these forces into an elliptical envelope and the earth rotates within its deformed water envelope (Fig. 7h). An observer would experience this as the rise and fall of the tides.

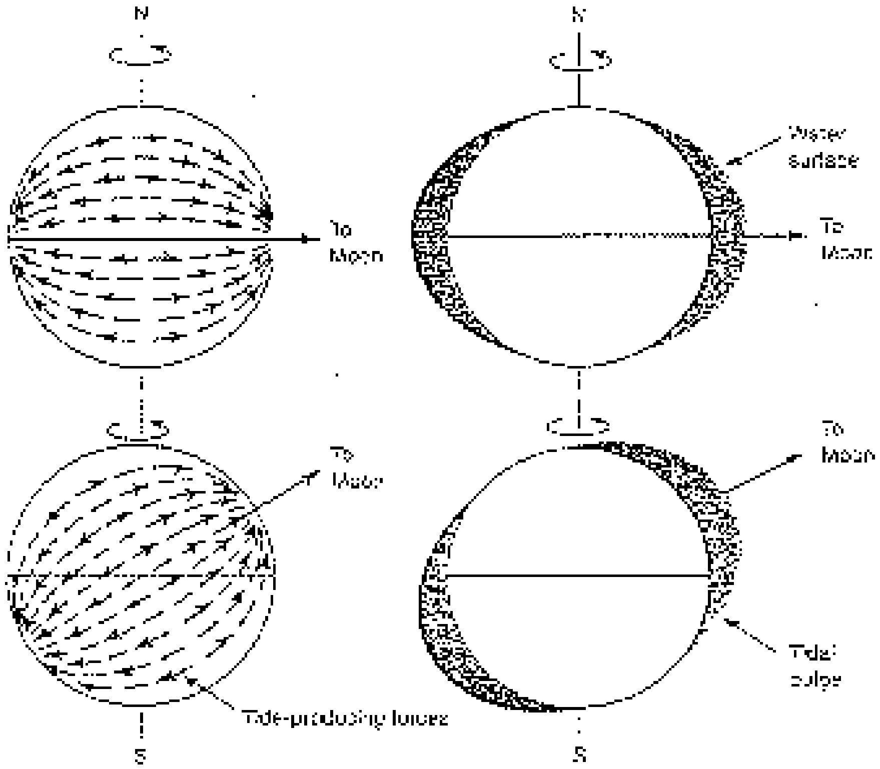


Fig. 7h. Tide-producing forces and the resulting tidal bulges on a water-covered earth with the moon in the plane of the earth's equator (upper) and above the plane of the equator (lower).

On the side of the earth nearest the moon, ocean water is drawn toward the moon because the distance between the two is slightly less than at the earth's center. As a result, the water surface is pulled by gravity, forming a bulge on the side nearest the moon. On the side opposite the moon, a centrifugal force (resulting from the combined earth-moon rotation around an axis) reduces the gravitational attraction. (Note that there is no such centrifugal force on the side closer to the moon because of the side's proximity to the mutual axis of rotation.) The two tidal bulges are areas of high tide, and between them are troughs or areas of low tide (Fig. 7h).

The moon passes over any location once every 24 hours, 50 minutes (one lunar or tidal day). On a water-covered earth, any point passes beneath two tidal crests and two tidal troughs during each tidal day. If the moon remained in the plane of the earth's equator, the two high waters at each location would be equal. However, the moon's position (and associated tidal bulges) shifts 28.5˚ north of the equator to 28.5˚ south of the equator. This changes the relative heights of high and low waters at any point. When the moon is not in the plane of the equator, there will be one high tide and one low tide each day.

The sun also affects tides, but to a lesser degree than the moon does. Interactions between the effects of the sun and moon account for some of the complexity involved in predicting tides. At certain times during the moon's travel around the earth, the sun and moon act together. At these times, the bulges, or crests, are highest, and water levels in the tidal troughs between them are lowest. These are called "spring tides." When the moon is near its first and third quarters, solar and lunar tides partially cancel each other, and daily tidal range is lowest. These tides are called "neap tides."