Lab 5—Convection

9 Questions

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Lab motivation and goals

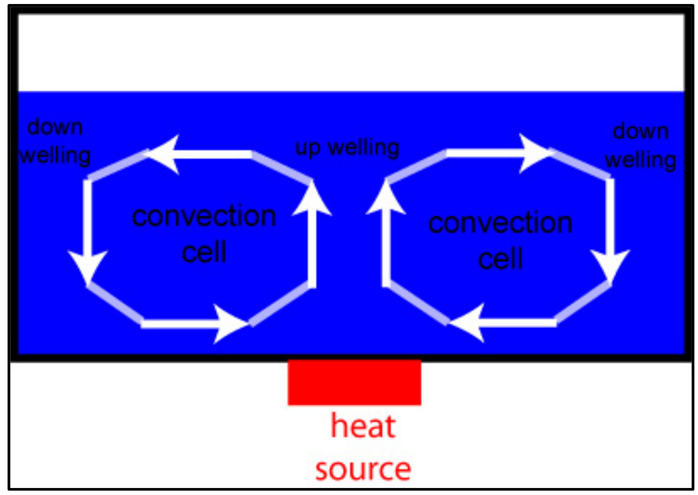
The primary goal of this lab is to explore the process of convection and related behavior for the simple reason that this behavior dominates so many earth system realms from the atmosphere, to the hydrosphere, to the mantle, to the core. It is a primary reason the earth is such a dynamic place. Convection also characterizes the outer shell of the sun, and is common in other planetary bodies. **This lab will focus on recognizing different patterns of convection, understanding what is driving the convection, and learning more about the different earth phenomena in which convection is a dominant factor.** The first part of the lab focuses on developing an understanding of the nature of convection and is a bit like a textbook, while the second part asks you to use what you have learned to recognize patterns of convection in videos or animations of convective behavior. You should spend up to an hour closely reading the first section, so that you can complete the rest of the lab with knowledge and efficiency.

What is convection?

Convection is the **transfer of heat from one place to another by mass movement**. Conduction is also a heat transfer mechanism, but one in which the material is static, and the heat moves through it as a heat wave. Boiling water is an example of vigorous convection. Convection is sometimes represented as behavior only fluids or gases exhibit, but, under the right conditions, substances that are normally considered solids (crystalline aggregates) can convect. The key is that <u>under certain conditions some materials act like a solid on a shorter time frame, but can flow like a fluid on a longer time frame</u>. For our purposes, an important example of convection in a solid is the earth's mantle (more on that later). There are different types of convection which are described below. A major distinction is between <u>buoyancy versus forced convection</u>.

Buoyancy convection occurs because some process (often differential heating) causes density differences at the same level within the fluid. Buoyancy convection is often cast as lighter material rising. However, it could also be cast just as well as heavier material sinking, and displacing the lighter material. A key aspect is that the gravitational attraction (force) at a given horizontal level in the liquid differs due to density differences causing the pressure to differ. Higher densities increase the pressure in that area and lower densities decrease the pressure, and the fluid responds by **moving from the high pressure to the low-pressure area**. Think of lava lamps. This YouTube video provides a 4-minute mini-lecture on buoyancy using the lava lamp example and is well worth viewing if you are unfamiliar with buoyancy and Archimedes principle: https://www.youtube.com/watch?v=DL3Ez9bxMTo

An important component of convection is a convection cell, which can be defined by the path a particle travels as it is involved in the convecting medium. Imagine a localized heat source beneath a fluid as depicted in the diagram below. Above the heat source the fluid becomes a bit hotter, and therefore a bit less dense in comparison to the now denser fluid to the side. Simultaneously, the less dense and hotter fluid rises, while the cooler, denser fluid moves in under it from the sides and a circulation cell is established. If this is in a container, the walls of the container can determine the geometry of the convection cell, but if there are no walls in the vicinity then a significant variety of geometries and patterns of convection cells can develop, especially in three dimensions.



In the figure to the right, two simplified convection cells are shown, induced by a localized heat source. The area above the heat source is an area of upwelling, whereas down welling occurs along the margins. In this example, since the heat source is fixed the position of the convection cells will also be fixed. With water, only slightly different temperature differences are needed to produce convection. This is of course a schematic diagram and the actual paths are more curved and complex as you will see.

Often the upwelling or downwelling areas form either a column (a plume if it is upwelling) or a sheet-like geometry. The sheets can join to form a variety of polygonal geometries. The geometry can be fixed or migrating. The geometry of the "container," depth of the convecting layer, and geometry of the heating/cooling source all play a role in the specific convection geometry. You will have the opportunity to explore some of these different geometries later on in this lab.

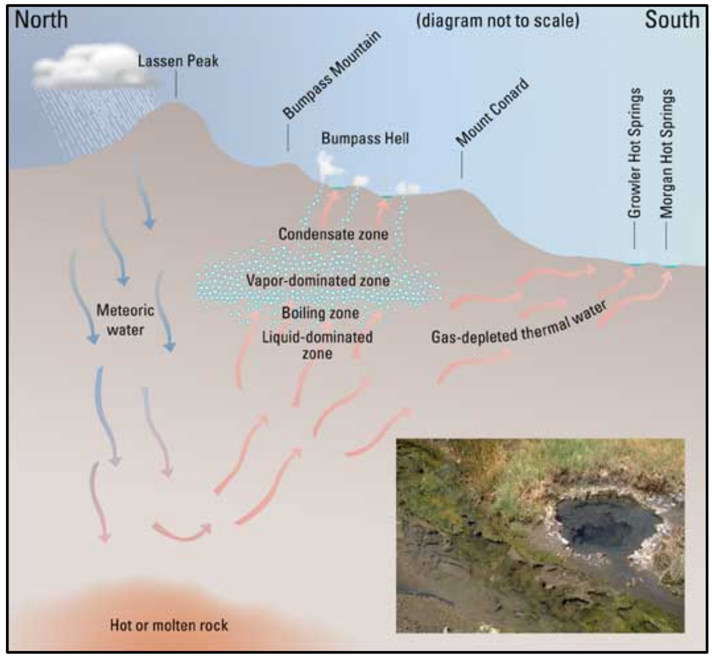
Some possibilities for how temperature differences can be created include: **a) localized heat sources at the bottom, b) even heating from below, c) localized cooling sources at the top, d) even cooling at the top, or d) localized heating from within**. These in turn will produced different convection patterns. Localized heating from below can occur in the atmosphere when some local surface material absorbs more of the sunlight that falls on it (instead of reflecting it), and then reradiates that energy as heat that warms the air above it. This often forms local "thermals" which soaring birds (or gliders) utilize to climb higher. Here's a YouTube video showing examples of small and large thermals in air: https://www.youtube.com/watch?v=Fx90BAxDrMk

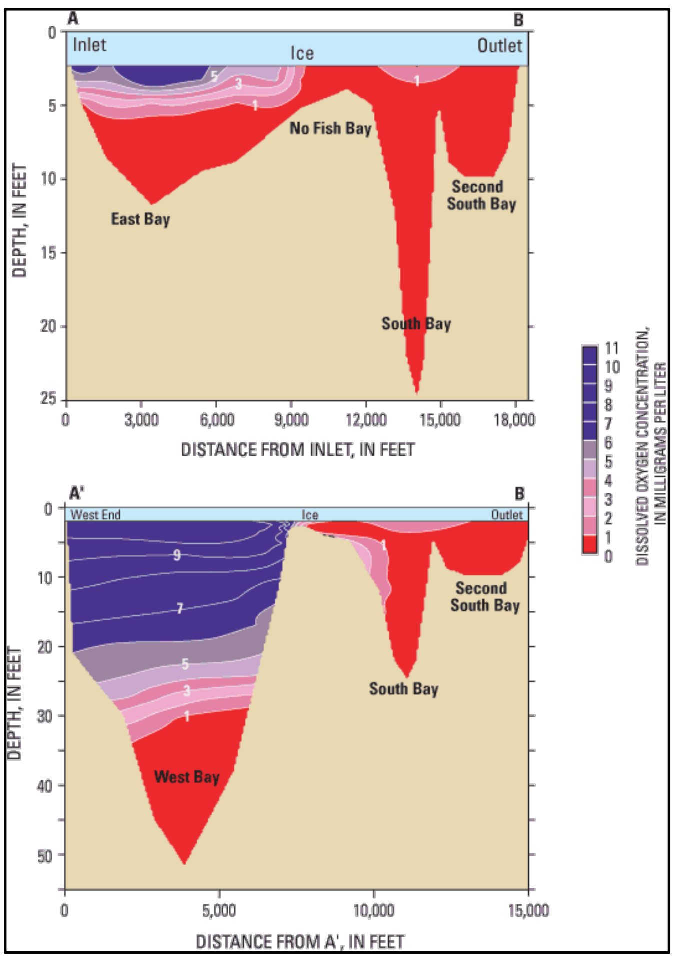
Localized heating can also occur in a body of water where hot springs occur, or in a groundwater system where an intrusion of hot magma has occurred (which can create overlying hot springs at the surface). The latter example results in hydrothermal convection cells in groundwater systems (see the diagram below).

Image to right is of Old Faithful geyser in Yellowstone Park – a surface manifestation of a complex hydrothermal convection system associated with this large volcanic center.
Image source: http://www.usgs.gov/newsroom/article.asp?ID=1954&from=rss#.Vo_STnuDnAo

During the winter, ocean water can be cooled from above by cold Arctic air or even melting sea ice. Since some small part the sun's radiation is absorbed as it passes through the atmosphere, the atmosphere can also be considered as heated from within to some degree. However, more heating occurs at the base of the atmosphere because it is thicker and able to absorb more of the solar radiation. Heating at the base of a convecting medium also occurs inside the earth where heat is leaking out of deeper portions of the earth. Lastly, radioactive material distributed through the earth also causes heating from within, and some materials are richer in the radioactive material than others.

Right: schematic image of a hydrothermal circulation cell beneath Lassen Peak in California that results in surface hot springs. The fluids are primarily moving along a host of fractures in the rock. Image source: [*http://pubs.usgs.gov/fs/2002/fs101-02/*](http://pubs.usgs.gov/fs/2002/fs101-02/)

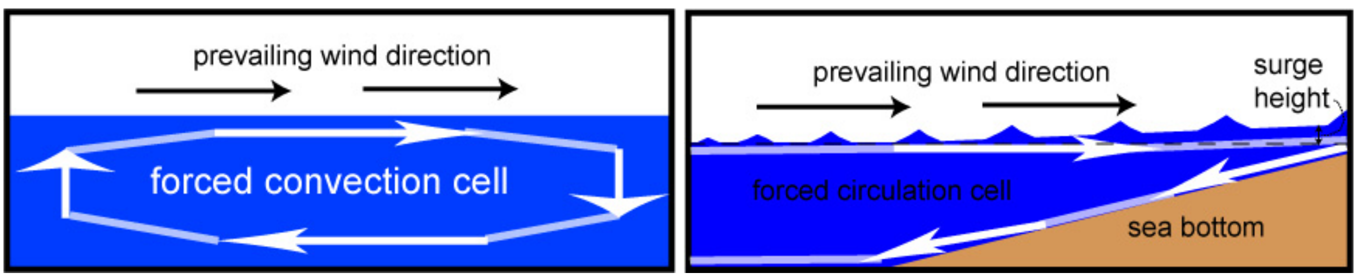




Note that heating from above and cooling from below will actually *inhibit* convection. Why? Because if you heat from above then the upper fluid will be warmer and less dense than that below, and so buoyancy forces will maintain the existing distribution of fluids. Likewise, if you cool from below the fluid at the bottom will gets denser, and again buoyancy keeps the fluids where they are and does not drive movement. Indeed, what will happen is that fluid becomes density stratified with layers of less-dense fluid above the more-dense, a stable situation. Such **density stratification** is commonly seen in lakes and some other bodies of water (oceans), and can serve to inhibit convection. The denser, bottom waters become chemically distinct, depleted in oxygen, because the stable situation seals these waters off from the oxygen-rich atmosphere above. The stratification of water bodies plays an important role in the carbon cycle of the earth by providing a chemical environment wherein carbon can be preserved in sediments.

The image above displays cross sections of a Wisconsin lake showing stratification in the amount of dissolved oxygen in the water. This is in part due to the density stratification and the colder waters at depth that don't interact with the atmosphere, and thus become depleted in oxygen. Naturally, the amount of oxygen influences the biologic activity at that level. Image source: http://pubs.usgs.gov/sir/2005/5071/#N10162

Forced convection is distinctly different from buoyancy convection in that some force, other than density differences, induces movement. It still results in convection since as the material moves, the heat it contains moves with it, but it is not heat-content-related density differences that drive the convection. The simplest example is wind blowing on the water surface which moves the surface water in the direction the wind moves. Through friction the wind induces the water to move. In some cases, the wind can blow so strongly over a lake that it causes it to **overturn**. Overturning occurs when an existing density stratification is destroyed, and the deeper waters come up to the surface, mixing with overlying layers. This can cause the release of hydrogen sulfide from the fetid, oxygen-poor waters that rise from the bottom, resulting in a rotten egg smell. Overturning can cause fish kills by bringing such toxic water to the surface, but the mixing process is also an important mechanism that brings oxygen back to deep waters, allowing organisms to inhabit the deeper areas of the lake. A complex interplay between buoyancy and forced convection can occur in a convecting body. Obviously, prevailing winds on the ocean surface can (and do) play an important role in oceanic circulation.



Diagrams showing the geometry of a simple convection cell expected in a body of water due to a strong prevailing wind direction. The wind can actually mound the water up against a shoreline increasing the pressure in the water underneath and causing a return (offshore) flow that helps maintain the convection cell as long as the wind blows, as shown in the diagram on the right. These dynamics are very important during hurricanes that cause storm surges (which will be explored some in a subsequent lab on coasts), one of the deadliest aspects of a storm.

While density differences due to differential heating/cooling are very common, this is not the only mechanism by which density differences can occur. Convection in the oceans is often described as thermo-haline convection—the thermo- part relates to temperature as described above, but the haline part refers to the salt content. Saltier water is more dense than fresher water, and this produces pressure differences that drive convection. In this way, evaporation can produce denser (saltier) waters that sink. Technically, one could have circulation of water caused by salinity differences where all the water is at the same temperature, which would by definition not qualify as convection (since heat is not being transported). However, in practice the waters vary in their temperature and heat content as well as salinity. It can be thought of as a forced convection component. If you would like more information, a series of videos can be found at the following link that explore convections in different realms: https://www.youtube.com/playlist?list=PLF6E21061FD16AD89

Patterns of convection

One important consideration of a convection pattern is its stability. With buoyancy-driven convection caused by localized heat sources or with forced convection, the pattern is more likely to be stable, with relatively fixed positions of upwelling or downwelling determined by the localized heating or cooling. With more distributed heating from within, the pattern can migrate. This is definitely the case with the atmosphere (think of thunderstorms).

The depth or thickness of the convecting fluid layer plays an important role in determining the convection pattern. In laboratory experiments, really tall or really wide convection cells tend to be unstable, so cells that are roughly as tall as they are wide tend to be more common. This allows you to put some constraints on the depth of the convecting layer if you see the width of a cell at the surface.

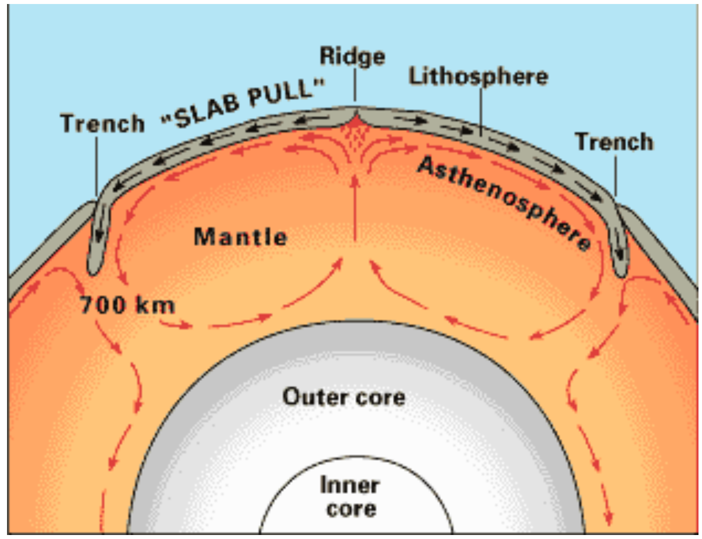
The pattern is also sensitive to both the temperature difference between the base and the top of the convecting layer and the viscosity of the fluid. If you do not remember, viscosity describes the resistance to flow, so that something with lower viscosity flows more easily. The viscosity of water is less than that of honey at the same temperature. More complicated and often shifting patterns develop with lower viscosities and greater temperature contrasts (which are associated with higher rates of heat flow).

In a strongly stratified system, different convection cells can develop in the different layers. There can be some sort of connection between the two because an upwelling in a deeper layer can be thought of as a localized heating element beneath the overlying layer. However, the convection patterns can be different in the two layers. Stratified convection likely occurs inside the earth, with the core representing one layer with its own convection pattern, and the overlying mantle another layer with its pattern. There is believed to be stratification of convection within the mantle also.

Plate tectonics and convection

Abundant evidence has accumulated that the outer shell of the earth is broken up into distinct portions called plates, and that the plates move large horizontal distances with respect to one another. The plates are large – entire continents are embedded in them. The boundaries where plates meet are where much geologic activity, such as earthquakes and volcanism is concentrated. At some plate boundaries the plates are moving apart and new plate material is added to their edges as they diverge. In other places, plates move toward each other and one of the plates sinks back down into the mantle and is recycled in the interior of the earth. In order for the outer shell of the earth to behave in such a fashion, some type of convection has to be happening in the interior.

This is a simple image showing a linkage between plate motions and convection in the underlying mantle. While useful to introduce the basic concepts, we know that in detail the convection pattern is much more complex. For one thing the mantle is stratified into an upper and lower mantle at about 670 km depth. Each mantle layer has distinctly different viscosities, and mantle convection is at least partly stratified into a shallower set of cells, and deeper ones. In addition, the actual pattern is much more *complex than depicted here. Image from USGS site: http://pubs.usgs.gov/gip/dynamic/unanswered.html*



Yet, the interior of the earth is largely solid, made up of minerals such as olivine and pyroxene. We know this from the way it transmits earthquake waves. This raises the question—how can a solid convect? It turns out that **whether a material can be considered a solid or fluid is dependent on the time frame considered**. There are materials that behave as solids over a relatively short time frame, but behave as fluids over a long timeframe, under the same conditions. These materials are called **rheids,** and earth's mantle behaves in this way. The mantle is made out of minerals, solids, but its nature is such that at the temperatures and pressures deep in the earth, this solid can slowly convect at speeds of centimeters per year. As a rheid it has a viscosity, and it is this viscosity that helps determine the rate of plate motions. In a simple fashion we can deduce that places where plates are coming apart are sites of shallow upwelling and places where plates move toward each other are sites of downwelling.

In addition to this there are places like Hawaii where there is concentrated volcanic activity in the middle of a plate. The prevailing explanation is that a rising plume of hotter mantle rock from depth is causing localized melting of the mantle. This molten material rises to feed the volcanic eruptions and growth of the island with time. Interestingly, the presently active volcanic island of Hawaii is at the end of a chain of islands which get older (in terms of when they were volcanically active) as you go to the north. After the islands, the pattern continues as a series of submerged seamounts, which used to be active volcanic islands, but have since sunk and eroded beneath sea level. The thought is that this is a track of how the plate moved over a plume, and this provides an opportunity to gain insight about plate motions and convection, a model which is depicted in the diagram below.

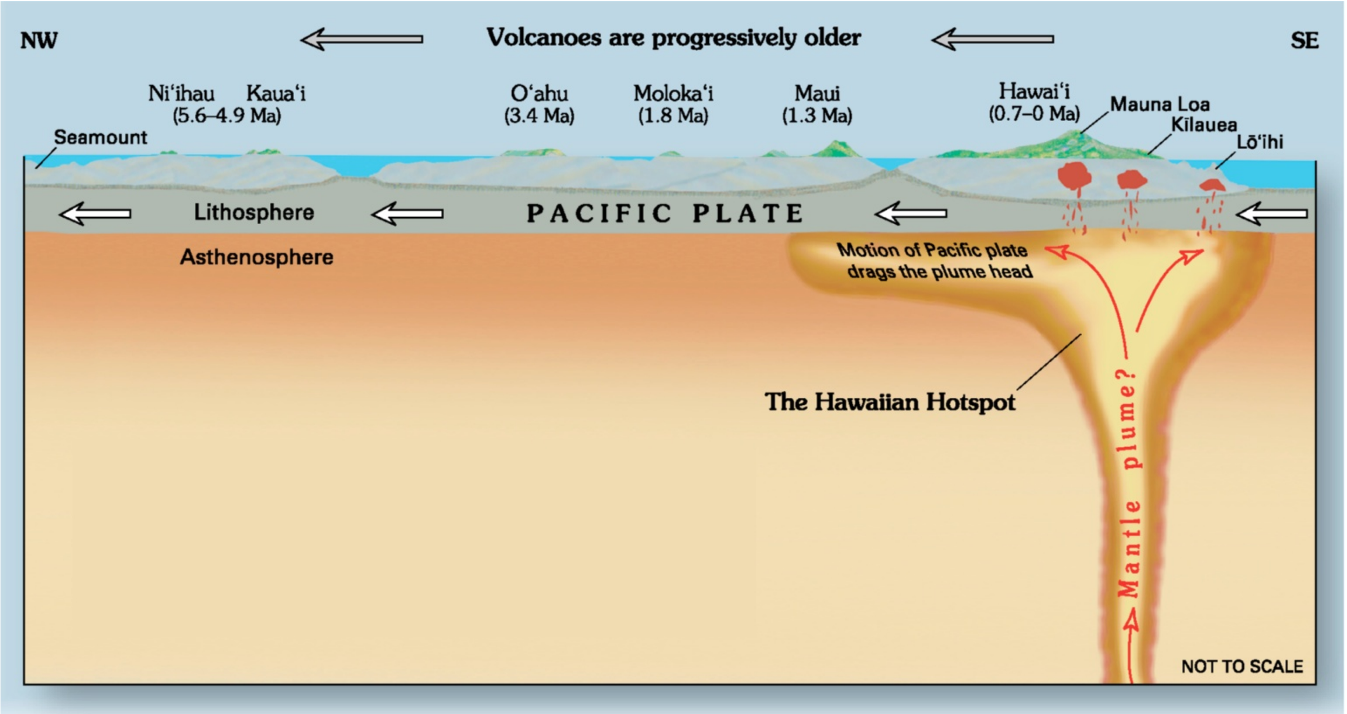


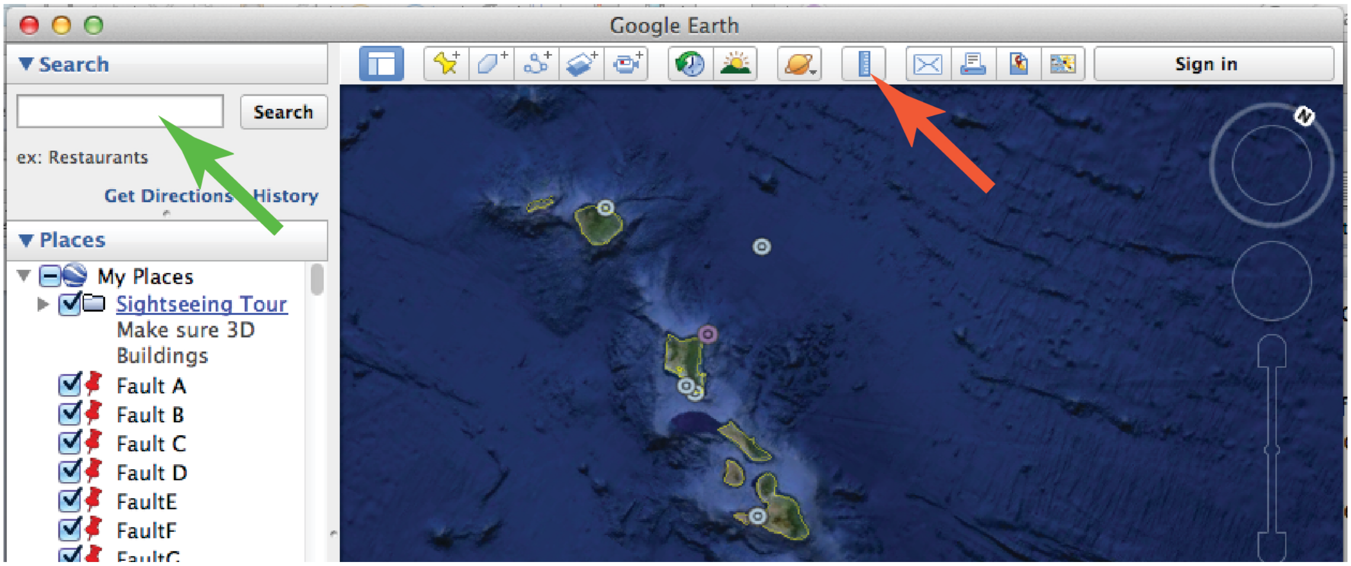
Image depicting when the various volcanic islands in the Hawaiian chain were active and how they were related to an underlying mantle plume. Source of this USGS image: http://upload.wikimedia.org/wikipedia/commons/f/f1/Hawaii_hotspot_cross-sectional_diagram.jpg

The example of this island chain provides an interesting opportunity to gain insight into the speed of relative movement between the hotspot plume and the overlying plate, which you will do. The ages of the islands are indicated in the diagram above. Ma stands for millions of years, so the island of Kauai, for example, is roughly 5 million years old. In our model, at that time Kauai was over the plume and the big island of Hawaii had not yet formed on top of the Pacific plate. All that is needed to get an estimate of the speed of movement is to obtain a distance from Hawaii to Kauai, or between Hawaii and some other island shown above.

Google Earth exercise (2.5 pts)

Choose one of the older islands to the northwest that you are going to use to calculate the rate of movement. Use the software program **Google Earth** to find the distance between your chosen island and the big island of Hawaii using the **ruler tool**. If you have not used Google Earth before take time to familiarize yourself with the program and how it works. This is a wonderful software package and web resource that we will use in several more labs.

There is a small text window in the upper left part of the program window where you can type (or paste) in either the geographic name of a place, or the latitude and longitude coordinates. In this case you can **type in Hawaii and hit the enter button**, and the program will navigate the view screen to that part of the earth. There are a set of navigation icons in the upper right part of the image window that you can use to zoom in and zoom out, change the area of view, or change the view perspective. In the upper menu bar is a ruler icon, which will compute the distance between any two points in the map image that you click on. Note that a new window will open which will give the distance. Use the point roughly (by eye) in the center of each of the Hawaiian Islands that you chose to measure the distance between the two (it will be a bit of an estimate). Obtain this distance **in kilometers**. Remember that the older island was once where Hawaii is now. Then **calculate then rate of movement in centimeters per year (cm/yr):** simply divide the distance the island has moved away from the hotspot by the time it took to move that distance (the age of the island).



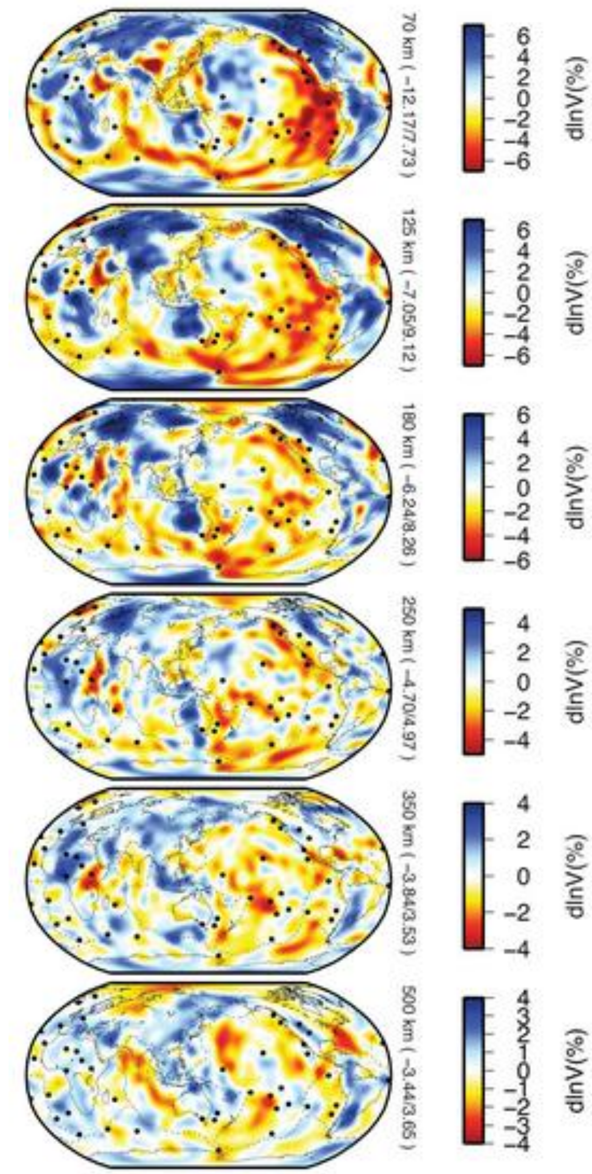
Screen shot of portion of the Google Earth image. The green arrow shows the search box where you can type in a location to navigate to, and the red arrow shows where the ruler tool is.

Question 1: Name of chosen island: **Maui**
Question 2: Distance between Hawaii (main island) and your chosen island in kilometers:
45 kilometers
Question 3: Age of chosen island (from the diagram above):
1.3 million years
Question 4: Relative movement rate in centimeters per year:
(1 kilometer = 100,000 centimeters)
4,500,000 cm/1,300,000= **3.46 cm/yr**

The number you have calculated gives you a minimum estimate of how fast convection occurs within the mantle, which is pretty neat!

As you might guess or infer from the fact that there is relative movement between hot spot plumes and the plates, and from the complicated geometry of plate boundaries on the earth, the convection pattern deep inside the earth (in the mantle) is complex. Indeed, there is ongoing significant debate among geophysicists as to the exact nature of the convection pattern. However, with new techniques of both imaging and modeling the earth's interior we are beginning to unravel part of the story.

The image to the right is quite a complicated one, but it provides some insight into the actual pattern of convection in the earth's mantle. By looking carefully at the seismic (earthquake) waves that pass *through different parts of the mantle scientists can map in three dimensions small differences that reflect the convection. Each of the global maps here is for a given depth starting at 70 km. As a rough guide, the red areas represent slightly hotter areas and are areas of upward movement, while bluer layers represent slightly colder areas and likely reflect downward movement. At the shallower levels the pattern can be directly related to plate boundaries, but less so at depth. The black dots represent the position of hotspot mantle plumes such as Hawaii. Image source: VedLekic, Berkeley Seismological Laboratory, Barbara Romanowicz, Berkeley Seismological Laboratory/IRIS Consortium: http://www.iris.edu/hq/gallery/photo/9168*



Interpreting convection (12.5 pts)

Below is a list of 13 videos on the web that demonstrate various examples of convection.

Choose 5 videos that are fairly different from each other from the list of video selections, and for each write a **mini report** that uses what you have learned in this lab to describe the nature of the convection evident in the video. Your reports will be judged on the basis of what another student could learn from reading your answer. Specific elements to include in your video report are provided below. <u>Due to variation in video content, you won't be able to answer/ address all the questions below – address as many as are pertinent to that specific video. I do look for drawings/illustrations, so please include those.</u> **Please write in paragraph format** (not list format).

a) Clearly indicate which video you are making a report on (title, URL).
b) What is the convecting medium?
c) What is driving the convection (heating from below, cooling from above, internal heat sources)?
d) Is there a forced component and if so what is doing the forcing? If it is forced convection, how is the forcing influencing the convection?

e) What is the pattern of convection (locations of up-welling, locations of down-welling, spoke or sheet geometry, stable or shifting cells, clockwise or counterclockwise motions)? Make a drawing of the pattern. *If you are familiar with and have access to a drawing program (e.g. Inkscape or Adobe Illustrator) you can draw a sketch that describes the patter of convection and insert it into your report. You can also make a sketch on paper, use your phone to take a picture, and then insert that into the document. PowerPoint also has some tools with which you can create your own diagram.*

f) What are the approximate vertical versus horizontal dimensions of any circulation cells involved?

g) What is the approximate speed of convection in units of meters per hour? A simple visual estimate will suffice (e.g. centimeters per minute versus meters per second).

h) Is the convection pattern stable or do the sites of upwelling and down welling migrate or change?

i) If it is a video of a computer or experimental model, describe what natural system it is trying to emulate. If it is not explicit in the video, then suggest a possibility of what natural phenomena it could relate to.

j) Does any stratification exist, and if so what is its character?

k) Is there anything else worth sharing about what the video demonstrated regarding convection?

Address as many of these questions as you can in your report, which should be in paragraph format.

Question 5: Report on first video of your choice: http://www.youtube.com/watch?v=QBVMm9i-pvo

The convecting medium in the experiment is water. The convection is driven by the cooling from above, as the ice melts, the cold, denser water from the melting ice cube sinks to the bottom, moving the warmer water upward. The dye shows a clear pattern of convection as you can see the down-welling current. The vertical dimension is the floating ice to the bottom while the horizontal dimension is the dye spreading at the bottom after it sinks. The convection pattern is stable throughout the video. This video can be used to visualize how the atmosphere works as cold air sinks and warm air rises. There is clear temperature stratification seen in the experiment.

Question 6: Report on second video: http://www.youtube.com/watch?v=vQucpUWV1HM&list=PLE45831F832D17595

The convecting medium in the lava lamp is the liquid, specifically the wax and water-like substance. The convection is driven by heating from below, as the heat from the lamp causes the wax to rise. As the wax cools, it becomes denser and sinks, moving the warmer wax upward. The wax shows a clear pattern of up-welling and down-welling as it cycles through the lamp. The vertical dimension is from the heat source at the bottom to the top of the lamp, while the horizontal dimension is the spread of the wax as it cools at the top. The convection pattern remains stable throughout the video. This can be used to model how magma behaves beneath the Earth's surface, where heated magma rises.

Question 7: Report on third video: https://www.youtube.com/watch?v=pesdbAZO264

The convecting medium in the experimental setup is a mix of silicon, oil and aluminum powder. Convection is driven by heating from below and cooling from above. As it heats you can notice hexagonal convection cells. The vertical dimension is from the heat source at the bottom to the top, while the horizontal dimension is the spread of the cells. The convection pattern remains stable throughout the experiment. This can be used to model how convection occurs in the Sun's outer layers or in any system with similar temperature-driven movements.

Questions 8: Report on fourth video: https://www.youtube.com/watch?v=ueCtAlHXxCU

The convecting medium in this experiment is a collection of steel balls on an inclined plane. The convection is driven by vibration from the wall at a frequency of 20 Hz, as well as weak gravity pulling the spheres toward the wall. The vibrating wall forces the spheres into different phases, such as crystal, turbulent, and convective patterns. The vertical dimension is the height of the plane, and the horizontal dimension is the movement of the spheres. The convection pattern shifts as the amplitude of the vibrations increases. This experiment can be used to model granular convection and gas-solid interactions.

Questions 9: Report on fifth video: https://www.youtube.com/watch?v=suSWBETQzRQ

The convecting medium in this experiment is cooking oil in a heated pan. Convection is driven by heating from below as the pan transfers heat to the oil. The hot areas (represented by the yellow/orange colors) show upwelling, where the heated oil rises, and the cooler areas (purple) depict downwelling, where the cooler oil sinks. After swirling the oil to disrupt the pattern, the convection cells quickly reestablish themselves, showing a clear and consistent upwelling and downwelling motion. The vertical dimension is from the heated bottom of the pan to the surface of the oil, while the horizontal dimension is the hexagonal pattern formed by the convection cells. The convection pattern is stable and reorganizes rapidly after disturbance. This can model convection in fluids, similar to processes seen in our atmosphere or oceans.

List of videos/animations of convection in different systems to construct your reports from:

- Video of green ice cube melting in clear water - http://www.youtube.com/watch?v=QBVMm9i-pvo
- Video of a variety of simple water tank experiments showing a variety of circulation configurations - http://www.youtube.com/watch?v=shaS6q3BUOc
- Lava lamp video - http://www.youtube.com/watch?v=vQucpUWV1HM&list=PLE45831F832D17595
- You-tube time lapse video of growing thunderhead cloud - http://www.youtube.com/watch?v=kapTREk0gXg
- Computer animation of global atmospheric circulation - http://www.youtube.com/watch?v=qh011eAYjAA Much of global atmospheric circulation is driven by convection. That

convection is shaped in a major way by the fact that the earth is also rotating (inducing what is known as the Coriolis effect).

- Infrared cloud image of atmospheric circulation: http://www.youtube.com/watch?v=ikX7SV-y2GE . This is a University of Wisconsin product showing images from the infrared band (which is a function of heat given off by the circulating clouds).
- Computer model of ocean surface temperature changes for the India Ocean - http://www.youtube.com/watch?v=ZVssbK0K4wc . Remember that both prevailing winds and the Coriolis effect (which is how the rotation of the earth influences fluid movement patterns) are at work here.
- Computer model for global ocean surface currents and temperatures - http://www.youtube.com/watch?v=elu5Rm_Tjx4 . For this one you might want to increase the screen to full size. A companion animation for just the Gulf Stream in the North Atlantic can be found at http://www.youtube.com/watch?v=NC-IJozpnl0 .
- Weather in a tank - http://www.youtube.com/playlist?list=PL5FF83BFC4BCD42CE . This sets up convection in a rotating cylindrical tank and allows you to understand a bit about how the earth's rotation influences the convection. Note that there are short clips both from above and from the side, and you should watch from both perspectives. Watching several times will allow you to pick up on details.
- Erta Ale volcano, Ethiopia – lava pond surface - http://www.youtube.com/watch?v=KARzrNa7y_4 . This is rather spectacular footage from a volcano in Africa. You naturally can't see into the lava to see the three-dimensional character of the convection, but you can tell and infer a lot from the surface activity. Focus especially on what happens to the colder (still quite hot) and darker crust on top of the lava. Another shorter video of the same lava pond: http://www.youtube.com/watch?v=PZjPGdXMMso
- Actual images of solar convection and an experimental set-up using aluminum powder in silicon oil: https://www.youtube.com/watch?v=pesdbAZO264 .
- Pattern in cooking oil made visible with an infrared camera: https://www.youtube.com/watch?v=suSWBETQzRQ . Note in this video that they swirl the pan of oil to disturb the pattern so that you can watch how it reestablishes itself. The hot colors are hotter areas of upwelling, and the colder colors are areas of downwelling.
- Convection in granular material (metal balls): https://www.youtube.com/watch?v=ueCtAIHXxCU Read the support material carefully. By vibrating the bottom faster and faster they are stimulating heating from below and you can 'see' what is happening at an atomic level on our macro level.

Please let us know if any of these links do not work so that we can update them (thanks).