From Climate Change to Ice Ages and Dynamics of the Earth

Global warming and especially sea level change strongly affect the environment and human society. In order to better monitor climate and sea level change, we need to have a good understanding of the enduring effects of the last Ice Age, which includes changes in global sea level, earth’s gravity field, rotational motion and earthquakes. Fortunately, with recent advancement of satellite technology, we are beginning to unravel the mysteries of the last Ice Age and its link to recent global warming. This article describes the effects of the last Ice Age on the dynamics of the earth and the link to global warming.

Last year (2007) the Intergovernmental Panel on Climate Change or IPCC released its Fourth report. The key point in this IPCC report is that global warming is real and greenhouse gases have increased markedly as a result of human activities. The current rate of warming is found to be about 0.7 degrees Celsius per century globally. However, depending on the world’s fossil fuel consumption, the global temperature increase over this century is predicted to be between 1.1 to 6.4 degrees Celsius. These numbers are just the globally averaged temperature changes, local temperature increase is expected to be much higher and the range of seasonal highs and lows in temperature would also widen. In fact, IPCC warned that global warming would lead to more extreme weather patterns. For example, there would be severe drought at one place, but severe flooding elsewhere. There will be more intense heat waves but at the same time more chilling cold spells. The number of cyclones and their intensity are also expected to increase, with storm tracks and jet streams moving further pole-wards. Recently weather satellites have confirmed that the tropics are indeed expanding pole-wards and getting larger. This means that subtropical deserts are expanding into the heavily populated mid-latitudes, putting stress on our food and water supply and thus our economy. The expansion of deserts and the loss of habitat for animals and plants may also lead to their extinction! The changing climate and the expansion of the tropics is also accompanied by the spread of diseases!

Another hazard of global warming is from the rise in global sea levels. Since more than two-thirds of the world’s largest cities lie near the coast, global sea level rise makes them vulnerable to flooding. For example, if sea level rises by 1 meter, then about half of
Bangladesh would be submerged by water and a hundred million people around the globe would be displaced. To make matter worse, sea level rise also leads to coastal erosion: a meter rise in sea level can cause more than a hundred meters of retreat in shoreline. Thus it is important to know the rate of global sea level rise. Fortunately, instruments for measuring tides have been deployed around the globe more than sixty years ago. This long record from tide gauges have shown that mean sea level rises at a rate of about 1.8 millimeters per year relative to land (see figure on the right). Similar information is also available from the TOPEX/Poseidon and Jason sea surface altimetry satellites, which measure the height of the sea relative to the center of the Earth for the last decade or so. The globally averaged rate of sea level rise from satellite altimetry is significantly higher, at approximately 3 millimeters per year (see figure above). This implies that the rate of sea-level rise is accelerating - an inference that is supported by the recently observed rapid ice movement in Antarctica and Greenland and the rapid disintegration of ice shelves. Taking this acceleration into account, Rahmstorf and colleagues proposed that global sea level may rise by 1.4 meters by the year 2100 which is three times that predicted by IPCC!

To understand the difficulty of measuring sea level rise, we need to understand what are the contributions: Warming of the surface sea water causes it to expand thermally and therefore partly contributes to the rise in global sea level. In addition, the melting and shrinkage of land ice, glaciers and snow coverage add water to the oceans, further causing global sea level to rise. Another important contribution is from the deformation of the ocean floor and the changes in the Earth’s gravity field due to a process called
“glacial isostatic adjustment” or equivalently “postglacial rebound”. In the following, I will explain what these terms mean and discuss some of their effects.

What is “glacial isostatic adjustment”? During the last ice age, much of northern Eurasia, North America, Greenland and Antarctica were covered by extensive ice sheets. The ice was as thick as three kilometers during the last glacial maximum about 20,000 years ago. Three kilometers is more than five times the height of the tallest building today! The enormous weight of this ice caused the surface of the Earth to deform under the ice load, forcing the “fluid” mantle rocks to flow away from the loaded area (see cartoon). At the end of the ice age when the glaciers retreated, the removal of the weight from the depressed land led to uplift or rebound of the land and the return flow of mantle rocks back under the deglaciated area. This is much like pressing your thumb on a basketball – your thumb creates a depression underneath but a “peripheral bulge” around because the air displaced under your thumb flow to form the surrounding bulge. As you release your thumb, the depressed part of the ball rebounds but the peripheral bulge subside so that the ball recovers its original shape. However, due to the extreme viscosity of the mantle, the recovery process on Earth takes many thousands of years.

Since the glacial isostatic adjustment process causes the land to move relative to the sea, ancient shorelines are found to lie above present day sea level in
areas that was once glaciated. On the other hand, places which was uplifted during glaciation now begins to subside. Therefore ancient beaches are found below present day sea level in the bulge area (see cartoon). The “relative sea level data”, which consists of height and age measurements of the ancient beaches around the world, tells us that glacial isostatic adjustment proceeded at a higher rate near the end of deglaciation nine thousand years ago than today. The current uplift rate has been accurately measured by the GPS or Global Positioning System. The glacial isostatic adjustment process is most obvious in northern Europe and Canada where the rate of land rebound today can exceed 10 millimeters per year – a rate comparable to the growth of your fingernails. This land uplift caused Nordic ports to relocate their harbors several times in the past centuries in order to reach the sea and an arm of the Baltic Sea became a freshwater lake in Sweden. The land uplift also causes the north side of the Great Lakes in North America to tilt upwards relative to their south shore resulting in a southward flow of lake water. In the same way, glacial isostatic adjustment affects water drainage of lakes and rivers and thus agriculture.

The glacial isostatic adjustment process also affects global sea levels. The ice sheets at the last Glacial Maximum was so massive that global sea level fell by about 120 meters. Thus continental shelves became exposed and many islands became connected with the continents through dry land. This is the case between the British Isles and Europe, between Hong Kong, Taiwan, the Indonesian islands and Asia and also between Siberia and Alaska. This allowed people and animals to migrate through the land-bridges during the last glacial maximum (see picture above).
The draining of fresh, melted ice-water into the oceans during deglaciation can also slow down and can even shut down the so called thermohaline circulation in the oceans. Currently northern Europe and Greenland is warmed by the Gulf Stream, thus the slowing or shut down of the ocean circulations could result in rapid cooling of the polar regions. Some scientists even believe that in this way, global warming can bring in the next ice age!

During deglaciation, the melted ice water return to the oceans thus sea level increases again. However, geological records of sea level changes show that the redistribution of the melted ice water is not the same everywhere in the oceans - depending upon the location, the rise in sea level at a certain site may be more than that at another site. This is due to the gravitational attraction between the mass of the melted water and the other masses such as remaining ice sheets, glaciers, water masses and mantle rocks.

Ice, water and mantle rocks have mass, and as they move around, they exert a gravitational pull of other masses towards them. Thus, Earth’s gravity field, which is sensitive to all mass on the surface and within the Earth, will become affected by the redistribution of ice and melted water on the surface of the Earth and the flow of mantle rocks within.

Today, more than six thousand years after the last deglaciation terminated, the flow of mantle rocks back to the glaciated area causes the overall shape of the Earth to become less oblate. With the launch of the pair of GRACE twins satellites in 2002, (see picture on left) the changes in Earth’s gravity field has been measured with unprecedented precision and promises to give us better understanding of the last ice age and current global warming.
The long-term rotational motion of the Earth is affected by the tidal interaction between the moon and the earth (see picture on the right) and also by the glacial isostatic adjustment process. To understand how the latter affects Earth’s rotational rate, we note that the movement of mass on and beneath the Earth's surface affects the Moment of Inertia of the Earth. So by a well known physical principle call the Conservation of Angular Momentum, the rotational motion must also change. This is illustrated in the case of a rotating ice skater: as she pulls in her arms, her moment of inertia decreases and as a consequence, she rotates faster. On the other hand, as she extends her arms, her moment of inertia increases and her spin slows down. Likewise, after the end of deglaciation, the dominant mass movement is from the return flow of the mantle rocks back to the glaciated areas at high latitudes, making the shape of the Earth less oblate, thus the rotation rate of the Earth increases today. The increase in Earth's rotation rate due to glacial isostatic adjustment alone causes the length of day to decrease by about 0.7 milli-seconds per century. The changes in the oblateness of the Earth also affects the orbital motion of artificial satellites and was first determined by the LAGEOS satellite in the 1980s.
In addition to the changes in the Earth's rotational rate, the changes in the Moment of Inertia due to Glacial Isostatic Adjustment also cause the rotational axis to move from the current position near the North Pole towards the center of the ice masses at glacial maximum, thus it is moving towards eastern Canada at a rate of about 1 degree per million year (see picture on right). This drift of the Earth's rotational axis in turn affects the centrifugal potential on the surface of the earth and thus also affects sea level changes.

According to the theory of Plate Tectonics, plate-plate interaction results in earthquakes near plate boundaries. However, large earthquakes are found in deglaciated areas in eastern Canada (see figure on the right) and northern Europe which are far from present-day plate boundaries. Recent
studies found that large glacial loads generally suppress earthquakes, but rapid deglaciation promotes earthquakes. The rebound stress that is available to trigger earthquakes today is of the order of 1 MPa. This stress level is not large enough to rupture intact rocks but is large enough to reactive pre-existing faults that are close to failure. Thus, both glacial isostatic adjustment and past tectonics play important roles in today's earthquakes in eastern Canada and southeast USA, including the magnitude 8 New Madrid earthquakes of 1811.

Finally, studies of the glacial isostatic adjustment process give us information about how fast mantle rocks flow, how thick past ice sheets were and how ice thickness changed in the past. The study of mantle flow is important to our understanding of plate tectonics, mantle dynamics and the thermal evolution of the Earth. Ice thickness history is important to the study of glaciology, paleoclimate and changes in global sea level. But for global warming and sea level change studies, understanding glacial isostatic adjustment is crucial to our ability to monitor recent global change more accurately! Thanks to recent advances in satellite technology, this goal can probably be reached in the next few years!