Tipping Points, Thresholds, Triggers, and Abrupt Climate Change

Tipping points, thresholds and abrupt changes - these are the wildcards in climate change, or in any environment. They describe the rapid transition in an environment or ecosystem from one stable state to another. These stable states are common in all ecosystems, and most, if not all ecosystems have more than one stable state. Everything from the microclimate around a single clump of grass in the desert to our entire planet can be considered an ecosystem and they all have different states that can be triggered or initiated based on some criteria, often the concentration of a single thing in an ecosystem, like nitrogen (a common plant nutrient).

The Earth's environment is the most complicated of all ecosystems, so let's consider a smaller ecosystem to understand how some tipping points work. The microclimate around a single clump of desert grass is a good place to start. In the Chihuahuan Desert of west Texas and Mexico and species of grass called chino grass often forms clumps from a foot or two in diameter to tens of feet in diameter. Surrounding these clumps is nearly bare desert gravel with scattered cactus for hundreds of feet in all directions. Not everyone knows that a single clump of grass can be an entire ecosystem, but it certainly can in these cases. There are numerous species of plants and animals that can live in, on and under this micro ecosystem. The grass creates a cool shady area with extra organic material in the soil. These things allow different and more animals and other plants to live in and around this microclimate than otherwise live in the more sterile desert that surrounds the clump of grass. Many species of young plants can only live in the shade of other plants. These plants are themselves host to other insects and animals broadening the diversity of the grass clump ecosystem

The extra organic material in the soil allows different worms and beetles and most importantly the soil microorganisms to flourish, where just a few feet, or even a few inches away, the relatively sterile desert hosts a completely different, and much less diverse assemblage of creatures.

The Desert Grasshopper Mouse: At the top of the micro ecosystem is a little carnivore – the desert grasshopper mouse. Yet all of these creatures, including birds that oftenest in the grass, can be virtually eliminated when a cow or two come along and rip the grass cluster out of the ground by the roots. Cows are actually quite efficient at doing this and are in fact responsible for the extreme desert-like appearance of much of the deserts in the southwest. This is an example of a mechanical trigger. Remove the major support entity of the ecosystem and even though all of the insects, and the mice and birds and soil microorganisms remain, they lose their shade and either flee or fry.

An example of an abrupt climate change caused by a mechanical trigger of the Earths ecosystem is a catastrophically disintegrating ice sheet. We know that ice sheets have catastrophically disintegrated in the past and that sea level has risen up to 16 feet per century for multiple centuries in a row because of catastrophically disintegrating ice sheets. Sixteen feet per century is an average of over a foot and a half per decade, whereas in the twentieth century, sea level has risen only 7 to 8 inches. In the last 2,000 to 3,000 years, sea level has changed relatively little.

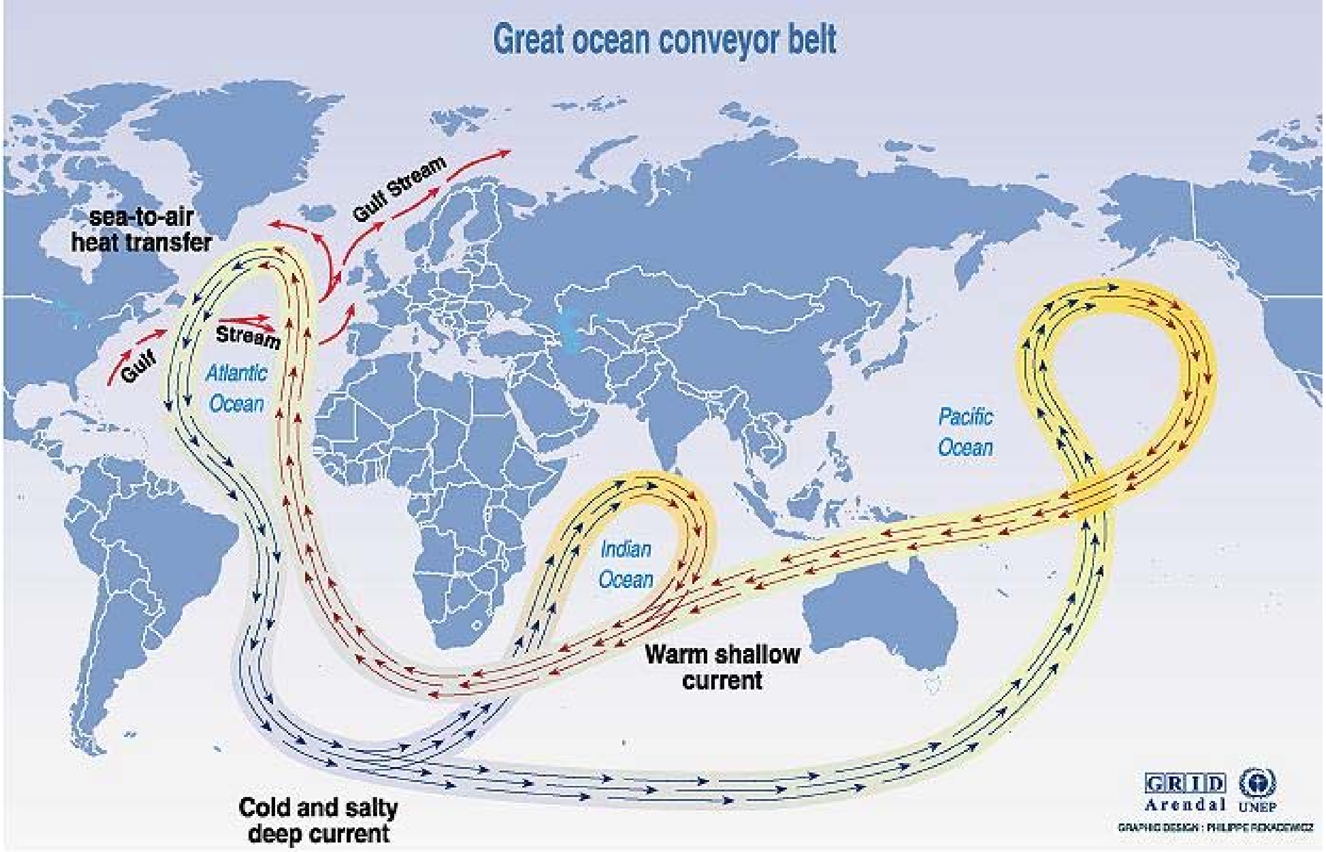
During these catastrophic ice sheet collapses, we see extensive marine deposition of sands, gravels and boulders thousands of miles away from their points of origin, Geologist can these tell materials came from Northern North America and were transported completely across the ocean to near Europe in the North central Atlantic. These materials were transported in and on vast fleets of icebergs during periods that have been labeled Hienrich events by their discoverer Halmut Heinrich.

Iceberg Armadas: Six times since about 60,000 years ago, armadas of possibly millions of icebergs have set off across the Atlantic from the Laurentide Ice Sheet – the great ice sheet of North America. They were released from the great ice sheet by mechanisms still under hypothesis over periods of two or three centuries each time. They left a vast layer of sands and gravels on the floor of the North Atlantic, completely different from typical ocean sediments, as much as 8 inches deep, as far away as the eastern North Atlantic, and nearly two feet thick closer to North America.

These iceberg armadas could have been caused by temperature variations during the last ice age, or changes in precipitation patterns, or other more complicated things. More snow could have caused destabilization of the ice rivers that drained the ice sheet; or periodic warming could have lubricated the path of the ice sheet to the ocean with meltwater; or a natural binge/purge cycle, where ice shelves build up over long periods then disintegrate over short periods could be the culprit – or all of the above. In the wake of these vast armadas of hundreds of thousands or millions of icebergs, huge quantities of fresh, non salty meltwater are delivered to the ocean.

Thermohaline Shutdown Trigger: The thermohaline circulation is a global extension of the Gulf Stream. The Gulf Stream is what keeps northern Europe as warm as Southern New England. What The Gulf Stream is warm ocean waters flowing north from the tropics. The further north it gets, the cooler it gets, and the more water evaporates from the current leaving colder saltier water. If it weren't for the Gulf Stream, northern Europe would be as cold (or colder) than similar latitudes around the globe. Ireland for example, is the same latitude as the middle of Hudson Bay in Canada. Central Norway is the same latitude as Iceland and the great ice sheet of Greenland.

Basically, the colder and saltier water gets, the denser, or heavier it gets. By the time the Gulf stream reaches the British Islands, some of it is so dense that it starts to sink. The further north the current flows, the more it sinks until finally, north of the North Atlantic, off the coast of Norway where the Gulf Stream meets the Barents Sea, all of the Gulf Stream has sunk into the depths. The sinking water has to go somewhere. What it does is to flow south at great depths This is the beginning of the thermohaline circulation – a great oceanic circulation that flows along the bottom of the oceans from the Atlantic around Africa and Australia to the central Pacific off of Japan, then returns to the tropical Atlantic on the surface along roughly the same path where it repeats the Gulf Stream segment, warming Europe and the Northeast coast of America with all of the heat it transports. Amazingly, this circulation can take 1,000 years to complete one loop.



Source: Broecker, 1991, in Climate change 1995, Impacts, adaptations and mitigation of climate change: scientific-technical analyses, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 1996.

So the iceberg armadas in the North Atlantic release a vast amount of fresh water into the salt water of the North Atlantic. Geologic evidence also tells us that the armadas are often accompanied by great flows of fresh meltwater from the North American Ice Sheet. All of this fresh water lowers the salinity of the North Atlantic. This is the trigger, the climate threshold that must be passed, the tipping point in the climate system. The thermohaline circulation relies on dense cold salty water to sink in the far, far North Atlantic.

The fresh water released by the iceberg events is much less dense than the warm salty waters flowing north from the subtropical Atlantic and Gulf of Mexico, and it doesn't sink. The Thermohaline circulation is shut down, or at least significantly slowed. This allows "normal" cold to penetrate far south into Europe. Ice core climate records indicates that these events could have had a global affect and temperature changes could have been lowered by a global average of as much as 7 to 9 degrees F.

Dynamical Ice Sheet Disintegration: This is a very scary and very real mechanism by which ice shelves can disintegrate and is likely to have been involved with Heinrich events. The textbook example, the best observed and explained (and largest) ice shelf to disintegrate in modern times, is the Larson B ice shelf in Antarctica.

In 2002, the Larsen Ice Shelf had been showing stress for two years. A warming atmosphere and warming ocean currents were taking their toll. The ice shelf was as large as Rhode Island and over 700 feet thick.

This is the calving of an iceberg nearly a half mile long. The ice front, or end of the glacier, is shown to be 250 feet high.
Image Credit: Jason Amundson, University of Fairbanks, Alaska

The Larsen B was a floating ice shelf and didn't have a significant impact on sea level through it's disintegration. But several other mechanisms involved with ice shelf disintegration could have impacts on sea level. The upstream inland ice sheet ice is of major importance here. After the disintegration of the Larsen B, the glaciers feeding the ice cap from the ice sheet were suddenly free to flow. Their speed increased in some instances by as much as eight times.

The increased fresh water represented by the disintegrated glacial ice has effects already illustrated in impacts to sinking waters and ocean currents. The Antarctic is a significant source of current drivers as well as the North Atlantic. These ocean current drivers are called deep water formation areas. When salt water freezes, it expels much of its salt. This salt adds to the density of the cooling waters in the freezing areas that are already increasing in density because of their falling temperature. This added density helps assure that these waters sink. This sinking is what keeps ocean currents flowing. As the denser waters are forced to sink by their density, other water must come from somewhere to replace these waters and ocean currents are born. These sinking waters are then called “deep waters” and are one of the most important parts of our planet’s climate system.

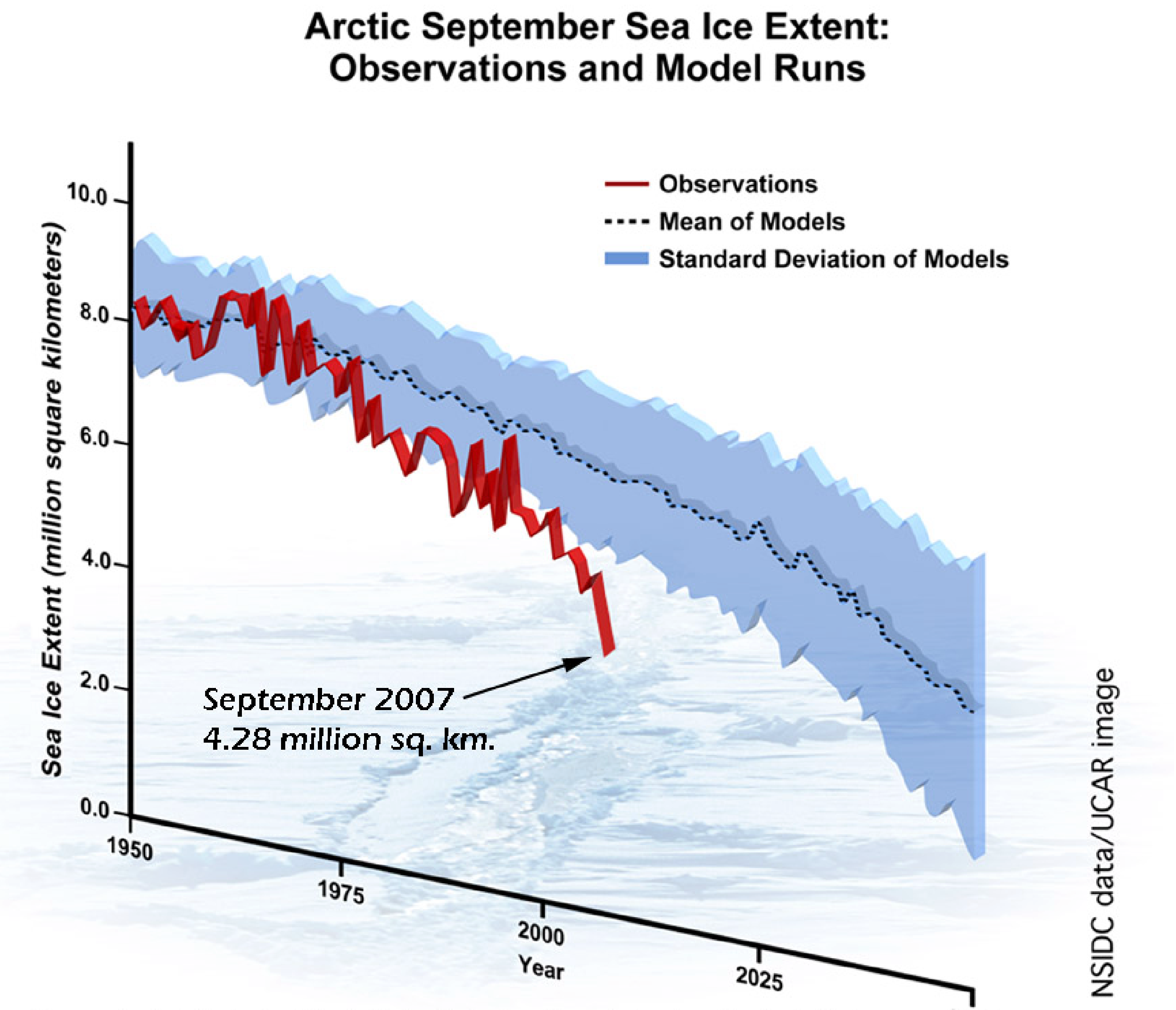
When an ice shelf disintegrates, the resulting icebergs and bergy bits melt much more rapidly than the much, much larger ice shelf because so much more ice is exposed to seawater from the millions of pieces from the disintegration. The fresh water influx, in enough quantity, will alter the formation of deep water and subsequently alter the ocean currents. As our climate warms, and ocean current dynamics change, ice sheet disintegration on this scale could impact the ocean currents. Larger events have an even greater opportunity to impact the currents.

Antarctica is ringed with ice shelves ranging in size from a fraction the size of the Larsen B to the West Antarctic Ice Sheet, the size of Mexico. To give some sort of perspective to the risk of ice shelf disintegration, the Larsen B has very likely not disintegrated in previously in 100,000 years or more, making this event unprecedented in the last 100,000 years.

Artic Sea Ice Threshold: Arctic summer sea ice exists with a very important feedback that could lead to abrupt changes. This feedback mechanism is albedo, or the reflectivity of ice. Ice reflects up to 90% of the heat from the sun. Water absorbs up to 90% of the heat from the sun. This is an 8 fold difference in energy between the two systems. As ice melts, the change in energy going into the environment is like the difference between a cool breeze in the shade in the rocky mountains and the inside of a black car with the windows rolled up in the Texas desert. With this much more energy going into the environment we start seeing ice extents records shattered like the one in the Arctic at the end of the summer melt season in 2007.

Ice still forms in the Arctic in the wintertime, but all of that extra heat is still in the Arctic ocean. The ice is thinner, and melts sooner when the sun comes back. This leads to even more warming in the environment in this feedback loop. The ice melts faster and faster as more and more energy is absorbed by more and more open water until one season there is no more ice. When the ice is gone, all of that energy that went into melting the ice must go somewhere. It goes into the atmosphere and warms the rest of the planet.

Another feedback is rapidly released with diminishing Arctic sea ice, and this is water vapor. As the sea ice melts earlier every season, more water is open for a longer time each year. Open water can contribute much more water vapor into the atmosphere than ice, and water vapor is an even stronger greenhouse gas than carbon dioxide.



Stroeve, et. al., Arctic Sea Ice Extenet: Decline Faster than Forecast, American Geophysical Letters, Volume 34, February 2006 (2006 data)
Updated with 2007 data by Bruce Melton, October 2007
National Snow and Ice Data Center (NSIDC),
University Corporation for Atmospheric Research (UCAR)

The tipping point in Arctic sea ice has likely passed. Half of the climate models used in the IPCC climate scenarios predict a sea-ice free Arctic within this century. The National snow and Ice Data Center projects an ice free arctic by the year 2020. The US Naval Ice Prediction Program projects an ice free Arctic by the year 2013.

Permafrost Melt: The Arctic has already warmed 4 to 7 degrees F. An estimated 14% of the World's carbon is stored in Arctic permafrost. Twenty-three percent of the Earth's land mass in the northern hemisphere is covered in permafrost. That's 10.1 million square miles or 6.5 billion acres, most of it in the Northern Hemisphere. If your kitchen floor were the Earth's land surface, one out of five of those square floor tiles would be permafrost.

This bog, outside of Fairbanks, was a normal forest just a few years ago. Melting permafrost is creating lakes like this all across the Arctic and Sub Arctic.

The carbon in permafrost is in the form of frozen and partially decomposed plant materials buried in the permafrost creation process in the northern tundra. What happens is that for 10 to 14 weeks a summer season (the growing season above the Arctic Circle) plant matter in the tundra actively grows. It lives atop the permafrost in what is called an "active layer". This active layer is composed mostly of partially decomposed plant material (dead tundra mosses and herbaceous plants and completely decomposed plant material in the form of soil).

The active layer is just inches to at the most a few feet thick and is almost always near saturation because of the permafrost below, and is quite spongy and full of air. As the permafrost plants grow (which can often be measured in fractions of an inch per year), the depth of the active layer stays relatively the same, so these deep spongy mats of moss like plants tend to get frozen into the permafrost before they completely break down. This is how permafrost has formed for 100s of thousands of years. There have been very few periods in the last 3 million years on Earth, when temperatures have been warmer than today, that would allow greater permafrost melting than is occurring today.

AS the permafrost formed, winter season ice tended to push the partially rotting vegetation further down into the permafrost where it stayed in the deep freezer, totally preserved, until now. Permafrost can be up to 4,000 feet thick and up 70% water. Permafrost over 2,000 feet thick can be 750,000 years old.

This is called a drunken forest. These trees lean because the permafrost beneath their roots is melting.

The temperature of permafrost at depths greater than 20 to 30 feet is surprisingly stable, and the relationship between average annual temperature, heat energy from the Earth's interior and thermodynamic physics allows a fairly accurate analysis of climate change from temperatures encountered in boreholes in permafrost. Oil well boreholes in the Alaskan Arctic were analyzed in the mid 1980s and it was found that there had been 3 to 7 degrees Fahrenheit of warming in the permafrost in the last several decades to a century. In 2003 the same boreholes were evaluated again and it was found that an additional 5 degrees Fahrenheit of warming had occurred in the permafrost showing there likely has been significant acceleration of the warming of permafrost in northern Alaska. This trend is shown to be similar in many other areas of the Arctic.

Two things can happen when permafrost melts. Either a lake forms, or the melt water drains away. When the melt water drains away, it can play a part in the freshening of the ocean and formation of deepwater in the North Atlantic affecting the thermohaline circulation. The partially decomposed plants in the permafrost, once thawed, complete their decomposition cycle, releasing carbon into the atmosphere in the form of carbon dioxide and methane.

If a lake forms, the decomposition process proceeds under anaerobic conditions, in other words, there is no, or little oxygen involved in the process. Subsequently there is a much greater output of methane (methane has 23 times the global warming effect than does carbon dioxide). The greenhouse gasses emitted from the melting permafrost adds more heat to the environment through the greenhouse effect, which creates more permafrost melt. This is a climate tipping point that once started is irreversible. As we see from the reanalysis of the oil well bore holes, the rate of temperature increase is rising very rapidly, approximately doubling the temperate increase assumptions derived in the initial study.

As the permafrost melts and the soils drain, larger vegetation grows, generally conifer forests. These forest have an additional warming feedback of their own as it is more difficult for snow to stick to a conifer, so it reflects less and absorbs more heat than snow – much more heat. Vegetation absorbs 60% to 70% of the suns energy. This energy stays in the ecosystem and melts snow. Snowmelt is earlier, so more energy can then be absorbed by the ground and put to work melting more permafrost and releasing more carbon dioxide and methane.

Implications of the decomposition of this extraordinary amount of carbon, and the effects of the discharge of a likewise extraordinary amount of water into our northern oceans are still poorly understood. What is fairly well understood however is that during the paleistory of this planet, permafrost coverage during periods as warm as are projected by the IPCC were 40 to 60% less than exists today. The possible high rate of these changes, and especially the implications of CO2 and CH4 discharge into the atmosphere are what are most troublesome.

These are drunken power poles. Permafrost melt does not discriminate.

Forest Die-off:

Climate change is difficult for many plant species. Pine, Spruce and Fir trees all have their invasive pests that take advantage of trees in distress because of climate change. Bark beetles are the worst. They attack when trees are weakest, during drought. Drought is in many areas a common part of climate change. When trees are in stress because of drought, they produce less sap and sap less sap is just what a bark beetle wants to see because, it’s the sap that pushes the bark beetle out of it’s burrow and keeps the tree healthy.

Another significant climate change effect that enhances bark beetles infestations is the lack of cold. In areas where winter temperatures fall below 20 degrees below zero for more than a couple of weeks each winter, bark beetles have a hard time living though the winter and their infestations are small. But vast areas of North America, Northern Europe and Russia, that formerly were lucky enough to have these extra cold temperatures nearly all winter long, are finding that these temperatures, for the required durations to kill the pests are just not happening any more. The temperatures in northern areas are in some places 20 or more degrees warmer than they were just 20 to 30 years ago. Average temperatures across Alaska for example are 4 to 7 degrees warmer. Northwestern Canada average temperatures are 10 degrees warmer. The Rocky Mountains, even in Colorado and Wyoming are likewise being affected. Higher altitude mimics higher latitude.

Spruce bark beetle has killed three million acres of trees in southern Alaska.

Alaska's Kenai Peninsula 3 million acres killed in a spruce bark beetle outbreak, the Yukon nearly a million, British Columbia is in the middle of an infestation of pine bark beetle that has killed 15 million acres, and now the Central Rockies is in the middle of an extraordinary epidemic of pine bark beetle infestation that experts say will completely wipe out 22% of the forest in the central Rockies in 3 to 5 years. Over 1.5 million acres of trees have been killed to date, last year the infestation increased by 50% from 1 million acres to 1.5 million acres.

Here's the tipping point involved with forests: A researcher working for the Canadian forest service has calculated that the death of the 15 million acres of trees in British Columbia will result in the emission of as much carbon as all of Canada's gasoline and diesel vehicles emit in 5 years. This emission of CO2 is of course exactly the opposite of what forests are supposed to do absorb CO2. The great risk is hundreds of millions of acres of forests in the far north of North America and Russia. As the climate warms even more, these forest are extremely vulnerable to the same changes in environment that have cause the devastation in southern Alaska, southwestern Yukon, British Columbia and now the Central Rockies.

Thousands of bark beetles per tree are responsible for these galleries that kill infected trees.

Conclusion: In a paper titled *Tipping elements in the Earth's climate system*, published in the proceedings of the National Academies of Science in February 2008, the authors say:

> *"Society may be lulled into a false sense of security by smooth projections of global change. Our synthesis of present knowledge suggests that a variety of tipping elements could reach their critical point within this century under anthropogenic climate change. The greatest threats are tipping the Arctic sea-ice and the Greenland ice sheet, and at least five other elements could surprise us by exhibiting a nearby tipping point."*

References:

1. National Snow and Ice Data Center (sea level change).
2. Bond and Loti, Iceberg discharges into the North Atlantic on Millennial Time Scales During the Last Glaciation, 1995.
3. Broecker, Thermohaline Circulation, the Achilles Heel of Our Climate System Will Man-Made CO2 Upset the Current Balance, Science, November, 1997.
4. Broecker, What If the Conveyor Were to Shut Down? Reflections on a Possible Outcome of the Great Global Experiment, GSA Today, January, 1999.
5. Alley, et. al., Abrupt Climate Change, Science, March, 2003.
6. Carlo, et. al., Evaluation of seismic data acquired with a streamer on the Jakobshavn Glacier, Greenland, CRESIS Technical Report 130, July 2007
7. Rignot, et. al., Accelerated ice discharge from the Antarctic Peninsula following the collapse of the Larsen B ice shelf, Geophysical Research Letters, 2005.
8. Domack et. al., Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch, Nature, August,2005.
9. Lenton, et. al., Tipping elements in the Earth's climate system. Proceedings of the National academy of Science, February, 2008.
10. Lachenbruch and Marshall, Changing Climate Geothermal Evidence, Science, 1986.
11. Nelson, Unfrozen in time, Science, March, 2003.
12. Saunders, et. al., Hotter and Drier: The West's Changed Climate, Rocky Mountain Climate Organization, March 2008.
13. Kurz, et. al., Mountain pine beetle and forest carbon feedback to climate change, Nature April, 2008.