

Changing the forest and the trees— Is it climate?

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With each passing year, more and more people around the world have heard that the Arctic and far north of the planet are in a period of major climate change. Much of the public awareness about high latitude climate change involves coastal regions, where glaciers, sea ice, and projections of declining polar bear populations offer visible, often dramatic events and images that make memorable stories. But less-noticed events in the boreal forest of interior Alaska represent another sign, and also a cause, of climate change.

The boreal forest has long been the most intact of all the Earth's forest regions. Even though about half of the area of forest globally has been used or changed so that it no longer has tree cover, the boreal forest still occupies nearly the same extent now that it did at the beginning of human civilization. But now climate change has begun to affect the boreal more than any other forest region, and Alaska has been affected as early and as much or more than any other part of the boreal region.

National leaders, Alaska resource managers, and rural residents are interested in learning what has caused the change in climate and how Alaska forests are changing as a result. They are concerned about what future changes are possible. And increasingly, after years of study by many investigators, there are some answers.

Warming up to the boreal forest

The two great surface features of the far north, boreal land cover and Arctic Ocean ice cover, are not just passive objects acted upon by climate change, they are also a significant factor in Earth's climate balance because of their surface reflectivity.

At scales that range from our clothing options to whole sections of the planet, dark surfaces absorb light energy and release some as heat, and light-colored surfaces reflect light and keep surfaces cooler. It is widely understood that changing the Arctic Ocean from a white, snow- and ice-covered surface to dark, open ocean water would warm the planet considerably. But less appreciated is the fact that the entire planet would be about 2°C colder if it weren't for the presence of the dark, rough-textured, conifer trees that grow across vast expanses of the northern part of the globe.

The boreal forest also plays a major climate-regulating role by influencing the level of greenhouse gases in Earth's atmosphere. Trees in general are very effective in storing the carbon dioxide they take up from the atmosphere to build their tissues in the

Cover image: Drought-injured birch trees at Rosa-Keystone Dunes Research Natural Area in the Shaw Creek region of the Tanana Valley State Forest northeast of Delta Junction, Alaska, June 24, 2010. The near-record hot and dry weather of July 2009 so stressed trees across lowland central Alaska that root dieback occurred. As a result, in 2010 foliage mass is abnormally low (you can see through the canopy), and leaves are small, injured, and yellowish even in early to mid-summer. This is the second such stress episode in the past decade, and considerable tree death is likely if such weather conditions persist. Photo taken by G. Juday, using Canon EOS 5D camera with 24-105mm lens.

form of the wood in their trunks and stems. In addition, and in the boreal forest in particular, cold soils and waterlogged acid soils make up a vast reservoir of plant litter representing carbon that has been taken out of the atmosphere and which is generally not subject to decay and re-release.

The amount of stored carbon of the far northern forest and tundra vegetation and soils is roughly equivalent to the carbon dioxide in the atmosphere today. But this stored carbon is only out of circulation to the extent that fires, warm temperature decay, and drying of wetlands do not move it back into the atmosphere. Warmer temperatures could mean less storage, and thus more greenhouse gases in the atmosphere, which cause more warming—a classic positive feedback. Given this potential of the boreal forest to amplify and reinforce an initial warming, the recent history of the factors in Earth's climate system that cause warming are an important signal of future change.

Changes in Earth's temperature regime, warmer or colder, can be particularly disruptive in the far north because they are usually greater compared with lower latitudes. In fact, the Arctic and Subarctic regions in general, and Alaska in particular, have experienced some of the greatest amounts of warming on Earth over the last few decades. Since the 1950s, mean annual temperatures in Alaska have increased by 2° to 3°C and in winter by up to 4°C. The greatest amount of warming has occurred over land areas and less over sea surfaces. (For further information see the Alaska Climate Research Center: <http://climate.gi.alaska.edu/>)


Of course, in the distant past temperatures have been far warmer than now on the top of the planet. What's different today is that human societies and users are invested in the resources and environments that are familiar to us. Climate change puts most of our anticipated future uses into question. And if climate change is of great enough magnitude it may quickly take some natural resource options off the table. Eventually the forests of the north will adjust to a new climate, as happened in the distant past. As forests adjust to a new climate, new opportunities for human uses will be created. The challenge for society is that the problems of climate change effects on forests often occur quickly (fires, insect outbreaks), while new opportunities usually take at least the amount of time necessary for a new generation of trees to grow to maturity. Boreal Alaska trees are in their prime when they are a century old, and even for several decades after. But a little over a century ago people were not planning and preparing for climate change, and there were no cities where Anchorage and Fairbanks exist today. This means it's really not too early to start planning and preparing for an altered climate of the future.

Fortunately for our ability to understand and anticipate likely changes, most of the variability in Earth's temperature and related climatic features is accounted for by four factors—solar variability, changes in coupled ocean and atmospheric circulation, volcanic activity, and finally changes in the levels of greenhouse gases and other human-caused compounds in the atmosphere. These main climate-forcing processes are responsible for a variety of influences, some of them decisive, on the condition of the forests of Alaska and the far north.

Cycling with the Sun

From the time of ancient Chinese astronomers, people have recorded spots on the Sun. These dark “spots” are actually huge convective storms of intense magnetism on the surface of the Sun, most of which are so large they could easily swallow the Earth. One of the first uses of the newly invented optical telescope in the early 1600s was to carefully map and count the visible spots on the Sun’s surface. The long-term increase and then disappearance of these sunspots were eventually found to follow a roughly eleven-year pattern, which is now called the solar cycle. The first one that was systematically counted was named Cycle 1. Currently Cycle 24 is just underway. In addition to the eleven-year changes from maximum to minimum sunspot numbers there have been systematic changes in the highest sunspot counts at the maximum, and even in the occurrence of the cycles themselves. A multi-decade period of low or no sunspots is called a grand minimum.

This decadal-scale to century-scale solar (sunspot) variability is associated with, and is partly responsible for, variation in the Earth’s surface temperatures. What has been learned only recently is that sunspots themselves reduce the amount of energy emitted by the sun (solar irradiance). However, the occurrence of sunspots is more than compensated for by the simultaneous development of bright regions on the Sun called faculae, which increase solar irradiance. The net result is that more energy is directed toward the Earth during times that can be characterized by greater sunspot activity. As the time between successive solar cycles decreases and solar activity (reflected by sunspot number) increases, the Earth’s temperature increases. Exactly how much influence solar variability has on global temperatures is debated. Although a few climatologists argue that solar variability accounts for a significant part of recent global warming and cooling, the consensus of the scientific community is that solar variability has



Low sun angle at midnight, looking north across Birch Lake along the Richardson Highway in northern Alaska, June 24, 2010. Unique characteristics of the far north, such as long summer day length, permafrost, and limited numbers of species, and specific characteristics of boreal Alaska such as a semi-arid climate and unique genetic diversity from glacial refugia, require specialized and local knowledge to evaluate the effects of climate warming. Photo taken by Glenn Juday.

been responsible for only a minority share of Earth's temperature increase over the past century.

In general, the direct change in solar irradiance between the solar sunspot maximum and minimum is too modest to directly produce all of the change in Earth surface temperatures that occurs during the course of the solar cycle. However, if some mechanism, such as increased admission of energy through the atmosphere, amplifies the slight energy boost of a solar maximum then a notable temperature effect of solar variability is plausible. In one study, the upward trend of total solar irradiance as measured by the ACRIM satellite is estimated to have contributed between 10 and 30 percent of the global surface temperature increase during the period 1980–2002.

In the longer term context, for the past century the general trend of solar variability has been toward a temperature-increasing influence. According to indirect (proxy) measurements or reconstructions of past solar activity based on isotope changes in the atmosphere during solar maxima, the sun has been much more active in the last sixty years than at any time over the last several millennia. Sunspot numbers averaged about 29 (s.d. 16) at solar maximum over the last 8,000 years. But the average number of sunspots at solar maximum since 1940 has been 75, which is over 2.5 standard deviations above the long-term average. The highest solar sunspot count of the past century occurred in 1957, which ironically was the International Geophysical Year that saw the first international scientific campaign to measure such phenomena.

It's clearly not the only factor, but there is an intriguing coincidence between solar activity, high latitude temperatures, and forest effects. At the time of the strong 1957 solar maximum, Alaska and other high latitude northern hemisphere locations experienced a very warm summer, and the most severe drought of the twentieth century. In 1957 Alaska experienced the greatest area burned (2.02 million ha) for the following half-century, exceeded only in 2004. The warm and dry weather conditions in Alaska in 1957–58 produced a distinctive marker ring series across most tree species and site types because of reduced ring width caused by warm temperature-induced drought stress. The warm weather in 1957 and 1958 also stimulated one of the largest white spruce cone crops (seeds released in 1958) of the previous several decades. In the boreal forest of Alaska most of the white spruce between twenty-five to sixty-five years old encountered today actually date from the 1958 cone crop. Similarly, solar peaks of the 1980s and 1990s were generally associated with high summer temperatures in interior Alaska, increased wildland fire, and high drought stress in trees. Solar minima generally were also associated in time with cooler temperatures, better tree growth on dry sites, and low total area burned.

Solar Cycle 23 appears to have ended in December 2008, but a prolonged lull in solar activity (August 2008 was first month in the previous century with no sunspots at all) made defining the end of Cycle 23 somewhat challenging. The solar maximum for Cycle 24 is now forecast to occur in 2013 and reach only a modest maximum sunspot number compared to recent decades.

As long as this weak solar activity persists, the Earth, and especially the far north, is likely to experience a weaker warming influence than occurred in the solar cycles typical of the past century. It is conceivable that a grand minimum could occur in the future, which would represent a long-term cooling influence. The last series of grand minima coincided with the Little Ice Age, an irregular period that caused a series of global cooling issues for humans and the ecosystems that support them. But solar activity is not the only process causing temperature variability. And even the strongest cooling influence of solar variability can be counteracted or overcome by other factors affecting Earth's temperature.

The ocean and atmosphere: keeping in circulation

The Earth is so much hotter near the equator than in the polar regions that air and water are set in motion, in the form of weather and ocean current systems, to even out the temperature imbalance. The chronic movement of air masses in weather systems along the same routes drags along the surface of the ocean and eventually steers the major ocean currents along well-defined pathways. Because of the rotation of the Earth, warm rising air masses spin around a predominant weather pattern.

General atmospheric circulation, including the path of the storm systems, in both Northern and Southern hemispheres takes the form of ring-like modes or patterns of variability that circle around the poles. These modes oscillate between high “index” and low “index” conditions. High “index” conditions of air mass motion are marked by below-average barometric pressure over the polar cap regions, above-normal pressure in mid-latitudes, and by enhanced westerly air motion in the subpolar (55 degrees latitude) regions. Low “index” conditions have the opposite departures from mean conditions. A name is typically applied for the location of the oscillation. In the US, the north polar oscillation is often referred to as the Arctic Oscillation (AO), whereas in Europe the phenomenon or its extension over the North Atlantic Ocean is usually called the North Atlantic Oscillation (NAO). The fluctuations in the modes of ocean and atmospheric circulation occur on time scales ranging from a week to decades.

The vast Pacific Ocean Basin south of Alaska is one of the dominant surface features of the Earth, and the two alternate modes of Pacific Ocean and atmosphere circulation variability have an influence on much of the planet's weather. “El Niño” (Actually El Niño/Southern Oscillation or ENSO) refers to a persistent Pacific Ocean circulation pattern in which the tropical trade winds weaken and become warmer, and warm water replaces cold upwelling water in the eastern equatorial Pacific. Nearly all of Alaska is distinctly warmer for the six to eighteen months of a typical ENSO, because the location and movement of prevailing weather systems more effectively scoop up air from latitudes near Hawaii and direct it north to Alaska.



Author (Glenn Juday) with Japanese exchange student Miho Morimoto from Hokkaido University in northern Japan, Quartz Lake vicinity, near Delta Junction, Alaska, July 2010. Cores extracted from the drill-like corer (blue handle) provide a record of the tree's growth performance based on ring-width and the physical and chemical properties of the wood. This tree is about a century old, and registers increasingly unfavorable climate conditions in recent decades. Photo taken by David Klein.

The opposite mode of an ENSO is a “La Niña” event. During the La Niña pattern, the trade winds become stronger, and cold, nutrient-rich water upwells along much of the eastern tropical Pacific Ocean. Alaska is colder than average during “La Niña” conditions because a persistent high-pressure system northeast of Alaska allows cold polar air to flow from the northeast to the southwest over much of the state. La Niñas tend to closely follow El Niños in the ocean/climate cycles. Circulations that do not match the extreme patterns of El Niño or La Niña are termed “Niño neutral” and represent a majority of years.

Of the oscillation modes, boreal Alaska is most strongly affected by the ENSO, but with a definite influence of the AO detectable. Essentially, as one moves farther south in the state (closer to the Pacific Ocean) there is an increasing ENSO signal, and as one moves from the center of the state toward the Arctic coast there is an increasing AO signal.

Although the year-to-year change in the total area burned in Alaska that is explained by the El Niño condition is relatively small (~16%), many of the largest forest fire years in Alaska are strong El Niño years. Growth of most trees on moisture-limited

sites in interior Alaska is directly tied to the alternating ENSO conditions in the same way that weather and climate changes are produced by solar variability. In the Interior, highest rates of growth occur during the cool/moist ENSO regime (La Niña), and lowest rates of growth during the ENSO period (El Niño) that produces hot/dry conditions. Trees in the cooler, moister parts of western Alaska, which is influenced by the Bering Sea, grow most in warm years and least in the cool years. Because these patterns are so strongly expressed in the trees, climate reconstruction can be developed from tree-rings for the period before instrument-based measurements of temperature. The reconstructions show that reversals of the Pacific climate state from the “warm” North American phase to the “cold” North American phase have occurred throughout the last four centuries on the scale of every few decades, although the size and location of the area affected varied somewhat.

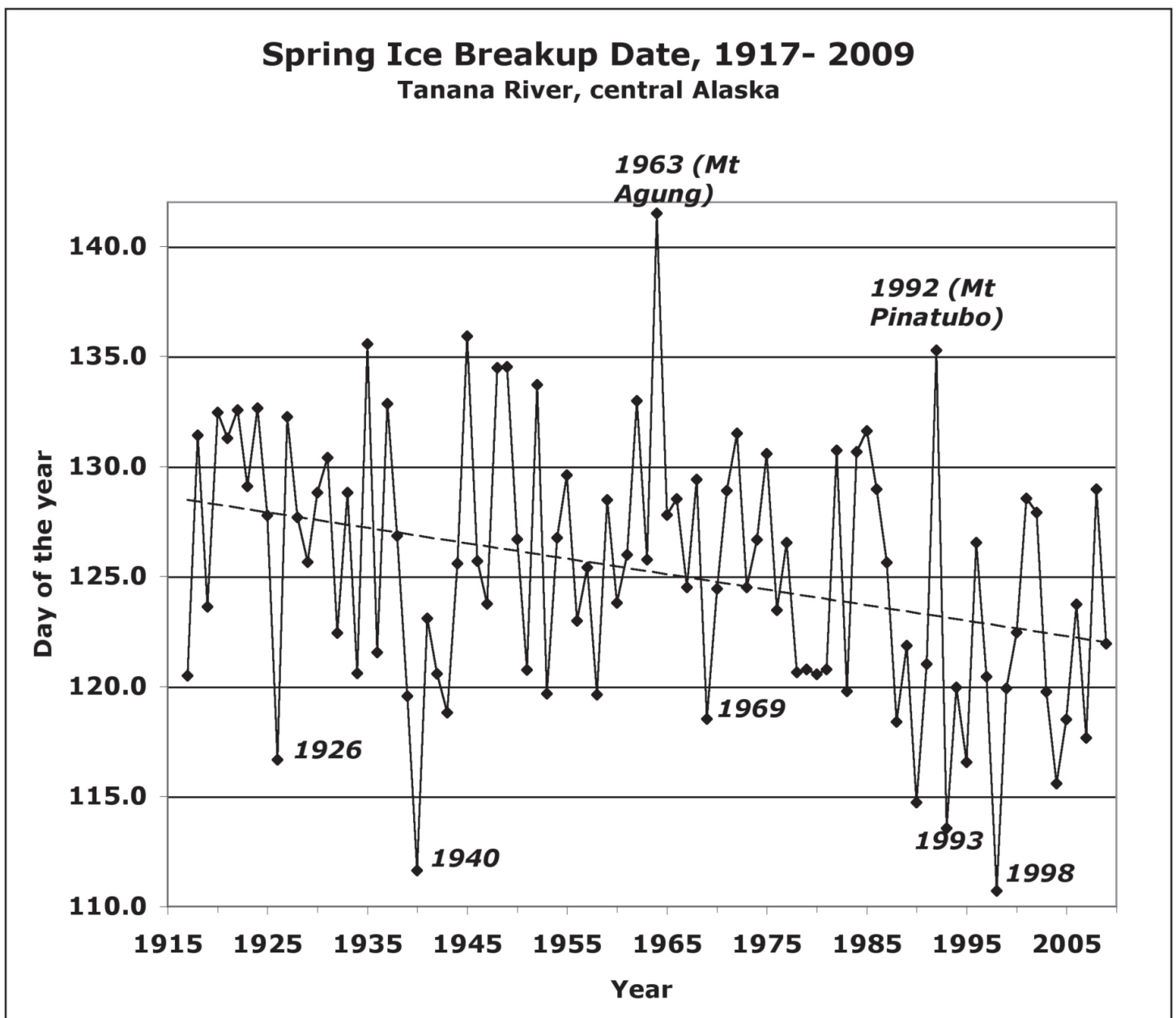
The strongest El Niño measured up to that time occurred in 1983, but was then surpassed by the 1997–98 El Niño. The exceptionally strong El Niño of the late 1990s was in turn followed by an exceptionally strong and prolonged La Niña.

These events produced pronounced effects on Alaska weather and forest conditions. The earliest spring breakup of river ice in the 90-year series on the Tanana River took place in 1998 under the influence of the record strong El Niño (Figure 1). The strong 1999-2002 La Niña cool period provided relief from warm season drought stress, and represented the most climatically favorable period for tree ring growth of upland white spruce since before the 1976-77 climate regime shift. In fact, this series

of years with cool weather may even have prevented tree death from cumulative effects of heat and drought on some particularly sensitive sites.

During the last few decades of the twentieth century, “warm” ENSO conditions with respect to the influence on Alaska weather were frequent, strong, and persistent. A return to the alternate, cooler mode of influence occurred from 1999-2002, followed by more record warmth. Certainly the extended cool

Figure 1. Time of spring ice breakup on the Tanana River at Nenana, Alaska. Years with high values represent late spring breakup (cold) and years with low values represent early breakup (warm). The highlighted years are single-year anomalies associated with short-term volcanic cooling (1963, 1992—above the line), or strong El Niño warming (1926, 1940, 1969, 1993, 1998—below the line) influences. The overall trend of the data, indicated by a least squares regression fit (dashed line), is downward toward earlier breakups, consistent with a long-term warming trend. Most other natural systems in Alaska with a long-term record show the same general trend.



weather of 2008 in coastal Alaska was consistent with the strong cold mode of atmosphere/ocean circulation. But at the same time that this cold Pacific influence was happening, the Arctic Ocean was setting records for minimum ice extent. What, then, is the outlook for the ocean/atmosphere contributor to climate variability and forest conditions?

ENSO is essentially a large-scale mechanism for dissipation of excess heat in the Pacific Basin. The warming influence of increasing greenhouse gas concentrations continues to retain more energy in the Earth climate system. If there is more heat retained in the climate system, then there is more heat to transfer, and stronger and more prolonged El Niño events (followed by strong La Niña events), in contrast to “Niño neutral” years, would logically follow. So, by this logic, decadal-scale variability of ENSO, AO, and NAO is likely to be superimposed on a longer-term century-scale warming.

Still, the uptake, storage, and movement of heat around the planet by the world ocean is not fully understood yet, especially as it related to events that happen or shift between alternate modes so infrequently that modern science has not yet been in existence long enough to observe them. Abrupt changes from mode shifts appear to be more likely, and there is a real potential for climate surprises from this form of variability.

Blowing your top: volcanic effects

Volcanic eruptions that are rich in sulfur aerosol compounds and powerful enough to inject material into the upper atmosphere (a small minority of all eruptions) cause a brief one- to three-year global cooling influence. The sulfur aerosols cool the Earth’s surface by causing the atmosphere to reflect more solar radiation, including reflection back into space before it can enter the Earth climate system. The cooling can be strong, but is short-term.

Following this particular kind of eruption, the new volcanic aerosol components of the upper atmosphere absorb some solar radiant energy as well as some of the extra, reflected energy from the Earth’s surface. As a result of these gains in radiant energy, the stratosphere is gradually heated, while the atmosphere near the surface experiences a more immediate cooling. When the eruption is in the tropics, this slower, upper atmospheric heating is greater near the equator than in the high latitudes, producing a stronger heat imbalance from the equator to the polar regions, especially in winter. During the Northern Hemisphere winter this enhanced temperature/energy gradient strengthens the jet stream, producing winter warming of Northern Hemisphere continents by heat transport from the south following the quicker post-eruption cooling of the atmosphere near the Earth’s surface.

The short, acute cooling influences of major volcanic eruptions during the warm-season have left distinctive patterns

in Alaska and global tree-ring series. These patterns, which vary by region, are still being studied. One of the most distinctive and informative volcanic events in Alaska is indicated by the tree ring formed in 1783, the year of a particularly sulfate-rich eruption at the Laki volcanic field in Iceland. The first generation of Alaska tree-ring investigators noticed some unusual properties of the 1783 ring and suggested a connection to a cold temperature anomaly. A successive generation of investigators took up the challenge and made a tentative connection between volcanic eruption, global-scale cooling, and tree-ring growth. A recent synthesis with access to sophisticated geophysical, climatic, and tree-ring data provides an example of the profound effects volcanic events can produce.

Long-term tree ring records indicate that 1783 was the coldest summer in over 400 years in northwestern Alaska. European explorers in coastal Northwest Alaska reported famine and population decrease of Alaska native people sometime between 1779 and 1791. Early and contemporary anthropological studies indicate possible famine in nearby areas at around the same time. Inuit oral history describes extreme cold in summer causing famine and death a few centuries ago in northwest Alaska. The oral history and tree ring evidence indicate that in much of northern Alaska, summer in 1783 was terminated by snow and freezing conditions in late June, which persisted until the next year.

One of the major volcanic cooling events of the twentieth century was the Mount Pinatubo eruption of June 1991 in the Philippines. The Mount Pinatubo eruption reduced global mean air temperatures by mid-1992 up to 0.5°C at the surface and 0.6°C in the troposphere. Effects persisted for several months and were followed by above-average warmth in 1993 as would be expected from a tropical eruption. In Alaska the 1992 cooling effect was severe. The 1992 snow-free season in central Alaska was from May 20 to September 12, the shortest of the century. The early snowfall clumped on deciduous trees in fully leafed-out condition, and weighted the trees so heavily that many bent or snapped. Even white spruce that survived were severely weakened from stem breakage and became infestation centers for engraver beetles (*Ips*) that killed many trees. The strong early growth season warming in boreal Alaska in 1993 produced very favorable conditions for a spruce budworm outbreak that year.

Enhanced levels of volcanic activity in the second half of the twentieth century, according to well calibrated and verified climate models, have contributed a net cooling effect that masked the magnitude of other warming influences, including greenhouse gases. If volcanic activity falls back to a lower level, the next several decades would experience an additional warming influence (less cooling) compared to the previous several decades. Volcanic activity capable of causing a one- to three-year cooling effect on Earth is highly irregular and not currently predictable. A strong eruption is a low probability but would be a high forest-impact event in Alaska over the next decades, while a lack of eruptions would allow greater climate influence of the other forcing influences.





Above: Spruce grouse in an area burned by the 1983 Rosie Creek Fire in the Experimental Forest unit of Bonanza Creek Long Term Ecological Research site, southwest of Fairbanks, Alaska, October 2009. Major changes in the Alaska boreal forest of the past few decades, such as large areas of fire and insect-killed trees and the regeneration of new forest, confront wildlife species with challenges and opportunities that in turn shape the forest and provide ecosystem services for people in a constantly shifting scene. Photo taken by David Spencer.

Opposite, top: White spruce seedling with orange-colored leaf rust disease, Quartz Lake near Delta Junction, Alaska, July 2010. Even if precipitation rises to meet the additional water demand generated by recent high temperatures, new forest health challenges such as diseases would likely emerge to damage existing boreal species. Such a combination of warmer and wetter weather was associated with new disease problems in boreal forest of central British Columbia in recent years. Photo taken by Glenn Juday.

Opposite, bottom: Budworm damage to a white spruce seedling, Chena Ridge Road area southwest of Fairbanks, June 2006. Spruce budworm outbreaks in central Alaska occur after summers with optimum distribution of high temperature anomalies at critical stages in the insect's life cycle. Populations of budworm at the outbreak level were not known in central Alaska until extreme warmth of the post-1976 period, when a sudden climate regime shift produced suitable temperatures. Sustained outbreak level populations of budworm kill large amounts of white spruce in Canada. Photo by Paul Renchen.

It's a gas: greenhouse gas sources and sinks

Greenhouse gases absorb some of the energy escaping from the Earth's surface and atmosphere and re-radiate it back down to the near-surface. They act in a way similar to a blanket—they don't add heat themselves, but slow the escape of heat energy that is already present. As a result, one characteristic of a greenhouse-caused warming is that cold temperature increases (winter temperatures, daily low temperatures) are stronger and often steadier than increases in the upper range of temperatures. Several features of recent Alaska warming, including disproportionate winter warming and nighttime warming, are completely consistent with a predominantly radiative forcing—greenhouse gas type of warming.

In the last several decades the Earth has warmed beyond the level associated with the combination of long-term solar influence, volcanic influence, and periodic ocean-atmosphere circulation changes. There is no big mystery as to why. While there is a need for even greater precision, and there are always a few surprises in any process of scientific study, no unknown factor is required to explain surplus warming of recent decades. The extra warming matches well with standard calculations of the warming influence of increased concentrations of greenhouse gases in the atmosphere. Aside from water vapor, the two most important greenhouse gases are carbon dioxide and methane.



Smoke column from Willow Creek Fire, along the Tanana River south of the University of Alaska Fairbanks campus, June 22, 2010. This view is across the Fairbanks Experiment Farm. The fire was ignited by a “dry” lightning strike on June 10, and persisted even after heavy rains because of extreme cumulative drying, serving as a reminder of the altered condition of central Alaska boreal forest in response to recent warming. Photo taken by Glenn Juday.

The increase in atmospheric greenhouse gases has been directly measured for about half a century, and even the annual increases are accurately measured.

Increasing greenhouse gas concentrations in the atmosphere come about both directly and indirectly. Direct causes include human additions of these gases to the atmosphere from fossil fuel combustion, newly invented industrial compounds that produce a greenhouse effect, cement production, and petroleum production. Geologic carbon dioxide is also naturally vented from volcanoes. Indirect causes increasing greenhouse gases are mainly destruction of vegetation that decreases plant uptake and storage of carbon dioxide, allowing more to stay in the atmosphere, and human alteration of the methane production and uptake.

The annual net movement of carbon from atmospheric carbon dioxide into plant carbon is called the terrestrial carbon sink, and a similar sink exists in the oceans. The terrestrial sink stores an amount of carbon equivalent to 15 to 30 percent of annual global emissions from fossil fuel combustion and industrial activities. In other words, without the uptake and storage of carbon dioxide by land vegetation, the increase of greenhouse gases would be happening even more rapidly and reach higher levels.

From 1981 to 1999, different forest regions of the world contributed the major influence on the terrestrial carbon sink, both positively and negatively. Biomass carbon gains (removal of carbon from the atmosphere) occurred in the Eurasian boreal and temperate regions and in North American temperate forests. This terrestrial carbon uptake was a result of new forests growing on sites that previously had been cleared and were now rebuilding carbon storage. By contrast, losses of stored carbon to the atmosphere and less uptake of carbon in tree growth occurred in some parts of the Canadian boreal forest and in the Alaskan boreal forests. In those areas reduced carbon uptake was a response to accelerated disturbance by wildland fire and insects, which increased tree death, and also from hotter and drier conditions less favorable for tree growth. Increased forest disturbances such as fire and insect-caused tree death can also promote speeded up decomposition (by soil warming) of carbon in stored in soils, and its release as greenhouse gases.

Finally, current human use and management of the boreal forest have been affected carbon balance as well. Tree harvest and the manufacture of wood products that are kept from decomposition on a long-term basis can represent a net movement of carbon from the atmosphere into storage. However, this effect is almost always overcome by forest

management systems of repeated short cycles of tree growth and cutting that often accompanies commercial forest management. Under such multiple short rotations, less carbon stays in storage (in both wood and soil organic matter) than in a forest growing undisturbed for the equivalent time period.

Active suppression of forest fires can sustain more carbon in storage, at least on a short or medium-term basis, than would otherwise be the case. Replacing forests with almost any other land cover reduces carbon dioxide uptake and storage, and reforesting bare land increases net uptake and storage. Overall this suggests that northern ecosystem management could be a significant contributor to future management of the carbon cycle.

Hillside covered with drought-injured birch trees at Rosa-Keystone Dunes Research Natural Area in the Shaw Creek region of the Tanana Valley State Forest northeast of Delta Junction, Alaska, June 24, 2010. Top dieback (leafless branches) and sparse, yellowish leaves in early to mid-summer indicate the severely stressed condition of all the trees, showing that the condition affects whole landscapes. Photo taken by Glenn Juday, using a Canon EOS 5D camera with 24-105mm lens.

On the record: climate trends in Alaska

Instrument-measured weather data in central Alaska start with the University Experiment Station (UES) in 1904. The UES station was established as a function of the USDA Agricultural Experiment Station, which subsequently became the University of Alaska Agricultural and Forestry Experiment Station in the 1930s. Early Fairbanks weather data also come from downtown locations and the airstrip at Weeks Field. Since 1948, weather data have been collected at a “First Order” National Weather Service station at Fairbanks International Airport. Some urban heat island effect is present in the first order Fairbanks record, but it can be controlled by reference to long-term overlap with stations in rural Alaska, most of which also begin in the 1942-1950 time period. A reconstructed record is possible from 1917 in Anchorage, 1921 at Denali National Park and Talkeetna in inland Southcentral Alaska.

These available longer term temperature records tell a consistent story. Across most of Alaska the greatest magnitude of the warming seasonally has been in the winter, but temperatures

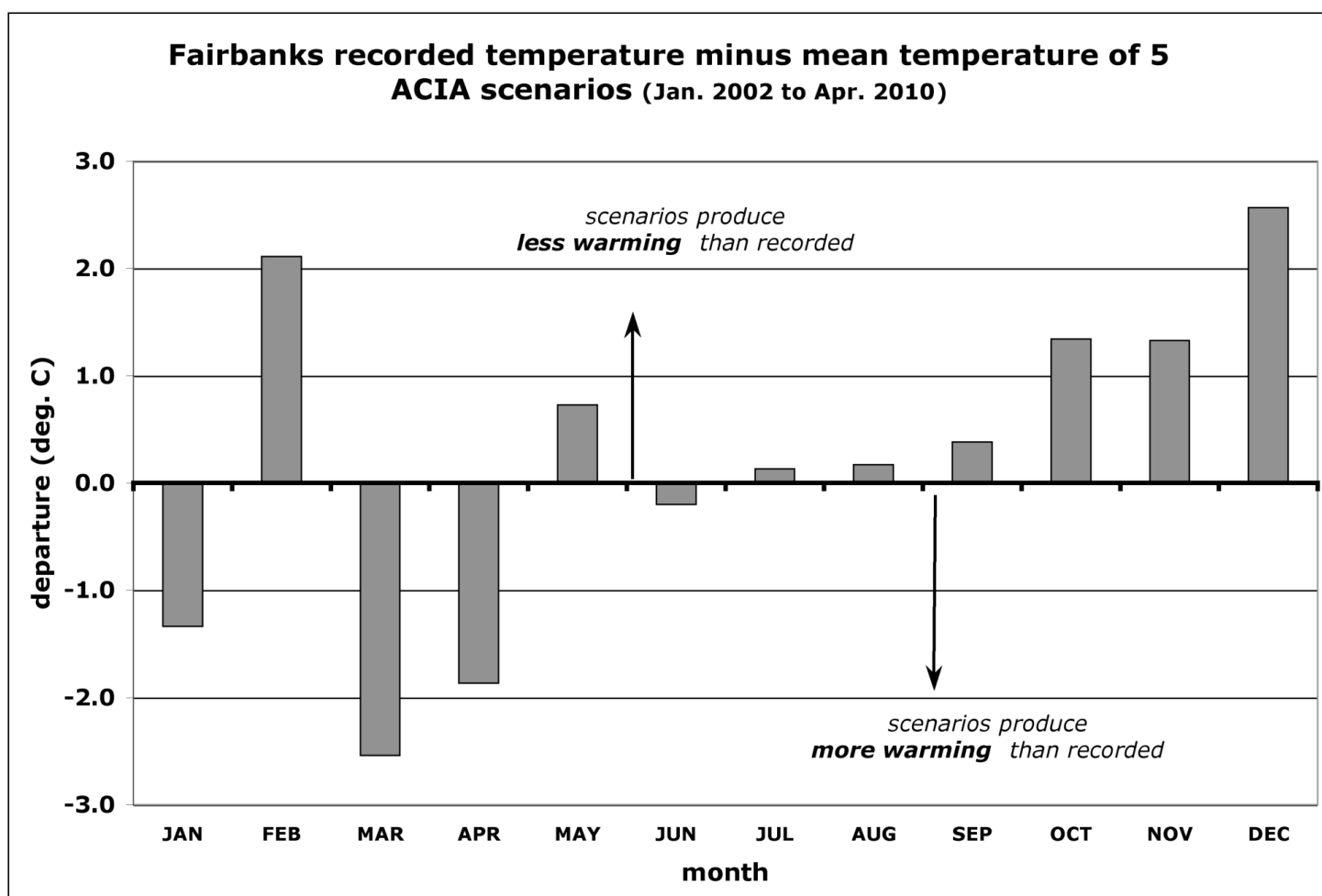


Table 1. List of five atmosphere-ocean general circulation models (GCMs) that were used to generate climate scenarios of the twenty-first century for the *Arctic Climate Impact Assessment (ACIA)*.

| GCM acronym | Lead development institution |
|-----------------|---|
| 1. CGCM2 | Canadian Centre for Climate Modelling and Analysis (Canada) |
| 2. CSM_1.4 | National Center for Atmospheric Research (USA) |
| 3. ECHAM4/OPYC3 | Max Planck Institute for Meteorology (Germany) |
| 4. GFDL-R30_c | Geophysical Fluid Dynamics Laboratory (USA) |
| 5. HadCM3 | Hadley Centre for Climatic Prediction and Research (UK) |

See: Kattsov, V.M., and Kallen, E. 2005. Future Climate Change: Modeling and Scenarios for the Arctic, Chapter 4, pp 99-150, In: *Arctic Climate Impact Assessment*. Arctic Council. Cambridge University Press. ISBN 978-0-521-86509-8.

Figure 2. Comparison of Global Climate Circulation Model scenario-generated temperatures for the grid cell containing Fairbanks, Alaska compared to temperatures actually recorded during the 100-month period from January 2002 through April 2010. Overall, the scenarios generated realistic temperatures compared to the record, with a slight tendency for recorded data to be warmer (0.23 degrees C) than projected by the scenarios. Comparison is with the mean of the five climate scenarios used in the *Arctic Climate Impact Assessment (ACIA)*.



during the ecologically important spring and summer have increased as well. In central Alaska locations including Fairbanks, autumn temperatures have actually decreased slightly in recent decades. The reason for autumn cooling is not completely clear, but it is related to differences in the number of strong storms that pull warmth northward between the early and later period of the record.

In the highly continental climate region of central Alaska the mean of daily high temperatures during the warm-season increased only very slightly during the twentieth century, but the mean of daily low temperatures increased by more than 3°C. One result is a considerable increase in growing season length in central Alaska, which while still highly variable, now averages 120 days at many stations. The concentration of warming in the daily temperature minima is consistent with a process operating to dampen heat loss (greenhouse gases) rather than amplify energy input (e.g. increased solar luminosity).

Records of direct precipitation over the last 50 to 100 years do not show the same strong trend as temperature. In some Alaska regions precipitation increased (along portions of the southern coast), but the North Slope, Interior Alaska, and the Kenai Peninsula did not experience noticeable increase in precipitation. Across much of central and Interior Alaska, annual total precipitation is quite low. Precipitation in the 100-year Fairbanks climate record is about 280 mm/year. White spruce trees do not naturally occur in North America when annual precipitation is lower than the Fairbanks average.

Some of these Alaska climatic trends are synergistic in their effects. For example, as temperatures increased, snowmelt occurred earlier in the spring, which ended the period of snowpack accumulation and lengthened the period of evaporation of liquid moisture. As a result, despite steady levels of precipitation, plants experienced greater evapotranspiration demand under this type of climate change. Given the marginal supply of effective moisture for tree growth across much of lowland central Alaska, the result has been very strong, sustained, and widespread moisture stress in most of the Alaska boreal forest.

Summing it all up: how good are scenarios?

Scientists construct quantitative interactive models of the climate system based on the known factors that affect climate. Although there is always room for improvement, and what is unknown is obviously not in these models, still they can be useful tools of analysis. Strictly speaking, climate scenario models can't be used for prediction, for the simple reason that the outcomes are affected more by assumptions—such as what will world fossil fuel use be in 10, 20, or 30 years?—than by precision of available estimates of the main variables. Just change the assumptions about the future in the scenario, and you get a different outcome. However, the models can be used to calculate reasonably well a

climate outcome that would occur if the controlling variables were to actually follow a defined path of change from the present (and, of course, if all the major controlling factors are set correctly). These scenarios of change are really stories of plausible outcomes *if* change were to follow a defined script. If the assumptions in the script are plausible, then the outcomes are plausible too.

Current mathematical representations of the Earth's climate are also limited in their spatial resolution. The number of calculations that must be done to represent the weather at a particular place on the surface of the planet is very large. The whole planet must be represented to make the model interactive, and the scenarios must go through a “spin-up” phase to see that they produce realistic output compared to recorded data. Finally, Global Circulation Models (GCMs) calculate results for many years into the future. The amount of time needed for the task could become too great to get done in a reasonable time period.

The main way to keep the number of calculations low enough even to be feasible is to reduce the number of blocks or grid cells that represent the surface of the Earth. Even so, the largest, fastest supercomputers churn away for days and weeks to produce the answers for the whole planet. As a result, the product or output that the current generation of GCM scenarios produces is a crude representation of averaged and homogenized large blocks of the Earth's surface, not the subtle and diverse place we actually live in. On the other hand such models do represent reasonably well global-scale changes, such as the change of seasons, the climate of the recent past as they go through their spin-up operation, and even the cooling effects of a volcanic eruption such as Mt. Pinatubo. But it is well understood that as you examine smaller intervals of time and more and more restricted parts of the Earth, scenarios are more likely to depart from the actual course of events. Are the GCMs reliable in their calculations about likely futures, especially at the local level rather than the entire globe? There is a good test case available.

One of the major synthesis studies and analyses of scenarios for a specific region of the Earth (rather than a more generalized global analysis) was the *Arctic Climate Impact Assessment* (ACIA). The ACIA Scientific Document was released in 2005. It used mid-range projections of human population increase, fossil fuel use, land cover change, etc. Special computer runs of five leading GCMs were spun up for the period 1900 to 2001, and then the scenario projections for 2001 to the year 2099 were used as a basis of analysis. A large team of authors was asked to assess what the Arctic region would be like if climate were to change over the next century in the way the scenarios calculated. The ACIA was an analysis based on the specified assumptions, not strictly a prediction, but we can now compare the first decade of GCM climate scenario output in ACIA to actual recorded data to see how realistic the scenarios were.

Figure 2 shows the recorded monthly temperature averages for Fairbanks during the period January 2002 (date at which ACIA analysis began) through April 2010 versus the mean temperature of the five ACIA-designated scenarios (for the full report see: www.acia.uaf.edu/pages/scientific.html). Overall, the



Spruce budworm at the UAF campus, June 2008. The western portion of Fairbanks and Chena Ridge was the center of the most severe spruce budworm attack of white spruce trees in Alaska during 2007 and early 2008. This is the third or fourth instar larvae which overwintered as a second-stage larva. With sufficient warmth, this insect develops into an adult moth by late June, mates, and lays eggs that hatch in August. Photo by Steve Winslow.

combined five-scenario mean annual temperature was only 0.23 degrees C below the recorded mean temperature at Fairbanks during the period. The scenarios produced temperatures notably close to those recorded at Fairbanks during the summer months, especially June through September. The scenarios generally produced less than the recorded warming in the first part of winter, and greater than recorded warming in the second part of winter (Figure 2).

What does this comparison of the scenarios with the record tell us? At the least, even when focusing on a single grid cell for only a few years, we can see that effects that were examined in the ACIA analysis were realistic in the near term. Overall the scenarios were a reasonably good representation of what happened, or even a bit conservative in projecting temperature increases. So, the case on behalf of the effects that were projected for the future in the ACIA analysis appears to be strengthened.

Is global warming real?

Yes, the Earth has been warming. The far north, and Alaska in particular, have been on the leading edge of the evolving change in the climate system. Forests in Alaska are both subjects and actors in the processes of change. The explanation for the vast majority of change in the climate can be found in the four main influences that affect temperatures in the short and medium term: solar variability, ocean-atmosphere circulation, certain volcanic eruptions, and changes in greenhouse gases in the atmosphere. There are very important questions about the rate at which heat storage and release from the oceans affect the rate of atmosphere warming and the possible cooling effect if cloud cover were to increase, but in general no large amount of Earth's

temperature variability remains to be explained by an unknown factor.

In any process of scientific study, standard procedure is to reduce the number of variables that may affect the outcome, ideally down to one that is tested as the most likely cause. The results obtained from this way of conducting investigations allow the highest confidence that the explanation offered actually caused the result. However, this technique of doing good investigations should not be confused with the way something as complex as the Earth's climate system actually functions. In reality, the various influences on temperature are not in competition with one another. Explaining temperature changes is not a case of either/or, such as solar variability versus greenhouse gases, but rather both/and. All the factors that influence temperatures—how warm or cold the Earth is at a given time—all happen at the same time to produce the result.

One useful way to think of it is that increasing greenhouse gases—the effect that people have control over—will make the Earth climate system warmer than it otherwise would have been. Unless there is a strong net cooling direction to the other three temperature-affecting influences, the Earth as a whole will warm as atmospheric greenhouse gases increase. In a few cases, the altered way that the global climate system operates at an overall warmer level will result in a net cooling in restricted geographic locations. That is no surprise, and has happened many times before.

Natural cycles and irregular years of extra warmth or cold are likely to continue in the future as they have in the past. But if strong increases of greenhouse gases in the atmosphere continue, the Earth climate system will retain more heat, causing an upward trend in temperatures, other factors remaining roughly equal. In fact, the climate system has not fully adjusted yet to

the recent increases in greenhouse gases, so decades of warming influence are ahead of us. If solar sunspots do not cease, and cooling volcanic eruptions occur at long-term numbers, then the upward warming influence of greenhouse gases, superimposed on underlying cycles and events caused by other temperature – affecting factors, would produce a pattern of staircase increases in average temperatures. Cool years would still occur, but would just not be as cold as previously. Warm years would be more frequent, more sustained, and occasionally more severe.

Humans are intensely social creatures, and it is sometimes a struggle for us to separate political/civic values from established empirical fact and scientific uncertainty. All of these realms of knowledge are legitimate parts of the climate change issue. But each element should be respected for what it is. The fact that temperatures have increased, and greenhouse gas increases are nearly certain to increase temperatures further (given likely assumptions about the future), are not reasons to either adopt unwise public policy measures or to avoid adopting needed public policies.

We happen to live in a changing world and to have recently assembled the capability to understand the likely near-term direction of climate change under specified circumstances. As hard as it was to gain that understanding, the real challenge ahead is to gain the wisdom to deal with it in the most constructive way.

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Changing the forest and the trees—Is it climate?

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