Climate Science

Volcanism and Climate Variability / Snow and Ice Albedo Feedback in Earth's Climate System

---

NATIONAL CLIMATOGRAPHIES

Background:

One of the missions that NOAA's National Climatic Data Center(NCDC) undertakes is the summarization and compilation of a variety of climate statistics from their archive of weather data that have been submitted to the Center from the national network of weather stations. These summaries are then disseminated, providing the public with information about the climate of the nation, whether on a local, state or regional level. NCDC produces several series identified under the title "The Climatography of the United States." Literally, *climatography* represents a quantitative description of climate that usually involve development of tables and charts that portray the characteristic values of selected climatic elements at a station or over an area. Some of these climatographies provide a variety of daily, monthly and annual normal climate data for agricultural, transportation and other interests.

NOTE: -- According to NCDC, new normals for the basic climate elements (temperature and precipitation) covering the new 1981-2010 interval became available in July 2011. However, these normals have not been provided in files that have user friendly format. Additional climatographies (e.g., growing seasons) for 1981-2010 will be made available during 2013.

The following current climatographies that are available online from NCDC are based on the contemporary 1971-2000 standard climatological averaging interval in terms of Monthly, Daily, Divisional and Supplemental products:

Climatography of the United States No. 20 "Monthly Station Climate Summaries for 1971-2000"

This climatography publication contains station summaries of the temperature, precipitation, snow, and degree-day unit elements averaged for the 1971-2000 interval for 4273 stations throughout the coterminous United States. The statistics include means, median (precipitation and snow elements), extremes, mean number of days exceeding threshold values, and probabilities for monthly precipitation and freeze data. A table for each station includes heating, cooling, and growing degree-day units for selected base temperatures.

These data in this climatography, arranged alphabetically by state, can be obtained in either for the each station or from the entire state in Adobe PDF format.

Climatography of the United States Number 81 -- "Monthly Station Normals of Temperature, Precipitation, and Heating and Cooling Degree Days, 1971 - 2000"

This document provides monthly climatic normals data for 7937 sites that record temperature and/or precipitation data, including First Order stations at National Weather Service Offices, principal climatological stations, and volunteer "cooperative" observer stations across the United States and its territories. The data contained this publication are based on monthly maximum, minimum, and mean temperature and monthly total precipitation records collected for each year in the 30-year period of

1971 through 2000.

The data in this climatography, arranged alphabetically by state, can be obtained in Adobe PDF format or text format.

Climatography of the United States, No. 81, Supplement No. 1 --"Precipitation Probabilities and Quintiles, 1971-2000"

This supplement contains the monthly and annual precipitation values for each of the 7937 stations in the Climatography No. 81 document corresponding to three probability levels: 0.10, 0.50, and 0.90. The CLIM81 Supplement No. 1 product is available for free download in either Adobe PDF format or in ASCII format.

Climatography of the United States, No. 81, Supplement No. 2 -- "Annual Degree Days to Selected Bases, 1971-2000"

This supplement contains annual heating and cooling degree-day normals for the 7937 stations in Climatography No. 81 have been computed to various base temperatures (65, 60, 57, 55, 50, 45, and 40 degrees Fahrenheit for heating degree days and 70, 65, 60, 57, 55, 50, and 45 degrees Fahrenheit for cooling degree days). The CLIM81 Supplement No. 2 product is available for free download in either pdf format or in ASCII format.

Climatography of the United States Number 84 -- "Daily Normals and Precipitation Probabilities, 1971 - 2000"

This document contains the daily climatic normals data from the 7937 observing sites described above that record temperature and/or precipitation data. These data include daily 1971-2000 normal maximum, minimum, and mean temperature, heating and cooling degree day units and precipitation for each day of the year, four seasonal averages (Winter, Spring, Summer, and Autumn), and the annual average or total. Monthly and annual precipitation probabilities and quintiles are also included.

These data in this climatography, arranged alphabetically by state, can be obtained in either ASCII or Web format.

Climatography of the United States Number 85 -- "Divisional Normals and Standard Deviations of Temperature, Precipitation, Heating and Cooling Degree Days, 1931 - 2000 (1931 - 1960, 1941 - 1970, 1951 - 1980, 1961 - 1990, 1971- 2000.)"

This document includes normals and standard deviations for the five 30-year normals periods and the 70-year period between 1931 - 2000 for each of 344 climate divisions found across the continental United States, plus additional climate divisions in Alaska, Hawaii, Puerto Rico, the Virgin Islands, and the Pacific trust territories. The normals and standard deviations include values for each month along with the annual value.

The CLIM85 product is available for free download in separate files:

Temperature data are available in either PDF or ASCII format.
Precipitation data are available in either PDF or ASCII format
Heating Degree Day values are available in either PDF or ASCII format
Cooling Degree Day values are available in either PDF or ASCII format

In addition, **Climatography of the United States No. 60 --** " Climates of the States" represents a narrative describing the general climate and associated geography of the state. Some Internet links to various state and station climate summaries and other weather data are also included in the documents.

The individual documents in this series are available by state.

Volcanism and Climate Variability

Driving Questions: *How does volcanism influence climatic conditions? How long is its presence felt?*

Educational Outcomes: To describe the impacts of volcanic eruptions on the amounts of solar radiation reaching Earth's surface, especially in terms of resulting temperature variability. To determine how volcanoes cause temperature departures from long-term mean values and for how long. To explain how proxy data have been employed to relate historical explosive volcanic eruptions to temperature variability.

Objectives: After completing this investigation, you should be able to:

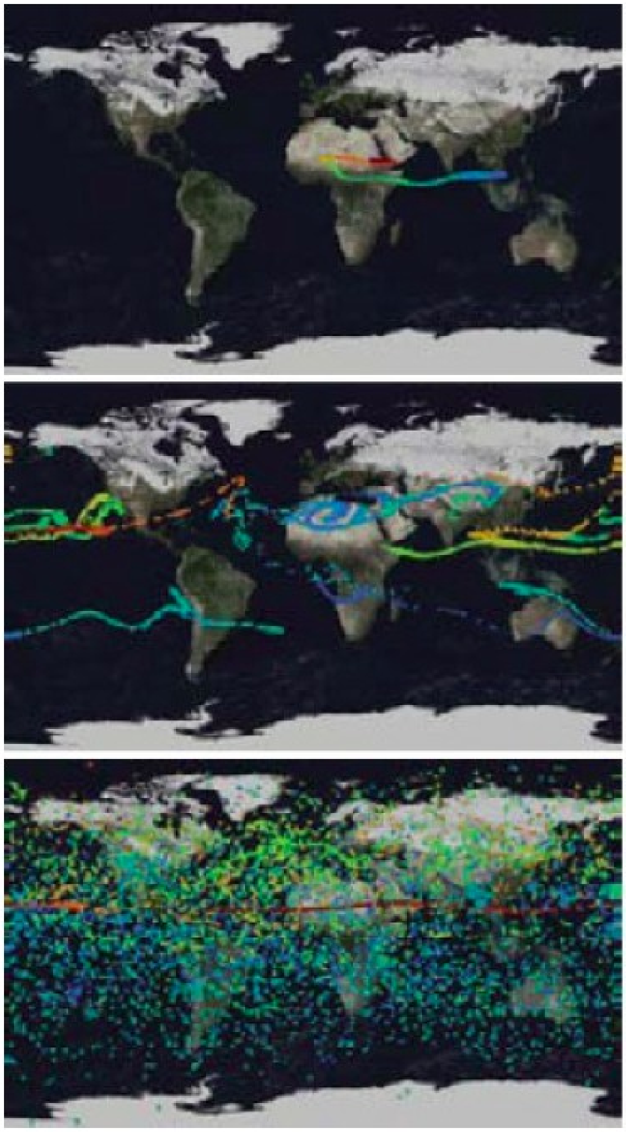
- List several natural forcing agents and mechanisms of Earth's climate system.
- Describe how one mechanism, volcanic activity, affects the system.
- Show how a series of proxy data can be used to explain observed climate variability.

Impacts of Volcanism on Climate Variability

Climate variability is the fluctuation of climatic elements such as temperature about the long-term mean value. The important question is: When does a difference from the climatic mean value, usually based on the average of the past three complete decades, constitute a sustainable change from the previous state and when is it just the natural variability of a statistical value about its constant mean? The boundary conditions of Earth's climate system are themselves variable forcings that drive the system to achieve slightly different states from one year to the next. We must be guided by the science and mathematics of such systems to discern through statistical analysis the level of confidence in deciding that real climate change has occurred.

The most significant boundary condition for Earth's climate system is the energy input to the system, energy received from our Sun. Although there are slight variations in the intensity of solar energy received at Earth's orbit from one year to the next and noticeably over the 11-year sunspot cycle, for most purposes we can consider this input to be relatively constant.

One sometimes significant variation of this energy input to the Earth system occurs when volcanoes eject large quantities of ash and gases into the atmosphere. Ash particles, if fine enough in size and shot high enough into the atmosphere, can have fairly long lifetimes aloft. The gases erupted, particularly sulfur dioxide, can combine with atmospheric water vapor to form sulfuric acid and then become solid sulfate aerosols in the stratosphere. The stratosphere (the atmospheric layer above the troposphere) is an extremely stable layer for air motions and very dry without precipitation. Particles at stratospheric altitudes, typically 11 to 18 km (7 to 11 mi) or higher, have residence times measured in years. **Figure 1** shows the dispersal of fine ash and sulfur dioxide over about a two-month period from the June 1991 massive volcanic eruption of Mount Pinatubo in the Philippines as demonstrated by a NASA Mount Pinatubo Particle Model. The eruption spewed materials that spread into the global? stratosphere and contributed to a –0.3 C° Northern Hemisphere temperature anomaly in the following year, 1992.



(a). 19 June 1991

(b). 3 July 1991

(c). 23 August 1991

Figure 1.
Global spreading of sulfur dioxide and dust from June 1991 Mount Pinatubo eruption over about a two-month period following the eruption. [NASA Scientific Visualization Studio]

Observe an animation of the NASA Mount Pinatubo Particle Model by going to: *http://svs.gsfc.nasa.gov/vis/a000000/a002300/a002389/*. To animate, select one of the animation formats listed to the right of the top image (e.g., MPEG-1). In both Figure 1 and the animation, red is high and blue is closer to Earth's surface.

1. The Mount Pinatubo Particle Model shows that the initial atmospheric flow of erupted fine ash and sulfur oxide was from **[(*west to east*)(*east to west*)]**. Subsequently, the prevailing westerlies dispersed the material to higher latitudes.

2. The Mount Pinatubo Particle Model shows that within two months of the 1991 event, eruption products from the point source at 15.1 degrees North latitude spread around the globe **[(*only in the tropical latitudes*)(*only in the Northern Hemisphere*)(*from tropical to polar latitudes in the***

***Northern and Southern Hemispheres*)]**.
The fine ash and sulfur dioxide from violent volcanic eruptions such as the 1991 Mount Pinatubo episode can block incoming solar radiation, thus decreasing the energy available at Earth's surface for atmospheric warming. In this way the year or so following extremely violent volcanic explosions can be cooler than normal across much of the planet.

Eventually air motions will mix these particles into the lower troposphere where atmospheric circulation, precipitation, and the constant pull of gravity will bring them back to Earth's surface. Although recorded history of such volcanic activity is relatively short, layers of volcanic dust and sulfur particles found in sediment and glacial ice cores can be sources of information on ancient volcanic eruptions and proxy climate data. **Remarkably, the volcanic eruption record even appears in tree growth rings!**

Tree Rings as Temperature Proxies: Trees in middle and high latitudes react to the dominant annual cycle in solar radiation by growing and adding a layer of new wood each year. It has long been known that for trees located in marginal habitats (locations that support only a few species or individuals because of limiting environmental conditions), the width of the annual ring of growth is related to the temperature and precipitation of that season. Thus a cross-section from felled trees or even a small diameter core bored from a living tree can provide clues to the sequence of climate conditions to which the tree was subjected during its growth. Considerable success has been achieved in using tree growth ring records for reconstructing the chronology of past droughts. Of course there are many subtleties involved in tree ring interpretation. For more information, see: *http://www.ltrr.arizona.edu/dendrochronology.html*.

A more recent insight has been within the tree rings' structure itself. For each yearly ring, there are two types of wood, a lighter, less dense early wood layer and a darker, denser latewood section. According to the latest findings, the density of the latewood portion of each layer is most closely correlated to the temperature of that year. To account for variations in location, age of the tree, etc., the studies are typically done by creating anomalies for each year of the sequence. This process has been carried out for many trees in the marginal Northern Hemisphere boreal forest where the growing season is short and particularly sensitive to climatic variability.

One researcher in this area, Keith Briffa with the Climatic Research Unit of the University of East Anglia (UK), has done extensive work relating northern tree rings to temperature. His dataset is available from NCDC's World Data Center (WDC) for Paleoclimatology linked from the course webpage under **Climate Variability**, Climate Forcing Data. Click on this link and scroll down to the list under Volcanic Aerosols, then click on *"Major Volcanic Eruptions, 600 Years, Briffa et al. 1998"*. There, you will find Northern Hemisphere temperature reconstructions of dimensionless yearly sequences of tree ring latewood density anomalies and one sequence of Northern Hemisphere temperature anomalies. The time series values are for the years from 1400 to 1994. Such series of values would be useful to anyone who wishes to study variations of these quantities over time.

Below the time sequences are two summary tables of data from the WDC website. **Table 1** is a ranking of the most negative 5% of the tree ring density anomalies and the corresponding temperature anomalies including year of occurrence.

Table 1. Ranking of the Northern Hemisphere most negative 5% of tree-ring anomalies (NHD1) and corresponding temperature anomalies (NH anom. C degrees).

Rank	Year	NHD1 sValue	NH anom. degrees (C)
1	1601	–6.90	–0.81
2	1816	–4.33	–0.51
3	1641	–4.31	–0.5
4	1453	–4.24	–0.5
5	1817	–3.76	–0.44
6	1695	–3.50	–0.41
7	1912	–3.33	–0.39
8	1675	–3.13	–0.37
9	1698	–3.08	–0.36
10	1643	–2.99	–0.35
11	1699	–2.96	–0.35
12	1666	–2.89	–0.34
13	1884	–2.89	–0.34
14	1978	–2.80	–0.33
15	1837	–2.78	–0.32
16	1669	–2.77	–0.32
17	1587	–2.64	–0.31
18	1740	–2.61	–0.3
19	1448	–2.57	–0.3
20	1992	–2.56	–0.3
21	1836	–2.48	–0.29
22	1818	–2.45	–0.29
23	1495	–2.42	–0.28
24	1968	–2.38	–0.28
25	1742	–2.35	–0.27
26	1783	–2.35	–0.27
27	1667	–2.35	–0.27
28	1642	–2.22	–0.26
29	1819	–2.21	–0.26
30	1446	–2.20	–0.26

3. The latest volcanic eruption evidenced in the list (which occurred at Pinatubo, Philippines) was in 1991. According to the table, its Northern Hemisphere tree-ring anomaly value (listed for 1992) of –2.56 corresponded to a Northern Hemisphere temperature anomaly of **[(*–0.26*)(*–0.28*)(*–0.3*)]** °C.

4. According to the Table 1 listing, the **[(*1600s*)(*1700s*)(*1800s*)(*1900s*)]** were subjected to the greatest negative tree-ring anomalies and corresponding temperature anomalies.

5.

Table 2 is a listing of the largest explosive volcanic eruptions since 1400 including the year, name of volcano, location by latitude and longitude.

Table 2. Largest explosive volcanic eruptions since AD 1400.

Year	Season	Volcano and region	Lat. (deg)	Long. (deg)	VEI
1450	–	Aniakchak, Alaska	56.9N	158.1W	5(?)
1452	–	Kuwae, Vanuatu, SW Pacific	16.8S	168.5E	6
1471	3yr	Sakura-Jima, Japan	31.6N	130.7E	5(?)
1477	1	Bardarbunga (Veidivotn), Iceland	64.6N	17.5W	5(?)
1480	–	St Helens, Washington, US	46.2N	122.2W	5(+)
1482	–	St Helens, Washington, US	46.2N	122.2W	5
1580	–	Billy Mitchell, Bougainville, SW P	6.1S	155.2E	6
1586	–	Kelut, Java	7.9S	112.3E	5(?)
1593	–	Raung, Java	8.1S	114.0E	5(?)
1600	1	Huaynaputina, Peru	16.6S	70.9W	6(?)
1640	3	Komaga-Take, Japan	42.1N	140.7E	5
1641	1	Parker, Philippines§	6.1N	124.9E	6
1660	–	Long Island, New Guinea	5.4S	147.1E	6
1663	3	Usu, Japan	42.5N	140.8E	5
1667	4	Shikotsu (Tarumai), Japan	42.7N	141.3E	5
1673	2	Gamkonora, Halmahera	1.4N	127.5E	5(?)
1680	–	Tongkoko, Sulawesi	1.5N	125.2E	5(?)
1707	1	Fuji, Japan	35.4N	138.7E	5
1739	3	Shikotsu (Tarumai), Japan	42.7N	141.3E	5
1800	1	St Helens, Washington, US	46.2N	122.2W	5
1815	2	Tambora, Lesser Sunda Is	8.3S	118.0E	7
1835	1	Cosiguina, Nicaragua	13.0N	87.6W	5
1853	1	Chikurachki, Kurile Is	50.2N	155.0E	5(?)
1854	1	Sheveluch, Kamchatka	56.7N	161.4E	5
1883	3	Krakatau, west of Java	6.1S	105.4E	6
1886	3	Okataina (Tarawera), New Zealand	38.1S	176.5E	5
1902	4	Santa Maria, Guatemala	14.8N	91.6W	6(?)
1907	2	Ksudach, Kamchatka	51.8N	157.5E	5
1912	1	Novarupta (Katmai), Alaska	58.3N	155.2W	6
1932	2	Azul, Cerro (Quizapu), Chile	35.7S	70.8W	5(+)
1956	2	Bezymianny, Kamchatchka	56.0N	160.6E	5
1980	2	St Helens, US	46.2N	122.2W	5
1982	2	El Chichon, Mexico	17.4N	93.2W	5
1991	3	Pinatubo, Philippines	15.1N	120.4E	6

In Table 2, VEI (Volcanic Explosivity Index) is a measure of the explosive strength of a volcanic eruption based on amount of ejecta and plume height with increasing numbers corresponding to increasing strength. The season of the eruption (where known) is denoted by a digit, 1 = winter (Dec-Feb), 2 = spring (Mar-May), 3 = summer (Jun-Aug), and 4 = fall (Sep-Nov).

5. According to the VEI rating listed in Table 2, the most explosive eruption of the period given was Tambora in the year **[(*1482*)(*1600*)(*1815*)]**. The worldwide effect of this event is chronicled in the *AMS Climate Studies* text as "the year without a summer".

6. From Table 2, the most frequently erupting volcano was **[(*St. Helens*)(*Pinatubo*)(*Krakatau*)]**.

Table 3 employs data from Tables 1 and 2 to search for patterns between major explosive volcanic eruptions and negative (cold) Northern Hemisphere temperature anomalies as related to tree ring density anomalies.

Table 3 is constructed so the Eruption Years listed in the left column are the same as those listed in Table 2. These Eruption Years are the dates of occurrence of the 34 largest explosive volcanic eruptions in the time period 1450-1991. Dates (in italics) plotted in Table 3 were acquired from Table 1 which provided data on the years with the 30 most negative tree-ring and corresponding temperature anomalies. These italicized dates were plotted when the first anomaly year matched the year of the eruption or the year following the eruption. Subsequent anomaly years are plotted when there is no skip in years following the initial anomaly year.

Table 3. Eruption year and subsequent year(s) with cold temperature anomaly.

Eruption Year	Year of Cold Temperature Anomaly				
	Same Yr	Yr + 1	Yr + 2	Yr + 3	Yr + 4
1450					
1452		*1453*			
1471					
1477					
1480					
1482					
1580					
1586		*1587*			
1593					
1600		*1601*			
1640		*1641*	*1642*	*1643*	
1641	*1641*	*1642*	*1643*		
1660					
1663					
1667	*1667*				
1673					
1680					
1707					
1739		*1740*			
1800					
1815		*1816*	*1817*	*1818*	*1819*
1835		*1836*	*1837*		
1853					
1854					
1883		*1884*			
1886					
1902					
1907					
1912	*1912*				
1932					
1956					
1980					
1982					
1991		*1992*			

7. According to Table 3, a total of **[(*3*)(*4*)(*5*)]** cold temperature anomalies occurred in the same year as a major eruption.

8. According to Table 3, a total of **[(*3*)(*5*)(*9*)]** cold temperature anomalies appeared for the first time in the year following the year of major eruption ("Year + 1").

9. Of the 34 greatest explosive volcanic eruptions listed in Table 3, about **[(*15*)(*25*)(*35*)]** % of them were followed by at least one of the most negative 5% of tree-ring anomalies and corresponding temperature anomalies as listed in Table 1 within the same year or one year following a major volcanic eruption.

10. Therefore, one can conclude that it is **[(*likely*)(*not at all likely*)]** that volcanic particles in the atmosphere from major explosive eruptions could result in blocking sunlight and lowering surface air temperatures.

11. Some of the eruptions had a fairly long-lasting effect. For instance, Tambora in 1815 was acknowledged as the most violent eruption in recent history with VEI = 7. Table 3 shows that Tambora's eruption probably led to significant cold temperature anomalies for **[(*2*)(*3*)(*4*)(*5*)]** subsequent years.

12. Another way in which a lasting atmospheric cooling effect may occur is shown in the Table 1 rankings by the years 1641, 1642, and 1643. These years coincided or followed the eruptions of **[(*Komaga-Take*)(*Shikotsu*)(*Sakur-Jima*)]** in Japan in 1640 and Parker in the Philippines in 1641. It is likely that both eruptions simultaneously contributed to atmospheric cooling for at least two years.

In fact, cooling by volcanic sulfur dioxide and fine ash in the upper atmosphere may have resulted from other periods of significant and/or sustained but less dramatic eruptions. For example, 1968 is number 24 in rank, yet does not follow a listed volcanic explosion. However, Mt. Agung on Bali in Indonesia erupted violently in 1963-64, killing 1700 people. It was a massive sulfur-rich episode and was noted for its stratospheric aerosol input.

Summary : The primary external boundary condition of solar energy input to Earth's climate system can be impacted significantly by internal processes in the climate system that provide variability to the resulting annual state. One significant variation in the amount of this energy absorbed into the Earth system occurs when volcanoes eject large quantities of ash and gases into the atmosphere producing particles that reflect and scatter solar energy which would otherwise wend its way through the climate system. In total, Earth's climate system is the sum of all such processes and therefore exhibits inherent variations on scales of years to decades and millennia.

SNOW AND ICE ALBEDO FEEDBACK IN EARTH'S CLIMATE SYSTEM

Driving Questions: *What impacts do snow and ice albedo have on climate? Is the amount of snow and ice on Earth decreasing?*

Educational Outcomes: To describe the seasonal and permanent snow and ice cover impacts on global and regional climates. To explain how the presence or absence of snow and ice cover controls patterns of heating and cooling over Earth's surface more than any other surface feature. To examine observations that show a global-scale decline of snow and ice for many years, including the polar amplification of surface temperatures in the high latitudes of the Northern Hemisphere.

Objectives: After completing this investigation, you should be able to:

- Describe polar amplification and the observed changes in snow and ice cover in recent decades.
- Explain the concepts of positive and negative feedback and provide examples of such feedbacks resulting from different Earth surfaces including snow cover, ice, bare ground, and open water.

Polar Amplification: Observational data of Earth surface temperatures have shown an unequivocal pattern of planetary warming. However, this warming trend has not been uniform around the globe. **Figure 1** traces temperature change for three latitude bands (Northern, Low, and Southern Latitudes) from 1900 through 2011, based on their average annual global mean surface temperatures for the period of 1951-1980. Note the different temperature anomaly scales in the three graphs. In the individual Figure 1 graphs, black data points connected by dotted lines are actual temperature anomaly curves. The red curves are based on five-year running averages, and the green bars show uncertainty estimates.

1. All latitude bands in Figure 1 show long-term temperature anomaly trends, especially since the 1970's, indicating **[(*cooling*)(*steady temperatures*)(*warming*)]**.

2. Based on the red five-year running mean curves from 1900 to 2009, the greatest warming occurred in the **[(*northern-*)(*low-*)(*southern-*)]** latitude band.

The IPCC *(Climate Change 2007)* reported that during essentially the same time period, the average surface temperature in the Arctic increased at almost twice the global rate. This greater temperature increase in the Arctic is termed **Polar Amplification.** The term is generally not applied to the Antarctic as it has not experienced such a dramatic increase.

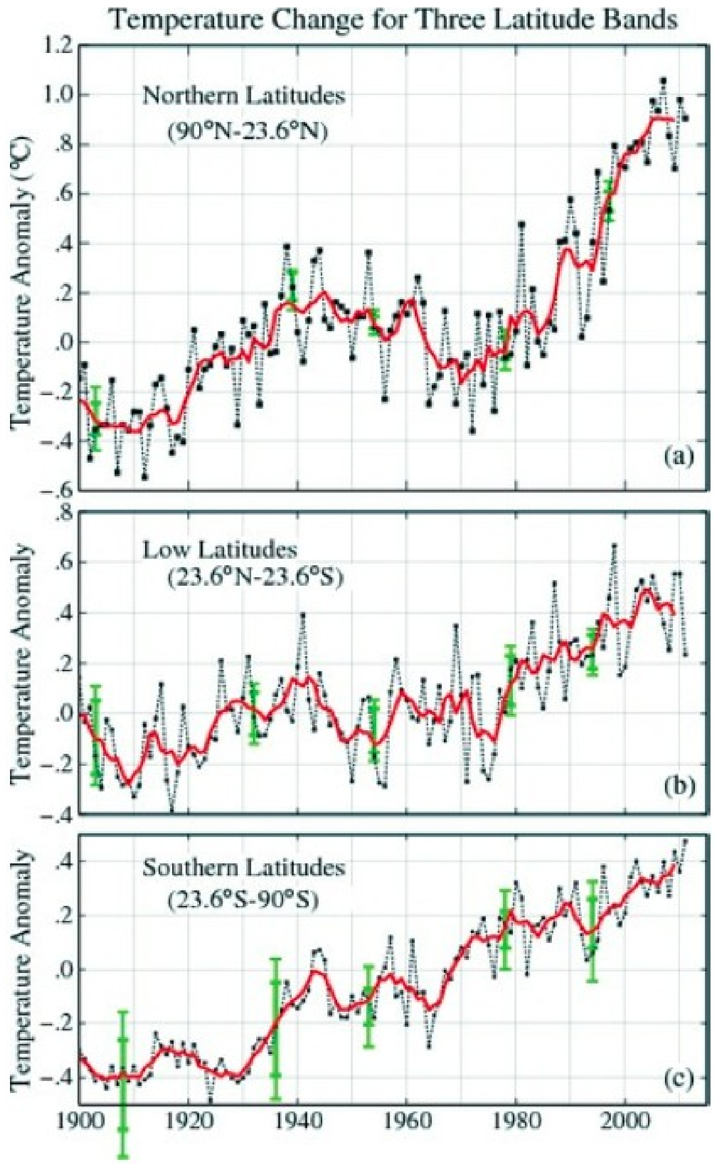


Figure 1.
Temperature departures (anomalies) from the long-term global mean surface temperature by latitude bands, 1900-2011. [Goddard Institute for Space Studies/NASA]

Figure 2 is an IPCC *(Climate Change 2007)* depiction of surface temperature anomalies at high latitudes and associated snow and ice conditions.

3. Compare Figure 2's surface air temperature anomaly graphs (A) north of 65 degrees N and (G) south of 65 degrees S. They show that in recent decades the increase in surface air temperatures was significantly greater in the **[(*Arctic*)(*Antarctic*)]**.

4. Figure 2's graphs depicting Northern Hemisphere anomalies of (B) sea ice extent, (C) frozen ground extent, and (D) snow cover extent for recent decades indicate trends of **[(*increasing*) (*steady*)(*decreasing*)]** values. These are expected outcomes of Polar Amplification.

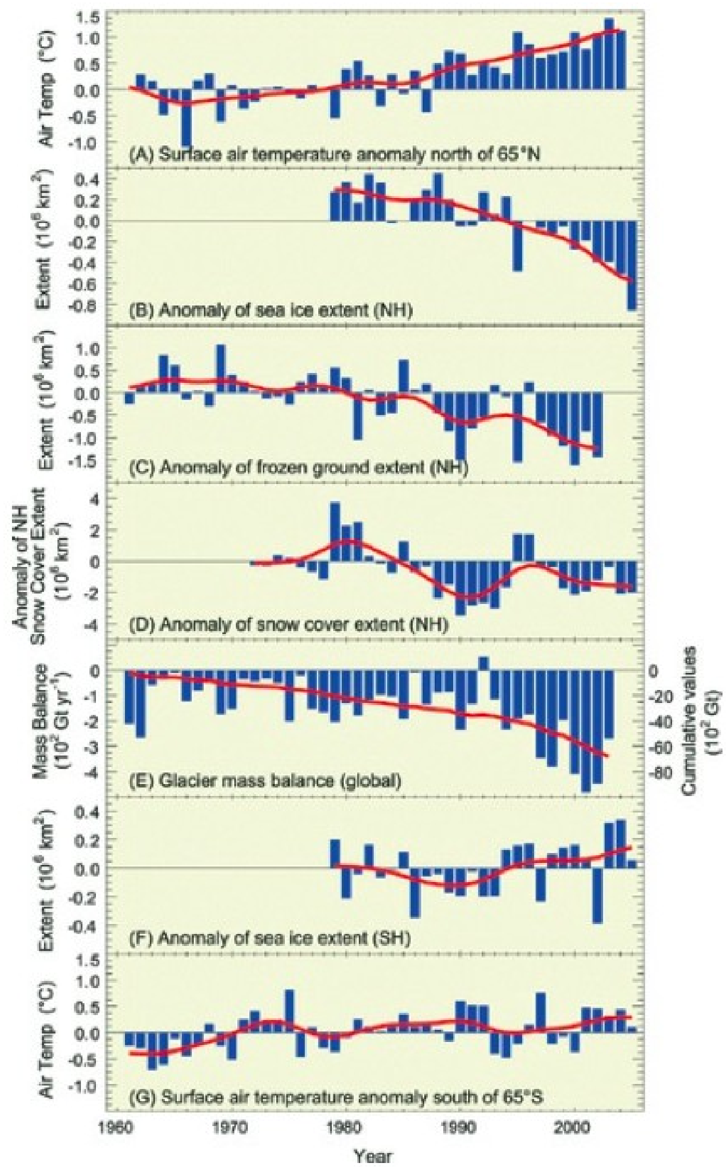


Figure 2. Departures from the long-term means of high latitude Northern and Southern Hemisphere surface temperatures (A and G) and sea ice extent (B and F), and Northern Hemisphere frozen ground extent (C) and snow cover extent (D). [IPCC Climate Change 2007, Physical Science Basis]

A number of boundary conditions and feedback mechanisms result in Polar Amplification. We will investigate feedback mechanisms at work in the Arctic where the highest latitudes are ocean environments covered by ice for much of the year (and, of course, at sea-level altitude). [This contrasts with the Antarctic where the geography is land surrounded by water, and its surface found at an average altitude of about 2500 m (8200 ft).]

Feedback: The sequence of interactions between climate controls determines how Earth's climate system responds to a disturbance (or perturbation) of the boundary conditions of the system. These interactions constitute *feedback* in the system. As defined by the IPCC, "An interaction mechanism between processes in the climate system is called a **climate feedback** when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it." There are many feedback mechanisms or processes in the climate system.

A feedback that reinforces the original process is called a *positive feedback.* An example of a positive climate feedback is the water vapor — greenhouse effect. An increase in surface temperature enhances
evaporation at Earth's surface which introduces more water vapor into the atmosphere. Being a strong absorber of IR, greater concentrations of water vapor trap more terrestrial radiation which results in heating and a further increase in atmospheric temperature.

A feedback that tends to reduce the process that caused it is called a negative feedback. An example of negative feedback is the interaction of plant growth with atmospheric CO_2 concentration. Increasing CO_2 concentration due to human activity, or other causes, stimulates plant growth. Greater photosynthesis requires additional CO_2, and the source of this CO_2 is the air. This removal of CO_2 from the atmosphere acts to reduce atmospheric CO_2 concentrations, thereby slowing the rate of increase of CO_2.

In summary, a feedback which strengthens the original forcing mechanism is a positive feedback. A feedback which weakens the original mechanism is a negative feedback.

Incident solar radiation is a primary boundary condition of Earth's climate system. The albedo of Earth's surface determines the fraction of incident solar radiation that is converted to heat. (The lower the albedo, the greater the percentage of incident radiation absorbed and subsequently radiated upward as heat.) Therefore, all other factors being equal, the air temperature over a high albedo surface (e.g., ice cover) is lower than over a low albedo surface (e.g., open water).

5. The albedo of an ocean water surface is considerably lower than the albedo of sea ice, that is, a water surface absorbs more of the sunlight striking it than does an ice surface. (Refer to your textbook to review albedo values over different surfaces.) Hence, shrinkage of the Arctic sea ice cover and the attendant increase in ice-free ocean surfaces would result in **[(*greater*)(*about the same*)(*less*)]** absorption of solar radiation during the Arctic summer.

6. This absorption of solar radiation produces **[(*higher*)(*minimal change in*)(*lower*)]** sea surface temperatures.

7. With higher air and water temperatures in the Arctic, we would expect the rate of melting of Arctic sea ice cover to increase and lead to further warming. This is an example of **[(*positive*) (*negative*)]** feedback. This ice/albedo feedback is summarized graphically in **Figure 3.**

8. In Figure 3, "Thinner Ice Cover" and "Less Snow Cover" cause "More SW (solar short wave radiation) to be absorbed in system" because thinner ice cover and less snow cover **[(*increases*) (*decreases*)]** the surface albedo.

9. In Figure 3, evaporation is accounted for in the box entitled "Increased Summer Open Water". Less sea-ice cover and higher sea surface temperatures in the Arctic Ocean would mean **[(*higher*) (*lower*)]** rates of evaporation and a more humid lower atmosphere.

10. Another sequence of processes involves feedback related to clouds. A more humid atmosphere in the Arctic would likely increase the cloud cover. Clouds cause both cooling (by reflecting sunlight to space) and warming (by absorbing outgoing infrared radiation from Earth's surface and radiating some of that energy downward). During the long dark polar winter, clouds would have a warming effect. Since the primary process at this time of the year is radiative cooling, this wintertime situation is an example of a **[(*positive*)(*negative*)]** feedback on temperature.

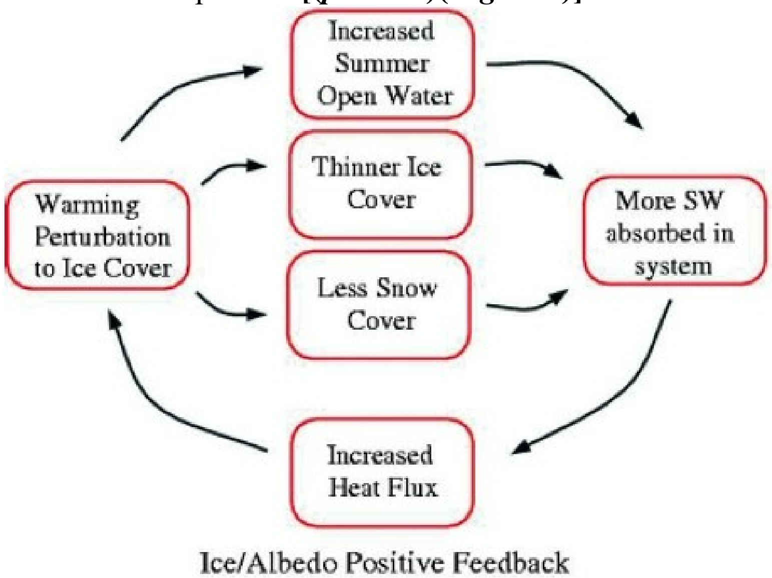


Figure 3.
A graphical representation of the ice/albedo positive feedback operating in the Arctic Ocean. Boxes enclose changes in specific climate controls. "SW" refers to solar short wave radiation. Arrows represent interactions between controls directed from a cause to an effect. (From Marika Holland, 2000. "Variability in Arctic Sea Ice: Causes and Effects." UCAR. *http://www.asp.ucar.edu/colloquium/2000/Lectures/holland.html*).

11. In summer, the impact of greater cloud cover depends on the height of the clouds. Cooling would prevail with an increase in low cloud cover, thereby providing **[(*positive*)(*negative*)]** feedback. Warming would likely accompany an increase in high cloud cover, thereby providing the opposite feedback.

12. The presence or absence of snow cover has significant impacts on weather and climate. Because of higher temperatures in recent decades the extent of seasonal snow cover has decreased. In Figure 3, follow the path from "Less Snow Cover" through short wave radiation absorption and onward. This reduction in snow cover is a **[(*positive*)(*negative)*]** feedback mechanism, further strengthening Polar Amplification.

Snow Cover: In winter, the impact of snowstorms on weather and climate lingers long after the storm ends. **Figure 4** is a visible MODIS image of the Great Lakes area showing bare ground to the south and southwest, snow cover around Lake Superior extending southward, open water in Lakes Superior and Michigan, frozen lakes in the northwest, and clouds in the northeastern portion of the image. Note the open-water darker lake surfaces, a demonstration of water's lower albedo.

Compare the albedo of the unfrozen Great Lakes with the albedo of the frozen Minnesota lakes in the northwestern part of the image.

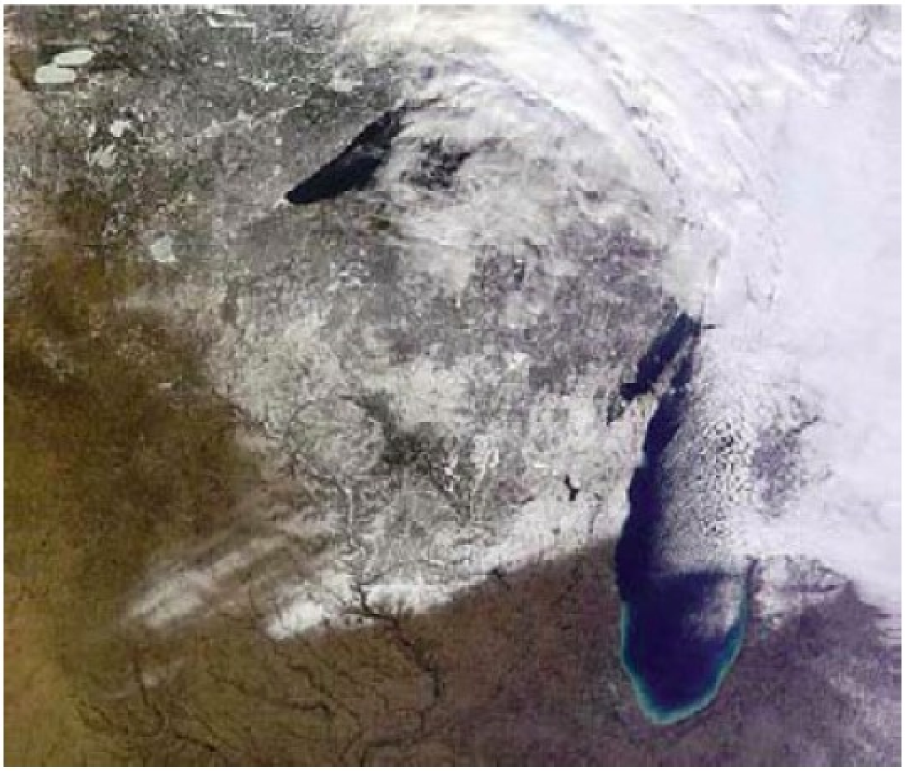


Figure 4.
Great Lakes area with snow cover, bare ground, open water, and lake ice, 24 December 2011. [MODIS]

13. In Figure 4 it can be seen that the snow cover is highly reflective of sunlight, returning large amounts of incident solar energy back to space. The lower-albedo bare ground reflects less of the sunlight striking it. Assuming that in the cloud-free regions in the image it was midday and the rate of incoming solar radiation was relatively uniform over the area, the **[(*snow-covered*)(*bare*)]** ground would experience a greater heating effect by the sunlight.

14. Imagine the same snow-covered and bare areas were at midday suddenly covered by a highly-reflective cloud or aerosol (e.g., smoke, dust) layer as in the northeastern portion of the image. With such a transformation, the **[(*snow-covered*)(*bare*)]** ground would experience the greater change in the sunlight's heating effect. This example is intended to demonstrate only one of numerous changes in environmental conditions that can lead to complex adjustments in Earth's climate system.

Summary: The presence or absence of snow and ice cover controls patterns of heating and cooling over Earth's surface more than any other surface feature. The higher latitudes of the Northern Hemisphere are especially impacted, resulting in Polar Amplification. Polar Amplification, in turn, impacts other boundary conditions of Earth's climate system.