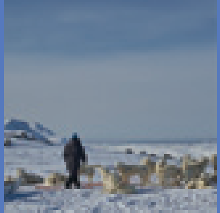
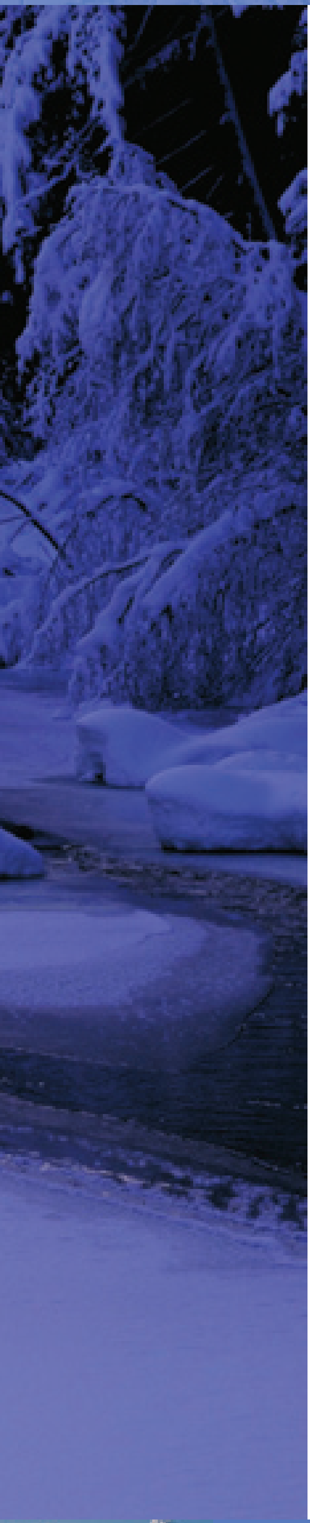
Snow and Ice



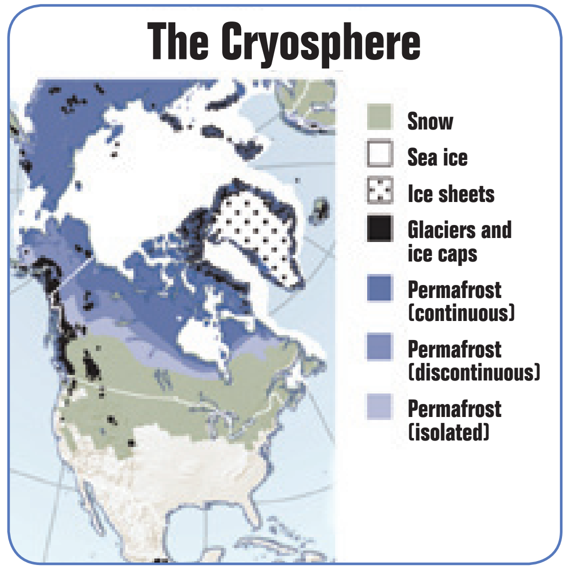
Arctic Sea Ice

Glaciers

Lake Ice



The Earth's surface contains many forms of snow and ice, including sea ice, lake and river ice, snow cover, glaciers, ice caps and sheets, and frozen ground. Together, these features are sometimes referred to as the "cryosphere," a term for all parts of the Earth where water exists in solid form.



Source: UNEP, 2007[1]

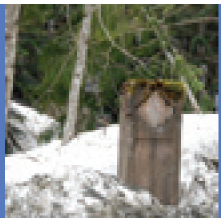
Snow and ice are an important part of the global climate system. Because snow and ice are highly reflective, much of the sunlight that hits these surfaces is reflected back into space instead of warming the Earth. The presence or absence of snow and ice affects heating and cooling over the Earth's surface, influencing the planet's energy balance.

Climate change can dramatically alter the Earth's snow- and ice-covered areas. Unlike other substances found on the Earth, snow and ice exist relatively close to their melting point and can change from solid to liquid and back again. As a result, prolonged warming or cooling trends can result in observable changes across the landscape as snow and ice masses shrink or grow over time.

Changes in snow and ice cover, in turn, affect air temperatures, sea levels, ocean currents, and storm patterns. For example, melting polar ice caps add fresh water to the ocean, increasing sea level and possibly changing currents that are driven by differences in temperature and salinity. Because of their light color, snow and ice reflect more sunlight than open water or bare ground, so a reduction in snow cover and ice causes the Earth's surface to absorb more energy from the sun.

Changes in snow and ice could not only affect communities and natural systems in northern and polar regions, but also have worldwide implications. For example, thawing of frozen ground and reduced sea ice in the Arctic could affect biodiversity on local and global scales, leading to harmful effects not only on polar bears and seals, but also on migratory species that breed or feed in these areas. These same changes could affect human societies in several ways, such as by compromising food availability. For communities in Arctic regions, reduced sea ice could increase coastal erosion and exposure to storms, threatening homes and property, while thawing ground could damage roads and buildings. Reduced snow cover could diminish the beneficial insulating effects of snow for vegetation and wildlife, while also affecting water supplies, transportation, cultural practices, travel, and recreation for millions of people.

Snow Cover



Snowpack

Arctic Sea Ice

This indicator tracks the extent of sea ice in the Arctic Ocean.

Background

Sea ice is a key feature in the Arctic Ocean. During the dark winter months, sea ice covers nearly the entire Arctic Ocean. In summer, some of this ice melts because of warmer temperatures and long hours of sunlight. Sea ice typically reaches its minimum extent in mid-September, then begins expanding again through the winter.

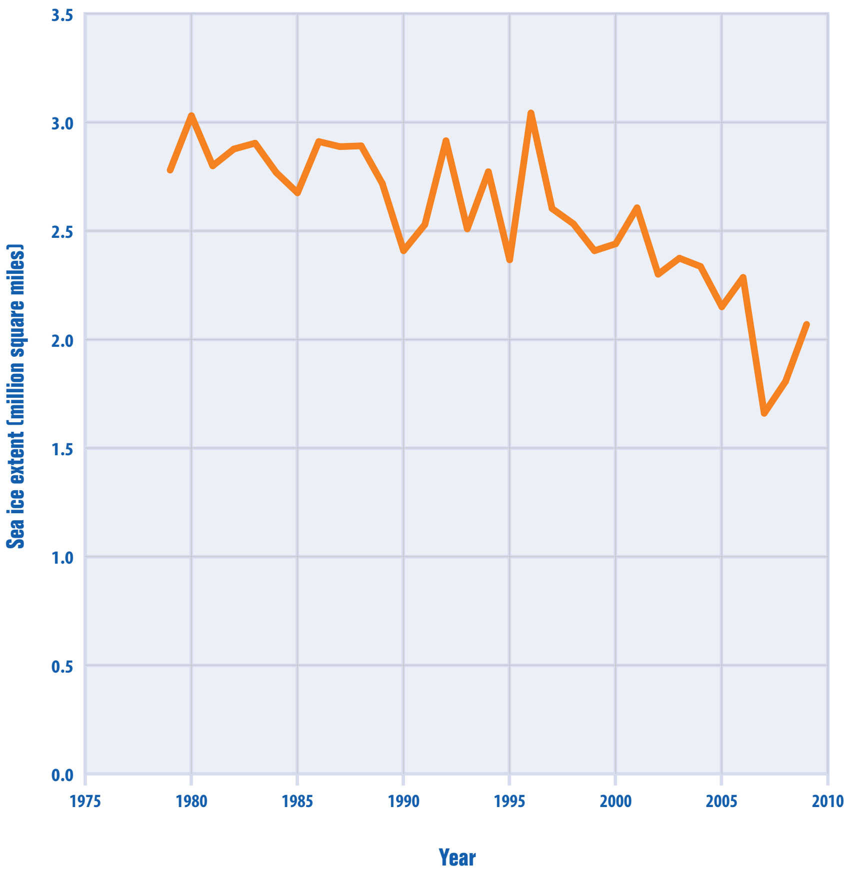
The extent of area covered by Arctic sea ice is considered a sensitive indicator of global climate because a warmer climate will reduce the amount of sea ice present. Because sea ice is more reflective than liquid water, it also plays a role in regulating global climate by keeping polar regions cool. (For more information on the effects of surface color on reflecting sunlight, see the Snow Cover indicator on p. 52.) Thus, as the amount of sea ice decreases because of increased air temperatures, the Arctic region's ability to stabilize the Earth's climate is reduced, potentially leading to a "feedback loop" of more absorption of solar energy, higher air temperatures, and even greater loss of sea ice.

Arctic mammals, such as polar bears and walruses, rely on the presence of sea ice to preserve their hunting, breeding, and migrating habits. These animals might become threatened if birth rates decline or access to food sources is restricted

(Continued on page 47)

Figure 1. September Average Arctic Sea Ice Extent, 1979–2009

This figure shows Arctic sea ice extent from 1979 through 2009 using data from September of each year, which is when the minimum extent typically occurs.

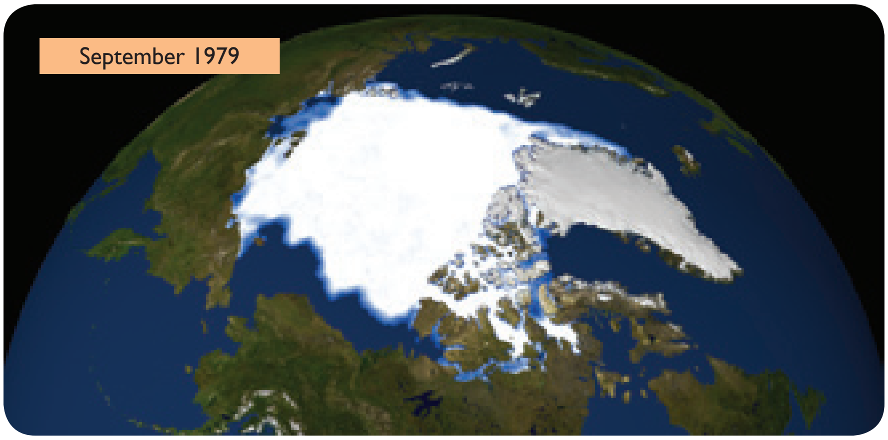


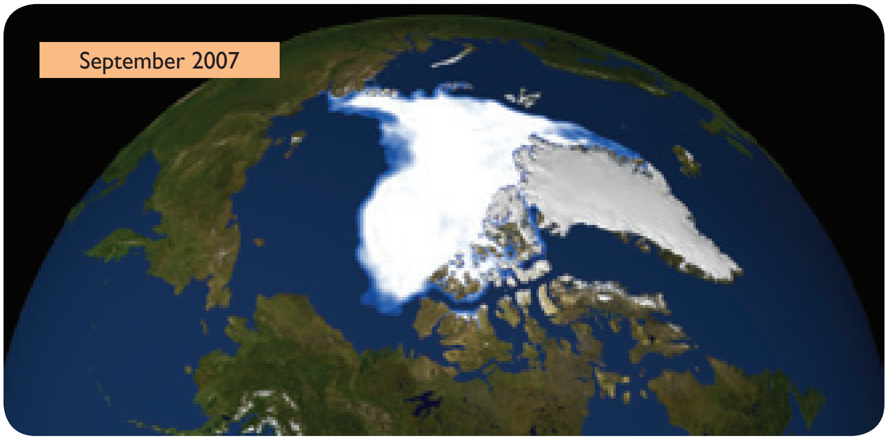
Data source: NSIDC, 2009[2]

Key Points

- The lowest sea ice extent on record occurred in September 2007. Compared with the previous minimum set in September 2005, the 2007 total reflected a loss of 490,000 square miles of sea ice—an area larger than Texas and California combined (see Figure 1).
- Compared with the 1979 to 2000 average, the extent of Arctic sea ice in 2007 was lower by 1 million square miles—an area approximately the size of Alaska and Texas combined (see Figure 1).
- Although September 2009 saw an increase in sea ice extent compared with 2007 and 2008, the 2009 sea ice extent was still 24 percent below the 1979 to 2000 historical average.
- Although the annual minimum of sea ice extent typically occurs in September, all months have shown a decreasing trend in sea ice extent over time.[3]

Dwindling Arctic Sea Ice





Source: NASA, 2009[4]

because of diminished sea ice. Impacts on Arctic wildlife, as well as the loss of ice itself, threaten the traditional lifestyle of indigenous Arctic populations such as the Yup'ik, Iñupiat, and Inuit. In addition to reducing the number of animals available to hunt, diminished sea ice extent and earlier melting can severely limit hunting seasons and access to hunting grounds, making traditional subsistence hunting more difficult. While diminished sea ice can have negative ecological effects, it can also present positive commercial opportunities. For instance, reduced sea ice opens shipping lanes and increases access to natural resources in the Arctic region.

About the Indicator

This indicator reviews trends in Arctic sea ice extent from 1979 to 2009. Sea ice extent is defined as the area of ocean where at least 15 percent of the surface is frozen. Data are collected throughout the year, but for comparison, this indicator focuses on sea ice extent data for September of each year. This is because September is typically when the sea ice extent reaches its annual minimum after melting during the summer months. Data for this indicator were gathered by the National Snow and Ice Data Center using satellite imaging technology.

Indicator Limitations

Increasing temperatures associated with climate change are not the only factor contributing to reductions in sea ice. Other conditions, such as fluctuations in oceanic and atmospheric circulation and typical annual and decadal variability, also affect the extent of sea ice. Additionally, changes in the age and thickness of sea ice—a trend toward younger and thinner ice—might also increase the rate at which the ice melts in summer, making year-to-year comparisons more complex.

Data Sources

The data for this indicator were provided by the National Snow and Ice Data Center and are available online at: http://nsidc.org/data/seaice_index/archives/index.html. The National Snow and Ice Data Center also produces a variety of reports and a seasonal newsletter analyzing Arctic sea ice data.

Glaciers

This indicator examines the balance between snow accumulation and melting in glaciers, and describes how the size of glaciers around the world has changed over time.

Background

A glacier is a large mass of snow and ice that has accumulated over many years and is present year-round. In the United States, glaciers can be found in the Rocky Mountains, the Sierra Nevada, the Cascades, and throughout Alaska. A glacier naturally flows like a river, only much slower. It accumulates snow at higher elevations, which eventually becomes compressed into ice. At lower elevations, the "river" of ice naturally loses volume because of melting and ice breaking off and floating away. When melting is exactly balanced by new snow accumulation, a glacier is in equilibrium and is neither growing nor shrinking.

Glaciers are important to humans and ecosystems because their normal melting process provides a reliable source of stream flow and drinking water, particularly late in the summer when seasonal snowpack has melted away. A large portion of Earth's fresh water is found in glaciers, including the polar ice sheets. Glaciers are also important as an indicator of climate change. Physical changes in glaciers—whether they are growing or shrinking, advancing or receding—provide visible evidence of changes in temperature and precipitation. If glaciers lose mass to melting and breaking off (particularly the Greenland and Antarctic ice sheets), they ultimately add more water to the oceans, leading to a rise in sea level (see the Sea Level indicator on p. 40).

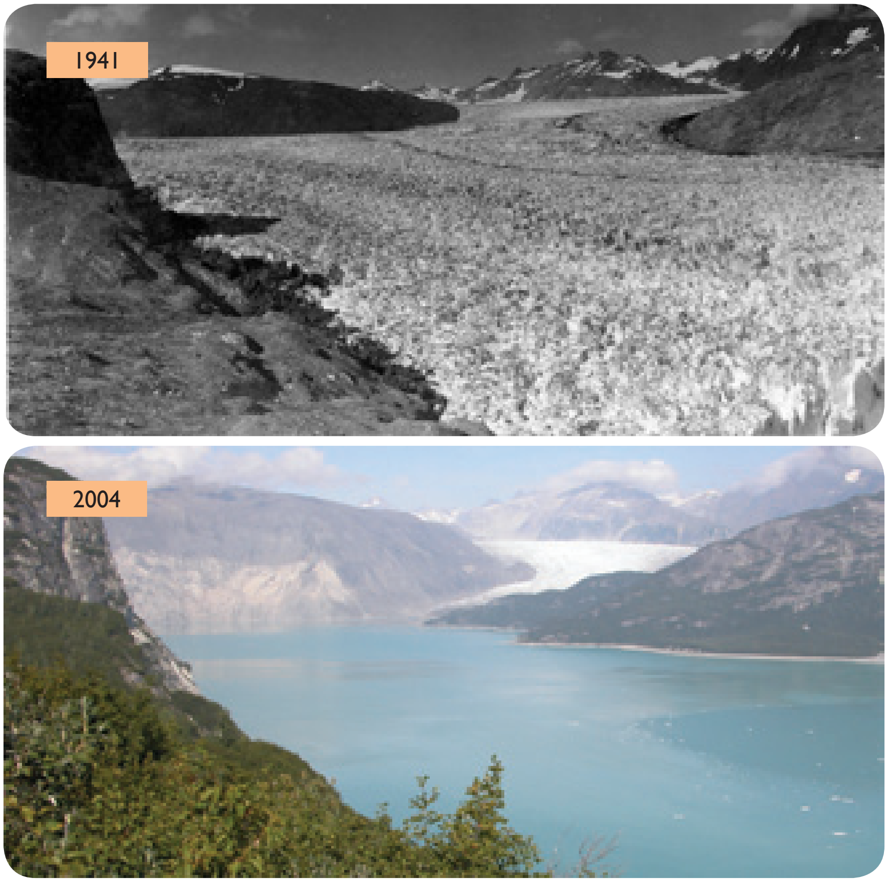
About the Indicator

This indicator is based on long-term monitoring data collected at glaciers around the world. At many glaciers, scientists collect detailed measurements to determine mass balance, which is the net gain or loss of snow and ice over the course of the year. A negative mass balance indicates that a glacier has lost ice or snow. Looking at cumulative mass balance over time will reveal long-term trends. For example, if cumulative mass balance becomes more negative over time, it means glaciers are melting faster than they can accumulate new snow.

Figure 1 shows the total change in volume of glaciers worldwide since 1960, when widespread measurement began to take place. The overall change in volume was determined by collecting all available measurements, then estimating a global trend based on the total surface area of

(Continued on page 49)

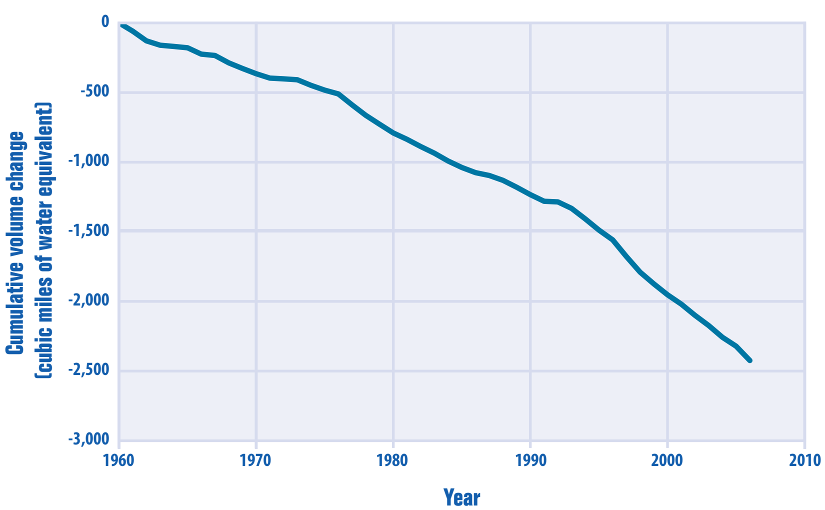
Photographs of Muir Glacier, Alaska, 1941 and 2004



Sources: Field, 1941;[5] Molnia, 2004[6]

Figure 1. Change in Volume of Glaciers Worldwide, 1960–2006

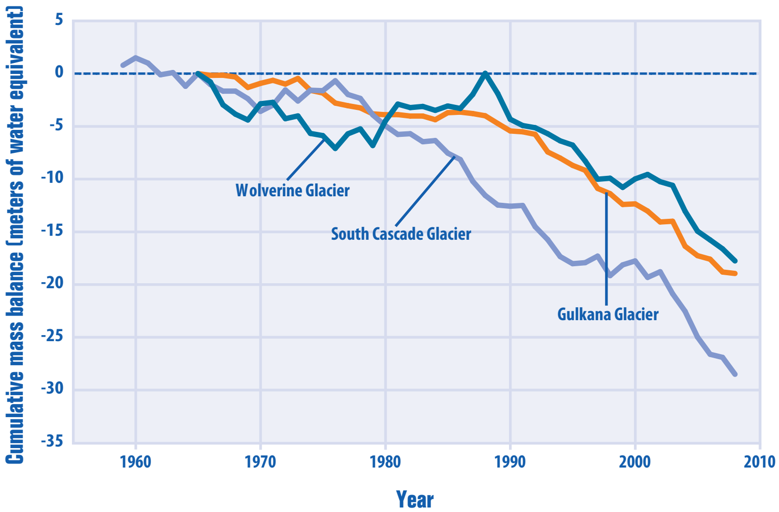
This figure shows the cumulative change in volume of glaciers worldwide beginning in 1960. Negative values in later years indicate a net loss of ice and snow compared with the base year of 1960. For consistency, measurements are in cubic miles of water equivalent, which means the total amount of ice or snow lost has been converted to the equivalent volume of liquid water.



Data source: Dyurgerov, in press[7]

Figure 2. Mass Balance of Three Typical U.S. Glaciers, 1958–2008

This figure shows the cumulative mass balance of the three U.S. Geological Survey "benchmark" glaciers since measurements began in the 1950s or 1960s. For each glacier, the mass balance is set at zero for the base year of 1965. Negative values in later years indicate a net loss of ice and snow compared with the base year. For consistency, measurements are in meters of water equivalent, which means the amount of ice or snow has been converted to the equivalent amount of liquid water.



Data source: USGS, 2009[8]

Key Points

- Since 1960, glaciers worldwide have lost more than 2,000 cubic miles of water (see Figure 1), which in turn has contributed to observed changes in sea level (see the Sea Level indicator on p. 40). The rate at which glaciers are losing volume appears to have accelerated over roughly the last decade.
- All three U.S. benchmark glaciers have shown an overall decline in mass since the 1950s and 1960s (see Figure 2). Year-to-year trends vary, with some glaciers gaining mass in certain years (for example, Wolverine Glacier between 1986 and 1988). However, most of the measurements indicate a loss of mass over time.
- Trends for the three benchmark glaciers are consistent with the retreat of glaciers observed throughout the western United States, Alaska, and other parts of the world.[9] Observations of glaciers losing mass are also consistent with warming trends in U.S. and global temperatures during this time period (see the U.S. and Global Temperature indicator on p. 22).

Glaciers Shown in Figure 2

glaciers worldwide. Figure 2 shows trends for three "benchmark" glaciers that have been extensively studied by the U.S. Geological Survey: South Cascade Glacier in Washington state, Wolverine Glacier near Alaska's southern coast, and Gulkana Glacier in Alaska's interior. These three glaciers were chosen because they are representative of other glaciers in their regions.

Indicator Limitations

The relationship between climate change and glacier mass balance is complex, and the observed changes at the three U.S. benchmark glaciers might reflect a combination of global and local climate variations. Slightly different measurement methods have been used at different glaciers, but overall trends appear to be similar.

Long-term measurements are available for only a relatively small percentage of the world's glaciers, so the total global trend in Figure 1 is also based in part on some of the best available estimates. The total in Figure 1 does not include the Greenland and Antarctic ice sheets. Other evidence suggests that these ice sheets are also experiencing a net loss in volume.[10]

Data Sources

The University of Colorado at Boulder provided the global trend in Figure 1. Its analysis is based on measurements collected from a variety of publications and databases. An older version of this analysis was published by the U.S. Global Change Research Program in 2009,[11] and the latest version is expected to be published in the scientific literature sometime in 2010.

The U.S. Geological Survey Benchmark Glacier Program provided the data for Figure 2. These data, as well as periodic reports and measurements of the benchmark glaciers, are available on the program's Web site at: http://ak.water.usgs.gov/glaciology.

Lake Ice

This indicator measures the amount of time that ice is present on lakes in the United States.

Background

The formation of ice cover on lakes in the winter and its disappearance the following spring depends on climate factors such as air temperature, cloud cover, and wind. Conditions such as heavy rains or snowmelt in locations upstream or elsewhere in the watershed also affect lake ice duration. Thus, ice formation and breakup dates are key indicators of climate change. If lakes remain frozen for longer periods, it can signify that the climate is cooling. Conversely, shorter periods of ice cover suggest a warming climate.

Changes in ice cover can affect the physical, chemical, and biological characteristics of a body of water. For example, ice influences heat and moisture transfers between a lake and the atmosphere. Reduced ice cover leads to increased evaporation and lower water levels, as well as an increase in water temperature and sunlight penetration. These changes, in turn, can affect plant and animal life cycles and the availability of suitable habitat. Additionally, ice cover affects the amount of heat that is reflected from the Earth's surface. Exposed water will absorb and retain heat, whereas an ice- and snow-covered lake will reflect the sun's energy rather than absorb it. (For more information on ice and snow reflecting sunlight, see the Snow Cover indicator on p. 52.)

The timing and duration of ice cover on lakes and other bodies of water can also affect society—particularly shipping and transportation, hydroelectric power generation, and fishing. The impacts can be either positive or negative. For example, reduced ice cover on a large lake could extend the open-water shipping season, but require vessels to reduce their cargo capacity because of decreased water levels.

About the Indicator

This indicator analyzes the dates at which lakes freeze and thaw. Freeze dates are when a continuous and immobile ice cover forms over a body of water. Thaw dates are when the ice cover breaks up and open water becomes extensive.

(Continued on page 51)

Key Points

- The time that lakes stay frozen has generally decreased since the mid-1800s. For most of the lakes in this indicator, the duration of ice cover has decreased at an average rate of one to two days per decade (see Figure 1).
- The lakes covered by this indicator are generally freezing later than they did in the past. Freeze dates have grown later at a rate of roughly half a day to one day per decade (see Figure 2).
- Thaw dates for most of these lakes show a general trend toward earlier ice breakup in the spring (see Figure 3).
- The changes in freeze and thaw dates shown here are consistent with other studies. For example, a broad study of lakes and rivers throughout the Northern Hemisphere found that since the mid-1800s, freeze dates have occurred later at an average rate of 5.8 days per 100 years, and thaw dates have occurred earlier at an average rate of 6.5 days per 100 years.[12]

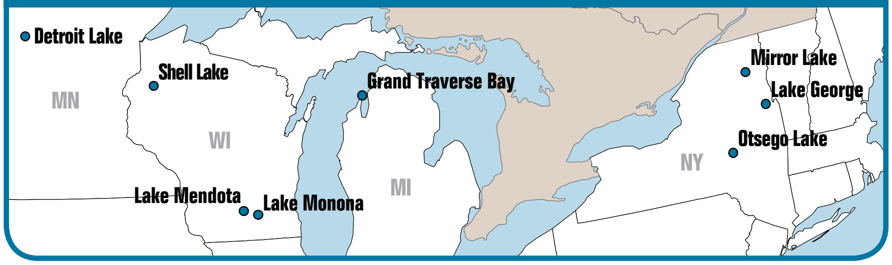
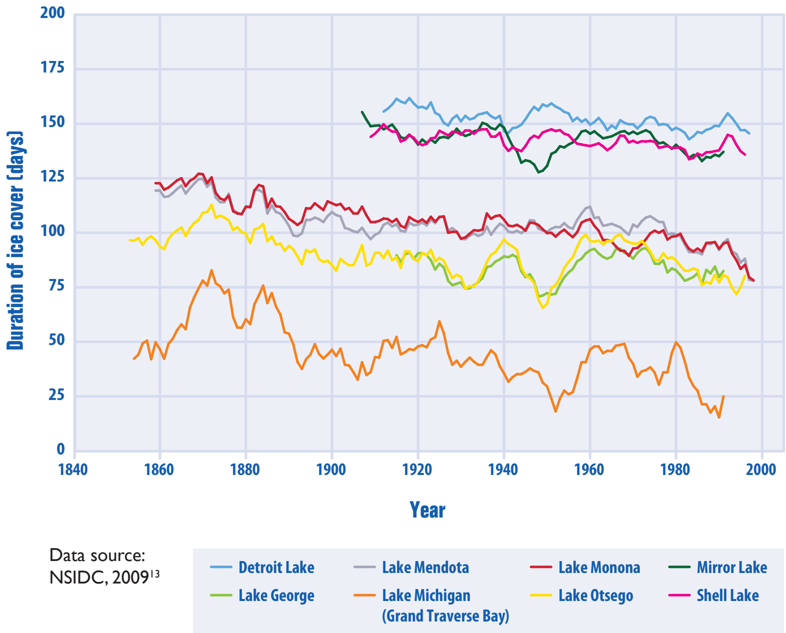


Figure 1. Duration of Ice Cover for Selected U.S. Lakes, 1850–2000

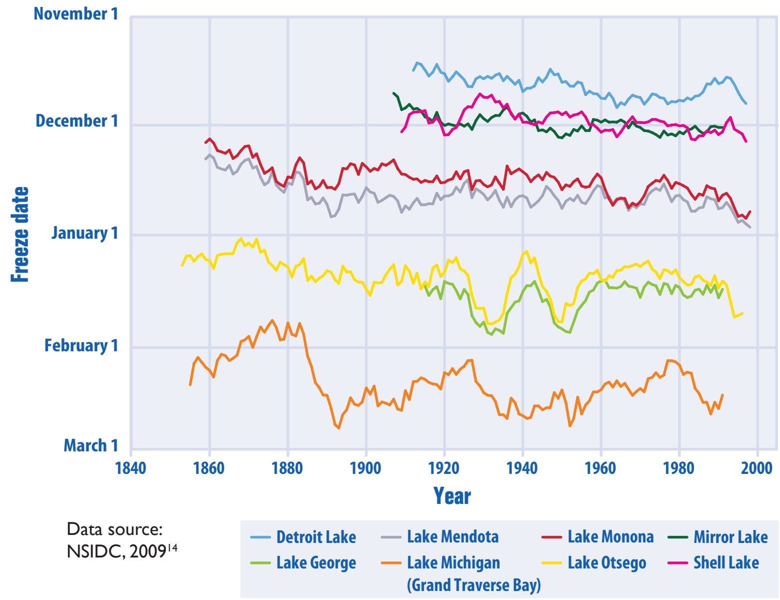
This figure displays the duration (in days) of ice cover for eight U.S. lakes. The data are available from approximately 1850 to 2000, depending on the lake, and have been smoothed using a nine-year moving average.



Data source: NSIDC, 2009[13]

Figure 2. Ice Freeze Dates for Selected U.S. Lakes, 1850–2000

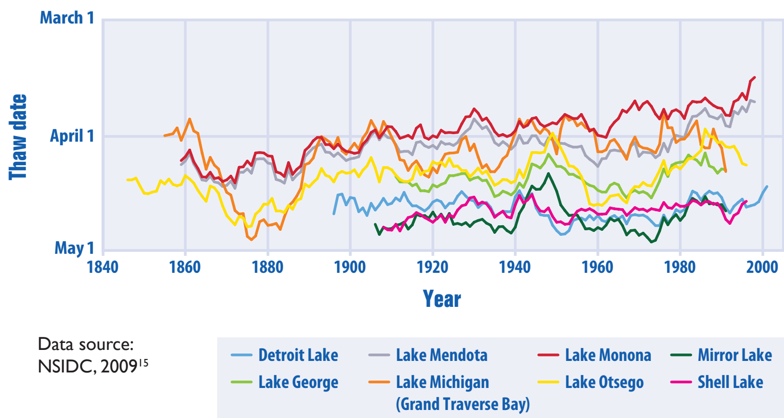
This figure shows the "ice-on" date, or date of first freeze, for eight U.S. lakes. The data are available from approximately 1850 to 2000, depending on the lake, and have been smoothed using a nine-year moving average.



Data source: NSIDC, 2009[14]

Figure 3. Ice Thaw Dates for Selected U.S. Lakes, 1850–2000

This figure shows the "ice-off" date, or date of ice thawing and breakup, for eight U.S. lakes. The data are available from approximately 1850 to 2000, depending on the lake, and have been smoothed using a nine-year moving average.



Data source: NSIDC, 2009[15]

Freeze and thaw dates have been recorded through visual observations for more than 150 years. The National Snow and Ice Data Center maintains a database with freeze and thaw observations from more than 700 lakes and rivers throughout the northern hemisphere. This indicator focuses on eight lakes within the United States that have the longest and most complete historical records. The lakes of interest are located in Minnesota, Wisconsin, Michigan, and New York.

Indicator Limitations

Although there is a lengthy historical record of freeze and thaw dates for a much larger set of lakes and rivers, some records are incomplete, ranging from brief lapses to large gaps in data. This indicator is limited to eight lakes with fairly complete historical records.

Data used in this indicator are all based on visual observations. Records based on visual observations by individuals are open to some interpretation and can differ from one individual to the next. In addition, historical observations for lakes have typically been made from the shore, which might not be representative of lakes as a whole or comparable to more recent satellite-based observations.

Data Sources

Data were obtained from the Global Lake and River Ice Phenology Database, which is maintained by the National Snow and Ice Data Center. These data are available at: http://nsidc.org/data/lake_river_ice.

Snow Cover

This indicator measures the amount of land in North America that is covered by snow.

Background

The amount of land covered by snow at any given time is influenced by many climate factors, such as the amount of snowfall an area receives and the timing of that snowfall. Air temperature also plays a role because it determines whether precipitation falls as snow or rain, and it affects the rate at which snow on the ground will melt. As temperature and precipitation patterns change, so can the overall area covered by snow.

Snow cover is not just something that is affected by climate change; it also exerts an influence on climate. Because snow is white, it reflects much of the sunlight that hits it. In contrast, darker surfaces such as open water absorb more light and heat up more quickly. In this way, the overall amount of snow cover affects patterns of heating and cooling over the Earth's surface. More snow means more energy reflects back to space, while less snow cover means the Earth will absorb more heat and become warmer.

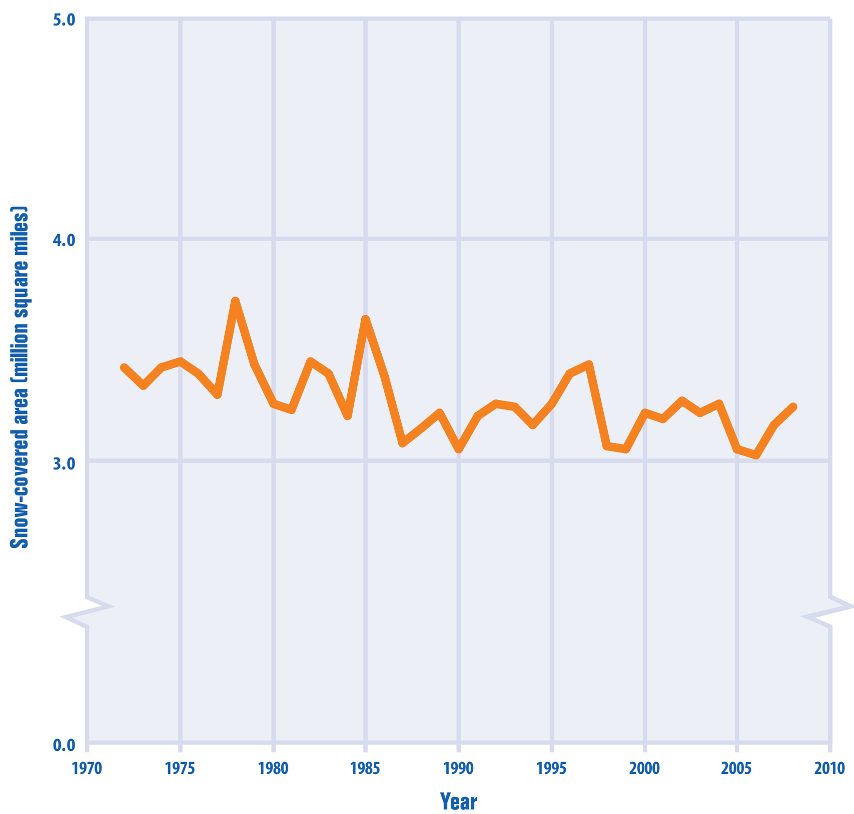
On a more local scale, snow cover is important for many plants and animals. For example, some plants rely on a protective blanket of snow to insulate them from sub-freezing winter temperatures. Humans and ecosystems also rely on snowmelt to replenish streams and ground water.

About the Indicator

This indicator tracks the total area covered by snow across all of North America since 1972. It is based on maps generated by analyzing satellite images collected by the National Oceanic and Atmospheric Administration. The indicator was created by analyzing each weekly map to determine the extent of snow cover, then averaging the weekly observations together to get a value for each year.

Figure 1. Snow-Covered Area in North America, 1972–2008

This graph shows the average area covered by snow in a given year, based on an analysis of weekly maps. The area is measured in square miles. These data cover all of North America.



Data source: Rutgers University Global Snow Lab, 2009[16]

Key Points

- Overall, during the period from 1972 to 2008, snow covered an average of 3.3 million square miles of North America (see Figure 1).
- The extent of snow cover has varied from year to year. The average area covered by snow has ranged from 3.0 million to 3.7 million square miles, with the minimum value occurring in 2006 and the maximum in 1978 (see Figure 1).
- Looking at averages by decade suggests that the extent of North America covered by snow has decreased steadily over time. The average extent for the 1970s (1972 to 1979) was 3.43 million square miles, compared with 3.3 million for the 1980s, 3.21 million for the 1990s, and 3.18 million from 2000 to 2008 (see Figure 1).

Indicator Limitations

Although satellite-based snow cover maps are available starting in the mid-1960s, some of the early years are missing data from several weeks during the summer, which would lead to an inaccurate annual average. Thus, the indicator is restricted to 1972 and later, with all years having a full set of data.

Because it examines only yearly averages, this indicator does not show whether trends in overall snow cover are being driven by decreases in winter extent, summer extent (at high elevations and latitudes), or both. An analysis of more detailed weekly and monthly data suggests that the largest decreases have come in spring and summer.[17]

Data Sources

The data for this indicator were provided by the Rutgers University Global Snow Lab, which posts data online at: http://climate.rutgers.edu/snowcover. It is based on measurements collected by the National Oceanic and Atmospheric Administration's National Environmental Satellite Data and Information Service at: www.nesdis.noaa.gov.

Snowpack

This indicator measures trends in mountain snowpack in western North America.

Background

Temperature and precipitation are key factors affecting snowpack, which is the amount of snow that accumulates on the ground. In a warming climate, more precipitation will be expected to fall as rain, not snow, in most areas—reducing the extent and depth of snowpack. Snow will also melt earlier in the spring.

Mountain snowpack is a key component of the water cycle in western North America, storing water in the winter when the snow falls and releasing it in spring and early summer when the snow melts. Millions of people in the West depend on the springtime melting of mountain snowpack for power, irrigation, and drinking water. In most western river basins, snowpack is a larger component of water storage than man-made reservoirs.[18]

Changes in mountain snowpack can affect agriculture, winter recreation, and tourism in some areas, as well as plants and wildlife. For example, certain types of trees rely on snow for insulation from freezing temperatures, as do some animal species. In addition, fish spawning could be disrupted if changes in snowpack or snowmelt alter the timing and abundance of stream flows.

About the Indicator

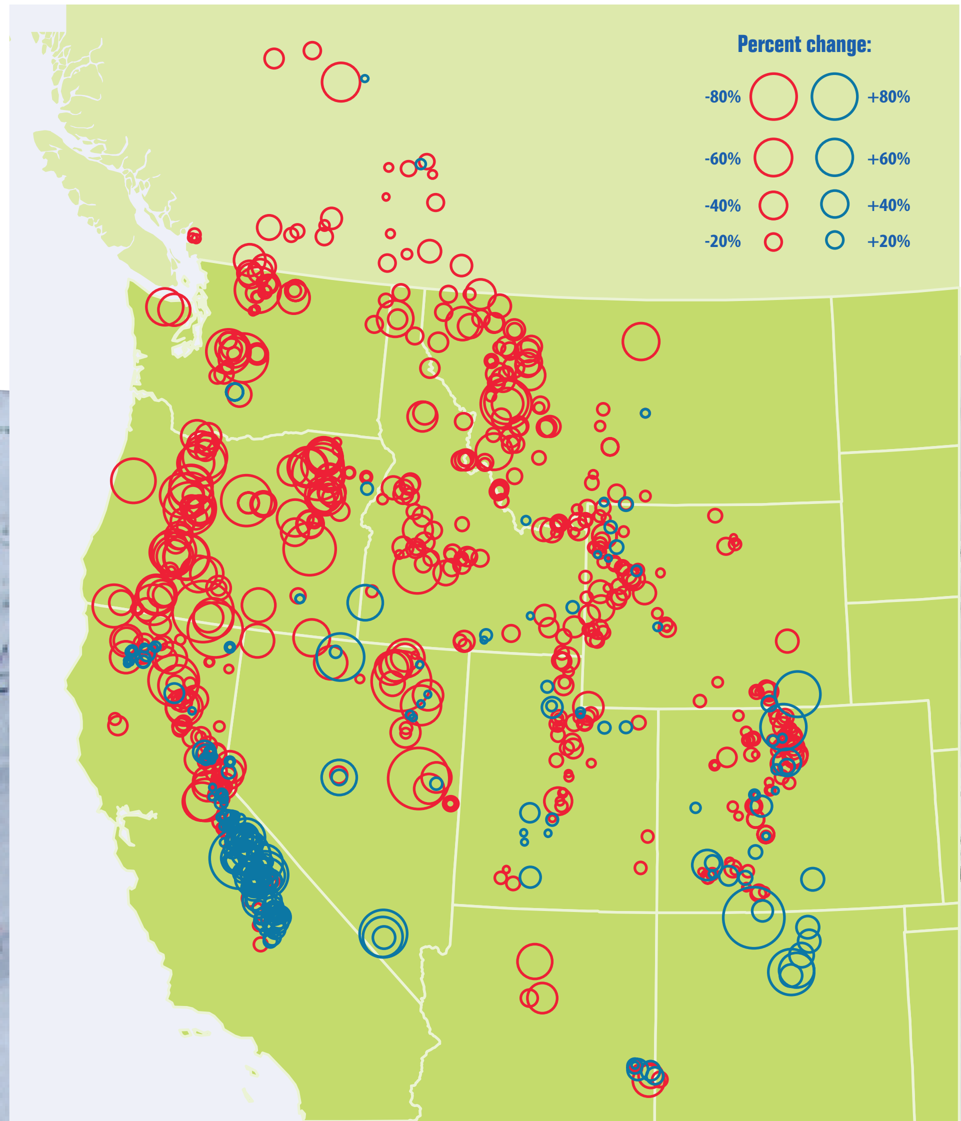
This indicator uses a measurement called snow water equivalent to determine trends in snowpack. Snow water equivalent is the amount of water contained within the snowpack at a particular location. It can be thought of as the depth of water that would result if the entire snowpack were to melt.

The U.S. Department of Agriculture and other collaborators have measured snowpack since the 1930s. In the early years of data collection, researchers measured snow water equivalent manually, but since 1980, measurements at some locations have been collected with automated instruments. This indicator is based on data from approximately 800 permanent

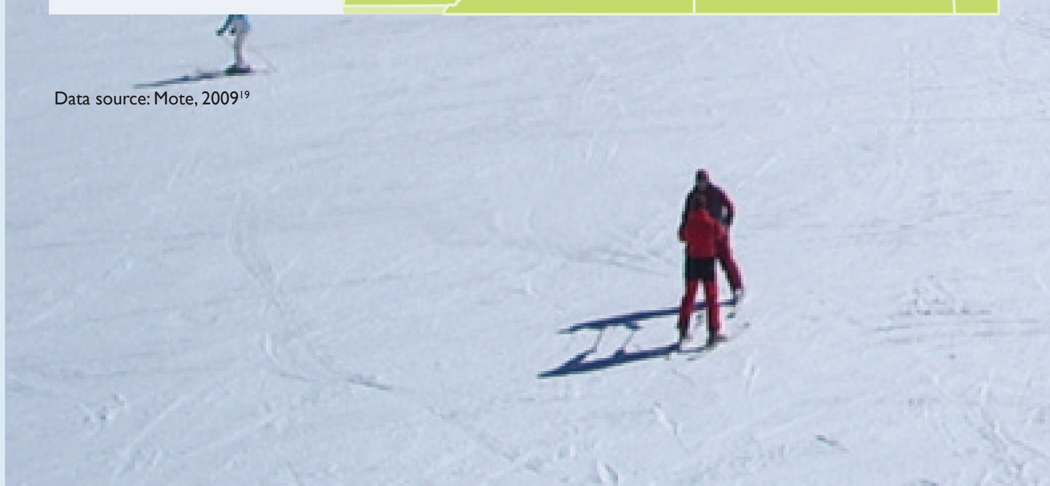
(Continued on page 55)

Figure 1. Trends in April Snowpack in the Western United States and Canada, 1950–2000

This map shows trends in snow water equivalent in the western United States and part of Canada. Negative trends are shown by red circles and positive trends by blue.



Data source: Mote, 2009[19]



Key Points

- From 1950 to 2000, April snow water equivalent declined at most of the measurement sites (see Figure 1), with some relative losses exceeding 75 percent.
- In general, the largest decreases were observed in western Washington, western Oregon, and northern California. April snowpack decreased to a lesser extent in the northern Rockies.
- A few areas have seen increases in snowpack, primarily in the southern Sierra Nevada of California and in the Southwest.

research sites in the western United States and Canada. The indicator shows trends for the month of April, which could reflect changes in winter snowfall as well as the timing of spring snowmelt.

Indicator Limitations

Natural changes in the Earth's climate could affect snowpack in such a way that trends might slightly differ if measured over a different time period. The 1950s registered some of the highest snowpack measurements of the 20th century in the Northwest. While these values could be magnifying the extent of the snowpack decline depicted in Figure 1, the general direction of the trend is the same regardless of the start date.

Although most parts of the West have seen reductions in snowpack, consistent with overall warming trends shown in the U.S. and Global Temperature indicator (p. 22), snowfall trends may be partially influenced by nonclimatic factors such as observation methods, land use changes, and forest canopy changes.

Data Sources

Data for this indicator came from the U.S. Department of Agriculture's Natural Resources Conservation Service Water and Climate Center. The map was constructed using methods described in Mote et al. (2005).[20] The U.S. Department of Agriculture data are available at: www.wcc.nrcs.usda.gov.