State of the Climate at Blue Hill Observatory: 1885-2022

The founding objective of the Blue Hill Meteorological Observatory (BHO) in 1885 was to establish the first private observatory for the measurement of weather and climate in the United States in support of special investigations in meteorology. The continual and meticulous recording of temperature, moisture, precipitation, snowfall, wind, pressure, clouds, sunshine and many other parameters at a location that was distinctly elevated above the surrounding surface obstructions was intended over time to provide a unique perspective of the state of the lower atmosphere and the local weather. Considerable care has been taken to continue the use of traditional instrumentation and observing methods to ensure the highest degree of continuity in the measurements as possible. After more than 138 years, the BHO observations form the most consistent and most extensive climate record in North America. They are an irreplaceable resource that today supports the Blue Hill Observatory & Science Center's mission to advance climate research and public education of atmospheric science. In recognition of the quality and long duration of the Blue Hill climate record, the World Meteorological Organization has recognized BHO as a Centennial Observing Station, one of only eleven such sites in the United States.

The location of BHO at the 635-foot summit of Great Blue Hill within the 7000-acre Blue Hills Reservation ten miles south of Boston, Massachusetts has provided a relative degree of isolation from the local urban growth over the last century. The extent to which urban warming in the vicinity of Boston and vegetation changes on Great Blue Hill have affected the Observatory climate data has not been fully established. However, these are only two of the complex and overlapping factors on multiple scales that may influence the observations at BHO. With a great deal of certainty, the science community has attributed the recent rise in global temperature to human activity related to the burning of fossil fuels, and this "greenhouse warming" is consequently one of the contributing factors in the significant temperature increase recorded at the Observatory since the late 19th century. The purpose and relevance of the BHO climate record are to provide a reliable, accurate and invaluable historical context in which to improve our understanding of Earth's climate. This report will focus on the state of extremes in the climate measurements at Blue Hill.

Looking first at the past calendar year, 2022 was the fourth warmest year on record at Blue Hill, continuing a long upward trend in temperature since the late 19th century. After a cold and snowy start in January, much of the year was warm: the spring season (March-May) 2022 tied as the fifth warmest, July 2022 was the warmest month ever observed at Blue Hill, and summer (June-August) 2022 was the second warmest on record. Annual precipitation was about twenty percent less than average during 2022, and a six-month dry period from March to August brought intervals of severe to extreme drought to the area during the summer. Snowfall was well above average during January though much below average the rest of the year. Annual mean wind speed tied as the third lowest on record, extending a dramatic drop in wind speed at the Observatory in recent decades.

Temperature

Among the many parameters recorded at Blue Hill, multiple indicators reflect the changes that have occurred at this location over more than a century, though the trend in surface temperature is among the most prominent. The BHO annual mean temperatures since the middle 19th century are shown in black in Figure 1. All data from February 1, 1885 to the present were observed on the summit of Great Blue Hill. Earlier temperatures from 1831 through January 1885 were observed from two nearby valley locations that overlapped with BHO measurements for several years in the 1880's, which allowed the valley data to be adjusted to the summit location, and these temperature data are shown for historical context. Most of the upward trend since the 19th century was observed directly on the summit. Centered running mean temperatures are also shown for 10-year (blue) and 30-year (red) periods that smooth the data to illustrate decadal scale changes.

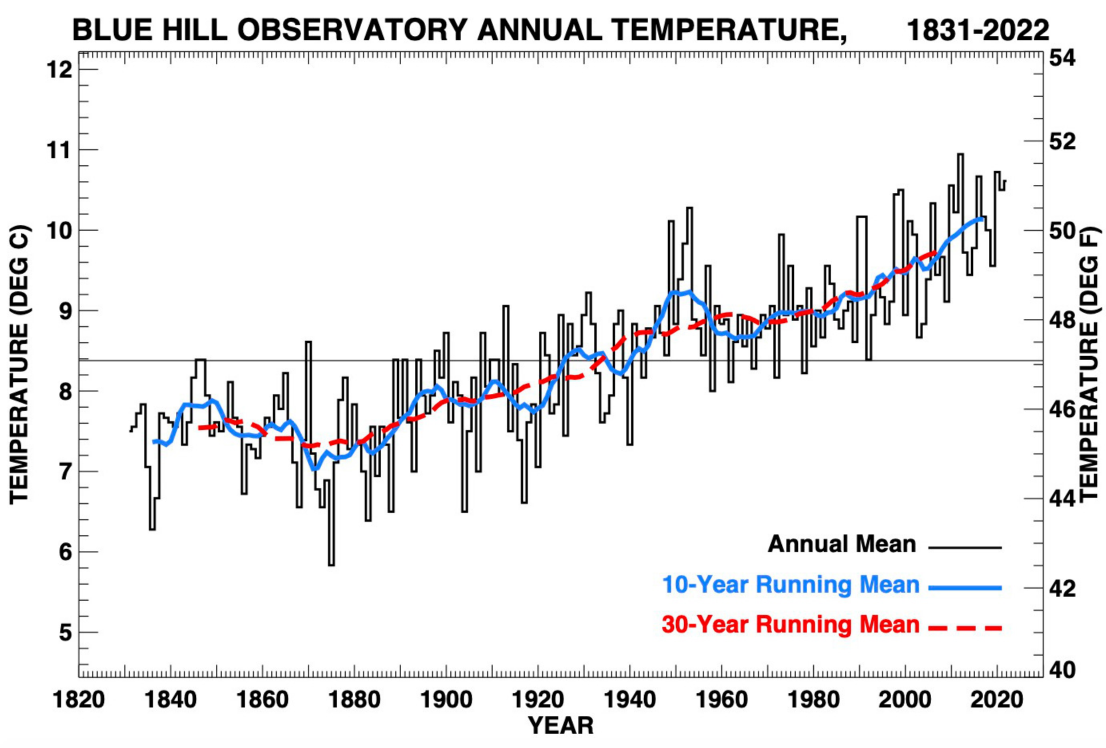

Figure 1. Blue Hill Observatory annual mean temperature (black, histogram) from measurements taken on the summit of Great Blue Hill (1885-present) and adjusted to the summit from two nearby surrounding locations (1831-1884). Units are labeled in degrees Celsius and degrees Fahrenheit. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin black line is the 1831-2022 mean.

Applying a linear fit to the annual temperature data over the period 1885 to 2022 indicates an upward trend of +0.18 °C/decade (+0.32 degrees F/decade) with a better than 99.9% confidence that the trend is statistically significant. The warmest year on record was 2012 at 10.9 °C (51.7 degrees F), and nine of the ten warmest years on the entire period of record at Blue Hill have occurred in the last 25 years.

An essential component of assessing climate change impacts is to look beyond mean values and to identify any shifts in extremes over time. At Blue Hill, daily high maximum and low minimum temperature records represent a very comprehensive picture of diurnal temperature extremes from a total of more than 100,000 observations. Figure 2 summarizes the total number of daily high (red) and low (blue) temperature records in each decade since 1885 from the daily record list as it existed at the end of 2022. Each decade in Figure 2 represents record counts over 10 years except for the 1880's, which represent only 1885-1889 and the 2020's, which include only the years 2020-2022. A clear pattern is apparent in Figure 2 illustrating that record high temperatures are becoming more frequent and record low temperatures are becoming much less frequent over time.

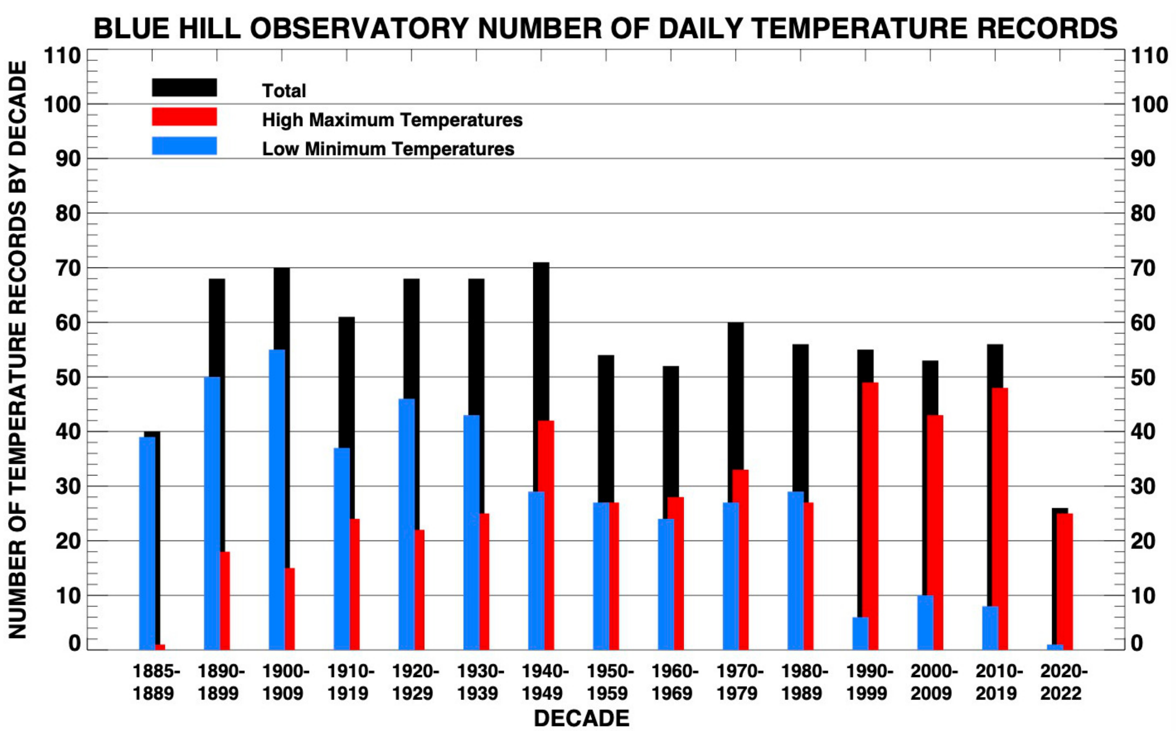

Figure 2. Blue Hill Observatory number of daily high maximum temperature records (red), number of daily low minimum temperature records (blue), and the total (black) for each decade from measurements taken on the summit of Great Blue Hill (1885-present). The decade for the 1880's includes only five years and the decade for the 2020's includes only three years.

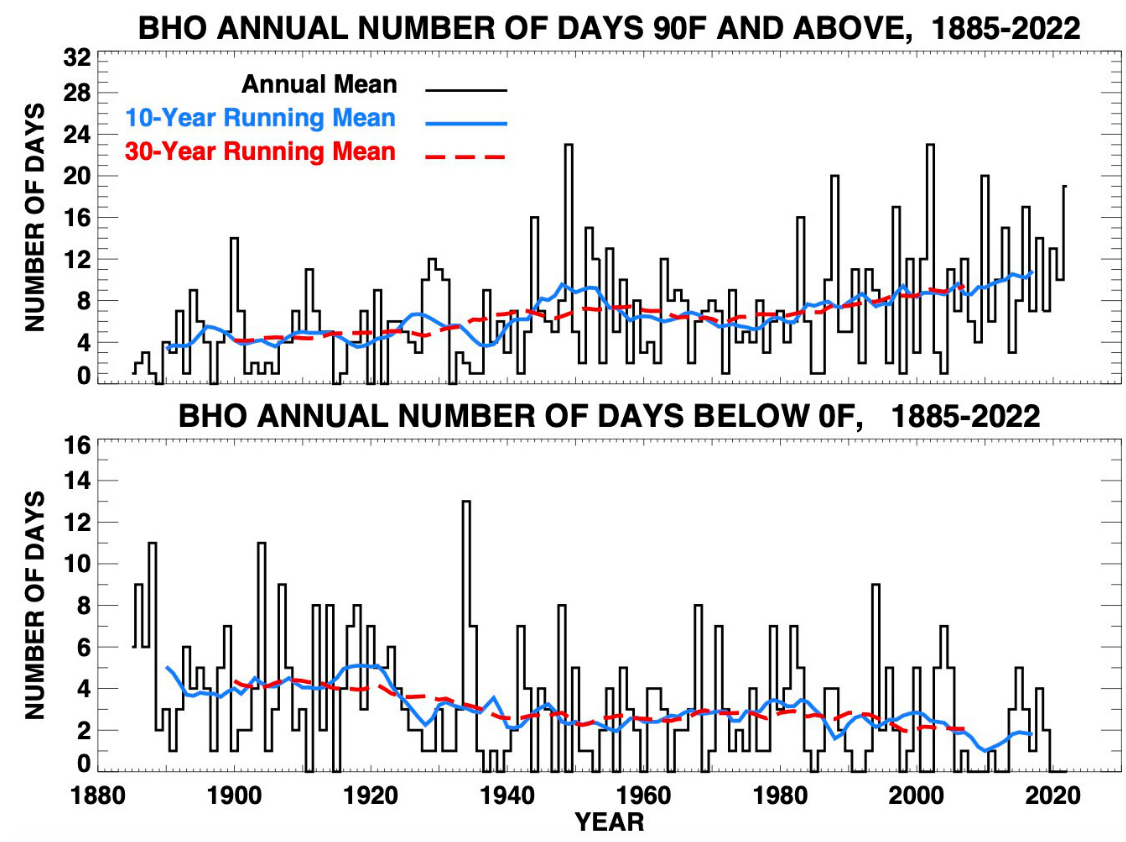

Figure 3. Blue Hill Observatory annual number of daily maximum temperatures of 90 deg F and above (top panel) and annual number of daily minimum temperatures below 0 deg F (bottom panel) from measurements taken on the summit of Great Blue Hill (1885-present) Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods.

A different measure of changes in temperature extremes that is easily perceived is the annual number of warm days each year that reach or exceed 90 deg F and the number of extreme cold days each year with minimum temperatures below 0 deg F as shown in Figure 3. Interestingly, during the late 19th century the number of 90-degree days (top panel in Figure 3) and the number of days below 0 deg F (bottom panel) were roughly the same at about four per year. Since then, the number of extreme cold days has gradually dropped to about two per year on average, while the number of the extreme hot days by this measure has more than doubled to about ten per year on average.

Table 1 lists the individual extreme values for temperature, precipitation, snowfall, wind speed, and barometric pressure for the BHO period of record from 1885-2022. It's notable that most of these absolute extremes are distributed throughout the climate record period, and all decades since the 1930's are represented.

Record Type	Extreme Value	Date
Highest Maximum Temperature	101 degrees F	10 August 1949 2 August 1975
Lowest Minimum Temperature	-21 degrees F	9 February 1934
Longest Heat Wave	9 days	11-19 August 2002
Greatest Diurnal Temperature Range	53 degrees F (Max: 52F, Min: -1F)	3 December 1890
Greatest Storm Rainfall	12.77 inches	18-19 August 1955
Greatest 1-Hour Rainfall	3.02 inches	18 June 1998
Greatest Storm Snowfall	38.7 inches	24-28 February 1969
Greatest 24-Hour Snowfall	29.0 inches	31 March – 1 April 1997
Greatest Snow Depth	46 inches	15 February 2015
Highest Wind Gust (Calculated)	186 mph (+/- 30 mph), S	21 September 1938
Highest 5-Min. Wind Speed	121 mph, S	21 September 1938
Highest 1-Hour Wind Speed	84 mph, SSE	21 September 1938
Highest Sea-Level Pressure	31.08 inches	13 February 1981
Lowest Sea-Level Pressure	28.42 inches	4 March 1971

Table 1. Blue Hill Observatory extremes of temperature, precipitation, snowfall, wind speed, and barometric pressure over the period of record from 1885-2022.

Precipitation/Snowfall

The highly disruptive effects of flooding events and winter snowstorms make rainfall and snowfall among the most impactful aspects of the weather, so it is especially important that changes in precipitation means and extremes be carefully monitored and investigated to improve our predictive capabilities. At Blue Hill, total annual precipitation, which includes rainfall and the liquid equivalent of all frozen precipitation (snow and sleet), has shown a gradual increase in recent decades. Figure 4 shows the total annual precipitation since 1886 and the 10-year and 30-year running means, which smooth the highly variable yearly amounts and illustrate the decadal and long-term changes. In terms of annual extremes, six of the ten wettest years at BHO have occurred since 1990 including 1998, the wettest year, with 180.3 cm (71.00 inches), and nine of the ten wettest years have occurred since 1970.

Frozen precipitation, defined for this study as hydrometeors that accumulate on the ground in frozen form during the winter, spring and fall months such as snow, ice pellets (or sleet), snow pellets, etc., is even more temporally variable than total liquid equivalent precipitation. Other than a single instance of a trace of sleet in early June 1907, these types of frozen precipitation have never occurred at BHO from June through September. Hail, which occurs infrequently during some convective precipitation events at Blue Hill, is frozen precipitation, but it is not considered in this study. Although freezing rain occurs more frequently than hail at Blue Hill, that is not frozen precipitation since it falls in liquid form and freezes on contact with the ground when the surface is sufficiently cold. Total snowfall for the entire cold season from October through May is shown in Figure 5. A linear fit to these data shows a modest upward trend of +2.4 cm/decade, or just under one inch per decade over the period of record. The 10-year running mean (blue curve in Figure 5) shows that decadal variations in total snowfall followed a roughly 50-year cycle since the early 20th century. From 1885 to 1990, 12 seasons exceeded 228 cm (90 inches) of snowfall; since 1990, nine seasons have exceeded this amount, including 2014-2015, the snowiest season on record, with 383.0 cm (150.8 inches) and 1995-1996, the previous record season, with 366.8 cm (144.4 inches). Seven of the ten largest snowstorms at BHO have occurred since 1997, and all ten have occurred since 1960.

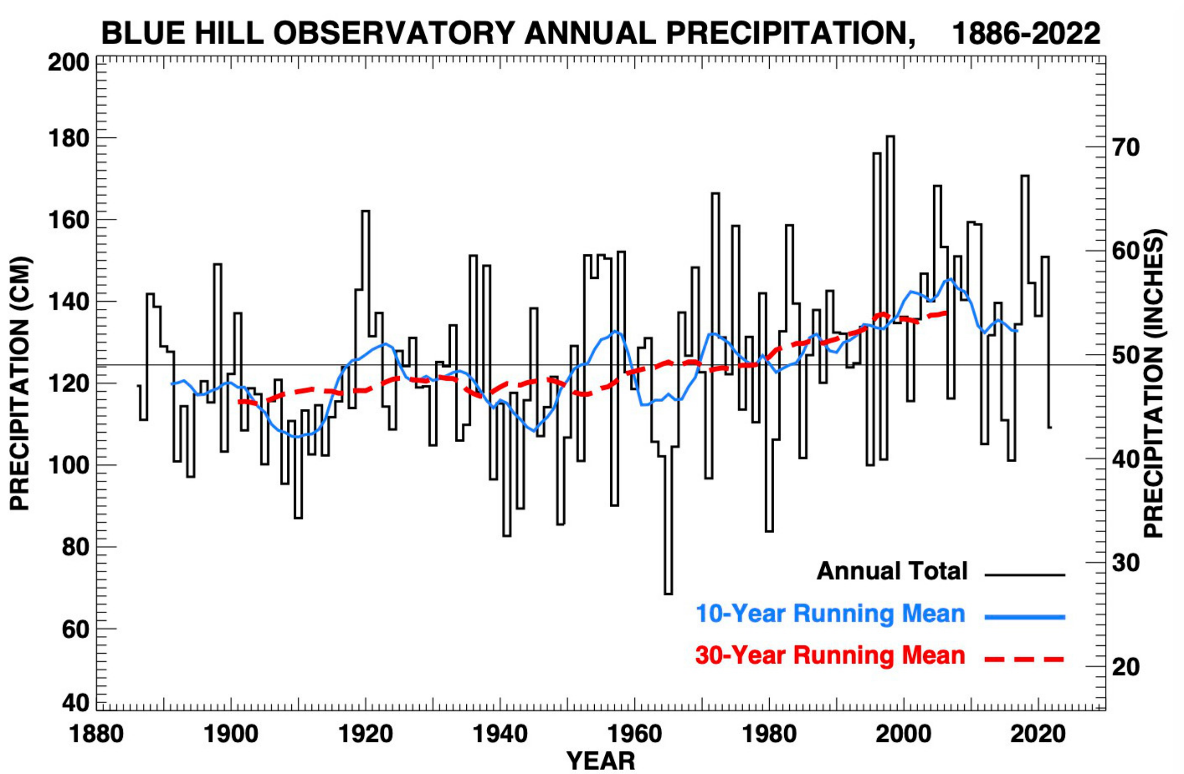

Figure 4. Blue Hill Observatory annual precipitation (black, histogram) from measurements taken on the summit of Great Blue Hill (1886-present). Units are labeled in centimeters and inches. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizontal line is the 1886-2022 mean.

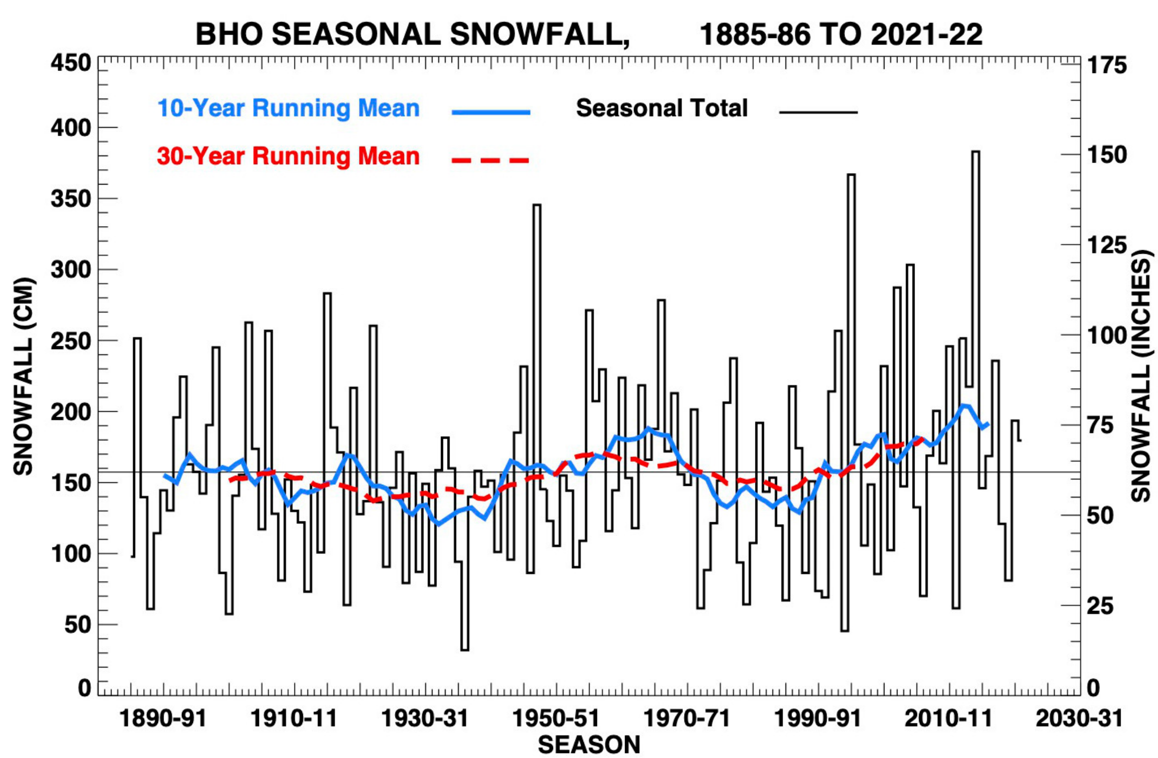

Figure 5. Blue Hill Observatory total October to May seasonal snowfall (black, histogram) from measurements taken on the summit of Great Blue Hill (1885-present). Units are labeled in centimeters and inches. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizonal line is the 1885-2022 mean.

Precipitation and snowfall extremes can be examined from several perspectives including the amount and the frequency. Figure 6 reflects the later and shows the annual number of days of measurable precipitation (top panel) and measurable snowfall (bottom panel). The former is the count of days each year with 0.01 inches or more of liquid equivalent precipitation (including melted snow and sleet), and the latter is the count of days each year with 0.1 inches or more of snow and sleet. For total precipitation, the long-term average is 135 measurable days per year (about 37 percent of the total days). The highest number in any year was 170 days (46%) in 1916, and the lowest number was 105 days (29%) in 1980. Interestingly, 1916 was not an especially wet year with 45.50 inches (actually slightly drier than average), while 1980 was the third driest year on record with 32.99 inches. This discrepancy shows that the number of measurable days is a different way to characterize precipitation amounts, extremes, and changes over time. Although there is little if any long-term trend in this quantity, there are large decadal variations, and the running means have been on a gradual upward trend since the 1970s. For annual snowfall alone, the long-term average is about 28 measurable days per year (about 8 percent of the total days). The highest number was 50 days (14%) in 1907, and the lowest number was only 11 days (3%) in 1973. 1907 was a relatively snowy year with 99.8 inches, but a dozen years brought more snow. This result means that the average "snow day" brought only two inches of snow in 1907, while the snowiest calendar year, 2015, which brought 141.1 inches from January to December, had an average measurable snowfall of about 4 inches on the 36 "snow days" that year. Obviously, this difference reflects the varying size of the individual snowfall events in those specific years. The average amount of snow per "snow day" has increased from about 1.7 to 2.5 inches over the last century.

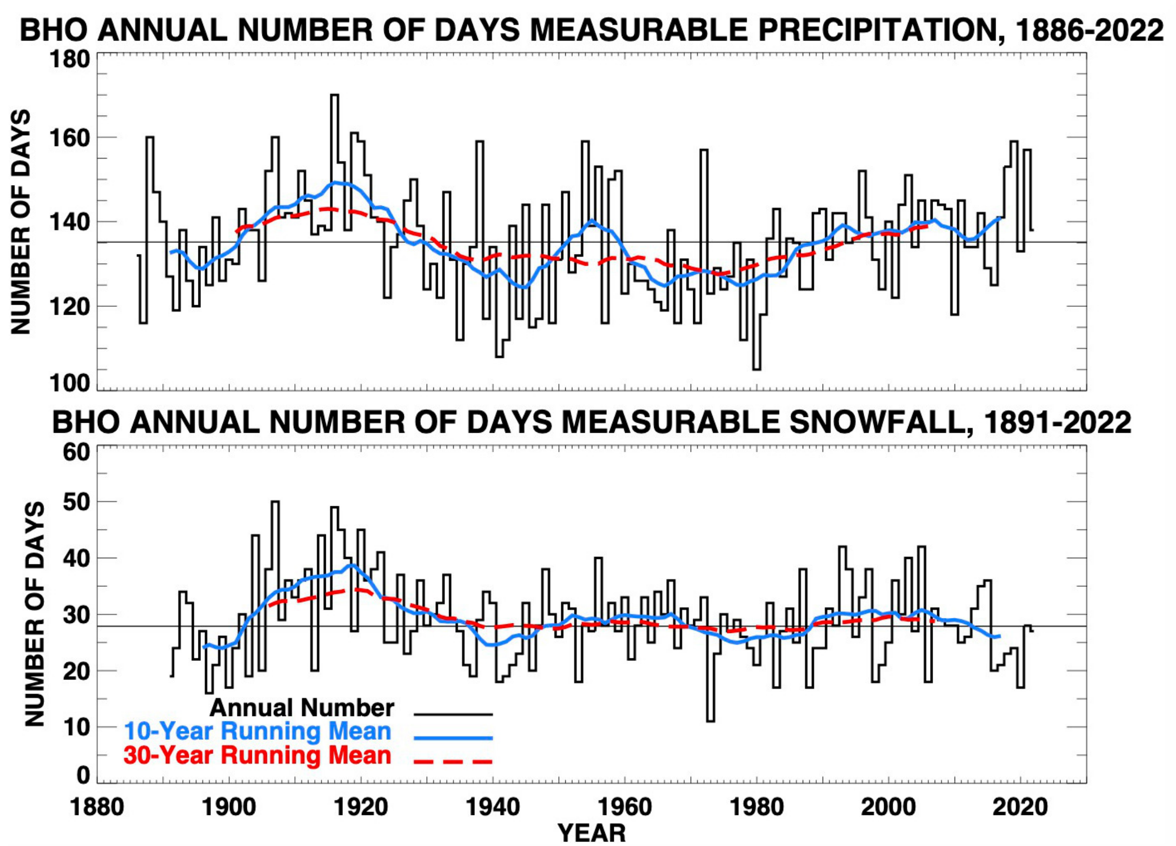

Figure 6. Blue Hill Observatory annual number of days with measurable precipitation (black, top panel) and annual number of days with measurable snow and sleet (black, bottom panel). Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizonal line is the 1886-2022 mean in the top panel and the 1891-2022 mean in the lower panel.

Precipitation extremes can also be examined by looking at short time-period heavy amounts. Figure 7 shows the annual number of hours with heavy precipitation (bottom panel) and the total yearly amount of heavy precipitation in those hours (top panel), where heavy precipitation is defined as any amount more than 0.30 inches (0.76 cm) in an hour. These statistics have only been tabulated for the period 1940-2022. The average number of hours with heavy precipitation is about 17 per year, with a slight upward trend of several days since the 1940's. The two most extreme rainfall events of the 20th century at BHO are very apparent in Figure 7. The greatest number of hours with heavy precipitation in one year was 45 in 1955, which brought a total of 22.87 inches of rainfall, and 21 of those hours, representing 13.14 inches of rain, occurred during August 1955 primarily during the torrential rains brought by Tropical Storm Diane that month. The second greatest number in one year was 42 in 1998, which brought a total 20.96 inches of heavy rainfall, and 14 of those hours, representing 10.01 inches of rain, occurred in June 1998, primarily on the 13th and 18th of that month. Both of these excessive rainfall events are also represented in the weather extreme lists in Table 1 as the largest single storm rainfall total (12.77 inches) on 18-19 August 1955 and as the largest one-hour rainfall total (3.02 inches) on 18 June 1998.

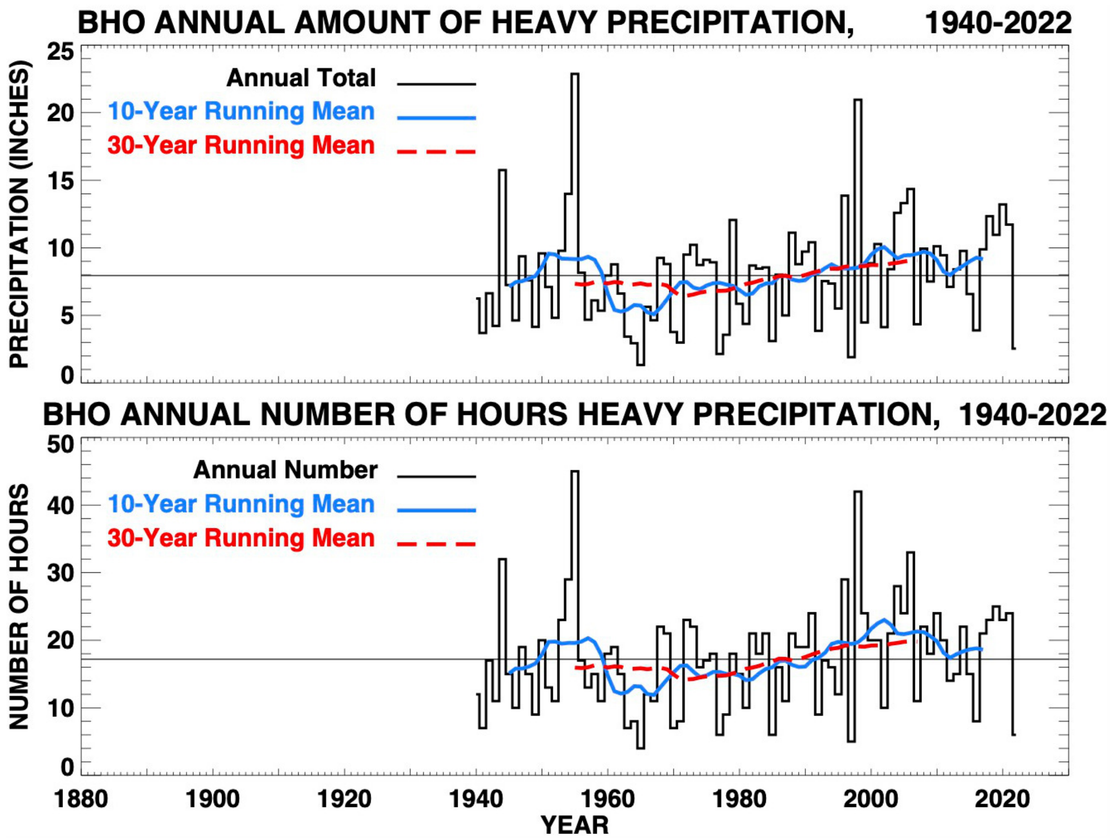

Figure 7. Blue Hill Observatory annual number of hours with heavy precipitation (black, bottom panel) defined as more than 0.30 inches per hour, and annual total of heavy precipitation in those hours (black, top panel), since 1940. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizonal line is the 1940-2022 mean.

Another approach to analyzing precipitation extremes is to count the number of one-inch or greater precipitation events, defined as a total of 1.00 inches or more spanning a continuous period of any number of hours with at least a trace of precipitation, and this statistic is plotted in Figure 8. This diagnostic shows a very slight upward trend since the middle of the 20th century with a long-term average of 15 one-inch rain events each year. The greatest number of such events was 25 in 1958, which was matched in 2011, and the lowest number was only 4 in 1965, which was the driest year on record with only 26.96 inches of precipitation (see Figure 4).

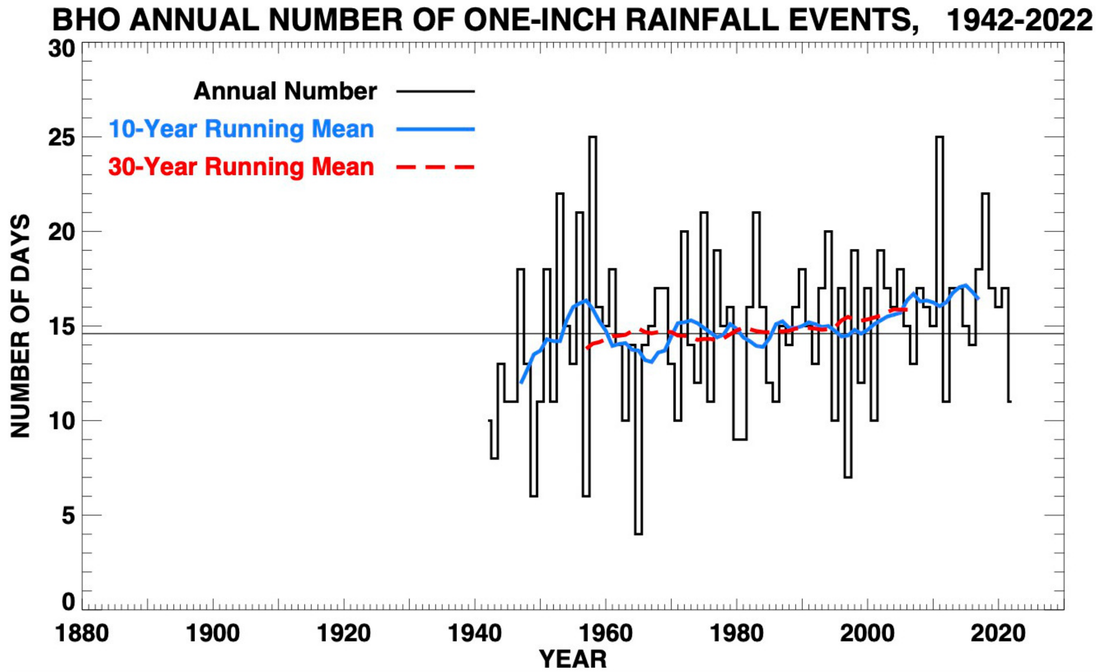

Figure 8. Blue Hill Observatory annual number of one-inch or more precipitation events (black) summed over any period of continuous hours with at least a trace of precipitation since 1942. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizonal line is the 1942-2022 mean.

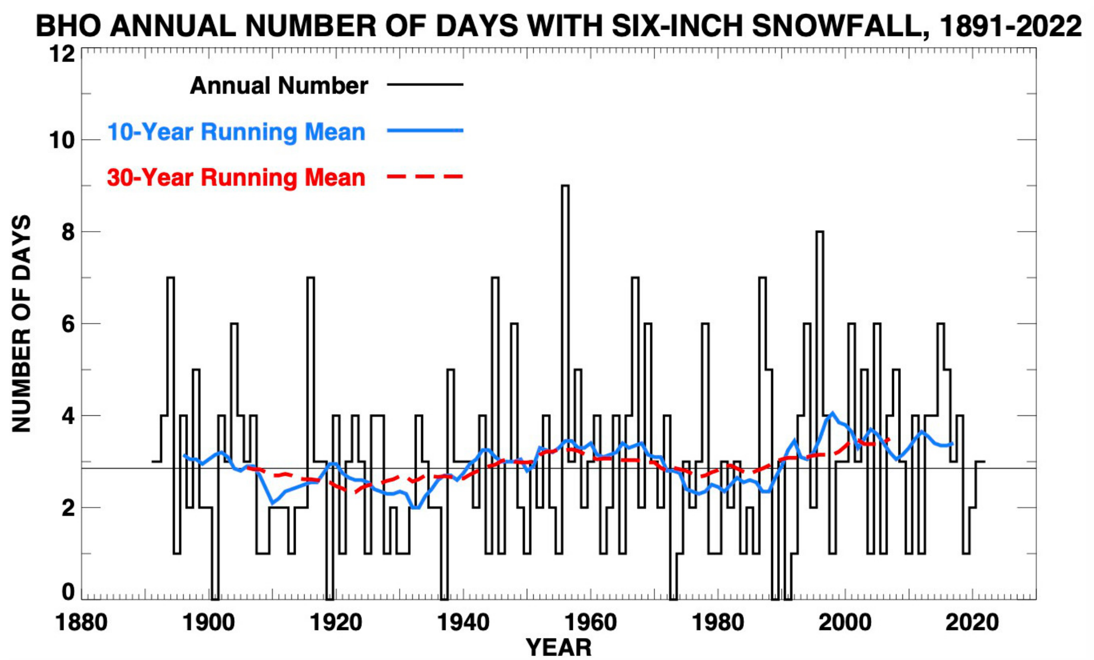

Figure 9. Blue Hill Observatory annual number of calendar days with six-inches or more of snowfall (black) since 1891. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizonal line is the 1891-2022 mean.

A comparable statistic for snowfall extremes is the annual number of calendar days with six inches or more of frozen precipitation, and the time series of this value is plotted in Figure 9. The average number of days with six inches of snow per year is around three, and the vast majority of years has between one and four. Little or no trend is apparent over the last 130 years. Six years since 1891 had no such days, and the greatest number in one year was nine in 1956, which was the fourth snowiest year on record. The snowiest year on record, 2015, had only six days with at least six inches of snow, and all of them occurred in a three-week period during the historic, extreme snowfall in late January to mid-February of that year.

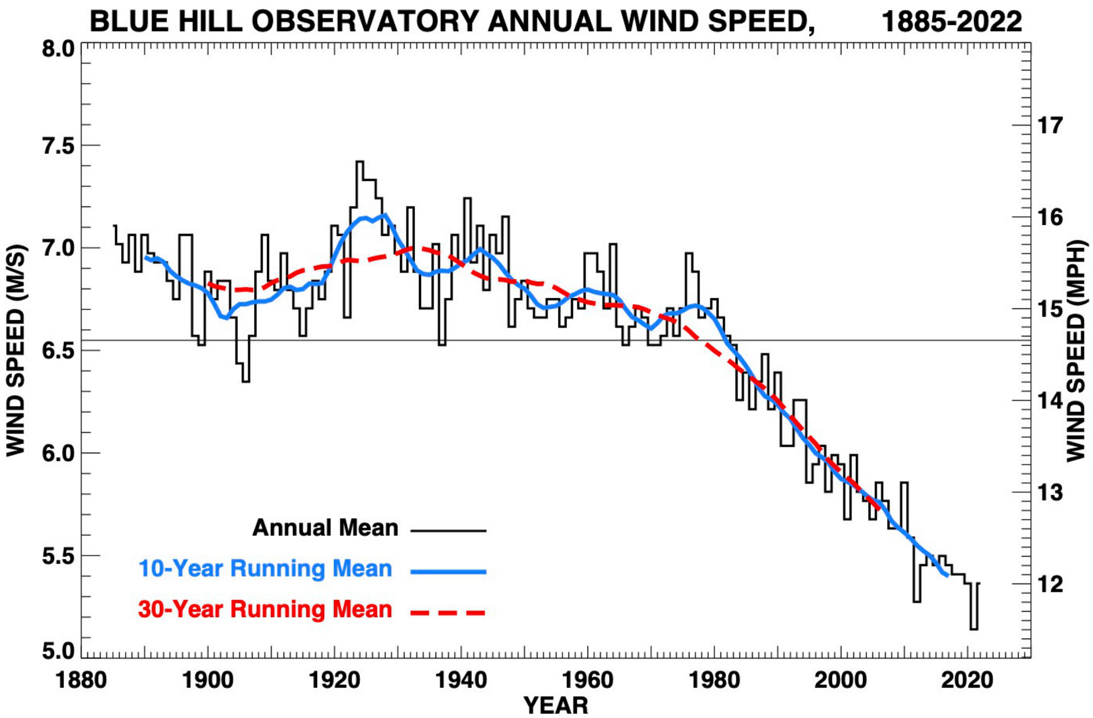

Figure 10. Blue Hill Observatory annual mean wind speed (black, histogram) from measurements taken on the summit of Great Blue Hill (1885-present). Units are labeled in meters/second and miles/hour. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizontal line is the 1885-2022 mean.

Wind Speed

One of the most dramatic changes in any climate parameter measured at Blue Hill is the steady drop in the annual mean wind speed in recent decades as shown in Figure 10. A slow decline in the 10-year mean annual wind speed (blue) that began in the 1940's became a sharper, steady drop after 1980, falling nearly 20 percent from 6.7 m/s (15.0 mph) in that year to 5.4 m/s (12.1 mph) recently, and a new record low annual wind speed of 11.5 mph was set in 2021. The cause of the decline remains under investigation, though it may be related to the shifting of mid-latitude storm tracks and their higher winds to higher latitudes, or to the poleward expansion of the lower wind speeds associated with the tropics. This so-called global stilling is consistent with wind speed changes at other locations across North America and Europe in recent decades, though is nowhere seen more dramatically than in the Blue Hill annual wind speed record.

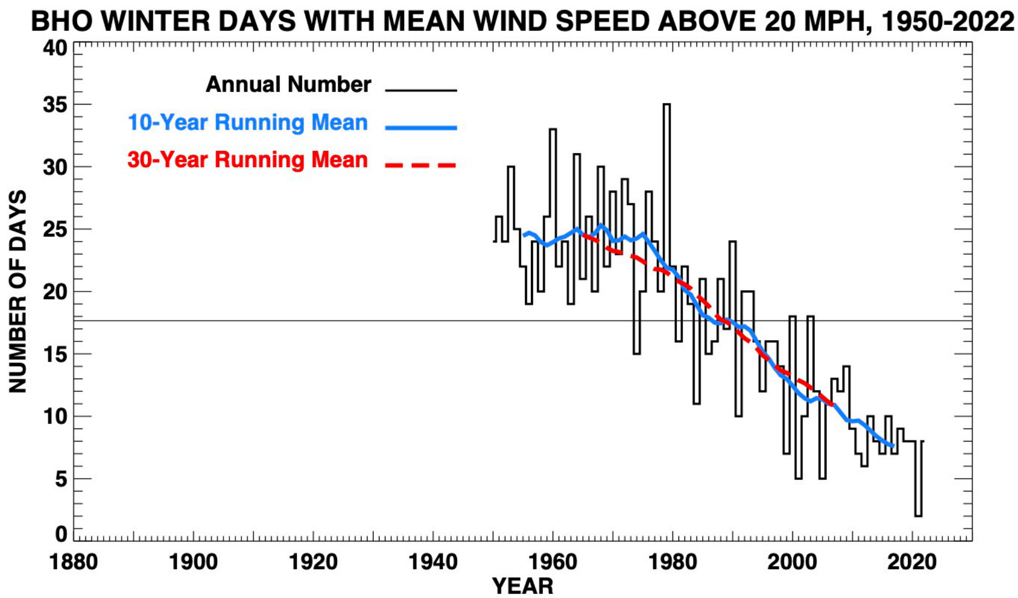

Figure 11. Blue Hill Observatory number of winter days with average wind speed of 20 mph or more (black, histogram) from measurements taken on the summit of Great Blue Hill (1950-present). Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizontal line is the 1950-2022 mean.

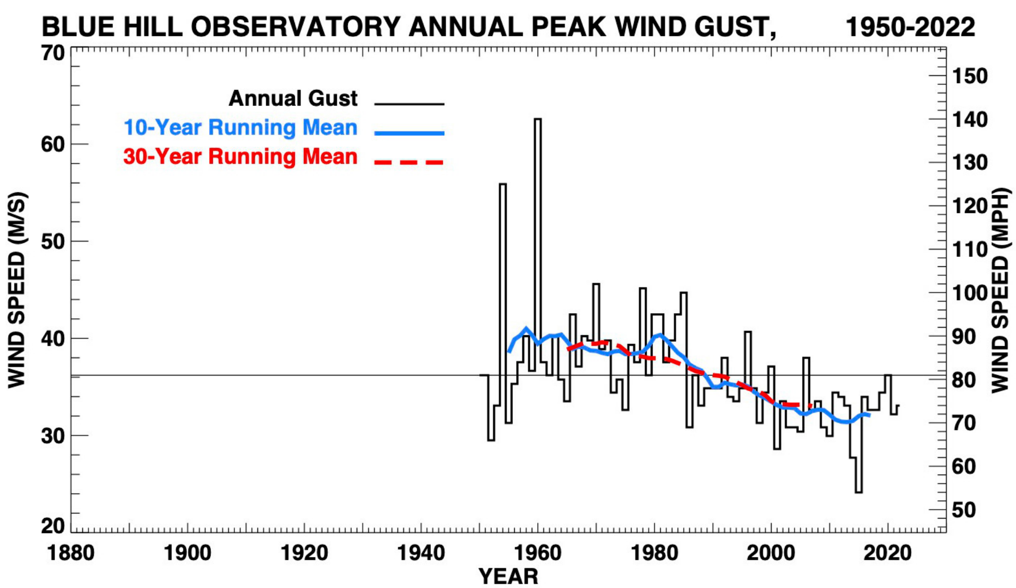

Figure 12. Blue Hill Observatory annual peak wind gust (black, histogram) from measurements taken on the summit of Great Blue Hill (1950-present). Units are labeled in meters/second and miles/hour. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizontal line is the 1950-2022 mean.

Wind speed extremes show a comparable decrease in recent decades as shown in Figure 11 and Figure 12. The number of days during the winter months (January, February, and December) with a mean wind speed of 9 m/sec (20.0 mph) or more for each year since the middle 20th century is shown in Figure 11. After holding somewhat steady from the 1950's through the 1970's and reaching a peak value of 35 days (out of 90) in 1979, this measure of daily extreme winds has been on a steady decline from a 10-year mean of 25 days in the middle 1970's to about eight days over the last decade. The number reached a new low of only two days in 2021. Looking at even more extreme winds, Figure 12 shows the highest peak gust measured at Blue Hill for every year since 1950. Prior to that year, wind gust measurements at BHO were very sporadic. Annual peak gusts are also in decline over much of this period, though the drop appears to have slowed in the most recent decade. While the station record wind gust of 186 mph, S (see Table 1) during the Great New England Hurricane of 1938 is not plotted here, two later extremes, 140 mph, SSE during Hurricane Donna on 12 September 1960 and 125 mph, SE due to Hurricane Carol on 31 August 1954, are shown, and extreme wind gusts in this range have not been approached since. The last gust to 100 mph or more at Blue Hill occurred during Hurricane Gloria on 27 September 1985, and the last gust to 90 mph or more occurred during a strong winter storm on 27 January 1996. The lowest annual gust was only 54 mph during 2015. Figures 10-12 demonstrate clearly that the decline in wind speeds at BHO are very persistent over time scales from annual means to daily averages to 1-2 second wind gusts.

Bright Sunshine

Among the most consistent parameters observed at Blue Hill is the daily duration of bright sunshine, which has been measured with three very similar Campbell-Stokes sunshine recorders that were used consecutively from 1886-1897, 1898-1993, and 1993 to present. This instrument consists of a solid glass sphere that focusses direct sunlight onto a replaceable, treated paper card held in a metal frame below the glass. As the sun moves across the sky each day, the focused sunlight scorches or burns through the card leaving a permanent record of sunshine duration for times when the direct solar beam is sufficiently intense (or "bright") to surpass the burn threshold of the card. The cumulative length of the burn marks is converted to minutes of bright sunshine and to a percent of possible sunshine for each day. The annual average bright sunshine is just over 52 percent, which varies among the years from the lowest value of 47 percent in 1889 and 1919 to a high of 60 percent in 1965, which was also the driest year on record. Figure 13 shows the annual bright sunshine and the smoothed running means for the full period of the sunshine record at BHO. While there is little overall trend, a period of higher-than-average bright sunshine occurred during the 1960's to early 1970's that decreased to a minimum in the 1980's with

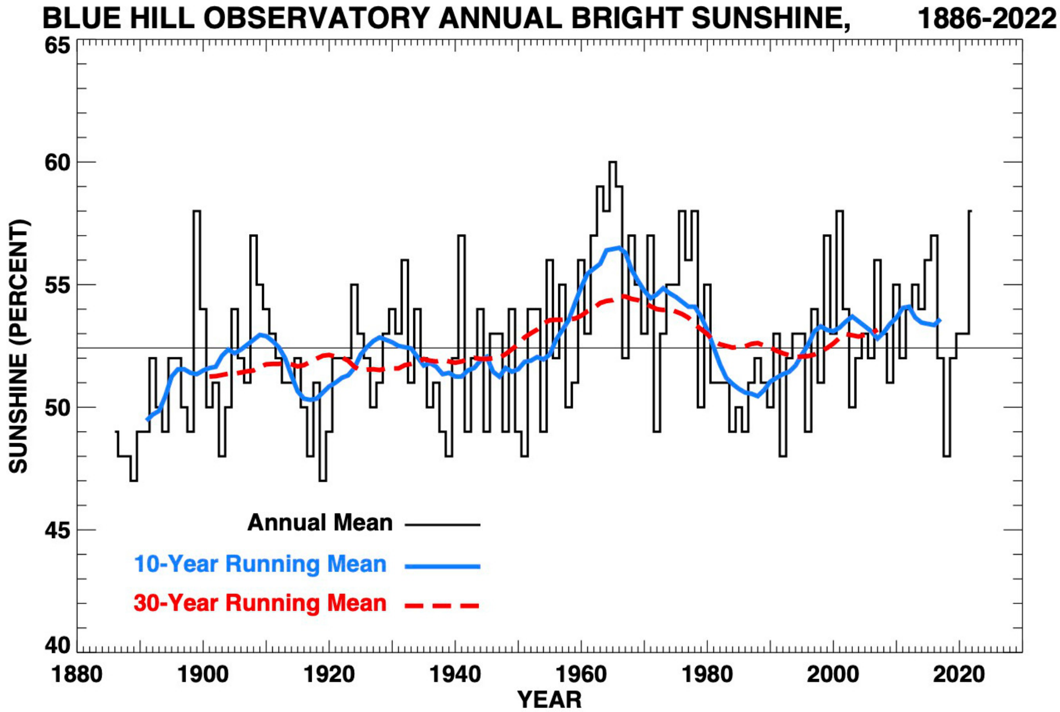

Figure 13. Blue Hill Observatory annual mean bright sunshine (black, histogram) expressed as a percent of possible sunshine from measurements taken on the summit of Great Blue Hill (1886-present). Units are labeled in percent. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizontal line is the 1886-2022 mean.

generally recovering sunshine in recent decades despite reaching a minimum of 48 percent in 2018, which was the lowest annual sunshine in the last 30 years. Ongoing research shows some dependence of the annual bright sunshine changes since the 1960's on cloud cover changes and also on the presence of atmospheric aerosols, especially in the 1970's and 1980's, which can reduce the intensity of sunlight when the sun is near the horizon and the solar beam passes through more atmosphere and therefore hinder the sun card from burning. Reduced aerosol emissions in recent decades have allowed both the bright sunshine duration and observations of horizontal visibility to improve since the 1990's.

Bright sunshine extremes can be examined by counting the number of days each year that were primarily overcast (0-2% sunshine) and clear (98-100% sunshine) as plotted in Figure 14 for the period 1950-2022. The time series of overcast days shows little long-term trend, though it's notable that the longest period of relatively few overcast days were among the driest on record in the early 1960's. Clear sky days also show little long-term trend over these years, though multi-year reductions in clear days due in part to the ejection of aerosols into the atmosphere are apparent due to the eruption of El Chichon in early April 1982 and in 1992-1993 following the eruption of Mount Pinatubo in June 1991.

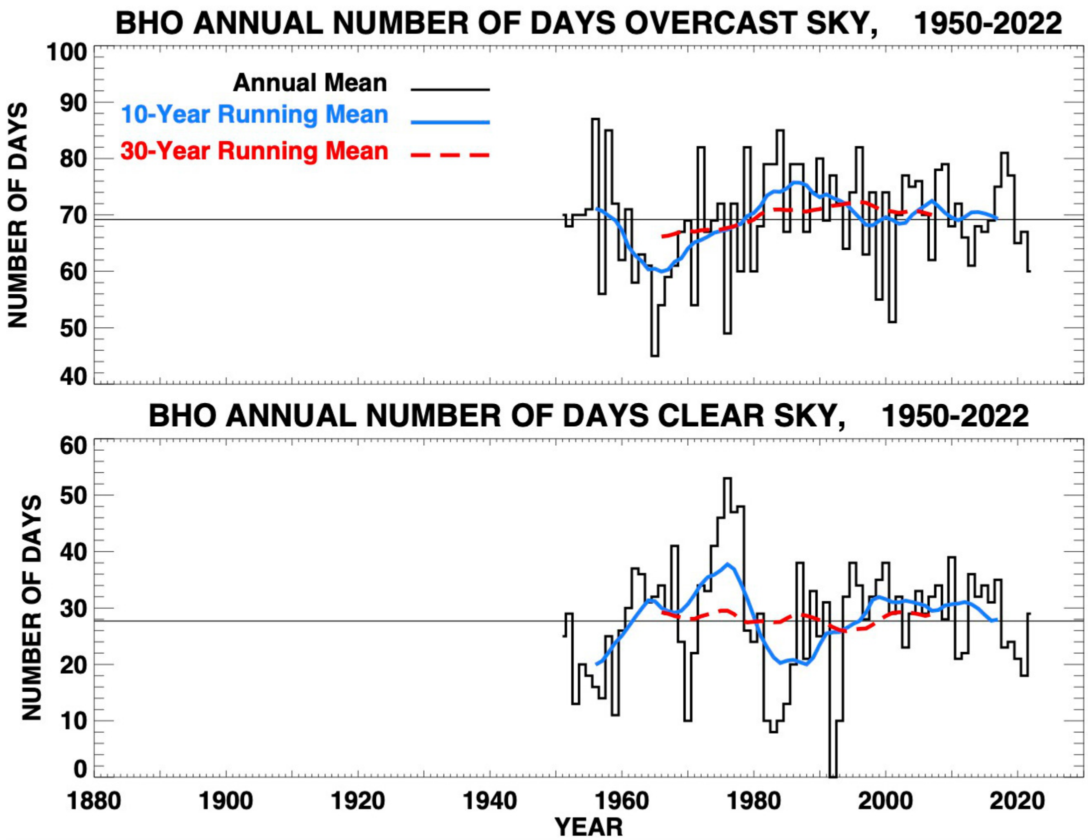

Figure 14. Blue Hill Observatory annual number of overcast days with 0-2% sunshine (black, histogram; top panel) and annual number of clear days with 98-100% sunshine (black, histogram, bottom panel) from measurements taken on the summit of Great Blue Hill. Centered running means are also shown for 10-year (blue, solid) and 30-year (red, dashed) periods. The thin horizontal line is the 1950-2022 mean.

The long duration of the Blue Hill climate record provides an essential context in which to study climate changes and these data are especially well-suited to this effort, since several decades or more of continuous, accurate data are necessary to establish the significance of trends relative to natural variability. Maintaining the extensive BHO climate record into the future and using it to inform the public about atmospheric science are critically important objectives of the Blue Hill Observatory & Science Center that will help ensure that this irreplaceable scientific and educational resource will continue to provide an invaluable historical perspective on ongoing, long-term, local climate changes.

[The author acknowledges the assistance of the staff, volunteers, and students who contributed to the data entry and analysis that supported some of the content in this report. For more information about the Blue Hill measurements, observing practices, history and educational programs, visit the Observatory web site at bluehill.org.]