A Holistic Assessment of 1979–2016 Global Cryospheric Extent

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Key Points:

- Holistic changes in global cryospheric extent have not previously been quantified.

- Each year, global cryospheric area extent decreased $87\pm11\times10^3$ km$^2$.

- Climate change resulted in a decline of the duration and number of cryospheric cover by 2 or more days/decade.

Abstract

The cryosphere plays a major role in earth’s climate system. Most cryospheric assessments focus on one or more of its components and their response to climate change. However, to date, there has not been a comprehensive evaluation of the entire global cryosphere. We therefore
determine such a holistic estimate and quantify changes to the hemispheric and global cryosphere due to climate change, by synthesizing sea ice, snow cover, and frozen ground extents into one global cryospheric extent dataset. The 1981–2010 climatology of daily global cryospheric extent ranges from $45.7\pm0.7\times10^6$ to $87.2\pm2.0\times10^6$ km$^2$ (9.0%–17.1%), from $13.3\pm0.8\times10^6$–$66.3\pm1.7\times10^6$ km$^2$ (5.2%–26.0%) in the Northern Hemisphere (NH), and from $17.9\pm0.3\times10^6$ to $33.6\pm0.4\times10^6$ km$^2$ (7.0%–13.2%) in the Southern Hemisphere (SH). The monthly maximum cryospheric extent of $85.84\pm1.91\times10^6$ km$^2$ occurs in December, whereas minimum occurs in July with $45.92\pm0.70\times10^6$ km$^2$. During 1979–2016, global cryospheric area extent lost approximately $87\pm11\times10^3$ km$^2$/yr, with a decrease of $102\pm9.7\times10^3$ km$^2$/yr in the NH that was partly offset by an increase of $14.6\pm4.4\times10^3$ km$^2$/yr in the SH. The first day of cryospheric cover was delayed by 3.6 days at a rate of 0.95 days/decade, and the last day advanced by 5.7 days, at a rate of 1.5 days/decade. The duration and number of cryospheric cover days decreased by 8.7 days and 7.6 days over the study period, respectively. These variations of global cryospheric extent are correlated with rising air temperatures. Our findings highlight the importance of assessing the cryosphere as a whole, and provide a way to quantitatively estimate its overall changes.

1. Introduction

According to ongoing temperature analyses, the average global temperature on Earth has increased by slightly more than 1°C since 1880 (NASA GISS, 2020). Furthermore, the near-surface atmosphere in high-latitude and high-altitude regions has warmed faster than elsewhere (Pepin et al., 2015; Wang et al., 2017). Observational records of ocean heat content show accelerated warming as well (Cheng et al., 2019). The global temperature rise has resulted in a worldwide cryospheric reduction as evidenced by, e.g., a strong increase in ice loss (Box et al., 2018), pervasive ice sheet mass loss (Smith et al., 2020), large decreases in sea ice cover and thickness (SWIPA, 2017), terrestrial snow cover extent decreases (Jeong et al., 2017; Box et al.,
Climate warming has resulted in substantial cryospheric changes, which can influence the surface energy and moisture balance, surface and subsurface hydrology, carbon exchange between the soil and the atmosphere, and ecosystem diversity and productivity. The cryosphere plays a unique role in its interactions with the atmosphere due to its high albedo, the coexistence of water in all three phases, and phase changes associated with large amounts of latent heat (Qin et al., 2018). These characteristics also play a significant role in climate system. Cryospheric changes have significant impacts on hydrological processes in terms of, e.g., the sea level, runoff, and freshwater. Global mean sea level is rising at an accelerated rate in recent decades due to increasing ice loss from the Greenland and Antarctic ice sheets, as well as continued glacier mass loss and ocean thermal expansion, representing a “high confidence” IPCC finding (Pörtner et al., 2019). Glacier melt, permafrost thaw, and snow cover decreases all influence hydrological processes via surface runoff (Bayard et al., 2005; Ye et al., 2009; Quinton et al., 2013; Carey et al., 2014). The global cryosphere is the largest reservoir of freshwater, containing more than 3/4 of earth’s total amount. Current cryospheric changes threaten the global freshwater reservoir, particularly in high mountain regions where cryospheric melting threatens water supplies (Immerzeel et al., 2010; Gao et al., 2019). Terrestrial and subsea permafrost degradation potentially accelerate carbon release by contributing a substantial carbon-climate feedback not only due to the intensity of its climate forcing, but also the size of the carbon reservoir in permafrost soils (Schuur et al., 2015; Olefeldt et al., 2016; Shakhova et al., 2017; Knoblauch et al., 2018; Bowen et al., 2020).

Although the cryosphere plays a significant role in the earth system, most cryospheric assessments focus on changes in individual components only. For example, glaciers are retreating worldwide, with the total mass loss increasing from 40±9 Gt/yr during 1979–1990, to 50±14 Gt/yr in 1989–2000, to 166±18 Gt/yr in 1999–2009, and finally to 252±26 Gt/yr during 2009–2017 (Rignot et al., 2019). Due to the strong influence of CO₂ emissions and human actions on future
ice loss, 2017’s cumulative World Heritage glacier ice volume of 12,000 km$^3$ has been projected to decrease 33–60% by 2100 (Bosson et al., 2019). For sea ice, its Arctic extent shows a decreasing trend in all months (Meier et al., 2012), reaching a maximum in March, with an average trend of −12.8%/decade, and the minimum in September, with an average trend of −2.7%/decade (Perovich et al., 2018). In the Antarctic, sea ice extent changed little from 1978 to 2015, with a slight positive trend and reaching a maximum in September 2012. However, there was a record decrease in 2016’s austral spring (September–November) (Turner et al., 2017). For snow, its extent derived from satellite data indicates an overall decrease, with the largest declines in spring (Kunkel et al., 2016). The new GlobSnow 3.0 dataset indicates that the 1980–2018 NH annual maximum snow mass was 3062±35 Gt (Pulliainen et al., 2020). 78 % of mountain areas are experiencing a decrease in snow, characterized by a snow cover duration decrease up to 43 days (Notarnicola, 2020). For frozen ground, the global mean annual permafrost temperature has increased 0.29±0.12°C during 2007–2016 (Biskaborn et al., 2019). Global climate models predict that the near-surface (down to 5 m) permafrost area will decrease by 80% or more by the end of the 21st century (Koven et al., 2013; Guo et al., 2016). Soil freeze depth decreased by 1.8±0.3 cm/decade in China (Peng et al., 2017), and 4.5 cm/decade in the Eurasian high latitudes (Frauenfeld et al., 2011). Studies focusing on lake/river ice phenology and their response to climate find that, based on remote sensing of about 13,300 Arctic lakes in 2000–2013, there are significant trends towards earlier break-up, stronger than previously reported (Šmejkalová et al., 2016). Spatial heterogeneity is evident, with declines in ice cover duration at 43 lakes and increases or minimal changes at 28, as indicated by passive microwave satellite remote sensing data (Du et al., 2017).

Changes in cryospheric extent and phenology have thus been extensively documented for individual components. However, a holistic assessment of the entire cryosphere and its changes is essential to determine the cryosphere’s response to climate change, its feedbacks to the climate system, and the resulting impacts on the environment and society. All major climate change assessment reports on cryospheric variability, such as the Intergovernmental Panel on Climate
Change (2013), Arctic Monitoring and Assessment Programme (2017), and the Arctic Report Cards (e.g., Osborne et al., 2018), are essentially cryospheric component assessments. Each assessment thus demonstrates only partial changes in the cryosphere, rather than overall cryospheric change. A holistic assessment of the cryosphere would substantially improve understanding of its impacts on the other spheres of our planet—the atmosphere (including the climate system), hydrosphere, biosphere, and lithosphere.

No previous studies have quantified global cryospheric extent and characterized its variability and long-term changes. Thus, the novelty and primary purpose of this study are to determine the spatial and temporal changes in the global cryosphere from 1979 through 2016 by synthesizing multiple cryospheric elements into one holistic, global cryospheric area extent record. Additionally, we determine the response of changes in cryospheric area extent to climate change, both regionally and globally.

2. Data and Methods

2.1 Data

Data sets used in this study include sea ice, snow cover, and near-surface frozen soils. Area extent of both the Greenland and Antarctic Ice Sheets is included in either snow cover or near-surface frozen soil products. Lake and river ice extent is not explicitly specified but they are generally included in the area extent of the near-surface frozen soils. We essentially synthesize three major data products: near-surface frozen soil data, snow cover extent data, and sea ice area extent. To analyze the cryospheric extent’s relationship with climate change, air temperature data are used. We also use in-situ station observations to validate our global cryospheric area extent.

2.1.1 Sea ice extent

Sea ice is a major cryospheric component for the Arctic and Antarctic oceans. Here, we use the
daily sea ice extent dataset for 1978–2016 with 25 km × 25 km spatial resolution from the National Snow and Ice Data Center (NSIDC; https://nsidc.org/data/G02135/versions/3). This NSIDC sea ice index is derived from two data sets: the near-real-time Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) daily polar gridded sea ice concentrations, and the sea ice concentrations from Nimbus-7 Scanning Multi-channel Microwave Radiometer and DMSP SSM/I-SSMI/Sounder passive microwave data. These data sets are used to generate the daily and monthly values that comprise the sea ice index record of sea ice extent and concentration from November 1978 to present. The daily sea ice extent shows the extent of ocean covered by ice at any concentration greater than 15% for a given day.

2.1.2 Snow cover extent

For global snow cover extent, there is no long time-series product available derived either from satellites or observations. While many observational products are available for the Northern Hemisphere, this is not the case in the Southern Hemisphere. Rather than combine different data sets for different hemispheres, we therefore use snow depth from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim) for 1979 to 2016 with a spatial resolution of 0.25° × 0.25°, available at https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/. The spatial variability of ERA-Interim snow depth exhibits overall better agreement with ground observations than other datasets, e.g., the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2; Xiao et al., 2020).

2.1.3 Near-surface frozen soils

Daily ground surface freeze/thaw status data span from 1979 to 2016 and are available at 25 km × 25 km resolution from NSIDC (http://nsidc.org/data/nsidc-0477). These data are derived based on brightness temperature time series through a modified seasonal threshold algorithm used to identify ground surface freeze/thaw status (Kim et al., 2017). Each grid cell has its own threshold to define freeze/thaw status through a linear relationship between brightness temperature and daily
surface air temperature derived from ERA-Interim. Due to ground surface freeze/thaw status potentially switching back and forth within one day, the algorithm set AM and PM thresholds using the corresponding daily minimum and maximum surface air temperature, and the brightness temperatures corresponding to the ascending and descending orbital data. Thus, the ground surface freeze/thaw status includes transitional (AM frozen and PM thawed) and inverse transitional (AM thawed and PM frozen) conditions. The respective mean annual spatial classification accuracies are 90.3 and 84.3% for PM and AM overpass retrievals relative to global weather station measurements (Kim et al., 2017). This data product also includes the Greenland and Antarctic ice sheets, which comprise a substantial and important component of the cryosphere.

2.1.4 Air temperature

Global monthly average air temperature data were obtained beginning in 1979 from the University of East Anglia’s Climatic Research Unit time series version 4.04 (https://crudata.uea.ac.uk/cru/data/hrg/). The product is provided at a horizontal latitude-longitude resolution of 0.5 \( \times \) 0.5° and consists of surface air temperatures interpolated from meteorological stations across global land areas (Harris et al., 2020). The monthly temperature anomalies are highly correlated (in 95% of cases, \( R \geq 0.56 \)) with their withheld validation data and mean absolute errors \( \leq 0.87°C \) in 95% of cases, and ranging 0.25–0.75°C (Harris et al., 2020).

2.1.5 Station data

Station data are used in this study to verify our daily cryospheric extent dataset. The global summary of the day (GSOD) product is produced by the National Centers for Environmental Information with inputs from integrated surface data. The GSOD dataset is made up of more than 28,000 stations from 1929 to the present, and includes minimum, maximum, and mean air temperature, snow depth, air pressure, dewpoint temperature, wind speed, and precipitation variables (ftp://ftp.ncdc.noaa.gov/pub/data/gsod). Here, maximum temperature and snow depth for 1979–2016 were used to verify the near-surface frozen soil and snow cover. Stations with missing
information like latitude or longitude are not included in this study.

2.2 Methods

To combine the three major cryospheric components into one global cryospheric extent dataset, we grid all products into one uniform $0.25^\circ \times 0.25^\circ$ spatial resolution using nearest neighbor interpolation at the daily time scale. For the ground surface freeze/thaw status, the twice daily (AM and PM) values were averaged into daily resolution, and also interpolated to the $0.25^\circ \times 0.25^\circ$ spatial resolution using nearest neighbor interpolation. For snow cover, ERA-Interim snow depths are used to identify snow cover based on daily snow depths greater than 1 cm. The snow cover extent dataset also again includes ice sheets, i.e., Greenland and Antarctica. Sea ice extent is available at the daily time scale, except for the time period from 1 Nov. 1978 to 19 Aug. 1987 when data were only available every other day. For this period, we interpolated the sea ice extent into daily resolution.

Finally, we combined all three datasets into one, where each grid cell was classified as cryosphere if it contains at least one of the frozen surface types: frozen ground (including ice sheets), snow cover, or sea ice cover. If a grid cell contains one or more cryospheric variables, it is defined as one single cell occupied by cryosphere. Based on this classification, we produced the daily cryospheric extent dataset.

To assess the long-term spatiotemporal variability of the cryosphere, we calculate both the area extent and the percent cover. For area extent, we calculated the daily areas for the NH, SH, and the whole globe. We also create monthly and annual area extents to quantify changes in cryospheric area extent based on the daily area extent datasets in each year. All area extent calculations are based on equal area projections. The percent cover is calculated as the ratio of days that each grid contains cryospheric cover during the defined time scale, e.g., per month, or per year.
To characterize the timing and duration of cryospheric cover, we identify the first date (FD), last date (LD), duration (DR), and number of days (ND) of cryospheric cover. To accurately capture the NH and SH cold and warm seasons, we defined the cryospheric year as June 1 of the current year to May 30 of the following year for the NH, and December 1 of the current year to November 30 of the following year for the SH. The FD and LD variables are defined as the first and last date, respectively, that the surface is covered by cryosphere. DR is defined as the time span between FD and LD. The ND variable corresponds to the sum of days that the surface is covered by the cryosphere in one cryospheric year.

We investigate anomalies of monthly and annual variables with respect to the 1981–2000 long-term average. Trends are calculated using linear regression of the anomalies. Statistical significance of trends was established using two-tailed t-tests at the 95% confidence level. Time series are smoothed using wavelet analysis. The uncertainty of the trends is also determined using the 95% confidence level.

The daily cryospheric extent is verified using the GSOD product. Daily maximum air temperature below/above 0°C was used to identify the soil freeze/thaw status based on the methodology of Zhang et al. (2003). An et al. (2009) showed that snow depths of more than 0.5 or 1 cm can be used as the standard for identifying snow cover, and we therefore apply a 1 cm threshold. If the ground was either frozen or covered by snow, the pixel was considered to be covered by cryosphere. If the ground was thawed and not covered by snow, the pixel was considered as not covered by cryosphere. Over the ocean, cryospheric cover is specified by sea ice presence. To verify our reconstructed daily cryosphere extent dataset, 14,310 stations were used for validation. The observed daily cryospheric status at each station is determined based on the above method using observed daily minimum air temperature and snow depth. Next, the reconstructed daily cryospheric extent value at each station location is extracted. The observed (GSOD) cryospheric status is then used to verify our reconstructed daily cryospheric extent.

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3. Results

3.1 Climatology of global cryospheric extent

3.1.1 Daily cryospheric extent

The daily climatology of global cryospheric extent exhibits a gradual decrease from about $87.2 \pm 2.0 \times 10^6$ km$^2$ on Jan. 1 to about $45.7 \pm 0.7 \times 10^6$ km$^2$ on Jul. 19, and then increases to $86.5 \pm 2.3 \times 10^6$ km$^2$ on Dec. 9, followed by a period of slow variability (Figure 1a). The general NH variability of daily cryospheric extent mimics these global characteristics. The differences are in that the largest area extent of $66.3 \pm 1.7 \times 10^6$ km$^2$ occurred on Jan. 25, followed by a decrease to the lowest value of $13.3 \pm 0.8 \times 10^6$ km$^2$ on Aug. 23, and finally an increase to the end of the season (Figure 1b). In the SH, the variability is opposite. The lowest extent of $17.9 \pm 0.3 \times 10^6$ km$^2$ occurs on Feb. 24, followed by an increase to the highest value of $33.6 \pm 0.4 \times 10^6$ km$^2$ on Sep. 12, and then a decrease until the end of the year (Figure 1c). The standard deviation of the global extent is $0.48 – 3.35 \times 10^6$ km$^2$, corresponding to $0.1\%–0.6\%$ of the global cryospheric area. In the NH, the standard deviation is $0.60 – 3.42 \times 10^6$ km$^2$, representing $0.2\%–1.3\%$ of the NH cryospheric area. In the SH, the standard deviation is $0.29 – 0.91 \times 10^6$ km$^2$, or $0.1\%–0.3\%$ of the SH cryospheric area. The fluctuations of daily cryospheric extent were larger in the NH than in the SH, and the global extent fluctuations are in between. For the daily cryospheric extent, the average maximum extent was $87.2 \pm 2.0 \times 10^6$ km$^2$, while the minimum was $45.7 \pm 0.7 \times 10^6$ km$^2$.

3.1.2 Monthly cryospheric extent

The climatology of global cryospheric percentage and area extent for each month during 1981–2010 was calculated to determine the monthly cryospheric extent (Figure 2 and Table 1). Typically, the global cryosphere reached its maximum monthly extent in December or January whereas the
minimum occurred in July or August. The monthly maximum and minimum cryospheric area extent are $85.84\pm1.91\times10^6$ km$^2$ and $45.92\pm0.70\times10^6$ km$^2$, respectively. As expected, the cryospheric extent in the NH and SH are also opposite. The maximum cryospheric percentage and area extent occur in January, when most areas experience cryospheric extent greater than 90%, and area extent reaches $65.46\pm1.55\times10^6$ km$^2$. Conversely, the minimum cryospheric percentage and area extent occurs in August, with only a small area of cryospheric extent greater than 80%, mainly in the high latitudes, where area extent reaches $13.27\pm0.78\times10^6$ km$^2$. In the SH, the maximum and minimum cryospheric percentage and area extent occurred in September and February, with areas of $33.43\pm0.35\times10^6$ km$^2$ and $18.22\pm0.33\times10^6$ km$^2$, respectively. Spatially, most of the NH high-latitude and altitude regions are more than 95% covered by cryosphere in December, January, and February, and cryospheric percentage declines from north to south. From February to August, the cryospheric percentage declines quickly, e.g., on the Tibetan Plateau, it declines from 90% to less than 15%, and decreases upslope. From August to December, the percentage and area extent both increase. These patterns are reversed in the SH.

3.1.3 Annual global cryospheric extent

The spatial patterns of the 1981–2010 mean annual cryospheric extent (Figure 3) indicate that greater annual percentages are located primarily in the high latitudes and altitudes, e.g., more than 95% cover is found on the Antarctic continent, Greenland, and north of 85°N, and the northwest Tibetan Plateau. In the NH, the annual cryospheric percentage decreases with decreasing latitude. Taking the 90°E meridian as an example, cryospheric percent cover changed from 100% in the highest latitudes, then decreased to 80–90% in eastern Siberia, about 50–70% in the 45°N–60°N regions, then decreased to less than 20% in the Taklimakan desert in western China, increased again to about 40–60% on the Tibetan Plateau, and finally decreases to near zero in the south. This latitudinal pattern is similar between the NH and SH.
3.2 Variability of cryospheric area extent

The annual mean global cryospheric area extent decreased significantly from 1979 to 2016 at a rate of about $87\pm11\times10^3$ km$^2$/yr (Figure 4a). From 1979 to the late 1980s, area extent decreased slightly, followed by a slight increase until 1995. Thereafter, it again decreased until 2007 with a subsequent increase to 2013, and finally a decrease until 2016 (Figure 4a). Annual mean NH cryospheric area extent shows a remarkable decline, with a decrease of about $102\pm9.7\times10^3$ km$^2$/yr (Figure 4b), with similar interannual variability as the global mean. In the SH, a small increase at a rate of about $14.6\pm4.4\times10^3$ km$^2$/yr is evident (Figure 4c). Because the decrease in the NH was six times greater than the increase in the SH, thus the global pattern was dominated by the NH.

Focusing on individual months, statistically significant decreases in monthly cryospheric area extent occurred from 1979 through 2016 in all months except for May (Figures 5 and 6). The significant decrease ranged from a minimum of $37\pm10\times10^3$ km$^2$/yr in June to a maximum of $177\pm27\times10^3$ km$^2$/yr in November. The decrease was greater than $100\times10^3$ km$^2$/yr from January to March and from October to December. In the NH, statistically significant negative trends occurred in all the months (Figures 5 and 7). The maximum and minimum decreases, respectively, were $180\pm28\times10^3$ km$^2$/yr in November and $50\pm12\times10^3$ km$^2$/yr in May. In the SH, there were no significant trends in November, December, January, or February (Figures 5 and 8). The other months experienced a small increase, with a maximum of $26\pm8$ km$^2$/yr in May and a minimum of $12\pm6$ km$^2$/yr in July. Decreases in the NH are larger than the increases in the SH. Thus, the overall decreasing trend in monthly global cryospheric area extent was again dominated by the NH.

3.3 Changes of the timing and duration of cryospheric cover

The long-term mean timing and duration of the global cryospheric cover was found to vary
greatly over 1981–2010 (Figure 9). In the NH, FD occurred in June and July north of 70°N, with onset progressing from August to December moving from north to south, except for some regions on the Tibetan Plateau. Some low latitude and coastal regions do not experience FD until January and February. In the SH, FD occurs in June in the north, and in December in the south. LD occurs between January and June in the NH, and between August and December in the SH. DR ranges from 10 or fewer days south of 25°N and north of 30°S, to instead last throughout almost the entire year in high latitude and high-altitude regions (e.g., the Antarctic and Arctic poles and the Tibetan Plateau). On the Eurasian continent, DR is mostly between 100 and 250 days. In North America, DR ranges from 120 days to 250 days. The spatial pattern of global ND is very similar to DR, with the expected latitudinal and altitudinal variability.

The spatial trends of the timing and duration of cryospheric cover over 1979–2016 were statistically significant (Figure 10). FD advanced at a rate of 0.95 days/decade, indicating that the FD of cryospheric cover occurred later. In the Arctic Ocean and Antarctic regions, there were no significant changes in FD. For LD, the mean trend was −1.5 days/decade, meaning it occurred earlier. The DR of global cryospheric extent decreased at −2.3 days/decade, indicating a shorter time period in some areas. However, most regions are near zero, indicating little change in DR. The ND of cryospheric cover also decreased, at a rate of 2.0 days/decade. The spatial pattern is similar to DR’s.

4. Discussion

4.1 Responses to climate change

Both observational and modeling studies indicate that high-latitude and high-altitude regions are experiencing disproportionate warming (Pepin et al., 2015; Wang et al., 2017). We find that the overall global and NH cryospheric area extent experienced significant decreases, while a small increase is evident in the SH. These results are significantly associated with climate change, except
for in the SH (Figure 11). Detrended global and NH cryospheric area extents correlate negatively with detrended air temperature, however, there is no such association in the SH. Similarly, Arctic sea ice and NH spring snow cover have decreased in extent (e.g., Kunkel et al., 2016; Perovich et al., 2017). Turner et al. (2017) indicated that the sea ice extent exhibited virtually no change from 1978 to 2015, with a slight positive trend, and reached a new maximum in September 2012. There is high confidence in strong regional differences of these changes, with extent increasing in some regions and decreasing in others. The main component contributing to SH cryospheric extent change is Antarctic sea ice, characterized by large interannual variability around the continent. Due to this large variability, the observed Antarctic sea ice extent trends are still within the range of internal variability, and an anthropogenic signal has not yet emerged. Ice increases in western Ross Sea are the primary drivers of the positive trend since 1979 (Hobbs et al., 2016). The mechanisms for these changes are still not clear. Internal modes of variability like the Interdecadal Pacific Oscillation’s (IPO) switch from its positive to its negative phase, and a cooling of tropical Pacific sea surface temperatures. Both a slowdown of the global warming trend and an intensification of the Amundsen Sea Low have been reported, with regional circulation changes in the Ross Sea region and a resulting increase of sea ice (Meehl et al., 2016). A negative IPO phase has also been associated with sea-level pressure anomalies and low-level winds near Antarctica, which can result in increasing Antarctic sea ice extent (Meehl et al., 2016). Sea ice expansion could also be attributed to accelerated basal melting of Antarctic ice shelves, whereby the melt water causes a cool, fresh surface layer that protects the surface from the deeper, warmer waters (Bintanja et al., 2013). The cryospheric extent decrease in 2016 could be attributed to advection of relatively warm air masses into the sea ice zone, due to atmospheric circulation anomalies (Turner et al., 2017). As our cryospheric area extent record effectively synthesizes Earth’s frozen “sphere” and is strongly and directly related to global air temperature increases, it is therefore an effective data record to gauge both the drivers and consequences of climate change.
4.2 Uncertainties in the cryospheric extent data record

Our underlying assumptions, data sources, and analysis choices may introduce uncertainties, which are important to recognize as caveats. Some of these uncertainties relate to the cryosphere’s definition, data limitations, and the spatial resolution, as described below.

4.2.1 Definition: The definition of the cryosphere varies from snow and ice formation, to including all forms of frozen water such as glaciers, ice sheets, snow cover, sea ice, lake and river ice, permafrost, solid precipitation, etc. The Encyclopedia of Astrobiology defines the cryosphere to encompass all of Earth’s locations with low temperatures and frozen water, which includes cold deserts (Arndt, 2011; Qin et al., 2018). IPCC (2013) considers the cryosphere to be comprised of snow, river and lake ice, sea ice, glaciers, ice shelves and ice sheets, and frozen ground. Thus, the choice of definition will play a role in the cryospheric area extent. Here, it is not our intent to redefine the cryosphere, but rather we focus on the cryospheric cover on Earth’s surface. The cryospheric area extent can be directly detected by in-situ measurements and satellite remote sensing. We include glaciers, ice sheets, sea ice, snow cover, seasonally frozen ground and/or near-surface frozen soils, and lake/river ice. This area extent does not explicitly include permafrost, because permafrost underlies a thawed active layer with a thickness that varies from a few tenths of a meter to several meters. However, permafrost area does not change substantially over short time periods and is included during winter, but not in summer when the near-surface soil has thawed. Subsea permafrost is treated the same way as terrestrial permafrost.

4.2.2 Datasets: The availability and quality of data to represent the various cryospheric components also introduces uncertainty. We used several datasets, including satellite and reanalysis products. Near-surface soil freezing and sea ice are mostly derived from passive microwave satellite remote sensing, although the snow cover was based on the ERA-Interim reanalysis which is known to be problematic. Each data product has its own uncertainties, thus, all of these uncertainties are inherently introduced into our new cryospheric data record.
4.2.3 Resolution: The spatial and temporal resolution of the original input data differs and some products had to be spatially and/or temporally resampled. For example, sea ice and near-surface freeze/thaw status data both have 25 km × 25 km spatial resolution, whereas snow cover is on a 0.25° × 0.25° grid. Finally, some missing data were interpolated, which also influences the accuracy.

While there are thus uncertainties in our data record, this is the first time such an effort has been attempted. Our cryospheric area extent record is provided in light of the above caveats. However, to validate our daily cryospheric extent dataset, we used in-situ station records from more than 14,000 locations. Most locations have an accuracy greater than 90% (Figure 12), with an overall mean accuracy of approximately 96.6% at all stations. The validation did uncover some regions, particularly in Europe, where accuracy is lower. These regions are confined to precise political boundaries, and we thus speculate that this is an artifact of GSOD, caused by the availability and quality of station observations for particular countries. Overall, this validation illustrates the high quality of our daily cryospheric extent dataset, and our resulting estimates of its spatial and temporal variability.

5. Conclusions

A new long-term (1979–2016) daily cryospheric area extent data record is developed and presented at the hemispheric and global scales. This data record is particularly important for studies on the cryosphere, climate, and other associated disciplines.

The climatology analyses indicate that the daily global cryospheric extent ranged from 87.2±2.0×10^6 km^2 to 45.7±0.7×10^6 km^2. The monthly maximum and minimum cryospheric area extent was similar, at 85.84±1.91×10^6 km^2 and 45.92±0.70×10^6 km^2, respectively.

Long-term trends in the annual mean cryospheric extent indicate that Earth lost 87±11×10^3 km^2
of cryospheric area each year during 1979–2016, dominated by losses in the NH (102±9.7×10^3 km^2) that were slightly offset by increases in the SH (14.6±4.4×10^3 km^2). Similar statistically significant decreases in monthly area extent are evident for all months of the year, except for May.

The spatial variability in the timing and duration of the cryospheric extent exhibits a zonal latitudinal and altitudinal pattern across the globe. For the overall mean, FD was delayed by 0.95 days/decade, and LD advanced by 1.5 days/decade. The resulting DR and ND of cryospheric cover both decreased at rates of 2.3 and 2.0 days/decade, respectively.

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Table 1. Monthly mean cryospheric area extent climatology for 1981–2010.

| Month    | NH (10^6×km^2) | SH (10^6×km^2) | Globe (10^6×km^2) |
|----------|----------------|----------------|-------------------|
| January  | 65.46±1.55     | 20.12±0.54     | 85.58±1.70        |
| February | 64.29±1.83     | 18.22±0.33     | 82.51±1.86        |
| March    | 57.23±1.88     | 19.02±0.41     | 76.25±1.82        |
| April    | 43.23±0.94     | 21.70±0.51     | 64.93±1.03        |
| May      | 27.89±0.88     | 25.07±0.49     | 52.96±0.98        |
| June     | 17.84±0.64     | 28.52±0.41     | 46.36±0.60        |
| July     | 14.61±0.68     | 31.32±0.38     | 45.92±0.70        |
| August   | 13.27±0.78     | 32.91±0.33     | 46.18±0.74        |
| September| 14.69±1.17     | 33.43±0.35     | 48.12±1.11        |
| October  | 27.99±2.82     | 32.87±0.33     | 60.85±2.67        |
| November | 47.09±2.79     | 30.71±0.33     | 77.80±2.71        |
| December | 60.40±1.80     | 25.45±0.63     | 85.84±1.91        |
Figure 1. Daily 1981–2010 climatology of cryospheric extent for the (a) globe, (b) NH, and (c) SH. The black line is the area percentage for each day.
Figure 2. Monthly climatology of cryospheric area extent (%) relative to the 1981–2010 means.
Figure 3. 1981–2010 climatology shown as the percentage of each grid cell that is occupied by one or more cryospheric components.
Figure 4. Anomalies of 1979–2016 cryospheric area extent relative to the 1981–2010 means for the (a) globe, (b) NH, and (c) SH. Statistically significant (p<0.05) slopes (km$^2$/yr) are indicated with asterisks. Thick curves are smoothed using wavelet analysis, bold lines represent the linear regression trends, and shading shows the ±1 standard deviation of annual anomalies.
Figure 5. Trends in regional-average cryospheric extent during 1979–2016 for the globe, NH, and SH. Statistically significant ($p < 0.05$) slopes are indicated by asterisks.
Figure 6. Global monthly 1979–2016 cryospheric extent anomalies relative to the 1981–2010 means. Statistically significant (p < 0.05) slopes (km^2/yr) are indicated by asterisks. Thick curves are smoothed using wavelet analysis, bold lines represent the linear regression trends, and
shading shows the ±1 standard deviation of annual anomalies.
Figure 7. As in Figure 6, but for the NH.

Figure 8. As in Figure 6, but for the SH.
Figure 9. 1981–2010 climatology of the (a) first date, (b) last date, (c) duration, and (d) number of days that the near-surface is covered by cryosphere.
Figure 10. Spatial variability of statistically significant (95% level) changes in the (a) first date, (b) last date, (c) duration, and (d) number of days that the near-surface is covered by cryosphere during 1979–2016.
Figure 11. Correlation between the monthly detrended cryospheric area extent and detrended surface temperature for the (a) globe, (b) NH, and (c) SH.
Figure 12. Validation of daily cryospheric extent based on NCEI GSOD stations during 1979–2016.