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Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Indicators of Physical and Biological Trends around the McMurdo Station, Antarctica

A Literature Review

Janet P. Hardy

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Final Report

Prepared for National Science Foundation, Division of Polar Programs,
Antarctic Infrastructure and Logistics
Arlington, VA 22230

Under Engineering for Polar Operations, Logistics, and Research (EPOLAR)
EP-ANT-14-06, "Program and Technical Support to NSF-PLR Antarctic Infrastructure and Logistics."

Abstract

The United States Antarctic Program (USAP) is managed by the National Science Foundation, Division of Polar Programs (NSF-PLR), which has the responsibility for all logistics and operations related to U.S. scientific research in Antarctica and aboard ships in the Southern Ocean. For years, scientific literature has focused on global environmental change and, in particular, the accelerated change occurring, and predicted to occur, in the polar regions.

This report summarizes documented changes that have occurred in Antarctica, with a focus on the Ross Sea region, as well as projections of environmental change expected to occur in the next 100 years. Many of the observed changes in the Ross Sea region since 1960, such as increased air and soil temperature, decreased glacial extent, and sea level rise, are consistent with a warming climate; however, the observed increase in sea-ice extent does not fit an expected pattern and is explained by a shift in circumpolar circulation. Models predict the observed changes to continue over the next 100 years, except that they anticipate the sea-ice extent in the Ross Sea region to decrease significantly. This report also presents potential implications of these changes for USAP operations and logistics, primarily in response to the reduced sea-ice extent and higher air and soil temperatures.

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Preface

This study was conducted for the National Science Foundation, Division of Polar Programs (PLR), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-14-06, "Program and Technical Support to NSF-PLR Antarctic Infrastructure and Logistics." The technical monitor was George Blaisdell, Chief Program Manager, NSF-PLR, U.S. Antarctic Program.

The work was performed by Janet P. Hardy (Research and Engineering Division, Loren Wehmeyer, Acting Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, the Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

LTC John Tucker was Acting Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

AABW	Antarctic Bottom Water
AFDD	Accumulated Freezing Degree-Days
a.s.l.	Above Sea Level
ATDD	Accumulated Thawing Degree-Days
AWS	Automated Weather Stations
BP	Before Present
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics, and Research
ERDC	Engineer Research and Development Center
GCM	Global Climate Model
IGY	International Geophysical Year
IPCC	International Panel on Climate Change
LGM	Last Glacial Maximum
Ma	Million Years Ago
N/A	Not Available
NS	Not Significant
NSF	National Science Foundation
PLR	Division of Polar Programs
RCP	Representative Concentration Pathway
READER	Reference Antarctic Data for Environmental Research
SAM	Southern Hemisphere Annular Mode
SWE	Strong Wind Event
USAP	United States Antarctic Program

Unit Conversion Factors

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
inches	0.0254	meters

1 Introduction

1.1 Background

The United States Antarctic Program (USAP) is managed by the National Science Foundation, Division of Polar Programs (NSF-PLR), which has the responsibility for all logistics and operations related to U.S. scientific research in Antarctica and aboard ships in the Southern Ocean. USAP operates three permanent research stations on the continent, McMurdo Station (77°51′ S, 166°40′ E), Amundsen-Scott South Pole Station at the geographic South Pole, and Palmer Station (64°46′ S, 64°03′ W), and it also relies on icebreakers and research vessels to conduct its missions (resupply or science). The largest of the U.S. stations, McMurdo, can support up to about 1000 residents during the summer and is the main science and logistical hub for USAP. McMurdo Station is located on the southern tip of Ross Island with the McMurdo Sound and Ross Sea to its north and the Ross and McMurdo Ice Shelves to its south and west (Figure 1). For over 20 years, the U.S. Army Corp of Engineers, Cold Regions Research and Engineering Laboratory (CRREL) has provided engineering expertise to help solve operational challenges faced by the USAP. Therefore, the purpose of this report is to inform the USAP of the potential implications of environmental changes to their operations in the McMurdo Station region.

“By 2100, the mean air temperature at the Earth’s surface is predicted to increase by 1.4°C to 5.8°C, with a disproportionate effect at high altitudes and latitudes” (Yergeau 2014). Climate scientists have long understood that global climate change is going to affect the polar regions sooner and to a greater extent than lower and mid-latitude regions of the earth. Therefore, my report summarizes current literature on the historical physical and biological data and on the trends and changes in Antarctica within the last 50 years. The general historical context of the Antarctic climate is based on a recent report (Turner et al. 2014) that updated an extensive 526-page overview report on Antarctic climate change and the environment (Turner et al. 2009). Additionally, my report summarizes specific published research on the physical and, to a lesser extent, biological changes that have occurred on the continent, with a focus on the Ross Sea and McMurdo Region. This report concludes with model predictions for future changes in the next 100 years and possible implications for USAP operations and infrastructure.

Figure 1. Map of Ross Sea, Ross Ice Shelf, and the McMurdo Station vicinity, Antarctica. (Image courtesy of the Polar Geospatial Center, http://www.pgc.umn.edu/.)

1.2 Historical context

In general, paleorecords show that periods of long-term stability and periods of change are both normal within the climate system. These records also show that non-linear, abrupt climate change can occur. As Turner et al. (2014) discussed climate change in Antarctica at length, this *Historical context* section is fully derived from their work.* The following is a sum-

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* Turner et al. (2014) cites in their text the individual studies and research articles they use. While all sources of information are referenced, some text is verbatim as appeared in the literature and is shown in quotes.

mary of key historical data, globally and from Antarctica, since the Cretaceous period (130 million years ago [Ma]):

- Temperatures in the Cretaceous period were 6°C to 7°C higher than at present with little or no ice on land.
- The Southern Ocean is thought to have begun cooling about 35 Ma.
- The first continental-scale ice sheets formed on Antarctica around 34 Ma, likely due to a decline in atmospheric CO_2 levels, resulting in global temperatures around 4°C higher than at present. During this period, the Antarctic ice sheets were likely warmer and thinner than the current ice sheet.
- A sharp cooling took place around 14 Ma, and the ice sheet thickened to approximately today's configuration.
- "During the Pliocene, 5–3 Ma, mean global temperatures were 2°C–3°C above pre-industrial values; . . . and sea level was 15–25 m above today's."
- During the Pleistocene glaciations (post 2.6 Ma), the long periods of cold went through cycles of warming and cooling with periodicities of 20,000; 41,000; and 100,000 years.
- Periodically during the Pleistocene, there would be short, warm interglacial periods like during the last 10,000 years.
- Ice-core records show that in Antarctica, the pre-industrial cold periods were on average 9°C lower than interglacials. Ice sheets expanded in glacial periods with the sea level dropping by 120 m on average.
- During the last interglacial period, about 130,000 years before present (BP), temperatures were as much as 5°C higher than pre-industrial temperatures; and the sea level was at least 6.6 m higher than at present, suggesting significant loss of Greenland and Antarctic ice.
- "Diatom data from sediment cores show that during the Last Glacial Maximum (LGM), about 21,000 years BP, Antarctic sea ice was double its current extent in winter and also increased in extent in summer in at least some ocean sectors."
- The last major global climate change event occurred during the transition from the LGM to the Holocene, about 12,000 years BP.
- Continuing into the Holocene, sea-ice expansion and contraction affected the mammal and seabird distributions and general ecosystem functioning.
- Significant warming events occurred between 11,500 and 9000 years BP, 7000 and 3000 years BP, and 4000 and 2000 years BP and likely raised temperatures by no more than around 0.5°C–1°C.

- Species assemblages and distributions responded to the periods of temperature changes in the Holocene, particularly in response to the changing extent of sea ice.

While history shows variations in climate over time, changes in the atmosphere, ice, and ocean systems since the instrument period have been more pronounced and rapid than during the Holocene. These measured changes, initiating with the International Geophysical Year (IGY, 1957–58), include the following:

- The Southern Hemisphere Annular Mode (SAM) has become more positive, resulting from stronger circumpolar westerly winds in the austral summer and autumn (15%–20% increase in wind strength) as pressure dropped around the coast of Antarctica and increased at mid-latitudes.
- "Surface temperature trends show significant warming across the Antarctic Peninsula and to a lesser extent the rest of West Antarctica since the early 1950s, with little change across the rest of the continent."
- West Antarctic warming has been linked to sea-surface temperature changes in the tropical Pacific, especially during the spring, because of its affect on the atmospheric circulation at high southern latitudes.
- West Antarctic ice-core data show a sharp increase in the rate of warming in the past 20 years to about 0.7°C per decade.
- The South Pole Station shows statistically significant cooling in recent decades.
- Based on Antarctic radiosonde temperature profile data, the atmosphere has warmed at the mid-tropospheric level, and the stratosphere above it has cooled (by about 0.5°C per decade) over the last 50 years.
- Since 1957, there has been no statistically significant change in snowfall on Antarctica, on average; but snowfall trends vary across the continent with the greatest accumulation in the Antarctic Peninsula.
- Stratospheric ozone amounts began to decline in the 1970s; but due to the success of the Montreal Protocol, which became effective in 1989, the size of the ozone hole has now stabilized but is not yet decreasing.
- "Changes in temperature and precipitation have also increased biological production in lakes and have altered species assemblages, mainly due to decreases in duration and extent of lake ice cover." Some plants in the maritime Antarctic have increased in abundance in response to climate change.

- "The overall reduction in total ice-shelf area during the last five decades has been estimated to be over 28,000 km^2 (Cook and Vaughan 2010)." This reduction has been attributed to both surface and subsurface melting.
- The Amundsen Sea area of West Antarctica is the most rapidly changing region of the Antarctic ice sheet, which is due, in part, to the increased delivery of warm, circumpolar deep water to sub-ice-shelf cavities.
- Across the East Antarctic ice sheet, the most dramatic changes are close to the coast with a mixture of thickening and thinning among the fringing ice shelves.
- Data suggest that in the 1990s to 2000s, global sea level rose at a rate of 3.3 mm/year, which is higher than predicted by the Intergovernmental Panel on Climate Change (IPCC 2007). West of the Antarctic Peninsula, the upper ocean temperatures have risen nearly 1.5°C since the 1950s and have become more saline in the summer due to changes in the rate of sea-ice production.
- "Marked freshenings of the dense AABW [Antarctic Bottom Water] have been observed in the Ross Sea and Indian/Pacific sectors of the Southern Ocean."
- Between 1991 and 2007 and "at latitudes poleward of 40°S, CO_2 in the ocean increased faster than it did in the atmosphere, suggesting that the ocean became less effective as a sink for atmospheric CO_2."
- Based on satellite measurements, the annual mean Antarctic sea-ice extent has increased 1.3% per decade between 1979 and 2010. This trend is linked to wind-driven changes in ice advection.
- The greatest increase in sea-ice extent has been in the Ross Sea and is estimated at about 4.5% per decade. This increase is linked primarily to changes in the SAM and secondarily to the Antarctic Circumpolar Wave. An intensification of the freshwater cycle, freshening the waters of the Ross Sea, has also played a role in increasing the sea-ice cover.
- "The Southern Ocean ecosystem was significantly disturbed by whaling during the early part of the 20th century, by sealing before that and by fishing since the mid-1900s." Humpback whales seem to be recovering while other populations remain low.
- Marine ecosystems of the Western Antarctic Peninsula have been impacted by the reduction of sea-ice habitat by 85 days/year and by the secondary effects on the food web.

- Phytoplanktons have increased around the entire Antarctic continent, and the “Ross Sea shelf area accounts for 27% of the CO_2 removed from the atmosphere by the entire Southern Ocean (Arrigo et al. 2008).”
- In McMurdo Sound, the reconstructed temperature history, using the permafrost thermal profile from 30 m deep boreholes, suggests a slight cooling from 1998 to 2003, followed by a slight warming to 2008.

2 The Physical Environment

The following trends in the physical environment are primarily specific to the Ross Sea and McMurdo regions with occasional reference to conditions at South Pole or the Palmer Station (Antarctic Peninsula region). This section on the physical environment is compiled from numerous peer-reviewed, published articles, primarily from the last five years. In general, LaRue et al. (2013) found that in the Ross Sea region, changing weather patterns have brought slightly warmer temperatures and stronger winds, with corresponding increases in sea-ice extent and persistence and more predictable coastal polynyas.

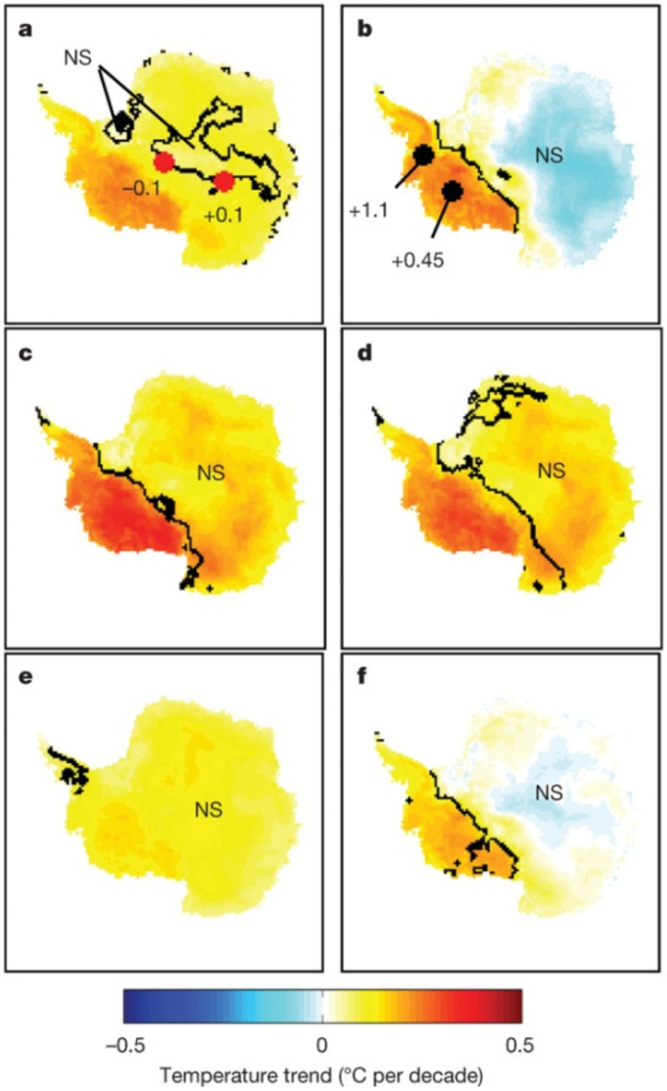
2.1 Air temperature

Thompson et al. (2011) noted that “anthropogenic emissions of ozone-depleting gases also lead to marked changes in surface climate, through the radiative and dynamical effects of the Antarctic ozone hole.” They found that the influence of the Antarctic ozone hole has led to a range of significant summertime surface climate changes over the continent and the Southern Ocean, which strongly resemble the most prominent pattern of SAM.

Temperature data from 50 years of radiosonde ascents above Antarctica closely resemble surface-temperature trend reconstructions, suggesting coupling between the surface and trends aloft (Screen and Simmonds 2012). Data averaged across eight Antarctic stations suggest a vertical profile of temperature change, characterized by mid-tropospheric warming and stratospheric cooling. In particular, during winter and spring, the Ross Ice Shelf and McMurdo region shows the most pronounced mid-tropospheric warming (0.1°C to 0.2°C per decade), which is coupled to surface warming (Screen and Simmonds 2012).

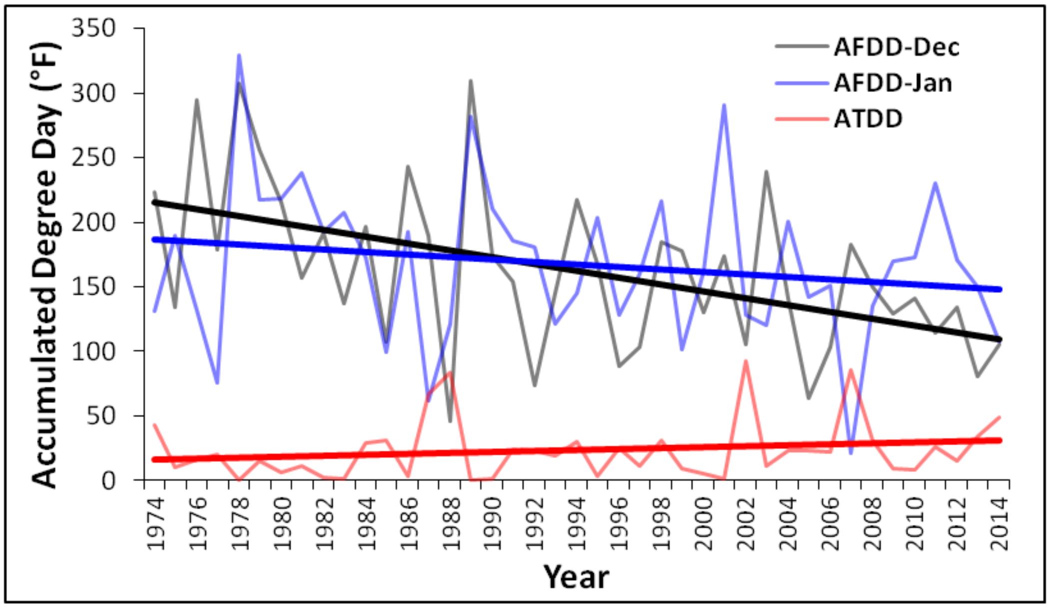
Steig et al. (2009) assessed the Antarctic ice-sheet surface-temperature changes from 1957 to 2006 and showed that significant warming extends beyond the Antarctic Peninsula throughout much of West Antarctica to include the Ross Sea and McMurdo region (Figure 2). They found that West Antarctica warmed at a rate of 0.17 ± 0.06°C per decade, and East Antarctica also warmed significantly at a rate of 0.10 ± 0.07°C per decade.

Figure 2. “Spatial pattern of temperature trends (degrees Celsius per decade) from reconstruction using infrared (T_{IR}) satellite data. *a*, Mean annual trends for 1957–2006; *b*, Mean annual trends for 1969–2000 . . . , *c*–*f*, Seasonal trends for 1957–2006: winter (June, July, August; *c*); spring (September, October, November; *d*); summer (December, January, February; *e*); autumn (March, April, May; *f*). Black lines enclose those areas that have statistically significant trends at 95% confidence. . . . NS (not significant) refers to areas of insignificant trends. Red circles and adjacent numbers in *a* show the locations of the South Pole and Vostok weather stations and their respective trends (degrees Celsius per decade) during the same time interval as the reconstruction (1957–2006). Black circles in *b* show the locations of Siple and Byrd Stations, and the adjacent numbers show their respective trends for 1979–1997” (Steig et al. 2009).



An unpublished analysis (Hardy et al. 2014) looked at 40 years of freezing and thawing degree-day data from McMurdo Station and showed a decreasing trend since 1974 of accumulated freezing degree-days for both December and January at McMurdo Station (Figure 3). Additionally, this same analysis showed an increasing trend since 1974 of annual, accumulated thawing degree-days at McMurdo Station.

Figure 3. Accumulated freezing degree-days (AFDD) for both December (*black lines*) and January (*blue lines*) and the annual accumulated thawing degree-days (ATDD) (*red lines*) with corresponding linear trend lines from 1974 to 2014 at McMurdo Station.



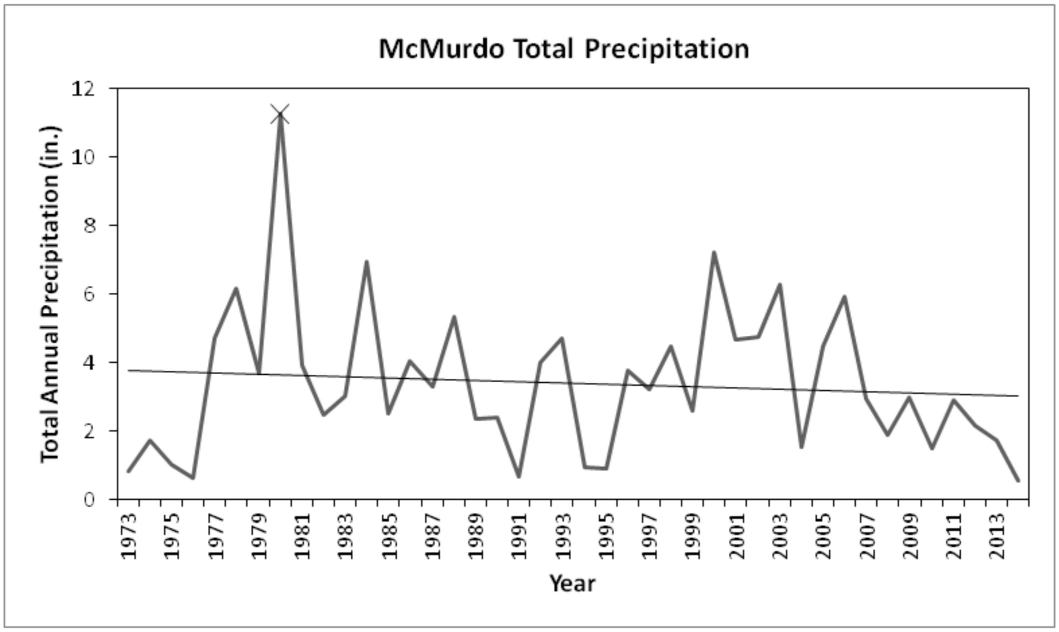
At the South Pole, the Lazzara et al. (2012) analysis found a slight decrease in the temperature and pressure over 1957–2010, but these decreases are not statistically significant.

2.2 Precipitation

Outside of Turner et al. (2014), the literature appears to have little current and reliable data on changes to precipitation. This lack of precipitation data is due, in part, to the difficulty of measuring precipitation, which leads to our current and poor understanding of the variability of precipitation in Antarctica (Cohen 2013). One study by Bromwich et al. (2011) evaluated the temporal variability of the Antarctic surface mass balance, approximated as precipitation minus evaporation, and Southern Ocean precipitation by using five global reanalyses during 1989–2009. Their results were inconclusive in the Ross Sea region and highlight spurious trends and the need for using caution in this kind of reanalysis, especially for climate change trends.

Precipitation data collected at McMurdo Station from 1973 to 2014, as provided by the U.S. Air Force, 14th Weather Squadron, provides some insight into the long-term trend in total annual precipitation in this area (Figure 4). The linear trend line on the plot has a slope of −0.0182, suggesting a trend toward decreasing precipitation in the past 41 years. However when the 1980 data are removed (point denoted by "×"), the slope of the linear trend line becomes less significant at −0.0006. Much of the precipitation recorded during 1980 occurred October and November. This supports the Turner et al. (2014) conclusion that there has been no statistically significant change in precipitation since 1957.

Figure 4. Total annual precipitation in inches from 1973 to 2014 as recorded at McMurdo Station. Included in this plot is the linear trend line for these data. The data point from 1980 is denoted by an "×."



At the South Pole Station, Lazzara et al. (2012) noted that, for the period 1983–2010, the average annual snow accumulation decreased at a statistically significant downward rate of −2.9 mm/year.

2.3 Winds

Using Reference Antarctic Data for Environmental Research (READER) from ten coastal Antarctic stations, for the period of 1961–1990, Turner et al. (2005) report that all but two of the stations recorded increasing mean wind speeds over recent decades.

Chenoli et al. (2013) present the first climatology of strong wind events (SWEs) at McMurdo Station, based on data from automated weather stations (AWS) and READER. In their study, a SWE at McMurdo Station was defined as a wind speed that is 11.3 m/s and higher. Since 1979, McMurdo Station observations show a small decrease in the number of SWEs; but the trend is not significant. Chenoli et al. (2013) also note that several observational studies used a blowing snow threshold of 10 m/s but that, during the winter, wind speeds as low as 7 m/s can result in blowing snow. The distribution of directions of all SWEs from 1979 to 2005 shows a bimodal distribution with one group of SWEs clustered between 135° and 180° and a second group over 45°–90°. The wind rose for McMurdo Station shows that the *strongest winds* are almost always from the 135° to 180° (southeasterly) direction. Years with many SWEs are associated with a deep climatological low centered over the northeastern Ross Ice Shelf. Years with few winter SWEs have a weakened mid-tropospheric vortex over the Ross Ice Shelf. The mean wind speeds of all SWEs were observed to be higher from the direction 135°–180° (southeasterly) (15 m/s) than from 45° to 90° (12 m/s) (Chenoli et al. 2013).

Foehn winds are a major climatological feature of the Dry Valleys and are caused by topographic modification of southwesterly airflow, which is related to the occurrence of synoptic-scale cyclones in the Amundsen and Ross Sea region (Speirs et al. 2013). The frequency and duration of foehn winds affect the region’s temperature records as they frequently cause summer temperatures to rise above 0°C, leading to extensive melt and thaw. Speirs et al. (2013) noted a positive relationship between summer foehn wind regimes in the McMurdo Dry Valleys, Antarctica, and the SAM based on the 20-year climatology in that region. The SAM significantly influences foehn wind frequency during the Antarctic summer and autumn months. Accordingly, analysis of the region’s weather and climate records and predictions of future impacts of climate change on the Dry Valleys is incomplete without consideration of foehn winds and their influence.

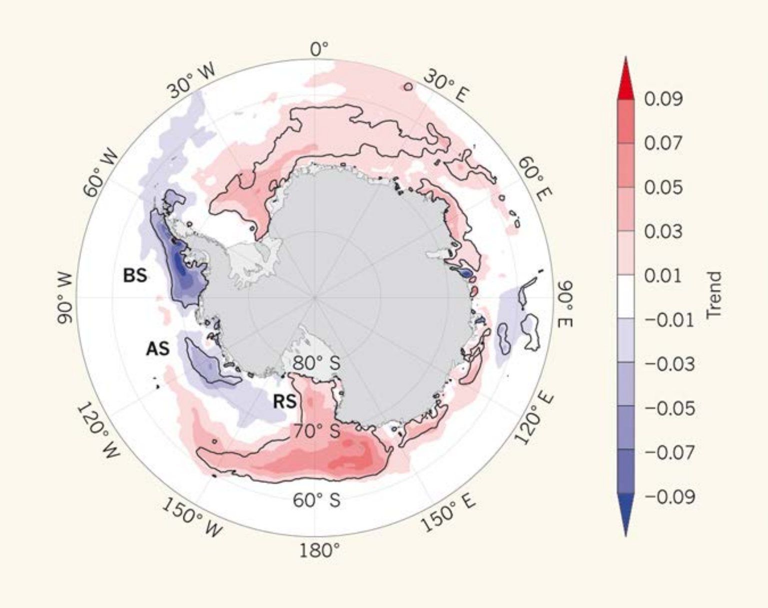
Lazzara et al. (2012) show that the South Pole seasonal mean wind speed over a 54-year period (1957–2010) shows a consistent pattern of decreasing speed for all seasons with a significant downward trend of

0.28 m/s/decade. In contrast to the mean wind speeds, the maximum wind speeds increase for the summer and transition seasons; and these increases are statistically significant.

2.4 Sea ice

Several references (King 2014; Li et al. 2014; Turner et al. 2014; Zolfagharifard 2014) documented not only the slight rise in overall winter sea-ice extent around Antarctica but also a changed distribution that includes a retreat in the Bellinghausen Sea and a compensating advance in the western Ross Sea. This long-term trend in ice extent closely matches long-term trends in winds over the Southern Ocean and is driven by a deepening of the climatological low-pressure center over the Amundsen Sea because of increasing temperatures in the tropical and North Atlantic (Li et al. 2014). Figure 5 shows the trend in fractional sea-ice cover per decade as calculated from 1979 to 2012 (King 2014).

Figure 5. Trend in fractional sea-ice cover per decade as calculated from 1979 to 2012 (King 2014). BS = Bellinghausen Sea; AS = Amundsen Sea; RS = Ross Sea.



2.5 Glacier ice

Paolo et al. (2015) used satellite radar altimeter observations to record the changes in ice-shelf thickness and ice-shelf volume from 1994 to 2012. They defined eight Antarctic ice-shelf regions, for which the cumulative change in ice-shelf thickness between 1994 and 2012 ranged from +2.0

m/decade in the Queen Maud region to −19.4 m/decade in the Amundsen region. For the Ross Sea region, the change during the same period was −2.1 ± 0.5 m/decade. Additionally, Paolo et al. (2015) provide evidence that the rate of Antarctic ice-shelf volume loss has accelerated since 2003, compared to 1994 to 2003. "The total circum-Antarctic ice-shelf volume loss was negligible (25 ± 64 km^3/year) during 1994–2003 and then declined rapidly by 310 ± 74 km^3/year after 2003."

Lescroël et al. (2014) state that in Antarctica, "increased ice shelf instability will lead to more frequent iceberg calving, including very large icebergs (hundreds of square kilometers)." More specifically, the only observed mega-iceberg calving event in the Ross Sea prior to 2001 occurred in 1983. In 2002 another iceberg, C19, calved off the Ross Ice Shelf and exited the Ross Sea. It is not clear if the calving of the 2001 icebergs C16 and B15A and the 2002 iceberg represent a trend or not, but the outflow of the Ross Ice Shelf has been accelerating owing to a number of climate-related factors (Lescroël et al. 2014).

2.6 Permafrost

Guglielmin and Cannone (2012) evaluated 13 years (1997–2009) of ground data from the Italian Antarctic station, Mario Zucchelli, in the Ross Sea (74°44′ S, 164°01′ E, 205 m a.s.l. [above sea level], not far from McMurdo Station). "Since 1997, summer ground surface temperatures [at this station] showed a strong warming trend (0.31°C per year) although the air temperature was almost stable;" and the active layer showed a thickening trend (1 cm per year) (Guglielmin and Cannone 2012). They report that the summer ground surface temperature increase was primarily influenced by an increase in total summer radiation and supported by an increase in summer thawing degree-days. At this location and at all measured depths, the permafrost mean annual temperature increased by approximately 0.1°C per year. "The dichotomy between active layer thickness and air temperature trends can produce large unexpected and unmodeled impacts on ecosystems and CO_2 balance" (Guglielmin and Cannone 2012).

2.7 Biology

Ainley et al. (2013) evaluated a 39-year dataset on the abundance and size of the Antarctic toothfish population in McMurdo Sound:

> Fish length and condition increased from the early 1970s to the early 1990s and then decreased. Fish length positively correlated with Ross Sea ice extent in early spring, a relationship possibly caused by more ice encouraging larger fish to move farther south over the shelf and into the study area. Fish condition positively correlated with the amount of open water in the Ross Sea during the previous summer (Feb), perhaps reflecting greater availability of prey with the higher productivity that more open water brings. . . . We hypothesize that this decrease [beginning in the late 1990s] is related to the industrial fishery, which began in the 1996–97 austral summer.

Researchers studying the distribution of Adélie penguins note an increase of the species in the Ross Sea region, attributable to multiple environmental changes. “As a result of the earlier-opening and longer-lasting polynyas, the Adélie penguin (*Pygoscelis adeliae*) colonies along the Ross Sea coast grew during the 1980s–90s, affecting almost 40% of the world population (approximately 2.5 million breeding pairs)” (LaRue et al. 2013). While that rapid population growth has ceased, these colonies and others within the Ross Sea are sensitive to ice sheet and glacier retreat. Lyver et al. (2014) assessed trends in abundance and growth rate of the Adélie penguin colonies of the southern Ross Sea by using aerial photographic surveys from the breeding seasons of 1981–2012:

> In the last four years, the numbers of Adélie penguins in the Ross and Beaufort Island colonies (southern Ross Sea metapopulation) reached their highest levels since aerial counts began in 1981. . . . Both climate factors and recovery of whale populations likely played roles in the trends among southern colonies until 2000, after which depletion of another trophic competitor, the Antarctic toothfish . . . , may explain the sharp increasing trend evident since then.

Forcada and Hoffman (2014) note that on South Georgia Island, fur seals have significantly altered due to changes in food availability resulting from changing climate conditions. Adverse climate conditions are reducing the Antarctic krill availability and stressing the food supply for the fur seals.

Their three decades of data show a declining population of fur seals along with a significantly lower female seal birth weight. Forcada and Hoffman (2014) conclude that as the climate changes, many fur seal pups are not surviving to adulthood; and the population is declining.

3 Future Predictions

3.1 The next 100 years

Similar to section 1 of this report, *Historical context,* this section, *The next 100 years,* is a summary of the individual and relevant studies and research articles cited in Turner et al. (2014). While all sources of information are referenced, some text is verbatim as appeared in the literature and is shown in quotes.

Antarctica's large regional climate variability makes it difficult to assess the accuracy of climate models in predicting change. The global climate models used in the IPCC assessments (IPCC 2007, 2013) provide a range of responses depending on each global climate model's (GCM's) processes and sensitivities for each of the future scenarios under consideration (IPCC 2013). The degree to which the Earth's climate changes over the next century depends on both existing and future greenhouse-gas concentrations under a wide range of emission scenarios. The "business-as-usual," higher-emission scenario of the IPCC (2007) assumes a doubling of CO_2 and other gases by 2080. These scenarios may be too conservative, or the GCMs may be underestimating the climate sensitivity, given that some indicators are already changing faster than predicted in the IPCC projections (Boden et al. 2012). Despite the uncertainties, models predict the following:

- As the ozone hole recovers, the SAM will become more negative during the austral summer, while in other seasons, increasing greenhouse gasses will strengthen the SAM and result in stronger circumpolar westerly winds. Ozone hole recovery and increased greenhouse gases act in opposite senses on the SAM and with different seasonality.
- IPCC (2007) models predict that by 2100, surface temperatures will remain well below freezing over most of Antarctica but that surface warming will still be significant over land and grounded ice sheets (0.34°C/decade with a range from 0.14°C/decade to 0.5°C/decade). "The largest atmospheric warming projected by the models is over the sea-ice zone in winter (0.7 ± 0.45°C per decade off East Antarctica), because of the retreat of the sea-ice edge and the consequent exposure of the ocean."

- "A global warming of 3°C is expected to cause larger temperature change in Antarctica (due to polar amplification mechanisms). A 4°C warming in Antarctica within 100 years is abrupt compared to the past temperature variations documented in Antarctic ice cores (with the fastest change around 4°C per 1000 years during the last deglaciation)".
- Numerical models currently underestimate precipitation across the Antarctic continent; however, most models predict, in the coming century, a precipitation increase over Antarctica that is larger in winter than in the summer.
- Based on model outputs, snowfall may increase by 20% over the continent with greater precipitation and accumulation in the Antarctic coastal region.
- Springtime concentrations of stratospheric ozone are expected to fully recover by the end of the 21st century.
- Increased temperatures may promote growth and reproduction of terrestrial biology but may also cause drought and its related effects on a local scale.
- Warming temperatures may increase the likelihood of an invasion by non-indigenous species to Antarctica, possibly carried by humans, animals, and water and air currents.
- Currently, ice-sheet models do not accurately predict the observed behavior of ice sheets, which reduces the value of these models for predictive purposes. Regression modeling suggests that the global sea level may rise up to 1.94 m by 2100, as opposed to the 0.59 m suggested by the IPCC (2007). Due in part to isostatic rebound, sea-level rise is expected to vary spatially with a minimum in sea-level rise in the Southern Ocean and a maximum in the Arctic Ocean.
- Based on model predictions, the Southern Ocean is expected to be an increased sink of atmospheric CO_2 for the remainder of the 21st century.
- "Penguin colonies north of 70°S are projected to decrease, but growth might occur to a limited extent south of 73°S."
- "The most likely regions of future change are those that are changing most today."

3.2 Climate

There is general agreement that the ozone depletion has protected the Antarctic continent from warming and actually led to a spring and summer cooling in the lower-stratosphere; but with the anticipated recovery of the ozone hole, continent-wide warming in summer is expected. Thompson et al. (2011) discuss the impact of the ozone hole on climate changes over Antarctica and the Southern Ocean. They expect that over the next few decades, recovery of the ozone hole and increases in greenhouse gases will have significant but opposing effects on the SAM and its attendant climate impacts during summer. Yergeau (2014) predicts that by 2100, the mean air temperature at the Earth's surface will increase by 1.4°C to 5.8°C with a disproportionate effect at high altitudes and latitudes.

Genthon et al. (2009) reviewed the climate models participating in the Fourth Assessment Report of the IPCC (IPCC 2007) and note that all climate models predict a significant surface warming of Antarctica by the end of the 21st century under a moderate greenhouse-gas scenario. All models but one predict a concurrent precipitation increase, but the models differ on the extent of the increase.

Weatherly and Helble (2010) developed projections for 80 years in the future for McMurdo Station and Pegasus Airfield air temperatures and the expected duration of the melt season (as defined as temperatures above −5°C and −2°C). From the fourth IPCC report (IPCC 2007), they use a projection of 2.6°C increase in air temperature for Antarctica as derived from GCM simulations for 2080–2090. Given current observed surface melting at the Pegasus Runway, there are currently 6 to 30 days per year when the Pegasus runway melts and is not operable. Weatherly and Helble (2010) translate the projected 2.6°C warming in 2080, into a melt season for Pegasus Runway that lengthens to 30 to 60 days.

3.3 Sea ice

In Antarctica, while net sea-ice cover (i.e., the area of ocean covered by ice) has increased over the past few decades owing to wind changes brought largely by mid-latitude warming and the Antarctic Ozone Hole, modeled predictions point to a decrease of net sea-ice cover by 5%–15%, depending on sector, by 2025–2052 (Lescroël et al. 2014). Concomitantly, the increased instability of the ice shelf will encourage more frequent iceberg calving, including icebergs larger than 100 km^2.

Using a combined sea ice, ocean, and ice-shelf model of the Ross Sea, Smith et al. (2014) examined the effects of projected changes in atmospheric temperatures and winds on the aspects of the ocean circulation likely important to primary production. Their modeling study suggests that the recent increase in the summer sea-ice cover in the Ross Sea is short-lived; and they project that the area will soon experience a major drop in ice cover in summer, which will substantially alter the area's food web. The Smith et al. (2014) modeled summer sea-ice concentrations in the Ross Sea decreased 56% by 2050 and 78% by 2100.

3.4 Glacier ice

The final report of the IPCC (2013) notes that the average rate of ice loss from the Antarctic ice sheet has likely increased from 30 Gt/year in 1992–2001 to 147 Gt/year in 2002–2011. There is very high confidence that these losses are mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica. IPCC (2013) projects that by the end of the 21st century, the global glacier volume, excluding glaciers on the periphery of Antarctica, will decrease by 15% to 55% for Representative Concentration Pathway (RCP) scenario RCP2.6 and by 35% to 85% for RCP8.5 (medium confidence). This supports the Lescroël et al. (2014) predictions of increased ice-shelf instability and increased iceberg calving. Similarly, Paolo et al. (2015) conclude, "If the present climate forcing is sustained, we expect a drastic reduction in volume of the rapidly thinning ice shelves at decadal to century time scales, resulting in grounding-line retreat and potential ice-shelf collapse."

3.5 Biological life

The Smith et al. (2014) predictions of decreased sea-ice concentration by 2050 and 2100 suggest that components of the Ross Sea food web will likely be severely disrupted, creating significant but unpredictable impacts on what is widely accepted as the ocean's most pristine ecosystem.

Multiple studies (LaRue et al., 2013; Lescroël et al., 2014; Lyver et al., 2014) suggest continued changes in average sea-ice conditions and environmental and biotic factors are likely to affect the distribution of Adélie penguins. As the sea ice disappears in the northernmost Antarctic regions, Adélie penguin colonies will be forced to move southwards, as is occurring in the western Antarctic Peninsula region. According to Lyver et al. (2014), Adélie penguins require adequate ice for resting but not so much that they have to travel long distances to access open water. As the sea ice disappears, so do the Adélie penguins. Lyver et al. (2014) predict that by 2050, 75% of the Adélie penguin colonies north of 70°S will decrease or disappear due to the changing sea-ice conditions. "The Ross Sea, which features the southernmost marine habitat on Earth and already harbors 38% of the world's Adélie penguin populations, might then become the last refuge for Adélie penguins" (Lescroël et al. 2014). While the Ross Sea may remain a suitable habitat for a large proportion of the Adélie penguin population in the next 20 to 40 years, after this, the sea-ice cover is predicted to decrease by 5%–15%, which may threaten this habitat.

Similarly, noting the 2001 impact of two giant icebergs grounding on Ross Island on multiple species, Lescroël et al. (2014) states that the presence of large icebergs in the Ross Sea, having calved off from the Ross Ice Shelf, can affect the local sea-ice dynamics, which may then affect different species of the northern Ross Sea. According to Lescroël et al., (2014), one of the icebergs caused the death of many incubating adult Emperor penguins and therefore reduced the chick production. The Weddell seals were temporarily affected when the icebergs altered the sea-ice dynamics, reducing the seals' access to ocean feeding via cracks in the sea ice. The Adélie penguins' dispersal rates increased as they had to travel farther to forage, resulting in less food delivered to the chicks and lowered chick production (fewer than 0.2 compared to 0.8–1.36 chicks per pair in years prior to the icebergs) (Lescroël et al. 2014). With increased warming and ice-shelf instability, mega-iceberg frequency is likely to increase substantially in McMurdo Sound and the Ross Sea compared to the frequency during the Holocene (20 times per millennium) (Lescroël et al. 2014).

4 Implications for Logistics, Operations, and Infrastructure

Current and future changes in the physical and biological environment in Antarctica have several implications that could potentially affect USAP's mission to provide support in Antarctica. As discussed in this report, Table 1 summarizes recent and future potential for environmental changes in the McMurdo and Ross Sea area with some data specific to the whole continent. Models predict that 100 years from now, there will be increasing temperatures, reduced sea-ice extent, increased depth of the active layer, more strong wind events, increased ice sheet instability leading to more icebergs, and possibly the creation of a more suitable habitat for Adélie penguins, at least on a temporary basis.

Table 1. Summary of observed (since about 1960) and projected (next 100 years) changes in sea-ice extent, surface temperatures, precipitation, wind speed, glacier ice, sea level, permafrost, and biology. Where observations or projections are not available, they are denoted as N/A. Sources of this information are found within this report and are referenced in the text.

Variable	Since about 1960	Next 100 Years
Sea-Ice Extent	Increased 4.5% per decade in Ross Sea	Decrease by 78% in Ross Sea
Air Temperature	Increased 0.1°C –0.2°C per decade	Increase 0.14°C –0.5°C per decade
Precipitation	No change	Increase—especially in winter
Wind Speed	Increased	Increase in circumpolar winds
Glacier Ice	Decreased	Decrease continent wide by 15% to 85%
Sea Level	Rise, 3.3 mm/year since 1990	Rise, up to 1.94 m globally
Permafrost	Mean annual increase of 0.1°C/year	N/A
Biology	Adélie population growth in Ross Sea	Unpredictable for 2100

Depending on the extent of these changes and their timing, USAP should consider the following possible implications:

- With predicted stronger circumpolar westerly winds, ice redistribution around the continent may result in more variable ice cover extent in the Ross Sea on a year-to-year basis. Currently, the Ross Sea is experiencing an increase in ice cover due to redistribution, but the expectation that this cover will decrease in the future may result in enhanced variability of sea-ice extent from year to year. This factor primarily affects planning for the icebreaker (*if* it will be needed) and resupply vessels during years with low ice extent.

- At some point, the access to McMurdo Station via the icebreaker, research vessel, cargo ship, and tanker may become easier due to reduced sea-ice cover. However, the reduced sea-ice cover exposes more open water to solar absorption, heating the surface water, which may increase the erosion and instability of the ice-shelf edge. The sea-ice presence also protects the ice-shelf face from mechanical erosion from wave action. Icebergs in McMurdo Sound may become more common due to increased ice-shelf calving and, therefore, pose a larger threat to the ships. If 100-year predictions are correct, the reduced sea-ice cover may contribute to increase shoreline erosion as USAP observed during the 2013–2014 season, impacting the stability of the ice pier and eroding the seawater intake jetty and the wastewater outflow jetty.
- An increase in McMurdo Ice Shelf instability and calving may threaten the snow roads connecting the Scott Base Transition to the Williams Airfield and the fuel line to the airfields, possibly requiring relocation of both.
- A predicted increase in snow accumulation, especially in the continental interior, could make traveling conditions more difficult over the plateau during the South Pole overland traverses. Another potential challenge for the traverse is increased glacier movement that could increase crevasse occurrences and reduce snow-bridge strength.
- Rising air temperatures will affect the melting (and therefore stability) of snow, ice, and frozen ground that serve as foundations and that are instrumental for air and ground transport.
- Higher air temperatures will likely mean a reduction in the number of fly days for wheeled aircraft (C-17) operations during the melt season, as experienced in recent years due to strength deterioration of the runway. White ice runways may close for daytime operations, preferring the colder nighttime operations.
- The cost of runway maintenance will likely increase and may also be an opportunity for change in air operations. Additionally, the inability to maintain a white ice runway for wheeled aircraft will result in a shift in operations to the smaller, less efficient LC-130s with skis.
- Depending on the ice content of the permafrost in and around the McMurdo station, warmer temperatures will enhance permafrost thaw-

ing and increase melt with potential ice buildup due to surface water flow and will possibly affect the stability of some building foundations.
- With enhanced melting of snow, ice, and ground ice above and around McMurdo Station, meltwater volume and rates may exceed the capacity of the drainage system and cause erosion and increased delivery of sediments and contaminants to the Winter Quarters Bay and McMurdo Sound.
- The prediction of increased precipitation in coastal regions, particularly in winter, will result in more blowing snow, snow drifting, and snow management challenges. More snow will require additional maintenance time to clear the snow from roads, buildings, drainage channels, etc., at the beginning of the summer season. Buildings designed and built based on current snow management expectations may not be as suited for a new climate regime of changed precipitation and wind patterns.
- Similarly, increased precipitation may also require modification of current procedures for building and maintaining USAP's snow roads and runways.
- An increase in the frequency, duration, and magnitude of synoptic and mesoscale forced SWEs in the Ross Island vicinity may damage structures and other infrastructure used by USAP and may hamper aircraft activity. Additionally, increased windiness has the potential to transport more dust and dark particles to the snow surface, reducing surface albedo and further increasing melt on the snow roads, runways, and airfields.
- Predicted sea-level rise resulting from a warmer global climate and the melting of polar ice may have less (or at least delayed) impact in the Ross Sea compared to other parts of the world due to isostatic rebound of the Antarctic continent.
- If the Ross Sea region becomes the primary remaining habitat for Adélie penguins, there may be additional environmental regulations to protect the penguin habitat in the region, which may potentially affect USAP operations in the future.
- The potential for non-indigenous and invasive species to be introduced to the McMurdo environment and their ability to thrive in the warmer climate may require extra effort on behalf of USAP to initially avoid their introduction and then eradicate as necessary.

The McMurdo region has experienced many of these operational and logistical challenges due to environmental change. For example, the reduced sea-ice extent in McMurdo Sound during the 2013–14 season caused some shoreline erosion near the jetties and affected the ice pier. Similarly, in recent years, the Pegasus Runway experienced mid-summer melt sufficient to close the runway for some time. During the summer of 2014–15, the USAP pre-planned to close Pegasus Runway for mid-summer operations. Given the prediction of environmental change as discussed in this report (see Table 1 for a summary), the USAP can anticipate that the operational and logistical challenges experienced in recent years will continue into the future.

5 Summary

This report summarizes recent literature on the physical and biological changes in and around Antarctica for the past, present, and the predicted future. It first considers the environment of the Antarctic continent and the Southern Ocean in a historical context based on ice-core and other records and reviews periods of environmental change in the records since the Cretaceous Period. In general, historical environmental change occurred over many thousands (and millions) of years, showing periods of warming and cooling with associated sea level changes throughout the record. The report then discusses the specific components of the environment—atmosphere, air temperature, wind speeds, precipitation, sea ice, glacier ice, permafrost, and biology—in terms of the published data on changing conditions since the instrument period (roughly 1960) with a focus on the McMurdo and Ross Sea regions. Much of the current and available literature concentrates on changes that have occurred in the past few decades, most of which are consistent with a warming climate that is accentuated in the polar regions. Some of those changes include higher air and ground temperatures, a loss of glacier ice mass, and a rise in sea level. When these relatively recent changes are seen in a historical timeframe, they are considered “abrupt” in that the speed at which they have occurred has impacted the environment’s ability to adapt to the change. In the McMurdo and Ross Sea region of Antarctica, many of the environmental changes of the past 30 years are projected to continue and in some cases accelerate. One exception is that the sea-ice extent in the Ross Sea has increased in recent decades due to wind redistribution; however, a decrease in sea-ice extent by 78% is projected in 100 years.

Finally, this report concludes with potential implications of these changes for USAP’s operations and logistics in the McMurdo vicinity. Many of the implications are related to a reduction in sea-ice extent affecting the integrity of the ice pier, jetties, and the resistance of the shoreline to erosion. The higher air temperatures will require greater diligence in designing and maintaining the miles of snow roads and runways during the warmer summer months. As penguins and other species adapt to the environmental changes, the southern Ross Sea region may become a more vital habitat, requiring special protection. Perhaps one of the most reliable indicators of expected change in the future and the subsequent implications for operations is to look at the changes and challenges currently experienced by the USAP.

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# REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* May 2015	**2. REPORT TYPE** Technical Report/Final	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE

Indicators of Physical and Biological Trends around the McMurdo Station, Antarctica

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Janet P. Hardy

5d. PROJECT NUMBER

5e. TASK NUMBER
EP-ANT-14-06

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Cold Regions Research and Engineering Laboratory (CRREL)
U.S. Army Engineer Research and Development Center (ERDC)
72 Lyme Road
Hanover, NH 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CRREL SR-15-1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Science Foundation, Division of Polar Programs
Antarctic Infrastructure and Logistics
Arlington, VA 22230

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Engineering for Polar Operations, Logistics, and Research (EPOLAR)

14. ABSTRACT

The United States Antarctic Program (USAP) is managed by the National Science Foundation, Division of Polar Programs (NSF-PLR), which has the responsibility for all logistics and operations related to U.S. scientific research in Antarctica and aboard ships in the Southern Ocean. For years, scientific literature has focused on global environmental change and, in particular, the accelerated change occurring, and predicted to occur, in the polar regions.

This report summarizes documented changes that have occurred in Antarctica, with a focus on the Ross Sea region, as well as projections of environmental change expected to occur in the next 100 years. Many of the observed changes in the Ross Sea region since 1960, such as increased air and soil temperature, decreased glacial extent, and sea level rise, are consistent with a warming climate; however, the observed increase in sea-ice extent does not fit an expected pattern and is explained by a shift in circumpolar circulation. Models predict the observed changes to continue over the next 100 years, except that they anticipate the sea-ice extent in the Ross Sea region to decrease significantly. This report also presents potential implications of these changes for USAP operations and logistics, primarily in response to the reduced sea-ice extent and higher air and soil temperatures.

15. SUBJECT TERMS

	Environmental change	NSF
Antarctica	EPOLAR	Penguin
Climate trends	McMurdo Station	Ross Sea

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	40	