Projections of Future Air Temperatures and Melt Season Duration for McMurdo Station and Pegasus Runway

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ABSTRACT:

McMurdo Station, Antarctica relies on aircraft transport link to Christchurch, New Zealand for personnel, supplies and equipment. Aircraft operations use the landing sites maintained on a sea-ice runway in McMurdo Sound, on a snow runway at Williams Field and on compact glacial (white) ice on the Pegasus Runway. These runways can support operations until seasonally warm temperatures in December-February produce surface melting and weakening the support for aircraft load weight. This paper looks 80 years into the future to assess the changes in daily air temperatures and the duration of melting season that would be expected as the climate warms due to increasing CO2. Projections of a 2.6ºC increase in air temperature for Antarctica from GCM simulations for 2080-2090 from the fourth IPCC report are added to daily mean temperatures for McMurdo and its supporting runways. The occurrence of surface melting between -5 ºC and -2 ºC in observations indicate a melt season for the coldest Pegasus runway currently between 6 and 30 days. For future warm climate temperatures in 2080, this melt season lengthens to 30 to 60 days. The severity of melt during this extended melt season will depend strongly on future changes in cloud cover, winds, and precipitation (both rain and snow). The implications of this temperature change on supporting operations in Antarctica, in relation to the distances between runways and McMurdo Station are presented.

Keywords: Antarctica, climate change, ice runway, glacial melt

INTRODUCTION

McMurdo Station, Antarctica relies on aircraft transport links to Christchurch, New Zealand for personnel, supplies and equipment. Seasonal aircraft operations use the landing sites maintained on a sea-ice runway in McMurdo Sound, on a snow runway at Williams Field and on compact glacial (white) ice on the Pegasus Runway. These runways can support operations until seasonally warm temperatures in December-February produce excessive surface melting that weakens the support for aircraft load weight. The duration of the runway operating season can be affected by an excessive number of days with melting surface temperatures within the season.

The goal of this paper is to look at the recently observed temperatures at McMurdo and analyze the mean duration of the melt season that affects runway operations, and to look 80 years into the future to project the changes in air temperatures and duration of melting season that would be expected as the climate warms due to increasing CO_2. Projections of air temperature increases for Antarctica from GCM simulations from the IPCC Fourth Assessment Report are added to daily mean temperatures for McMurdo and the Pegasus runway to estimate the change in melt season duration that may be expected to occur in the 21st Century.

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The severity of melt during an extended melt season also depends strongly on the seasonal variability in temperatures, cloud cover, winds, and precipitation. The implications of adding a temperature change on top of the observed variability on supporting operations in Antarctica are discussed in this paper.

DATA

Antarctic Automatic Weather Station Data

The Automatic Weather Stations project (AWS), conducted by the University of Wisconsin-Madison, has established AWS sites in Antarctica that have collected meteorological observation data including temperature, wind speed, precipitation. These data are available on the AWS-AMRC (Antarctic Meteorological Research Center) website as spreadsheets for each year and month. The data include daily-average temperatures, as well as some hourly observations where they are available.

The primary data of interest in this project are for McMurdo Station, and other data include the supporting runways (Ice Runway-NZIR, Pegasus Field-NZPG, and Williams (Willy) Field-NZWD). The monthly average temperatures from these locations (and several other stations) are shown in Figure 1.

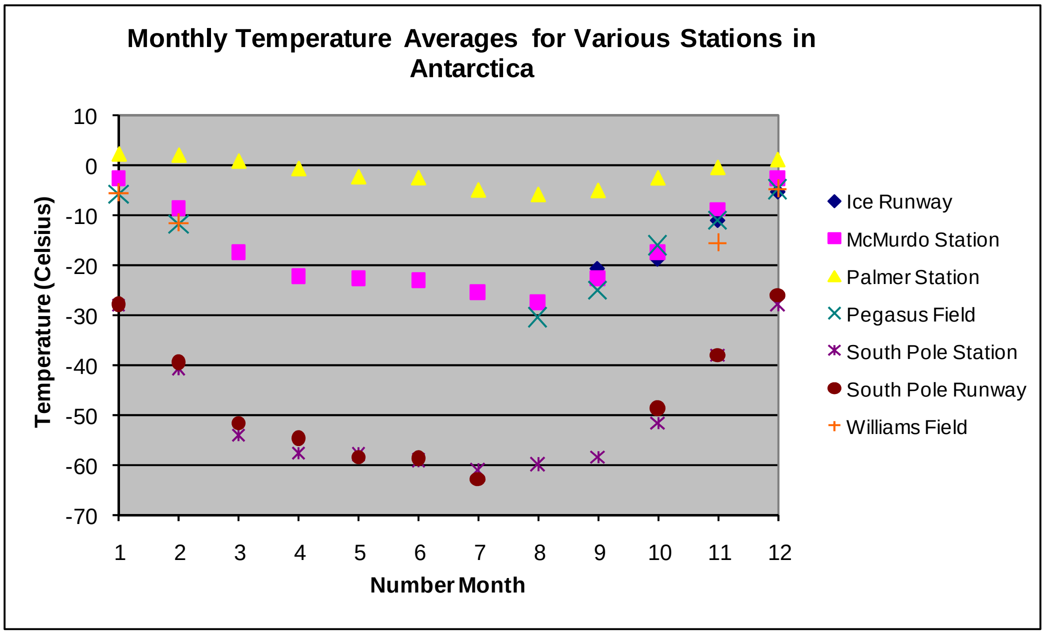


Figure 1. Monthly average air temperatures from several AWS locations at McMurdo Station, South Pole Station, and their supporting runways, including Pegasus Field.

METHODS AND ANALYSIS

Air Temperature Correction for Pegasus Runway

Hourly and daily temperatures are recorded at the Pegasus Runway with the beginning of aircraft operations and through the summer season, but data are not available for all years that McMurdo observations have been made. In order to directly compare the number of days of melting between sites, we use a proxy for daily air temperatures at Pegasus

$$T_{day}(\text{Pegasus}) = T_{day}(\text{McMurdo}) - 3.13\ ^{\circ}\text{C}$$

The observed daily temperatures for the McMurdo Station over summer months (November-February) of 1998-2008 were used to determine the following derived quantities:

- the number of days that surface melt that had occurred at that McMurdo Station, based on an air temperature criteria described below,
- the daily temperatures for the same seasons at the Pegasus Runway location (by a proxy correction), and the number of days that melt had occurred at Pegasus,
- the number of days of melt that are likely to occur at McMurdo and Pegasus for a future warm climate with a specified temperature increase.

Air Temperature criteria for determining melt conditions

Melting of the snow and ice surfaces occurs at a material temperature of 0 ºC; however, direct observations of surface temperatures at these locations are not usually available. For this study, we use the recorded air temperatures as a proxy for melting conditions with a parameterization for the air temperature criteria. Past observations over snow and ice surfaces in summer in the high latitudes show that surface melt begins when the recorded air temperatures exceed -5 ºC, owing to the additional contributions of downward solar radiation and longwave (thermal) radiation to the surface energy balance. The specific air temperature or which the surface reaches a melting temperature depends strongly on the radiative and cloud conditions, wind speed, humidity and the surface albedo. Measurements of temperature and snow albation with the CRREL ice mass balance buoys also supports that summer melting in the high latitudes (under daylight conditions) begins between -5 ºC and -2 ºC. An additional considerations for using a temperature lower than -2 ºC for future climate is that the direct longwave increase at the surface for a doubling of CO_2 (from 350 ppm to 700 ppm) is approximately 4 W m^{-2}. While this is a small (<2%) increase over the average downward longwave of approximately 250 W m^{-2}, it would push the surface energy balance towards melting at a lower air temperature. For this project, these two air temperatures are used as criteria for determining the days with melting conditions for McMurdo Station and Pegasus runway.

This correction is based on the mean linear regression bias between simultaneous daily McMurdo and Pegasus temperatures (C. Vuyovich and R. Haehnel). Therefore a day with mean temperature at McMurdo of -4 ºC would count as a melt day (using the -5 ºC criteria), but would not register as a melt day at Pegasus at -7.13 ºC.

Duration of Melt Season at McMurdo and Pegasus Runway

Based on these melting air temperature criteria, the number of days with observed melting at McMurdo and Pegasus Runway from each season (November-February) from 1998-1999 to 2009-2010 shown in Table 1. There is approximately 30 days difference between using -2 ºC and -5 ºC for the melting criteria for both locations, which is consistent with the variations in other variables (cloud conditions, etc) that affect the observable melt conditions.

There is also significant year-to-year variability in the number of days on melt at these locations depending on the melt criteria. The warmer location, McMurdo, has 20 days of range between maximum and minimum duration for T >-5 ºC. The Pegasus runway has 18 days of range for the days where T > -2 ºC. These maximum and minimum days are used to project the range in the melt season duration that would be expected in a warmer climate (see Fig. 3).

Table 1 Number of days meeting the melting temperature criteria (-5 ºC and -2 ºC) for McMurdo Station for the observed summer seasons (Nov.-Dec.-Jan.-Feb.) and for Pegasus runway using the proxy temperature correction of -3.13 ºC for each day of the observed years.

	McMurdo Obs		Pegasus Obs Proxy	
Years (NDJF)	**Days T> 5ºC**	**Days T>-2 ºC**	**Days T>-5ºC**	**Days T>-2 ºC**
1998-99	61	37	35	3
2000-01	56	15	14	0
2001-02	63	40	40	14
2002-03	58	21	20	2
2003-04	53	26	26	5
2004-05	76	44	43	5
2005-06	65	33	32	5
2006-07	65	40	39	18
2007-08	57	31	31	7
2008-09	57	29	27	2
2009-10	72	33	31	2
Average	**62.1**	**31.7**	**30.7**	**5.7**

Projected Temperature Changes for Future Climate Scenarios

The projected temperature changes from climate change applied in this study are taken from the Intergovernmental Panel on Climate Change (IPCC) 2007 Fourth Assessment Report chapter 11 on Regional Climate Projections (Christensen et al. 2007). Table 2 below shows the predicted change in air temperature from 1980-1999 to 2080-2099 for the (land-only) region of Antarctica across the range of 21 global climate models (GCMs) for the A1B scenario (a moderate CO2 emission scenario). The median (50%ile) temperature response for December-January-February is 2.6˚C. This value is used in this report as the assumed warming applied to (added to) the daily temperatures from McMurdo Station observations and the derived Pegasus runway temperatures.

Table 2 Antarctic regional averages of temperature projections (ºC) from a set of 21 global models in the multi-model dataset for the A1B scenario. The mean temperature responses are shown for the seasons and annual mean and for the percentile categories across the distribution of GCM model runs. The responses are first averaged for each model over all available realisations of the 1980 to 1999 period from the 20th Century Climate in Coupled Models (20C3M) simulations and the 2080 to 2099 period of A1B.[Adapted from Christensen et al 2007].

Season	Min	25%	**50%**	75%	Max
DJF	0.8	2.2	**2.6**	2.8	4.6
MAM	1.3	2.2	2.6	3.3	5.3
JJA	1.4	2.3	2.8	3.3	5.2
SON	1.3	2.1	2.3	3.2	4.8
Annual	1.4	2.3	**2.6**	3.0	5.0

The additional 2.6 ºC warming is added to the daily temperatures at McMurdo Station and the proxy temperatures for Pegasus runway, with the number of days for each month from November through February for the years 1998 to 2008 (see Appendix A). The total days for each melt season are shown in Table 3 for McMurdo Station for the observed years and for the additional warming, and in Table 4 for the Pegasus runway data. For McMurdo, the melt season increases by 24 to 26 days on average, while for Pegasus the season increases by 30 days for both temperature criteria (suggesting this change is less sensitive to the criteria used.) For both McMurdo and Pegasus this is a significant increase over the currently observed season, and could potentially affect the aircraft operations at Pegasus if this warming is reached in the 21st Century on a consistent basis, rather than only for isolated years.

Table 3 Number of days meeting the melting temperature criteria (-5ºC and -2ºC) for McMurdo Station for the observed years and with added warming of 2.6 ºC.

Years (NDJF)	McMurdo Observed	McMurdo Obs +Warm	McMurdo Obs	McMurdo Obs+Warm
	Days T > -5 ºC		Days T>-2 ºC	
1998-99	61	86	37	60
2000-01	56	90	15	53
2001-02	63	85	40	60
2002-03	58	78	21	54
2003-04	53	72	26	50
2004-05	76	95	44	71
2005-06	65	88	33	61
2006-07	65	84	40	63
2007-08	57	87	31	54
2008-09	57	73	29	54
2009-10	72	90	33	68
Average	**62.1**	**84.4**	**31.7**	**58.9**

Table 4 Number of days meeting the melting temperature criteria (-5ºC and -2ºC) for Pegasus Runway using the -3.13 ºC correction to the observations, and with added warming of 2.6 ºC.

Years (NDJF)	Pegasus		Pegasus	
	Obs Proxy	Obs+Warm	Obs Proxy	Obs + Warm
	Days T > -5 ºC		Days T>-2 ºC	
1998-99	35	76	3	39
2000-01	14	60	0	21
2001-02	40	71	14	41
2002-03	20	53	2	18
2003-04	26	50	5	22
2004-05	43	71	5	39
2005-06	32	60	5	29
2006-07	39	63	18	39
2007-08	31	52	7	27
2008-09	27	59	2	22
2009-10	31	69	2	37
Average	**30.7**	**62.2**	**5.7**	**30.4**

Due to the natural year-to-year and decade-to-decade variability in the climate system, we cannot expect this warming to be observed in a monotonic upward temperature trend. However, if the warming is assumed to occur linearly over the next 80 years, the trend in increasing melt season would be approximately 3.0 to 3.8 days of melt per decade. The projected number of days per year for future decades is shown in Table 5, with projected increases in the minimum and maximum number of days based on the range in the observed McMurdo data.

Table 5 Projected number of days meeting the melting temperature criteria (-5 ºC and -2ºC) for Pegasus Runway with added warming of 2.6 ºC over 80 years, for each decade for 1999-2089.

	Days T > -5 ºC			Days T >-2 ºC		
Years	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1999-2009	14	31	43	0	5.7	18
2010-2019	18	35	47	2.6	9.3	20.8
2020-2029	23	39	51	5.2	12.2	23.7
2030-2039	27	43	55	7.8	15.1	26.6
2040-2049	32	47	59	10.5	18	29.5
2050-2059	36	51	63	13.1	20.8	32.3
2060-2069	41	54	68	15.7	23.7	35.2
2070-2079	45	58	72	18.3	26.6	38.1
2080-2089	50	62	76	21	30	41

Since there is a range in days of melt that depend on the temperature criteria, the mean number of days of melt for future decades are shown in Fig. 2 for the average of the days for -2 ºC and -5 ºC criteria, with the vertical range between these values shown. The range remains similar over the decades as the relative increase in days is insensitive to the temperature criteria. This trend also illustrates the fact that the number of days expected in 2080-2089 over T>-2 ºC are greater than the number of days at present for Pegasus runway for T>-5 ºC.

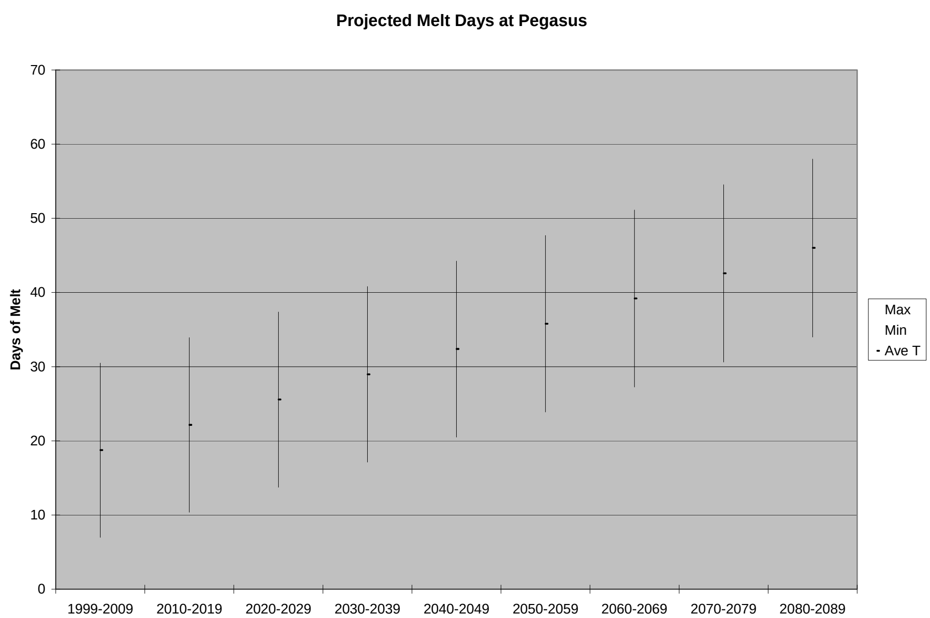
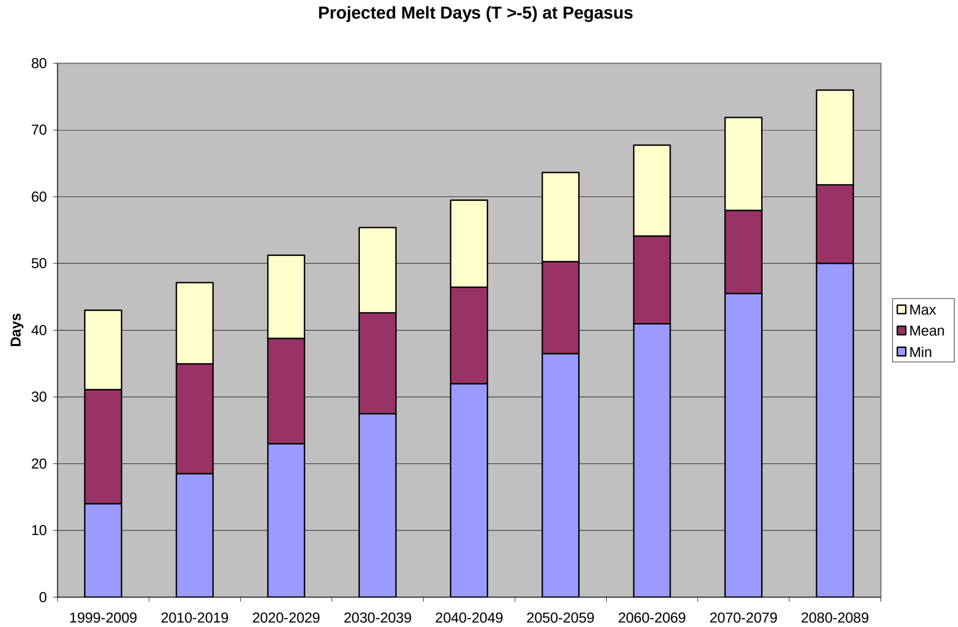


Figure 2. Projected number of days at Pegasus Runway using the average of -5 ºC and -2 ºC temperature days for the average number of days per season (central point) and the minimum and maximum days per season (vertical bar), using the added 2.6 ºC warming over the next 80 years.

The projected minimum, median and maximum numbers of melt days at Pegasus for each decade are also shown in Fig. 3 for both temperature criteria. While there was a maximum of 18 days of melt (at T>-2 C) at Pegasus observed for 1999-2008, the projected minimum for this criteria exceeds this 2080-2090 with 21 days.



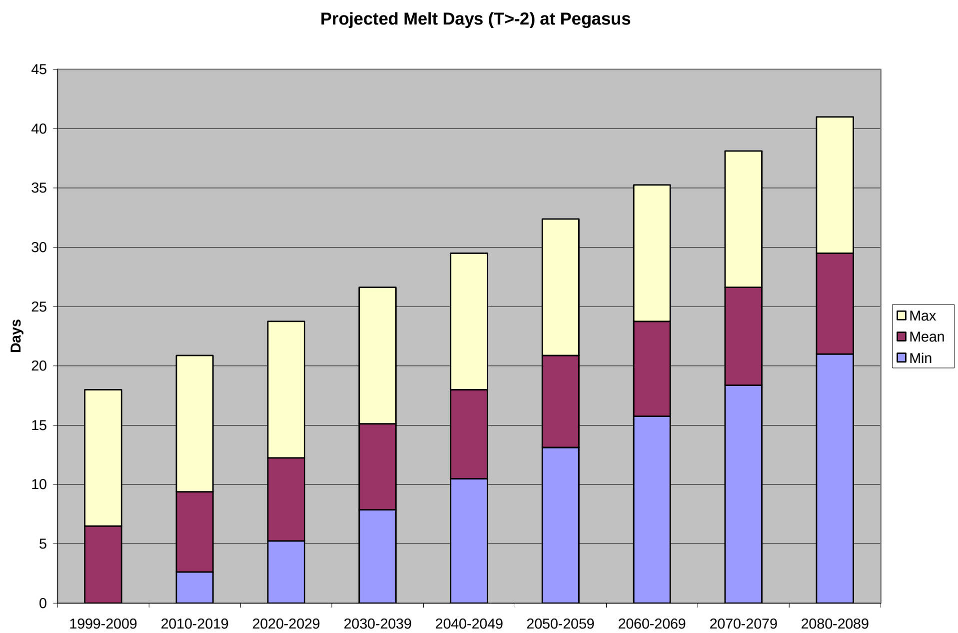


Figure 3. Projected number of days meeting the melting temperature criteria at Pegasus Runway (-5 ºC, top, and -2ºC, bottom) for each decade for the minima (blue), mean (red) and maxima (white) using the added 2.6 ºC warming over the next 80 years.

SUMMARY AND DISCUSSION

Using the temperature increase of 2.6 ºC from the median (50%ile) response of the GCMs from the IPCC's A1B scenario over 80 years, out to the 2080-2090 period, the average change in melt season duration at Pegasus runway is 24.7 days with T > -2 ºC, and 32.5 days for T >-5 ºC (Table 5). If this increase is assumed to be linearly increasing in time over 8 decades, there would be an increase of between 3 to 4 days of melt per decade through the 21st Century.

Since this temperature change is taken from the median of the GCMs responses for the A1B scenario, it implies there is a 50% probability that the temperature change will meet or exceed this point. Following this assumption, there would be 50% probability of the melt season at Pegasus exceeding 30 days a year by 2080, which is approximately equal to the current melt season observed at McMurdo (and the current sea ice and snow runways).

Table 5 Summary of projected melting days for Pegasus Runway

	Days T > -5 ºC	**Days T>-2 ºC**
Observed (1998-2008)	30.7 days	5.7 days
Observed + warming (2080-2090)	62.2 days	30.4 days
Difference over 80 years	32.5 days	24.7 days
Trend per year	0.406 days yr^{-1}	0.308 days yr^{-1}
Trend per decade	4.06 days	3.08 days

Possible impacts of projected warming on NSF's Polar Logistics Operations

Having the air temperature at the Pegasus runway become warmer in the coming decades and resemble the current temperatures at McMurdo (and Williams Field) could result in a similar impact on shortening the season of aircraft operations. Based on these projections and whether observations of temperatures continue to show increases in temperature in this region, the logistics program may need to adapt to these changes with a number of options, including:

- Reduction of aircraft operations in the melt season – this may reduced the number of missions supported of the ability to schedule personnel changes or supplies.

- Cargo transportation by icebreaker transport, and overland sled transport – this is also dependent on the future condition of the Ross Sea ice cover and the trafficability on snow and ice routes in warmer temperatures.

- Relocation of aircraft operations to colder locations – this would involve increasing the distance and transport time back to the current McMurdo location.

- Shift to smaller or lighter aircraft, possibly with ski landings – this may be possible for a longer period of warmer temperatures in the summer over the white ice runway.

Uncertainties and other considerations

This analysis is based on a scenario of projected future events, each with different probabilities of occurrence and uncertainties. The following sections describe a number of sources of uncertainty in this analysis that would affect the results if the future climate does not correspond to these projections.

Alternate climate scenarios and outcomes

The numbers in this analysis are based on the moderate A1B emission scenario and the average outcome of 21 GCMs used in the IPCC. It is not possible (in the scope of this analysis) to assign a probability on whether global emissions of CO_2 and other greenhouse gases (including uncertain contributions from natural methane sources, for example) will follow the A1B scenario or whether greater or lesser emissions will occur. If future emission rates continue, and CO_2 in the atmosphere increases at nearly 1% per year as observed, then it will exceed the A1B scenario significantly in the 21st Century, with corresponding greater climate response likely.

Local temperature changes versus projected climate change

McMurdo Station and its runways are located in a region of varied and variable surfaces; it is bordered by the ice sheet and sea ice in the Ross Sea. The representation of future climate change in the narrow transitional coastal region between ice sheet and ice-covered ocean by the GCMs can be dependent on their spatial grid resolution (often from 2 and 5 latitude or 200 -600 km) and the physical processes over ice and how they are parameterized (such as turbulent transfer over ice and low-level cloud processes).

A more detailed and comprehensive assessment of regional climate change would involve additional statistical downscaling, which might include adjustments in temperature by location and other variables such as radiation, winds, clouds and precipitation based on observed meteorological data and GCM modeling. A second downscaling approach would use dynamical modeling with a regional climate model (RCM) of the Ross Sea region with boundary conditions adapted from past observations and additional changes for future climate from GCM scenarios.

Precipitation, clouds, and other forcing changes

This analysis considers primarily surface air temperature increases and its potential impact on the melt season. As mentioned in section II, other variables such as additional longwave radiation may also affect the surface melting conditions as climate changes. Other forcing changes, such as local increases in precipitation, humidity, cloud cover, and winds might occur in a currently unforeseen manner. The largest change would occur if the sea ice cover in the Ross Sea experiences an abrupt change and a shorter seasonal duration, which would allow greater heat and moisture transfer with the atmosphere and amplify the impacts in the coastal region of McMurdo. While GCMs have included these kinds of changes in their coupled climate simulations, the specific changes in this narrow region become more uncertain as the large-scale climate changes.

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