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An Exceptional Summer during the South Pole Race of 1911-1912

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Capsule Summary

The race for the South Pole during the summer of 1911-1912 was marked by exceptionally high temperature and pressure anomalies experienced by both Amundsen and Scott.

Abstract.

The meteorological conditions during the Amundsen and Scott South Pole expeditions in 1911-1912 are examined using a combination of observations collected during the expeditions as well as modern reanalysis and reconstructed pressure datasets. It is found that over much of this austral summer, pressures were exceptionally high (more than two standard deviations above the climatological mean) at both main bases, as well as along the sledging journeys, especially in December 1911. In conjunction with the anomalously high pressures, Amundsen and his crew experienced temperatures that peaked above -16°C on the polar plateau on December 6 1911, which is extremely warm for this region. While Scott also encountered unusually warm conditions at this time, the above average temperatures were accompanied by a wet snowstorm that slowed his progress across the Ross Ice Shelf. Although January 1912 was marked with slightly below average temperatures and pressure, high temperatures and good conditions were observed in early February 1912, when Scott and his companions were at the top of the Beardmore Glacier. When compared to the anomalously cold temperatures experienced by the Scott polar party in late February and March of 1912, the temperature change is in the top 3% based on more than 35 years of reanalysis data. Scott and his companions therefore faced an exceptional decrease in temperature when transiting to the Ross Ice Shelf in February/March 1912, which likely made the persistent cold spell they experienced on the Ross Ice Shelf be perceived as even more intense by comparison.

1. Introduction

The Norwegian and the British Antarctic Expeditions to the South Pole are often regarded as the height of the heroic age of Antarctic exploration. Using a team of five men and primarily relying on dog sledges, Roald Amundsen first reached the geographic South Pole on December 14, 1911. Just over a month later, a team of five men led by Captain Robert Falcon Scott reached the South Pole on January 17, 1912, only to find a tent left by Amundsen. While Amundsen and the remaining crew at the main Norwegian base at Framheim were able to safely leave the Antarctic continent in late February 1912, Scott and his four companions, who primarily man-hauled their sledges and supplies, unfortunately perished on their return journey to their main base of Cape Evans on Ross Island. Figure 1 shows the routes of each polar expedition, as well as the location of their main bases.

The stories of these heroic journeys have been documented in several books, but are also recorded in journals kept by many of the members of both polar parties. Both teams kept meteorological logs of the weather conditions at their main bases and at least daily measurements made by various sledging parties, containing primarily pressure and temperature data. In particular, the extensive analysis of the observations by British meteorologist George Simpson provides substantial insight into the conditions faced by the teams. Using this data in comparison with contemporary automatic weather station data on the Ross Ice Shelf (called the ‘Barrier’ by both polar parties), Solomon and Stearns (1999) and Solomon (2001) concluded that the weather in March of 1912, when Scott and his two remaining companions perished, was much colder and persistent than average, and was a primary cause of their tragic end. Here it is demonstrated that the atmospheric pressure and associated temperature conditions throughout much of early December 1911 and late February – March 1912 were also exceptional across the location of the South Pole race, and likely across much of Antarctica. In the context of the colder than average conditions in March 1912 experienced by Scott and his polar party, this places an even more dramatic change in the weather coming down from the south polar plateau to the Ross Ice shelf, and therefore might have also made these cold spells be perceived as more intense by comparison. It is not our intent to contrast the leadership styles or other factors that led to the vastly different outcomes between the Norwegian and British Antarctic South Pole expeditions as done by Huntford (1985), but to rather demonstrate that the pressure and temperature conditions during the journey to the pole in December for both polar parties and back in February / March for Scott were unique in many aspects.

2. Data and Methods

The primary source of data for the British Antarctic expedition comes from atmospheric temperature and pressure data analyzed by Simpson, who first published the records and other aspects of the Antarctic meteorology in a three-volume set in 1919 (Simpson 1919, 1923). The third book provides numerical tables of observations at Cape Evans and all the field party observations. For the field party observations, latitude and longitude are given when they were determined by theodolite or sextant. Observations at Cape Evans were generally taken every hour, while up to three data points were typically taken by the field parties (often morning, lunch time, and evening). Rather than focusing on daily minimum temperatures as done in Solomon and Stearns (1999), this study uses daily means for both temperature and pressure, averaging all available well-exposed sling thermometer observations for each day that they were recorded. Exposure to the free airstream is critical for accurate measurements of atmospheric temperature, and both expeditions used sling thermometers that were twirled to ensure this (Simpson (1919), pp. 17-18; Moen (1915), pp. 49-50). Minimum thermometer data recorded underneath the sledges reported by the Scott expedition are not used because they can display a cold bias due to pooling of cold air beneath the sledges, impeding the airflow needed for accurate temperature measurements (Simpson 1919, p. 19). Similar results for the sling thermometer data along the sledging journeys are obtained using daily maximum and minimum temperatures, or by averaging the measured maximum and minimum temperatures rather than all available observations (Fig. S1), despite some of the differences discussed between these values in Simpson (1919). In addition to the meteorological observations from the main polar party led by Scott, we also make use of data from shorter duration sledging parties in support of the main British polar party (such as the Dog Sledge party, the Motor Sledge party, and the First Relief party), available in Simpson (1923).

For the Norwegian expedition, meteorological observations were published in 1915, which similarly includes observations at their main base of Framheim and observations during the dog sledging journey to the South Pole and back (Mohn 1915). For the Framheim observations, the three-times daily pressure and temperature observations from April 1911 - January 1912 are used. On the main polar journey, there are often three observations per day from 19 October 1911 through 26 January 1912; daily mean temperature and pressure are used, averaging over all available observations each day.

To place the observations in a climatological context, pressure and temperature measurements at McMurdo, the main U.S. Antarctic base situated on the southern tip of Ross Island in very close proximity to the British base of Cape Evans (Fig. 1), are employed, although sea ice conditions at the two stations often differ, which can affect climate. Hourly observations from 1957-2016 are analyzed, obtained from the British Antarctic Survey. During the summer, pressures at McMurdo are similar to those across the Ross Ice Shelf / Barrier (Costanza et al.

2016), and this single point with the longest continuous record therefore provides an estimate of pressure across the entire Ross Ice Shelf, as will be demonstrated later. Further, the seasonal pressure reconstructions at McMurdo presented in Fogt et al. (2016a) are examined, which extend the seasonal mean pressure at this location back to 1905. Further information on the pressure reconstruction techniques can be obtained in Fogt et al. (2016a,b), but during summer (December - February, DJF), the pressure reconstruction at McMurdo correlates at r=0.872 with observations during the period of overlap; it is therefore deemed that this pressure reconstruction is the best available estimate of pressure variability at McMurdo over the early 20th century. While pressures can be considered fairly uniform, local temperatures are well known to be highly variable around Ross Island and on parts of the Ross Ice Shelf, due for example to katabatic and foehn winds, and variations in sea ice cover (e.g., Bromwich, 1989, Spiers et al., 2012; Costanza et al. 2016).

To estimate the long-term climatological context of the meteorological conditions along the sledge journeys for both Amundsen and Scott, daily mean temperature and pressure from the European Centre for Medium Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Int) are used. This reanalysis is available at 0.75° x 0.75° latitude / longitude resolution, and compares well to surface observations of Antarctic climate (Bracegirdle and Marshall 2012). The climatological aspects of near-surface temperature on the Ross Ice Shelf and surrounding polar plateau in ERA-Interim (Fig. S2) agree well with temperature maps from interpolated AWS data discussed in Costanza et al. (2016), including the relatively colder temperatures extending westward from Roosevelt Island toward the Transantarctic mountains and the relatively warmer air on the Ross Ice Shelf near many of the major glacial valleys in the Transantarctic mountains. However, in places of steep terrain, especially within the

Transantarctic mountains when the journeys ascended glaciers (the Axel-Heiberg for Amundsen and the Beardmore for Scott, Fig. 1) to reach the polar plateau, there are differences in the surface elevation between ERA-Int and the real-world reflected in the observations collected on both sledge journeys. To account for this, the model elevations in ERA-Int (determined from the invariant variable geopotential, Fig. S3) were corrected to a best estimate taken along each sledging journey track in Fig. 1 from Google Earth. For temperature, a standard atmospheric environmental lapse rate of 6.5°C per km was used to adjust ERA-Int temperatures to the actual elevation; despite large differences in the ERA-Int elevations within the Transantarctic mountains, the corrected temperature climatology from ERA-Int agrees well with observations by Amundsen and Scott (Fig. S4). Further, 85% of the elevations from Google Earth are within 50 m of the 1-km Bedmap2 surface elevation data (Fretwell et al. 2013), implying less than 0.4°C difference after correction using the environmental lapse rate. This uncertainty is small compared to the >5°C anomalies focused on here. Elevation-corrected pressure data are not used in this study, as only pressure measurements taken on the Barrier are investigated. For all these locations, the reported elevations by both Scott and Amundsen were below 100m, and the differences between the ERA-Int model's surface elevation and those from Google Earth were less than 50m, therefore having negligible impact on our interpretation of the pressure climatology.

ERA-Int provides a daily location-dependent climatological (1981-2010) average and standard deviation and daily maximum and minimum (1979-2015) elevation-corrected temperature along the tracks of both parties. This allows us to approximate how unusual the daily measured conditions were for each party along their routes. For pressure comparisons, three century-length gridded reanalyses / pressure datasets are also briefly examined, namely the

ECMWF 20th century reanalysis (ERA-20C), the Hadley Centre gridded mean sea level pressure version 2 (HadSLP2; Allan and Ansell 2006), and the National Oceanic and Atmospheric Administration – Cooperative Institute for Research in Environmental Studies (NOAA-CIRES) 20th century reanalysis, version 2c (20CR, Compo et al. 2011). In all cases, austral summer is defined as the December-February (DJF) average.

3. Results

While recent research has discussed the negative summer pressure trends across much of Antarctica associated with the trend toward the positive polarity of the Southern Annular Mode (SAM; Turner et al. 2005; Fogt et al. 2016b; Jones et al. 2016), there is not much known about Antarctic pressure variability prior to 1957. The seasonal pressure reconstructions of Fogt et al. (2016a,b) provide additional detail on this, and the pressure reconstruction for McMurdo is presented in Fig. 2a. Notably, there is a large positive spike during summer 1911/12, when seasonal mean pressures rise above 1000 hPa. The reconstruction pre-1957 shows only one other summer with pressures above 1000 hPa, in 1925/26, as discussed in Fogt et al. (2016b), while the direct observations display one summer in 1976/77 when they exceed 1000 hPa. This ranks the McMurdo pressure during the summer of the South Pole races in the top three highest over the last 110 years, highlighting its exceptional character; similar conclusions are reached when examining the pressure reconstruction at Amundsen-Scott South Pole station (Fig. S5). In comparison with the seasonal mean pressures recorded during 1911/12 at Framheim and Cape Evans in Fig. 2b, as well as three gridded pressure datasets (20CR, ERA-20C, and HadSLP2), it is clear that the DJF 1911/12 pressure is much higher in magnitude than the other seasons during these two years (and above the summer McMurdo climatological average of 992.03 hPa), with all six datasets agreeing with this anomaly.. Remarkably, the summer averaged observed pressure values at Framheim (December-January only) and Cape Evans are within 0.8 hPa of the reconstructed value (which is based solely on Southern Hemisphere midlatitude pressure data, Fogt et al. 2016a), indicating that pressures were fairly uniform across the Ross Ice Shelf in summer, and that the McMurdo pressure reconstruction performs near perfectly when compared with the Cape Evans observations. Looking across the entire Antarctic continent in DJF 1911/12 using the 20CR reanalysis (Fig. 2c), which assimilated the surface pressure data at both Framheim and Cape Evans, both the reanalysis anomalies (contoured / shaded) and the observations (equatorward of 60°S) and reconstruction (poleward of 60°S, except for Orcadas, near the Antarctic Peninsula at 60.7°S, 44.7°W, which has observations back until 1903, Zazulie et al. 2010) pressure anomalies (circles) indicate that this summer was exceptional across all of the high southern latitudes. The station-based pressure reconstruction anomalies are strongly positive over Antarctica, in agreement with 20CR, with the standardized anomaly almost always greater than 2 standard deviations from the 1981-2010 mean, and some of the observed/reconstructed anomalies at the stations > 6.0 hPa. The overall pattern in Fig. 2c is consistent with a very strong negative SAM index year, and both ERA-20C and HadSLP2 similarly show this structure, although with differing magnitudes of the anomalies over Antarctica (Fig. S6). SAM index reconstructions in Jones et al. (2009) for DJF 1911/12 were strongly negative, with the Fogt SAM index reconstruction showing a value of -3.867 in this year, the second most negative since 1850, only slightly weaker than in 1964. Thus, there is a larger body of supporting evidence that not only were pressures well above average across the Ross Ice Shelf in DJF 1911/12, but also across the entire Antarctic continent in conjunction with a strong negative SAM index year.

To further investigate the exceptional nature of this summer, daily mean pressure and temperature observations at Cape Evans and Framheim Bases, as well as from the sledging records when Scott and Amundsen were on the Barrier (defined here as elevations below 100 m) are investigated in Fig. 3. The 1911/12 observed pressures are compared to the daily McMurdo climatological mean (1981-2010) and ±2 standard deviation envelope (black line and shading, respectively, in Fig. 3a) to provide a climatological context. All observations, including sledging data from both Amundsen and Scott, indicate pressures frequently above 1000 hPa, more than two standard deviations above the McMurdo daily climatological means, from late November through December 1911. During summer, pressure anomalies are fairly uniform across the Antarctic continent (Fogt et al. 2016b), especially across the Ross Ice Shelf (Fig. S7; Costanza et al. 2016), allowing for a comparison of the sledging pressure data while the parties were on the Barrier along with their pressure observations at each base. From the Cape Evans observations, daily mean pressures are again anomalously high during early February 1912, and return to within the 2 standard deviation range of McMurdo daily mean observations in mid-February, remaining within this envelope throughout March 1912. Many of these daily mean pressure observations would be records in comparison to the 60+ years of McMurdo observations (not shown), which is most comparable to the pressure at Cape Evans, about 15 miles from McMurdo and at the same elevation (near sea level; Fig. 1).

Temperatures during the period in December 1911 when pressures were particularly high are examined in Fig. 3b, plotted as daily anomalies from the ERA-Int climatology at each location and day, since temperature varies much more than pressure across the Ross Ice Shelf (Costanza et al. 2016). Using seasonal mean data, Marshall (2007) demonstrated that warmer temperatures are common during SAM negative years in Antarctica (outside of the Antarctic

Peninsula), when the pressure is above average poleward of 60°S. However, from ERA-Int data, the relationship between pressure and temperature across Antarctica is much weaker in monthly data, and much stronger on the Antarctic plateau than the Ross Ice Shelf, with the latter only showing statistically significant (p<0.05) pressure / temperature correlations in November and February (Fig. S8). It is therefore not surprising to see a strong positive temperature anomaly for the Norwegian polar party temperatures in early December (Fig. 3a), when Amundsen was already on the polar plateau above the Axel Heiberg glacier and approaching the South Pole (Fig. 1). At their peak on 6 December 1911, the temperatures measured by Amundsen exceeded -16°C, which represents an anomaly relative to our estimate from ERA-Int climatology of more than 10°C (note, elevation corrections to ERA-Int daily mean temperatures account for very little of this large positive anomaly; elevation differences average only 3 meters for the period 1-10 December between ERA-Int and Google Earth along Amundsen's route). Amundsen's sledging temperature measurements during this time are much warmer than the hourly and daily mean observations collected at the South Pole station since 1957, even when accounting for the average differences in temperature between Amundsen's location and the South Pole, which is often colder than nearby areas due to pooling of cold air in the slightly lower elevation (Comiso 2000). The daily mean temperature measured at the South Pole on December 7, 2015 of -19.8°C (max hourly temperature of -18.2°C) is the only comparable warm day before December 11th, otherwise observed South Pole daily mean temperatures have never exceeded -20°C in this portion of early summer. Using the closest ten-minute quality controlled data at the Henry automatic weather station (-89.0°S, -0.39W; also corrected for warm temperature bias at low wind speeds following Genthon et al. 2011), daily maximum temperatures above -20°C occurred for two consecutive days in 2015 and 2012, but these are quite warm exceptions to the normal conditions (Fig. S9). In contrast, Amundsen experienced four continuous days with daily mean temperatures exceeding -19.0°C and temperature anomalies from the ERA-Int climatology greater than 10°C. At the onset of this warm weather on December 5, 1911, Amundsen noted that '*...there was a gale from the north, and once more the whole plain was a mass of drifting snow. In addition to this there was thick falling snow, which blinded us and made things worse, but a feeling of security had come over us and helped us to advance rapidly and without hesitation, although we could see nothing.*' (Amundsen 1913, p. 107). The blizzard like warm weather continued on through December 8th, when it finally gave way to clearer and calmer conditions. At this time, Amundsen reflects on the warmer conditions, writing '*The weather had improved, and kept on improving all the time. It was now almost perfectly calm, radiantly clear, and, under the circumstances, quite summer-like: -0.4°F* [-17.5°C]. *Inside the tent it was quite sultry. This was more than we expected*' (Amundsen 1913, p. 115). Later, on that same day, he further noted '*The warmth of the past few days seemed to have matured our frost-sores, and we presented an awful appearance.*' (Amundsen 1913, p. 116). Little did he and his companions know that these 'summer-like' conditions in early December 1911 were exceptionally warm, even though this region frequently experiences warm air intrusions from the Ross Ice Shelf (Hogan 1997).

Although not as exceptional, Scott's party also experienced warm conditions in excess of 5°C above the ERA-Int climatological mean during 5-8 December 1911 (Fig. 3b), when he and his team were on the Ross Ice Shelf. As for the Amundsen polar party, the warm conditions experienced by the British expedition at this same time were also accompanied with a blizzard on the Ross Ice Shelf, which kept them immobile during the Dec 5-8 1911 period. In contrast to the relative dryness of the high Plateau, conditions on the Ross Ice Shelf can be wet when flow conditions allow an influx of relatively warmer marine air. During this time, Edward Wilson, the doctor on the British polar party, frequently mentions in his journal the warm, wet conditions, with heavy wet snow, as noted on December 8, 1911: '*We woke up to the same blizzard blowing from the S. and S.E. with warm wet snow +33* (°F) [0.56°C]. *All three days frightfully deep and wet...It has been a phenomenal warm wet blizzard different to, and longer than, any I have seen before with excessive snowfall.*' (King 1972, p. 212).

Despite the warm conditions experienced by both parties in early December on the Ross Ice Shelf and polar plateau, temperature anomalies at the northern end of the Ross Ice Shelf recorded at Cape Evans and Framheim were slightly negative throughout December (Fig. 3b). The negative temperature anomalies at these locations are consistent with the fact that the SAM influence is much weaker on the perimeter of the continent, especially at McMurdo, compared to the interior (Marshall 2007). Additionally, local conditions such as the extent of sea ice cover, likely influenced temperatures differently at these sites than poleward along the sledging tracks, in agreement with the overall weak and insignificant pressure - temperature correlations on the northern Ross Ice Shelf throughout much of October – March (Fig. S8).

To gain further insight on the temperatures experienced by the polar parties throughout their entire sledging journey, the temperature anomalies along the tracks of both Amundsen and Scott are compared to the ERA-Int climatological (1981-2010) and maximum / minimum daily mean (1979-2015) temperature anomalies (for each day and location along the tracks in Fig. 1) in Fig. 4. Amundsen's temperature anomalies are almost entirely positive until January, with some values in early December when pressures were the highest (Fig. 3) being well above the maximum anomaly in ERA-Int (Fig 4a); these temperature anomalies are consistent with the above-average pressure anomalies at Framheim throughout all of December and the stronger positive pressure-temperature correlations on the polar plateau (Fig. S8), where Amundsen spent much of the month of December. Temperature anomalies along Scott's track are also available from the first and second return parties (Fig. 4b), which were sent back to Cape Evans from near the bottom of and the top of the Beardmore Glacier, respectively; temperature data collected in these sledging records indicate a warm December, especially in early December when a few high temperature records were observed compared to ERA-Int values, consistent with the negative SAM influence in summer (Fig. 2), and the stronger temperature – pressure correlations during December along the Transantarctic mountains (Fig. S8) near Scott's route (Fig. 1).

Even though both polar parties spent some time on the polar plateau in January 1912, where temperature-pressure relationships are stronger (Fig. S8), due to the much smaller pressure anomalies at this time at Cape Evans and Framheim, it is not too surprising to see both parties observe colder than average temperatures (Figs. 4a,b). Because of the reduced temperature variability in January (indicated by the gray shading in Figs. 4a,b), these below average temperature anomalies rarely are lower than -5°C, and are generally smaller than the positive anomalies in early December 1911. Further, while a few of the colder temperature measurements for each party in January 1912 may have fallen below two standard deviations from the ERA-Int climatological mean (for that location / day), the two parties never simultaneously observed persistent strong cold spells, unlike the warm spell in early December discussed previously (Fig. 4c).

When the pressure measurements at Cape Evans become exceptionally high again in early February 1912 (Fig. 3a), conditions change for Scott's party, and persistent above average temperature anomalies were recorded again on the polar plateau (Fig. 4b). Similar to the blizzard conditions in early December he encountered on the Ross Ice Shelf, Scott makes frequent note of these warm conditions at the top of the Beardmore Glacier, providing further evidence that they were exceptionally warm and not an artifact of elevation adjustments to the ERA-Int data. When the daily mean temperature anomalies were the highest on February 9th and 10th 1912, more than 8°C and 10°C above the ERA-Int climatological average (Fig. 4b), respectively, Scott writes: '*Very warm on march and we are all pretty tired. To-night it is wonderfully calm and warm, though it has been overcast all the afternoon*' (Huxley 1913, p.389) on February 9, and '*...snow drove in our faces with northerly wind-very warm and impossible to steer, so camped...The ice crystals that first fell this afternoon were very large. Now the sky is clearer overhead, the temperature has fallen slightly, and the crystals are minute'* (Huxley 1913, p. 390). Although the temperatures fell slightly on the evening of the 10th, they remained warm, with anomalies from the ERA-Int climatology generally at or above 5°C until February 14th. Notably, Scott makes no further mention of the warmer weather, and instead writes more on the crevassed conditions, finding the next depot, and the failing health of seaman Evans. However, during these unusually warm days, Scott's team slowed their pace, spending time collecting geologic specimens. They failed to reach a key life-saving supply depot by only about 12 miles when Scott's party died a few weeks later, and it is plausible that they may have survived if they had not slowed down on these days. The unusual warmth of early February, consistent with the timing of exceptionally high pressures at Cape Evans and Framheim (Fig. 3a), may have contributed to that choice.

These much warmer-than-average temperatures in early February were followed by unusually cold conditions in late February and March 1912, as shown in Figs. 4b-c and discussed in Solomon and Stearns (1999). It should be noted that the sling thermometer used by Bowers, who collected the meteorological observations for the Scott polar party, broke on March 10; the instrument and method used for later data noted by Scott in his diary are unknown and those data are not examined here. Examining all available sling thermometer temperature anomalies from the various sledging parties (Fig. 4c), including the Dog Sledge party, the Motor Sledge party, and the First Relief party (who were sent to find and attempt to rescue Scott and his companions if needed in March 1912), the general pattern of a warmer-than-average December 1911 emerges (especially early December), and the warmer-than-average conditions experienced by Scott in early February also stand out as exceptional; these temperature anomalies are overall consistent with the exceptionally high pressure anomalies throughout December and again in early February recorded at Cape Evans. Importantly, temperature anomalies are plotted in Fig. 4, and therefore these warm conditions, particularly in early February experienced by Scott's crew, exceed the climatologically averaged locally warmer temperatures on the Beardmore Glacier compared to nearby places in the Transantarctic mountains (Fig. S2). Similarly, the colder temperatures experienced by Scott and his companions in early March are below the climatologically averaged (1981-2010) locally colder temperatures in the central and western Ross Ice Shelf, where they were located at this time (Costanza et al. 2016; Fig. S2).

The cold spell experienced by Scott in late February and March 1912 has been discussed as an element that led to the weakening of several of the Scott polar party and played a role in their fate (Solomon and Stearns, 1999). Consistent with the findings of Solomon (2001), the present analysis suggests that although the daily averaged temperatures at this time were unusual, they were not record cold, and they do not fall below the 2 standard deviation threshold based on the ERA-Int climatology. Despite Scott writing that '*...no one in the world would have expected the temperatures and surfaces which we encountered at this time of year'* (Huxley 1913, p. 416) in his letter to the public, it was likely not the cold temperatures per se, but rather their persistence, that played a role in their demise, as argued by Solomon (2001). However, the change in temperature anomalies from early to late February, associated with the tail end of the exceptionally high pressures at Cape Evans (Fig. 3a), is nonetheless exceptional. As discussed earlier, Scott and his companions were at the top of the Beardmore Glacier in early February 1912, and because there are larger differences here in the elevation of the ERA-Int model and the real world (Fig. S3), a portion of the temperature anomalies at this time may be due to an underestimation of the climatological temperature when correcting for the elevation difference in ERA-Int. To provide the most conservative estimate, ERA-Int temperatures were also corrected using the dry adiabatic lapse rate of 9.8°C km^{-1} rather than the environmental lapse rate of 6.5°C km^{-1} used in all of our previous analyses. Following this adjustment, the warm spell during February 9-15 is then contrasted with the cold spell from February 27 – March 5, using histograms of the ERA-Int corrected temperature difference between these two periods at the respective locations on Scott's route in Fig. 5, plotted as both a raw difference and anomalies (which removes the seasonal cycle). Scott's absolute difference of 19.58°C and anomaly difference of 12.58°C clearly stand out as unique: in only one year during 1979-2015 was there a similar large swing in temperatures on these days (and in ERA-Int these are still smaller than that observed by Scott, although it just falls in the same 2-degree wide histogram bin). Such a difference, based on the approximate normal distribution of the data in Fig. 5, has a probability of p<0.001 occurring in any given year, highlighting that the change from a warm early February to a cold late February was exceptionally rare. Notably, the temperature change remains in the top 3% of the data distribution when using various window lengths (from 4 – 15 days) for both the warm and cold spells (Fig. S10), and is therefore not sensitive to the specific range of dates chosen. As such, this unique and dramatic change would have undoubtedly made the colder temperatures experienced soon after on the Barrier be perceived as even colder, perhaps justifying the surprise that Scott conveyed in his letter to the public about these cold conditions.

4. Conclusions

While several studies have focused on the unusually cold conditions Scott and his companions experienced in March 1912 (Solomon and Stearns 1999; Solomon 2001), new analysis presented here highlights that for both expeditions, many aspects of the summer of 1911/12 were also exceptional in terms of the meteorological conditions. Most impressive was the prolonged period of anomalously high pressures recorded during December 1911 at the bases of Cape Evans and Framheim, as well as by the sledging parties while on the Ross Ice Shelf. Associated with these pressure values that frequently and persistently exceeded two standard deviations from the climatological average at McMurdo were warmer-than-average conditions in the interior of the Ross Ice Shelf, near the Transantarctic mountains, and on the polar plateau, in wet and dry blizzard conditions, respectively. In particular, Amundsen's polar party observed temperature anomalies in excess of 10°C (an absolute daily mean temperature of -15.5°C) on the plateau in their approach to the South Pole; comparable warmth has only once been observed in over 60 years of temperature measurements during December 1- 10 at the Amundsen-Scott South Pole station. At the same time, Scott experienced warmer-than-average temperatures as well while on the Barrier, with warm wet snow that delayed their journey several days. While both temperature and pressure remained below to near average in January 1912, Scott experienced much warmer-than-average conditions on the descent down the Beardmore Glacier in early February, followed by much colder-than-average temperatures on the Ross Ice Shelf in early March. The period of warmth, consistent with another period of exceptionally high pressures at Cape Evans, may have lulled Scott's party into slowing down, and it is possible that they would have reached their key next depot if they had not done so. Although temperatures naturally turn colder at this time of year with the onset of winter, over 30 years of ERA-Int data indicate that during 1979-2015, the temperatures rarely (p<0.05) changed as sharply as Scott and his men experienced. Reconstructions of the pressure at individual stations across Antarctica, as well as early SAM index reconstructions, further indicate that the summer of 1911/12 was marked by one of the strongest negative SAM years since 1850. Notably, the summer of 1911/12 was also marked with El Niño conditions in the tropical Pacific (reflected to some extent by the Southern Oscillation pattern in Fig. 2c), and other research suggests that the combination of El Niño events with negative SAM phases act to amplify the atmospheric response across the Pacific sector of Antarctica (L'Heureux and Thompson 2006; Fogt et al. 2011). It was therefore likely that the combination of these two climate patterns gave rise to the overall exceptional summer during the South Pole race, which makes this incredible story even more of a legend.

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Figure Captions

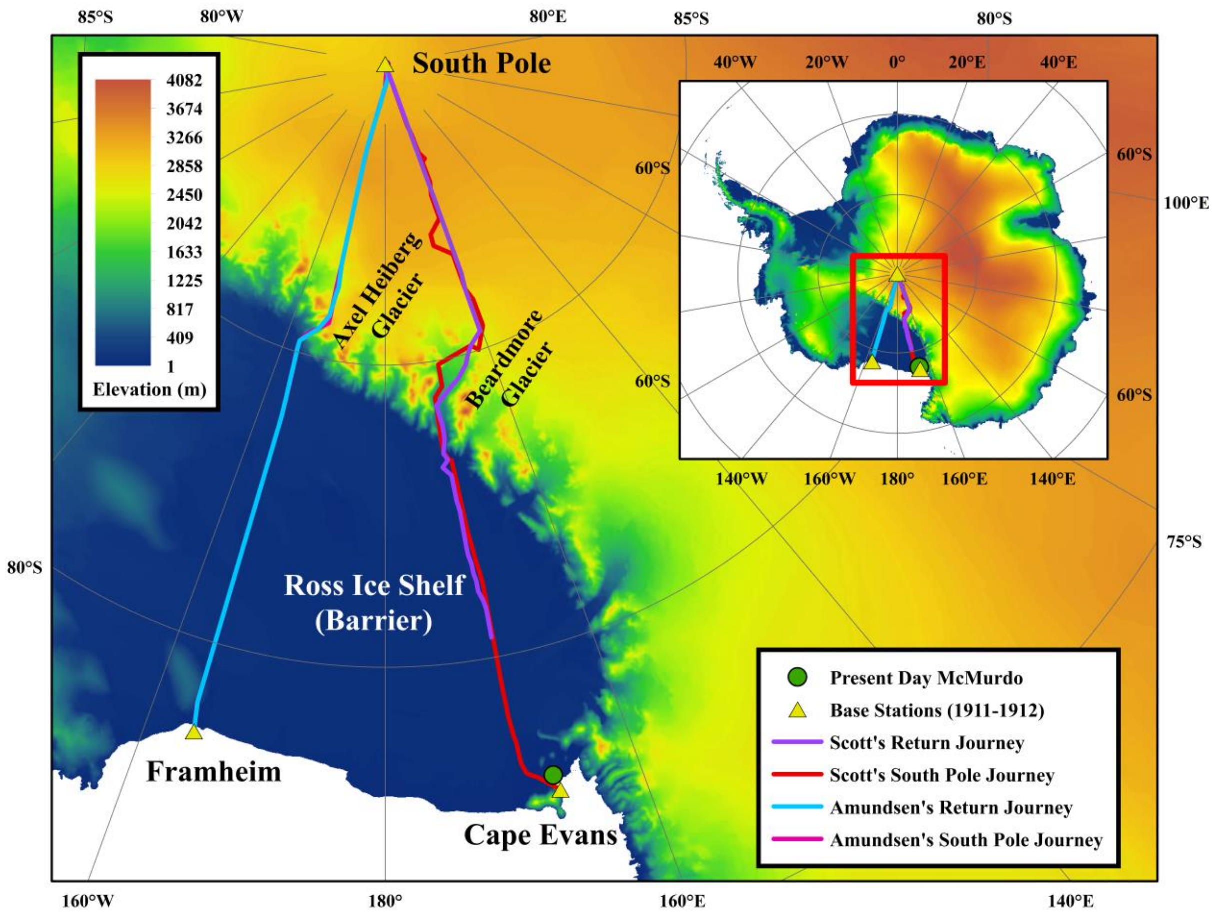
Figure 1. Map showing the routes of Scott and Amundsen, along with key locations. The return journey for Scott is only depicted for when meteorological observations were collected up until March 10, 1912.

Figure 2. a) Summer mean pressure observations (black) and reconstructions with 95% confidence intervals (gray band) for McMurdo station (see Fig. 1 for location). b) Comparison of seasonal mean pressures from observations, gridded pressure datasets, and reconstructions (and their 95% confidence intervals, gray shading) during 1911-1912. c) 20CR pressure anomalies and standard deviations (contoured and shaded, respectively), along with circles indicating observed midlatitude pressure anomalies (equatorward of 60°S) and Antarctic pressure reconstruction anomalies (poleward of 60°S), with anomaly magnitude given by the legend. Anomalies are relative to the 1981-2010 climatological mean.

Figure 3. a) October 1911 – March 1912 daily mean pressure data from the British and Norwegian bases, and along the sledging routes on the Barrier/ Ross Ice Shelf when the elevations are <100 m. The McMurdo daily mean climatological pressure and 95% confidence interval (±2 standard deviations, gray shading) are given for reference. b) Daily mean temperature anomalies, calculated from the 1981-2010 ERA-Int climatology for day / location, during December 1911.

Figure 4. a) Along track temperature anomaly for Amundsen, as well as the ±2 standard deviation envelope and maximum and minimum along-track temperature anomaly. Anomalies are calculated with reference to the ERA-Int 1981-2010 daily climatology for each day/ location, corrected to elevation using a lapse rate of 6.5°C km^{-1}. b) As in a), but for sledging measurements along the Scott route. The thin purple lines represent the maximum and minimum temperature anomalies for the second return party. c) Combined plot of all available sledging temperature anomalies during 1911-1912.

Figure 5. Temperature difference histograms for the a) absolute and b) anomaly temperature difference from ERA-Int during 1979-2015 for February 9-15 minus February 27-March 5, 1912. The x-axis is binned in 2°C increments. The differences as recorded by the Scott polar party are indicated with a red outline. To provide the most conservative estimate, ERA-Int temperatures were corrected for elevation differences using the dry adiabatic lapse rate of 9.8°C km^{-1}.



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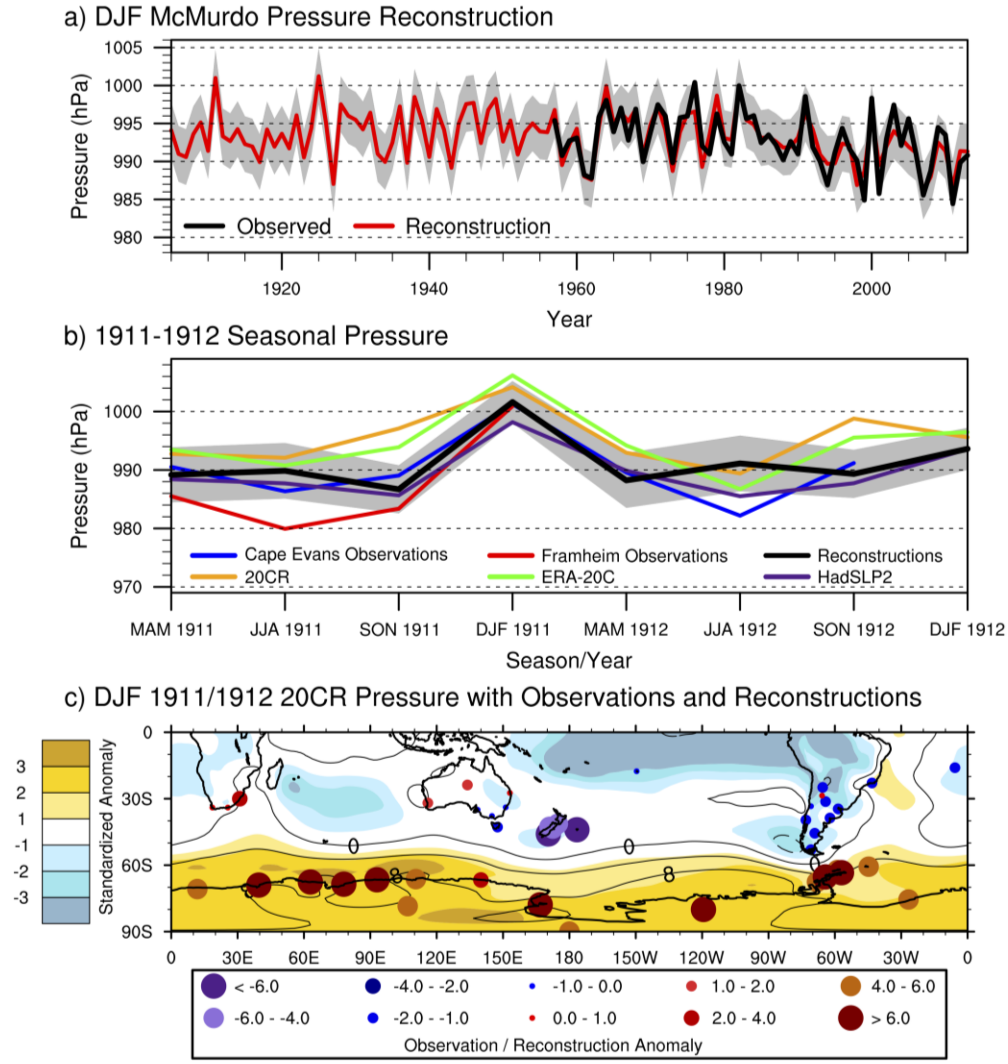

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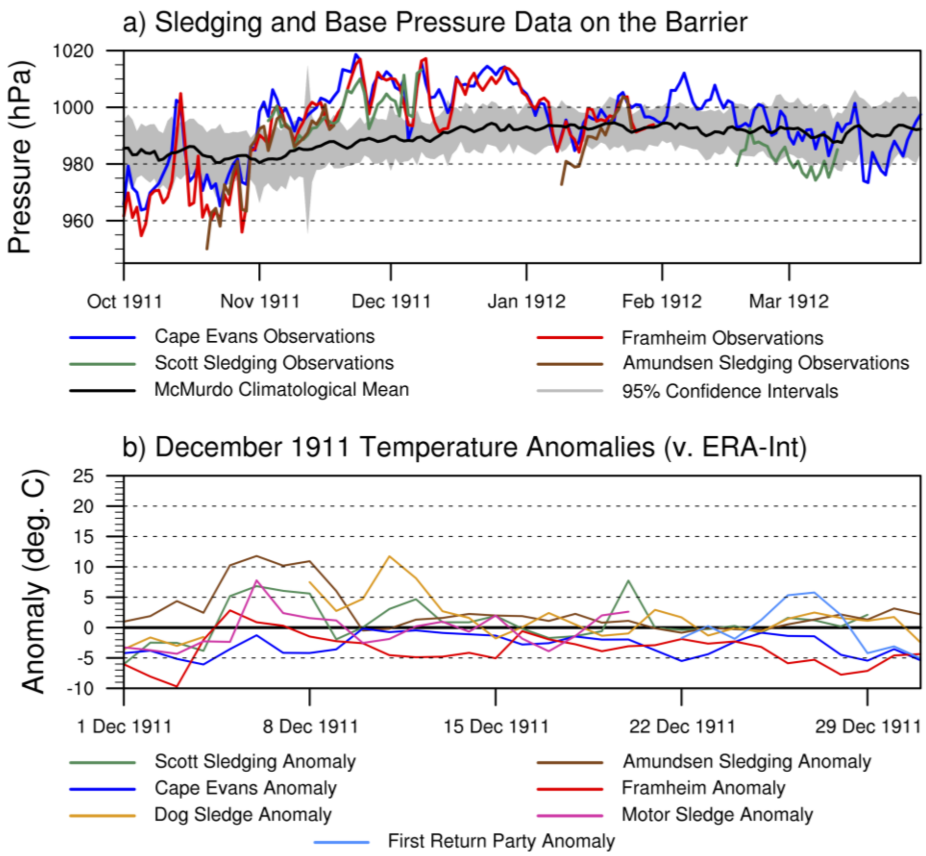

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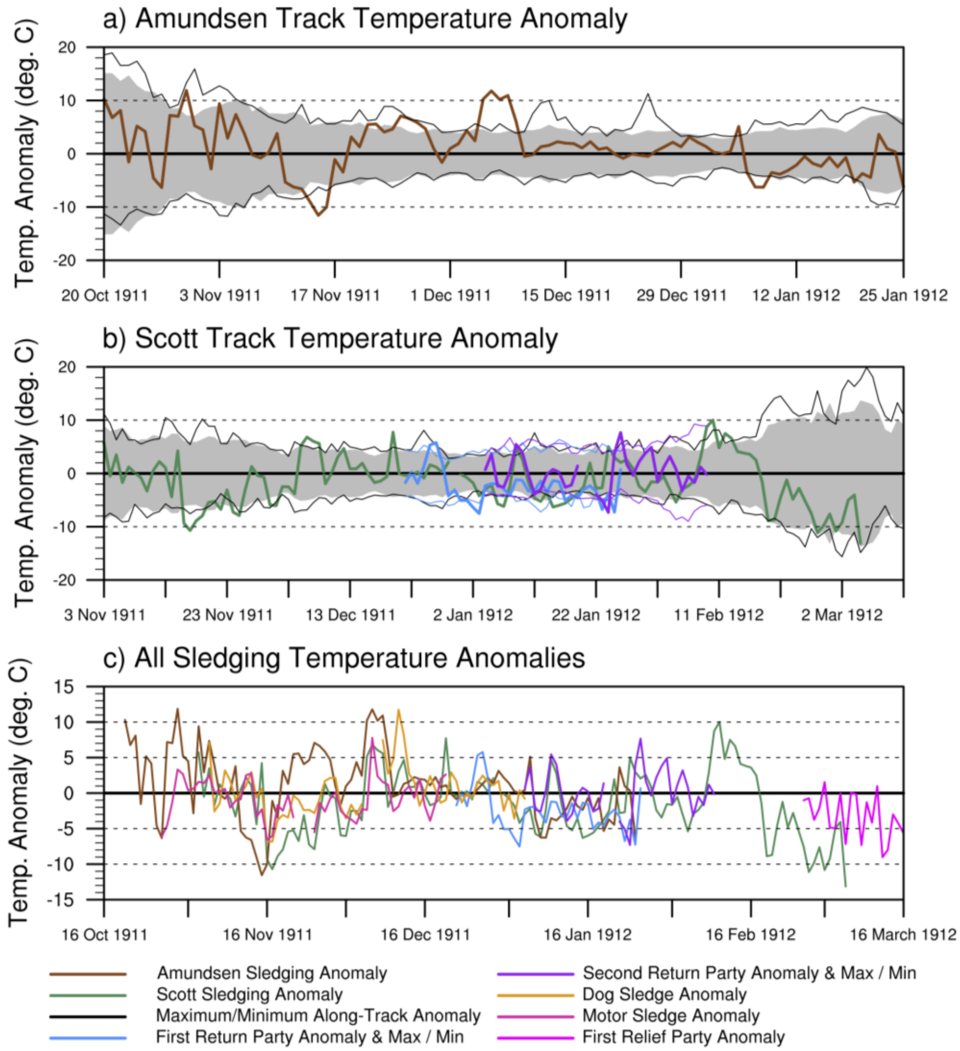

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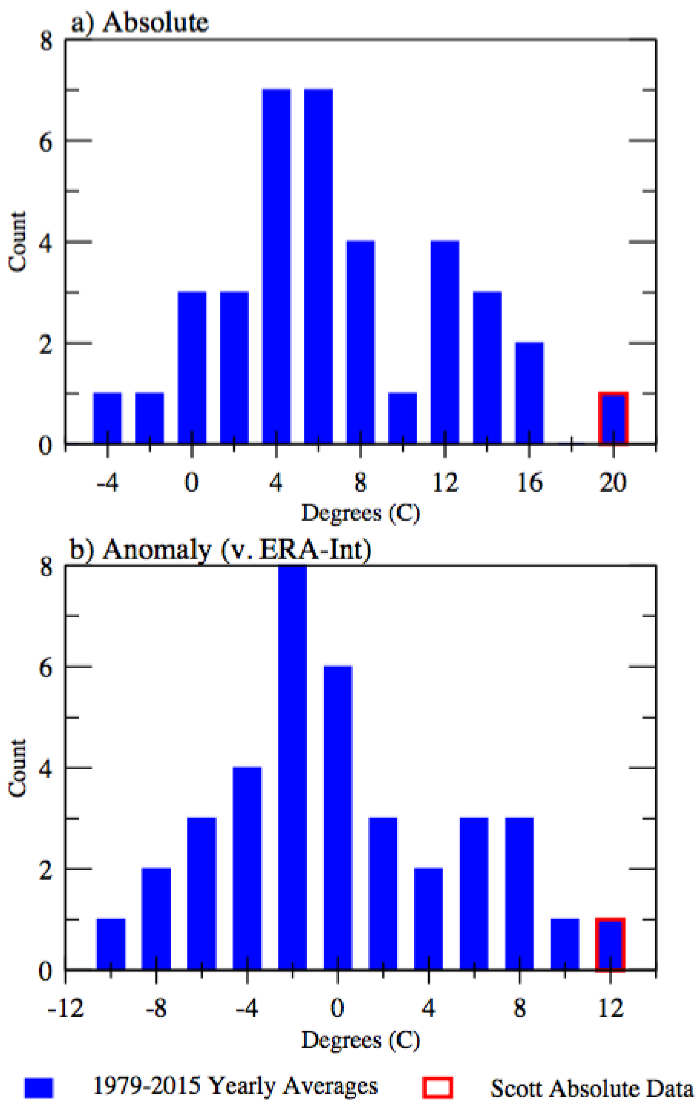

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