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A 30-Year satellite based climatological dataset of Antarctic Cloud Mass Meridional Transport events

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Abstract. Cloud Mass Meridional Transport events (CMMTs) are poleward propagating synoptic scale cloud masses that flux heat and moisture over the Antarctic continent for more than 48 consecutive hours. These events are vital for the surface mass balance and annual precipitation totals of the Antarctic Ice Sheet. Regardless of their shape and size, CMMTs are vertically developed, must penetrate more than 200 km onto the continent, and propagate southward for their entire duration. Presented here is a 30-year CMMT climatological dataset from November 1992 to December 2022 that uses infrared satellite composite imagery to manually identify and track landfalling CMMTs across seven regions around Antarctica. Previous climatologies built to study Antarctica's atmosphere have been limited in time or are derived from reanalyses and algorithms instead of physical observations. The goal of this satellite-derived dataset is to supplement Antarctic forecasting operations and to ensure that reanalyses and weather forecasting models accurately resolve these high-impact events in both time and space. A total of 1,386 CMMTs were identified, lasting 2.81 days on average. Sixty percent of CMMTs occur over East Antarctica with heightened activity in austral winter. The longest event recorded in this time frame was 13 days long in May 1998, but events like this one are rare given that 91% of CMMTs lasted less than four days. The satellite composite imagery, comma-separated value files, and monthly text documents defining the time and spatial distribution of each CMMT are publicly accessible at the Antarctic Meteorological Research and Data Center (AMRDC) Data Repository at the University of Wisconsin-Madison (AMRDC, 2022; Chambers, 2026; Chambers et al., 2026). Links to these data are listed in Sect. 6 on data availability.

1 Introduction

Antarctica is one of the coldest and driest places on Earth. The little precipitation it does receive contributes substantially to the annual total snow accumulation of its ice sheets, especially those in East Antarctica (Gorodetskaya et al., 2014; Maclennan et al., 2022). Most of this precipitation falls from cloud masses formed by orographic lifting along the coastline, as seen over the Antarctic Peninsula (AP), and from synoptic scale and mesoscale systems transporting heat and moisture poleward from the lower latitudes (King and Turner, 1997; Vichi et al., 2019; Kirchgaessner et al., 2021; Baiman et al., 2023). Although it is

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important for cloud development, the former is not a focus of this study. Instead, attention is directed toward synoptic scale events that redistribute energy poleward on the order of hours to weeks (Moreno-Ibáñez, 2024).

This redistributive process noted above is known as a Cloud Mass Meridional Transport event (CMMT). CMMTs are synoptic scale poleward propagating masses of clouds that make landfall over the mainland Antarctic continent for more than 48 consecutive hours (Staude, 2007). While related to extratropical cyclones, polar lows, and atmospheric rivers (ARs), the structure and shape of a CMMT is less important to its definition than the meridional wind component and moisture content. Unlike CMMTs, atmospheric rivers are generally defined by their narrow bands of enhanced horizontal water vapor transport (American Meteorological Society, 2026). These events are often identified using a relative or absolute magnitude of integrated water vapor (IWV) or IWV transport (IVT) within the modeling community (Wick et al., 2013; Rutz et al., 2014; Ralph et al., 2018; Shields et al., 2018; Rutz et al., 2019). Conversely, extratropical cyclones and polar lows often resemble a comma or spiral as they advect warm air vertically ahead of a frontal wave, eventually resulting in precipitation (Rasmussen and Turner, 2011; Simmonds and Rudeva, 2012; Stoll et al., 2021). Furthermore, both types of events are associated with deep convection in the tropics that creates anomalous diabatic heating for mid-tropospheric wave patterns to emerge in the Southern Hemisphere's mid-latitudes (Wang et al., 2019; Clem et al., 2022; Zhai et al., 2023; Kurita et al., 2025; Wille et al., 2025). The resulting Rossby wave trains often propagate eastward and poleward through mid-latitude jet streaks before embedding into a zonal wave 3 pattern in the Southern Ocean (Clem and Fogt, 2015; Wang et al., 2019; Goyal et al., 2021; Baiman et al., 2024; Wille et al., 2025).

There are several pathways for identifying when and where CMMTs make landfall, including archived satellite imagery. Previous applications of these data include, but are not limited to, operational weather forecasting, the study of polar lows, and atmospheric motion vectors in the troposphere (Velden et al., 1997; Lazzara et al., 2003; Lazzara et al., 2014; Krinitskiy et al., 2018). Despite these applications, satellite data over Antarctica have had limited use in long-term climatologies. Past Antarctic climatologies used satellites to investigate surface winds and ice surface temperatures, but were limited to specific regions and contain less than 20 years of observable data (Carrasco and Bromwich, 1993; Comiso, 2000; Staude, 2007; Palm et al., 2018; Heinemann et al., 2019).

The introduction of a 30-year satellite climatological dataset is significant because it is one of the first over Antarctica that relies strictly on satellite observations, rather than climate models or reanalyses (Fogt et al., 2012; Hirasawa et al., 2013; Guan and Waliser, 2017; Shields et al., 2018; Seefeldt et al., 2021; Wille et al., 2021; Maclennan et al., 2023; Wille et al., 2025). Since these other methods vary widely in their forecast capabilities, initial conditions, and parameters, generalizations must be made by inversely approximating how the atmosphere behaves (Hakim et al., 2016; Parker, 2016). These generalizations mean that each type of model interprets the atmosphere differently. If there are minute differences between the models, then identical initializations can proliferate into distinct, and sometimes contrasting, atmospheric reconstructions (Maclennan et al., 2022; Shields et al., 2022; Wille et al., 2025). Thus, near-surface temperatures, wind speeds, the frequency of atmospheric rivers, and precipitation totals may be under or overestimated (Hodges et al., 2011; Gossart et al., 2019; Rutz et al., 2019; Hassler and

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Lauer, 2021; Shields et al., 2022). In more extreme circumstances, the uncertainty of AR caused precipitation in reanalyses can sharply increase poleward of 85° S due to the absence of observational data (Maclennan et al., 2022).

A key objective of this CMMT dataset is to be a verification for numerical and theoretical based methods. Satellite based products offer a physical alternative to identifying trends in location, frequency, and duration of CMMTs, especially in the absence of sufficient data for reanalyses. This climatological dataset may also benefit machine learning (ML) algorithms that struggle with differentiating between cloud top temperatures and the Antarctic surface (i.e., ice sheets) in the infrared (IR) spectrum (Bromwich et al., 2012). Since land ice is often directly below landfalling cloud masses over Antarctica, it is important for these algorithms to correctly discern between the two. Therefore, the human component of this climatology allows for interpretation that may not be present in ML models used today. Secondly, it aims to benefit Antarctic forecasting operations. Low cloud ceilings and snowy conditions inland restrict small aircraft operations that are required for transporting personnel and equipment to many otherwise inaccessible sites.

Following this introduction, Sect. 2 contains criteria for defining CMMTs and how the climatology was organized. Section 3 addresses gaps in the data and what quality control checks are taken to ensure that the CMMTs are accurately assessed. Data collection and an overview of the results are given in Sect. 4 along with a brief discussion of the data in Sect. 5. Sections 6 and 7 will include information on where to access the dataset used in this study and any notable takeaways from this project.

2 Methods

The three following subsections pertain to defining a CMMT event, the parameters of the satellite composite imagery used, and the inclusion and exclusion of specific areas over Antarctica.

2.1 CMMT criteria

As defined in Sect. 1, CMMTs must continuously landfall for more than 48 hours. A temporal minimum of two days is chosen to discern between high-impact weather events on the continent and less severe weather systems. High-impact events can be considered as multiple, small reoccurring systems or one large system hitting the same area for a sustained period. With a threshold of 48 hours, there is a higher certainty that a cloud mass satisfies all the criteria needed to become a CMMT. These systems must also propagate poleward for their entire duration. While the moisture found in CMMTs originates in the tropics and mid-latitudes, the focus of this study is directed to where and when it is transported over Antarctica. Cloud masses developing inland or along the coastline are ignored.

Should a cloud mass make landfall, it also needs to have significant penetration inland. To achieve this, the cloud mass must move approximately 200 to 300 km poleward from the coastline. This boundary adjusts its location relative to changes in the coastline's position. By enforcing this criterion, we can further understand the interplay between the zonal and meridional wind components.

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The vertical development of a cloud mass is the final component needed to define a CMMT. These types of clouds will typically have a colder and brighter signature in the IR range (Takemi et al., 2004). Consequently, thicker clouds often have a larger liquid water path and a higher specific humidity. Thus, thicker clouds can be an indicator of higher moisture content (Holloway and Neelin, 2009; Zhang and Klein, 2013). To find these types of clouds, infrared window data (10.7 – 11.0 μm) from multiple satellites are utilized (Kohrs et al., 2014). Minor differences do appear in the assembled data because each satellite varies slightly in the wavelengths it uses. However, there is typically a strong agreement in the location and depth of the clouds since more satellites have the necessary sensors to observe cloud masses at a smaller range of wavelengths within the IR window (Kohrs et al., 2014). Wavelengths from the water vapor window (6.2 – 6.9 μm) were also considered, but ultimately rejected since the Antarctic Meteorological Research and Data Center (AMRDC) at the University of Wisconsin-Madison did not produce these composites until the mid-2000s. As a result, more than 30% of the satellite data are missing from the water vapor composites.

A user's interpretation is still needed to weigh the validity of cloud mass depth and its penetration inland. To address this problem, we used an enhancement originally designed for Project FROST (First Regional Observing Study of the Troposphere) that utilizes a simple, single band approach in the IR bands (Turner et al., 1996). This enhancement prioritizes the identification of colder clouds by stretching the mid-range of a typical temperature scale to the extremes, deemphasizing warm, lower-level clouds. While it also enhances other cloud features beyond the scope of this study, it isolates the massive clouds and storm systems that are the focus of this dataset. Normally, unenhanced IR composites capture brightness temperatures between 180 K–330 K. However, we are not worried about temperatures above freezing over the Antarctic nor the top of the atmosphere. So, areas between 180 K–207 K and 283 K–330 K are removed from either end of the temperature scale. This allows IR values between 207 K–283 K to utilize the entire grey scale. Since this study is not directed towards identifying individual pixels of cloud top temperatures, the manipulation of these data via the Project FROST's enhancement is sufficient for large-scale systems. Figure 1 highlights how enhancing the images simplifies the tracking process of cloud top temperatures by showing the progression of a three-day CMMT from 02 Mar 2021, 02 UTC to 06 Mar 2021, 00 UTC. The event begins with a low-pressure system off the coastline of Queen Maud Land and an AR around 20 degrees to the east of its center. Since the spiral is a darker grey, it does not count as a part of the CMMT. Instead, the AR has a bright enough cloud top temperature to meet the criteria needed as it makes landfall. After 24 hours, the cloud mass moves a couple hundred kilometers inland, surpassing the boundary for significant penetration. By 05 Mar, the system shifts a few degrees to the east and has some pockets of insufficient cloud depth within the body of the system. Finally, the system dissipates on 06 Mar because the cloud mass is no longer being reinforced by other cloud masses offshore nor does it have enough depth to continue as a CMMT. The lack of vertical development reduces the chances that this system would produce substantial amounts of precipitation going forward.

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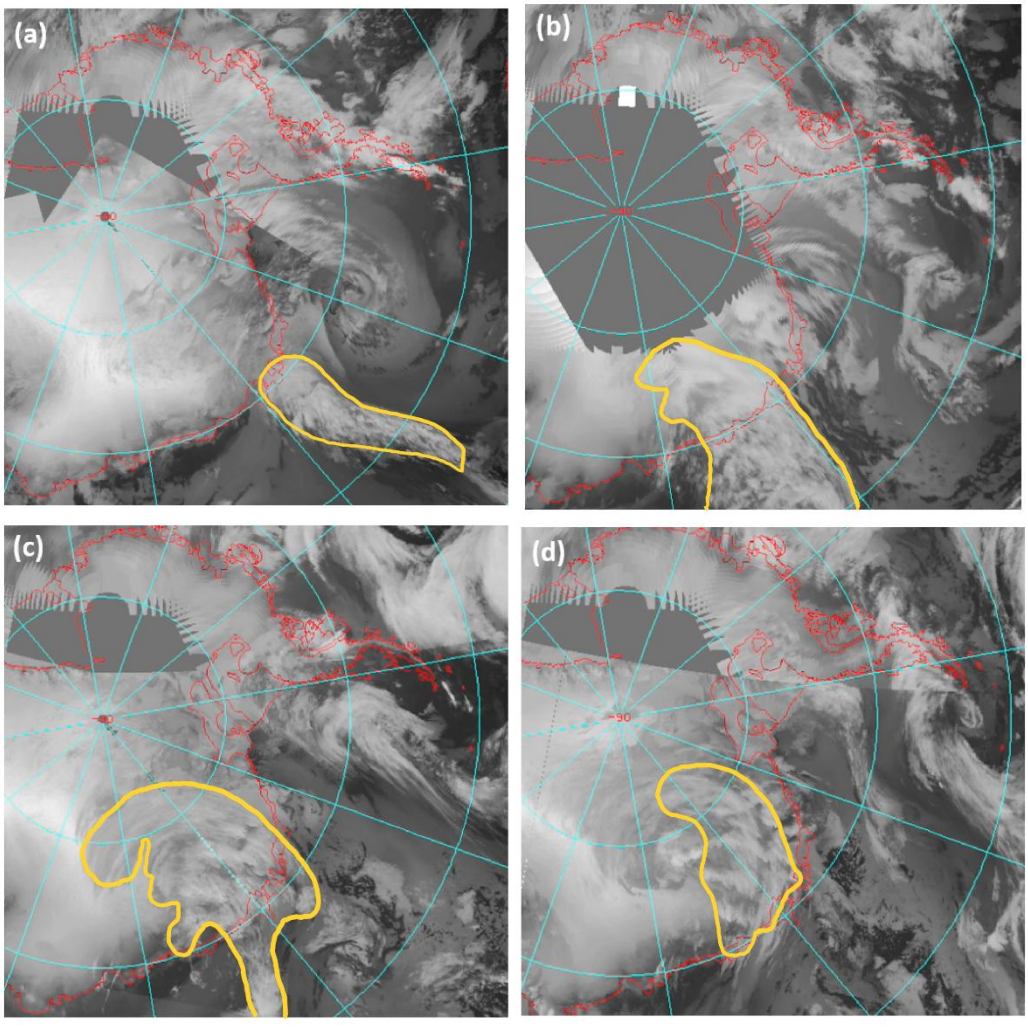


Figure 1: Satellite composite images following a three-day CMMT over Queen Maud Land from 02 Mar 2021, 02 UTC to 06 Mar 2021, 00 UTC. (a) The beginning of the event at 02 Mar 2021, 02 UTC. (b) 03 Mar 2021, 09 UTC. (c) 05 Mar 2021, 00 UTC. (d) The ending of the event at 06 Mar 2021, 00 UTC. The yellow outlines in each panel reflect the boundary of the tracked cloud mass as it makes and sustains landfall.

Beyond the criteria provided so far, there are additional rules required for defining CMMTs and the variables used later in Section 4. On multiple occasions, cloud masses are continuously tracked through the ending of a month. Any event that starts in one month (or year) and ends in another will only be counted for the starting month. As long as the event lasts one hour in the first month, it will be counted as a part of that month rather than the following one.

Other rules pertain to a cloud mass that is either reinforced by a separate system or a CMMT splitting into two distinctly different cloud masses. A reinforcing cloud mass must make landfall within 12 hours of the previous cloud mass and at approximately the same location to consider them the same event. If there are more than 12 hours of separation between the

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events propagating onshore, then they remain as two separate events as long as they meet the other CMMT criteria. The inverse involves one cloud mass splitting into two poleward propagating systems. Should the CMMT split apart, the branches are still considered one event unless a distinct gap forms between the cloud masses. If a visible gap exists, then the cloud mass propagating in the original direction of the CMMT is considered the ongoing event. The diverging cloud mass starts as a separate event when it is no longer connected to the main event and retains the criteria needed for a CMMT.

2.2 Tracking CMMTs and satellite composites

A challenge with viewing Antarctica via satellites is that, individually, neither geostationary nor polar orbiting satellites are optimal sources of data. Geostationary satellites can provide continuous coverage over the tropics and mid-latitudes, but their ability to view the poles is restricted by the curvature of the Earth and higher zenith angles (NOAA, 2023). A high zenith angle leads to skewed imagery compared to almost nadir observations over the tropics. Alternatively, polar orbiting satellites have a finer spatial resolution that benefits cloud mass observations over Antarctica. However, they only take comparatively narrow swathes of observations over the region every one to two hours — meaning that they alone do not provide sufficient coverage for this study (NOAA, 2023). To address this issue, the process outlined in Kohrs et al. (2014) highlights how AMRDC uses the Man computer Interactive Data Access System (McIDAS) software to blend geostationary and polar orbiting satellite data into a single South Pole Stereographic projection. These Antarctic satellite composites have been archived by AMRDC since 1992 and are publicly accessible to everyone (Lazzara et al., 2003; Lazzara et al., 2026). Combining continuous geostationary and polar orbiting satellite data improves the spatial coverage and reduces anomalously high geostationary brightness temperatures over such high latitudes.

The production of composite imagery mitigates many of the risks associated with single sourced satellite data, but spatial coverage is still a lingering problem. The satellite composites display grey areas when there are no satellite data available for inclusion. These areas are more often found in the 1990s and 2000s, as fewer satellites existed for observations at the time. This resulted in missing data occasionally covering more than half of the high polar plateau, the Ross Ice Shelf, and areas around the geographic South Pole. These regions of missing satellite data add to the difficulty of tracking systems closer to the geographic South Pole, yet seldom disrupt the viewer when a CMMT is making landfall or has moved a couple hundred kilometers inland as detailed in Sect. 2.1.

By the 2010s, the temporal and spatial resolution improved considerably. Three-hourly composites were taken from November 1992 until 08 Apr 2009, 00 UTC, when AMRDC transitioned to hourly satellite composite images. This increase in the temporal resolution provides finer details of a cloud mass' direction — making CMMTs easier to identify and reducing the impact of missing data. The spatial resolution has also benefited from technological advancements. The data were refined from 10 km after ten years of operations down to 4 km in the present (Kohrs et al., 2014). Finer spatial resolutions resolve smaller processes in the clouds that might not have been visible before. These improvements allow for a higher precision of a CMMT's start and end time.

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When tracking CMMTs via satellite composites, the total number of events are written down alongside the days affected by CMMTs. The total number of events is a straight-forward calculation while the days affected by a CMMT is a rounded down value to the nearest day. For example, a two-day event can be considered anything between 48–71 hours, and a three-day event is anything between 72–95 hours. Furthermore, the total number of days affected does not take into account simultaneous events. This means that three two-day events making landfall at the same time in different regions would be counted as six days' worth of CMMTs impacting the continent. Lastly, like the CMMT criteria introduced in Section 2.1, the days affected are counted exclusively for the starting month rather than being split between multiple months. Hence, consistency between the number of events per month and days affected are maintained.

2.3 Regions of interest

The climatology is divided into seven distinct regions: two in West Antarctica and five in East Antarctica (Table 1 and Fig. 2). Acronyms listed in Table 1 only appear in the metadata for the monthly text files. Work done by Staude (2007) initially defined four regions that covered small, limited sections of Antarctica. Since then, the boundaries have evolved to incorporate more areas of the continent that are prone to poleward moisture transport. Each region's coastline is between 30 and 60 degrees wide and is influenced by preserving continuity from older boundaries and utilizing natural geographical features (i.e., Antarctic Peninsula, Ross Ice Shelf).

Region	Acronym	Longitudinal Bounds
Marie Byrd Land	**MB**	**150° W to 120° W**
Ellsworth Land	**EL**	**120° W to 75° W**
Queen Maud Land	**QU**	**30° W to 30° E**
Enderby Land	**EN**	**30° E to 75° E**
Queen Mary Coast	**QR**	**75° E to 120° E**
Wilkes Land	**W**	**120° E to 150° E**
Victoria Land	**V**	**150° E to 180° E**

Table 1: The seven regions in the CMMT climatology including their acronyms and longitudinal boundaries.

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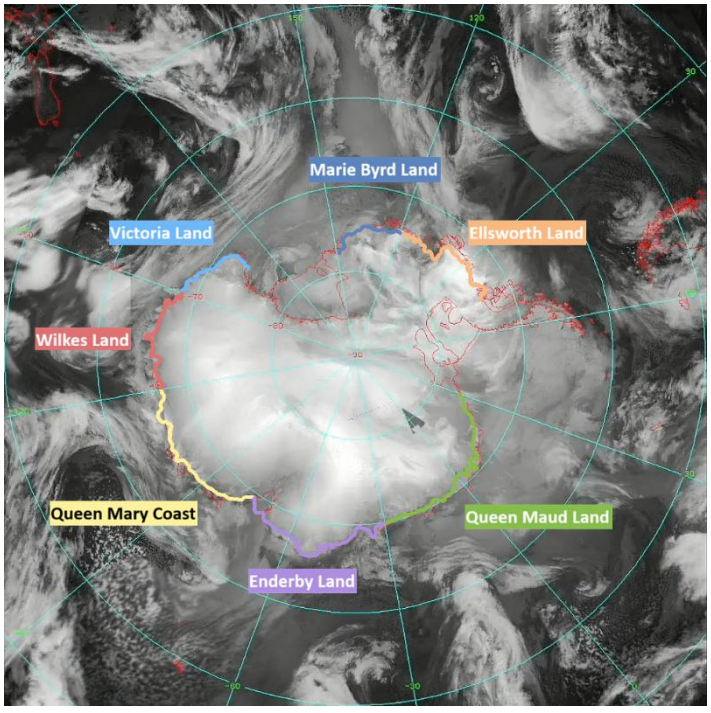


Figure 2: A satellite composite detailing the seven regions in the CMMT climatology. A CMMT begins when it makes landfall along one of the colored and bolded boundaries. Outcroppings of ice shelves and small islands may appear equatorward of the boundaries.

Although CMMTs are tracked across a significant majority of the continent (Fig. 2), the AP and most of the major ice shelves are excluded from this analysis. The complexity of the mesoscale and synoptic scale processes around the AP combined with its mountainous topography make the identification of CMMTs difficult. This is further challenged by the combination of zonally dominated westerlies in the subpolar latitudes and orographic lifting on the windward side of the AP (Kidson, 1988; Hartmann and Lo, 1998; Swart and Fyfe, 2012; Kirchgaessner et al., 2021; Boschat et al, 2023). The mountainous topography and westerlies cause much of the moisture to condense out over the AP before traveling southeastward to the Filchner and Ronne ice shelves. This results in the cloud masses potentially making a second landfall over the ice shelves after previously crossing over the Transantarctic Mountains, further complicating the CMMT tracking process.

The Ross Ice Shelf, like the AP, has complicated synoptic and mesoscale processes from its location between the Southern Ocean and Transantarctic Mountains. Katabatic drainage from the mountains creates a mean southerly surface flow for most of the ice shelf (Parish and Bromwich, 2007; Seefeldt and Cassano, 2008). Since CMMTs are defined by their poleward transport, the katabatic flow would limit their overall effectiveness upon making landfall (Staude, 2007).

Sea ice, small ice shelves, and islands are mostly neglected when identifying landfalling events on the Antarctic coastline. Since the sea ice extent is a seasonally fluctuating boundary, it produces inconsistencies in where CMMTs make landfall. These problems would only be amplified when the sea ice extent is at its maximum. Most small ice shelves are also omitted. There

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are instances where ice shelves are considered as part of the coastline (i.e., Amery Ice Shelf near Enderby Land). If there are protrusions or recesses of ice shelves near the coastline, they can artificially alter the start and end times of a CMMT by a couple of hours. For longer events, this may not pose an issue, but for events close to 48 hours, having precision is important.

As seen in the AP, many systems near Antarctica do not exclusively rely on a northerly, meridional flow. Therefore, skirting events are introduced to account for poleward propagating systems that have a large zonal flow component. A skirting event is a CMMT that zonally propagates into two or more regions while continuously making landfall. In the climatological dataset, skirting events are not bound to one region and are instead defined by their general location over Antarctica. Skirting events in Marie Byrd Land and Ellsworth Land are represented by West Antarctic Skirting events (WAS), while Queen Maud Land, Enderby Land, Queen Mary Coast, Wilkes Land, and Victoria Land are designated as East Antarctic Skirting events (EAS). Every region a CMMT travels through is recorded in the metadata (i.e., Marie Byrd Land to Ellsworth Land) and then placed into one of the two skirting categories to prevent overcounting. Events that cross over the AP, the Ross Ice Shelf, or other excluded regions will not count as a skirting event but may be considered as two individual CMMTs should they satisfy the criteria in each region respectively. This means that a single CMMT cannot start in Ellsworth Land, propagate eastward over the AP and the Filchner Ice Shelf, before skirting into Queen Maud Land.

3 Quality control and addressing missing data

Multiple researchers at AMRDC have contributed to the monumental task of tracking 30 years' worth of CMMT data since the mid-2000s. Thus, measurement bias may become a problem when subjective, human based observations are used for a dataset. Therefore, it is imperative to minimize any errors and ensure there is consistency in identifying the temporal and spatial bounds of CMMTs.

Similar to training datasets used by ML algorithms, researchers at AMRDC utilize October 2009 as a test month for their training. A consensus has formed for where and when CMMTs are found. To begin training, a base definition of CMMTs is given. No extra information on techniques or methods is provided to reduce confirmation and observer biases. The trainee is then given time to go through hourly satellite composite images of the training month. Here, they record the timing and location of every CMMT they observe. Once completed, their results are compared to the work of previous researchers to identify any areas of improvement. The testee will run through the same month again to apply what was learned. The test taker can repeatedly practice on this month, or another analyzed month to gain a stronger understanding of the CMMT data. They may begin applying this knowledge to undocumented months once they are comfortable with the content.

As an additional layer of quality control, we reevaluated older data from 1992–2012. Any translation errors from the monthly text files used to document the duration and location of CMMTs were corrected to maintain the integrity of the dataset. A thorough review of CMMTs from November 2012–December 2022 was necessary to ensure that CMMT criteria were consistently employed as the researcher's skill improved over time. Any discrepancies were adjusted in accordance with the standards of newer work.

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Furthermore, some events have extenuating circumstances that create challenges for the viewer. Data missing for more than 12 hours, anomalously high cloud top temperatures, and coastal orographic lift are a few of the many examples found in the composites. Some of these challenges may require a justification as to why they begin or end at a specific time. Justifications are written in the monthly text files as metadata in the AMRDC archive.

Large gaps, defined as periods of 12 or more consecutive hours, offer a substantial challenge to identifying CMMTs. When this many data are missing, the beginning or ending of an event may not be evident because the system can dissipate, or retreat from the coastline without being observed. Of the total 264,432 hours from 01 Nov 1992, 00 UTC to 31 Dec 2022, 23 UTC, only 7,658 hours, or 2.9% of the total data are missing when considering the 12+ hour gaps. Most months are minimally impacted except for April–May 1994 and January–February 2016, which are all missing more than half of their composite images. However, no months are removed from the study. The sample size of the hourly data and the number of months analyzed ensure that the overall results of the study are minimally impacted by the missing data. In instances where a <12-hour data gap occurs while tracking an ongoing event, the observer utilizes contextual clues from the locations of synoptic scale systems and planetary wave patterns to approximate the beginning or ending of the cloud mass. There is a high confidence that the observer's estimations are close to the actual time when the gap is less than 12 hours since cloud masses are often still visible before and after small breaks in the data. When the gap is larger than 12 hours, or the system cannot be tracked through the blackout, the potential start and end times are documented at the point when the data disappears or returns.

Since 1992 is the only incomplete year in the dataset, some figures will specify that they are only using data from 1993 and onward. Calculations that identify monthly totals and seasonal variability include data from 1992. A higher sample size found in monthly calculations reduces the overall impact from the ten months of missing data.

4 Results

The total number of events, the duration, the seasonal variability, and the number of days affected by CMMTs are investigated over all of Antarctica before being broken down into skirting events and the seven individual regions (Table 1).

4.1 Antarctica

Over Antarctica, a total of 1,386 CMMTs made landfall, affecting 3,902 days. This averages to around 3.83 CMMTs per month, or about 46 per year (Fig. 3). A subtle increase of about 0.21 events per year occurs in the climatology (Fig. 3a), while the number of days affected by CMMTs decrease by 4 hours and 19 minutes per year (Fig. 3b). Although the total number of CMMTs and the number of days affected by CMMTs have opposite trends over the study period, they qualitatively appear to have a positive correlation.

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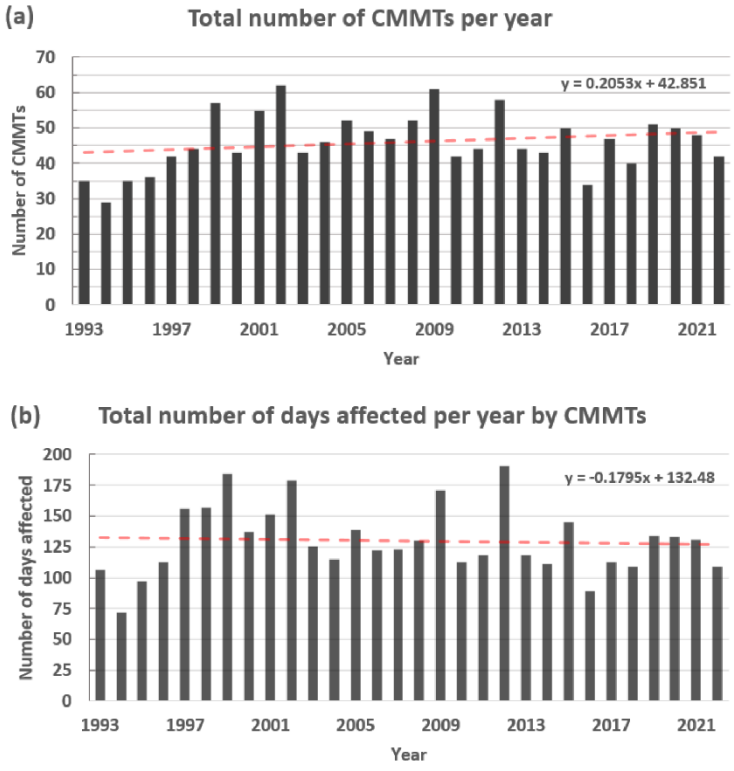


Figure 3: The total number of (a) CMMTs and (b) days affected by CMMTs per year from 1993–2022. A red, dashed linear trendline and the resulting equation is overlain in both panels.

The duration and frequency of Antarctic CMMTs are also explored. On average, CMMTs last around 2.81 days (~67 h). The longest CMMT lasted 13 days in May 1998, followed by a 12-day event in September 1999. While these events can last a long time, they are rare. Approximately 55% of CMMTs are two days long and around 91% of CMMTs are four days or shorter (Fig. 4). These shorter-lived events have only become more evident as the average duration of a CMMT has decreased due to the number of events increasing and the number of days affected by CMMTs decreasing (Fig. 3). As for the frequency of CMMTs, there are approximately 3.80 ± 1.90 CMMTs per month over Antarctica (Fig. 5).

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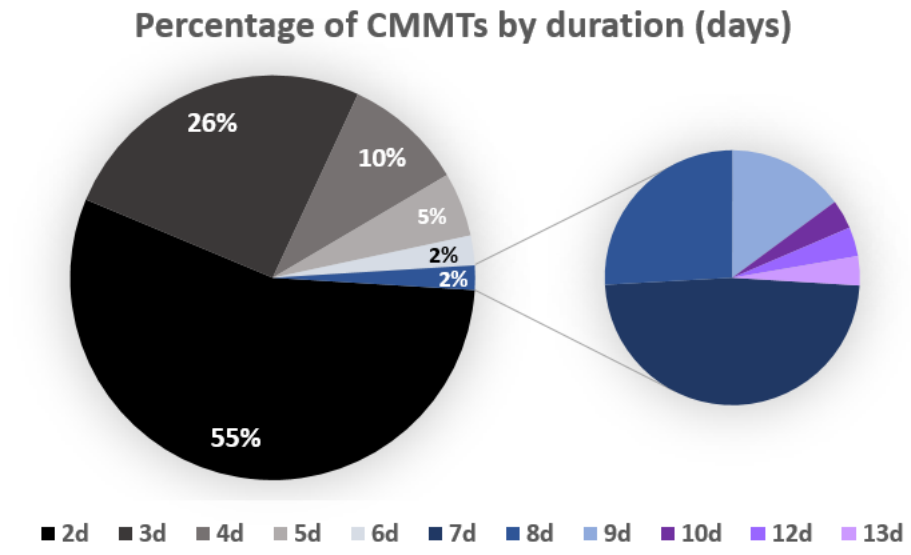


Figure 4: The percentage of CMMTs over Antarctica by duration in days (d) from November 1992–December 2022. CMMTs lasting between 7–13 days are in the smaller pie chart. No percentages are displayed since they only account for 2% of the total events. 11-day events are excluded given that none were recorded during the study.

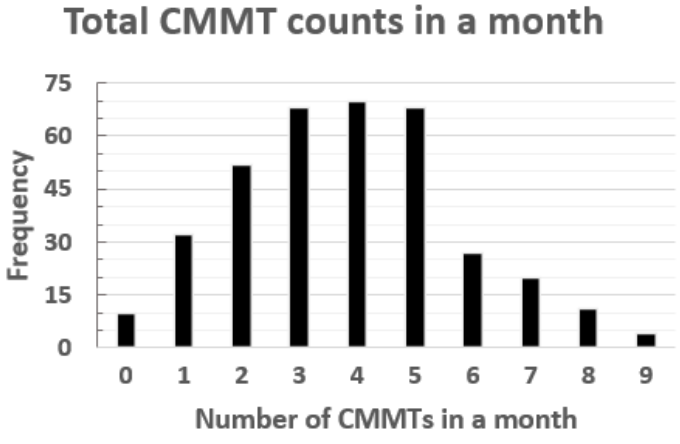


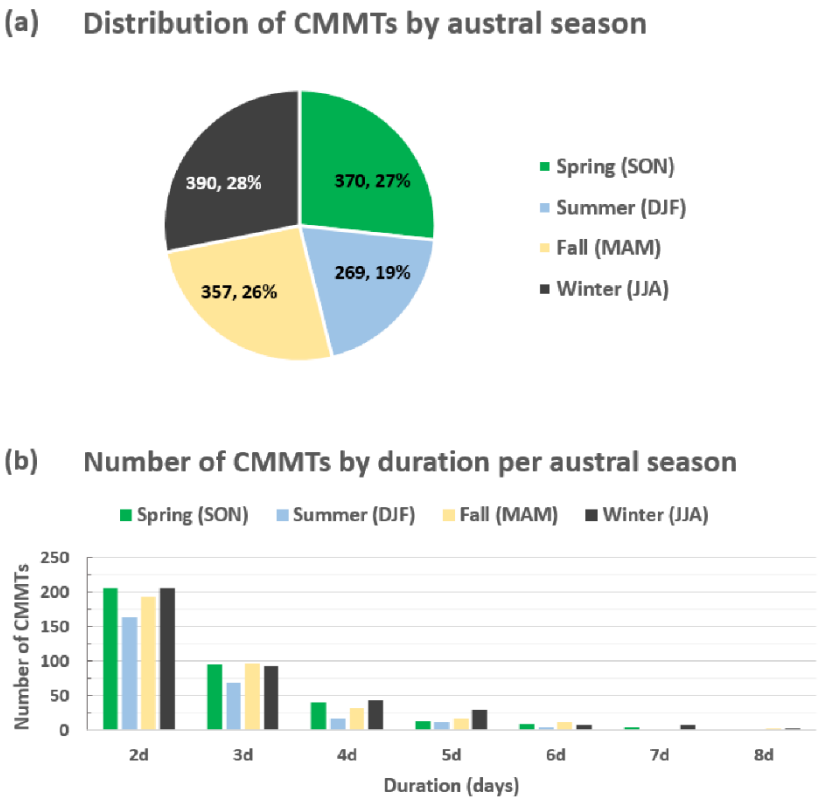
Figure 5: Total CMMT counts for each month from 1992–2022.

CMMTs can then be broken down into four austral seasons. It is shown that austral winter (JJA) is the busiest season with 390 CMMTs for the recorded period or approximately 28% of the events (Fig. 6a). Austral spring (SON) and fall (MAM) are equally as active with 27% (370 events) and 26% (357 events) respectively. Activity is reduced to 19% (269 events) for austral summer (DJF). Figure 6b also displays the total number of events by duration per austral season. These results are consistent with Fig. 4 since most of the events last between two to four days year-round. Seasonal trends throughout the 30 years can additionally be found by grouping the total number of CMMTs into monthly bins. Figure 7 reveals two peaks in CMMT activity for all of Antarctica. The first peak is between May, June, and July, while the second peak falls between October and November.

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285

Figure 6: (a) The percentage of CMMTs from November 1992–December 2022 for each austral season. Austral spring equals September, October, and November. Austral summer equals December, January, and February. Austral fall equals March, April, and May. Austral winter equals June, July, and August. (b) The number of CMMTs by duration for each austral season from November 1992–December 2022. Events longer than nine days exist but are excluded due to their minimal impact on the total 290 **number of events.**

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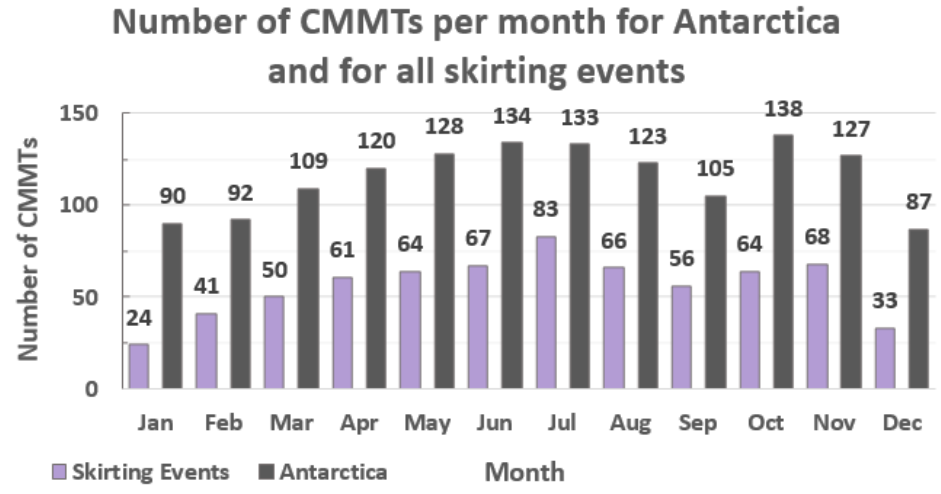


Figure 7: The total number of CMMTs recorded in each month from November 1992–December 2022 for Antarctica (dark grey) and all skirting events (lime green).

4.2 Skirting events versus non-skirting events

The meridional wind component can be considered a key feature of CMMT events. However, the zonal wind component cannot be neglected when looking at systems propagating onshore. Of the 1,386 CMMTs, 677, or 49%, are skirting events in either West or East Antarctica (Fig. 8). Of these skirting events, 41% are in West Antarctica and 59% are in East Antarctica.

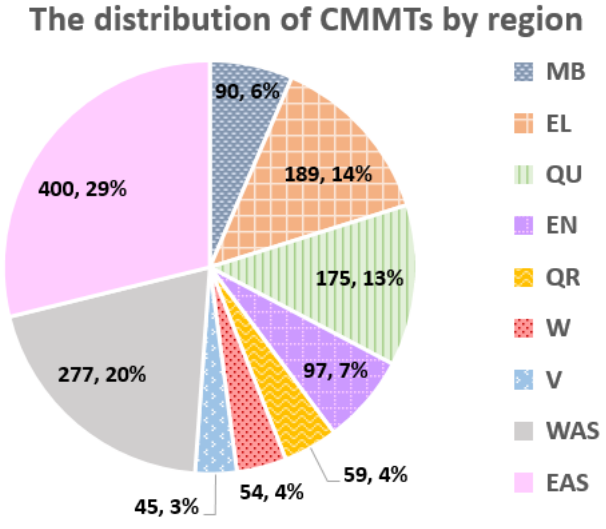


Figure 8: The number and percentage of CMMTs from November 1992–December 2022 divided into the seven regions from Table 1 plus the West & East Antarctic Skirting events.

Skirting events also last slightly longer than their non-skirting counterparts and have increased in duration since 1992 (not shown). On average they typically last 3.33 days (~80 h) in West Antarctica and 2.79 days (~67 h) in East Antarctica. For non-

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skirting events, with the exception of Ellsworth Land at 2.81 days, each region averages less than 2.60 days (~62 h) per event. A longer average duration also means fewer two-day skirting events. Two-day events comprise 55% of the total CMMTs over Antarctica while only accounting for 48% of skirting events.

Many of the monthly and seasonal patterns addressed in Sect. 4.1 are equally representative of skirting events. Skirting CMMTs are most active in austral winter while austral summer only accounts for 14% of these events. As noted previously (Fig. 7), there are two peaks of increased activity over winter and spring. While skirting events and all of Antarctica have peaks in October and November, the peak in late austral fall and early winter shifts from May–Jul to Jun–Aug.

4.3 Regional Analyses

The seven regions are individually examined to locate where non-skirting events are more common. Despite West Antarctica's shorter coastline, Marie Byrd Land and Ellsworth Land are hit by 40% of the total non-skirting CMMTs. Of that 40%, roughly two-thirds make landfall over Ellsworth Land. In East Antarctica, a majority of the events occur in either Queen Maud Land or Enderby Land, with very few making landfall in the other three regions. No more than twelve non-skirting CMMTs make landfall in a given year for any region.

In relatively inactive regions like Queen Mary Coast, Wilkes Land, or Victoria Land, events are often only two days long. Queen Mary Coast, in particular, has the shortest average duration of 2.40 days. The duration of CMMTs over Marie Byrd Land and Ellsworth Land average 2.70 days compared to 2.53 days over East Antarctica. However, a shorter average duration doesn't necessarily imply a higher frequency. Of the 362 months analyzed, there is a 76% chance that a single region will have zero CMMTs in a given month. The likelihood of a zero-event month decreases to 58% in Ellsworth Land and increases to 88% in Victoria Land.

When comparing the seasonal variability for the individual regions, many of them do not follow the findings listed above for skirting events and Antarctica. In Marie Byrd Land, CMMTs are more commonly found in January–June, while Ellsworth Land exhibits more activity in austral fall and winter. Queen Maud Land has two peaks in activity, just like those found in skirting events, but are located in austral spring and fall rather than the winter, which is the least active season for this region. Enderby Land has over 37% of its events in austral summer. Queen Mary Coast has stronger periods of activity in June and July, but also has a higher percentage of CMMTs falling in austral spring (27%) and summer (23%). Wilkes Land, despite having a limited number of events, is most active in the austral winter (35%) and summer (26%). Austral spring (19%) and fall (20%) are relatively inactive except for March, which is the third most active month in this region. Victoria Land has 31% of CMMTs making landfall in austral summer. Similar to the results of Marie Byrd Land, Victoria Land has a major decrease in activity from June–August. Only seven (15%) non-skirting events are recorded in austral winter.

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5 Discussion

The compilation of these data provides the Antarctic community with access to a comprehensive 30-year satellite-derived CMMT dataset that addresses the lack of infrared data over the continent. By manually tracking these patterns across the seven different regions — both non-skirting and skirting alike — successes and caveats are identified and addressed below.

One of the largest obstacles to this dataset is human subjectivity when identifying CMMTs. Biases are bound to happen whenever humans are involved, especially in situations where discrepancies between satellites lead to differing cloud top temperatures for the same cloud mass. Given the large spatial scale of this study, any minor discrepancies in the satellite data can certainly increase the difficulty and time spent reviewing a specific event, but minimally impact the ability to track CMMTs over long periods of time. Additionally, water vapor composites could have supplemented the IR data by acting as another method for verifying events. However, the sheer amount of missing data from early in the record and the limited number of satellites capable of detecting wavelengths in the water vapor window would lead to further complications in viewing the data. Yet, it is important to remember that ML algorithms may also produce different outputs depending on the model used, the training data, and its parameterization. One of the greater successes of manually tracking CMMTs is the ease of identifying clouds over ice sheets and ice shelves. As noted in Bromwich et al. (2012), ML algorithms struggle with differentiating between the cold temperatures found on clouds and sheets of ice. Offshore, this may be less of a problem, but for the definition of CMMTs, it is vital for ML algorithms to correctly identify these differences upon making landfall.

Choosing to categorize skirting events into two broad areas also may have artificially lowered the count of CMMTs in regions where skirting events begin. In West Antarctica, a majority of its skirting events begin in Marie Byrd Land before propagating eastward into Ellsworth Land. Should the system meet all of the CMMT criteria, the skirting event would be documented in the WAS section, rather than Marie Byrd Land or Ellsworth Land. Future work could be aimed at developing a better method for counting each individual region of a skirting event. However, such work is nontrivial when considering the synoptic scale lifespan of these events. Attention is needed to prevent CMMTs from being counted more than once when dividing the total number of days between affected regions. The current method of defining a skirting event helps avoid these complications but it is not without its own issues.

6 Data availability

The satellite-based 30-year Antarctic CMMT dataset is publicly available at the Antarctic Meteorological Research and Data Center at the University of Wisconsin-Madison as a comma-separated value file here: https://doi.org/10.48567/6ja1-8681 (Chambers, 2026). Monthly ASCII text files detailing the time and location of the CMMTs listed in the csv files can also be found at the following link: https://doi.org/10.48567/jjkq-qp49 (Chambers et al., 2026). The hourly satellite composites and monthly animations used to compile the datasets are also available at https://doi.org/10.48567/y8as-0m56 in the following

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Preprint. Discussion started: 22 October 2026
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formats: compressed files (*.zip, *.kmz), netcdf (*.nc), movie (*.mp4), McIDAS AREA (*.area), and picture (*.jpg, *.png) (AMRDC, 2022). More monthly videos will be added in the future in an effort to recover missing months.

7 Conclusions

A satellite-based climatological dataset of CMMT events was created spanning November 1992–December 2022 and seven regions across Antarctica. This dataset is one of the first of its kind to forgo the use of reanalyses and ML algorithms in favor of the manual identification of CMMTs. These data will help improve the forecasting capabilities in Antarctica and may lead to safer operating conditions for those who deploy to the continent. They also serve as another way to verify the atmospheric state over the Southern Ocean and Antarctica. The application of criteria such as cold cloud top temperatures, significant penetration inland, and a duration of more than two days are necessary to identify the time and location of Antarctic CMMTs. The precision of these results is verified by researchers conducting practice tests on specific months before reconvening to form a consensus. This ensures that the CMMT's definition remains consistent as new researchers are trained in the future.

Based on the dataset, the number of CMMTs per year has increased over time, coinciding with a decrease in their average duration and an insubstantial decrease in the days affected by CMMTs each year. Skirting events in austral winter are the most common type of CMMT over Antarctica. Non-skirting events primarily made landfall in Ellsworth Land and Queen Maud Land, followed by Enderby Land and Marie Byrd Land.

Future research at AMRDC will continue to compare this physical dataset against various tracking algorithms and diagnostic variables within reanalyses. By ensuring that the time and space matchup between physical and theoretical spaces, we can ensure that major findings in these models are realistic and representative of Antarctica.

Author contributions

JMC was responsible for curating the dataset, the visualization and analysis of the data, and a majority of the writing process. MAL formulated the research question of this paper, developed some of the early data programs to create and maintain the composites, and supervised JMC through the entire research process along with acquiring the funding necessary to conduct this investigation. HZ co-advised JMC and helped revise and edit the manuscript. DEM has continuously developed and refined the data programs and services used to create and maintain the satellite composites. DEM, SO, and TZ provided many edits and suggestions during the writing process that helped improve the overall flow of the manuscript.

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LMK provided assistance in the preliminary stages of the investigation and gave JMC insight on possible connections between CMMTs and long-term temporal patterns in the Southern Hemisphere.

Competing interests

The authors declare that they have no conflict of interest.

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