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RESEARCH

Rare snowfall in Southern Namibia: synoptic dynamics of cold-air intrusion and climate hazard processes in arid regions

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Abstract

Namibia, a predominantly hot and arid country, rarely experiences snowfall, which is generally restricted to elevated southern regions during winter. On 5 August 2025, light snowfall and sleet were reported near Aus, representing a rare occurrence of wintertime frozen precipitation associated with atmospheric variability in a subtropical dryland environment. This study investigates the synoptic and thermodynamic conditions associated with the event using ERA5 and documentary evidence from media reports and eyewitness accounts, while acknowledging the absence of official meteorological observations at Aus and the limitations in direct snowfall verification. The analysis identifies a short-lived cold-air intrusion, with 850 hPa temperatures approximately 1.5 K (kelvin) below the 1979–2024 winter climatological mean, representing a notable but not extreme cold anomaly rather than an absolute temperature value. Synoptic analysis indicates that the event occurred within a northward-amplified upper-tropospheric trough associated with negative 500 hPa geopotential height anomalies and enhanced cyclonic circulation over southwestern Africa. The interaction between the amplified trough and a subtropical jet stream exceeding 60 m s^{-1} contributed to a dynamically favourable environment for large-scale ascent. At lower levels, a strengthened meridional pressure gradient and persistent southerly wind anomalies indicate a deep cold-air intrusion extending through much of the troposphere, consistent with transport of cooler air from higher southern latitudes rather than confirmed Antarctic-origin air. Although mid-level humidity anomalies were modest, transient moisture availability combined with dynamically induced ascent and local orographic effects over elevated terrain likely supported the development of frozen precipitation. The results suggest that snowfall in southern Namibia can occur when moderate cold anomalies, limited moisture availability, and organized synoptic-scale circulation patterns coincide, without requiring record-breaking thermodynamic conditions. However, uncertainties remain regarding the relative contributions of moisture transport, terrain-induced effects, and precipitation microphysical processes because of limited observational coverage and the spatial resolution of reanalysis datasets. This case provides a diagnostic assessment of a rare cold-season precipitation event and demonstrates how naturally occurring atmospheric circulation variability can occasionally produce frozen precipitation in climatologically warm and arid environments.

1 Introduction

Climate change is influencing large-scale circulation patterns and the frequency of extreme weather events, including heatwaves, floods, and episodic cold-air outbreaks (Clarke et al. 2022; Beniston et al. 2007; Olaoluwa et al. 2022). While much attention has focused on warming and drought, regions with typically arid climates can occasionally experience unusual cold-weather phenomena, highlighting the complexity of climate variability and extremes (Ryti et al. 2016; He et al. 2023; Gao et al. 2024). Understanding these rare events is critical for improving forecasting, climate modelling, and regional preparedness (Sippel et al. 2024; Camps-Valls et al. 2025; Peings et al. 2012;

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Pagani et al. 2017). In addition, emerging research suggests that climate change may influence the meridional structure and persistence of mid-latitude circulation systems, potentially modifying the behaviour of jet streams and cold-air intrusions that affect subtropical regions. Nevertheless, assessing whether climate change has altered the frequency, intensity, or spatial characteristics of such cold-air intrusions requires dedicated attribution studies, long-term climatological analyses, and climate model assessments, which are beyond the scope of the present work. Instead, this study focuses on the synoptic-scale atmospheric processes and thermodynamic conditions responsible for a single rare snowfall event. Namibia provides an illustrative example of climate vulnerability in dryland subtropical regions, where rising temperatures and rainfall variability affect water security, agriculture, and livelihoods. Rising temperatures, reduced and variable rainfall, and frequent droughts pose a significant threat to water security, agriculture, and livelihoods, particularly in areas where poverty and inequality already exist. These climate-related pressures increase societal sensitivity not only to heat and drought but also to atypical cold-season extremes that fall outside normal adaptive experience. Namibia, located in southwestern Africa, is predominantly hot and dry, with minimal rainfall and frequent droughts. Winters (June–August) are generally cool and dry, while the rainy seasons occur from September to November and again from February to April (Lendelvo et al. 2018; Wyss et al. 2022; Angula and Kaundjua 2016; Kgabi et al. 2016). Namibia's climate is predominantly arid and subtropical, with low and highly variable rainfall and generally high temperatures across most of the country. These climatic conditions make snowfall an exceptionally uncommon phenomenon. Snowfall events are primarily associated with elevated regions, where increased altitude lowers surface temperatures and occasional incursions of cold air masses during winter frontal systems can create conditions suitable for snow formation (Mendelsohn et al. 2002). Recent observations of light snowfall in Namibia during August 2025 further illustrate the rarity of these events and their association with transient cold-weather systems affecting southern Africa (African Farming, 2025). Historical records indicate that strong cold fronts occasionally extend unusually far north from the Southern Ocean, bringing cooler air into the region (Forzini et al. 2025; Andersen et al. 2020; Kgabi et al. 2016). These cold-air intrusions can create conditions conducive to fog formation, a low-lying cloud, particularly along the Namibian coast. These equatorward extensions of mid-latitude systems are dynamically significant because they can transport relatively cold high-latitude air into subtropical regions and occasionally create favourable conditions for rare frozen precipitation events. Although the broader influence of climate change on such circulation patterns remains an important research question, understanding the atmospheric mechanisms responsible for individual events provides a necessary foundation for future climatological assessments. Such equatorward extensions of mid-latitude systems are dynamically significant, as projected changes in Southern Hemisphere circulation could influence their frequency or spatial reach under continued global warming. However, snowfall in Namibia requires a precise combination of synoptic-scale dynamics, cold-air advection, and localized moisture availability. Although snow accumulation is typically light and short-lived, rare events, such as the early August 2025 snowfall around Aus, demonstrate that these meteorological conditions can occasionally align to produce this exceptional phenomenon.The early August 2025 event provides a valuable case study for examining the atmospheric processes associated with rare snowfall in an arid subtropical environment. Light snow and sleet were reported in the media near Aus, southern Namibia, during the event period (African Farming, 2025). The event occurred during a short-lived cold spell characterized by below-average winter temperatures. Using ERA5 reanalysis data, this study investigates the associated synoptic circulation, thermodynamic structure, and moisture conditions to identify the atmospheric mechanisms that contributed to this rare frozen precipitation event. Understanding these processes provides further insight into the occurrence of wintertime cold-air intrusions and rare precipitation events in climatologically warm and dry regions. Rather than attributing this event to climate change, this study investigates the synoptic circulation, thermodynamic structure, moisture conditions, and vertical atmospheric processes that enabled snowfall in an otherwise arid subtropical environment. Analysing such rare extremes within a climate change context is important for assessing how variability and long-term trends interact to shape emerging risk profiles in arid southern Africa. This study examines the synoptic and surface temperature conditions that contributed to the event, utilizing reanalysis data and observational records to identify the key atmospheric drivers responsible for this rare phenomenon. Understanding these events contributes to a better grasp of wintertime cold-air intrusions and rare precipitation occurrences in arid southern African regions.

2 Data and methods

2.1 Study area

Namibia is located in southwestern Africa between approximately 17°S and 29°S and 11°E and 25°E (Fig. 1) and is

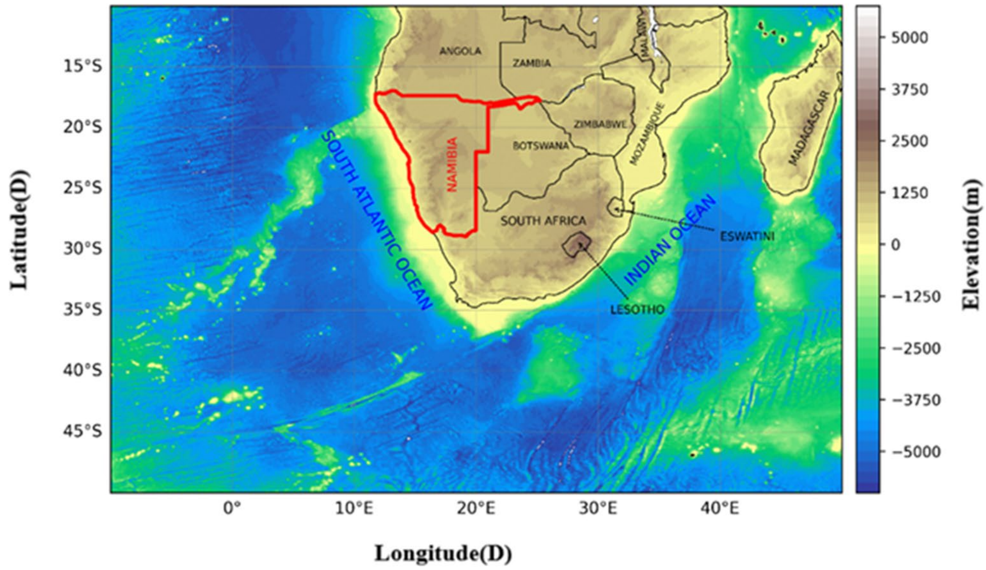

Fig. 1 Topography of southern Africa showing the study region. Shading represents elevation (m), and the red outline indicates the Namibia mask used for spatial averaging

characterized by a predominantly arid to semi-arid climate, with low and highly variable annual rainfall and generally high temperatures (Kgabi et al. 2016; Mendelsohn et al. 2002). The study focuses on southern Namibia, including the Aus region and the Aus Mountains, where elevations exceed 1,000 m above sea level. Winters (June–August) are typically dry and cool, with pronounced diurnal temperature variations. The regional climate is controlled by the interaction of subtropical high-pressure systems, mid-latitude westerlies, and complex topography, which occasionally allows cold-air intrusions into southern Namibia. During these events, temperatures over elevated terrain may fall below freezing, creating conditions favourable for snowfall (Mendelsohn et al. 2002).

2.2 Data

This study investigates the synoptic and thermodynamic conditions associated with the rare snowfall event over southern Namibia on 5 August 2025 using ERA5 reanalysis data. The analysis domain covers southern Africa (10°W–50°E, 50°S–10°S), with regional averages calculated over Namibia using a geographic mask derived from national boundaries. All spatial averaging was performed using cosine latitude weighting to account for variations in grid-cell area. Monthly mean ERA5 pressure-level fields for June–August (JJA) from 1979 to 2024 were used to establish the climatological reference period. Event-scale evolution was analysed using 6-hourly ERA5 pressure-level and surface fields for 1–10 August 2025. The variables analysed include 500-hPa geopotential height, 850-hPa air temperature and relative humidity, zonal and meridional wind components at 200, 500, and 850 hPa, 2-m air temperature, mean sea-level pressure, vertical velocity, and potential vorticity. Snow-depth data from MERRA-2 were used only for climatological comparison. Anomaly and percentile analyses were calculated relative to the ERA5 JJA climatology (1979–2024), while snow comparisons were based on the 1991–2020 reference period.

2.3 Methodology

The methodological framework combines synoptic analysis with anomaly-based and percentile diagnostics to evaluate the dynamical and thermodynamic characteristics of the August 2025 snowfall event. Temperature anomalies and percentile rankings were calculated relative to the ERA5 JJA climatology (1979–2024) to assess the rarity of the observed atmospheric conditions.

Synoptic evolution was examined using circulation and thermodynamic diagnostics, including geopotential height, wind anomalies, potential vorticity, vertical velocity, and humidity fields. These diagnostics were used to identify upper-level trough development, cyclonic circulation anomalies, cold-air intrusions, vertical motion, and moisture availability associated with the event. The upper-level dynamical structure was assessed through the relationship between the 200-hPa jet stream and the 500-hPa trough configuration. Relative vorticity patterns were evaluated qualitatively, while explicit vorticity-advection and moisture transport calculations were not performed.

The daily mean 2-m air temperature was calculated from 6-hourly values as

$$T_{mean} = \frac{1}{n}\sum_{i=1}^{n} T_{2m,\,i} \tag{1}$$

where $T_{2m,\,i}$ represents 6-hourly temperature values and $n=4$ per day. The daily minimum temperature was defined as

$$T_{min} = \min\left(T_{2m,i}\right) \tag{2}$$

Area-averaged values over Namibia were computed using cosine latitude weighting,

$$\langle X \rangle = \frac{\sum_i X_i \ \cos\left(\varphi_i\right)}{\sum_i \ \cos\left(\varphi_i\right)} \tag{3}$$

where φ_i is latitude.

A JJA climatology for 1979–2024 was calculated as:

$$\bar{X}_{JJA} = \frac{1}{N}\sum_{i=1}^{n} X_i \tag{4}$$

where N denotes the total number of JJA months. Anomalies were defined as deviations from this climatology:

$$\mathrm{X}' = \mathrm{X} - \bar{X}_{JJA} \tag{5}$$

Wind speed at 200 hPa was derived from zonal and meridional components:

$$V = \sqrt{u^2 + v^2} \tag{6}$$

To characterize cold-season background conditions, composite anomaly fields were constructed by selecting JJA months during 1979–2024 in which Namibia-averaged 850 hPa temperature anomalies were below a predefined negative threshold. The composite anomaly was computed as

$$\mathrm{X}'_{comp} = \frac{1}{M}\sum_{j=1}^{M} \mathrm{X}'_{j} \tag{7}$$

where M is the number of selected cold months.

Synoptic diagnostics were based on anomaly patterns of geopotential height, wind vectors, and dynamically relevant fields obtained directly from reanalysis datasets. Relative vorticity at 500 hPa and upper-level potential vorticity fields were analyzed from the reanalysis products to identify cyclonic anomalies, trough amplification, and equatorward PV intrusions associated with the cold outbreak. Spatial gradients in the vorticity and height fields were examined qualitatively to characterize regions of enhanced cyclonic development potential; no explicit vorticity-advection calculations were performed. The upper-level dynamical environment was assessed from the spatial configuration of the 200 hPa jet relative to the 500 hPa trough axis, including jet curvature and the location of jet entrance/exit regions. Vertical pressure velocity at 500 hPa (omega) was analyzed directly from ERA5 fields to diagnose large-scale ascent and subsidence associated with the frontal system. Negative omega values were interpreted as upward motion supporting cloud formation and precipitation, whereas positive values indicated subsidence. To quantify the spatial magnitude of anomaly fields, an area-weighted root-mean-square metric was computed as

$$RMS = \sqrt{\frac{\sum_i \left(\mathrm{X}'_{i}\right)^2 \mathrm{w}_i}{\sum_i w_i}} \tag{8}$$

where $w_i = \cos\left(\varphi_i\right)$ represents latitude weighting.

Event rarity was evaluated using percentile ranking within the 1979–2024 JJA distribution:

$$P_X = 100 \times \frac{\#(\mathrm{X}'_{i} < \mathrm{X}'_{event})}{N} \tag{9}$$

where N is the total number of historical JJA months. In this expression, X′ represents the Namibia-area-averaged anomaly of the relevant atmospheric variable. The symbol # denotes the number of historical JJA months satisfying the specified condition.

Snowfall conditions were further contextualized using MERRA-2 monthly snow depth data and ERA5 snow cover fields. The August 2025 monthly mean snow depth was compared with the 1991–2020 climatology to identify positive snow anomalies associated with the event.

This methodological framework integrates surface thermodynamic diagnostics, anomaly analysis relative to long-term climatology, composite cold-season conditions, and synoptic-scale circulation assessment to characterize the dynamical and thermodynamic environment of the rare August 2025 snowfall event in southern Namibia.

3 Results and discussion

3.1 Historical variability of winter anomalies

Figure 2 presents the JJA monthly anomalies of 850 hPa temperature and 500 hPa geopotential height over southern Namibia for 1979–2024. The time series reveals pronounced

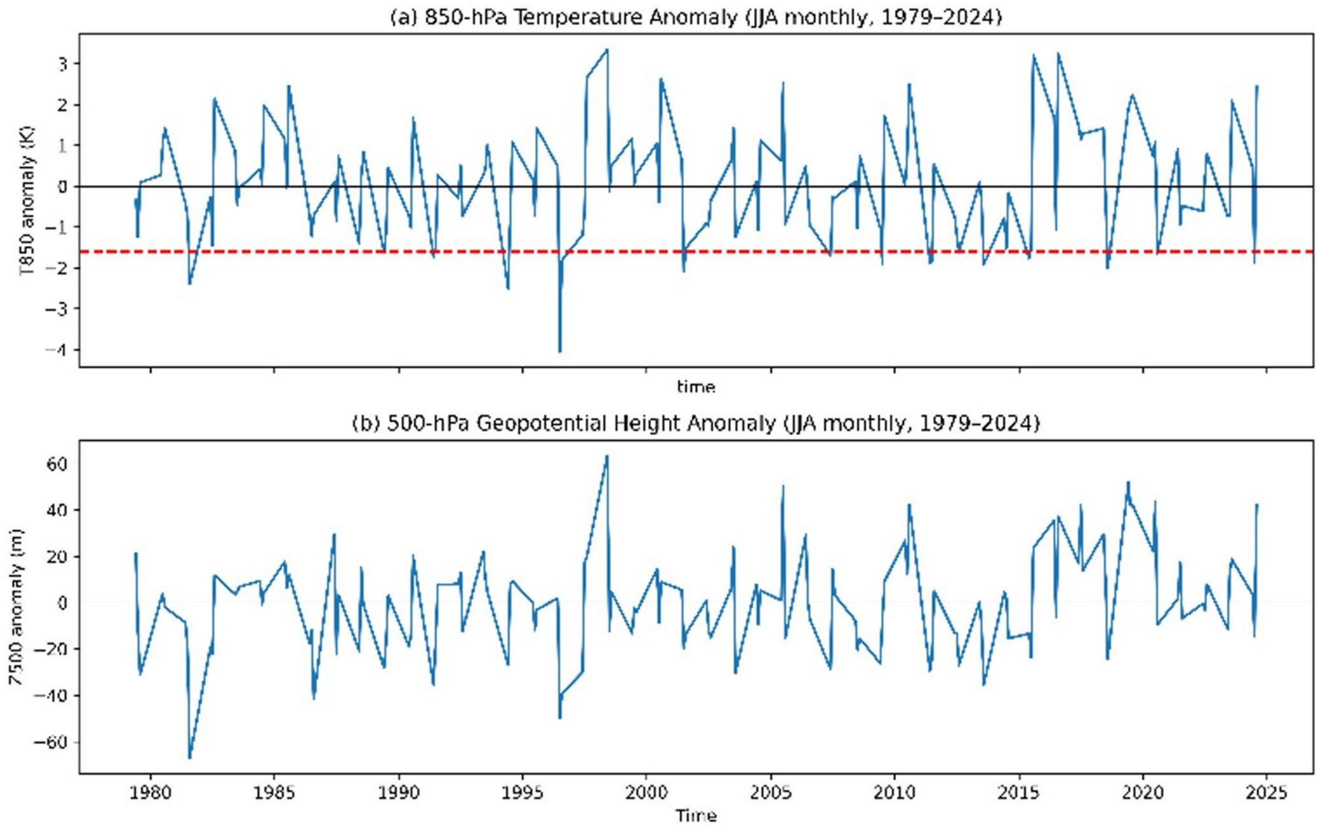

Fig. 2 JJA monthly anomalies over southern Namibia during 1979–2024: (**a**) 850 hPa temperature anomalies (K), with the −1.6 K cold-event threshold indicated by the red dashed line, and (**b**) 500 hPa geopotential height anomalies (m)

interannual variability in winter thermodynamic and dynamical conditions. Several cold-season months exhibit 850 hPa temperature anomalies below −2 K, indicating that episodic cold-air intrusions are a recurring feature of southern African winters. The August 2025 anomaly (−1.54 K), evaluated relative to this historical distribution, falls within the lower decile of the record but does not represent an unprecedented cold excursion. This indicates that while the event was notably cold, its thermodynamic intensity alone was not exceptional in a long-term climatological context. Similarly, Z500 anomalies display substantial variability, with multiple winters characterized by strong negative height departures associated with amplified trough activity. The 2025 event coincided with a period of markedly negative mid-tropospheric height anomalies, consistent with enhanced synoptic-scale disturbance. Together, these results suggest that the rarity of the August 2025 snowfall was not solely due to extreme cold, but rather to the combined dynamical and thermodynamic configuration examined in subsequent sections.

3.2 Evidence of anomalous snowfall in August 2025

Figure 3 presents the snow conditions associated with the August 2025 event using MERRA-2 snow-depth data and ERA5 snow-cover fields. Because the snowfall occurred during a short-lived event on 5 August 2025, monthly mean snow-depth fields are interpreted only as a regional climatological context rather than as a direct measure of event-day snowfall accumulation. Panel (a) shows the August 2025 mean snow depth from MERRA-2, indicating enhanced snow presence over parts of southern Africa, with localized maxima concentrated over elevated terrain. In comparison, the August climatological mean for 1991–2020 (Fig. 3b) shows much more limited and shallow snow coverage, consistent with the generally dry winter conditions of the region.

Panel (c) presents ERA5 snow-cover conditions on 5 August 2025, corresponding to the reported snowfall period. The snow-cover signal is spatially limited and mainly confined to mountainous areas, consistent with the localized nature of snowfall in southern Namibia. Together, these datasets indicate an anomalous snow event relative to typical August conditions and highlight that the event was localized and short-lived. The available reanalysis products indicate atmospheric conditions consistent with the reported snowfall event; however, the exact snowfall amount and duration cannot be quantified because direct high-resolution snow observations were unavailable.

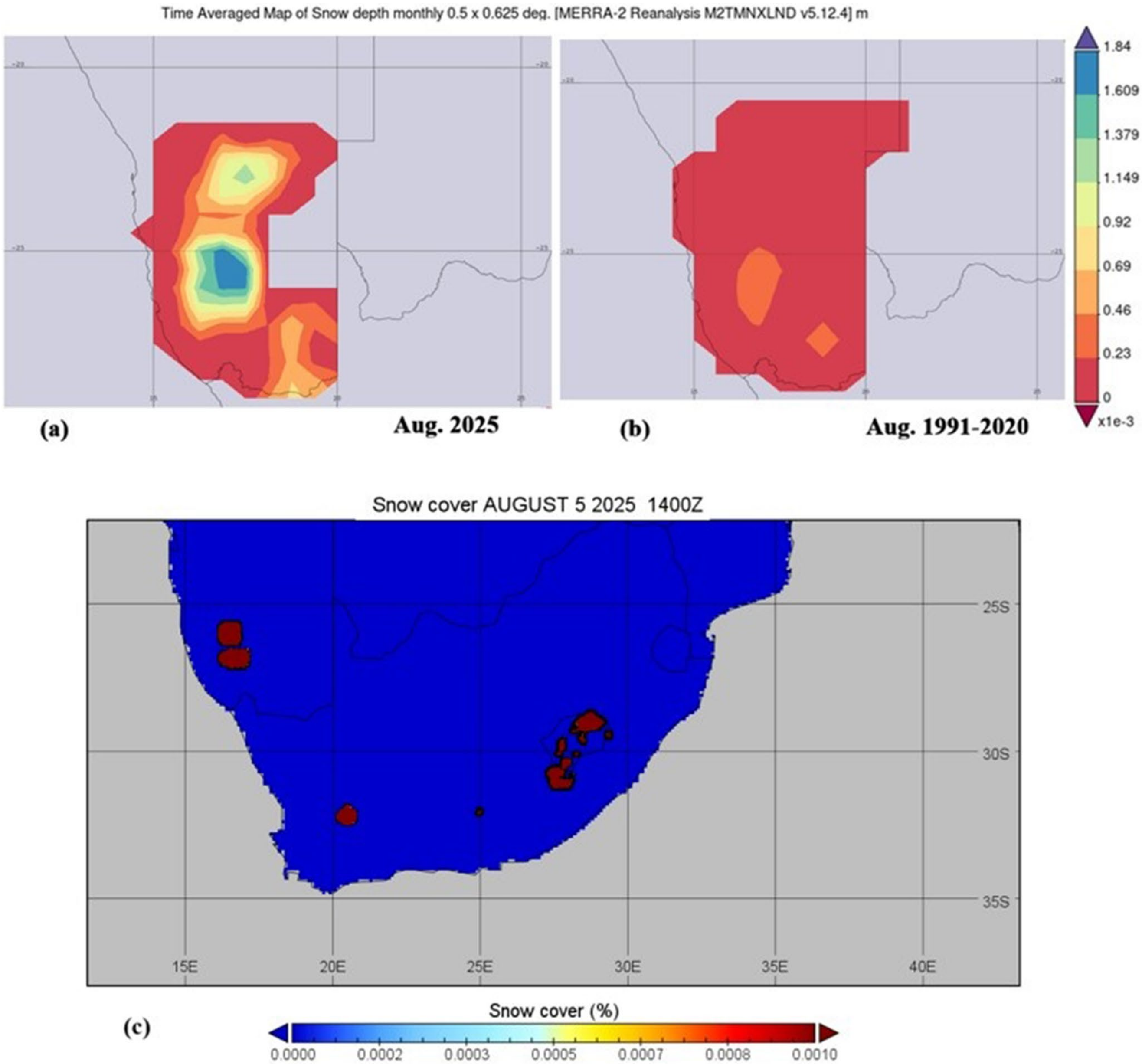

Fig. 3 Snow conditions over southern Namibia: (**a**) MERRA-2 monthly mean snow depth for August 2025, (**b**) August climatological mean snow depth (1991–2020), and (**c**) ERA5 snow cover on 5 August 2025

3.3 Surface temperature evolution during August 2025

Figure 4 illustrates the area-averaged 2-m air temperature evolution over Namibia during August 2025. The daily mean 2-m air temperature (Fig. 4a) indicates a clear cooling phase beginning around 4–5 August, followed by a pronounced decrease between 6 and 7 August. The lowest daily mean temperature reached approximately 10.9 °C, representing a short-lived negative temperature anomaly relative to typical winter conditions.

The daily minimum 2-m air temperature (Fig. 4b) shows a more pronounced decline, reaching approximately 3.5 °C on 7 August. This minimum occurred during the period of observed snowfall in elevated regions of southern Namibia. Although these temperatures do not represent extreme cold at the national scale, they are sufficiently low over high-elevation areas, such as Aus and the surrounding mountains, to support frozen precipitation when combined with adequate atmospheric moisture and synoptic-scale ascent.

Following 7 August, both the daily mean and daily minimum 2-m air temperatures gradually increased toward seasonal values, indicating the retreat of the cold air mass. The temperature evolution suggests that

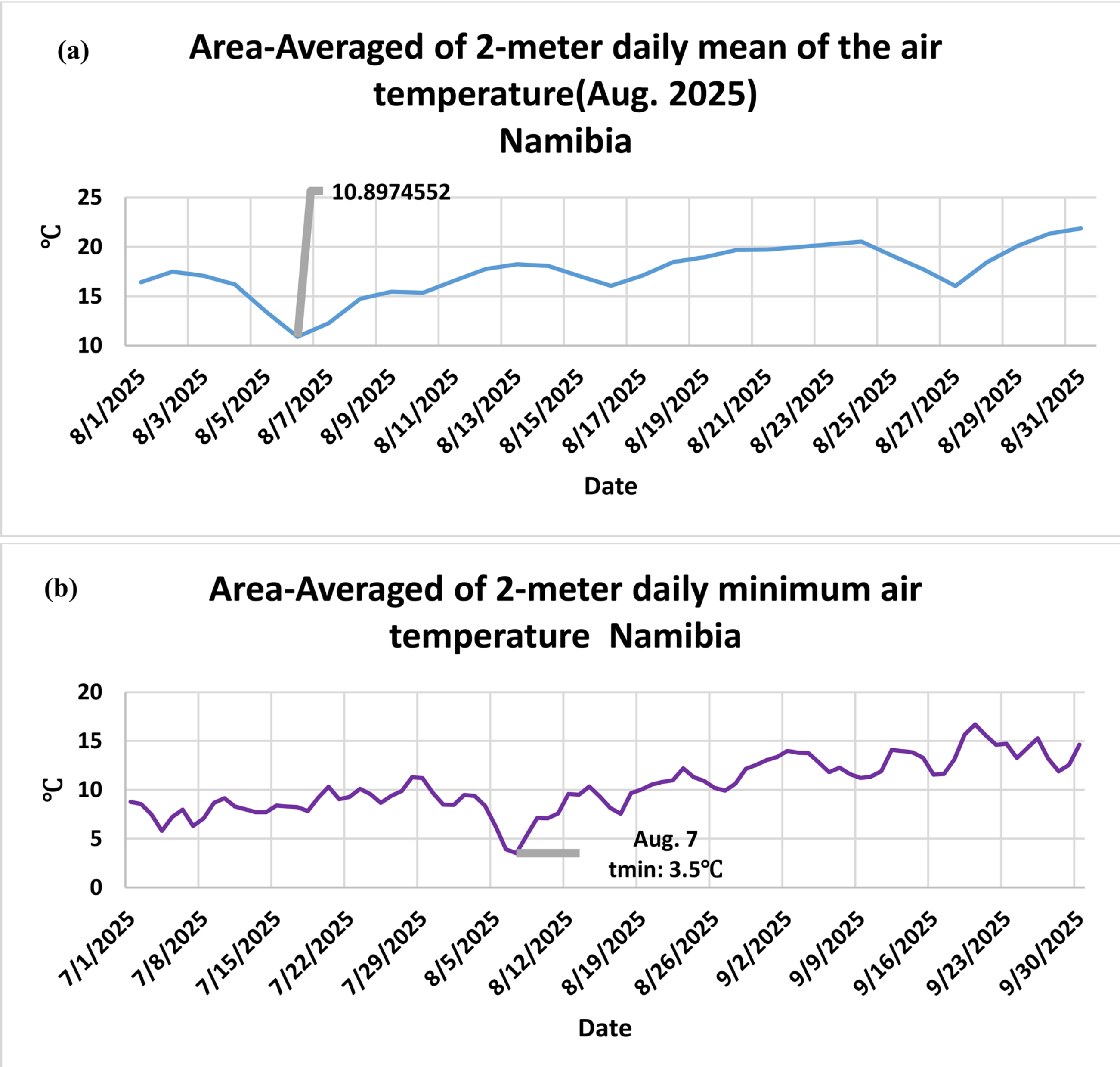

Fig. 4 Area-averaged 2-m air temperature over Namibia during August 2025: (**a**) daily mean 2-m air temperature and (**b**) daily minimum 2-m air temperature

the snowfall event was associated with a brief but well-defined cold-air intrusion rather than a persistent or record-breaking cold spell.

3.4 Spatial structure of daily minimum 2-m air temperature

Figure 5 presents the spatial distribution of daily minimum 2-m air temperature over southern Africa on 5 August 2025, together with the August climatological mean for the 1991–2020 reference period. On 5 August (Fig. 5a), minimum temperatures across southern Namibia generally ranged between 4 and 7 °C; however, these regional values do not fully represent the conditions at the snowfall location. The reported snowfall occurred in the elevated Aus region, where the spatial temperature field indicates substantially colder conditions, with daily minimum 2-m air temperatures of approximately 1–3 °C. These lower temperatures reflect the influence of elevation and local topography, which are important factors controlling near-surface thermal conditions. Although sub-zero temperatures were not widespread across Namibia, the colder conditions over high-elevation

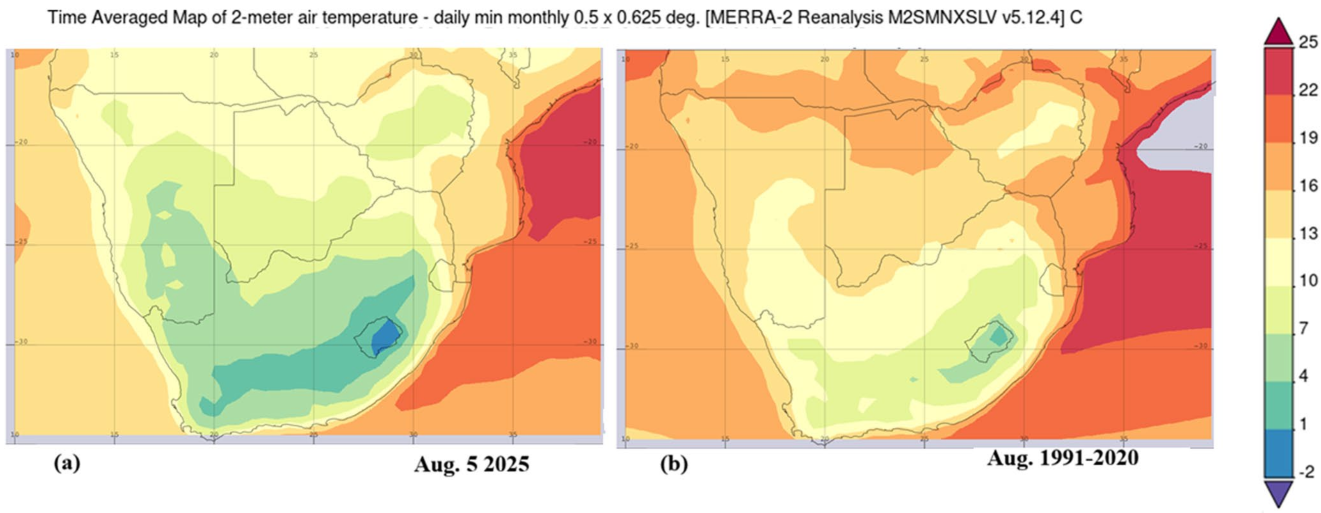

Fig. 5 Daily minimum 2-m air temperature (°C) over southern Africa on 5 August 2025: (**a**) observed conditions and (**b**) August climatological mean (1991–2020)

terrain, combined with sufficient moisture and synoptic-scale ascent, provided a favourable environment for frozen precipitation.

The August climatological mean (Fig. 5b) shows typical daily minimum 2-m air temperatures of approximately 7–10 °C over the Aus region and surrounding southwestern Namibia. Comparison with the event conditions indicates that temperatures at the snowfall location were several degrees below the climatological average, highlighting the strength of the cold anomaly during the event. While the observed temperatures were not extreme in an absolute sense, the combination of reduced near-surface temperatures, elevated terrain, moisture availability, and dynamical forcing created suitable conditions for snowfall.

This analysis complements the anomaly fields presented in Sect. 3.3 by demonstrating that the snowfall event was associated with both a marked regional cold anomaly and locally favourable thermal conditions at elevated sites such as Aus. The event therefore reflects the interaction between large-scale atmospheric circulation and local topographic effects rather than Namibia-wide temperature conditions alone.

3.5 Surface air temperature anomalies

Figure 6 presents the spatial distribution of surface air temperature anomalies over southern Africa on 5–7 August 2025. On 5 August (Fig. 6a), widespread negative anomalies are evident across Namibia and much of southern Africa relative to the 1991–2020 climatology. Over southern and central Namibia, temperature departures of approximately −2 °C to −4 °C indicate the presence of a well-defined cold winter air mass. This spatial pattern is consistent with a northward-penetrating cold front associated with a mid-latitude trough. In contrast, positive anomalies over the southwest Indian Ocean and parts of southeastern Africa suggest the development of a pronounced meridional temperature gradient. Such a gradient likely enhanced baroclinicity and supported the continued northward progression of the frontal system.

Figure 6b and c show that the cold anomalies persisted on 6–7 August, with locally stronger departures reaching approximately −8 K over southwestern Namibia, particularly across elevated regions near the Aus Mountains. These strongest anomalies were spatially localized, occurring mainly over the higher-elevation terrain of southern Namibia, while weaker negative anomalies extended across a broader surrounding region. These anomalies coincide with the timing of the lowest daily mean (≈10.9 °C) and minimum (≈3.5 °C) temperatures identified in Sect. 3.3. Although the temperature anomalies were not record-breaking, the persistent negative anomalies indicate the occurrence of unusually cool but seasonally typical winter conditions. When combined with available moisture and synoptic-scale ascent over elevated regions such as Aus, these thermodynamic conditions were sufficient to produce light snowfall and sleet. The anomaly patterns therefore suggest that the August 2025 snowfall resulted from a coherent winter cold-air intrusion rather than from an exceptional or unprecedented surface cooling event.

3.6 Synoptic evolution of the cold outbreak

Figure 7 illustrates the synoptic evolution of the August 2025 cold outbreak over southern Africa from 5 to 7 August. The 500 hPa geopotential height fields (Figs. 7a–c) show the development of a well-defined mid-latitude westerly trough extending equatorward from the Southern Ocean toward southern Africa on 5 August. The trough axis was

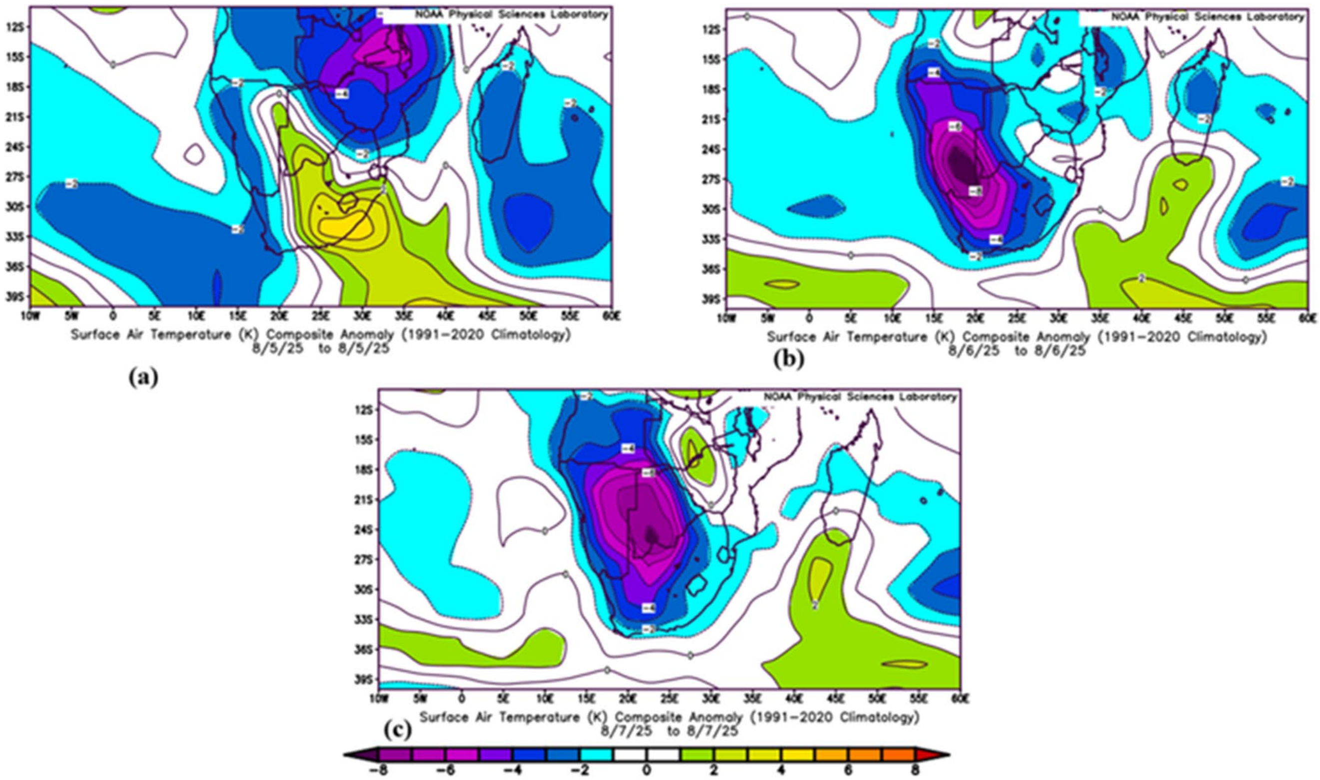

Fig. 6 Surface air temperature anomalies (relative to the 1991–2020 climatology) over southern Africa on (**a**) 5 August, (**b**) 6 August, and (**c**) 7 August 2025

positioned west of Namibia, placing southern Namibia within the dynamically active downstream sector of the system. The corresponding 500 hPa geopotential height anomalies (Figs. 7d–f) indicate negative departures relative to the 1991–2020 climatology, confirming that the trough amplitude was enhanced compared to typical winter conditions. Although not unprecedented in magnitude, the anomaly structure reveals a coherent large-scale disturbance capable of driving meridional cold-air transport into subtropical latitudes. At the surface, mean sea level pressure fields (Figs. 7g–i) show a frontal system crossing southern Namibia on 5 August, followed by the formation and maintenance of a surface low-pressure system. The associated pressure anomalies (Figs. 7j–l) highlight a strengthened meridional pressure gradient between the Southern Ocean and southern Africa. This configuration supported sustained southerly to southwesterly flow behind the front, enabling continued advection of relatively cold air into the region.

By 6–7 August, the upper-level trough evolved into a cut-off low structure, remaining quasi-stationary over southern Africa. The persistence of the upper-level circulation anomaly, together with the maintained surface pressure gradient, prolonged the cold-air intrusion. This vertically coherent structure indicates that the event was dynamically organized rather than a shallow surface cooling episode. Overall, the synoptic evolution demonstrates that the snowfall event was embedded within a classical winter baroclinic disturbance characterized by an amplified mid-tropospheric trough, negative height anomalies, and a coupled surface frontal system. These features collectively provided the dynamical framework necessary to support sustained cold-air advection and subsequent precipitation over southern Namibia.

3.7 Moisture evolution and low-level humidity structure

Figure 8 presents the evolution of 850 hPa relative humidity over southern Africa during 5–7 August 2025. On 5 August (Fig. 8a), relatively high humidity values were present over southern and southwestern Namibia, with local maxima exceeding 70–80%. This increase in low-level humidity coincided with the passage of the upper-level trough and the surface frontal boundary described in Sect. 3.5. The spatial overlap between the cold-air intrusion and enhanced low-level humidity provided a favorable thermodynamic environment for cloud development and transient precipitation.

By 6 August (Fig. 8b), relative humidity decreased substantially over much of southern Namibia, with drier conditions developing behind the frontal system. This post-frontal drying is consistent with the transition toward a more stable air mass following the passage of the disturbance. The reduction in low-level humidity likely contributed

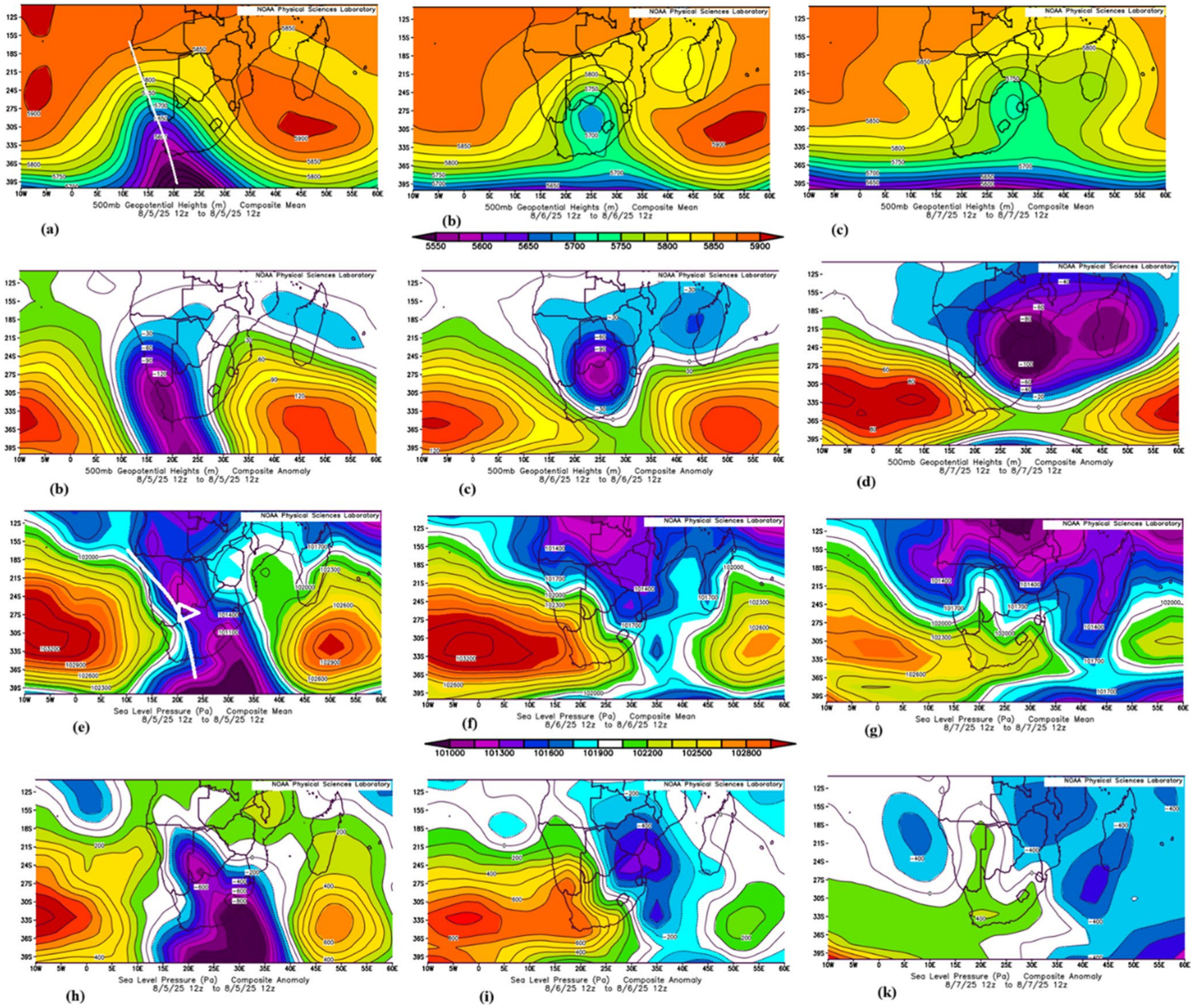

Fig. 7 Synoptic evolution of the August 2025 cold outbreak over southern Africa: 500 hPa geopotential height and anomalies (**a**–**f**) and mean sea-level pressure and anomalies (**g**–**k**) during 5–7 August 2025

to the short duration of the snowfall and sleet occurrence rather than allowing precipitation to persist during the entire cold period. On 7 August (Fig. 8c), further drying occurred across inland Namibia, while relatively higher humidity remained confined to limited regions associated with the residual circulation.

The temporal evolution of relative humidity indicates that the snowfall event occurred during a short interval when sufficiently low temperatures coincided with available atmospheric moisture. However, relative humidity fields alone do not provide information on the origin or transport pathway of the moisture. Detailed moisture diagnostics, such as specific humidity, integrated water vapour transport (IVT), moisture-flux vectors, and trajectory analysis, would be required to quantify the moisture sources and pathways. Domain-averaged humidity anomalies over Namibia were also not exceptionally large compared with climatology, suggesting that the event was not associated with an extreme moisture anomaly. Instead, the occurrence of frozen precipitation likely resulted from the combination of moderate moisture availability, cold temperatures, synoptic-scale ascent, and local terrain effects over elevated southern Namibia.

3.8 Upper-level dynamical forcing and vertical motion

Figure 9 integrates upper-tropospheric potential vorticity (PV) and mid-tropospheric vertical motion to diagnose the dynamical forcing associated with the 5 August 2025

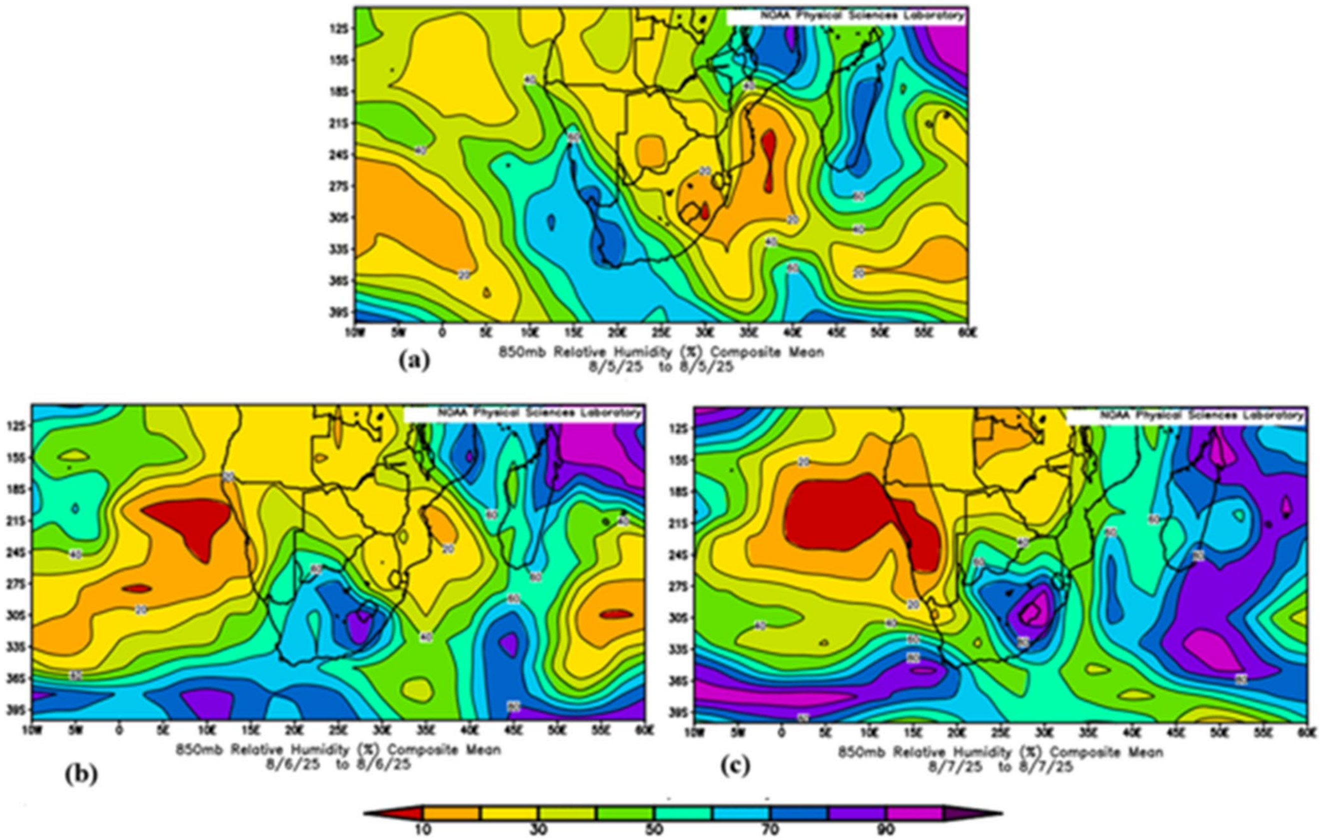

Fig. 8 850-hPa relative humidity (%) over southern Africa on (**a**) 5 August, (**b**) 6 August, and (**c**) 7 August 2025

event. The 300 hPa PV field (Fig. 9a) reveals a pronounced equatorward extension of high-PV air from the Southern Ocean toward southern Africa. This PV streamer marks the intrusion of relatively cold, stratospherically influenced air into subtropical latitudes and is dynamically consistent with the amplified mid-latitude trough described in Sect. 3.6. The downstream flank of the PV tongue was positioned over southwestern Namibia (ranging from 0.6 to a maximum at around −5 PVU) on 5 August, placing the region within a dynamically favourable sector for ascent. The 5 August 2025 PV streamer over southwestern Namibia reached values of around −5 PVU, comparable in magnitude to the strong PV anomalies (>5 PVU in absolute value) reported during the February 2023 cutoff low event and the 21 September 2024 cold outbreak (Fazel-Rastgar et al., 2025; Fazel-Rastgar and Mthembu 2025). However, the August 2025 event was characterized by an equatorward PV intrusion and enhanced ascent downstream of the trough, while the February 2023 and September 2024 events were linked to cutoff low development and stratospheric polar vortex disturbance, respectively.This configuration supports mid-level convergence (Fig. 9b) and upper-level divergence associated with positive omega at 200 hPa (Fig. 9c) downstream of the trough axis and enhances vertical coupling between upper- and lower-tropospheric circulation features.

The 500 hPa vertical pressure velocity field, omega (Fig. 9b), confirms the presence of synoptic-scale ascent ahead of the advancing cold front. Negative omega values over southern Namibia indicate upward motion sufficient to support cloud development and precipitation. In contrast, positive omega values to the west reflect subsidence associated with post-frontal ridging over the South Atlantic. The spatial alignment between the PV streamer aloft and the ascending branch of the omega field demonstrates that the snowfall event was embedded within a dynamically organized baroclinic disturbance. Rather than being driven solely by surface cooling, the event was supported by large-scale vertical motion induced by upper-level dynamical forcing. This vertical coherence between PV structure and ascent was critical in enabling precipitation within an otherwise dry subtropical environment.

3.9 Vorticity structure and jet dynamics

Figure 10 further describes the dynamical environment associated with the snowfall event using 500 hPa relative vorticity and 200 hPa wind fields on 5 August 2025 at 1200

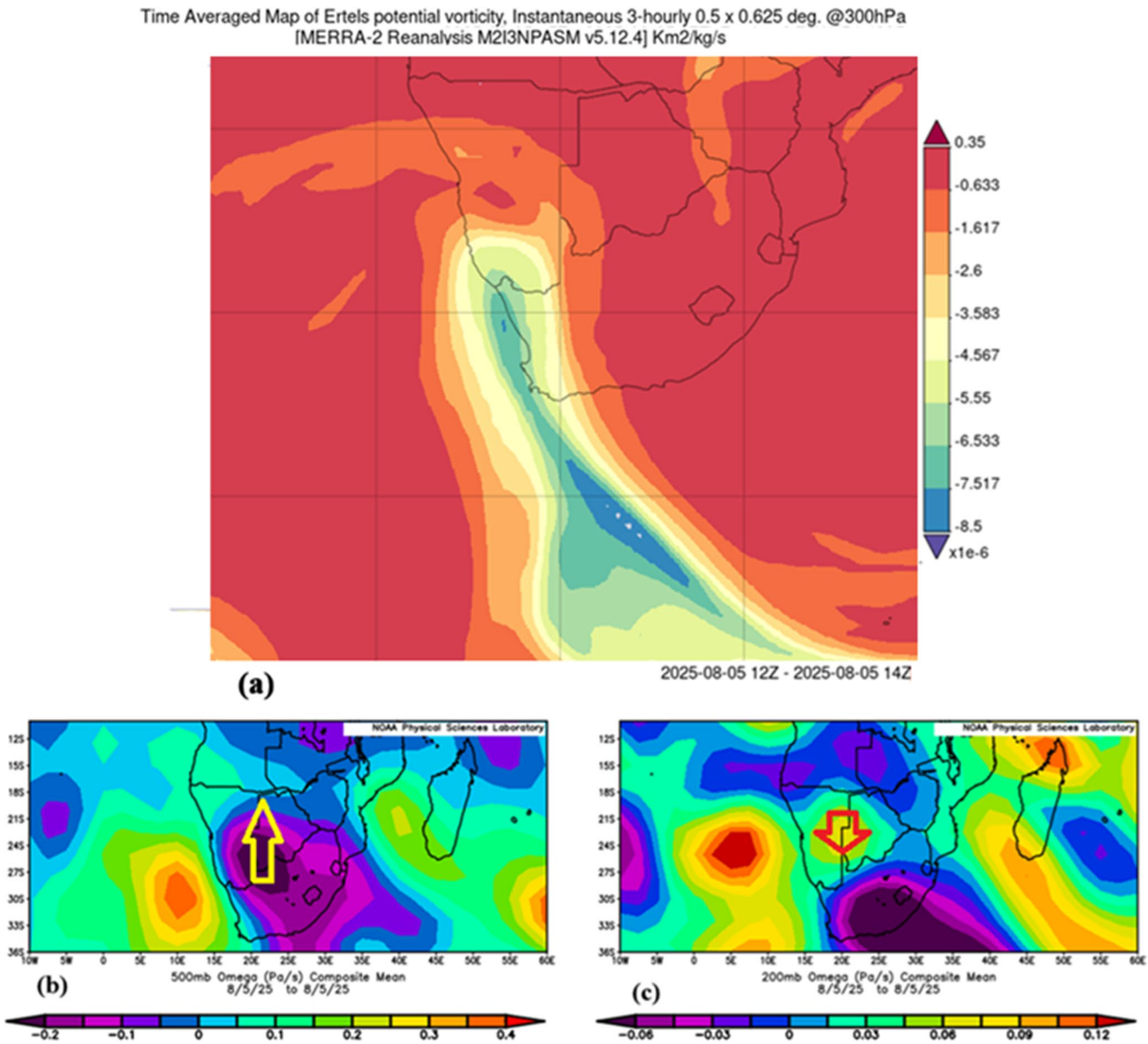

Fig. 9 Upper-level dynamical fields over southern Africa on 5 August 2025: (**a**) 300 hPa potential vorticity, (**b**) 500 hPa potential vorticity, and (**c**) 200 hPa vertical pressure velocity

UTC. The 500 hPa relative vorticity field (Fig. 10a) shows a cyclonic vorticity anomaly west of southern Africa, with values reaching approximately -4×10^{-5} s^{-1}, extending from the southwest Atlantic toward the southern African sector. The elongated northwest–southeast orientation of this feature is consistent with an amplified upper-level trough rather than a closed mid-tropospheric circulation. The strongest vorticity gradients occur along the eastern flank of the trough, indicating a region of enhanced dynamical activity associated with the disturbance.

At 200 hPa (Fig. 10b), the wind field shows a strong subtropical jet stream with wind speeds exceeding 45 m s^{-1} and locally reaching 60 m s^{-1} across the southern African sector. The jet exhibits pronounced cyclonic curvature around the trough axis, indicating strong upper-level flow deformation associated with the developing disturbance. Southern Namibia was located downstream of the trough within a region of enhanced upper-level flow, which is favourable for large-scale ascent when combined with the observed mid-tropospheric forcing.

The alignment between the 500 hPa cyclonic vorticity maximum, the accelerated 200 hPa jet flow, and the regions of ascent identified from the vertical velocity field indicates a dynamically coherent baroclinic system. These features suggest that the August 2025 snowfall event was associated with upper-level trough amplification and jet-related

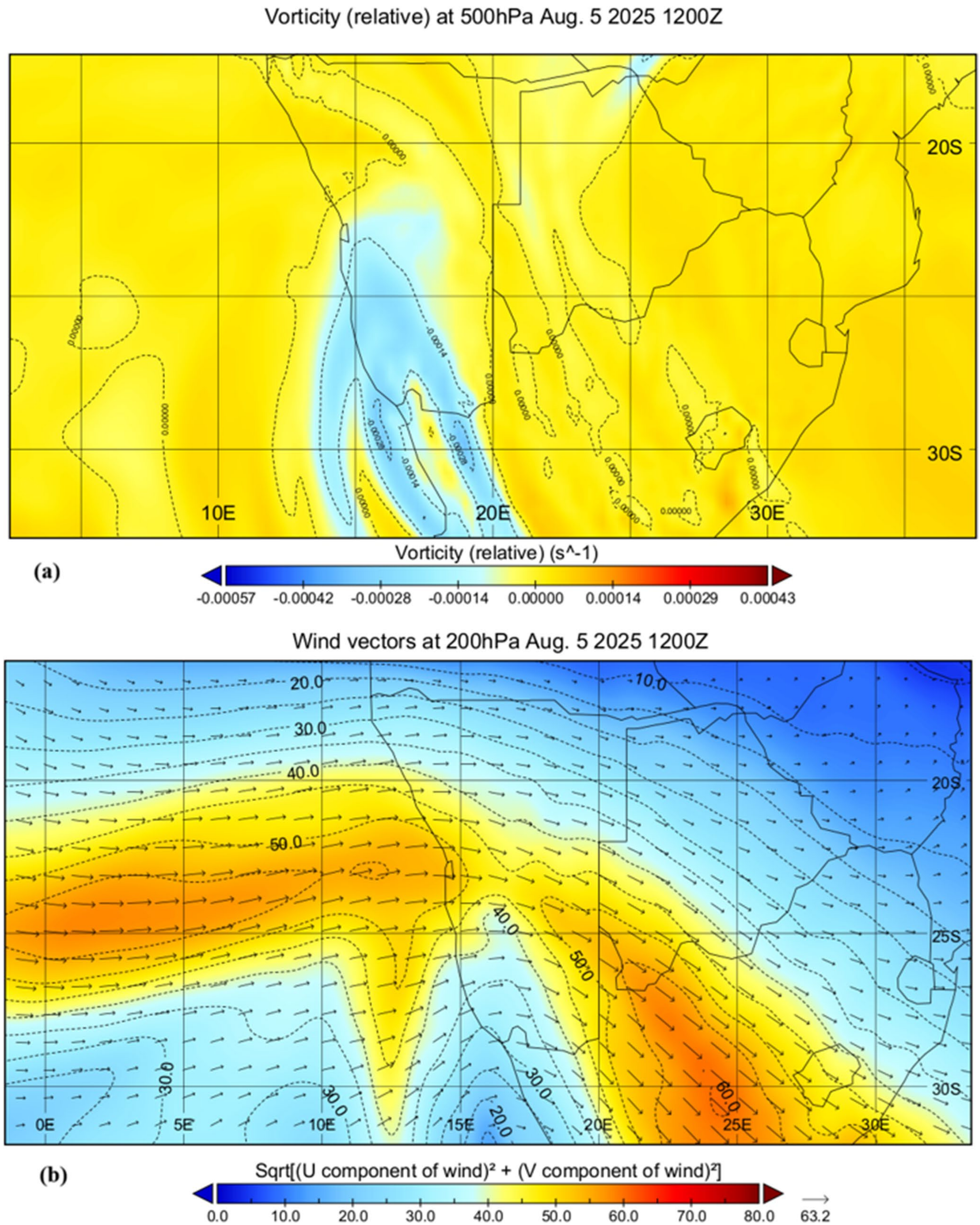

Fig. 10 Dynamical circulation fields over the study area on 5 August 2025 at 1200 UTC: (**a**) 500 hPa relative vorticity and (**b**) 200 hPa wind vectors

dynamical forcing, while local elevation and near-surface thermal conditions influenced the occurrence of frozen precipitation.

3.10 Meridional cold-air transport and polar intrusion

Figure 11 illustrates the anomalous wind structure associated with the cold-air intrusion. Surface wind speed and vector anomalies (Fig. 11a) reveal enhanced southerly to southwesterly flow extending from the Southern Ocean sector toward southern Africa. This pattern indicates that the cooling over Namibia was associated with large-scale meridional air-mass transport rather than localized radiative processes alone. Surface meridional wind anomalies (Fig. 11b) show a coherent south–north transport pathway, supporting the presence of a high-latitude cold-air intrusion affecting southern Namibia.

In the upper troposphere, 200 hPa wind anomalies (Figs. 11c–d) show a northward-displaced and meridionally

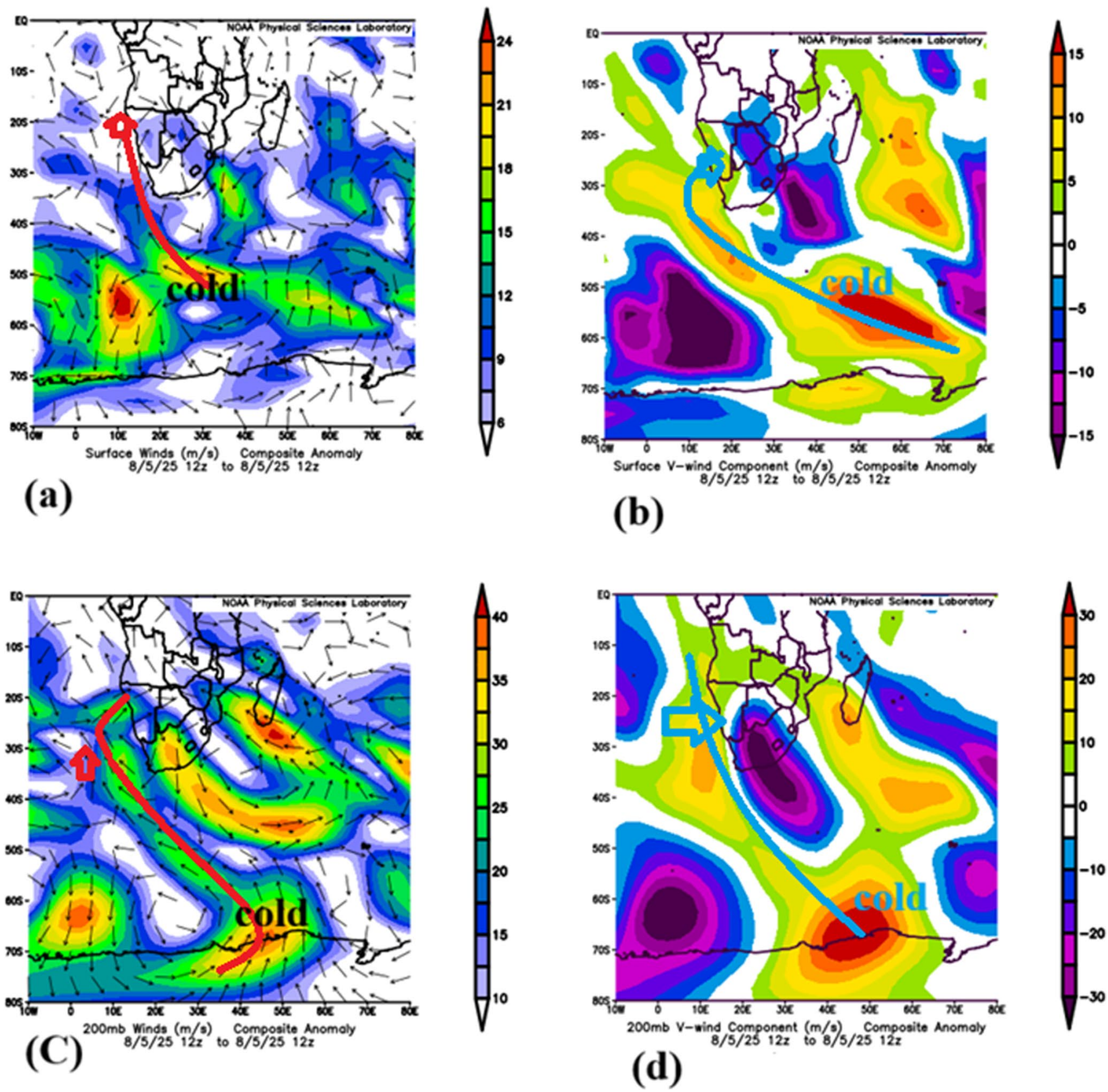

Fig. 11 Surface and upper-level wind anomalies over the study area on 5 August 2025 at 1200 UTC: (**a**–**b**) surface wind speed and vectors, and (**c**–**d**) 200-hPa wind speed and meridional (V-wind) anomalies

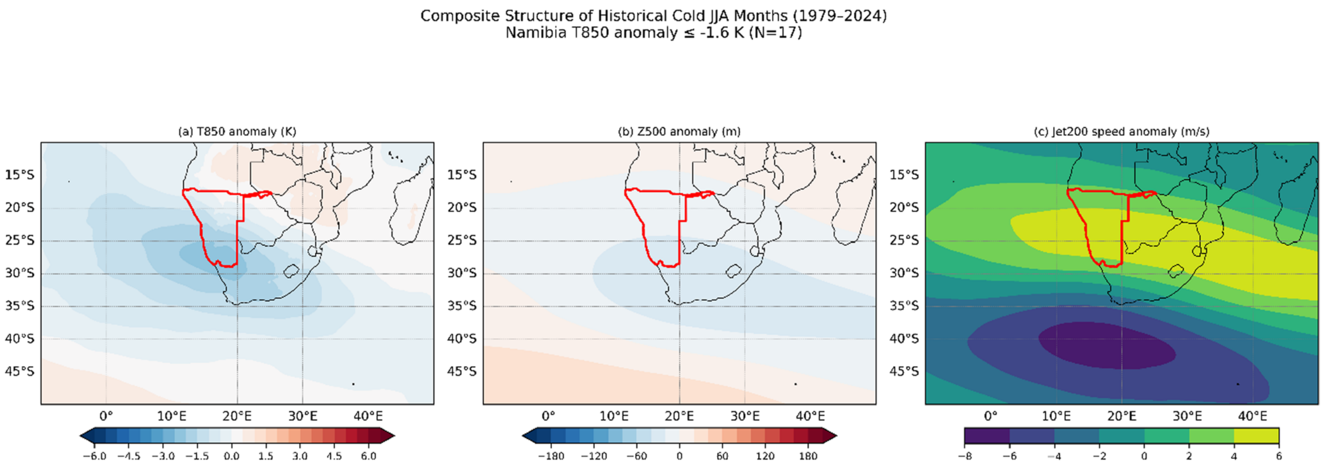

Fig. 12 Composite structure of historical cold JJA months (1979–2024) based on Namibia-area-averaged 850 hPa temperature anomalies ≤ − 1.6 K (N = 17). Panels show **(a)** 850 hPa temperature anomalies, **(b)** 500 hPa geopotential height anomalies, and **(c)** 200 hPa jet-speed anomalies

amplified jet structure. Strong southerly anomalies aloft are broadly consistent with the lower-level circulation, indicating vertical coherence of the cold-air transport through much of the troposphere. Although the precise source region of the air mass cannot be confirmed without backward trajectory analysis, the circulation pattern supports the interpretation of a deep southerly high-latitude cold-air intrusion. As this relatively cold air interacted with topographic uplift and synoptic-scale ascent, temperatures over elevated southern Namibia decreased sufficiently to support transient frozen precipitation. The event therefore reflects the combined influence of sustained meridional cold-air transport, upper-level dynamical forcing, and local terrain effects.

3.11 Composite structure of historical cold JJA months

A composite analysis was performed for JJA months during 1979–2024 in which the Namibia-area-averaged 850 hPa temperature anomaly was below − 1.6 K (17 cases). The composite 850 hPa temperature field shows a coherent region of negative anomalies extending across southern Africa, indicating that cold-season events are associated with broad-scale lower-tropospheric cooling rather than isolated local temperature variations.

Compared with this historical cold composite, the August 2025 event exhibited a similar large-scale circulation pattern, with negative 850 hPa temperature anomalies over southern Namibia and enhanced southerly flow. The magnitude of the 850 hPa temperature anomaly during August 2025 (~ − 1.5 K relative to the 1979–2024 JJA climatology) was comparable to, but slightly weaker than, the threshold used to define the composite events, indicating that the event was cold but not an extreme temperature anomaly.

The corresponding 500 hPa geopotential height composite reveals a pronounced mid-tropospheric trough over southern Africa, demonstrating that historical cold months are associated with amplified westerly wave activity and enhanced meridional flow. The August 2025 circulation also showed a northward-amplified trough and negative geopotential height anomalies, consistent with the composite cold-event pattern. However, the event did not represent an exceptional departure from the historical circulation variability.

The 200 hPa jet composite exhibits enhanced upper-level wind speeds downstream of the trough axis, indicating the importance of upper-level flow organization during cold-season events. Similarly, the August 2025 event was associated with a strengthened subtropical jet exceeding 60 m s^{-1}, suggesting a dynamically favorable configuration comparable to historical cold events.

Overall, the composite analysis demonstrates that the August 2025 snowfall event occurred within a circulation regime consistent with previous cold-season intrusions over southern Africa.

The event was therefore dynamically favorable but not unprecedented, with its uniqueness arising from the coincidence of moderate cold anomalies, transient moisture availability, and suitable conditions for frozen precipitation over elevated terrain Fig. 12.

4 Summary, conclusions, and recommendations

The rare snowfall event in southern Namibia during early August 2025 resulted from the combined influence of below-average winter temperatures, transient moisture availability, elevated terrain, and favorable atmospheric ascent. Surface observations show that daily mean and minimum 2-m air temperatures decreased to approximately 10.9 °C and 3.5 °C, respectively. Although these temperatures were not record-breaking, they provided a suitable thermal environment for frozen precipitation when combined with short-lived moisture availability and elevated terrain near Aus. The event demonstrates that rare snowfall in arid subtropical regions can occur through the interaction of moderate cold anomalies and favorable atmospheric conditions rather than requiring extreme surface cooling alone. Transient increases in low-level relative humidity during the cold-air intrusion further supported snowfall or sleet formation; however, the moisture source and transport pathways remain uncertain because detailed moisture-flux and trajectory analyses were not performed.

The synoptic environment was characterized by an amplified mid-latitude westerly trough extending northward over southern Africa, associated with negative 500 hPa geopotential height anomalies and enhanced cyclonic circulation west of the region. The associated potential vorticity anomaly, upper-level jet configuration, and vertical motion fields indicate a dynamically active environment that supported large-scale ascent over southwestern Namibia. The 500 hPa vertical velocity fields revealed upward motion ahead of the surface cold front, consistent with precipitation development. At upper levels, the 200 hPa subtropical jet exceeded 60 m s^{-1} and displayed pronounced curvature, placing southern Namibia within a region of enhanced upper-tropospheric forcing. A surface cut-off low and strengthened meridional pressure gradient supported persistent southerly to southwesterly flow, indicating a high-latitude cold-air intrusion. However, without air-mass trajectory analysis, the specific source region cannot be confirmed; therefore, the event is interpreted as a cold-air intrusion rather than a verified Antarctic-origin outbreak.

The August 2025 snowfall event highlights the importance of baroclinic wave dynamics, jet-stream variability, and transient moisture availability in producing rare frozen precipitation in arid subtropical environments. The event resulted from the interaction of moderate thermal anomalies, upper-level dynamical forcing, cold-air transport, and orographic effects rather than from extreme temperature or moisture conditions alone. Comparison with previous Southern African PV intrusion events, including the February 2023 cutoff low and the September 2024 cold outbreak, indicates that strong upper-level PV anomalies can contribute to diverse extreme weather outcomes depending on the background circulation and moisture availability.

Future studies should incorporate high-resolution numerical modelling, backward trajectory analysis, moisture transport diagnostics, and long-term climatological assessments of winter troughs and cold-air intrusions. Improved observations in remote and elevated regions are also needed to better quantify snowfall occurrence, accumulation, and local-scale processes. Despite limitations related to sparse observations, limited snowfall verification, and reanalysis resolution, this study provides a physically consistent assessment of how large-scale circulation variability and baroclinic wave processes can generate rare snowfall events in subtropical arid regions.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics N/A

Competing interests The authors declare no competing interests.

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