J. Mt. Sci. (2024) 21(6): 1941-1953 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-023-8509-4

Original Article

Classifying moisture sources associated with snowfall in the mountains of Lesotho

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Citation: Marinaki AM, Fitchett JM (2024) Classifying moisture sources associated with snowfall in the mountains of Lesotho. Journal of Mountain Science 21(6). https://doi.org/10.1007/s11629-023-8509-4

Abstract: An average of eight snowfall events occur each year in the eastern Lesotho Highlands. These snowfall events are typically associated with cut-off low (CoLs) systems and mid-latitude cyclones. However, the moisture sources of the snowfall are unclassified and unclear. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, an air mass back trajectory model, has been used to evaluate moisture source waters locally in southern Africa and internationally in China and Europe. This study uses HYSPLIT to determine the source moisture of snow in Lesotho. A list of all 82 snowfall events in Lesotho spanning 2017 to 2022 was compiled using the Snow Report SA Instagram page, including the date and location of snowfall. A 72-hour back trajectory for each snowfall event was initiated for both Afriski and the whole of Lesotho. This amounts to models of moisture source trajectories for 28 and 82 snowfall days, respectively. These air mass pathways are classified according to their frequency per snowfall event, per month in the snow season, per year and for the full period. From this, associated moisture source regions and dominant air mass trajectories were identified. This study reports that the air mass trajectories associated with Afriski and Lesotho as a whole are very similar. The most common pathway of air mass trajectories transporting snow-bearing moisture to Lesotho was an inland trajectory from the northern regions of southern Africa. This pathway makes up 16.6% of all trajectories reported and is associated with the Angola Low, the Congo Air Boundary and the St. Helena High Pressure.

Received: 27-Nov-2023
1st Revised: 21-Dec-2023
2nd Revised: 16-Jan-2024
Accepted: 10-Apr-2024

Keywords: Eastern Lesotho Highlands; Afriski; Snow; Cut-off Lows; HYSPLIT; Synoptic Climatology

1 Introduction

Approximately eight snowfall events occur annually in the Lesotho highlands (Stander et al. 2016; Grab et al. 2017). With 80% of Lesotho's land cover comprising high-lying regions and mountains, the topography is important for snowfall source identification in the region as it will be at its greatest density at high altitudes (Grab et al. 2017). These average eight snowfalls per annum, together with smaller and more isolated snowfalls, occur predominantly on its mountain peaks from May to September (Stander 2013; Grab et al. 2017). The high elevation and rugged topography in Lesotho are a barrier to air mass movements, inducing regional differences in snow distribution (Nel and Sumner 2008; Mills et al. 2012). There is a growing output of research that focuses on snowfall in the Drakensberg-Maloti Mountains of southern Africa as a bellwether of climate change (Sene et al. 1998; Grab and Linde 2013; Grab et al. 2017). Snowfall in Lesotho is broadly understood to be associated with Cut-off Low (CoL) systems and mid-latitude cyclones (Stander 2013; Wunderle et al. 2016). However, there is a lack of understanding of the attributes of Lesotho snowfall and its associated air mass pathways (Wunderle et al. 2016; Grab et al. 2017). In southern Africa, studies exploring moisture transport have primarily focused on rainfall (Leketa and Abiye 2020; Rapolaki et al. 2020; Geppert et al. 2022) and pollution deposition (Rose et al. 2020).

The HYSPLIT model is founded in Lagrangian Particle Dispersion which, as a fundamental of dispersion and atmospheric transport modelling, refers to the tracing of air parcel movement within the atmosphere (Xia et al. 2013; Katharopoulos et al. 2022). Given the adiabatic processes which produce snowfall, such an air parcel will maintain its temperature along its trajectory highlighting the relevance of such a process and the HYSPLIT model to a precipitation-related study (Bookhagan and Burbank 2010; Xia et al. 2013; Katharopoulos et al. 2022). Lagrangian Particle Dispersion models can provide detailed constructions and reconstructions of air mass transport and dispersion and they can account for air parcel interactions in the atmosphere such as vertical and horizontal mixing as well as atmospheric turbulence (Xia et al. 2013; Stein et al. 2015; Katharopoulos et al. 2022). These models have been used in exploring the moisture sources of snowfall in various regions around the world such as in China (Li et al. 2022), Iran (Bagheri et al. 2019) and Northern Europe (Bailey et al. 2021). The processes taking place in Lagrangian Particle Dispersion models can also take into consideration the vertical structure of the atmosphere which includes dry and wet deposition of air parcels which are important processes in the modelling of precipitation (Stein et al. 2015; Katharopoulos et al. 2022). Thus, specifically related to the HYSPLIT model, air mass back-trajectory analyses have been used to study the dispersion and transport of radionuclide plumes from a variety of sources (Moroz et al. 2010), wildfire smoke dispersion and transport (Rolph et al. 2009), wind-blown dust and how it moves (Ashrafi et al. 2014), and the transport and dispersion of air pollutants from all around the globe (Efstathiou et al. 2011).

Back-trajectories in HYSPLIT can effectively classify atmospheric circulation patterns, seasonality, volume and distance travelled by moisture in southern Africa (Leketa and Abiye 2020; Rose et al. 2020; Geppert et al. 2022). Using this back-trajectory analysis, moisture pathways can be classified according to the duration spent circulating a region before precipitation occurs such as in Leketa and Abiye (2020), where moisture patterns were observed up to three days before precipitation occurred. This is enhanced by the HYSPLIT back-trajectory of 72 hours as this is the average or mean residence time of moisture in the atmosphere in southern Africa (Leketa and Abiye 2020; Gimeno et al. 2021; Rose et al. 2020; Li et al. 2022), and falls within the period of influence of mid-latitude cyclones and Cut-off Lows in the region (Majodina and Jury 1996; Singleton and Reason 2006; Xulu et al. 2023). A similar approach can also detect the origin of moisture (Rapolaki et al. 2020) where back-trajectories were used to determine that rainfall pathways over Lesotho were more strongly associated with in-land moisture sources from inland rivers and lakes rather than moisture sources from the Atlantic Ocean by calculating the average number of times that precipitation occurred after a specific pathway (Rose et al. 2020; Li et al. 2022). Rapolaki et al. (2020) placed particular consideration on specific humidity in determining whether a parcel of air along a trajectory is moisture-bearing which, when calculating the maximum specific humidity of a parcel, can indicate the origins of moisture along the air mass trajectory. HYSPLIT back-trajectories can also be used in determining the frequency of precipitation contribution from different altitudes. Li et al. (2022) observed that 66% of precipitation in alpine regions originates from moisture sources at 2000 m above ground level (agl) by running back-trajectories over an alpine region at different heights for the same precipitation events. HYSPLIT can be used to determine where moisture originates from, how long moisture lingers over a region and from what altitudes moisture bears precipitation (Leketa and Abiye 2020; Rapolaki et al. 2020; Li et al. 2022). This study uses HYSPLIT back-trajectory analysis to explore the moisture sources associated with snowfall events in the eastern Lesotho highlands over the period of 2017-2022.

2 Study Site and Methods

2.1 Study site

Lesotho is a country located within the land borders of South Africa between 28°30'-30°40' S and 27°00'-29°30' E (Grab et al. 2017; Fig. 1). This small country has a total land area of 30,355 km² (Grab et al. 2017; Wunderle et al. 2016). The shared escarpment between South Africa and Lesotho which defines the topography of Lesotho, is one of the country's most prominent features. Lesotho is a high-lying country, with its highest mountain peak situated at 3482 m asl and its lowest point at 1400 m asl making it the highest low point of any country in the world (Linde 2011; Stander 2013). Due to its elevation, Lesotho experiences a much colder climate than most southern African countries with snowfall occurring from as early as March to as late as November (Grab et al. 2017; Wunderle et al. 2016). However, the summer rainfall season is when Lesotho experiences its greatest volume of precipitation with rainfall volumes ranging from 600-1000 mm (Grab and Linde 2013). Lesotho is a unique location as it is governed by the same climate systems as southern Africa however, with the added influence of alpine climatology.

The alpine climatology and regular snowfall

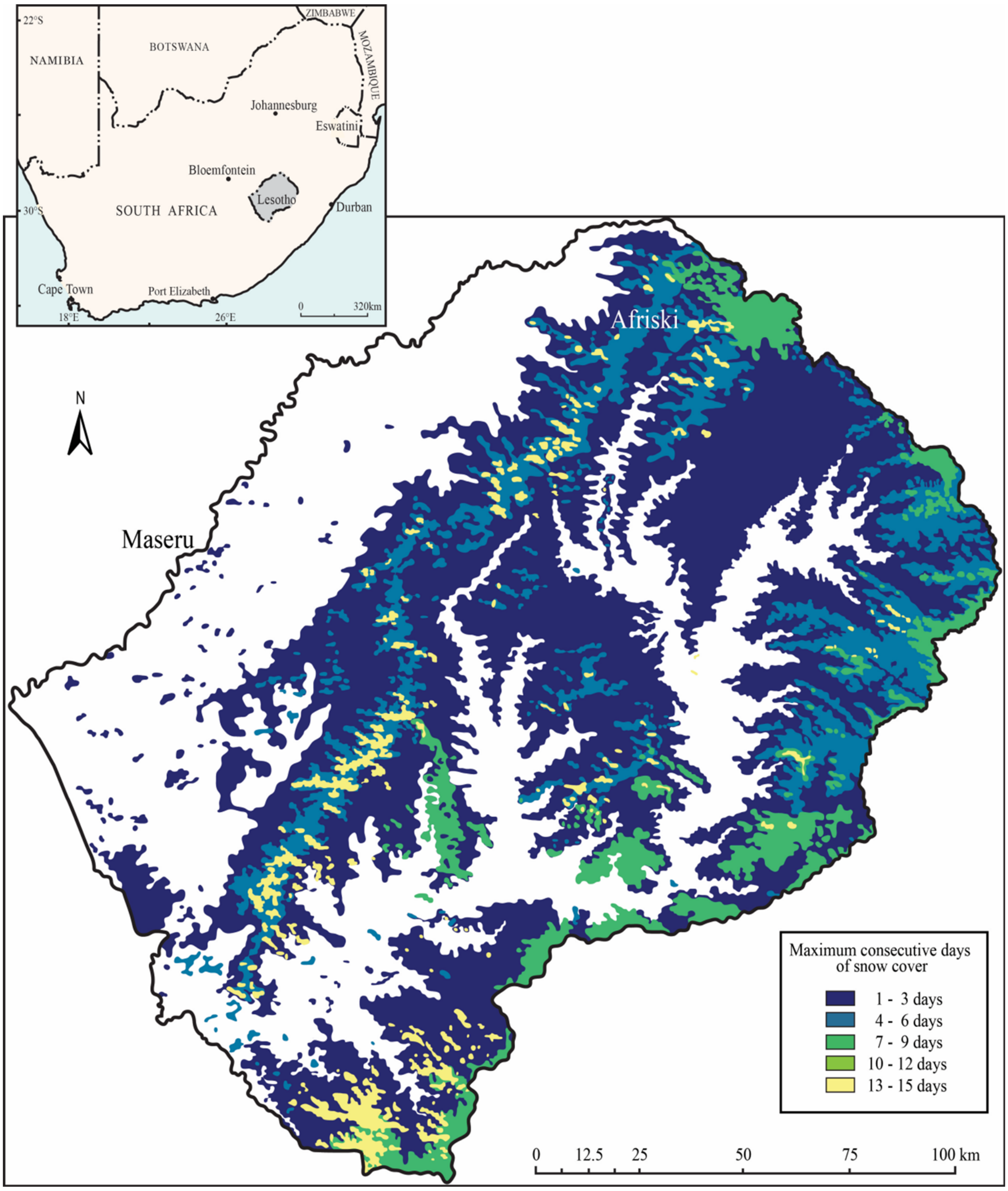

Fig. 1 Study site map representing Lesotho's geographical location and the maximum number of days where the ground is covered in snow as snow cover days.

facilitated the development of a ski resort in Lesotho, Afriski. Lesotho is regionally famous for its ski holidays and thus relies on the annual snow season for tourism (Hoogendoorn et al. 2020). As the only reliable source of snowfall in southern Africa, this country makes for a viable study site for any snow-related research within the region (Noome and Fitchett 2019). Afriski produces artificial snowfall for tourism because the snowfall at their location is too infrequent (Noome and Fitchett 2019). The topography of Lesotho also defines its flora and fauna profile. This is relevant because the vegetation of Lesotho is such that the snow against the vegetation is distinct in both satellite imagery and from webcams. Thus, this interplay between topography influencing vegetation and then vegetation influenced by snowfall is an important chain of events in the observation of snowfall.

2.2 Methods

The data collection and analysis methodology in this research is outlined in three sections. Firstly, identifying snowfall events in Lesotho through the use of Instagram as data collection. Secondly, the modelling process focuses on the HYSPLIT model settings and uses. Thirdly, the moisture source classification method for identifying the origins of moisture. The methodology employed in this study is informed by previous research on air parcel trajectories for moisture sources in mountainous regions globally (eg. Li et al. 2022), in Southern Africa (Leketa and Abiye 2020) and specifically in Lesotho (Fitchett et al. 2024). We do not argue that this is the only approach to the analysis of air parcel trajectories or moisture sources, but have applied this approach as it has been applied and tested against isotope records for the regions of interest (Leketa and Abiye 2020; Fitchett et al. 2024), and in regions of similar topographic landscapes (Li et al. 2022).

2.2.1 Data collection

Snowfall event data for Lesotho was obtained from Snow Report SA's Instagram page, spanning from 2017 to 2022. It was not possible to extend this study period as there is no meteorological data or comprehensive Instagram data confirming snowfall days before 2017 in Lesotho. The model applied however, has been used in shorter studies such as in Leketa and Abiye (2020) which spans two years and in Bagheri et al. (2019) which spans 12 months. Included in the snowfall record were snowfall events specific to Afriski which are shaded in grey for a comparison of snowfall events. Manual inspection of Instagram posts by Snow Report SA (snowreport.co.za) confirmed the snowfall events, ensuring accuracy and no conflicting dates. Hail and frost events were excluded from this record as well as any snowfall events that were unclear in either, location or date. Snowfall dates were identified as separate events rather than treating consecutive days of snowfall as one event. The HYSPLIT model was also used individually for each snowfall day. Using Instagram for data collection is efficient and cost-effective, offering precise dates and wide-ranging data in the public domain. This method surpasses satellite imagery, which lacks constant data collection and can be hindered by cloud cover. This is particularly important for the Lesotho study site as there is no meteorological data available in the country relating to the smaller or unobservable snowfall events.

2.2.2 HYSPLIT methodology

The HYSPLIT model, developed by NOAA, was used to recover a 72-hour back trajectory of the moisture in Lesotho for every snowfall event that occurred from 2017 to 2022. These back-trajectories are set to the location of Afriski, 28°49'22" S, 28°43'41" E. The 72-hour back-trajectory timeframe is a result of the three-day moisture residency in the atmosphere of colder alpine regions (Li et al. 2022). While a variety of studies indicate that 10 days is the residence time of moisture in the atmosphere, studies in localized highly mountainous regions such as this one use a shorter 72 hour back trajectory (Laderach and Sodermann 2016; Nieto and Gimeno 2019; Li et al. 2022; Fitchett et al. 2024). In addition, latitude, ocean-atmospheric dynamics of each ocean, and orographic uplift can shorten the lead time of moisture in the atmosphere emphasizing 72 hours as the most representative residence time of moisture in the atmosphere (Bookhagan and Burbank 2010; Gimeno et al. 2021; Escobar et al. 2022). The starting time parameter for the back trajectories run in this study was set at 08:00 for every trajectory to ensure consistency in the reconstruction of the moisture pathways. However, the model tracks moisture trajectories from the start of each day but due to the reporting of each snowfall on Instagram rather than exact times, the 08:00 start time was more suitable. Back-trajectories were calculated at different altitudes at an elevation of 500 m, 1000 m and 2000 m agl to classify the origin and pathway of moisture of every recorded snowfall event throughout each year. This elevation at 500m, 1000m and 2000m is configured by the topographical information of Lesotho, to produce a valid back-trajectory (Li et al. 2022; Rose et al. 2020; Bailey et al. 2021). These altitudes are informed by the literature on precipitation in the region and on precipitation in mountainous regions (Leketa and Abiye 2020; Li et al. 2022; Fitchett et al. 2024). Similarly, using three or less altitudes in the HYSPLIT model is sufficient to provide a valid result (Rapolaki et al. 2020; Rose et al. 2020). HYSPLIT in its back-trajectory function, incorporates gridded meteorological data, named GDAS, for each week of every month in the year extending back to December of 2004 which means that there are no data gaps associated with using this model for a six-year period. The horizontal resolution of GDAS is 1° and the temporal resolution is three hours (Stein et al. 2015). The model's settings ensure consistency in back trajectories and consider the atmospheric moisture residency in alpine regions. HYSPLIT was set to model vertical velocity which is the default setting that does not account for isentropic or isobaric changes. This is because this study was not concerned with pressure gradients between the different elevations that moisture followed along each pathway, referring to isobaric changes and isentropic changes as this process is assumed based on the orographic nature of the snowfall (Bookhagan and Burbank 2010; Li et al. 2016). Relative humidity was consulted and modelled sparingly to simply illustrate that not all air parcels are moisture-bearing however, this has few implications for the bigger picture in relation to the broad region from which snow-bearing moisture originates (Rapolaki et al. 2020; Fitchett et al. 2024). Non moisture-bearing parcels are included in the trajectories without relative humidity being measured along the pathway. Isolating the saturated pathways, which occur in varying proportions, would not contribute to defining the most representative pathway of snowfall bearing moisture in Lesotho (Rapolaki et al. 2020, Fitchett et al. 2024). In addition, the model was set to run back-trajectories only once or at zero hours as the data used was not hourly but based on the snowfall record compiled from Instagram (Fitchett et al. 2024).

2.2.3 Data analysis

Air parcel trajectories and moisture source regions were categorized manually based on the trajectories from the modelling process (Hegarty et al. 2013; Rose et al. 2020; Li et al. 2022). The HYSPLIT model produces a map of the user's chosen location with the moisture trajectories plotted at each elevation from their sources. From the 82 snowfall days, each map contains three trajectories for the three different altitudes the model is tracking hence the total number of trajectories is 246. These maps were used to manually count the volume of pathways from any given source to aggregate the most common moisture pathway for each month, altitude or elevation, year and the full study period. The pathways were separated or clustered into groups of different origin zones. These zones are informed by the pathways where pathways from similar directions and trajectories are grouped together (Rose et al. 2020; Fitchett et al. 2024). Maps of compiled accurate trajectories were used to analyse moisture origins. This was done for the entirety of Lesotho, with and without saturation and for the snowfall events that were reported from Afriski. This analysis aimed to determine if Afriski represents Lesotho's overall snowfall originates. It is also important to clarify that given that some parts of Lesotho are unreachable due to high elevation and rugged topography, there is no data on how much snowfall occurs on the snowfall days (Noome and Fitchett 2019; Fitchett et al. 2024). In addition, there is very rarely any deep snowfalls in Lesotho. It also examined the predominant moisture source considering origin points in the Atlantic or Indian Ocean and whether inland moisture sources were more common than the ocean origins. This approach validates the modelling coordinates and explores the relationship between moisture pathways and snowfall events (Rapolaki et al. 2020; Li et al. 2022).

3 Results

3.1 Compilation of snow events record

There were 82 days from 2017-2022 with reports of Lesotho experiencing snow, averaging 13.6 days per year (Table 1). Of these 82 days, 28 were tagged as snowfalls occurring specifically at Afriski Resort in Lesotho. The minimum number of snowfall days per year occurred in 2019 with nine days of snowfall, which notably occurred in discrete events through January, April, June, July, September and November. The greatest number of snowfall days experienced over this period was in 2021, with 18 snowfall days which were

Table 1 Reported snowfall events in Lesotho from 2017-2022. # represents snowfall events at Afriski

2017	2018	2019	2020	2021	2022
12 May#	23 Mar	3 Jan	14 April	26 Mar#	7 Apr
15 May #	30 Apr#	21 Apr#	15 April#	15 Apr	17 Apr#
16 May	12 May	22 Apr	25 April	23 Apr#	19 May
28 Jun#	14 May	25 Jun	28 April#	30 Apr#	21 May#
14 Aug	15 May	27 Jun	29 April#	1 May#	8 Jun
15 Sep	31 May#	1 Jul	26 May	2 May	10 Jun
4 Oct	7 Jun	5 Sep#	13 Jun	7 May#	20 Jun
10 Oct	14 Jul#	29 Sep	10 Jul	21 May	23 Jun
13 Oct#	15 Jul	14 Nov#	11 Jul	22 May#	25 Jun
16 Nov	9 Aug#		6 Aug	2 Jun	27 Jun
	10 Aug		16 Aug	5 Jun#	7 Aug
	11 Aug		18 Aug	30 Jun	15 Aug
	18 Aug#		30 Aug	9 Jul	19 Sep
	8 Sep		1 Nov#	12 Jul	25 Oct#
	3 Oct#			22 Jul	
	13 Oct#			27 Aug	
	10 Dec			7 Sep	
				27 Nov	

Fig. 2 Map demonstrating the proportional distribution of air mass trajectories for the full study period from 2017–2022 initiated at 500 m agl, 1000 m agl and 2000 m agl. The dominant trajectory is shown in orange.

experienced across eight months. Between 2017 and 2022, no snowfall was recorded in Lesotho during February.

3.2 Airmass trajectories for mean snowfall events in Lesotho

The predominant air mass pathway followed from 2017-2022 initiated inland beyond the borders of South Africa, in Botswana, Zambia and Angola (Fig. 2). This makes up 16.6% (n=246) of the proportions of different pathways leading up to snowfall events for the duration of the study period. This pathway followed an anticyclonic trajectory from Zambia directly south to Lesotho. The second most common air-mass pathway, accounting for 15.4% (n=246) of tracks, initiated in Lesotho at the southernmost point of Mozambique moving westward towards Lesotho. The least common air-mass trajectories for the study period initiated in the Indian Ocean. These tracked in a south-easterly direction of Lesotho far south in the Indian Ocean, accounting for 2.8% (n=246) of moisture pathways.

There is considerable inter-annual variability concerning neither the least nor the most dominant trajectories in each year (Fig. 3). The least dominant trajectories were also more variable than the most dominant. In 2017 and 2018, a similar trajectory from the African interior was most dominant, representing 26.6% (n=30) and 29.4% (n=51) of trajectories respectively. In 2017, this trajectory followed an anticyclonic pathway that initiated north of Namibia. In 2018, the dominant trajectory initiated slightly south of Zambia and followed a cyclonic pathway towards Lesotho. Both these pathways moved over Lesotho crossing the border at the same general location in the North of the country. The most common trajectory in 2019 initiated northeast of Lesotho on the coast of Mozambique with a frequency of 29.6% (n=27). This region of the Indian Ocean between Mozambique and Madagascar is evident as a source region in all years of the study period, to varying degrees (Fig. 3).

In 2020, a dominant trajectory originating from the Atlantic Ocean in the southwest direction of South Africa accounted for 28.5% (n=42; Fig. 3). Considering all the snowfall events, in 2021 a similar dominant pathway was noted, at 25.9% (n=54; Fig. 3). In contrast, 2022 saw a dominant anticyclonic pathway from the Indian Ocean near Lesotho. These patterns reflect variations in moisture sources and trajectories across different months. January and March reflected an Indian Ocean pathway as dominant, while a dominant northern inland origin occurred in April. May and June exhibited diverse air-mass origins, with anticyclonic pathways in both months. August showcased a dominant trajectory from the Atlantic Ocean, whereas September and October shared an anticyclonic dominant pathway from the northern coast of Mozambique (Fig. 4). December featured three equal-frequency trajectories, including anticyclonic and cyclonic pathways (Fig. 4). This reveals the dynamic nature of moisture sources and trajectories throughout the year. In this regard, it is important to explore the summer months as discreet months. The climatology of moisture transport will be unconvincing in summer therefore, aggregating the summer months as one season reduces the unique quality and consideration of each snowfall day and month (Li et al. 2022).

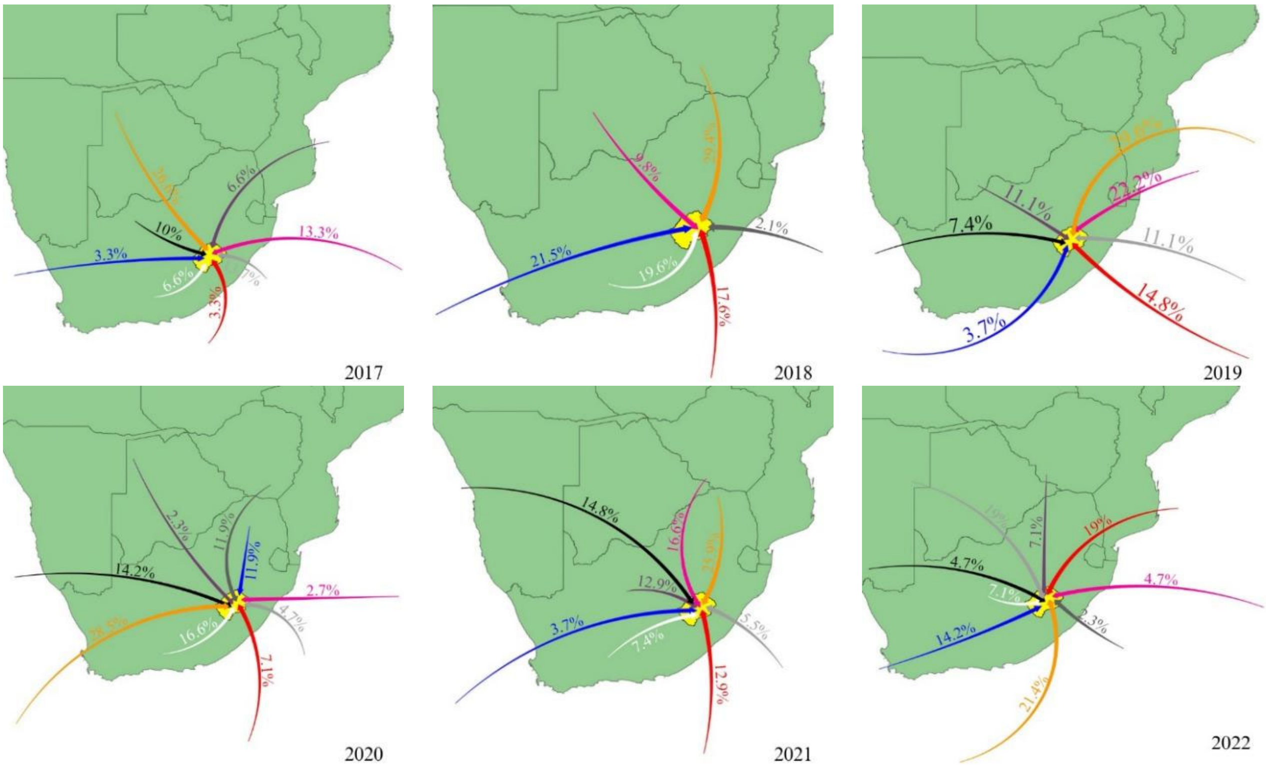

Fig. 3 Maps featuring the most common yearly air-mass trajectories from 2017–2022 initiated at 500 m agl, 1000 m agl and 2000 m agl. The dominant trajectory is shown in orange.

Additionally, given the diverse climate in southern Africa, there exist numerous interpretations for defining seasons, rendering this classification somewhat subjective (Roffe et al. 2019; van der Walt and Fitchett 2020; Loader et al. 2023).

3.3 Airmass trajectories for snowfall at Afriski

The predominant trajectory for the 28 snowfall days recorded at Afriski was an anticyclonic pathway originating from the African Interior north of Botswana, which occurred with a 28.5% frequency (n=84; Fig. 5). A total of 10 out of 11 trajectories modelled for snowfall events at Afriski were completely different to the trajectories from the whole of Lesotho and from the trajectories for saturated air masses (Fig. 2, 4 and 5). The only common trajectory was the pathway that originated on the south coast of South Africa (Fig. 5). Immediately south of Lesotho, this pathway occurred with a frequency of 3.5% (n=84) in relation to Afriski, 5% (n=84) in relation to saturation and 4.4% (n=84) in totality (Figs. 2 and 5). However, this pathway at Afriski was not the least dominant pathway. The least dominant pathway occurred with a frequency of 1.2% (n=84 from 2017-2022 (Fig. 5). This least dominant pathway originated from the Indian Ocean east of Mozambique (Fig. 5).

The one common trajectory between Afriski and the rest of Lesotho was the pathway that originated on the south coast of South Africa (Fig. 4). In comparison to the yearly total trajectories for the entirety of Lesotho, only 2021 and 2022 are confidently similar in their dominant and least dominant trajectories. The most notable difference between the monthly trajectories at Afriski and the rest of Lesotho was that Afriski experienced no January or December snowfall (Fig. 4). April and May were also the only two months where the trajectories for Afriski matched the trajectories for the rest of Lesotho with similar proportions of the dominant trajectory from the African interior north of South Africa (Fig. 4). Monthly mean trajectories between Afriski and the rest of Lesotho show similarities seasonally. However, according to the mean yearly trajectories and total trajectories, Afriski is notably different in its snowfall origins than the rest of Lesotho.

The calculated trajectory maps are categorized by zone and region in a methodology informed by the literature (Rose et al. 2020). The various figures have a different number of categories because each figure

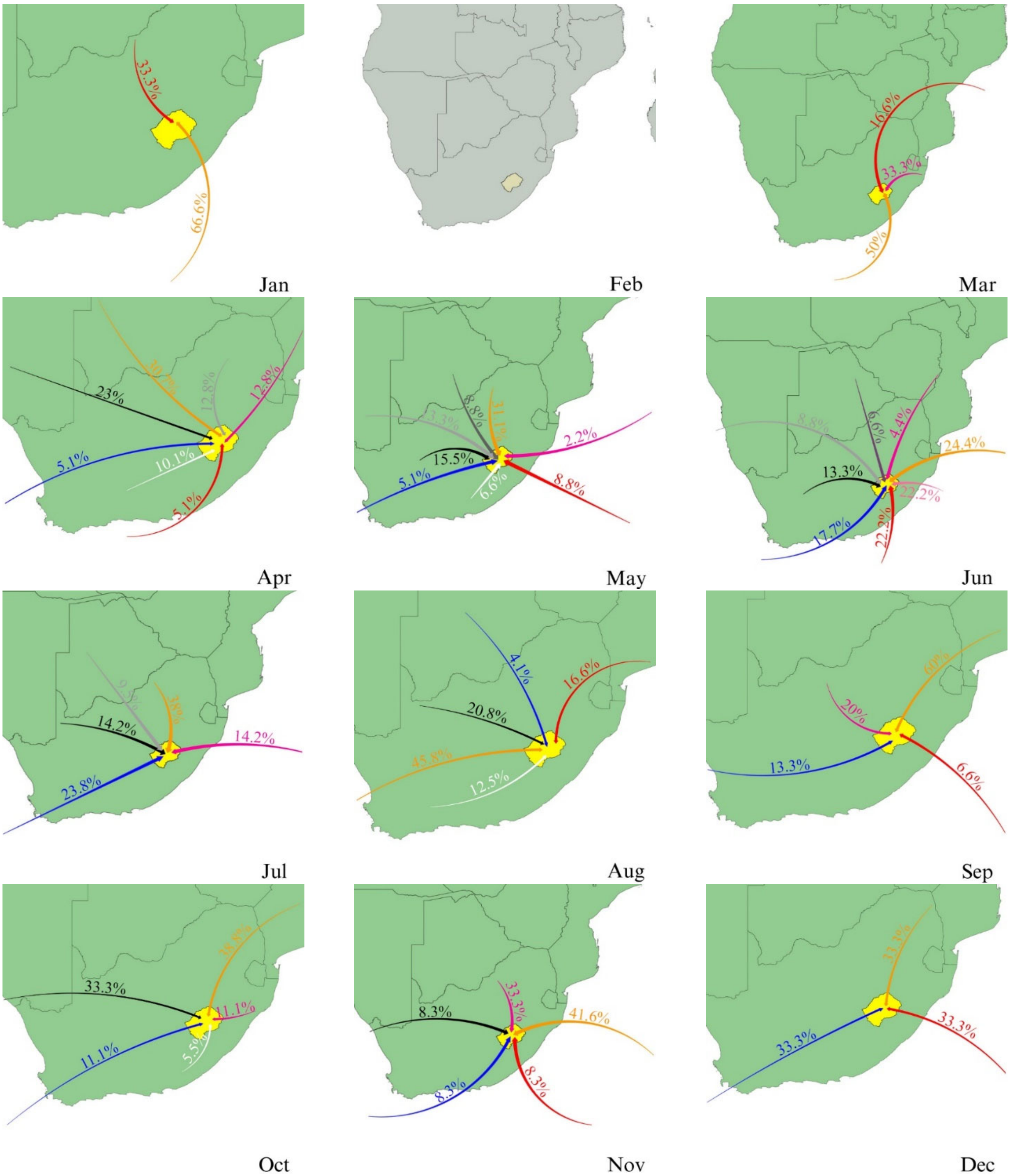

Fig. 4 Maps featuring the most common monthly air-mass trajectories from 2017–2022 initiated at 500m agl, 1000m agl and 2000m agl. The dominant trajectory is shown in orange.

represents a different number of snowfall days. Fig. 2 represents all 246 pathways from whereas in Fig. 3, each year has a different proportion of trajectories from the total 246 pathways. Similarly, Fig. 5 represents the 99 trajectories specific to snowfall events at Afriski and therefore the makeup of trajectories is different.

3.4 Air mass trajectories at different altitudes

With HYSPLIT being run at 500 m agl, 1000 m agl and 2000 m agl, the moisture pathways that originate inland are most dominant at each altitude (Table 2). This dominance is significant where 69% (n=84) of moisture pathways at 500 m agl originate inland, 63.2%

(n=79) of moisture pathways at 1000m agl originate inland and 50.6% (n=83) of moisture pathways at 2000 m agl originate inland (Table 2). These proportions, not only highlight the dominance of the inland origin point in snow-bearing moisture transport but also an increasing influence of oceanic pathways as altitude increases. Moisture pathway origins are also contingent on topography therefore the proportions of pathways will be different per different altitudes.

At 500 m, 1000 m and 2000 m agl the inland and Indian Ocean origin remain stable with minor variations as altitude increases (Table 2). However, the Atlantic Ocean origin points at 500 m and 1000 m agl are exactly 14 pathways respectively and the 2000 m agl altitude doubles the number of occurrences from this region (Fig. 6). At 2000 m agl in the Atlantic Ocean is double any other ocean origin point at any altitude (Fig. 6; Table 2).

Table 2 Moisture pathway and altitude origins (m above ground level) for the full period of 2017–2022

Origin	Moisture pathway			Totals
	500 m	1000 m	2000 m	
Inland	58	50	42	60.98%
Indian Ocean	12	15	13	16.26%
Atlantic Ocean	14	14	28	22.76%

Notes: Totals refers to the proportion of moisture pathways originating from inland, Indian Ocean and Atlantic Ocean.

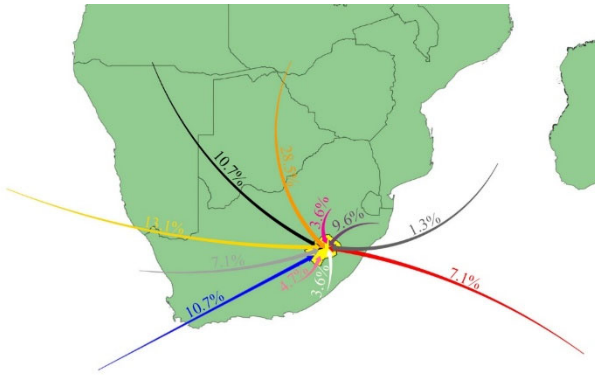

Fig. 5 A map featuring the most common air mass trajectories for the full study period from 2017–2022 at Afriski Resort initiated at 500 m agl, 1000 m agl and 2000 m agl. The dominant trajectory is shown in orange.

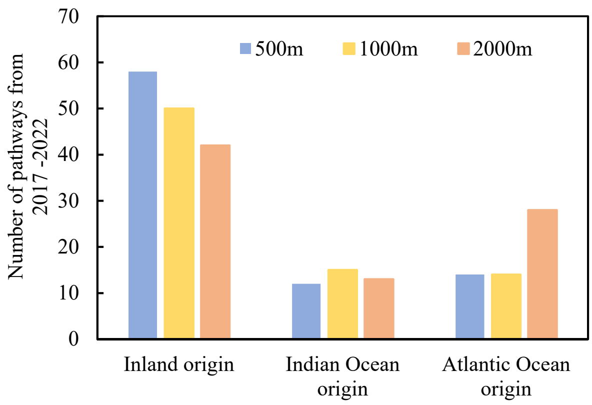

Fig. 6 Graph showing the total proportions of snowfall origins in Lesotho per altitude.

4 Discussion

Between 2017 and 2022 there was an average of 14 snowfall days. This aligns closely with the estimate of around eight snowfall occurrences annually in the region (Mulder and Grab 2009), as snowfall events may span more than one day. May and June, which are cooler months, experienced the most snowfall days of 14 and 15 respectively for the period 2017-2022. This correlates to the widespread acceptance that snowfall can be attributed to frontal depressions, or more specifically cold fronts, where the winter months experience the most snowfall (Fuenzalida et al. 2005; Favre et al. 2013; Stander et al. 2016). As the Intertropical Convergence Zone (ITCZ) shifts northward from the Tropic of Capricorn towards the Tropic of Cancer during austral winter, the westerlies are displaced equatorward (Unganai and Mason 2002). This displacement allows mid-latitude cyclones and CoLs to move towards Lesotho whereas, during summer these synoptic systems are typically too far south of Lesotho to produce snowfall (Saarinen et al. 2022).

CoLs create intense cyclogenesis on the surface of the earth which leads to strong winds, cold temperatures and precipitation (Fuenzalida et al. 2005). This knowledge extends to the region of southern Africa which includes Lesotho, highlighting that CoLs and their associated snowfall are predominant in the Lesotho region over the summer to the winter transition period (Favre et al. 2013). These CoL systems develop in elongated troughs of low pressure in the upper atmosphere representing a colder-than-usual area and are associated with atmospheric instability (Fuenzalida et al. 2005). These unstable weather systems rely on the topography of Lesotho to produce snowfall, through orographic uplift due to the mountainous terrain that forces the air to rise assisted by strong winds (Grab et al. 2017; Muofhe et al. 2020). Similar to CoLs, mid-latitude cyclones are important considerations for snowfall in Lesotho

(Gaughan et al. 2016). These synoptic systems are made up of the interaction of warm and cold air masses or fronts that are associated with the atmospheric instability that bears precipitation and snowfall (Philippon et al. 2012). Stander et al. (2016) draw attention to the air mass pathways and circulatory patterns of mid-latitude cyclones as an important consideration in the moisture origin point for snowfall-bearing climate systems in Lesotho.

CoLs and mid-latitude cyclones play a crucial role in determining the moisture sources for snowfall in Lesotho (Fuenzalida et al. 2005; Unganai and Mason 2002; Favre et al. 2013; Fitchett et al. 2024). CoLs originating in the sub-tropics northwest of Namibia can bring prolonged precipitation to Lesotho due to their slow-moving nature (Favre et al. 2013; Muofhe et al. 2020). The southward anticyclonic pathway of CoLs, as illustrated in Figs. 2-5, contributes to multiple days of snowfall in Lesotho. This pattern is reinforced by the movement and impact of the Angola Low (Pascale et al. 2019; Desbiolles et al. 2020). Additionally, mid-latitude cyclones induce unstable weather in areas near the low-pressure system (Linde 2011; Stander 2013). The combination of moist air advection from the Indian Ocean around Southern Africa and orographic processes in Lesotho results in significant snowfall, as evident from observations of the oceanic origin pathways (Figs. 2 and 5).

Focusing on Afriski, the predominant period of snowfall at Afriski is during the months of April and May, a month before the onset of the mean snowfall season for the whole of Lesotho, likely due to the very high altitude (1400m-3482m.asl) at the site. These variations for Afriski compared to Lesotho are highly important as the arrival of the snow season is critical for tourism (Noome and Fitchett 2019; Hoogendoorn et al. 2020). While Afriski artificially produces snowfall, the experiences of tourists are greatly enhanced when snowfall occurs, therefore one of the best adaptive responses to various challenges in the snow-based tourism sector is to adjust the season dates at locations such as Afriski for a more representative and effective snow season (Stockigt et al. 2018).

The mean moisture source back-trajectories for snow in Lesotho were characterised by moisture pathways originating within southern Africa, north of Botswana, following anticyclonic pathways. The Angola Low is situated north of Botswana and is characterized by a semi-permanent low-pressure system. This low pressure system over southwestern Africa, contributes to the region's humid and rainy conditions. Which explains how this system may relate to the moisture originates for snowfall in Lesotho (Desbiolles et al. 2020). A possible explanation for this movement may be a result of cooler sea surface temperatures and strong upwelling in the northern regions of the South Atlantic near the warmer currents of Angola caused by the St. Helena High Pressure (SHHP) (Desbiolles et al. 2020; Saarinen et al. 2022). Alternatively, the position of the Congo Air Boundary (CAB) in the formation of the Tropical Temperate Trough may also be responsible for the transportation of moisture to Lesotho (Howard and Washington 2019). Considering seasonality in an example such as the CAB, which is displaced north during the austral winter to impact the formation of snowfall in Lesotho which is why it is more closely associated with rainfall (Howard and Washington 2019). To illustrate this further, the Congo Air Boundary influences weather patterns by marking the transition between the moist air from the Atlantic and the drier air from the continent, often leading to convective activity (Howard and Washington 2019). Whereas the ridging associated with the SHHP may be a more significant indicator of where snowfall comes from as ridging can aid in the transportation of moisture (Pascale et al. 2019). In contrast, the St. Helena High Pressure, situated in the South Atlantic, promotes stable and dry weather over the surrounding ocean, influencing trade winds and impacting the climate of adjacent regions. The adjacent regions referred to are unstable weather conditions in Lesotho relating to snowfall (Pascale et al. 2019). Importantly, this suggests a more complex set of synoptic features associated with snowfall in Lesotho, and in particular in supplying moisture to the region. While the air mass trajectories do not preclude a dominant role of CoLs in inducing snowfall (Stander et al. 2016), greater analysis of the synoptic conditions for both summer- and winter-season snow in Lesotho would be of value.

Despite the seasonal, annual and monthly differences in the exact pathways of moisture at Afriski, a large proportion of these trajectories originate from the same broad region where the dominant trajectories originated from the African interior north of Botswana for the whole of Lesotho. The regional differences in the other non-dominant trajectories may be attributed to shortfalls in recording these events occurring at the highest altitudes or specific events and changes in global atmospheric circulations. These changes between Afriski and the rest of Lesotho may also be attributed to the direction in which moisture arrives at a location where Afriski experienced little to no snowfall from the Indian Ocean, however, this difference was not significant enough to sway the overall coherence across the country (Hammond et al. 2018; Rafiq and Mishra 2018).

Winter precipitation, including snowfall, in southern Africa has increased dramatically since the 1970s due to increased ocean temperatures under climate change conditions (Gaughan et al. 2016). Changes in sea surface temperatures and atmospheric pressure as a result of global warming increase the intensity of snowfall-inducing weather systems (Engelbrecht et al. 2009). As for the influence of climate change on the El Niño-Southern Oscillation (ENSO), current research suggests that climate change could lead to more frequent and intense El Niño and La Niña events. The warming of the ocean and changes in atmospheric circulation patterns are expected to affect the behaviour of ENSO, potentially amplifying the frequency with which Tropical Temperate Troughs and Cut-off Lows occur, causing extreme weather events (Fuenzalida et al. 2005). Increased frequency of CoLs in Lesotho, which rely on the topography of Lesotho to produce snowfall may increase the frequency of snowfall events. In the context of Lesotho's climate, climate change is projected to reduce the duration of snow cover in Lesotho's highlands, impacting water resources, agriculture, and ecosystems that rely on meltwater from the mountains. Furthermore, altered precipitation patterns associated with ENSO may exacerbate these trends, as the region's vulnerability to both ENSO-related weather events and climate change underscores the importance of adaptation strategies in the face of a changing climate.

5 Conclusions

In conclusion, this research paper was the first to explore the moisture source trajectories associated with snowfall in Lesotho. The most dominant air mass trajectories circulate to Lesotho from inland sources followed by the Atlantic Ocean at the highest elevations. This collection of air masses highlights the dominance of CoL systems in producing snowfall in Lesotho. Furthermore, this study aimed to clarify the origins of moisture sources associated with snowfall in Lesotho from 2017 to 2022. It addressed key areas such as the influence of mid-latitude cyclones, orographic processes and the impact of global atmospheric circulations. Using the HYSPLIT model, the dominant air mass pathway for snowfall in Lesotho was found to track from the northern regions of Southern Africa, possibly linked to the Angola Low and the St. Helena High Pressure. The study emphasised the significance of air mass trajectories over the interior and orographic processes in transporting snow-bearing moisture, challenging the traditional focus on rapid moisture influx from oceanic sources. While contrasting trajectories highlighted the importance of ocean origin points having a greater proportion of dominant trajectories, there is no singular ocean pathway that accounts for as much as the dominant inland pathway.

Reviewing the objectives, the study successfully compiled a list of snowfall events in Lesotho from 2017 to 2022, totalling 82 events. The 72-hour backward trajectory analysis using NOAA's HYSPLIT model classified 246 pathways, highlighting the frequency of air mass trajectories per month, year, and the full study period. Despite the limitation of a six-year timeframe, the study opens avenues for future research, suggesting a more extended record for comprehensive atmospheric circulation analysis and exploring climate dynamics in relation to ENSO cycles.Methodological and location-based prospects were outlined, encouraging potential studies in different regions or utilizing alternative trajectory classification methods, while also acknowledging the value of social media in data collection and community engagement in scientific research. While our methodologies in air parcel trajectory analysis are informed by prior work in mountainous regions, further research could include comparisons between methods of air parcel trajectory analysis and moisture source identification, with a critical focus on not only the amount of moisture in source regions, but also the importance of rugged topography in facilitating snowfall events with relatively low regional humidity.

Acknowledgments

We thank Wendy Phillips from School of Geography, Archaeology and Environmental Studies for the production of the study site map. We are grateful to the HYSPLIT platform enabling this research, and the Snow Report SA Instagram account. JF receives funding from the University of the Witwatersrand Friedel Sellschop Grant, and the Wits-UCL strategic partnership grant.

Author Contribution

AM: Data collection, data analysis, writing first draft. JF: Project conceptualization, modelling, supervision, editing of first and subsequent drafts.

Ethics Declaration

Availability of Data/Materials: All data used in this study are in the public domain.

Conflict of Interest: An ethics waiver was obtained from the University of the Witwatersrand Human Non-Medical Ethics Committee. The authors declare no competing interests, financial or otherwise.

Open Access

Funding note: Open access funding provided by University of the Witwatersrand.

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