A Comparison of South American and African Preferential Pathways for Extreme Cold Events

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ABSTRACT

In the Southern Hemisphere, a relatively well-known preferential pathway along which cold air surges equatorward is situated to the east of the Andes Mountains. In this study, a second preferred pathway is identified to the east of the African Highlands, with additional minor pathways identified east of the Brazilian Highlands and Madagascar. The primary objective of this study is to compare climatological and synoptic characteristics of extreme cold events (ECEs) along the Andes and African Highlands pathways. ECEs are defined as the top 1% coldest 925-hPa temperatures within the Andes and the African Highlands pathways using the 1977–2001 subset of the 2.5° × 2.5° 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40). ECEs within the Andes and African Highlands pathways are associated with dynamically forced anticyclogenesis and have low-level characteristics that vary substantially. Along the Andes pathway, ECEs feature 925-hPa temperatures as much as 17°C below normal, with 925-hPa southerly winds ranging from 0 to 10 m s⁻¹ and 925–700-hPa lapse rates as low as −3°C km⁻¹. In contrast, ECEs along the African Highlands pathway feature 925-hPa temperatures up to 10°C below normal, with 925-hPa southerly winds ranging from 5 to 15 m s⁻¹, and 925–700-hPa lapse rates generally between 2° and 5°C km⁻¹. Composite analyses reveal that despite stronger southerly winds, ECEs along the African Highlands pathway are typically not as cold or stable as those along the Andes pathway because cold air from Antarctica must traverse a longer distance over water to reach Africa.

1. Introduction

Continuous regions of north–south-oriented high terrain can modulate the movement of synoptic-scale cold air masses by contributing to terrain-channeled surges of this cold air into subtropical and tropical latitudes (e.g., Myers 1964; DiMego et al. 1976; Parmenter 1976; Garreaud 1999, 2000, 2001; Lupo et al. 2001).
Preferred pathways for these cold surges have been identified to the lee of many mountain ranges worldwide (Fig. 1) including the Rockies (e.g., Hartjenstein and Bleck 1991; Colle and Mass 1995), Sierra Madre (e.g., Schultz et al. 1997, 1998; Steenburgh et al. 1998), Himalayas (e.g., Sumi 1985; Tilley 1990), Andes (e.g., Garreaud 1999; Lupo et al. 2001), and Appalachians (e.g., Forbes et al. 1987; Bell and Bosart 1988). Statistical studies have revealed that cold surges in many of the aforementioned regions account for a large portion of the total variance in low-level temperature (Garreaud 2001). The impact of these cold surges on the agricultural industry, near the Andes in particular, provided motivation for many of these previous studies (e.g., Hamilton and Tarifa 1978; Quiroz 1984; Marengo et al. 1997a,b). Given the significant societal impacts and economic losses that can occur with cold surge events, including their linkage to high-impact weather in the subtropics and tropics, it is important to identify other preferred regions where cold surges may occur in the Southern Hemisphere. Furthermore, we need to gain a deeper understanding of how the physical processes driving these cold surge events compare to the better-studied Andes cold surge events.

Equatorward-moving cold air masses that originate in higher latitudes can become trapped in the lee of steep terrain extending from the front range out to a distance of one Rossby radius of deformation\(^1\) (Pierrehumbert and Wyman 1985). The cold air masses are associated with a surface anticyclone, and the upshepe flow on the equatorward side of this anticyclone is blocked by the steep terrain due to the increased low-level stability that accompanies the cold air mass (i.e., the Froude number\(^2\) \(\ll 1.0\); e.g., Manins and Sawford 1982). The resulting positive pressure perturbation near the mountains results in an ageostrophic equatorward flow associated with an along-barrier pressure gradient that advects this cold air equatorward (e.g., Hamilton and Tarifa 1978; Richwein 1980; Fortune and Kousky 1983; Forbes et al. 1987; Bell and Bosart 1988; Colle and Mass 1995; Bailey et al. 2003). The Coriolis force continues to act on this equatorward-directed ageostrophic flow, keeping the cold air mass tied to the terrain as it moves equatorward. This process is commonly referred to as “cold-air damming” (e.g., Forbes et al. 1987; Bell and Bosart 1988; Colle and Mass 1995).

Cold surges along high terrain often exhibit strong upper-tropospheric forcing for subsidence and 850-hPa cold-air advection (e.g., Colle and Mass 1995; Schultz et al. 1997, 1998). However, Lupo et al. (2001) found some case-to-case variability in the actual evolution of cold surge cases in the lee of the Andes. This variability could be associated with the intensity of surface anticyclogenesis that accompanies the Andes cold surges and the strength of the associated upper-tropospheric forcing.

In addition to trapping and channeling cold air equatorward, high terrain can affect the progression of

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1 A typical midlatitude Rossby radius of deformation \(Nh_m/f\) is 200 km, based on a 2.0-km mountain height \(h_m\), a 2.0 \(\times\) \(10^{-2}\) rad s\(^{-1}\) Brunt–Väisälä frequency \(N\), and a 1.0 \(\times\) \(10^{-4}\) s\(^{-1}\) Coriolis parameter \(f\). This value increases with decreasing latitude.

2 The Froude number is defined as \(U/Nh_m\), where \(U\) is the wind speed component normal to the mountain ridge and \(N\) and \(h_m\) are defined as above.
low pressure systems. As an example, shallow coastal mesoscale low pressure systems that form along the African Highlands tend to progress along the southern end of the African continent in the marine layer, as a stable atmospheric stratification and the Coriolis force anchor these cyclones to the terrain (Reason and Jury 1990; Reason et al. 2001; cf. Fig. 1). While African terrain-tied cyclones have been examined previously, it is interesting to note the dearth of research on the African Highlands as a favored area for terrain-tied cold surges.

The area east of the African Highlands is potentially less favorable for cold surges compared to east of the Andes because the African Highlands are lower and less steep than the Andes, and the area east of the Highlands borders the relatively mild southwestern Indian Ocean where the Agulhas Current transports warm tropical ocean water equatorward. Thus, within the framework of a broad investigation of Southern Hemisphere cold surge pathways, it is of particular interest to compare the lesser-studied African Highlands cold surge pathway, with the archetypal Andes cold surge pathway. Additionally, Hoskins and Hodges (2005) have illustrated that while the maximum in Southern Hemispheric wintertime [June–August (JJA)] low-level anticyclogenesis occurs near the southern tip of South America, there is also a local maximum in low-level anticyclogenesis near the southern tip of Africa (their Fig. 9c).

The purpose of this paper is to examine preferential pathways for cold surges in South America and Africa given that both continents extend poleward of 30°S in the Southern Hemisphere. The well-established Andes pathway will be compared and contrasted with the much lesser studied African Highlands pathway from both a climatological and compositing perspective to identify and diagnose synoptic-scale similarities and differences. The remainder of the paper is organized as follows. Section 2 will outline the data and methodology used for the study of these cold surge pathways. Section 3 will describe, compare, and contrast the Andes and African Highlands pathways in terms of seasonality, latitudinal variability, and composite synoptic patterns, while section 4 will briefly examine secondary pathways to the east of the Brazilian Highlands and to the east of Madagascar. Section 5 will synthesize the results and place them into the context of previous research.

2. Data and methodology

To investigate preferred pathways for cold surges in South America and Africa, twice daily (0000 and 1200 UTC) data from a 25-yr subset (1977–2001) of the 2.5° × 2.5° 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) were analyzed. This 25-yr climatology comprises 18 262 unique analysis times. This study focuses on the 1977–2001 subset of the ERA-40 because there is a significant improvement in the Southern Hemisphere analyses after the introduction of satellites in 1977 (Uppala et al. 2005).

Since some of the preferred pathways for cold surges occur near water, it was necessary to analyze climatological SSTs using a 20-yr average (1982–2001) of the 1.0° × 1.0° National Oceanic and Atmospheric Administration (NOAA) optimal interpolation (OI), version 2, dataset (Reynolds et al. 2002). The OI dataset began in November 1981, resulting in the utilization of only 20 years of SST data compared to 25 years of ERA-40 data in this study.

Previous research has shown that equatorward cold surges are often shallow phenomena (e.g., Colle and Mass 1995; Garreaud 2001; Lupo et al. 2001). Therefore, preferred pathways for cold surges were identified by calculating the percentage of time when the 925-hPa temperature was less than 16°C. This temperature threshold was selected because it was deemed to best highlight the signature of terrain-channeled cold surge pathways in the Southern Hemisphere (i.e., the increased frequency of cold air east of high terrain relative to other regions at the same latitude).

An increased frequency of 925-hPa temperatures less than 16°C occurs to the east of the Andes Mountains, Brazilian Highlands, African Highlands, and Madagascar compared to other locations at the same latitudes (Fig. 2). These four equatorward-pointing noses of increased frequency of sub-16°C temperature occurrences indicate the pathways this study will examine, termed the Andes, Brazilian Highlands, African Highlands, and Madagascar pathways, respectively. All four pathways have high terrain located to the west that helps to channel cold air equatorward. Figure 2 reveals that the Andes and African Highlands pathways are the two most distinct. Thus, a majority of this analysis will focus on these two pathways. Also of note are the regions of increased frequency of 925-hPa temperatures less than 16°C over the eastern Atlantic and eastern Pacific,

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3 The 2.5° × 2.5° National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) re-analysis showed qualitatively similar results, but was found to be less realistic near high terrain.

4 Temperature thresholds higher than 16°C yielded less distinct signatures of terrain-channeled cold surge pathways, while thresholds lower than 16°C masked the meridional extent of the pathways indicated from analyses of individual cold surges (not shown).
extending to the equator (Fig. 2). However, since these frequency maxima are largely in response to cooler SSTs that affect equatorward-moving air masses on the eastern flank of the oceanic subtropical anticyclones rather than cold air moving equatorward along high terrain, these regions will not be considered.

Beginning at 30°S and progressing equatorward, a point was chosen every 5° of latitude within each pathway (Fig. 2; Table 1). These points were the closest grid points to the high terrain that had a surface elevation below 500 m in the ERA-40 dataset, so that 925 hPa is above ground at these locations (there is modest variation in model terrain height among the pathway points). These points will be utilized to identify characteristics of extreme cold events (ECEs), defined as the analysis times featuring the top 1% coldest 925-hPa temperatures at each point within each pathway from the ERA-40 climatology. The top 1% of coldest 925-hPa temperatures was chosen as a reference for cold events because it enables comparisons to points at similar latitudes in different pathways and allows for the examination of the extreme tail of the temperature distributions. Since the examination will focus on the coldest 1% of analysis times at each latitude point, not all of the same analysis times necessarily appear at each latitude point within a given pathway, although there is significant overlap. Thus, we will not explicitly be examining cold surge characteristics, but rather ECEs that are inferred to result from terrain-channeled synoptic-scale cold surges.

3. Andes versus African Highlands pathways

The Andes and the African Highlands pathways are the most evident pathways in South America and Africa, respectively (Fig. 2). Along the Andes pathway, at least 0.25% of all analysis times in the 25-yr climatology (i.e., 47 analysis times) have 925-hPa temperatures less than 16°C as far equatorward as 10°S. The Andes pathway curves northwest, paralleling the bend in the Andes Mountains near 20°S, clearly reflecting the trapping of cold air along the high terrain out to one Rossby radius of deformation (Pierrehumbert and Wyman 1985). Garreaud (2001) calculated the Rossby radius of deformation at 25°S along the Andes to be 800 km, consistent with the width of the Andes pathway (Fig. 2). Interestingly, even with relatively high average SSTs (24–27°C) along the eastern coast of Africa, the meridional extent of the African Highlands pathway is very similar to the Andes pathway at the 16°C threshold, with 0.25% of analysis times (i.e., 47 analysis times) exhibiting 925-hPa temperatures less than 16°C at 10°S (Fig. 2).

a. Seasonality of ECEs

An examination of the monthly frequency of ECEs reveals that for all latitude points along the Andes pathway, the vast majority of ECEs occur in July, the
peak of austral winter (Fig. 3a). ECEs are most likely to occur between May and September, which is not surprising given the coincidence of these months with Southern Hemisphere winter. However, the monthly frequency of ECEs along the African Highlands pathway (Fig. 3b) shows a slightly different distribution from the Andes pathway. The maximum number of ECEs for all latitude points within the African Highlands pathway occurs in July and August. This slightly later maximum frequency along the African Highlands pathway is likely due to the thermal moderation of cold air by the Indian Ocean that lies to the east of the African Highlands, resulting in a slight seasonal lag in maximum ECE frequency.

Since July is typically one of the coldest months in the Southern Hemisphere midlatitudes and features many ECEs along both the Andes and African Highlands pathways (Figs. 3a,b), the spatial representation of these
two pathways during July is examined using frequency plots of July 925-hPa temperatures less than 16°C (Figs. 4a,b). Relatively rare instances of terrain-channeled air crossing the equator along the Andes pathway are indicated (Fig. 4a), consistent with the findings of Parmenter (1976) and Liebmann et al. (2009). Individual case studies (not shown) confirm this cross-equatorial push of cold air on multiple occasions in July throughout the 25-yr climatology. Additionally, similar to the yearly perspective of the Andes pathway (Fig. 2), the Andes pathway in July bends toward the northwest, coincident with the profile of the Andes Mountains equatorward of 20°S (Fig. 4a), highlighting the relationship between terrain orientation and flow channeling.
Along the African Highlands pathway, instances of terrain-channeled cold air extending to near the equator are also evident in the July climatology (Fig. 4b). However, the 0.25% threshold for 925-hPa temperatures less than 16°C only stretches to around 5°S, not as far equatorward as the 0.25% contour along the Andes pathway. This shorter extent of the African Highlands pathway is perhaps due to the relatively high July SSTs off the East African coast that range from 24° to 27°C in association with the warm Agulhas Current. Also of interest is a second equatorward pathway of cold air along the eastern coast of Madagascar that eventually merges with the African Highlands pathway around 10°S (Fig. 4b; the Madagascar pathway will be discussed further in section 4).

b. Latitudinal variations of meteorological variables within pathways

1) 925-hPa TEMPERATURE

The characteristics of ECEs vary by latitude within the Andes pathway, especially with respect to frequency distributions of meteorological variables relative to the corresponding weighted climatological mean at each point (Fig. 5a). For example, the top 1% of cold analysis times at 30°S are associated with 925-hPa temperatures that span from −5.0° to 4.0°C. This range compares to a climatological mean of 12°C at the same latitude. Progressing equatorward within the Andes pathway, the distributions of ECE temperatures move closer to the weighted climatological mean and generally exhibit a smaller range. The ECE 925-hPa temperature distributions show a larger latitudinal dependence poleward of 10°S. When an ECE along the Andes pathway occurs at the equator, the 925-hPa temperature is generally only 2.0°–6.0°C colder than the climatological mean. Thus, at increasing latitudes there is a greater absolute 925-hPa temperature disparity between ECEs and climatology.

The ECE 925-hPa frequency distributions of meteorological variables relative to the weighted climatological means along the African Highlands pathway show different characteristics than those along the Andes pathway. The ECE 925-hPa temperature frequency distributions at all seven latitude points along the African Highlands pathway are more peaked than those along the Andes pathway (Figs. 5a,b). These narrower frequency distributions are manifestations of a smaller 925-hPa temperature variability of ECEs along the African Highlands pathway when compared to ECEs along the Andes pathway. For example, ECEs at 30°S along the African Highlands pathway feature only a 4.0°C 925-hPa temperature range (i.e., 4.0°–8.0°C), about half the range for ECEs at the same latitude within the Andes pathway (Figs. 5a,b). Additionally, the ECEs at latitudes poleward of 10°S occur at generally higher temperatures than those along the Andes pathway (Figs. 5a,b). The climatological mean 925-hPa temperatures at each latitude within the African Highlands pathway are clustered from 15° to 20°C (Fig. 5b). The generally warmer ECEs and the smaller variability at each point within the African Highlands pathway are likely the result of the moderating influence of the water that lies adjacent to the African Highlands pathway. Additionally, the poleward tip of Africa is located ~20° of latitude farther equatorward than the poleward tip of South America, allowing for more modification of equatorward-moving Antarctic air by the underlying water. This difference in continentality is likely why previous statistical analyses have found a negative skew for low-level temperature observations to the lee of the Andes but not to the lee of the African Highlands (Garreaud 2001). Finally, the African Highlands are not as tall as the Andes Mountains, so the cold air is not as easily blocked along the African Highlands pathway (i.e., the Froude number is higher).

2) 925-hPa MERIDIONAL WIND

For cold air to surge equatorward along the Andes pathway, a southerly wind component is required. The 925-hPa meridional wind frequency distributions for ECEs along the Andes pathway generally show moderate to strong southerly winds (Fig. 6a). However, especially at higher latitudes such as 30°S, a few ECEs occur with northerly meridional wind components as large as 15 m s⁻¹ (Fig. 6a). An examination of synoptic maps for individual ECEs (not shown) indicates that northerly flow ECEs often occur near the end of multiple-day cold surge events when, before temperatures moderate, a cold anticyclone begins to pull away from the high terrain of the Andes, inducing northerly winds along the leeward slopes while temperatures initially remain cold. In general, ECEs have a much broader 925-hPa meridional wind frequency distribution as latitude increases along the Andes pathway (Fig. 6a), a likely result of midlatitude synoptic-scale wave progression (e.g., Hoskins and Hodges 2005). An examination of the weighted climatological 925-hPa
meridional winds along the Andes pathway reveals winds that are generally weak and northerly (southerly) poleward (equatorward) of 10°S (Fig. 6a).

Similar to the Andes pathway, the ECE frequency distributions of 925-hPa meridional wind speed become broader at more poleward latitudes within the African Highlands pathway (Fig. 6b). Additionally, African Highlands ECEs are occasionally associated with northerly winds at higher latitudes as cold anticyclones begin to pull away from the African coast (not shown). Even though the magnitude of the southerly meridional winds associated with ECEs is generally stronger along the
African Highlands pathway than along the Andes pathway, allowing cold Antarctic air to be transported more quickly equatorward (Figs. 6a,b), the corresponding 925-hPa temperature is not as cold on average in response to moderation by the underlying ocean (Figs. 5a,b). The weighted climatological means of 925-hPa meridional wind along the African Highlands pathway are not clustered around 0 m s\(^{-1}\) as they are along the Andes pathway (Figs. 6a,b). Instead, the climatological mean increases steadily from around \(-2.0\) m s\(^{-1}\) at 30°S to 10 m s\(^{-1}\) at the equator (Fig. 6b). This equatorward progression to southerly climatological mean wind speeds is a reflection of the Somali jet stream that is located immediately off the east coast of Africa (Findlater 1969; Hart et al. 1978). Thus, the Somali jet stream influences the distribution of meridional wind associated with African Highlands ECEs.

3) 925–700-hPa LAPSE RATE

Since terrain-channeled cold surges are typically shallow phenomena, 925–700-hPa lapse rates can also be
used as a proxy for intensity. In general, ECEs are associated with higher stability than the weighted climatology, which is expected given the cold surface and boundary layer temperatures. For the latitudes nearest the equator, Andes ECEs are associated with 925–700-hPa lapse rates that are only 1.0°–2.0°C km\(^{-1}\) more stable than climatology (Fig. 7a). However, for latitudes poleward of 15°S, ECEs can be associated with a broad range of 925–700-hPa stability profiles, ranging from near climatology to extremely stable inversions where 925–700-hPa lapse rates approach −3.0°C km\(^{-1}\) (Fig. 7a). Typically, the most extreme ECEs are associated with the most stable lapse rates (not shown). The weighted climatological mean 925–700-hPa lapse rates along the Andes pathway decrease from around 5.5°C km\(^{-1}\), close to the typical 6.0°C km\(^{-1}\) moist adiabatic lapse rate in the subtropics (e.g., Stone and Carlson 1979), at the equator to 3.0°C km\(^{-1}\) at 30°S (Fig. 7a). This distribution likely reflects the influence of low-level cold Antarctic air that is often able to penetrate into the poleward latitudes of
the Andes pathway given that cold air is only moderated by warmer SSTs over a relatively short fetch.

Similar to the results for the Andes pathway, the ECE frequency distributions of 925–700-hPa lapse rates broaden at more poleward latitudes along the African Highlands pathway (Fig. 7b). However, the 925–700-hPa lapse rates at the most poleward latitudes within the African Highlands pathway are rarely stable enough to be indicative of an inversion (i.e., negative lapse rates). The relatively warm water that lies beneath the African Highlands pathway (Fig. 2) often modifies the cold Antarctic air so that ECEs are generally more moderate along the African Highlands pathway than along the Andes pathway (Figs. 5a,b). Additionally, since the southern tip of Africa is located near 30°S, Antarctic air has to traverse a longer distance of relatively warm water before even arriving at the African Highlands pathway when compared to air arriving at the Andes pathway, acting to truncate the tail of the lapse rate distributions at more poleward latitudes (cf. Figs. 7a,b). Thus, ECEs along the African Highlands pathway are associated with air masses that are typically not as stable at more poleward latitudes when compared to those along the Andes pathway. The 925–700-hPa lapse rate weighted climatology is notably different along the African Highlands pathway. The climatological 925–700-hPa lapse rate at all latitudes within the African Highlands pathway hovers around 5.0°C km⁻¹ (Fig. 7b), slightly lower than the typical 6.0°C km⁻¹ subtropical moist adiabatic lapse rate, again likely a reflection of the relatively warm SSTs beneath this pathway.

4) STANDARDIZED ANOMALIES

To provide an additional perspective on the comparison of ECEs along the Andes and African Highlands pathways, the mean and spread of the standardized anomalies (e.g., Hart and Grumm 2001) corresponding to the ECE 925-hPa temperature, 925-hPa meridional wind, and 925–700-hPa lapse rate are computed (Figs. 8a and 8b, respectively). The standardized anomaly for each variable at each point along the pathways is computed by subtracting the monthly weighted climatological mean from the ECE mean and then dividing by the monthly weighted standard deviation. Larger standardized anomalies of a given meteorological variable associated with ECEs are indicative of more extreme departures of the variable from climatology.

The standardized anomaly perspective reveals that in comparison to African Highlands pathway ECEs, Andes pathway ECEs are characterized by more extreme 925-hPa temperature, 925-hPa meridional wind, and 925–700-hPa lapse rates, particularly for locations equatorward of 20°S. Poleward of 20°S along the Andes pathway, the magnitudes of these three variables become less extreme as latitude increases. Along the African Highlands pathway, a similar reduction in the magnitude of the anomalies with latitude is seen for 925–700-hPa lapse rates, but not for 925-hPa temperature or meridional wind (Fig. 8b). Along the Andes pathway, mean 925-hPa temperature anomalies associated with ECEs equatorward of 20°S range between ~−2.5 and ~−4.5 standard deviations (SD; Fig. 8a). These
magnitudes are larger than the $\sim -2.3$ SD anomaly that would correspond to the top 1% of coldest temperatures for a standard Gaussian distribution (e.g., Wilks 2006, his Table B1), thus indicating that the 925-hPa temperature distribution along the Andes is negatively skewed. In contrast, mean 925-hPa temperature anomalies range between $\sim -2.0$ and $-2.5$ SD along the African High-lands pathway (Fig. 8b), consistent with a near-Gaussian 925-hPa temperature distribution. In addition, the high static stability associated with ECEs along the Andes pathway is more anomalous compared to along the African Highlands pathway: mean 925–700-hPa lapse rate standardized anomalies associated with ECEs equatorward of 20°S along the Andes pathway range between $\sim -1.5$ and $-4.0$ SD (Fig. 8a) versus $\sim -1.5$ and $-2.5$ SD for ECEs along the African Highlands pathway (Fig. 8b). Of interest is that for both 925-hPa temperature and 925–700-hPa lapse rates associated with ECEs along the Andes pathway, the most extreme anomalies in terms of standard deviations occur preferentially at 15°S (Fig. 8a). No similar preferred region for extreme anomalies is seen along the African Highlands pathway (Fig. 8b).

Both the Andes and African Highlands pathways tend to feature extreme 925-hPa southerly winds relative to climatology (Figs. 8a,b). The southerly 925-hPa wind associated with Andes pathway ECEs tends to be slightly more extreme than those associated with African Highlands ECEs equatorward of 20°S; the Andes pathway ECEs feature mean 925-hPa meridional wind SDs ranging from +1.5 to +2.5 (Fig. 8a), whereas African Highlands ECEs feature mean 925-hPa meridional wind SDs ranging from +1.0 to +2.0 (Fig. 8b).

The spread of the standardized anomalies associated with ECEs along the Andes and African Highlands pathways (Figs. 8a,b) reveals that, in general, the standardized anomalies of 925-hPa temperature for ECEs at a given point vary little compared to the standardized anomalies of 925–700-hPa lapse rate or 925-hPa meridional wind. Furthermore, the standardized anomalies of lapse rates for ECEs at a given point along the pathways vary the most among the three meteorological variables considered. The latter finding is consistent with results in Fig. 7 that indicate a large spread in raw lapse rates, and thus static stability, for ECEs at a given point along both the Andes and African Highlands pathways.

c. Synoptic-scale composites

As a complement to the climatological frequency distributions and standardized anomalies of various meteorological parameters associated with ECEs in the previous subsections, synoptic-scale composites associated with ECEs along both the Andes and African Highlands pathways are presented. These composites comprise all ECEs (i.e., the analysis times featuring the top 1% coldest 925-hPa temperatures within each pathway) at 15°S along the Andes (Figs. 9a,b) and African Highlands (Figs. 10a,b) pathways, respectively. The latitude of 15°S was chosen for compositing because of its location near the center of each pathway and because 15°S is a preferred latitude for extreme conditions associated with ECEs along the Andes pathway [see Fig. 8, section 3b(iv)]. ECE composites at other latitudes within the pathways exhibit minor differences from those at 15°S, but the results are qualitatively similar to those presented herein.

The synoptic-scale environment associated with ECEs along the Andes pathway clearly illustrates how 925-hPa cold air parallels the high terrain and bends westward with the Andes Mountains around 15°S (Fig. 9a). For ECEs along the Andes pathway the 20°C isotherm at 925 hPa nearly reaches the equator, while the 16°C isotherm extends to 10°S. Composite southerly and south-easterly 925-hPa winds of $\sim 12.5$ m s$^{-1}$ are present at 15°S within the Andes pathway, indicative of the advection of cold air equatorward. Note that around 30°S, 925-hPa composite winds are northerly, likely the result of veering winds in advance of the next approaching midlatitude system (not shown). Additionally, the equatorward advection of cold air results in composite 925–700-hPa lapse rates that are less than 2.0°C km$^{-1}$ from $\sim 35°$ to 10°S. In general, these ECEs are associated with extremely cold, stable air that surges poleward within approximately one Rossby radius of deformation from the Andes Mountains ($\sim 800$ km at 25°S; Garreaud 2001).

As a complement to the synoptic-scale composites (Fig. 9a), composite departures from the weighted climatology for the Andes pathway are computed (Fig. 9b). The composite ECE environment along the Andes pathway contains 925-hPa temperatures that are more than 12°C below normal (Fig. 9b). Southerly meridional winds are more than 10 m s$^{-1}$ stronger than normal, and 925–700-hPa lapse rates are in excess of 3.0°C km$^{-1}$ more stable than the weighted climatology along the Andes pathway. These large departures from climatology reflect the typically shallow nature of the cold air that comprises Andes pathway ECEs.

The composite synoptic-scale environment for ECEs along the African Highlands pathway also reveals that cold air tends to follow the high terrain (Fig. 10a). The equatorward nose of cold air is not as distinct as along the Andes pathway, perhaps in part due to the lower terrain of the African Highlands compared to the Andes Mountains (Figs. 2, 9a, and 10a). However, the 20°C isotherm extends farther northward along the African Highlands pathway than along the Andes pathway, actually crossing the equator (Figs. 9a and 10a). The 16°C
isotherm reaches to 10°S, similar to the Andes pathway. Intense southerly winds approaching 12.5 m s⁻¹ are present along most of the east African coast in the composite ECE pattern (Fig. 10a). Recall that the Somali jet stream is a climatological feature characterized by strong southerly winds in this region (e.g., Findlater 1969; Hart et al. 1978). Composite 925–700-hPa lapse rates of 3.0°–4.0°C km⁻¹ extend along much of the
African Highlands pathway (Fig. 10a), but are not quite as stable as those along the Andes pathway (Fig. 9a).

An examination of departures of meteorological variables from the weighted climatology for ECEs along the African Highlands pathway reveals a distinctly different pattern than for ECEs along the Andes pathway (Figs. 9b and 10b). Recall that composite 925-hPa temperatures associated with ECEs are similar along the Andes and African Highlands pathways (Figs. 8a and 9a). In contrast, the 925-hPa temperature departure from climatology is only 4.0°–6.0°C along the marine-influenced African Highlands pathway (Fig. 10b), about half the departure that was present along the Andes pathway (Fig. 9b). Further, even though actual 925-hPa meridional ECE wind speeds along both the Andes and African Highlands pathways approach 12.5 m s⁻¹ (Figs. 9b and 10b).
The entrance region of a 50 m s$^{-1}$ east of a 250-hPa ridge in a region of quasigeostrophic forcing is located near the local maximum in JJA anticyclogenesis identified by Hoskins and Hodges (2005). Furthermore, the anticyclone is located to the poleward of the anticyclogenesis. The composite anticyclone location is similar to the maximum in JJA anticyclogenesis discussed by Hoskins and Hodges (2005). In addition, the center of the composite anticyclone is situated in the poleward-entrance region of a 50 m s$^{-1}$ 250-hPa jet stream, with the surface anticyclone spreading equatorward along the Andes in association with the Andean ECEs. The presence and configuration of the upper-level jet stream is similar to that found by Lupo et al. (2001) in their type-2 dynamically forced cold surge events. This ECE composite reveals the strong synoptic-scale dynamical forcing aloft associated with the ECEs along the Andes pathway.

The composite environment associated with ECEs along the African Highlands pathway reveals a slightly weaker ~1026-hPa anticyclone along the southeast African coast (Fig. 11b). Once again, this composite anticyclone is located near the local maximum in JJA anticyclogenesis. The anticyclone is located to the east of a 250-hPa ridge in a region of quasigeostrophic forcing. The 250-hPa ridge is not quite as amplified in the African Highlands composite (Fig. 11b), and the 250-hPa jet stream is slightly farther to the east of the African Highlands pathway when compared to its location relative to the Andes pathway, suggesting slightly weaker forcing for anticyclogenesis. However, in general, ECEs along both pathways appear to have dynamical support from the upper troposphere, resulting from similarly oriented synoptic-scale flow patterns.

4. Brief discussion of secondary pathways

An examination of the plot of 925-hPa temperature frequency <16°C for South America and Africa (Fig. 2) reveals two additional pathways for equatorward cold surges that are not as distinct as the previously discussed Andes and African Highlands pathways. These secondary pathways are located to the east of the Brazilian Highlands and Madagascar, respectively. An increased equatorward frequency of 925-hPa temperatures less than 16°C is evident along both the Brazilian Highlands and Madagascar pathways. These secondary pathways are clearer when investigating the July frequency of 925-hPa temperatures less than 16°C. During July, the Brazilian Highlands pathway stretches to nearly 5°S (Fig. 4a), whereas the Madagascar pathway appears to merge with the more distinct African Highlands pathway equatorward of Madagascar (Fig. 4b).

a. Brazilian Highlands pathway

Along the Brazilian Highlands pathway, ECEs occur most frequently during July and August at all latitudes (Fig. 12a). At all latitude points along the Brazilian Highlands pathway except at 5°S, the frequency of ECEs during July (~40%) is very similar to the frequency at the same latitudes along the Andes pathway (cf. Fig. 3a). However, August has a higher frequency of ECEs at all latitude points along the Brazilian Highlands pathway than along the Andes pathway (Figs. 3a and 10a). The relatively high frequency of ECEs in August along the Brazilian Highlands pathway is likely a result of the moderating influence of the South Atlantic Ocean, which underlies this pathway, and only allows ECEs to occur between May and October. This shift to a slightly later ECE maximum and the tighter window for their occurrence is very similar to that seen for ECEs along the ocean-modified African Highlands pathway (Fig. 3b).

The 925-hPa temperature frequency distributions of the ECEs relative to the weighted climatological means along the Brazilian Highlands pathway (Fig. 12b) fall between those along the Andes and African Highlands pathways (Figs. 5a,b). For example, at 30°S, 925-hPa temperatures associated with ECEs along the Brazilian Highlands pathway range from ~2.0° to 4.0°C, compared to a weighted climatological mean of 11°C (Fig. 12a). Especially at higher latitudes, the ECEs along the Brazilian Highlands pathway can be associated with lower temperatures than along the African Highlands pathway (Fig. 5b), but are not associated with temperatures as low as those along the Andes pathway (Fig. 5a). The 925-hPa temperature frequency distributions for ECEs along the Brazilian Highlands pathway likely fall between those of the other two pathways due to one of the
trajectories that cold air follows to arrive at the high terrain of the Brazilian Highlands. Cold air crosses the South American continent, whose southern extent is more poleward than Africa. Therefore, air masses associated with ECEs along the Brazilian Highlands pathway often start and remain colder than those along the African Highlands pathway. However, because the South Atlantic Ocean is located to the east of the Brazilian Highlands pathway, this cold air is likely moderated more quickly than along the Andes pathway. Thus, the ECEs along the Brazilian Highlands are not as cold as those along the Andes pathway.

Case study analyses (not shown) reveal that synoptic-scale systems that lead to ECEs along the Brazilian

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**FIG. 11.** Composites of sea level pressure (red dashed lines every 2 hPa), 250-hPa height (black lines every 12 dam), and 250-hPa wind (shaded in m s$^{-1}$) for all ECEs along (a) the Andes pathway at 15°S, 65°W (black dot) and (b) the African Highlands pathway 15°S, 40°E (black dot).
Highlands pathway are sometimes associated with ECEs along the Andes pathway two or three days earlier, suggesting that an initial continental source for cold air can affect ECEs along the Brazilian Highlands pathway. For example, ~24% (~26%) of ECEs at 20°S along the Brazilian Highlands pathway occur within two days (three days) of an ECE at 20°S along the Andes pathway. It is speculated that the overlap between ECEs along the Andes and Brazilian Highlands pathways is not larger due in part to the pronounced terrain-channeling effect of the Andes. While cold air still progresses eastward toward the Brazilian Highlands, the coldest air remains trapped along the Andes. Many of the other ECEs along the Brazilian Highlands pathway are associated with a cold anticyclone that is positioned a bit farther eastward (not shown) than the one associated with ECEs along the Andes pathway (Fig. 11a).

b. Madagascar pathway

Since the island of Madagascar spans about 10° of latitude, only three points are analyzed along the
Madagascar pathway, at 25°S, 20°S, and 15°S (inset in Fig. 13a). Along the Madagascar pathway, ECEs occur most frequently in August, and almost all occur between June and October (Fig. 13a). This time-of-year frequency distribution is similar to the African Highlands pathway, where the highest frequency of ECEs occurs during July and August (Fig. 3b). The Madagascar pathway begins 5° of latitude farther equatorward than the African Highlands pathway, and thus, cold air needs to cross more water before reaching the island. The moderating influence of this water likely plays a role in shifting the maximum month for ECEs to August along the Madagascar pathway.

The 925-hPa temperature frequency distribution of ECEs along the Madagascar pathway is similar to that along the African Highlands pathway (Figs. 5b and 13b). For example, 925-hPa temperatures associated with ECEs at 25°S along the Madagascar pathway span about 7.0°–11°C, and compare to a weighted climatological mean of ~15°C (Fig. 13b), whereas at the same latitude along the African Highlands pathway, 925-hPa temperatures associated with ECEs span about 5.0°–11°C, and compare...
to a weighted climatological mean of ~17°C (Fig. 5b). These similar values likely result from the close proximity of the two pathways to one another. Furthermore, just as along the African Highlands pathway, the Indian Ocean lies beneath the Madagascar pathway. Case study examples (not shown) reveal that many of the same synoptic-scale systems that cause ECEs along the African Highlands pathway also induce ECEs along the Madagascar pathway. For example, ~40% of ECEs at 20°S along the Madagascar pathway occur within two days following an ECE at 20°S along the African Highlands pathway. As mentioned previously, the Madagascar pathway appears to merge with the African Highlands pathway on the equatorward side of Madagascar.

5. Discussion and synthesis

a. Statistical viewpoint and pathway characteristics

The Andes pathway for ECEs has been documented extensively in the literature, in part because of the detrimental effects that cold surges have on the agricultural industry across South America (e.g., Marengo et al. 1997a,b). Additionally, the Andes pathway is well defined in an analysis of low-level temperature standard deviation and skewness (Garreaud 2001, his Fig. 4). Garreaud (2001) shows that the Andes pathway is represented by a high wintertime standard deviation and a skewness toward low temperatures, which are the result of cold surges that progress equatorward to the lee of the Andes Mountains. The results presented herein show that ECEs along the Andes pathway can feature 925-hPa temperatures that are 17°C lower than the weighted climatological mean at 30°S (Fig. 5a). Furthermore, the strongly negative 925-hPa standardized temperature anomalies (i.e., between ~−2.5 and ~−4.5 SD) associated with ECEs along the Andes pathway equatorward of 20°N (Fig. 8a) are indicative of a strong negative skewness in 925-hPa temperature distribution. The findings herein are consistent with the high variability in low-level temperature along the Andes pathway that Garreaud (2001) identified, and indicate that the relatively high temperature variance east of the Andes is linked to the occurrence of cold surges and associated ECEs along the landlocked pathway to the east of the tall Andes Mountains.

In contrast to the Andes pathway, the African Highlands pathway has not received much mention in the refereed literature. Garreaud (2001) shows that there is a moderately high wintertime standard deviation of low-level temperature along the African Highlands pathway, but the standard deviation is not nearly as high as along the Andes pathway (his Fig. 4). This difference is corroborated by the findings shown in Fig. 8. Even though cold surges and ECEs along the African Highlands pathway are not as intense or frequent as compared to those along the Andes pathway, likely due to lower terrain and marine modification, they are found to exhibit many similar low-level meteorological characteristics. For example, although the 925-hPa low-level composite ECE temperatures do not depart as substantially from the weighted climatological mean (i.e., ~6°C, Fig. 10b), these low temperatures are advected equatorward by anomalously strong southerly meridional winds along the African Highlands pathway in a similar manner as noted for ECEs along the Andes pathway (Figs. 8 and 9b). Thus, although the ECEs along the African Highlands pathway are not reflected as a sharp tail of a negatively skewed frequency distribution, they do still occur.

The results presented herein show that ECEs along both the Andes and African Highlands pathways feature similar looking upper-level patterns that are conducive to strong dynamical support for surface anticyclogenesis in conjunction with quasigeostrophic forcing for descent near a poleward jet entrance region. However, this dynamical support appears to be somewhat stronger for Andes ECEs, perhaps contributing to their increased intensity. Additionally, the significant variations in the structure and intensity of ECEs between these two pathways are also driven by low-level differences. For example, the African Highlands pathway occurs along shorter terrain (implying a higher Froude number for similar winds and stabilities) than the Andes pathways. Furthermore, the African Highlands pathway is located above relatively warm southwestern Indian Ocean waters that allow for thermal modification of cold Antarctic air. Finally, even though the southerly winds associated with ECEs along the African Highlands pathway are stronger than those associated with Andes ECEs, most of this difference is merely a reflection of the low-level Somali jet stream, a climatological feature located off the eastern coast of Africa (Findlater 1969).

b. ECEs at different latitudes

Many previous papers have identified the synoptic-scale characteristics of cold surges (e.g., Colle and Mass 1995; Schultz et al. 1997, 1998; Lupo et al. 2001). However, one of the benefits of examining ECEs at different latitudes within the same pathway, as is done in this study, is the ability to understand how a “cold event” changes based on its equatorward latitudinal penetration. Along the Andes pathway, ECEs, or the top 1% of cold analysis times at 925 hPa, feature a narrower range of 925-hPa temperatures with decreasing latitude (Fig. 5a), just as the overall skewness of the entire 25-yr climatology decreases with decreasing latitude (e.g., Garreaud 2001).
Additionally, the 925-hPa temperatures associated with ECEs depart less from the weighted climatology at lower latitudes within the Andes pathway. These Andean 925-hPa temperature distributions do not change in a linear fashion from south to north within the pathway. In fact between 15° and 20°S the distribution of ECEs “jumps,” with ECEs at more poleward latitudes associated with cold air at the core of the dynamically driven surface anticyclone (Fig. 11a) and those farther equatorward associated with the trapped cold air that funnels around the bend in the Andes terrain. Not only do 925-hPa temperature ECE frequency distributions narrow with decreasing latitude, but the 925-hPa meridional wind and 925–700-hPa lapse rate frequency distributions narrow as well (Figs. 6a and 7a). The broad 925-hPa meridional wind frequency distributions at higher latitudes are likely the result of meridional wind variations associated with synoptic-scale waves that tend to pass at more poleward locations, while the broad stability profiles at higher latitudes are closely related to the broad 925-hPa temperature frequency distributions at the same latitudes. Thus, an “extreme event” is not the same in terms of departures of meteorological variables from climatology at each latitude within the Andes pathway. Along the African Highlands pathway, ECEs feature 925-hPa temperature frequency distributions that also move closer to the weighted climatological mean with decreasing latitude (Fig. 5b). However, these 925-hPa temperature frequency distributions only become slightly narrower with decreasing latitude. These frequency distributions likely remain peaked at higher latitudes because the climatological frequency distribution of low-level temperature along the African Highlands is not negatively skewed as it is along the Andes pathway (Garreaud 2001) as a result of thermal modification from below. However, the 925-hPa meridional wind and 925–700-hPa lapse rate frequency distribution do both broaden with increasing latitude (Figs. 6b and 7b). Just as along the Andes pathway, this frequency distribution broadening is likely a result of increasing synoptic-scale wave activity at farther poleward latitudes.

c. Further work and opportunities

The work presented herein compares and contrasts preferred pathways for ECEs in South America and Africa from a climatological and synoptic-dynamic meteorology perspective. A natural extension of this work would be to use case studies and time-lagged composite analyses of cold surge cases comprising ECEs to evaluate in more detail the characteristics of cold surges (e.g., phase speed, zonal extent, temporal evolution, etc.) along the Andes and African Highlands pathways. Additionally, recent research by Liebmann et al. (2009) has shown that cold surges along the Andes pathway that reach equatorial regions can sometimes result in a region of precipitation that propagates eastward with characteristics similar to that of a convectively coupled Kelvin wave. Given that both the Andes and African Highlands pathways extend to the equator, a further examination of the atmospheric effects of cold surge events that approach and cross the equator may be enlightening.

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REFERENCES


