A Midlatitude Climatology and Interannual Variability of 200- and 500-hPa Cut-Off Lows

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ABSTRACT

A climatology of midlatitude 200- and 500-hPa cut-off low systems in the Northern and Southern Hemispheres is constructed from the NCEP–NCAR reanalysis by detecting and tracking, under one consistent method, all of the systems that persisted for more than 36 h for the 58 years of 1960–2017. This method identifies a cut-off low as a cold-core geopotential height minimum that is isolated from the main westerlies and with a strong temperature gradient on its eastern flank. The obtained spatial and seasonal distributions show preferred regions of occurrence and that within these regions there is a level-dependent seasonality of cut-off lows. Whereas 200-hPa systems are more frequent in summer and autumn, 500-hPa systems are more evenly distributed throughout the seasons. Within each region and at each level, the annual number of cut-off lows has been increasing over time, trends that are consistent with documented signals of climate change such as a weakening and poleward shift of the subtropical jets and an increase in blocking frequency. These trends explain as much as 64% of the variance in the annual number of cut-off lows. The contribution of the annular modes and El Niño–Southern Oscillation to the interannual variability of the number of cut-off lows per season in each hemisphere is also investigated. Only the Northern Hemisphere annular mode has a statistically significant negative correlation throughout all seasons that explains 18%–45% of the variance in the yearly number of Northern Hemisphere 500-hPa cut-off lows.

1. Introduction

Cut-off low systems are upper-level low pressure centers formed on the equatorward side of the polar or subtropical jet stream. These systems develop from a breaking Rossby wave in the form of a trough that experiences a marked tilting and subsequent breaking off, leaving a pool of cold air and cyclonic circulation detached from the extratropical jet (e.g., [Palmén and](#)

[Newton 1969](#); [Nieto et al. 2005](#); [Gimeno et al. 2007](#)). In the Northern Hemisphere, cut-off lows tend to occur over southern Europe and the eastern Atlantic coast, the China–Siberia region, the eastern North Pacific Ocean, and western North America (e.g., [Bell and Bosart 1989](#); [Price and Vaughan 1992](#); [Kentarchos and Davies 1998](#); [Nieto et al. 2005](#)). On the other hand, Southern Hemisphere cut-off lows are most frequent around the continental landmasses but especially over southeast Australia–New Zealand, southern South America, and southern Africa (e.g., [Fuenzalida et al. 2005](#); [Reboita et al. 2010](#); [Favre et al. 2012](#); [Pinheiro et al. 2017](#)).

In all these regions, cut-off lows are often associated with high-impact weather. For instance, [Bozkurt et al.](#)

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TABLE 1. Summary of multidecadal climatologies of cut-off low systems.

Reference	Period	Region	Level	Method
Parker et al. (1989)	36 years (1950–85)	24°–82°N	500 hPa	Geopotential height minimum
Bell and Bosart (1989)	23 years (1963–85)	20°–70°N	500 hPa	Geopotential height minimum
Smith et al. (2002)	47 years (1953–99)	Northern Hemisphere and Northeast United States	500 hPa	Geopotential height minimum
Nieto et al. (2005)	41 years (1958–98)	20°–70°N	200 hPa	Conceptual model of cut-off lows
Fuenzalida et al. (2005)	31 years (1969–99)	60°–10°S	500 hPa	Geopotential height minimum
Wernli and Sprenger (2007)	15 years (1979–93)	Northern Hemisphere	320–350 K	Closed contours of PV
Singleton and Reason (2007)	30 years (1973–2002)	Southern Africa	300 hPa	Geopotential height charts
Reboita et al. (2010)	21 years (1979–99)	50°–20°S	200, 300, and 500 hPa	Conceptual model of cut-off lows
Ndarana and Waugh (2010)	30 years (1979–2008)	50°–20°S	250 hPa	Geopotential height minimum
Favre et al. (2012)	30 years (1979–2008)	45°–10°S	500 hPa	Geopotential height minimum
Pinheiro et al. (2017)	36 years (1979–2014)	40°–15°S	300 hPa	Geopotential height minimum
Present study	58 years (1960–2017)	50°–20°S and 20°–70°N	200 and 500 hPa	Conceptual model of cut-off lows

(2016) associated an early autumn 500-hPa cut-off low with a flooding event in Chile's Atacama region (around 26°S in western South America) that left 31 dead, 16 people missing, and 16 588 people affected (ONEMI 2015). In Europe, Llasat et al. (2007) found that 7 of the 22 most “catastrophic” floods in Mediterranean Spain between 1950 and 2000 were associated with cut-off lows. Thus, the study of cut-off lows is key to reducing their negative impacts.

The mechanism by which a cut-off low may lead to a flooding event is driven by its polar origin. As the upper-level low reaches the warmer midlatitudes, the air column beneath the low destabilizes because of the cold air above (Hoskins et al. 1985). This destabilization of the lower levels may lead to a sudden development of deep convection, provided there is enough moisture supply and ascent, especially around the equatorward and eastern flank of the cut-off low (e.g., Price and Vaughan 1993; Antonescu et al. 2013; Škerlak et al. 2015; Vaughan et al. 2017). Other phenomena associated with cut-off lows are strong winds and snowfall around high-elevation mountain ranges such as the Andes (Vuille and Ammann 1997) and stratosphere–troposphere exchange through three mechanisms: convective erosion of the tropopause if convection beneath the cut-off low is deep enough so that a convective cell can erode the tropopause, clear-air turbulence on the sheared sides of the jet streak (from which cut-off lows form), and tropopause folding as the jet streak moves into a trough (Price and Vaughan 1993). Regardless of the mechanism involved, stratospheric–tropospheric exchange implies that, during the passage of a cut-off low, stratospheric air moves from the lower stratosphere into the troposphere.

This movement has been associated with increased ozone concentrations in midlatitude and subtropical areas (e.g., Gimeno et al. 1999; Rondanelli et al. 2002).

Traditionally, cut-off lows have been identified either as isolated cold-core geopotential height minima, located equatorward from the main westerlies on a certain isobaric surface, or, through the potential vorticity (PV) framework (Hoskins et al. 1985), as isolated PV maxima in the Northern Hemisphere (or minima in the Southern Hemisphere) located equatorward of the jet on a certain isentropic surface (Table 1). Because PV is a conserved quantity for a parcel that experiences no friction under adiabatic conditions (Hoskins et al. 1985), the use of the PV framework to define a cut-off low on a single isentropic surface has at least two advantages with respect to using a single isobaric surface: 1) tracing the low from its high-latitude origin in the stratospheric reservoir down to lower latitudes, and 2) providing a better representation of the Rossby wave-breaking process that leads to cut-off low genesis (Thorncroft et al. 1993).

Even though the use of the PV framework to define a cut-off low has become more frequent in recent years (e.g., Hernández 1999; Cuevas and Rodríguez 2002; Wernli and Sprenger 2007; Ndarana and Waugh 2010), most of the existing multidecadal climatologies of cut-off lows use an approach based on geopotential height maps (Table 1). The geopotential height approach, however, varies greatly among studies because of different criteria used to define cut-off lows. For instance, whereas Fuenzalida et al. (2005) used first and second derivatives of a continuous 500-hPa geopotential height field and a visual inspection to define a cut-off low from their 31-yr dataset, Price and Vaughan (1992) defined a

200-hPa cut-off low from their 5-yr dataset as any closed cyclonic geopotential contour or any closed circulation evident in the wind vectors.

Regardless of the criteria used to define a cut-off low on an isobaric surface, a key difference regarding the seasonality of cut-off low occurrence has been found between the middle and upper troposphere in both the Northern and Southern Hemispheres. For instance, whereas the frequency of 500-hPa cut-off lows in southern Africa and South America is a minimum during summer (Fuenzalida et al. 2005), 200-hPa cut-off lows in the same regions are least frequent during winter (Reboita et al. 2010; Pinheiro et al. 2017). A further example, but in the Northern Hemisphere, can be found in western North America. Whereas Bell and Bosart (1989) and Oakley and Redmond (2014) documented a summer minimum in the frequency of 500-hPa cut-off lows there, Nieto et al. (2005) found a summer maximum in the frequency of 200-hPa cut-off lows in this region.

Thinking that this level-dependent seasonality might be a consequence of the different regions, datasets, time periods used, or even criteria to define a cut-off low, Reboita et al. (2010) examined 200-, 300-, and 500-hPa cut-off lows in the Southern Hemisphere under one consistent method during the 21-yr period of 1979–99. They found this level-dependent seasonality regardless of the dataset used, a feature that Ndarana and Waugh (2010) associated with the dissimilar influence of the subtropical and polar-front jets on the Rossby wave-breaking events from which 250- and 500-hPa cut-off lows tend to form. Specifically, as the subtropical and polar-front jets act as waveguides for Rossby waves (i.e., the meridional growth of the Rossby wave's amplitude is restricted by the strength of the jet) (Hoskins and Ambrizzi 1993), Ndarana and Waugh (2010) found that Rossby wave-breaking events on the 310- and 330-K isentropic surfaces, driven by both the polar-front jet and the subtropical jet, were more likely to contribute to the occurrence of 500-hPa cut-off lows than to the occurrence of 250-hPa cut-off lows. These 250-hPa cut-off lows, instead, were more associated with Rossby-wave breaking events on the 330- and 350-K isentropic surfaces, which are mainly driven by the subtropical jet. As the subtropical jet moves poleward and intensifies in winter, Ndarana and Waugh (2010) argued that the seasonality of the subtropical jet is key for explaining the winter minimum and summer maximum in the frequency of 250-hPa cut-off lows. This relationship between the frequency of cut-off lows and the strength of the jet, however, has only been examined for the Southern Hemisphere under the PV framework, so there is no evidence that the level-dependent seasonality

of cut-off lows can be extended to the Northern Hemisphere.

Table 1 summarizes results from previous climatologies of cut-off lows. These studies have used different methods, studied only parts of the globe, analyzed different levels, and have had different time periods of analysis (some as short as 15 years). The novelty of the present study is that we will produce a large homogeneous dataset using one consistent method, one reanalysis, consistent levels, and the same time period to resolve discrepancies and gaps in the previous literature. The time period studied, 1960–2017, will be the longest period of cut-off lows analyzed (Table 1). Thus, the first goal of this paper is to assess the level-dependent seasonality of cut-off lows in both the Northern and Southern Hemispheres to detect 200- and 500-hPa cut-off lows. The choice of these pressure levels in particular is because in midlatitudes the 200-hPa level is usually within the lower stratosphere or the upper troposphere (Wilcox et al. 2012), making the detection of 200-hPa cut-off lows useful for studying the stratosphere–troposphere exchange associated with these systems (e.g., Price and Vaughan 1992). On the other hand, the choice of the 500-hPa level is because this level has been widely used in previous climatologies (Table 1), as the flow at 500 hPa is below the tropopause and steers weather systems affecting midlatitudes. Also, because the 500-hPa level is close to the summit of major mountain ranges such as the Andes (South America) or the Rockies (North America), this level is useful for establishing the effect of mountain ranges on cut-off low development, as Garreaud and Fuenzalida (2007) did through a modeling study of a 500-hPa cut-off low westward of the Andes. They found that the Andes delays the demise of a cut-off low by blocking the inflow of moist continental air that would otherwise initiate deep convection.

Additionally, because previous multidecadal climatologies show a positive and statistically significant trend in the annual number of cut-off lows for Southern Hemisphere regions (Fuenzalida et al. 2005; Favre et al. 2012) but no statistically significant trend for Northern Hemisphere regions (Nieto et al. 2007; Hu et al. 2010; Oakley and Redmond 2014), the second goal of this paper is to examine the interannual variability of the number of 200- and 500-hPa cut-off lows in all the main regions of occurrence to check whether the difference seen in the trends between Northern and Southern Hemisphere cut-off lows is due to the different methods of cut-off low detection. Last, the third goal of this paper is to use our dataset to explore the linear relationship between cut-off low occurrence across each hemisphere and the main planetary modes of climate variability.

This linear relationship is expected to be strong, as cut-off lows should be more frequent when the Rossby wave-breaking events and blocks are favored with a less zonal and weaker jet stream (Ndarana and Waugh 2010), such as during La Niña (Trenberth et al. 1998) or during the negative phase of the Arctic or Antarctic Oscillation (AO or AAO, respectively) (Thompson and Wallace 1998, 2000). However, statistically significant correlations have not been found when exploring the link between the yearly number of cut-off lows and the main planetary modes of climate variability in Europe (Nieto et al. 2007) or in the Southern Hemisphere regions (Fuenzalida et al. 2005), although Singleton and Reason (2007) found an increased number of 300-hPa cut-off lows over southern Africa during La Niña. This lack of statistically significant correlations implies that the link between planetary modes of climate variability and cut-off lows is still unresolved in both hemispheres.

This paper is organized as follows. Section 2 presents the dataset and describes the criteria that a grid point embedded near the center of a cut-off low must fulfill to be considered a cut-off low grid point. In section 3, the spatial distribution of these lows is assessed and compared with existing climatologies for two isobaric surfaces, and regions are defined for each level following areas with the greatest frequency of cut-off lows. Section 4 describes the annual cycle within these regions and shows the level-dependent seasonality of cut-off lows in both the Northern and Southern Hemispheres. Section 5 continues the analysis of cut-off lows within each region, but with a focus on the interannual variability on each level, discusses how this interannual variability is affected by the assimilation of satellite information in our dataset, and presents the trends. Finally, section 6 summarizes the paper and provides a few ideas for further research.

2. Data and methods

The climatology presented here is based on the conceptual model of cut-off lows described in Nieto et al. (2005) and Reboita et al. (2010) but applied to 200- and 500-hPa cut-off lows. The reason for not using a PV approach to detect cut-off lows on specific isentropic surfaces is that PV anomalies are not always associated with the arrival of an upper-level low, as these anomalies can also be a consequence of local heating (e.g., Wernli and Sprenger 2007). Thus, the conceptual model used here characterizes a cut-off low as a cold-core geopotential height minimum isolated from the main westerlies and possessing a highly baroclinic area eastward of the system (Fig. 1).

To detect cut-off lows, we extracted geopotential height, temperature, and zonal wind fields at the 200-,

FIG. 1. Schematic of the conceptual model used to detect cut-off lows (illustrated for the Northern Hemisphere, but applicable for the Southern Hemisphere as well). The letter “L” represents the position of the upper-level low in the geopotential height field (blue solid lines). Blue arrows represent the wind direction in every geopotential height contour, whereas the orange arrow and the green line represent the warm advection responsible for the thickness ridging and the baroclinic region eastward of the low, respectively.

300-, 500-, and 600-hPa levels from the four-times-daily National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global reanalysis data (Kalnay et al. 1996). This dataset has a horizontal grid spacing of 2.5° , allowing the identification of all cut-off lows whose longitudinal extension is larger than around 261 km (at 20°N and 20°S) and whose latitudinal extension is larger than around 278 km. This horizontal extension is large enough to capture cut-off lows, as their size is usually between 600 and 1200 km (Kentarchos and Davies 1998).

The climatology covers the 58-yr period 1960–2017 (the longest period of a previous study was 47 years in Table 1) and focuses on midlatitudes of the Northern and Southern Hemispheres. For the Northern Hemisphere, the study region covers from 20° to 70°N , whereas for the Southern Hemisphere the study region covers from 50° to 20°S . The reason to exclude cut-off lows detected poleward of these regions is because a visual inspection revealed those lows were not detached from the polar regions. Likewise, cut-off lows within the tropical belt (20°N to 20°S) were excluded as tropical cold-core cyclonic vortices differ from subtropical cut-off lows (Kousky and Gan 1981). Specifically, whereas subtropical cut-off lows tend to move eastward and form from the equatorward excursion of a trough, tropical vortices such as those that occur over northeastern Brazil tend to move westward and form, instead, from a narrow shear zone caused by the intensification of the Bolivian high and of the South Atlantic trough (Mishra et al. 2001).

The detection algorithm characterizes a candidate grid point as a cut-off low provided the following criteria are fulfilled (Figs. 1 and 2).

- 1) The candidate grid point must have a geopotential height that is at least 10 geopotential meters lower than the geopotential height in at least six of the eight surrounding grid points (Fig. 2a). This condition ensures the candidate grid point is a local geopotential height minimum.
- 2) There must be easterly flow in at least one of the four grid points located poleward of the candidate grid point (Fig. 2b). Regardless of the intensity of the easterly flow, this condition ensures that the candidate grid point is also isolated from the main westerly wind. We did not consider the meridional wind because, unless the cut-off low is embedded in a pure westerly flow, the meridional wind around the cut-off low is not an indicator of isolation from the main westerlies.
- 3) The candidate grid point must have a cold core and a thickness ridge eastward of the low. The existence of this thickness ridge is to ensure the thickness of the layer (i.e., 200–300 hPa for 200-hPa cut-off lows, 500–600 hPa for 500-hPa cut-off lows) located below the candidate grid point is lower than the thickness of the layer located immediately eastward (Fig. 2c).
- 4) A frontal zone must be found on the eastern flank of cut-off lows (Nieto et al. 2008). To identify this frontal zone, we used the thermal front parameter (TFP), defined by Renard and Clarke (1965) as the change of the temperature gradient in the direction of the temperature gradient. Whereas negative values of TFP are associated with polar air, positive values of TFP are associated with warm air, and the zero value represents the position of the frontal zone where the temperature gradient is maximum (Fig. 2d). The TFP is calculated at every grid point and level as a function of temperature T according to

$$\text{TFP} = -\nabla|\nabla T| \cdot \left(\frac{\nabla T}{|\nabla T|} \right).$$

Although the aforementioned criteria can be applied to detect cut-off lows in both hemispheres, synoptic experience shows that the main axis of Southern Hemisphere cut-off lows have a greater westward tilt than their Northern Hemisphere counterparts (Reboita et al. 2010). Indeed, the geopotential height distribution around 500-hPa cut-off lows in the Southern Hemisphere tends to be more asymmetric than in the Northern Hemisphere (Fig. 3). This asymmetry modifies the orientation of the temperature gradient, and as a

consequence the grid point to the east of the geopotential height minimum in the Southern Hemisphere does not usually have higher values of TFP and thickness, causing an underestimation in the number of cut-off lows detected in the Southern Hemisphere. Therefore, following Reboita et al. (2010) for each candidate grid point in the Southern Hemisphere, the thickness of the atmospheric layer below was compared with nine points to the northeast (Fig. 4c), and the corresponding TFP was compared with six points to the east (Fig. 4d). Once the modified criteria were applied to detect Southern Hemisphere cut-off lows, a sensitivity analysis consisting of detecting Southern Hemisphere 200-hPa cut-off lows during 2017 with the original criteria and with the modified criteria was applied. Whereas the original criteria detected 26 events during 2017, which were mostly clustered around southeastern Australia, the modified criteria detected 88 events distributed across the Southern Hemisphere (Fig. 5). Thus, the use of the modified criteria is justified as these criteria are more likely to detect Southern Hemisphere cut-off lows.

The adjustment of the criteria for detecting Southern Hemisphere cut-off lows does not affect the capability of the method of detecting cut-off lows that would also be detected with a non-automated method. An example is given in Fig. 6, where a cold-core closed geopotential height contour impinging upon northern Chile is successfully identified as a cut-off low, consistent with non-automated methods of detection (e.g., Price and Vaughan 1992; Kentarchos and Davies 1998). Once all the grid points that satisfied the above criteria were flagged as cut-off lows, a tracking algorithm was implemented to assess their position at every time step (Fig. 6). This tracking algorithm was the same as that described in Nieto et al. (2005) and was developed considering the following criteria:

- 1) For a given time step, several candidate grid points flagged as cut-off lows belonged to the same event when these points were next to each other or if two or more events have at least one grid point in common. Likewise, two cut-off lows were independent events if they did not share any grid points or if none of the grid points that belonged to one event were next to any of the grid points from the other event.
- 2) Because cut-off lows tend to be quasi-stationary or have a translational speed lower than 10 m s^{-1} (Fuenzalida et al. 2005; Reboita et al. 2010), it is unlikely that, during a 6-h period, a cut-off low travels a longer distance than their usual size (600–1200 km). Therefore, two systems detected on consecutive time steps were considered the same event when they shared

FIG. 2. Schematic of the algorithm employed to identify a grid point as a cut-off low in the Northern Hemisphere, applied to a 500-hPa cut-off low impinging southwestern Europe at 0600 UTC 13 Nov 2017. With respect to the surrounding grid points (bounded by a blue rectangle), the candidate grid point (bounded by a red square) must fulfil the criteria outlined in section 2 to be considered a cut-off low. These criteria are based on (a) the geopotential height distribution (gpm), (b) the zonal wind distribution (m s^{-1}), (c) the thickness distribution (m), and (d) the thermal front parameter (TFP) distribution ($\times 10^{-11} \text{ K m}^{-2}$).

FIG. 3. Composite of the geopotential height distribution around a 500-hPa cut-off low, based on all cases detected during 2017 for (a) the Northern Hemisphere (358 cases) and (b) the Southern Hemisphere (139 cases). Vertical and horizontal axes indicate latitudes and longitudes, respectively, relative to the cut-off low center, which corresponds to the intersection of the symmetry axes (red lines). In (b) the latitude axis was flipped to ease comparison with (a). Contour interval is 5 dam.

at least one grid point, or if any of the grid points from the second feature were next to any of the grid points from the first feature.

- 3) If two cut-off lows were separated in time by 24 h or less, they were considered to be the same feature provided they shared at least one grid point or if at least one of the grid points of the later system lay next to any of the grid points of the earlier system. In other words, we considered that, even if some of the criteria failed to be met continuously, a cut-off low was not split into two independent events if all of the criteria were once again met within 24 h from the last detection. Conversely, if two systems were separated in time by more than 24 h, then they were treated as independent events regardless of whether they shared a grid point or if one of the grid points of the later system lay next to any of the grid points of the earlier system.

Additionally, to remove transient events, cut-off lows with a duration of less than 36 h were removed from the dataset. Also, because of the improvement in the representation of meteorological information in the NCEP–NCAR reanalysis with the assimilation of satellite information since the late 1970s (Hines et al. 2000; Tennant 2004), we restricted our analyzed period to 1979–2017 in sections 3 and 4 to study the spatial distribution and the annual cycle of 200- and 500-hPa cut-off lows. (In section 5, we explore the interannual variability and trends starting in 1960.) This spatial distribution is based on the designation of one particular grid point as representative of each cut-off low. This grid point corresponded to the most poleward grid point on the first day of detection of each event. If any other grid point shared the same latitude, we used the

westernmost as the representative position of the low. This representation identifies the closest point to the westerlies where the circulation was cut off (Nieto et al. 2005).

Finally, monthly indices of climate variability modes between 1979 and 2017 were extracted from the NOAA–CPC database. These indices corresponded to the AO, the AAO, and the Southern Oscillation index (SOI), which were downloaded from <https://www.ncdc.noaa.gov/teleconnections/> and http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aa0/aa0.shtml.

3. Spatial variability

a. 200-hPa cut-off lows

In both hemispheres, cut-off lows tend to occur around three well-defined regions (Fig. 7). In the Northern Hemisphere (Fig. 7a), these regions are located over the northeastern Atlantic Ocean and southwestern Europe (hereafter simply referred to as Europe), northeastern China–Siberia and the northwestern tip of Alaska (hereafter Asia), and the northeastern Pacific Ocean and western North America (hereafter North America). These regions are qualitatively consistent with the preferred locations of 200-hPa cut-off lows described in the 5-yr climatology of Kentarchos and Davies (1998) and in the 41-yr climatology of Nieto et al. (2005). To further investigate cut-off lows within these regions, three latitude–longitude boxes were defined. For Europe, this box extends from 25° to 47.5°N and from 50°W to 40°E, for Asia from 40° to 62.5°N and from 100°E to 150°W, and for North America from 20° to 40°N and from 100°W to 180°.

FIG. 4. As in Fig. 2, but for identifying a grid point as a cut-off low in the Southern Hemisphere. The algorithm is applied to a 500-hPa cut-off low impinging northern Chile at 0000 UTC 4 Jul 2002.

FIG. 5. Spatial distribution of the number of times during 2017 that each grid point of the Southern Hemisphere was part of a 200-hPa cut-off low, after a nine-point smoothing. Cut-off lows detected with the original criteria of Nieto et al. (2005) appear as contours, whereas cut-off lows detected with the modified criteria of Reboita et al. (2010) are shaded (see section 2). Gray shaded area represents the polar region excluded from the climatology. Contour interval is one event.

From these regions, Europe is the region where cut-off lows were most frequent between 1979 and 2017, followed by Asia and North America (Table 2). A comparison between our counting of events and the counting made by Nieto et al. (2005) shows that, at least in Europe, the number of cut-off lows detected by our climatology is greater than the number of events detected by Nieto et al. (2005) during the common period of 1979–98. Indeed, whereas Nieto et al. (2005) found 285 cut-off lows in Europe between 1979 and 1998 (Nieto et al. 2007, their Fig. 2), we found 566 during the same period. This discrepancy arises because Nieto et al. (2005) used a daily dataset to build their climatology instead of our four-times-daily dataset and because Nieto et al. (2005) considered transient events as those that persisted for only 1 day instead of less than 36 h. Thus, our climatology can detect cut-off lows that persisted for any 6-h multiples beyond 36 h (i.e., 36, 42, 48, 54, 72 h, etc.) and not only those that persisted for 24-h multiples (i.e., 48, 72, 96 h, etc.). Nevertheless, the correlation coefficient between time series of the annual number of 200-hPa cut-off lows in Europe detected by Nieto et al. (2005) and by our climatology was fairly good (0.57), so despite the number of events detected in Europe being different between both studies, the interannual variability of cut-off lows in Europe captured by Nieto et al. (2005) is well represented in our climatology. As the spatial distribution is also well represented,

we are confident that our climatology is useful for studying Northern Hemisphere cut-off lows. No time series for comparison were available for Asia and North America.

In the Southern Hemisphere (Fig. 7b), 200-hPa cut-off lows were more frequent over southeastern Australia and New Zealand (hereafter Australia–New Zealand), the southeastern Pacific Ocean and subtropical South America (hereafter South America), and over southern Africa (hereafter Africa), consistent with the 31-yr climatology of Fuenzalida et al. (2005), the 21-yr climatology of Reboita et al. (2010), and the 36-yr climatology of Pinheiro et al. (2017). Just as in the Northern Hemisphere, three regions were defined to further study Southern Hemisphere cut-off lows. Within 50° and 20°S, these regions extend from 120°E to 150°W (Australia–New Zealand), from 120° to 30°W (South America), and from 0° to 60°E (Africa).

The number of events detected within each region shows a clear preference for cut-off low occurrence over Australia–New Zealand followed by South America and Africa, although cut-off lows in the Southern Hemisphere were not as numerous as in the Northern Hemisphere (Table 2). To check whether the number of events detected for each region was quantitatively consistent with the average number of cut-off lows per year documented by Reboita et al. (2010), we expanded the spatial extension of each region to match the regions defined by Reboita et al. (2010). We found fewer cut-off lows during the common period of 1979–99 despite using the same algorithm for cut-off low detection and tracking. Specifically, whereas Reboita et al. (2010) found an average of 53.7, 22.1, and 12.8 cut-off lows per year between 60°E and 130°W, 130° and 20°W, and 20°W and 60°E, respectively, we found an average of 30.0, 8.0, and 5.8 cut-off lows per year in each of those regions. The discrepancy between our counting of events and Reboita et al.'s (2010) is due to the inclusion of cut-off lows that persisted for 24 and 30 h in Reboita et al.'s (2010) dataset, although the inclusion of these events did not alter the spatial distribution of cut-off lows in the Southern Hemisphere, which is consistent between our work and that of Reboita et al. (2010).

Figure 8 shows the distribution of durations of cut-off lows within each of the main regions of occurrence in both the Northern and Southern Hemispheres in a form of a bar chart, which mimics a discrete form of a cumulative distribution function. Around 80% of the cut-off lows within each region persisted for up to 72 h before they were destroyed either by diabatic heating or by reabsorption into the jet at higher latitudes (e.g., Hoskins et al. 1985; Nieto et al. 2005). More persistent cut-off lows were rare, with less than 5% of them lasting

FIG. 6. Schematic of the cut-off low tracking algorithm applied to a 500-hPa event over South America. Shading corresponds to 500-hPa air temperature ($^{\circ}\text{C}$), white contours indicate 500-hPa geopotential height (gpm), and crosses indicate grid points that belong to a cut-off low (meeting criteria in section 2). At 1800 UTC 4 Jul and 0000 UTC 6 Jul, no grid points met all the criteria to define a cut-off low. However, we considered that all of the time steps belong to the same event.

FIG. 7. Spatial distribution of 200-hPa cut-off lows, after a nine-point smoothing, over the (a) Northern and (b) Southern Hemispheres. Each panel shows the number of times, between 1979 and 2017, that each grid point represents a cut-off low (see section 2). Gray shaded areas represent regions excluded from the climatology and blue lines define the boundaries of each region for further analysis.

for more than 5 days, consistent with the durations described by Price and Vaughan (1992) and by Nieto et al. (2005) for the Northern Hemisphere.

b. 500-hPa cut-off lows

Whereas 500-hPa cut-off lows in the Southern Hemisphere tended to occur around the same regions as those at 200 hPa, 500-hPa cut-off lows in the Northern Hemisphere occurred mainly over Asia and over northeastern North America and the northwestern Atlantic Ocean (Fig. 9). The latter region was not

identified as one of the main areas of 200-hPa cut-off low occurrence in the Northern Hemisphere, as in comparison the frequency of 200-hPa cut-off lows there is not as high as over Europe, Asia, or North America. Thus, to make a direct comparison between regions of frequent cut-off low occurrence, we added a fourth region to further study 500-hPa cut-off lows in the Northern Hemisphere. This new region, named Greenland, extended in a latitude–longitude box from 50° to 70°N and

TABLE 2. Number of cut-off lows detected in each region between 1979 and 2017. Even though Greenland is not a relevant region for 200-hPa cut-off low occurrence in the Northern Hemisphere, the number of 200-hPa events in this region is included here for completeness.

	Number of cut-off lows 1979–2017	
	200 hPa	500 hPa
North America	725	683
Europe	1234	2234
Asia	1115	3788
Greenland	562	3135
South America	508	991
Africa	234	493
Australia–New Zealand	983	1862

FIG. 8. Persistence of 200-hPa cut-off lows in all the regions, expressed as a percentage of cut-off lows that persisted for a given time interval.

FIG. 9. As in Fig. 7, but for 500-hPa cut-off lows. Note that the values in the color scale are different from 200-hPa cut-off lows.

from 95° to 5°W. All other regions, as they were still primary regions of cut-off low occurrence in midlatitudes, were kept the same to study 500-hPa cut-off lows.

Within the Southern Hemisphere regions, a well-defined occurrence maximum appears upstream from mountain ranges such as the Andes (South America) and the African plateau (Africa). As shown by Garreaud and Fuenzalida (2007) through a modeling study of a cut-off low near the Andes, these maxima are likely to be associated with the protective effect of the mountain barrier from the inflow of warm and moist air from the continent, which would otherwise restrict further development of the cut-off low, especially for the weaker ones (Pinheiro et al. 2017). Additionally, forced ascent of the impinging westerly flow weakens the upper-level low around the summits, making them less likely to persist downstream, as shown through a case study of a coastal cyclogenesis (Seluchi and Saulo 1998) and through a climatology of 500-hPa cut-off lows in North America (Smith et al. 2002).

The regions described above are qualitatively consistent with the main regions of 500-hPa cut-off low occurrence described in Bell and Bosart (1989) and Parker et al. (1989) for the Northern Hemisphere and in Fuenzalida et al. (2005), Reboita et al. (2010), and Pinheiro et al. (2017) for the Southern Hemisphere. However, within each region, 500-hPa cut-off lows tend to occur poleward with respect to 200-hPa cut-off lows, especially across the Atlantic Ocean and across the

northern and southern Pacific Ocean (Fig. 10). This poleward shifting of 500-hPa cut-off lows with respect to 200-hPa cut-off lows is consistent with the more prominent role in the middle troposphere of the polar-front jet in acting along with the subtropical jet as a waveguide for Rossby waves (Ndarana and Waugh 2010). Thus, as the occurrence of 500-hPa cut-off lows is not only driven by the strength of the subtropical jet but also by the strength of the polar-front jet, 500-hPa cut-off lows were more numerous than 200-hPa cut-off lows. Indeed, whereas at 500 hPa we found 13 791 cut-off lows in the Northern Hemisphere and 4516 in the Southern Hemisphere between 1979 and 2017, at 200 hPa we found 5136 cut-off lows in the Northern Hemisphere and 2216 in the Southern Hemisphere. As a consequence, only a few 500-hPa cut-off lows were also found at 200 hPa. For example, in 2017 we found 358 500-hPa cut-off lows in the Northern Hemisphere, of which only 16% shared at least one grid point with 200-hPa cut-off lows during the same day. For the Southern Hemisphere, this percentage rose to 29% of the 139 events detected there during 2017, a percentage that contrasts with the 72% found by Fuenzalida et al. (2005) for the 500-hPa cut-off lows they detected in 1999. As Fuenzalida et al. (2005) used the numerical scheme of Murray and Simmonds (1991) to track cut-off lows, it is likely that the discrepancy between our result and theirs is due to the different method of cut-off low detection. The average number of 500-hPa events per year was also computed to compare

FIG. 10. Spatial distribution of 200-hPa cut-off lows (shaded) and 500-hPa cut-off lows (contours) found between 1979 and 2017 after a nine-point smoothing in the (a) Northern and (b) Southern Hemispheres. Gray shaded areas represent regions excluded from the climatology.

with Reboita et al.'s (2010) result for Southern Hemisphere cut-off lows. During the common period 1979–99 we found an average of 99.3 events per year, which (because of the exclusion of systems that persist between 24 and 30 h in our dataset) represents nearly 70% of the 141.4 events per year found by Reboita et al. (2010).

With the exception of North America, 500-hPa cut-off lows were more frequent than at 200 hPa, especially in Asia and Greenland, where the number of 500-hPa cut-off lows increased around 4 and 6 times, respectively, with respect to the number of 200-hPa cut-off lows (Table 2). From all regions considered, the most favored one for cut-off low occurrence was Asia for Northern Hemisphere cut-off lows and Australia–New Zealand for Southern Hemisphere cut-off lows.

Within our defined regions, short-lived events (i.e., 500-hPa cut-off lows that persist for less than 72 h) were the most frequent, although they represent a smaller percentage than at 200 hPa (Fig. 11). Thus, 500-hPa cut-off lows tended to be more persistent than at 200 hPa. The mechanism by which some cut-off lows could have been more persistent than others involves the continuous injection of fresh polar air from the polar vortex, especially for higher-latitude cut-off lows (Price and Vaughan 1992) and the development of blocking anticyclones (Nieto et al. 2007), which weakens the mean zonal flow and consequently slows down the

reabsorption of the cut-off low by the westerlies (Hoskins et al. 1985).

4. Annual cycle

The annual cycle of 200- and 500-hPa cut-off lows in every region is shown in Figs. 12 and 13, respectively. In general, the frequency of 200-hPa cut-off lows is maximum in summer and minimum in winter, consistent with Nieto et al. (2005) (Fig. 12). More specifically, in the Northern Hemisphere the frequency of 200-hPa cut-off lows increases from May to July and decreases

FIG. 11. As in Fig. 8, but for 500-hPa cut-off lows.

FIG. 12. Annual cycle of 200-hPa cut-off lows for the main regions of occurrence for the (top) Northern and (bottom) Southern Hemispheres, expressed as a percentage of the total number of cut-off lows that occurred within each month between 1979 and 2017.

from August to November, when the frequency of events remains steady until March. For the Southern Hemisphere, although the overall pattern of frequency maximum in summer and frequency minimum in winter is similar, there are differences among the regions. In particular, the frequency of 200-hPa cut-off lows in Africa and South America increases from September to April and decreases from May to August, whereas the frequency of 200-hPa cut-off lows in Australia–New Zealand increases from October to March and decreases from April to June. Thus, the annual cycle of 200-hPa cut-off lows in Africa and South America is out of phase with respect to the annual cycle in Australia–New Zealand. This difference in the annual cycle might explain why Reboita et al. (2010) found that, unlike Australia–New Zealand where 200-hPa cut-off lows were more frequent in summer, 200-hPa cut-off lows over Africa and South America tended to occur preferentially in autumn. The summer and autumn maximum in 200-hPa cut-off low occurrence is consistent with the summer weakening of the upper-level westerlies (Kentarchos and Davies 1998).

At 500 hPa, the annual cycle of cut-off lows within each region of the Northern Hemisphere was less

marked than at 200 hPa (Fig. 13). However, unlike Europe, Asia, and Greenland where the frequency of 500-hPa cut-off lows was fairly evenly distributed among the months, in North America there was a well-defined summer minimum and two frequency maxima, which occurred in spring and autumn consistent with the seasonality of North American cut-off lows described by Parker et al. (1989) and Oakley and Redmond (2014). This difference in the annual cycle among the regions also occurred in the Southern Hemisphere. Specifically, 500-hPa cut-off lows over Australia–New Zealand were likely to occur at any time of the year, whereas the highest frequency of 500-hPa cut-off lows over Africa and South America occurred between May and October (the rainy season). This annual cycle of 500-hPa cut-off lows in the Southern Hemisphere is consistent with the results of Qi et al. (1999) for southeastern Australia and of Fuenzalida et al. (2005) for every Southern Hemisphere region. Thus, cut-off lows tend to have a level-dependent seasonality (most frequent in summer and least frequent in winter for 200-hPa cut-off lows and equally likely to occur at any season for 500-hPa cut-off lows), not only in the Southern Hemisphere as

FIG. 13. As in Fig. 12, but for 500-hPa cut-off lows.

documented by Reboita et al. (2010), but also in the Northern Hemisphere.

Just as in the Southern Hemisphere, the level-dependent seasonality of cut-off low occurrence in the Northern Hemisphere might also be explained by the dissimilar influence of the polar-front jet and subtropical jet on Rossby wave-breaking events (Ndarana and Waugh 2010). However, alternative hypotheses such as the development of subtropical midtropospheric anticyclones during summer might also contribute to the summer minimum in 500-hPa cut-off low frequency in Africa, South America, and North America by diminishing the upper-level low's lifetime (Fuenzalida et al. 2005).

5. Interannual variability

To better assess the decadal variability of the yearly number of 200- and 500-hPa cut-off lows in each region and to increase the likelihood of robust conclusions, the period of analysis was extended to the 58-yr period of 1960–2017. We test whether the assimilation of post-1979 satellite data in the NCEP–NCAR reanalysis might have changed the detection rate of cut-off lows compared to the pre-1979 satellite data (section 5a). Then,

we examine the trends in the number of cut-off lows during these 58 years (section 5b). Finally, we discuss the links between cut-off lows and Rossby wave breaking, blocking, and various climate/circulation indices (section 5c).

a. Influence of satellite data: 1960–78 versus 1979–97

The dataset was divided into two 19-yr periods: presatellite (1960–78) and postsatellite (1979–97) periods. For every region (Fig. 7), we assumed that the yearly number of cut-off lows was independent from one year to the next. A two-sample Student's *t* test with 36 degrees of freedom showed that, at the 95% level, in all regions of the Southern Hemisphere the average number of 200-hPa cut-off lows per year changed between the presatellite and the postsatellite period (Figs. 14b,d,f; Table 3). In contrast, the only region of the Northern Hemisphere where this change was statistically significant was North America (Fig. 14a). Specifically, the mean number of North American 200-hPa cut-off lows per year increased around 40% from the presatellite to the postsatellite period (Table 3). In Africa and Australia–New Zealand, the average number of 200-hPa cut-off lows per year increased around 78% and 22%, respectively (Figs. 14d,f) and, in South America, the yearly average

FIG. 14. Annual number of 200-hPa cut-off lows for each region of the Northern and Southern Hemispheres. In each panel, the dashed black line indicates the fitted linear regression line, whereas “Var. expl.” and “ p -value” are the fraction of the variance explained by the linear regression and its corresponding p value, respectively.

decreased around 38% (Fig. 14b). These results are consistent with the increased density of cut-off lows post-1979 around Africa and Australia–New Zealand and the decreased density over a large part of the Pacific Ocean (Reboita et al. 2010).

However, associating this change solely to the introduction of satellite data in the reanalysis is difficult, as other factors such as a signal of decadal variability or an overall trend may cause the time series to be nonstationary. For this reason, we also conducted a two-sample

TABLE 3. Annual average of 200- and 500-hPa cut-off lows for the presatellite (1960–78) and the postsatellite (1979–97) periods for every region, along with the results from the two-sample Student’s t test at the 95% level with 36 degrees of freedom. In parentheses, the variation in the average number of lows detected in the postsatellite period with respect to the presatellite period. As in Table 2, the statistics for 200-hPa cut-off lows in Greenland are included for completeness.

	200-hPa cut-off lows				500-hPa cut-off lows			
	1960–78	1979–97	t statistic	p value	1960–78	1979–97	t statistic	p value
North America	10.9	15.3 (40%)	−3.11	0.004	13.3	19.4 (46%)	−4.02	<0.001
Europe	31.5	28.1 (−11%)	1.88	0.069	52.9	55.9 (6%)	−1.34	0.188
Asia	25.3	27.0 (7%)	−0.91	0.367	87.1	95.9 (10%)	−3.71	<0.001
Greenland	13.4	15.8 (18%)	−1.98	0.056	70.5	76.9 (9%)	−1.91	0.065
South America	10.4	6.4 (−38%)	3.43	0.002	18.7	20.5 (9%)	−0.91	0.368
Africa	2.8	5.0 (78%)	−3.30	0.002	6.7	11.2 (67%)	−4.96	<0.001
Australia–New Zealand	19.5	23.8 (22%)	−2.89	0.007	37.7	45.2 (20%)	−2.55	0.015

FIG. 15. As in Fig. 14, but for 500-hPa cut-off lows.

F test with 18 degrees of freedom to show that the variance did not change between the presatellite and postsatellite periods in any region ($p > 0.1$ in all regions) at the 95% level. Thus, as the presatellite and the postsatellite time series of yearly cut-off low occurrence had similar variability with respect to the corresponding means, we are confident that the assimilation of satellite information in the reanalysis did not affect the detection of 200-hPa cut-off lows.

Similar tests were performed for 500 hPa. In all regions, 500-hPa cut-off lows increased from the presatellite period to the postsatellite period (Fig. 15), being statistically significant in four of the seven regions: North America, Africa, Asia, and Australia–New Zealand (Table 3). In contrast, in Europe, Greenland, and South America, the mean number of cut-off lows per year between both periods did not increase beyond 10% (Table 3). On the other hand, no change in the variance of the yearly number of 500-hPa cut-off lows was detected except for North America ($p = 0.03$ for the F test). Thus, the variability in the yearly number of

cut-off lows over North America increased between the presatellite and the postsatellite periods, despite assimilation of satellite data having less impact on the reanalysis in this region (Nieto et al. 2005). Consequently, assimilation of satellite data likely cannot explain this increase. Thus, we examine a larger period of reanalyses (1960–2017) to look for other trends.

b. Trends: 1960–2017

Time series of the yearly number of cut-off lows showed considerable interannual variability in all regions (Fig. 14). [We omit Greenland because it was not a primary region of 200-hPa cut-off low occurrence and because we are mainly focused on midlatitude cut-off lows.] For example, only eight 200-hPa cut-off lows per year occurred over North America in 1960 compared to 15–30 by the 2010s (Fig. 14a). This interannual variability can be quantified through the coefficient of variation (standard deviation divided by the mean) over the 58 years of data. The region with the greatest interannual variability in the Northern Hemisphere was North

America (39%), followed by Asia (23%) and Europe (20%). Because these regions were preferred areas of 200-hPa cut-off low occurrence, they were associated with larger coefficients of variation compared with the whole Northern Hemisphere (14%). Likewise, in the Southern Hemisphere, the region with the greatest interannual variability was Africa (63%), where cut-off lows were rather infrequent (i.e., low average), followed by South America (55%) and Australia–New Zealand (25%). Over the whole Southern Hemisphere, the coefficient of variation was 31%, a percentage that was mainly influenced by the high average of events per year in Australia–New Zealand compared with the other regions. These coefficients of variation were consistent with those computed by Fuenzalida et al. (2005) for Southern Hemisphere 500-hPa cut-off lows during 1969–99: Africa (50%), South America (37%), and Australia–New Zealand (27%).

Closer inspection showed decadal variability for 200-hPa cut-off lows over South America, with a reduced frequency between 1960 and the late 1980s, followed by an increased frequency from the early 1990s onward (Fig. 14b). No similar feature existed for the other regions, although in Europe, the annual number of 200-hPa cut-off lows showed around 30 cut-off lows per year between 1960 and 1990, followed by a marked positive trend from the early 1990s onward (Fig. 14c).

The positive trend was common to all regions and reflected the overall increased frequency of 200-hPa cut-off lows in both the Northern and Southern Hemispheres (Fig. 14). These trends were consistent with those in Fuenzalida et al. (2005), Favre et al. (2012), Ndarana et al. (2012), and Pinheiro et al. (2017) for Southern Hemisphere cut-off lows, but not with Nieto et al. (2007) for European cut-off lows, which did not include lows after 1998. The trends were well correlated with the time series ($r \geq 0.5$ in 75% of the time series) and statistically significant at the 95% level (Fig. 14). However, the importance of each trend in explaining the variance in the yearly number of cut-off lows differed between regions. Specifically, the trend in the Southern Hemisphere explained more than 30% of the variance, whereas North America was the only region in the Northern Hemisphere where the trend explained more than 10% of the variance.

At 500 hPa, the coefficient of variation in the Northern Hemisphere regions was the highest in North America (31%) followed by Europe (13%) and Asia (10%). Thus, 500-hPa cut-off lows had less interannual variability than 200-hPa cut-off lows. A similar result was found for the Southern Hemisphere regions, where the 500-hPa coefficient of variation was the highest in Africa (43%), followed by South America (32%) and Australia–New Zealand (22%), consistent with the coefficients computed by Fuenzalida et al. (2005). This

FIG. 16. Slope of the linear regression line with its corresponding 95% confidence intervals (expressed as cut-off lows per decade) for every region. Blue dots and lines are associated with 200-hPa lows, whereas red dots and lines are associated with 500-hPa lows. The black dashed line indicates zero slope.

smaller coefficient of variation compared to 200-hPa cut-off lows was mostly due to the higher number of 500-hPa cut-off lows per year (Table 3). This increased average was in turn associated with a positive trend that once again explained a greater portion of the variance in the Southern Hemisphere regions compared with the Northern Hemisphere regions (Fig. 15). Specifically, whereas at most 25% of the variance in the yearly number of 500-hPa cut-off lows was explained by the trend in the Northern Hemisphere regions, this percentage rose to at least 39% for the Southern Hemisphere regions. The positive trend explained 64% of the variance for Southern Hemisphere cut-off lows compared to 33% for Northern Hemisphere cut-off lows. Thus, positive trends in the yearly number of cut-off lows exist not only for the Southern Hemisphere as previously documented, but also for the Northern Hemisphere. In general, the increase in the number of cut-off lows per decade was larger for 500-hPa cut-off lows than for 200-hPa cut-off lows (Fig. 16). However, the difference between the 200- and 500-hPa slopes was not statistically significant at the 95% level in all regions except North America (Fig. 16).

c. Links with Rossby wave breaking, blocking, and climate indices

Cut-off lows frequently occur downstream of anticyclonic Rossby wave-breaking events (e.g., Thorncroft et al. 1993; Ndarana and Waugh 2010) and are favored as jet streams shift poleward (Rivière 2011). This poleward shifting of the jets has been widely documented (e.g., Hu and Fu 2007; Archer and Caldeira 2008; Pena-Ortiz et al. 2013) and has been linked with climate change through different mechanisms: poleward expansion of

TABLE 4. Correlations between the yearly number of 200- and 500-hPa cut-off lows per season between 1979 and 2017 in the Northern Hemisphere (NH) and the Southern Hemisphere (SH), and the main modes of climate variability (AO, AAO, and SOI) for each season. Numbers in boldface represent correlations that are statistically significant at the 95% level. For the NH, seasons were defined from December to February (winter), March to May (spring), June to August (summer), and September to November (autumn). For the SH, these months correspond to summer, autumn, winter, and spring, respectively.

	200-hPa cut-off lows				500-hPa cut-off lows			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
AO (NH)	−0.02	−0.23	−0.26	−0.09	−0.42	−0.45	−0.67	−0.54
SOI (NH)	0.05	0.02	−0.04	−0.15	−0.01	−0.10	−0.05	0.03
AAO (SH)	0.26	0.03	−0.22	0.04	0.25	−0.04	0.09	0.18
SOI (SH)	−0.05	−0.04	0.33	0.18	−0.01	−0.03	−0.06	−0.14

the Hadley cell (Frierson et al. 2007; Lu et al. 2007), poleward shifting of storm tracks (Yin 2005), widening of the tropical belt (Seidel et al. 2008), contraction of the winter pool of polar air (Martin 2015), and cooling of the stratosphere (Haigh et al. 2005; Williams 2006). Similarly, cut-off lows and blocking are closely related with each other and can be considered a single phenomenon (e.g., Langford 1960; Taljaard 1972). Thus, an increase in cut-off low occurrence should be consistent with an increased frequency of blocking, as has been observed over North America and upstream of Asia (Barnes et al. 2014). These blocking events split the jet stream into weaker branches (namely, the subtropical and polar branches), favoring the occurrence of cut-off lows in areas with weak westerlies (Kentarchos and Davies 1998; Fuenzalida et al. 2005), such as over southeastern Australia and Europe (e.g., Trenberth and Mo 1985; Nieto et al. 2007). Hence, the increasing frequency of blocking events over Australia and Europe may be associated with the increasing frequency of cut-off lows (Figs. 14c,f, 15c,f). In contrast, blocking in the Southern Hemisphere was decreasing (Renwick and Revell 1999; Wiedenmann et al. 2002; Dong et al. 2008), although these studies did not analyze data beyond 1999 when cut-off lows in the Southern Hemisphere began to be more frequent (Fig. 14h).

Across the Southern Hemisphere, but especially around the southern Pacific Ocean, cut-off low occurrence shifts equatorward during La Niña and poleward during El Niño (Favre et al. 2012). However, the annual number of cut-off lows does not seem to be affected by the phase of the ENSO cycle (Fuenzalida et al. 2005). Favre et al. (2012) argued that this lack of correlation arose because the link between ENSO and cut-off lows has spatial variability, even within the main occurrence regions. For example, cut-off lows over the western coast of southern Africa tend to be more frequent during La Niña, whereas cut-off lows over the eastern coast tend to be more frequent during El Niño (Favre et al. 2012) and the Atlantic coast of Europe had a negative

and statistically significant correlation between the annual number of cut-off lows and the ENSO cycle (Nieto et al. 2007). In our dataset, the linear correlation between the SOI and the number of cut-off lows per season, although consistently negative for 500-hPa cut-off lows in the Southern Hemisphere, was not statistically significant at the 95% level in either hemisphere at both 200 and 500 hPa (Table 4). In fact, the SOI explains at most only 10% of the variance of the yearly number of winter 200-hPa cut-off lows and 2% of the variance of the yearly number of spring 500-hPa cut-off lows.

Because the weakening of the jet can also be associated with a negative phase of the AO or AAO, we also examined these indices. Only the Northern Hemisphere showed a consistent negative correlation at both 200 and 500 hPa, but only 500-hPa cut-off lows had a correlation with the AO index that was statistically significant at the 95% level. Specifically, the AO explained 18%–45% of the variance in the annual number of 500-hPa cut-off lows. These negative correlations are consistent with weaker and more distorted westerlies during the negative phase of the AO (Thompson and Wallace 1998), and the correlations were stronger during winter and spring when blocking occurrence is more frequent over Europe (Nieto et al. 2007).

6. Summary

The first climatology of midlatitude 200- and 500-hPa cut-off lows over both the Northern and Southern Hemispheres presented here shows favored regions of occurrence, persistence, and seasonality that are consistent with previous climatologies for individual sectors or hemispheres. This consistency allowed a direct comparison between 200- and 500-hPa cut-off lows occurring within each region, namely North America, Europe, Asia, South America, Africa, and Australia–New Zealand. Even though we found an additional region where the occurrence of 500-hPa cut-off lows is frequent (namely, Greenland and northeastern North America), we excluded

this region for further analysis as this is not a favored region for 200-hPa cut-off low occurrence.

This direct comparison showed that 500-hPa cut-off lows tend to occur poleward and be more frequent than 200-hPa cut-off lows, and that Northern Hemisphere cut-off lows also have a level-dependent seasonality, as was found previously for Southern Hemisphere cut-off lows. Specifically, 200-hPa cut-off lows tended to be most frequent during summer and least frequent during winter, whereas 500-hPa cut-off lows tended to be more evenly distributed throughout the seasons. However, the seasonality of 500-hPa cut-off lows in each region is not uniform. In particular, there was a well-defined summer minimum in the frequency of 500-hPa cut-off lows in North America. Similarly, 500-hPa cut-off lows in South America and Africa were less frequent between late spring and early autumn. These seasonalities contrast with the annual cycle in the other regions (Europe, Asia, Greenland, and Australia–New Zealand), where 500-hPa cut-off low frequency is rather uniform throughout the year. Possible mechanisms explaining the level-dependent seasonality of cut-off lows involves the formation of midtropospheric anticyclones during summer that do not extend vertically above the tropopause (where the 200-hPa level is usually found in the extratropics) and the relative importance of the polar-front and subtropical jets in Rossby wave-breaking events leading to the genesis of 500- and 200-hPa cut-off lows. This relative importance may also explain why 500-hPa cut-off lows occur poleward of 200-hPa cut-off lows, as the polar-front jet is not as relevant as the subtropical jet in acting as a waveguide for Rossby waves that break to generate 200-hPa cut-off lows.

Another aspect investigated here dealt with the interannual variability of 200- and 500-hPa cut-off lows in every region, consistent with some previous literature, but also contrasting with other previous literature. At both levels, there was a marked positive trend consistent with documented signals of climate change, namely, a poleward shift of the jets (e.g., [Hu and Fu 2007](#); [Archer and Caldeira 2008](#); [Pena-Ortiz et al. 2013](#)) and a weakening of the subtropical jets (e.g., [Archer and Caldeira 2008](#)). The poleward shift of the jet is associated with increased anticyclonic Rossby wave breaking ([Rivière 2011](#)), which is the main mechanism responsible for cut-off low genesis ([Thorncroft et al. 1993](#)). In a similar way, the increased frequency of cut-off lows could also be related to enhanced blocking ([Barnes et al. 2014](#)), as synoptic experience shows that these features usually accompany each other (e.g., [Langford 1960](#); [Taljaard 1972](#); [Favre et al. 2012](#)). Therefore, our study shows that signals consistent with climate change could make the occurrence of cut-off lows more likely not only in the

Southern Hemisphere but also in the Northern Hemisphere. Thus, a suggested next step would be to attempt to attribute the degree of anthropogenic variability in the climate system and investigate how this variability influences the likeliness of high-impact weather associated with cut-off lows.

A step toward determining whether the observed trends were a signal of climate change was performed in this paper by analyzing the link between the occurrence of cut-off lows and the main modes of climate variability. There was no statistically significant correlation between ENSO and the total number of cut-off lows per year in either hemisphere, a result that agrees with some previous research. With respect to the correlations with the annular modes, only Northern Hemisphere 500-hPa cut-off lows showed consistently negative and statistically significant correlations with the AO for all seasons, although these correlations were stronger in winter and spring. These negative correlations are consistent with weaker westerlies in midlatitudes as a consequence of the reduced meridional geopotential height gradient during the negative phase of the AO ([Thompson and Wallace 1998](#)). As no similar consistency was found for the AAO and its correlation with Southern Hemisphere cut-off lows, we hypothesize that the weakening of the westerlies alone did not cause an increase in the number of these lows, and that the influence of the annular modes in cut-off low occurrence is not linear. Thus, an ingredients-based approach for cut-off low development should be investigated to assess how these ingredients are affected by the phase of the annular modes. This approach should help develop a seasonal forecast system for cut-off low occurrence, which because of the high-impact weather associated with these events (e.g., [McInnes and Hess 1992](#); [Vuille and Ammann 1997](#); [Seluchi and Saulo 1998](#); [Bozkurt et al. 2016](#)) should help mitigate economic losses.

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