In this study, two empirical equations driven by ERA5 reanalysis are used to determine a Lifting Condensation Level (LCL) climatology over South America (SA) from 1991 to 2021. Prior to calculating the LCL climatology, the performance of the empirical equations is verified through a case study conducted on December 30-31, 2021. Although the results of the equations compared to reference data show some deviations, they do not invalidate the application of the equations in a climatological study. The main findings of the climatology reveal that the LCL typically reaches a greater altitude at 1800 Z. The season during which the LCL reaches its maximum altitude varies depending on the climatic characteristics of the analyzed region. For instance, the greatest height of the LCL was observed during summer in Patagonia (4000 m), spring in Northeast Brazil (3000 m), winter in central SA (2000 m), and in Amazonia (1500 m). Additionally, in five cities studied across Brazil, the LCL exhibited a positive trend in altitude, accompanied by a negative trend in precipitation.

Keywords: Lifting Condensation Level. South America. Precipitation. Trend Analysis. Climate

### Climatology do Nível de Condensação por Levantamento sobre a América do Sul

Neste estudo, foram utilizadas duas equações empíricas, juntamente com dados da reanálise ERA5, para determinar a climatologia do Nível de Condensação por Levantamento (NCL) na América do Sul (AS) de 1991 a 2021. Antes de calcular a climatologia do NCL, o desempenho das equações empíricas é verificado através de um estudo de caso realizado entre 30 e 31 de dezembro de 2021. Embora os resultados das equações, comparados aos dados de referência, apresentem alguns desvios, estes não invalidam a aplicação das equações em um estudo climatológico. Os principais resultados da climatologia mostram que o NCL normalmente atinge a maior altitude às 1800 Z. A estação do ano em que o NCL atinge sua altitude máxima varia dependendo das características climáticas da região analisada. Por exemplo, a maior altura do NCL foi obtida durante o verão na Patagônia (4.000 m), na primavera no Nordeste do Brasil (3.000 m), no inverno no Nordeste do Brasil (3.000 m), no inverno no centro da AS (2.000 m) e na Amazônia (1.500 m). Além disso, em cinco cidades estudadas em todo o Brasil, o NCL apresentou uma tendência positivo em sua altitude, que foi acompanhada por uma tendência negativa na precipitação.

As air parcels rise in the atmosphere, they encounter an environment with lower atmospheric pressure, causing them to expand and cool. This cooling causes the air parcels to reach the dew point temperature, at which the relative humidity is 100%, indicating that the air parcels are saturated. The level at which saturation occurs is known as the Lifting Condensation Level (LCL; Wallace and Hobbs, 2006; Romps, 2017). A slight upward movement from the LCL results in air parcel condensation, initiating the formation of cloud droplets and, subsequently, clouds (Ahrens, 2003; Ferreira and Reboita, 2020; Wallace and Hobbs, 2006). Therefore, the LCL represents the minimum height at which cloud bases can be formed (Stackpole, 1967; Daidzic, 2019).

The LCL can be measured by instrument like LIDARS and ceilometers. But as these procedures involve huge financial costs, LCL can also be estimated using thermodynamic diagrams such as SkewT-LogP or empirical analytic expressions (Romps, 2017), when the 2-metre air temperature and dew point temperature are known. Espy (1836) was the first to propose an empirical expression for estimating the height of the LCL in meters (Table 1), which demonstrate that water vapor always condenses at a considerable height from the Earth's surface. Dirmeyer et al. (2013) presents an adapted version of Espy (1836)’s equation, where the coefficient 165 is changed to 125. Studies have also shown that cloud base height obtained through estimates are more accurate than that performed visually by observers working at weather stations when compared to data from ground-based LIDAR systems (Stull and Eloranta, 1985).

### Table 1. Equations to estimate LCL.

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<thead>
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<th>Author</th>
<th>Equation</th>
<th>Variables Description</th>
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| Espy (1836)                | \( z = Z_0 + 165 \times (T - T_d) \) | \( T = \) air temperature at 2 m (K)
|                            | [m] (1)                              | \( T_d = \) dew point temperature at 2 m (K)
| Dirmeyer et al. (2013)     | \( z = Z_0 + 125 \times (T - T_d) \) | \( Z_0 = \) altitude of the meteorological station in meters (m)
|                            | [m] (2)                              | \( Ps = \) surface pressure (hPa) reduced to the sea level
| Georgakakos and Brás (1984)| \( z = Ps \left( \frac{T - T_d}{223.15} + 1 \right)^{-3.5} \) | \( z = \) LCL in meters (m) or hectopascal (hPa)

According to Daidzic (2019), knowledge of the LCL is important for flight operations as it is related to vertical air motion and the atmospheric conditions, which are information needed to plan the flight route. Therefore, it is useful to know the LCL climatology in different regions of the world. However, climatological studies of LCL covering wide regions are still limited, partly due to the absence of observed data. Some of the few studies found in the literature defining the LCL climatology over large regions include Zhang et al. (2012), Costa-Surós et al. (2013), Dirmeyer et al. (2013) and Zhang et al. (2018). Zhang et al. (2018) estimated the height of cloud base over China using radiosonde data and found that there is great seasonal variability in the LCL, with a greater distance from the surface in the summer (2990 m) and a smaller distance (2380 m) in the winter. Similar results were obtained by Costa-Surós et al. (2013) in Girona, Spain. Zhang et al. (2012) conducted climatological studies of the LCL in Hawaii using radiosondes and ceilometers. The results showed that the height of the LCL in windward sectors is lower than in leeward sectors with heights of 850 and 1280 meters, respectively.

Other studies estimated LCL using data from numerical simulations and the expressions shown in Table 1. For instance, Dirmeyer et al. (2013) determined the height of the LCL in projections of 15 global climate models of the Coupled Model Intercomparison Project Phase 5 (CMIP5), considering the Representative Concentration Pathway 8.5 (RCP8.5) scenario, which indicates the worst-case scenario of greenhouse gases emissions. The hottest and driest regions are characterized by a higher value (values...
up to 3000 m) of the LCL, while regions with wet and/or cold conditions provide a lower LCL (values below 250 m). Future projections also indicated an increase in the height of cloud base across the globe (~93% of the planet) compared to the current climate, with some exceptions, such as central Africa. South America (SA) also shows an increase in LCL, particularly in the Northeast region of Brazil (NEB). One possible cause for the increase in the height of the cloud base in this region may be the increase in air temperature and decrease in specific humidity, resulting in air parcels saturating at higher altitudes.

Given the importance of LCL information for flight operations and understanding precipitation regimes in different regions, this study aims to determine the climatology of the LCL over South America (SA) from January 1991 to December 2021 using ERA5 151 reanalysis, a state-of-the-art grid-data, and equations 2 and 3.

**Methodology**

**Study Area**

SA, which extends from latitudes 55° S to 12° N, is the study area. There is a diversity of relief types in this region (Fig. 1), such as the Andes Mountains located in the west of the continent, the Sea and Mantiqueira Mountains between the south and southeast of Brazil, the Pampas in the southeast of the continent, the Amazon plain, and so on. Much of SA, from southern Amazonia to southeastern Brazil and Paraguay and north of Argentina, is influenced by a monsoon climate (Ferreira and Reboita, 2022; Reboita et al., 2010; Teodoro et al., 2021). This means that there is a well-defined dry (April to September) and rainy (October to March) seasons. In other sectors of the continent, the annual cycle of precipitation is distinct. For instance, in the north of SA, the maximum values occur between June to August (up to 1000 mm/season). In the east coast of Northeast Brazil, the rainy period is concentrated from January to June, but in the central part of this region, there is a semiarid climate in which precipitation is almost absent in austral winter (JJA). In the southern region of Brazil, the precipitation is well distributed throughout the year, while in Patagonia, the maximum precipitation is registered in winter.

Figure 1 also shows the cities (colored circles) that will be used in the validation of equations 2 and 3 and the subdomains (Amazon, Central, Northeast, and Patagonia) that will be addressed in the discussion of the climatological results. The selection of the cities is described in section 2.3.1. The selected subdomains represent key areas of SA from a climatological point of view since their precipitation is controlled by different meteorological systems (Ferreira and Reboita, 2022). During the wet period, the Amazon and central subdomains are greatly influenced by the low-level jet east of the Andes and by the South Atlantic Convergence Zone (SACZ), Patagonia is in the route of the transient synoptic systems, and Northeast of Brazil has its precipitation influenced by the semipermanent summer trough and by cyclonic vortices that develop associated with this trough.
Figure 1. Topography of South America (meters). Circles represent the cities chosen for the case study, and boxes indicate the subdomains (Amazon, Central, Northeast and Patagonia) addressed in the climatology section.

Data

For this study, different databases were used as follow.

ERA5 Reanalysis

The ERA5 reanalysis (Hersbach et al., 2020) from the European Centre for Medium-Range Weather Forecast (ECMWF), obtained from the Climate Change Service (https://climate.copernicus.eu/), has a spatial resolution of 0.25° x 0.25° and 137 vertical levels. For this study, the following variables were used: temperature at 2 m (T), dew point temperature at 2 m (Td), specific humidity (q) at 2 m, and surface pressure (Ps) reduced to the sea for the synoptic standard times of 0000, 0600, 1200, and 1800 Z from January 1991 to December 2021. Although the reanalysis has a horizontal resolution of 0.25°, a resolution of 1° was used in this study for two reasons: i) the study uses the synoptic scale, which...
does not require data at a high spatial resolution, and ii) to facilitate the processing of a large volume of data.

**Soundings**

Soundings available on the website of the University of Wyoming (UWYO; https://weather.uwyo.edu/upperair/sounding.html) were obtained for December 30 and 31, 2021. The soundings provide temperature (°C), dew point temperature (°C), mixing ratio (g/kg), relative humidity (%), and direction and wind speed (kts) at atmospheric pressure levels (from 1000 to 100 hPa). Based on the vertical profiles of these variables, SkewT-LogP diagrams were drawn. The LCL was estimated using the air temperature and dew point temperature of the first atmospheric level provided by the sounding, which can be considered near-surface information.

**Climate Prediction Center (CPC) Precipitation Data**

Daily precipitation analyses were obtained from the Climate Prediction Center (CPC, Chen et al., 2008), which are available at https://psl.noaa.gov/data/gridded/data.cpc.globalp_recip.html. The analyses are constructed from observations of rain gauges interpolated on the grid with a horizontal resolution of 0.5° x 0.5°. The data were obtained from January 1, 1991, to December 31, 2021, and were gathered in annual amounts.

**Analysis**

**Case Study**

Before using equation 2, which estimates the LCL height in meters, and equation 3, which provides the LCL height in hPa, to determine the LCL climatology over South America, we assessed the performance of the equations by comparing their values with those obtained using UWYO soundings represented on SkewT-LogP diagrams. This was a case study focused on two rainy days in most of Brazil: December 30 and 31, 2021. For contextualization of this rainy period, synoptic charts from the Center for Weather Forecasting and Climate Studies (CPTEC) for levels 250 and 850 hPa and the surface were used, as well as satellite images from GOES-16 (Geostationary Operational Environmental Satellite), channel 13 (infrared), at 1200 Z. These images show the brightness temperature at the top of the clouds. Cumuliform clouds of great vertical development have a cold top and a lower brightness temperature.

For the case study, we searched for locations with available sounding data and daily precipitation exceeding 15 mm at least on December 31. The selected locations (hereafter called cities) were São Paulo (Campo de Marte Airport), Rio de Janeiro (Tom Jobim International Airport), Manaus (Eduardo Gomes Airport), Brasília (Presidente Juscelino Kubitschek Airport), and Santa Maria (Santa Maria Airport). Except for Santa Maria, precipitation was not recorded.

Once the sounding data for each city was obtained, SkewT-LogP diagrams were drawn to provide the LCL. The SkewT-LogP diagram is a graph that allows obtaining several thermodynamic quantities from the known near-surface temperature and dew point temperature. For LCL height, the procedure begins with the upward movement of an air parcel from near-surface level, which in the example in Figure 2 is 1000 hPa, to upper levels (black line). This air parcel follows the dry adiabatic line (red dashed) until it intersects the mixing ratio line (green dashed) drawn from the dew point temperature (Ferreira; Reboita, 2020). The LCL height in hPa is obtained when the two lines meet. In the example, the LCL is obtained at 955 hPa. This information can be converted to geometric height (meters) using the hypsometric equation (Wallace and Hobbs, 2006):

\[
h = z_2 - z_1 = \frac{R_d * \bar{T}_v}{g} * \ln \left(\frac{p_1}{p_2}\right)
\]

where \(z_1\) and \(z_2\) are geometric heights (meters) at pressure levels \(p_1\) and \(p_2\) (hPa), respectively; \(R_d\) is the gas constant for dry air; \(\bar{T}_v\) is the mean virtual temperature of the layer (K); and \(g\) is the acceleration of gravity. In Figure 2, assuming \(p_1 = 1000\) hPa and \(p_2 = 955\) hPa, and , the LCL is 404.5 meters.

Equations 2 and 3 computed with the sounding data are validated by comparison with the LCL height from the SkewT-LogP. In addition, equations 2 and 3 are computed with ERA5 considering an average of the grid points around the shown in Figure 1. A flowchart of the methodology is shown in Figure 3.
Figure 2. SkewT-LogP diagram showing the LCL obtained from air temperature (continuous red line) and dewpoint temperature (continuous green line) on December 30, 2021, at 1200 Z for the Eduardo Gomes Airport (Manaus). Red dashed lines indicate dry adiabatic, green dashed lines indicate mixing ratio, blue dashed line indicates wet adiabatic and black circle indicates LCL.

\[
\frac{R_a*T_v}{g} * \ln \left( \frac{p_1}{p_2} \right) = \frac{287.058*(26.8+273.15)}{9.8} * \ln \left( \frac{1000}{955} \right) = 404.5 \text{ meters}
\]

Figure 2. Schematization and application of the data used in the methodology of the present study.

Climatology

Equations 2 and 3 and ERA5 reanalysis are applied to determine the LCL height climatology over SA. The LCL height is calculated for the four standard synoptic times: 0000, 0600, 1200 and 1800 Z, from 1991 to 2021, and seasonally averaged. In addition, we present annual time series for the five cities shown in Figure 1.

Case Study

Results

Case Study: December 30th and 31st, 2021

Figure 4 displays the daily accumulated precipitation on December 30th and 31st, 2021. During these two days, precipitation was recorded from southern Amazonia to southeastern Brazil, while the absence of rainfall occurred mainly south of 30°S. According to the synoptic charts (Fig. 5),
different atmospheric systems contributed to the rainfall. An upper-level trough at 250 hPa with its axis over central and southern Brazil (Fig. 5a-b), two well-defined low-level jets from the tropical Atlantic Ocean to the northwestern part of the continent and Northeast Brazil, and an inverted trough at low levels near the south-southeastern coast of Brazil (Fig. 5e-f). While the upper-level trough propitiated divergence over southeastern Brazil and, consequently, upward movement and decrease of surface pressure, both low-level jets merged and transported warm and moist air to southeastern and southern Brazilian regions (Fig. 5c-d). The displacement of the low-level jet to these regions was favored by both upper-level dynamic and by the near surface inverted trough.

The combination of the described systems created an ideal environment for cloud and precipitation development from northwest SA to southeastern Brazil and in some areas of northeast and southern Brazil (Fig. 5g-h). Images from channel 13 (infrared, 10.30 μm) of the GOES-16 satellite show clouds with great vertical development on December 30th (Fig. 5g), indicating that they have cold tops (brightness temperature below -60°C). Between the north and Midwest regions of Brazil, and closer to the Atlantic Ocean, the cloud band has a higher brightness temperature (-20°C), which indicates that it has a lower vertical development. From the 30th to the 31st, the cloudiness decreases over the region of São Paulo and moves to the northeast (Fig. 5h), affecting the south-central region of Minas Gerais.

Figure 3. Daily precipitation (mm) for South America on 30th (a) and 31st (b) of December 2021 obtained from CPC.
Figure 4. (a-b) Synoptic chart at 250 hPa showing the wind intensity higher 70 knots (shaded), streamlines (blue lines), subtropical jet (dashed red line) and polar jet (orange and white dashed lines); (c-d) synoptic chart at 850 hPa showing streamlines (orange), wind barbs (knots, cyan), and the isotherms of -2 and 2°C (black dashed line) and 0°C (continuous black line); (e-f) surface synoptic chart showing the synop, mean sea level pressure (yellow lines), inverted trough (yellow dashed line) and cold (blue line) and warm (red line) fronts; (g-h) images from channel-13 (infrared) of the GOES-16 satellite (filled: brightness 306 temperature of the top of the clouds). Source: CPTEC/INPE.
Before calculating the LCL climatology, it is important to know the performance (or the associated error) of equations 2 and 3 driven by sounding data and ERA5 reanalysis. For this reason, Figures 6 and 7 show the LCL height in hPa and meters, obtained from three procedures: (a) sounding data and SkewT-LogP, (b) sounding data with equations 2 and 3 and (c) ERA5 reanalysis with equations 2 and 3. Procedure (a) is considered the reference value to validate the equations. The analyses are applied to December 30th and 31st, 2021.

The calculation of LCL height using equation 3 with sounding data (green bars) or reanalysis data (blue bars), on both analyzed days, shows differences of up to 11% compared to reference data. Equation 3 does not perform better based on the data source used with it. In some cases, such as in Brasília (Fig. 6a), the use of sounding data produces results more similar to the reference data, but in others, such as in São Paulo (Fig. 6a), it is with the use of reanalysis data.

The magnitude of the differences is easier to visualize when the analysis is carried out for height in meters (Fig. 7). For example, in Santa Maria, in Figure 7b, equation 2 driven with sounding data shows a percentage error of +46%, indicating that LCL was estimated at a higher height in meters when compared to reference data. In the analysis of atmospheric pressure, the error corresponds to ~10% (Fig. 6b). In general, although there are errors in the estimates obtained with equations 2 and 3, these can be smoothed out in climatological studies, providing useful knowledge. So, they are used in our climatological study presented in next section.

Figure 5. LCL (hPa) obtained using sounding data and SkewT-LogP (reference data in black bars), sounding data with equation 3 (green bars) and ERA5 reanalysis with equation 3 (blue bars), for (a) 30th and (b) 31st of December 2021, at 1200 Z, for the cities of: Brasília/DF, Manaus/AM, São Paulo/SP, Rio de Janeiro/RJ and Santa Maria/RS. Over the green and blue bars, the values indicate the percentage difference of LCL height in relation to the reference data (black bars).

Figure 6. LCL (meters) obtained through the hypsometric equation applied to the results of sounding data and SkewT-LogP (reference data in black bars), sounding data with equation 2 (green bars) and ERA5 reanalysis with equation 2 (blue bars), for (a) 30th and (b) 31st December 2021, at 1200 Z, for the cities of: Brasília/DF, Manaus/AM, São Paulo/SP, Rio de Janeiro/RJ and Santa Maria/RS. Over the green and blue bars, the values indicate the percentage difference of LCL height in relation to the reference data (black bars).
**LCL Height Climatology**

**Annual Climatology**

Figure 8 shows the annual climatology of the LCL height in pressure coordinates (hPa, equation 3) and in meters (equation 2) from 1991 to 2021 for the synoptic standard times of 0000, 0600, 1200, and 1800 Z, using ERA5 reanalysis. The spatial pattern of the LCL is similar using both equations. LCL has its higher diurnal variability in the Amazon region since at 0600 Z (Fig. 8f) the height of the cloud base is approximately 1000 hPa (below 500 m altitude), while at 1800 Z (Fig. 8h), it is closer to 850 hPa (below 1500 m altitude). The LCL diurnal variability is also huge in the northeast of Brazil (NEB) and Patagonia. In the NEB, mainly in the northeastern Sertão, the four synoptic hours do not present LCL higher than 800 hPa (below 1750 m). In Patagonia, the LCL also indicates that the cloud base occurs distant from surface. In the central region of the continent (~20°S), the LCL occurs between 950 and 800 hPa (1000 m – 2500 m) in most of the synoptic times; the exception is 1800 Z, when it approaches 700 hPa (3000 m).

To understand the physical processes associated with the spatial variability of the LCL over SA, 2-meter air temperature (Fig. 8i, j, k, l) and specific humidity at 2-metre (Fig. 8m, n, o, p) are also presented. Specific humidity represents the mass of water vapor in a unitary mass of air (dry air plus water vapor) (Wallace and Hobbs, 2006). Basically, the hottest and wettest regions are the Amazon and the central part of the continent, while the coldest and driest regions are located near the Argentinian Patagonia and Uruguay.

According to the thermodynamics of the atmosphere (Wallace and Hobbs, 2006), colder regions may hold less water vapor in the atmosphere than warmer regions. Thus, if an air mass is cold and holds water vapor (but is unsaturated) in one place, a small shift into higher heights may cause it to reach saturation and therefore reach the LCL. In contrast, in hot regions with little humidity in the air, parcels will have to move to higher altitudes until the air reaches saturation. On the other hand, in hot regions with a lot of humidity, the air portions reach saturation at lower heights (Betts et al., 2014). Therefore, these thermodynamic concepts are the explanation for some regions in Figure 8 to have LCL more distant from surface (Patagonia and NE) than others (Amazon and Central SA).

For instance, in the case of NEB, there is lower availability of moisture in the atmosphere, but the temperature is high due to the intense active radiation warming of the surface (Fig. 8l and 8p). Therefore, the air parcels should present greater vertical displacement (reach higher heights) until they reach the dew point temperature and, consequently, the LCL. In Amazon, although it is an extremely hot region, the air is almost saturated, so a small displacement of the air parcel upward leads it to LCL, which will be closer to surface than in other areas of SA. At higher latitudes (south-central Argentina, which includes Patagonia), the air temperature is lower, as well as the concentration of water vapor, then the air parcels need to displace far from the surface to get saturation. In the Andes Mountains, LCL is influenced by the topography, which reaches about 7000 m of altitude (Monte Aconcagua, Argentina) thus making the LCL higher.
Figure 7. Annual climatology of (a-b-c-d) LCL at pressure levels (hPa), (e-f-g-h) LCL in meters (m), (i-j-k-l) 2-metre air temperature (°C) and (m-n-o-p) specific humidity at 2-metre (g/kg) in synoptic standard times (0000 Z is represented in line 1 and so on).

Season Climatology

Figures 9 and 10 depict the seasonality of LCL at pressure levels and in meters, respectively, for the four synoptic standard times. Across all seasons and analyzed times, in the Amazon region the cloud base is closer to the surface (~1000 hPa or 500 m). In much of center and southeastern Brazil (region of the South Atlantic Convergence Zone occurrence), the LCL is closer to the surface during austral summer (Fig. 9a-d, 10 a-d) than in the other seasons due to the warm and humid conditions typical of this season. On the other hand, it is in summer that southern Argentina experiences LCL more distant from surface (500 hPa or 5000 m). This could be linked to the warmer air in this period and low availability of moisture in the atmosphere, which persists throughout the year in this region. Much of the Argentinean Patagonia is situated in the leeward of the Andes, where the
air is drier, making it one of the possible factors causing the lack of moisture availability in the region.

Winter (Fig. 9i-l, 10i-l) is the season when southern Brazil has lower cloud base height and, in contraposition, NEB, center and southeastern Brazil show cloud base with higher altitude. In south of Brazil, the cloud base height decreases with the approach of winter and reaches its lowest value (higher than 950 hPa or lower than 750 m) during this season. This is suggested to be triggered by the supplying of humidity by the large number of cold fronts that reach the area during winter (period of intense baroclinity in the region, as discussed by Andrelina and Reboita, 2021). As the humidity meets the cold air of southern Brazil, LCL is easily reached. In a large area including NEB, center and southeastern Brazil, LCL reaches higher altitude during winter (Fig. 91 and 101), probably due to the influence of high-pressure systems, such as the South Atlantic Subtropical Anticyclone (SASA). The SASA action area is predominantly dry, and saturation occurs 414 at levels further away from the surface.

The LCL pattern is slightly different between transitional seasons (autumn and spring). During autumn, the LCL tends to be further from the surface (except in the Amazon) because much of the SA is acquiring drier conditions at this time of year. During spring, the situation is in an opposite direction, the continent is become wetter (Marengo et al., 2012; Ferreira and Reboita, 2022).

Figures 11 and 12, respectively, 2-metre air temperature and specific humidity at 2-metre, help in understanding the previous seasonal discussion and the daily LCL variability. While the specific humidity has seasonal variation that contributes to the LCL seasonality (Fig. 12), its diurnal variation is very small and the air temperature seems to be the main drive of the LCL height. For all regions (Amazon, Central SA, Northeast, and Patagonia), the time of 1800 Z exhibits the highest LCL height (Fig. 9d-h-l-p and 10d-h-l-p). The temperatures (Fig. 11) are mild for the times of 0600 and 1200 Z, since the Earth's surface emits long-wave radiation at night, causing it to cool down. At these times, the lowest temperatures predominate for a large portion of SA. Only in the northeastern Sertão, temperatures are above 24°C. During the day, the radiative warming of the air causes the increase of temperature that reaches its maximum at 1800 Z (Fig. 11p). As the specific humidity does not present great daily variability, an increase in air temperature causes the increase in the LCL altitude.
Figure 8. Seasonal climatology of LCL in pressure levels for SA: summer (DJF, a-b-c-d), autumn (MAM, e-f-g-h), winter (JJA, i-j-k-l) and spring (SON, m-n-o-p), for the synoptic standard times.
Figure 9. Seasonal climatology of LCL in meters for SA: summer (DJF, a-b-c-d), autumn (MAM, e-f-g-h), winter (JJA, i-j-k-l) and spring (SON, m-n-o-p), for the synoptic standard times.
Figure 10. Seasonal climatology of Temperature in °C for SA: summer (DJF, a-b-c-d), autumn (MAM, e-f-g-h), winter (JJA, i-j-k-l) and spring (SON, m-n-o-p), for the synoptic standard times.
Figure 11. Seasonal climatology of Specific Humidity in g/Kg for SA: summer (DJF, a-b-c-d), autumn (MAM, e-f-g-h), winter (JJA, i-j-k-l) and spring (SON, m-n-o-p), for the synoptic standard times.

Local Analysis

Figure 13 presents the annual time series for 0000, 0600, 1200, and 1800 Z of the LCL in meters, 2-metre air temperature, specific humidity at 2-metre, and precipitation for the five cities shown in Figure 1. Additionally, Table 2 displays the trend of these times series and highlights, in bold, the cases with statistical significance at a 95% confidence level based on the Mann-Kendall test (Mann, 1945; Kendall, 1975). The main information from Figure 13 is that regardless of the location, the LCL is higher at 1800 Z, agreeing with the results of the previous section. Moreover, there is a trend of increasing LCL over the years, which is generally significant at 1800 Z, except for Santa Maria (Fig. 13d).
Figure 12. Annual time series of LCL in meters (Equation 2 and ERA5 data) for the four synoptic standard times, and for 1800 Z the 2-metre air temperature (°C), specific humidity at 2-metre (g/kg) and precipitation (mm) for Brasília, Manaus, Rio de Janeiro, Santa Maria, and São Paulo.

In all cities, along with the positive trend of LCL, there is a positive trend in the 2-metre air temperature and negative one in specific humidity and precipitation (Table 2). This decrease in the annual precipitation may be a response of the lower specific humidity. In Brasília, LCL and precipitation trends are statistically significant at all synoptic times. In Santa Maria only air temperature shows a positive significant trend. São Paulo exhibits statistically significant trends for LCL in all synoptic times and in other variables, suggesting a relationship between the increase in LCL height and increase in air temperature and decrease in specific humidity. Rio de Janeiro and Manaus did not show significant precipitation trends (Table 2).

Table 2. Slope of the trend line. Statistically significant trends at level of 95% in Mann-Kendall test are shown in bold.

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<tr>
<td>São Paulo</td>
<td>9.367</td>
<td>4.446</td>
<td>8.439</td>
<td>27.903</td>
<td>0.070</td>
<td><strong>-0.026</strong></td>
<td>-12.55</td>
</tr>
</tbody>
</table>

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Conclusion

This study evaluated the performance of two empirical equations to compute the LCL and applied them in a climatological study for SA from January 1991 to December 2021. Validation of the equations: in this analysis we selected five cities that had sounding data in a rainy period (30th and 31st December, 2021). The LCL obtained through the sounding data and SkewT-LogP diagram were considered the reference data. So, the equations 2 and 3 for estimating LCL in meters and hPa, respectively, were solved using both sounding data and ERA5 reanalysis. Both equations showed deviations in relation to the observed data and there is no a better result in response of the chosen dataset. However, these deviations do not invalidate the application of the equations in a climatological study, since they can be smoothed when a lot of time steps are used.

SA LCL climatology: we determined the LCL climatology for SA between 1991 to 2021 using two empirical equations (equations 2 and 3) driven by ERA5 reanalysis. Although this methodology includes uncertainties (empirical equations and reanalysis data), the estimated LCL values can provide a good source of knowledge of its seasonal and daily variation in a large spatial view. Over SA, in general, LCL reaches higher altitude at 1800 Z, which is related with the diurnal cycle of air temperature. The season in which LCL presents higher altitude ranges according to the region of SA. Higher altitude of LCL is registered in summer in Patagonia (4000 m), spring in Northeast Brazil (3000 m), winter in central SA (2000 m) and in Amazonia (1500 m).

In areas that have warmer temperature and great availability of water vapor in the atmosphere the LCL tends to occur closer to the surface. The opposite occurs in areas where there are warm temperatures, however, low humidity. In this case, the air parcels need to reach higher altitude to get saturation. For cold air, excess of humidity leads to LCL to occur in low altitude. But in case of low humidity, LCL should be reached at higher altitude.

Local Analysis: in the five cities analyzed, the LCL shows a trend of increase but only Santa Maria the trend did not significant. In addition, air temperature registers a positive trend and specific humidity and precipitation, negative one. It can be suggested that there is a relationship between the LCL height and the decrease in precipitation.

Finally, we would like to highlight that is important to encourage the expansion of the sounding database in order to obtain in situ LCL. In addition, given the importance of the LCL for mesoscale and synoptic system analyses, it is suggested that correlations between the values of the cloud base height obtained in different events are evaluated, with a focus on the systems that produce high accumulated precipitation and, eventually, natural disasters.

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