Global climatology of low-level-jets: occurrence, characteristics, and meteorological drivers

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Abstract

Low-level jets (LLJs), wind speed maxima in the lower troposphere, impact several environmental and societal phenomena. In this study we take advantage of the spatially and temporally complete meteorological dataset from ERA5 to present a global climatology of LLJs taking into consideration their formation mechanisms, characteristics and trends during the period of 1992-2021. The global mean frequency of occurrence was of 21% with values of 32% and 15% for land and ocean. We classified the LLJs into three regions: non-polar land (LLLJ), polar land (PLLJ) and coastal (CLLJ). Over LLLJ regions, the average frequency of occurrence was of 20%, with 75% of them associated with a near-surface temperature inversion i.e. associated with inertial oscillation at night. Over PLLJ regions the LLJs were also associated with a temperature inversion, but were much more frequent (59%), suggesting other driving mechanisms than the nocturnal inversion. They were also the lowest and the strongest LLJs. CLLJs were very frequent in some hotspots, specially on the west coast of the continents, with neutral to unstable stratification close to the surfaces, that became more stably stratified with increasing height. We found distinct regional trends in both the frequency and intensity of LLJs, potentially leading to changes in the emission and transport of dust aerosols, polar ice and moisture over the world. However, it is currently unclear the evolution of the trends with global warming and what the implications are for climate and weather extremes. Future studies will investigate long-term trends for LLJs and the associated implications.

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Key Points:

- First global comprehensive low-level jet (LLJ) climatology using ERA5
- Polar LLJs are the strongest and most frequent among the detected types
- Distinct past trends in regional LLJ frequency and intensity

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Abstract

Low-level jets (LLJs), wind speed maxima in the lower troposphere, impact several environmental and societal phenomena. In this study we take advantage of the spatially and temporally complete meteorological dataset from ERA5 to present a global climatology of LLJs taking into consideration their formation mechanisms, characteristics and trends during the period of 1992–2021. The global mean frequency of occurrence was of 21% with values of 32% and 15% for land and ocean. We classified the LLJs into three regions: non-polar land (LLLJ), polar land (PLLJ) and coastal (CLLJ). Over LLLJ regions, the average frequency of occurrence was of 20%, with 75% of them associated with a near-surface temperature inversion i.e. associated with inertial oscillation at night. Over PLLJ regions the LLJs were also associated with a temperature inversion, but were much more frequent (59%), suggesting other driving mechanisms than the nocturnal inversion. They were also the lowest and the strongest LLJs. CLLJs were very frequent in some hotspots, specially on the west coast of the continents, with neutral to unstable stratification close to the surfaces, that became more stably stratified with increasing height. We found distinct regional trends in both the frequency and intensity of LLJs, potentially leading to changes in the emission and transport of dust aerosols, polar ice and moisture over the world. However, it is currently unclear the evolution of the trends with global warming and what the implications are for climate and weather extremes. Future studies will investigate long-term trends for LLJs and the associated implications.

Plain Language Summary

In this study, we investigated low-level jets (LLJs), strong winds in the lower atmosphere that have significant environmental and societal impacts. Using a comprehensive weather dataset spanning from 1992 to 2021, we created a global map of LLJs, categorizing them into three regions: non-polar land (LLLJ), polar land (PLLJ) and coastal (CLLJ). LLJs associated with temperature inversions were very common over land, but PLLJs were much more frequent. PLLJs were also the strongest and lowest. Coastal LLJs were prevalent on west coastlines and exhibited changing vertical temperature characteristics. On average, LLJs occurred in 21% of the time globally, with higher frequencies over land (32%) compared to the ocean (15%). Regional trends in LLJ frequency and intensity varied, with some areas experiencing more intense LLJs without changes in frequency while others presented an increase in both. The study emphasized the uncertainty surrounding the influence of LLJs on climate and weather extremes in a warming world, with future research aiming at exploring LLJ trends and their broader implications.

1 Introduction

Low-level jets (LLJ) are wind speed maxima in the lowest few hundred meters of the troposphere (Shapiro & Fedorovich, 2010; Ziemann et al., 2020). LLJs show a sharp decrease in wind speed above their core leading to the characteristic nose-like wind speed profile. They have diverse influences spanning from environmental to societal impacts, e.g. transport of moisture and pollutants (Angevine et al., 2006; R. Chen & Tomassini, 2015), aviation safety (Blackadar, 1957; Wittich et al., 1986), formation of dust storms (Schepanski et al., 2009) and wind power production (Gutierrez et al., 2016; Lampert et al., 2016; E. W. Luiz & Fiedler, 2022). Furthermore, LLJs are perceived as a mechanism for (sub)tropical moisture transport (Gimeno et al., 2016). They are also linked to the spatio-temporal variability of precipitation in certain regions, influencing the availability of freshwater for consumption, agriculture and ecosystems (Algarra et al., 2019). LLJs therefore play a role in the hydrological cycle (Pan et al., 2004), including the occurrence of droughts and floods (Algarra et al., 2019). Moreover, LLJs over coastal waters influence sea-surface temperatures by driving the upwelling of cold nutrient-rich waters with implications for the regional ecosystems and economic activities (Semedo et al., 2016).

In the classical theoretical description of inertial oscillations, LLJs develop due to the decoupling of nocturnal winds from the surface friction by the formation of a near-surface temperature inversion (Blackadar, 1957; Van de Wiel et al., 2010). These conditions typically occur over land at night, particularly during cloud-free conditions that allow strong radiative cooling near the surface (Sisterson & Frenzen, 1978; Beyrich, 1994). The associated weaker friction due to reduced eddy viscosity enables acceleration of the airflow aloft (Ziemann et al., 2020; Fiedler et al., 2013), with the development of a pronounced super-geostrophic wind speed maximum in the course of the night (Shapiro & Fedorovich, 2010). Such undisturbed inertial oscillations are a widely known formation mechanism of LLJs and are often called Nocturnal LLJs (NLLJ). In reality, the development of NLLJs diverts from the ideal fully decoupled and undisturbed inertial oscillation that was theoretically described by Blackadar (1957), due to reduced but not eliminated frictional effects (B. J. Van de Wiel et al., 2010), the occurrence of intermittent turbulence at night (B. Van de Wiel et al., 2003) and non-stationary environmental conditions (E. W. Luiz & Fiedler, 2022). Moreover, LLJs with a co-occurring temperature inversion can also be driven by other mechanisms, e.g., in the absence of nocturnal cooling. For example, LLJs can be formed when a near-surface temperature inversion is formed by warm air advection over relatively cool near-surface air. The associated tilt of the isobaric surfaces leads to a thermal wind that under certain conditions can manifest itself as a LLJ. LLJs have further been connected to synoptic- and mesoscale dynamical systems (G. T.-J. Chen et al., 2006; Li & Du, 2021; Corrêa et al., 2021; E. Luiz & Fiedler, 2023).

LLJs are known to occur in different regions around the world that favor the development of different types. Common locations for LLJ occurrence are coastal upwelling regions (Lima et al., 2022), hot deserts (Heinold et al., 2013; Fiedler et al., 2013) and continental polar regions (Tuononen et al., 2015; Heinemann & Zentek, 2021). LLJs in hot desert areas are usually NLLJs, although a fraction of the LLJs are connected to convective cold pools (Heinold et al., 2013). LLJs in hot deserts have strong implications for the formation of dust storms (Fiedler et al., 2013; Z. Han et al., 2022). Likewise, LLJs happening in continental polar regions (PLLJs), or cold deserts, are generated by the stabilization of the atmospheric boundary layer via near-surface cooling or warm air advection (Heinemann & Zentek, 2021). Other mechanisms for LLJ formation over cold deserts were also identified. The topography, for example, can lead to the formation of barrier winds, katabatic flows and tip jets, all of which may form wind profiles that can meet the LLJ criteria (Tuononen et al., 2015). In zones of high baroclinicity, such as synoptic or mesoscale fronts along an ice edge, the vertical shear of the geostrophic wind and surface friction can lead to the generation of baroclinic LLJs (Jakobson et al., 2013; Heinemann et al., 2021).

Coastal low-level jets (CLLJs) usually occur offshore of the west coast of different continents, e.g. USA, Chile/Peru, Australia, and Africa (Lima et al., 2022), with seasonal differences that depend on the region. In general, the differential heating leads to the formation of a high-pressure system over the ocean and a thermal low over land. The associated pressure differences lead to strong winds. Since the warm air subsides in the high pressure above the Marine Atmospheric Boundary Layer, and cooler, moist and well-mixed air resides above the ocean surface, the development of a temperature inversion in some distance to the surface happens (Beardsley et al., 1987). Reduced frictional effects in the inversion layer allow the formation of a CLLJ, which is not unlike the condition for a NLLJ, but occurs in this case also during the day and at higher levels, with a maximum usually in the lowest 1000ṁ a.g.l. (Garreaud & Muñoz, 2005; Soares et al., 2014; Ranjha et al., 2013).

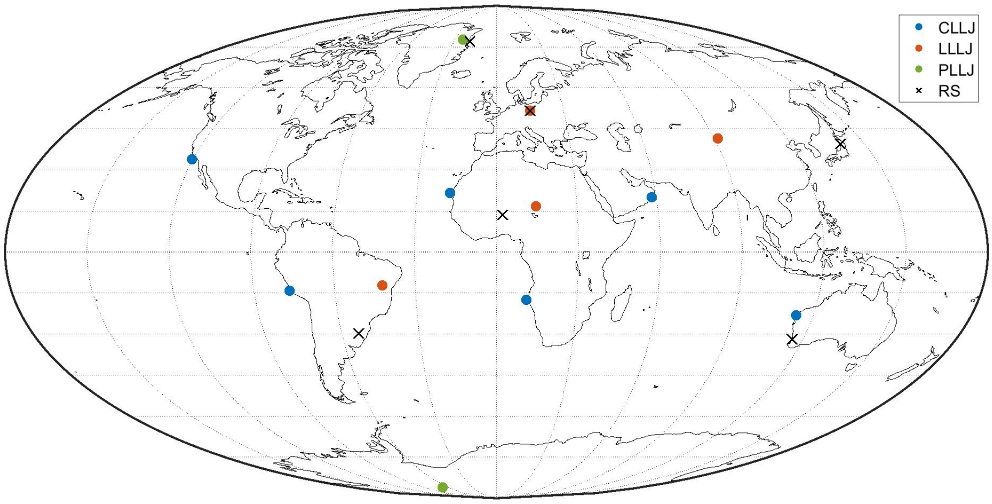

Figure 1. Location of the grid points selected for the analysis of LLJ types and the radiosonde (RS) sites for the evaluation of LLJs in ERA5.

Multiple studies for individual processes driving LLJs in different world regions exist, yet there is no global climatology accounting for more than single LLJ types with details on their relative occurrence frequencies and characteristics. In the present study, we take advantage of the spatially and temporally complete meteorological data with a sufficiently high spatial and temporal resolution as provided by the ERA5 reanalysis for 1992–2021 and an automated detection algorithm for LLJs to better understand LLJs from a global perspective. As we will see later, ERA5 is adequate for compiling a global LLJ climatology. Our focus is on three main aspects: (1) the global quantification of differently driven LLJs, (2) the characterization of governing physical processes of LLJ in occurrence hotspot regions distributed across the world and (3) an assessment of past trends for LLJs with global warming. In so doing, we present a comprehensive global climatology of LLJs accounting for the different physical driving mechanisms for their development.

2 Data and Methods

2.1 ERA5

ERA5 is the latest global reanalysis dataset from the European Centre for Medium-range Weather Forecasts (ECMWF) (Hersbach et al., 2020). ERA5 combines a state-of-the-art weather model with historical measurements (satellites, weather stations, etc.) to obtain a spatially and temporally consistent dataset covering the years since 1940. ERA5 provides global output for many different meteorological variables (Y. Han et al., 2021) on a grid with a horizontal resolution of about 30 km and 137 vertical levels. About 20 levels are within the first 1000 m a.g.l. giving a suitable vertical resolution to study LLJs. The temporal resolution of the output is variable, with hourly intervals being the finest resolution. For this work, we used data for wind speed, humidity, temperature and pressure on the model levels with a three-hourly resolution for 1992–2021 to compile the LLJ climatology over 30 years.

2.2 LLJ detection and classification

The identification and analysis of the LLJs in ERA5 are based on an automated detection algorithm developed earlier for the ERA-Interim reanalysis of ECMWF (Fiedler

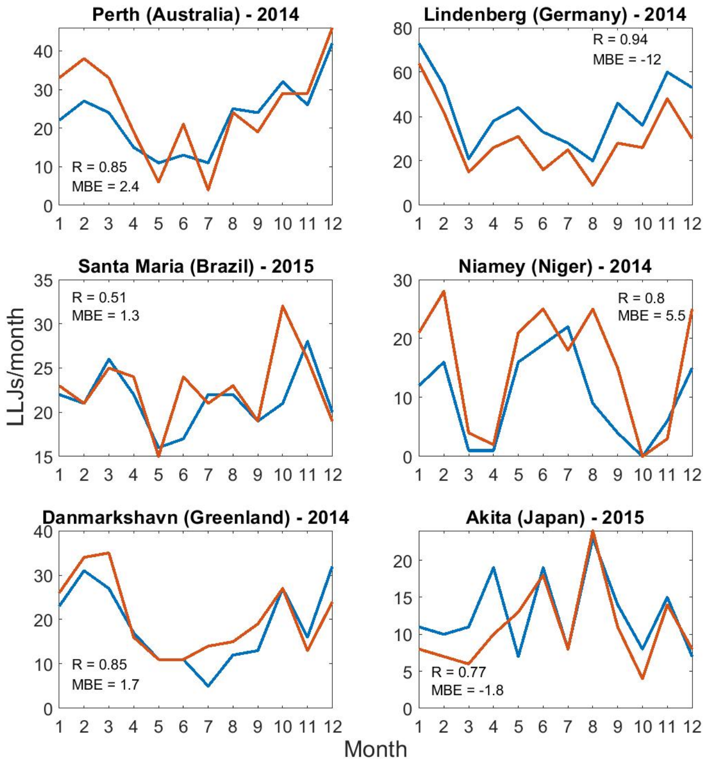

Figure 2. Validation of LLJ occurrence frequency in ERA5. Shown are the monthly mean number of LLJs detected in ERA5 and radiosondes at different sites. The comparison was done for the years 2014 or 2015, as stated in the title of the figures, due to the availability of radiosonde data. The selection of the sites (see Figure 1) is such that different climatic conditions are covered.

et al., 2013). We follow the same approach, except that we here do the initial identification of LLJ based on the wind speed profiles alone. This choice is made to allow the additional identification of LLJs that are not formed in the presence of a near-surface temperature inversion for a holistic analysis of different LLJ types. The criteria in the algorithm are set such that the algorithm detects LLJs with a characteristic nose-like wind profile as in Fiedler et al. (2013) and E. W. Luiz and Fiedler (2022). The LLJ core was identified as the wind speed maximum in the lowest 1000 m a.g.l. that satisfies the following criteria. First, a low-level wind speed maximum is identified as an LLJ if the vertical shear in the wind speed is more negative than $-0.005\ s^{-1}$ in the 500 m deep layer above the LLJ core. Second, we require a difference in the wind speed between the same layers of at least $2\,\mathrm{ms}^{-1}$. Both these criteria ensure a nose-like profile and exclude ambiguous cases. The detection algorithm was applied in every grid point to the three-hourly profiles over thirty years from ERA5.

The statistical analysis of the LLJ output lead the separation of the analysis into three different regions. Non-polar land areas, which has the prevalence of NLLJs following the classical inertial oscillation theory at night were called land LLJ (LLLJ). Polar land regions, which present a high frequency of NLLJs, but also a high ammount of LLJs from different sources, were called Polar LLJ (PLLJ). Near-coast regions with a area of 20 grid points around any land were called Coastal LLJ (CLLJ). The latter present the most different formation mechanism, as we will see later. Figure 1 marks the locations for the assessment of the dynamics of the different LLJ types at the mentioned regions.

We selected profiles in different locations where LLJs frequently form. From each of those praces, the grid point with the highest frequency of occurrence was selected to better understand the dynamics of LLJs through performing composite analyses. The selected regions are the following.

- A location in Antarctica and in Greenland were selected for studying PLLJs.
- For CLLJ, six locations over the ocean were picked. The Benguela current and the coasts of West USA, Chile/Peru, West Africa, West Australia and Oman.
- LLLJs were analyzed in the hot desert climates of the Saharan desert in Chad in North Africa and the Taklamakan desert in China, a region with semi-arid climate in Brazil and a temperate climate in Germany.

For the dynamical assessment of the LLJs, we used two different metrics for the atmospheric stability and the momentum flux, namely the vertical gradient in the virtual potential temperature ($\Delta\theta_v$) and the Richardson Number (Ri). A stably stratified air layer is characterized by an increase of θ_v with height. We here require $\Delta\theta_v > 0.001$ Km^{-1} for stable conditions to inform us about the co-occurrence of inversions with LLJs. Moreover, Ri provides information on the influence of the tendency of shear-induced vertical mixing which can be strong during LLJs. Large Ri values imply that the effect of the stable stratification is stronger than the effect of shear-driven turbulent mixing. The critical threshold for the transition between stable and unstable conditions is about 0.25, i.e., turbulence occurs when Ri is smaller than this threshold (Peng et al., 2022).

2.3 Validation of approach

We validated to what extent observed LLJs are reproduced by ERA5, applying the automated detection algorithm for LLJs to co-located profiles from ERA5 and radiosondes. To that end, we selected stations with quality-controlled radiosondes (RSs), obtained from the department of Atmospheric Science of the University of Wyoming. The chosen stations encompass different climates around the world and are situated in Perth (Australia), Lindenberg (Germany), Santa Maria (Brazil), Niamey (Niger), Danmakshavn (Greenland), and Akita (Japan). Figure 1 shows the locations of the analyzed sites. Although some of the RSs have been assimilated, it is useful to make this comparison. ERA5 for instance also assimilates data from satellite measurements and surface meteorological stations, assigns different weights to the different datasets for generating the analysis, performs an interpolation of the observation in time and space to match the model grid, and also depends on the forecast model state at the time of assimilation which is jointly influencing the analysis. Hence, we expect differences in the LLJs in RSs and ERA5 which we indeed see, but the general temporal variability of LLJs follows very similar patterns in across the different sites assessed here.

Specifically, the month-to-month variability in detected LLJs from the RSs is well reproduced by ERA5. Figure 2 shows the monthly co-variability of the number of LLJs in ERA5 and the RSs during one year at the sites. From those, the Probability of Detection (POD), comparing ERA5 to the RSs, ranged from 0.47 in Lindenberg (Germany) to 0.73 in Perth (Australia). The False Alarm Rate (FAR) ranged from 0.32 in Akita (Japan) to 0.6 in Niamey (Niger). Testing other sites than the ones included here led to similar results (not shown). It suggests that the month-to-month variability in the LLJ frequency of occurrence is reasonably well represented by ERA5. Also, the characterization of the LLJs by ERA5 is sufficiently good for our purposes. The average wind speed at the LLJ core was for instance very similar in ERA5 and the RSs ($\sim$11 ms^{-1}) with the LLJ core heights being underestimated by ERA5, with an average of 417 m in ERA5 against 537 m in the RSs of the analyzed sites. Note that the global average and averages over other sites can deviate from these numbers. For example, the ERA5 average LLJ core in Lindenberg (Germany) was slightly higher in ERA5, while in Santa Maria (Brazil) and Niamey (Niger), they were much lower.

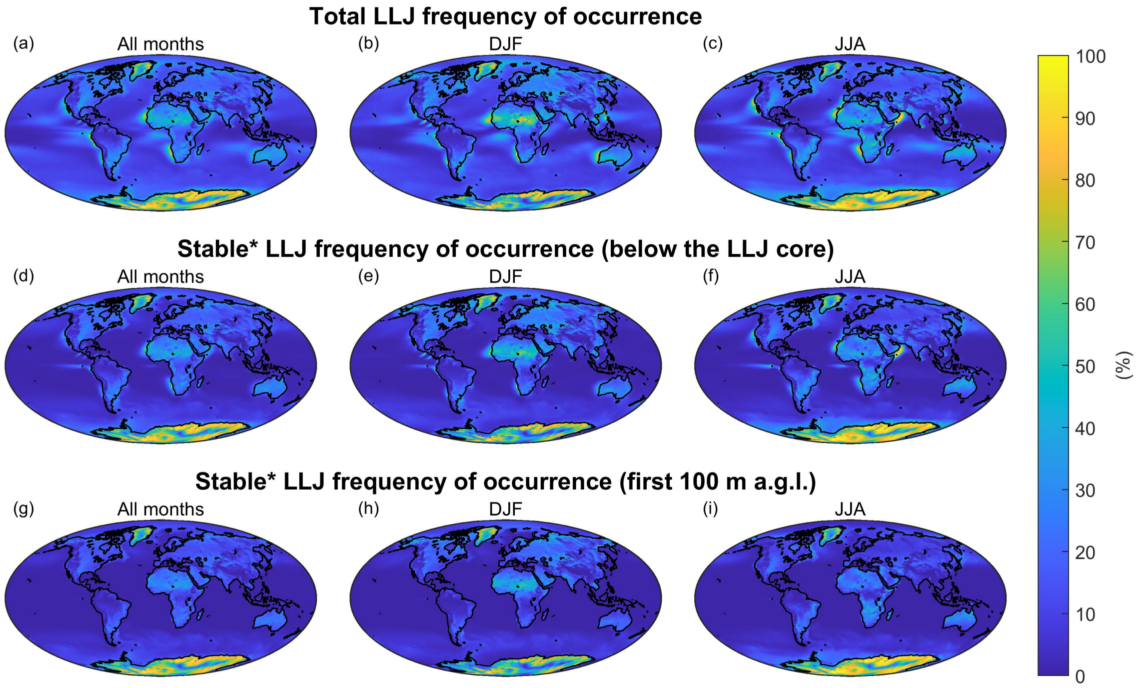

Figure 3. Spatial pattern of the occurrence frequency of LLJs in percent of all profiles. Shown are (a–c) the total frequency of occurrence of LLJs, (d–f) the frequency of occurrence of LLJs during stable conditions from the surface until the LLJ core, and (g–l) the same as (d–f) but for the lowest 100 m a.g.l. The left column shows the mean over all months, the middle for December, January, and February (DJF), and the right column for June, July, and August (JJA). *Stable LLJs were considered when $\Delta\theta_v > 0.001\,\mathrm{Km}^{-1}$, i.e. when we found the presence of a temperature inversion. The results are based on ERA5 for 1992–2021.

3 Results

3.1 Global LLJ occurrence

The global climatology of the frequency of occurrence of LLJs highlights several regional hotspots, including the continental polar regions and the offshore regions off the west coast of continents. Moreover, hot desert regions frequently witness LLJs, e.g. the Sahara and the Taklamakan deserts. Figure 3a–c shows the global frequency of LLJs averaged for all months, for winter and summer. Some regions show a pronounced seasonal variability in the LLJ occurrence frequency. Take for instance the Australian West Coast and Oman's East Coast, which have a maximum LLJ occurrence in just one of the two seasons (Figure 3b–c). Other regions have relatively similar LLJ occurrence throughout the year with slight differences in the exact location of the regional maximum, e.g. a small North-South difference in the maximum at the West African Coast. Also the land regions near the poles, namely Greenland and Antarctica, frequently see LLJs which are slightly more often occurring during polar night.

Figure 3d-i shows the frequency of occurrence of LLJs in the presence of a temperature inversion layer. Here, we compute the atmospheric stability based on the vertical

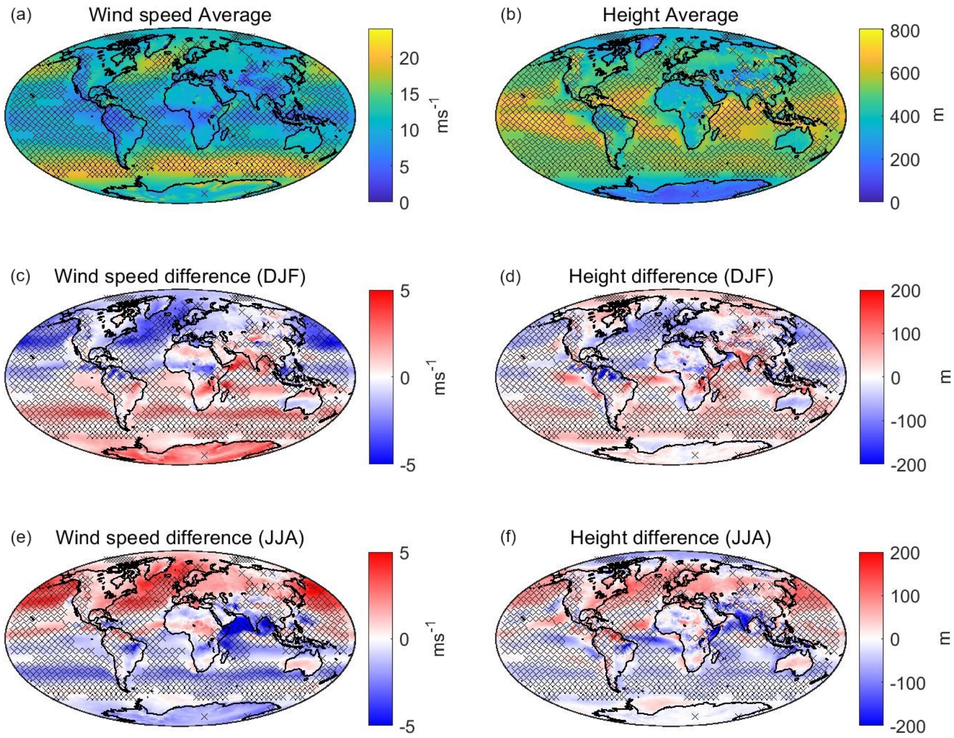

Figure 4. Spatial patterns of LLJ characteristics. Shown are the means for (a) wind speeds and (b) heights in the core of LLJs, and (c–f) the seasonal differences in the mean for December, January, and February (DJF), and June, July, and August (JJA). The dashed areas mask regions where the LLJ frequency of occurrence was smaller than 15%. The results are based on ERA5 for 1992–2021.

gradient in the virtual potential temperature from the surface until the LLJ core (Figure 3 d–f) and in the lowest 100 m a.g.l. (Figure 3g–i). LLJs in the absence of an inversion layer are typically less frequent. Coastal LLJs typically have no near-surface temperature inversion (e.g. in the lowest 100 m a.g.l), but present it accounting for all layers below the LLJ core, as indicated by the higher frequency of occurrence of LLJs for these conditions. Over regions offshore of coasts, we typically see a well-mixed marine boundary layer at the lowest levels underneath the LLJ core with an inversion above it. Most of LLJs without an inversion in the lowest levels happen over the ocean at up-welling regions west of the continents. On land, most of the LLJs happen with the presence of a near-surface temperature inversion, with formation mechanisms connected to inertial oscillations. During NLLJ, we still have a lower amount of weaker LLJs when the temperature inversion is broken by surface warming, which may account for the LLJs without the inversion presence. A detailed analysis of the vertical structure of the atmosphere for the different LLJ types and regions will be done in the next chapters.

The global mean in the frequency of occurrence of LLJs is 21%. It is important to mention that this is an average over all grid points and the regions closest to the poles have a higher weight. The mean frequencies for LLJs with a simultaneous appearance of an inversion measured by $\Delta\theta_v > 0.001\ Km^{-1}$ from surface until the LLJ core (in the lowest 100 m a.g.l.) occur in 15% (12%) of the profiles. The slight difference in the occurrence frequency of the LLJs with inversion layers at different altitudes can be explained by the neutral to unstable stratification close to ocean surfaces that become more stably stratified with increasing height. Specifically, the frequency of occurrence of LLJs

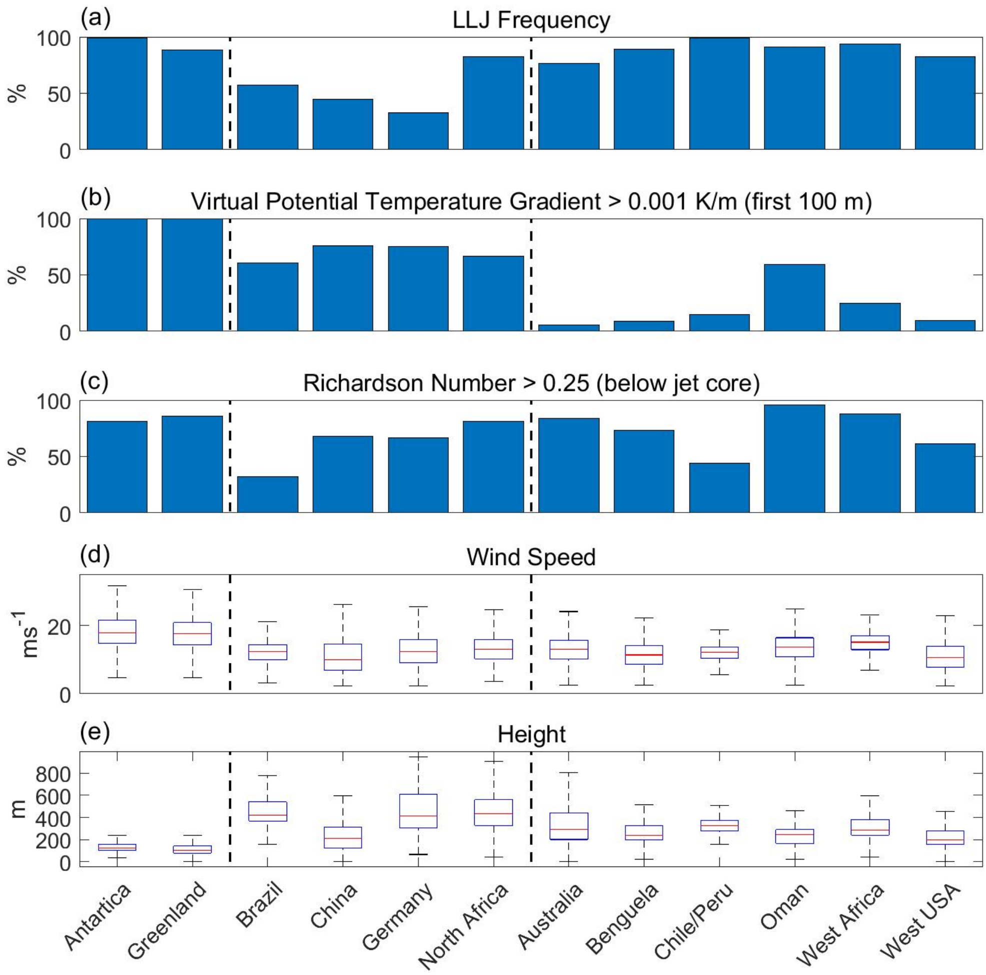

Figure 5. Statistics of different LLJ types at the selected locations. Shown are the (a) LLJ frequency of occurrence in % of all profiles, (b) percentage of LLJs with co-occurring virtual potential temperature gradient of $\Delta\theta_v > 0.001\,\mathrm{Km}^{-1}$ in the lowest 100 m a.g.l., (c) percentage of LLJs with the Richardson Number in the below the LLJ core $Ri > 0.25$, (d) statistics of the wind speed and (e) height of the LLJ cores showing the means (red), quartiles (box), and the 25 and 75 percentiles (whiskers). The vertical dashed lines separate (left to right) PLLJs, LLLJs, and CLLJs. The locations are marked in Figure 1.

averaged over oceans for all LLJ cases, with a stable stratification below the LLJ core and those with a surface temperature inversion in the lowest 100ṁ a.g.l is 15%, 8% and 5%, respectively. On land, the differences associated with a temperature inversion are less apparent, with average frequencies of occurrence of LLJs of 28–32%. On average, the frequency of occurrence of LLJs on land is higher than over the oceans, because many regions over the ocean have very small LLJ frequency of occurrence. This can be seen by the mask made for regions with frequency of occurrence smaller than 15% from Figure 4.

3.2 Global LLJ characteristics

Globally averaged, the mean wind speed of LLJs is about $12\,\mathrm{ms}^{-1}$, with a difference at the order of 10 % ($< 1\,ms^{-1}$) when we compute the average over ocean and land regions separately. The mean height of the LLJ cores differs more between the ocean with 419 m against land with 325 m. The global average of the LLJ core height is 371 m. Accounting for the co-occurrence of a temperature inversion for LLJs has a marginal influence on the globally averaged wind speed and height of the LLJ cores. The average height of LLJs for regions with frequencies of occurrence higher than 15% and a co-occurring temperature inversion, measured by $\Delta\theta_v > 0.001\ Km^{-1}$ underneath the LLJ core, is for instance 387 m.

Figure 4a–b shows the spatial patterns of wind speed and height of the LLJ cores averaged for 1992–2021 with a mask over the regions with frequency of occurence smaller than 15%. The value of 15% was chosen in this study as an objective criterion to analyze the regions with the main LLJ types defined here. The LLJ heights in both Antarctica and Greenland are less than 200 m a.g.l. which is lower compared to most other regions. The wind speed in the core of LLJs in these cold deserts is around 12 ms^{-1} which is stronger compared to most other land regions. Over ocean regions, stronger wind speeds in LLJ cores are seen in the extra-tropical storm tracks of both hemispheres, at around latitudes of 50°. Here the LLJ profiles can be connected with frontal systems associated with extra-tropical cyclones. Interestingly, the height of LLJ cores increases over oceans from the poles towards the equator, consistent with the deeper boundary layer over warmer tropical waters relative to cooler sea-surface temperatures towards the poles.

Seasonal differences in the LLJ intensity show a remarkably consistent hemispheric asymmetry, with typically stronger (weaker) LLJs across most of the summer (winter) hemisphere compared to the annual mean (Figure 4c–f). The asymmetry in the LLJ strength is most pronounced in the extra-tropics than in the tropics consistent with the stronger seasonal variation in near-surface temperatures. Typically higher summertime boundary layers over land in the extra-tropics also lead to regionally higher LLJ cores relative to the annual mean, e.g., for many mid-latitude regions in the northern hemisphere and over Australia during the summer seasons. An interesting opposite behavior of the described seasonality of the regional LLJ characteristics in the extra-tropics is seen along the coast of Oman. Here, the wind speed and height of the LLJ cores are higher (lower) during the winter (summer) months compared to the annual mean, due to its different driving mechanism: the Indian Monsoon (Ranjha et al., 2015).

3.3 LLJ Regions

We analyze LLJ dynamics in more detail for the three different regions inspired by existing classifications from the literature (see Methods Section for details), namely non-polar land low-level jets (LLLJs), coastal low-level jets (CLLJs) and polar low-level jets (PLLJs). Examples of averaged wind profiles for the year 2018 are found in Figure S1 from all locations marked in Figure 1. PLLJs were the strongest and lowest LLJs amongst the locations assessed here. In Antarctica, LLJs can have core wind speeds exceeding 20 ms^{-1} at heights well below 200 m a.g.l.. The PLLJs are, therefore, much lower than LLJs formed by reduced dynamical friction in hot deserts. The LLLJs locations presented the highest cores compared to all LLJ locations assessed, e.g., the Bodélé Depression in Chad, North Africa, has high NLLJ cores around 500 m a.g.l. in the mean for 2018.

We systematically assessed the regional LLJ differences by statistical analyses over the entire 30-year period with Figure 5, including atmospheric stability metrics, height and speed of the LLJ cores as well as the frequency of occurrence of the LLJs. Again, we can see the lower heights and higher wind speeds of PLLJs, while the highest LLJs are found at the LLLJ locations. CLLJs and LLLJs have similar wind speed characteristics. Most LLLJs coincide with stable stratification directly below the LLJ core, which allows for the balance of shear-induced mixing of momentum by the LLJ. This can be seen by the high simultaneity of LLJs and Richardson Numbers larger than 0.25 from surface until the LLJ core. The Brazilian site is an exception with less than 50% of the

LLJs having Richardson numbers exceeding 0.25. It implies that the LLJs here are typically less stable compared to the other locations, which implies some downward mixing of momentum. This aspect is further assessed in the following.

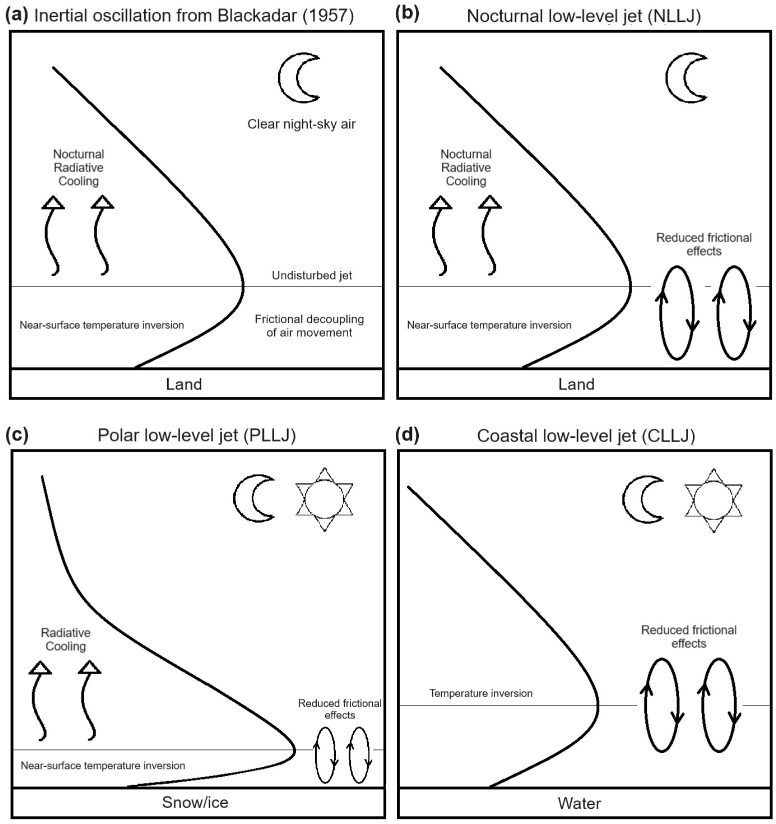

Figure 6. Schematic diagram of different LLJ types. Depicted are the conditions for the theory of an inertial oscillation (Blackadar, 1957) and the LLJ types analyzed in this study.

3.3.1 Non-polar land low-level jets (LLLJ)

In general, LLLJ regions present high frequency of NLLJs, which are formed by a mechanism similar to a inertial oscillation and usually occur during the night, when radiative cooling allows the formation of a near-surface temperature inversion. These mechanisms are schematically depicted in Figure 6a–b following the idealized theory of an inertial oscillation from (Blackadar, 1957) and accounting for non-stationary effects that are common in reality. The average frequency of occurrence over LLLJ areas is about 20%, with 75% of them coinciding with a near-surface temperature inversion. From the picked LLLJ locations (Figure 5), more than 50% of the LLLJ profiles coincide with a near-surface temperature inversion, measured by a mean of $\Delta\theta_v > 0.001\ Km^{-1}$ over the lowest 100 m a.g.l.. Similarly, a stable stratification underneath the most LLLJ locations allows a relatively stable development of LLJs, as measured by Ri > 0.25.

To better understand the development of NLLJs, Figure 7a–b shows a case study for an NLLJ in North Africa with a wind speed profile that is closest to the mean NLLJ profile for 2018. We see the transition from a well-mixed daytime boundary layer to the evening formation of a near-surface inversion. It implies increasing static stability after sunset (19 LST) initially seen as an increase in θ_v with height close to the surface. This

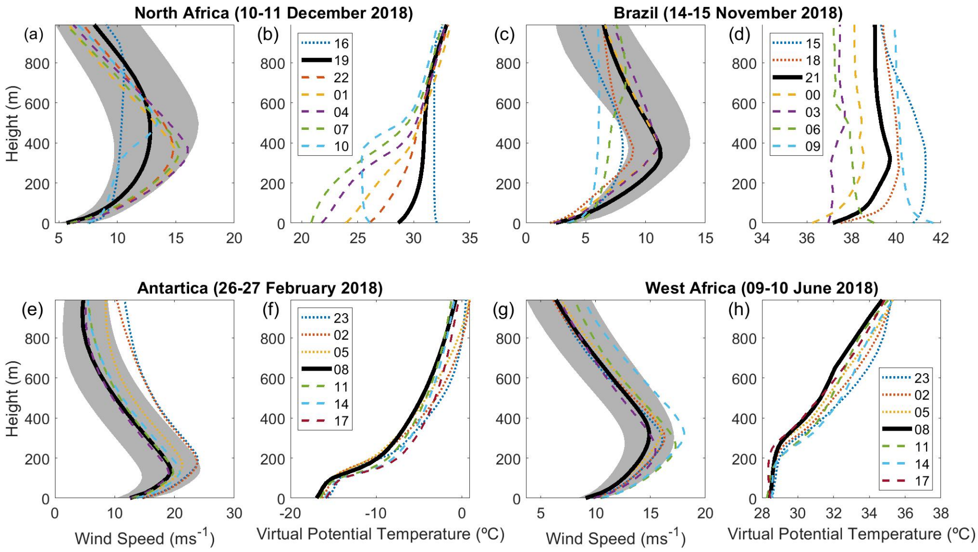

Figure 7. Case studies for the development of different LLJ types representative of their respective mean at the same location. Shown are the vertical profiles of (left) the wind speed and (right) the virtual potential temperature for the LLJ location and time stated in the title. The solid black lines are the wind profile of the selected LLJ that is most similar to the average for the LLJs at the same location in 2018. Shading marks the area of $\pm 1\sigma$, one standard deviation. Colored lines are the profiles for different hours before and after the selected LLJ to illustrate the development.

development continues by further surface cooling, deepening of the inversion layer up to 600 m a.g.l. in the course of the night. Simultaneously an NLLJ develops with the characteristic nocturnal acceleration of the air motion several hundred meters above the surface with a maximum at 04 LST and a subsequent slight deceleration associated with the turning of the wind field driven by the Coriolis force. The mid-morning breakdown of the NLLJ is associated with morning heating leading to a well-mixed boundary layer at 10 LST. At that time, the momentum of the NLLJ has been transferred to the surface and the core now appears about 100 m higher than at night.

The development of NLLJs at the Brazilian location can behave differently causing the lowest number of stable LLJs (compare Figure 5). Figure 7c–d shows the case study for a NLLJ in Brazil that is close to the 2018 mean. The wind speed profile of the NLLJ has characteristics similar to North Africa. However, in Brazil the inversion and hence the stability during the NLLJ was much weaker directly underneath the NLLJ and shallower until midnight compared to North Africa. The inversion decayed already during the night, specifically a well-mixed boundary layer is seen at 03 LST interrupting the nocturnal acceleration of the air motion. The momentum is subsequently transfered towards the surface causing the disappearance of the NLLJ already at 06 LST, much earlier than in North Africa.

In both case studies the wind speed in the core of the NLLJ is sub-geostrophic throughout the lifetime and there is no ideal change in the wind direction over time as one would expect from the theory of (Blackadar, 1957) (not shown). Deviations from the theory are to be expected since the assumption of stationarity is not fulfilled. Some cases, however, can show supergeostrophy. We see, for instance, for the NLLJ case study for Germany, a clear circular cyclonic change in the wind direction in the course of the night leading to a supergeostrophic wind speed in the NLLJ core, e.g., at 23 LST and 01 LST

(Figure S2). Supergeostrophy is expected from the theory but it is predicted to be a much smoother and gradual development, indicating that also in this case study non-stationary effects influenced the development of the NLLJ.

3.3.2 Polar low-level jets (PLLJ)

PLLJs are common throughout the year and mostly co-occur with a temperature inversion (Figure 5), namely in 90% of the cases in Antarctica and Greenland. The average frequency of occurrence of PLLJ over Antartica and Greenland is very high, about 59%; with some locations having values above 90%. This is broadly consistent with previous studies (e.g. Tuononen et al. (2015); Heinemann and Zentek (2021)). The development of PLLJs is similar to inertial oscillations that one expected due to near-surface inversion formed by little irradiance in polar nights causing low surface temperatures throughout the day for several months (Figure 6c). The very high frequency of LLJs coinciding with a near-surface temperature inversion (99%) at PLLJ regions suggest other different driving mechanism than NLLJs, since they also happen during day time. PLLJs can then be further favored by the cold surface, complex topography and baroclinicity (Tuononen et al., 2015).

Figure 7e–f shows a case study for Antarctica. It shows a snapshot of a long-lived PLLJ with a core at around 100 m with wind speeds of more than $20\,\mathrm{m\,s^{-1}}$. It occurs during stably stratified conditions that show only little variation over time with a particularly strong inversion around the LLJ core. Similar conditions can also be seen in Greenland (not shown). The case studies at both locations also showed a circular change of the wind direction over time, with a clockwise (anticlockwise) turning in Greenland (Antarctica) due to the Coriolis force. The selected case shown here for Antarctica also reached supergeostrophic wind speeds in the LLJ core, but this is not always the case, as suggested by the subgeostrophic PLLJ in a case assessed over Greenland (not shown).

Most continental LLJs, thus PLLJs and NLLJs have wind directions depending on the regional weather patterns causing differently oriented geostrophic wind vectors (Figure S3). It is interesting that they have a clearly prevailing direction per location. North African NLLJs, for instance, primarily have northeasterly directions (Figure S4), consistent with earlier findings based on another reanalysis (Fiedler et al., 2013). The largest spread in LLJ directions is seen for the location in Germany, consistent with different weather patterns driving LLJs there (E. W. Luiz & Fiedler, 2022).

3.3.3 Coastal low-level jets (CLLJ)

Most CLLJs form offshore off the west coast of continents. On average, the frequency of occurrence over the coast (19%) is bit higher than the frequency of occurrence over all ocean (15%). Differently from LLLJ regions, we can see some hotspots with values close to 90% for the CLLJ regions. These LLJs develop under different conditions than NLLJs and PLLJs (Figure 6d). CLLJs are rarely associated with a near surface temperature inversion. They occur most often during neutral to unstable atmospheric conditions in the mean over the lowest 100 m a.g.l.. The case study for West Africa shows that the boundary layer is rather neutral stratified close to the surface and becomes stably stratified around the CLLJ core (Figure 7g–h). Above the LLJ core, θ_v particularly strongly increased with height; an indicative of a stable stratification. Amongst CLLJ locations, Oman has most frequently a near-surface inversion, but this is still about 50% of the cases; less frequent than for PLLJs and most LLLJs (Figure 5b).

Depending on their location, CLLJs might undergo a strong seasonal cycle. The Benguela CLLJ, for example, can occur throughout the year, with differences in its mean frequency and the location of the maximum. Such differences depend primarily on the zonal pressure gradient near the surface (Lima et al., 2019). Differently, the seasonal cycle of CLLJ in Australia is strong, with a maximum in the frequency of occurrence during austral summer. The Oman CLLJ is unique by its location, synoptic forcing and its link to South Asia Monsoon (Ranjha et al., 2015). Hence it behaves differently throughout the year, with a maximum frequency of occurrence during July and August. The wind directions of CLLJs are typically parallel to the coastlines and usually towards the equator (S3 and S4). Again, Oman is the exception due to it's different dynamical forcing.

3.4 Past changes of LLJs

We assess to what extent LLJs might have changed during the past decades by computing linear trends (Figure 8a). The global averaged frequency of occurrence trend is of 0.02 %/year. There are regionally positive trends in the annually averaged frequency of occurrence of LLJs in the Arctic and eastern equatorial regions of the Atlantic and Pacific. The location with the largest positive trend is seen in the southern part of the Caribbean Sea. The positive trends in the Arctic and also in southern Greenland and western USA were especially strong during boreal winter. Amongst the selected locations for case studies, Chile/Peru had also an increase in the LLJ frequency of occurrence over time that is statistically significant at the 95% level of significance. Negative trends in the frequency of occurrence of LLJs are seen in the southern Indian Ocean, and to the southwest of the regions with positive trends in the Atlantic and Pacific. There is also a strong negative trend in the Barents Sea, which is most pronounced during boreal winter. Also, Northeast of the Oman LLJ region, a strong negative trend was seen during boreal summer, but is not seen in the annual mean. Amongst the locations for case studies, only Chile/Peru presented a positive trend.

Trends in the LLJ core wind speed (Figure 8b) are typically negative (positive) North (South) of 20 degrees North, with a global average of 0.02 $\mathrm{ms^{-1}year^{-1}}$. Most positive trends are seen over Antarctica, central and northeast Africa, and offshore of the western coasts of Africa. Negative trends were detected over central and eastern Europe, northern India, and the northern Pacific. Amongst the locations for case studies, Antarctica, Chile/Peru, North Africa, and West Africa had positive trends in the LLJ wind speed, whereas Germany had a negative trend.

4 Discussion

Some regions have seen higher frequency and intensity of LLJs over the past 30 years. Over the Amazon region, for example, the mean frequency of occurrence is relatively low, but our results indicate an increase in their frequency and intensity. These trends can imply changes in the precipitation in the Southern Amazonia and the La Plata River Basin. For instance, the amount of atmospheric moisture transported by the South American LLJ is comparable to the Amazon River (Arraut et al., 2012). This may increase the climate change impacts related to changes in land use (particularly deforestation) due to its influence on the water cycle (Zemp et al., 2014).

LLJs frequently form in desert areas such as Northern Africa (Fiedler et al., 2013). The NLLJs in Northern Africa play an important role in emitting mineral dust into the atmosphere (Schepanski et al., 2009; Heinold et al., 2013; Knippertz & Todd, 2012), which are known for several different impacts in the Earth system (Prospero et al., 2002; Washington et al., 2003). In some parts of North Africa, specifically in the Sahel, our results suggest a decreasing frequency of occurrence but little change elsewhere. The intensity of NLLJs, however, has increased over comparably larger regions in eastern parts of North Africa, including the Bodélé Depression in Chad which has been named as the dustiest place on Earth. These trends might have led to a change in regional dust storm frequency and intensity, e.g., a tendency to more intense dust storms associated with NLLJs in the Bodélé Depression and beyond.

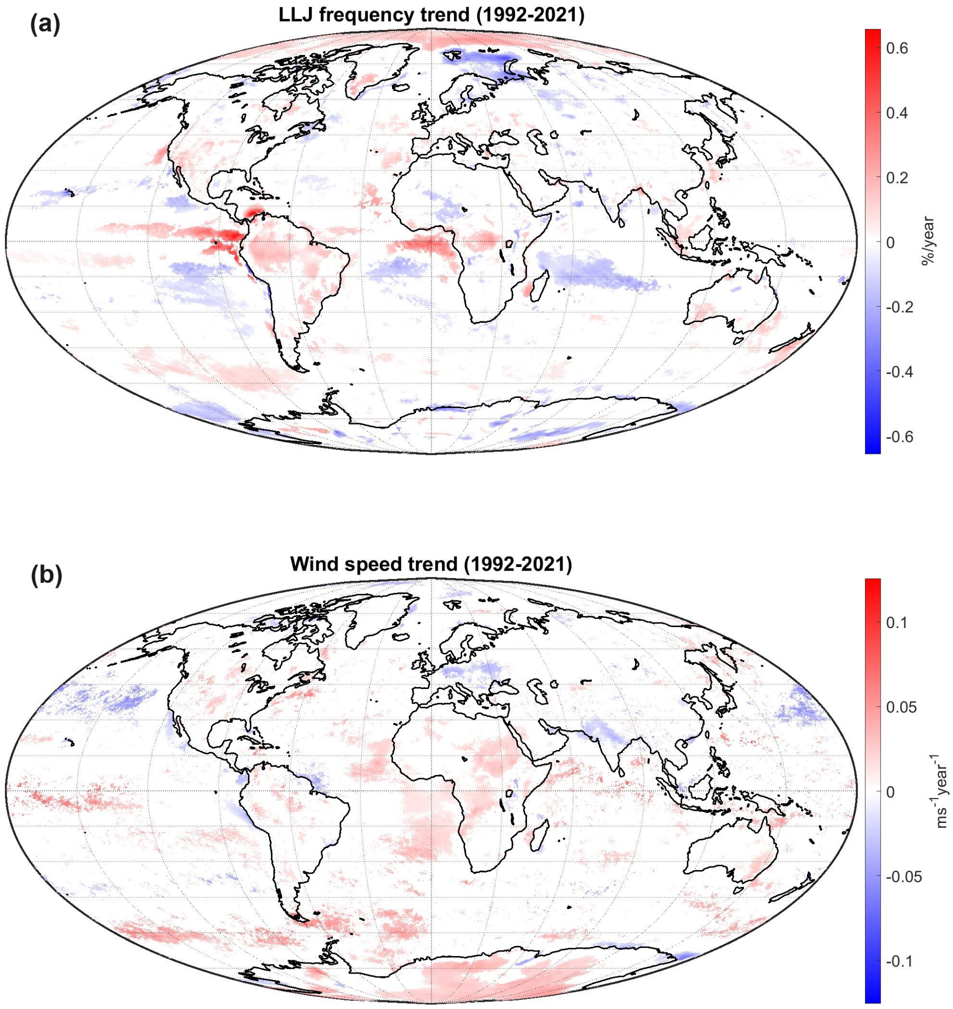

Figure 8. Past trends for LLJs for 1992–2021. Shown are the statistically significant linear trends in (a) the frequency of occurrence of LLJs and (b) the wind speed in the LLJ core. The results are based on ERA5 and for a 95% level of significance using the Mann Kendal test.

Changes in LLJs over the ocean can have implications for the transport of moisture, known to play a role in the hydrological cycle in several regions of the world, e.g., for the Asian monsoon systems. In particular, the Gulf of Bengal and the Indian Ocean function as primary reservoirs of moisture for the India Monsoon LLJ, the Southeast Asia Monsoon LLJ, and the China Monsoon LLJ (Algarra et al., 2019). We found no significant changes in the frequency of occurrence of the India Monsoon LLJ. However, in offshore regions along the coast of Oman and Somalia, we can see an increase in the LLJ intensity, while Northern India experiences a negative trend in the mean LLJ wind speed. These changes may have repercussions on the moisture advection potentially affecting precipitation formation downwind during the Indian summer monsoon.

We can see large areas with positive trends in wind speed at the LLJ core, and also at the fixed level of 100 m (not shown). Close to the surface (2–10 m), previously reported trends in wind speed are negative in different parts of the world (McVicar et al., 2012). The authors point to a global decrease in the wind speed near the surface, based on the results from different studies. The results discussed here concern the past changes of LLJs.

Future trends may not necessarily be the same. For example, Semedo et al. (2016) assessed changes in CLLJs, through experiments with the CMIP5 model EC-Earth for future scenarios. The model projected the largest regional increase in the frequency of occurrence, intensity, and height of LLJs for the Iberian Peninsula and the Oman CLLJs. CLLJ regions show in their study negative trends in the LLJ core wind speed, e.g., in West USA and West Africa. Different from the future development, we detected positive trends in the frequency of occurrence of CLLJ for the past that were regionally seen elsewhere, e.g., in Chile/Peru and West Africa.

LLJs also have impacts on wind power production, e.g., offshore wind power due to the high frequency of occurrence of CLLJs. Locations with more frequent and more intense CLLJs can be strongly affected since wind speed at the rotor layer can be strongly connected to the LLJ intensities. However, negative impacts on the wind turbines shall be also taken into consideration due to the higher shear connected to LLJs (E. W. Luiz & Fiedler, 2022). In addition, long LLJ events can also decrease wind variability (Kamath, 2010; Wimhurst & Greene, 2019), having a positive impact on the grid stability. Increased future LLJ frequency could therefore reduce the occurrence of ramp events in offshore areas (CLLJs) as well as over land (NLLJs).

5 Conclusion

A global climatology of low-level jets (LLJs) based on ERA5 was compiled with a focus on different driving mechanisms. The analysis encompasses the years 1992–2021 using the latest ECMWF reanalysis. Given the improvements in ERA5 compared to its predecessors for LLJ analysis (Lima et al., 2022), particularly the higher spatial and temporal resolution, improved data assimilation schemes, and an increased amount of assimilated observations, this study was able to analyze regional circulation features and characteristics of the associated LLJs.

The global mean frequency of occurrence was of 21%, with averages of 32% and 15% over land and ocean. The results were also presented over three specific regions with some differences on the main LLJ formation mechanism, as follow: non-polar land (LLLJ), polar (PLLJ) and coastal LLJs (CLLJ). The following findings were found:

- Over LLLJ areas, the most common LLJ type follows NLLJ formation mechanism, which is based by the classical theory of inertial oscillation over land. Interestingly, NLLJs are not dominating the LLJ formation from a global perspective, with mean occurrence frequencies of 20% over LLLJ regions. Some exceptions over the world can be metioned, e.g. the Bodélé Depression which stands out as a desert NLLJ hotspot globally.
- Over PLLJ areas, NLLJ can be also very frequent specially due to the prolonged stable and shallow boundary layer in polar winter, making the PLLJs the lowest and strongest LLJ. However, due to their extremely high frequencies, getting to values higher than 90%, also during day time, they can be further favored by other factors e.g. cold polar surfaces and katabatic winds over the ice shelf (Jakobson et al., 2013; Heinemann et al., 2021).
- CLLJs have different characteristics compared to NLLJs and PLLJs. There is no surface temperature inversion co-occurring with CLLJs but an elevated inversion layer around the core of the CLLJ that maintains their stability. Despite similar frequency of occurrence to LLLJ regions (19%), CLLJ present hotspots with values around 90%, specially on the west coast of the continents. The favorable conditions for the CLLJ formation are the presence of an elevated temperature inversion, e.g., due to the subsidence of air in the trade wind regions over cold waters from coastal upwelling and/or the advection of hot desert air over the relatively cool marine boundary layer offshore of the coast.

Our trend analysis indicates past changes in both the frequency and intensity of regional LLJs, including major sources for dust aerosols, polar ice, and moisture transport. It is currently unclear how these trends will continue with global warming and what the implications are, e.g., for climate feedbacks and weather extremes. Given the known relevance of LLJs under the current climate conditions, future studies will investigate long-term trends for LLJs and the associated implications in a warming world.

Open Research

The ERA5 dataset is available on the Copernicus Climate Change Service Information website (https://cds.climate.copernicus.eu). The Radiosondes data can be obtained from the department of Atmospheric Science of the University of Wyoming

(https://weather.uwyo.edu/upperair/sounding.html).

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Global climatology of low-level-jets: occurrence, characteristics, and meteorological drivers

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Key Points:

- First global comprehensive low-level jet (LLJ) climatology using ERA5
- Polar LLJs are the strongest and most frequent among the detected types
- Distinct past trends in regional LLJ frequency and intensity

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Abstract

Low-level jets (LLJs), wind speed maxima in the lower troposphere, impact several environmental and societal phenomena. In this study we take advantage of the spatially and temporally complete meteorological dataset from ERA5 to present a global climatology of LLJs taking into consideration their formation mechanisms, characteristics and trends during the period of 1992–2021. The global mean frequency of occurrence was of 21% with values of 32% and 15% for land and ocean. We classified the LLJs into three regions: non-polar land (LLLJ), polar land (PLLJ) and coastal (CLLJ). Over LLLJ regions, the average frequency of occurrence was of 20%, with 75% of them associated with a near-surface temperature inversion i.e. associated with inertial oscillation at night. Over PLLJ regions the LLJs were also associated with a temperature inversion, but were much more frequent (59%), suggesting other driving mechanisms than the nocturnal inversion. They were also the lowest and the strongest LLJs. CLLJs were very frequent in some hotspots, specially on the west coast of the continents, with neutral to unstable stratification close to the surfaces, that became more stably stratified with increasing height. We found distinct regional trends in both the frequency and intensity of LLJs, potentially leading to changes in the emission and transport of dust aerosols, polar ice and moisture over the world. However, it is currently unclear the evolution of the trends with global warming and what the implications are for climate and weather extremes. Future studies will investigate long-term trends for LLJs and the associated implications.

Plain Language Summary

In this study, we investigated low-level jets (LLJs), strong winds in the lower atmosphere that have significant environmental and societal impacts. Using a comprehensive weather dataset spanning from 1992 to 2021, we created a global map of LLJs, categorizing them into three regions: non-polar land (LLLJ), polar land (PLLJ) and coastal (CLLJ). LLJs associated with temperature inversions were very common over land, but PLLJs were much more frequent. PLLJs were also the strongest and lowest. Coastal LLJs were prevalent on west coastlines and exhibited changing vertical temperature characteristics. On average, LLJs occurred in 21% of the time globally, with higher frequencies over land (32%) compared to the ocean (15%). Regional trends in LLJ frequency and intensity varied, with some areas experiencing more intense LLJs without changes in frequency while others presented an increase in both. The study emphasized the uncertainty surrounding the influence of LLJs on climate and weather extremes in a warming world, with future research aiming at exploring LLJ trends and their broader implications.

1 Introduction

Low-level jets (LLJ) are wind speed maxima in the lowest few hundred meters of the troposphere (Shapiro & Fedorovich, 2010; Ziemann et al., 2020). LLJs show a sharp decrease in wind speed above their core leading to the characteristic nose-like wind speed profile. They have diverse influences spanning from environmental to societal impacts, e.g. transport of moisture and pollutants (Angevine et al., 2006; R. Chen & Tomassini, 2015), aviation safety (Blackadar, 1957; Wittich et al., 1986), formation of dust storms (Schepanski et al., 2009) and wind power production (Gutierrez et al., 2016; Lampert et al., 2016; E. W. Luiz & Fiedler, 2022). Furthermore, LLJs are perceived as a mechanism for (sub)tropical moisture transport (Gimeno et al., 2016). They are also linked to the spatio-temporal variability of precipitation in certain regions, influencing the availability of freshwater for consumption, agriculture and ecosystems (Algarra et al., 2019). LLJs therefore play a role in the hydrological cycle (Pan et al., 2004), including the occurrence of droughts and floods (Algarra et al., 2019). Moreover, LLJs over coastal waters influence sea-surface temperatures by driving the upwelling of cold nutrient-rich waters with implications for the regional ecosystems and economic activities (Semedo et al., 2016).

In the classical theoretical description of inertial oscillations, LLJs develop due to the decoupling of nocturnal winds from the surface friction by the formation of a near-surface temperature inversion (Blackadar, 1957; Van de Wiel et al., 2010). These conditions typically occur over land at night, particularly during cloud-free conditions that allow strong radiative cooling near the surface (Sisterson & Frenzen, 1978; Beyrich, 1994). The associated weaker friction due to reduced eddy viscosity enables acceleration of the airflow aloft (Ziemann et al., 2020; Fiedler et al., 2013), with the development of a pronounced super-geostrophic wind speed maximum in the course of the night (Shapiro & Fedorovich, 2010). Such undisturbed inertial oscillations are a widely known formation mechanism of LLJs and are often called Nocturnal LLJs (NLLJ). In reality, the development of NLLJs diverts from the ideal fully decoupled and undisturbed inertial oscillation that was theoretically described by Blackadar (1957), due to reduced but not eliminated frictional effects (B. J. Van de Wiel et al., 2010), the occurrence of intermittent turbulence at night (B. Van de Wiel et al., 2003) and non-stationary environmental conditions (E. W. Luiz & Fiedler, 2022). Moreover, LLJs with a co-occurring temperature inversion can also be driven by other mechanisms, e.g., in the absence of nocturnal cooling. For example, LLJs can be formed when a near-surface temperature inversion is formed by warm air advection over relatively cool near-surface air. The associated tilt of the isobaric surfaces leads to a thermal wind that under certain conditions can manifest itself as a LLJ. LLJs have further been connected to synoptic- and mesoscale dynamical systems (G. T.-J. Chen et al., 2006; Li & Du, 2021; Corrêa et al., 2021; E. Luiz & Fiedler, 2023).

LLJs are known to occur in different regions around the world that favor the development of different types. Common locations for LLJ occurrence are coastal upwelling regions (Lima et al., 2022), hot deserts (Heinold et al., 2013; Fiedler et al., 2013) and continental polar regions (Tuononen et al., 2015; Heinemann & Zentek, 2021). LLJs in hot desert areas are usually NLLJs, although a fraction of the LLJs are connected to convective cold pools (Heinold et al., 2013). LLJs in hot deserts have strong implications for the formation of dust storms (Fiedler et al., 2013; Z. Han et al., 2022). Likewise, LLJs happening in continental polar regions (PLLJs), or cold deserts, are generated by the stabilization of the atmospheric boundary layer via near-surface cooling or warm air advection (Heinemann & Zentek, 2021). Other mechanisms for LLJ formation over cold deserts were also identified. The topography, for example, can lead to the formation of barrier winds, katabatic flows and tip jets, all of which may form wind profiles that can meet the LLJ criteria (Tuononen et al., 2015). In zones of high baroclinicity, such as synoptic or mesoscale fronts along an ice edge, the vertical shear of the geostrophic wind and surface friction can lead to the generation of baroclinic LLJs (Jakobson et al., 2013; Heinemann et al., 2021).

Coastal low-level jets (CLLJs) usually occur offshore of the west coast of different continents, e.g. USA, Chile/Peru, Australia, and Africa (Lima et al., 2022), with seasonal differences that depend on the region. In general, the differential heating leads to the formation of a high-pressure system over the ocean and a thermal low over land. The associated pressure differences lead to strong winds. Since the warm air subsides in the high pressure above the Marine Atmospheric Boundary Layer, and cooler, moist and well-mixed air resides above the ocean surface, the development of a temperature inversion in some distance to the surface happens (Beardsley et al., 1987). Reduced frictional effects in the inversion layer allow the formation of a CLLJ, which is not unlike the condition for a NLLJ, but occurs in this case also during the day and at higher levels, with a maximum usually in the lowest 1000ṁ a.g.l. (Garreaud & Muñoz, 2005; Soares et al., 2014; Ranjha et al., 2013).

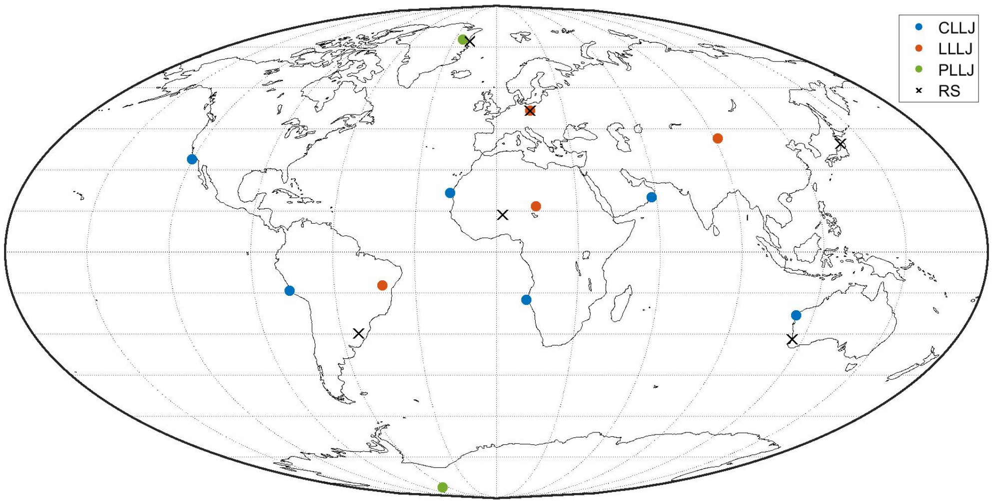

Figure 1. Location of the grid points selected for the analysis of LLJ types and the radiosonde (RS) sites for the evaluation of LLJs in ERA5.

Multiple studies for individual processes driving LLJs in different world regions exist, yet there is no global climatology accounting for more than single LLJ types with details on their relative occurrence frequencies and characteristics. In the present study, we take advantage of the spatially and temporally complete meteorological data with a sufficiently high spatial and temporal resolution as provided by the ERA5 reanalysis for 1992–2021 and an automated detection algorithm for LLJs to better understand LLJs from a global perspective. As we will see later, ERA5 is adequate for compiling a global LLJ climatology. Our focus is on three main aspects: (1) the global quantification of differently driven LLJs, (2) the characterization of governing physical processes of LLJ in occurrence hotspot regions distributed across the world and (3) an assessment of past trends for LLJs with global warming. In so doing, we present a comprehensive global climatology of LLJs accounting for the different physical driving mechanisms for their development.

2 Data and Methods

2.1 ERA5

ERA5 is the latest global reanalysis dataset from the European Centre for Medium-range Weather Forecasts (ECMWF) (Hersbach et al., 2020). ERA5 combines a state-of-the-art weather model with historical measurements (satellites, weather stations, etc.) to obtain a spatially and temporally consistent dataset covering the years since 1940. ERA5 provides global output for many different meteorological variables (Y. Han et al., 2021) on a grid with a horizontal resolution of about 30 km and 137 vertical levels. About 20 levels are within the first 1000 m a.g.l. giving a suitable vertical resolution to study LLJs. The temporal resolution of the output is variable, with hourly intervals being the finest resolution. For this work, we used data for wind speed, humidity, temperature and pressure on the model levels with a three-hourly resolution for 1992–2021 to compile the LLJ climatology over 30 years.

2.2 LLJ detection and classification

The identification and analysis of the LLJs in ERA5 are based on an automated detection algorithm developed earlier for the ERA-Interim reanalysis of ECMWF (Fiedler

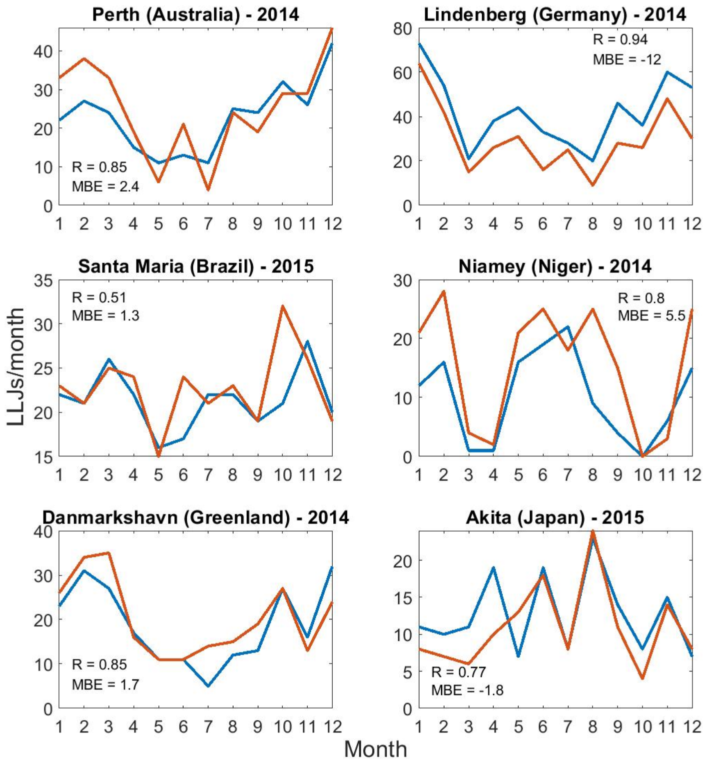

Figure 2. Validation of LLJ occurrence frequency in ERA5. Shown are the monthly mean number of LLJs detected in ERA5 and radiosondes at different sites. The comparison was done for the years 2014 or 2015, as stated in the title of the figures, due to the availability of radiosonde data. The selection of the sites (see Figure 1) is such that different climatic conditions are covered.

et al., 2013). We follow the same approach, except that we here do the initial identification of LLJ based on the wind speed profiles alone. This choice is made to allow the additional identification of LLJs that are not formed in the presence of a near-surface temperature inversion for a holistic analysis of different LLJ types. The criteria in the algorithm are set such that the algorithm detects LLJs with a characteristic nose-like wind profile as in Fiedler et al. (2013) and E. W. Luiz and Fiedler (2022). The LLJ core was identified as the wind speed maximum in the lowest 1000 m a.g.l. that satisfies the following criteria. First, a low-level wind speed maximum is identified as an LLJ if the vertical shear in the wind speed is more negative than $-0.005\ \mathrm{s}^{-1}$ in the 500 m deep layer above the LLJ core. Second, we require a difference in the wind speed between the same layers of at least $2\,\mathrm{ms}^{-1}$. Both these criteria ensure a nose-like profile and exclude ambiguous cases. The detection algorithm was applied in every grid point to the three-hourly profiles over thirty years from ERA5.

The statistical analysis of the LLJ output lead the separation of the analysis into three different regions. Non-polar land areas, which has the prevalence of NLLJs following the classical inertial oscillation theory at night were called land LLJ (LLLJ). Polar land regions, which present a high frequency of NLLJs, but also a high ammount of LLJs from different sources, were called Polar LLJ (PLLJ). Near-coast regions with a area of 20 grid points around any land were called Coastal LLJ (CLLJ). The latter present the most different formation mechanism, as we will see later. Figure 1 marks the locations for the assessment of the dynamics of the different LLJ types at the mentioned regions.

We selected profiles in different locations where LLJs frequently form. From each of those praces, the grid point with the highest frequency of occurrence was selected to better understand the dynamics of LLJs through performing composite analyses. The selected regions are the following.

- A location in Antarctica and in Greenland were selected for studying PLLJs.
- For CLLJ, six locations over the ocean were picked. The Benguela current and the coasts of West USA, Chile/Peru, West Africa, West Australia and Oman.
- LLLJs were analyzed in the hot desert climates of the Saharan desert in Chad in North Africa and the Taklamakan desert in China, a region with semi-arid climate in Brazil and a temperate climate in Germany.

For the dynamical assessment of the LLJs, we used two different metrics for the atmospheric stability and the momentum flux, namely the vertical gradient in the virtual potential temperature ($\Delta\theta_v$) and the Richardson Number (Ri). A stably stratified air layer is characterized by an increase of θ_v with height. We here require $\Delta\theta_v > 0.001$ Km^{-1} for stable conditions to inform us about the co-occurrence of inversions with LLJs. Moreover, Ri provides information on the influence of the tendency of shear-induced vertical mixing which can be strong during LLJs. Large Ri values imply that the effect of the stable stratification is stronger than the effect of shear-driven turbulent mixing. The critical threshold for the transition between stable and unstable conditions is about 0.25, i.e., turbulence occurs when Ri is smaller than this threshold (Peng et al., 2022).

2.3 Validation of approach

We validated to what extent observed LLJs are reproduced by ERA5, applying the automated detection algorithm for LLJs to co-located profiles from ERA5 and radiosondes. To that end, we selected stations with quality-controlled radiosondes (RSs), obtained from the department of Atmospheric Science of the University of Wyoming. The chosen stations encompass different climates around the world and are situated in Perth (Australia), Lindenberg (Germany), Santa Maria (Brazil), Niamey (Niger), Danmakshavn (Greenland), and Akita (Japan). Figure 1 shows the locations of the analyzed sites. Although some of the RSs have been assimilated, it is useful to make this comparison. ERA5 for instance also assimilates data from satellite measurements and surface meteorological stations, assigns different weights to the different datasets for generating the analysis, performs an interpolation of the observation in time and space to match the model grid, and also depends on the forecast model state at the time of assimilation which is jointly influencing the analysis. Hence, we expect differences in the LLJs in RSs and ERA5 which we indeed see, but the general temporal variability of LLJs follows very similar patterns in across the different sites assessed here.

Specifically, the month-to-month variability in detected LLJs from the RSs is well reproduced by ERA5. Figure 2 shows the monthly co-variability of the number of LLJs in ERA5 and the RSs during one year at the sites. From those, the Probability of Detection (POD), comparing ERA5 to the RSs, ranged from 0.47 in Lindenberg (Germany) to 0.73 in Perth (Australia). The False Alarm Rate (FAR) ranged from 0.32 in Akita (Japan) to 0.6 in Niamey (Niger). Testing other sites than the ones included here led to similar results (not shown). It suggests that the month-to-month variability in the LLJ frequency of occurrence is reasonably well represented by ERA5. Also, the characterization of the LLJs by ERA5 is sufficiently good for our purposes. The average wind speed at the LLJ core was for instance very similar in ERA5 and the RSs ($\sim 11\,\mathrm{ms}^{-1}$) with the LLJ core heights being underestimated by ERA5, with an average of 417 m in ERA5 against 537 m in the RSs of the analyzed sites. Note that the global average and averages over other sites can deviate from these numbers. For example, the ERA5 average LLJ core in Lindenberg (Germany) was slightly higher in ERA5, while in Santa Maria (Brazil) and Niamey (Niger), they were much lower.

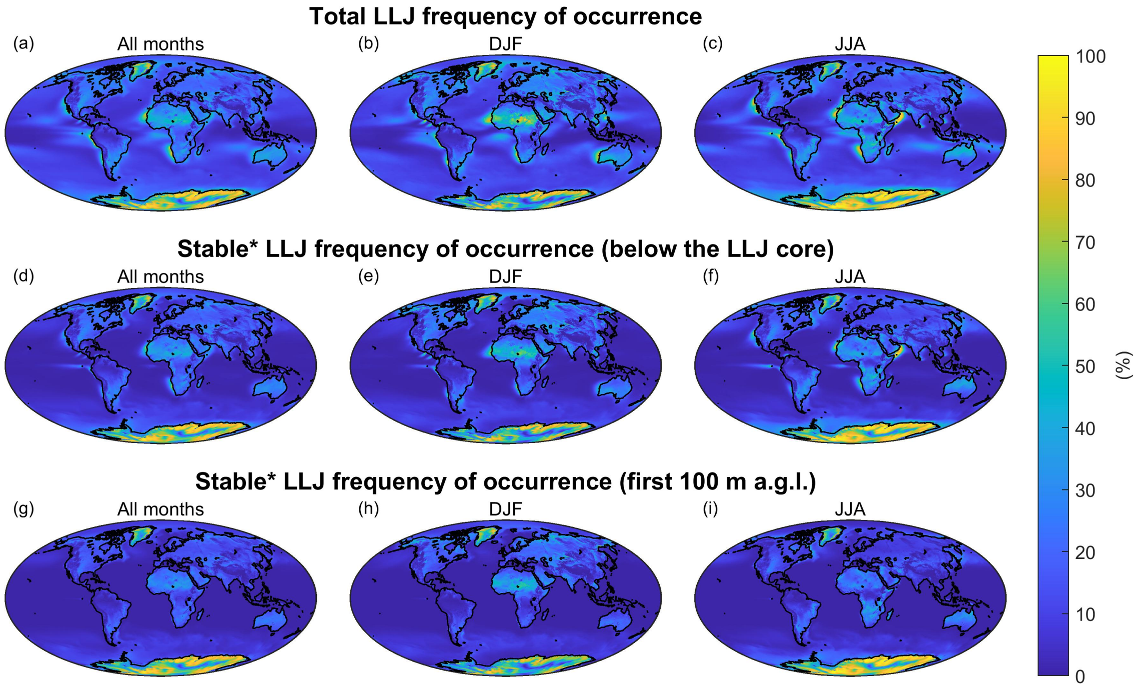

Figure 3. Spatial pattern of the occurrence frequency of LLJs in percent of all profiles. Shown are (a–c) the total frequency of occurrence of LLJs, (d–f) the frequency of occurrence of LLJs during stable conditions from the surface until the LLJ core, and (g–l) the same as (d–f) but for the lowest 100 m a.g.l. The left column shows the mean over all months, the middle for December, January, and February (DJF), and the right column for June, July, and August (JJA). *Stable LLJs were considered when $\Delta\theta_v > 0.001\,\mathrm{Km}^{-1}$, i.e. when we found the presence of a temperature inversion. The results are based on ERA5 for 1992–2021.

3 Results

3.1 Global LLJ occurrence

The global climatology of the frequency of occurrence of LLJs highlights several regional hotspots, including the continental polar regions and the offshore regions off the west coast of continents. Moreover, hot desert regions frequently witness LLJs, e.g. the Sahara and the Taklamakan deserts. Figure 3a–c shows the global frequency of LLJs averaged for all months, for winter and summer. Some regions show a pronounced seasonal variability in the LLJ occurrence frequency. Take for instance the Australian West Coast and Oman's East Coast, which have a maximum LLJ occurrence in just one of the two seasons (Figure 3b–c). Other regions have relatively similar LLJ occurrence throughout the year with slight differences in the exact location of the regional maximum, e.g. a small North-South difference in the maximum at the West African Coast. Also the land regions near the poles, namely Greenland and Antarctica, frequently see LLJs which are slightly more often occurring during polar night.

Figure 3d-i shows the frequency of occurrence of LLJs in the presence of a temperature inversion layer. Here, we compute the atmospheric stability based on the vertical

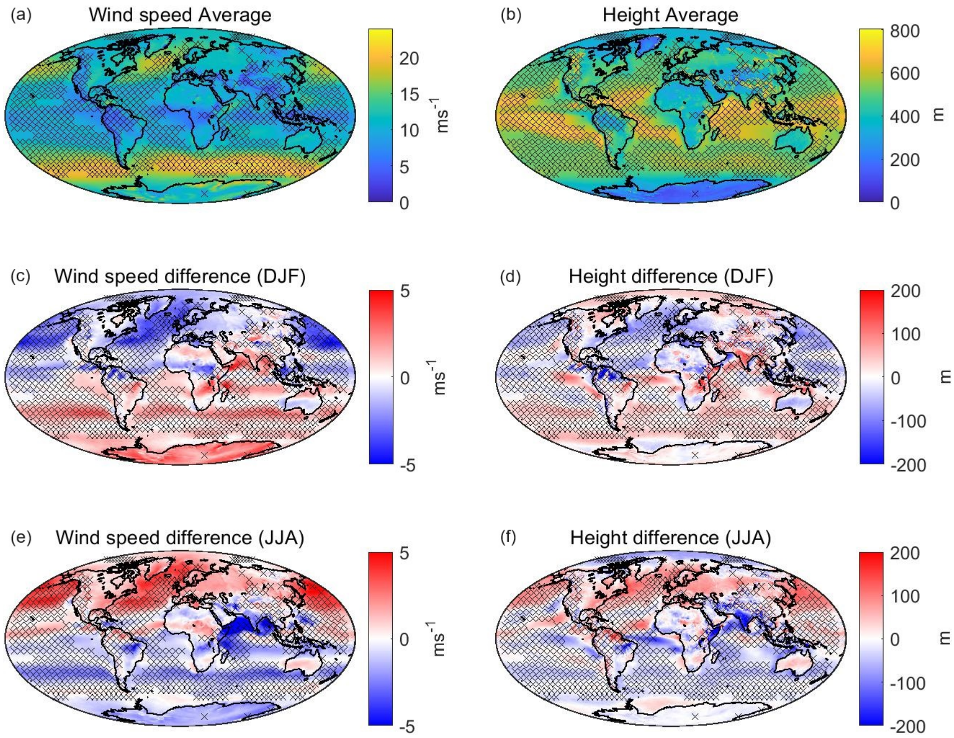

Figure 4. Spatial patterns of LLJ characteristics. Shown are the means for (a) wind speeds and (b) heights in the core of LLJs, and (c–f) the seasonal differences in the mean for December, January, and February (DJF), and June, July, and August (JJA). The dashed areas mask regions where the LLJ frequency of occurrence was smaller than 15%. The results are based on ERA5 for 1992–2021.

gradient in the virtual potential temperature from the surface until the LLJ core (Figure 3 d–f) and in the lowest 100 m a.g.l. (Figure 3g–i). LLJs in the absence of an inversion layer are typically less frequent. Coastal LLJs typically have no near-surface temperature inversion (e.g. in the lowest 100 m a.g.l), but present it accounting for all layers below the LLJ core, as indicated by the higher frequency of occurrence of LLJs for these conditions. Over regions offshore of coasts, we typically see a well-mixed marine boundary layer at the lowest levels underneath the LLJ core with an inversion above it. Most of LLJs without an inversion in the lowest levels happen over the ocean at up-welling regions west of the continents. On land, most of the LLJs happen with the presence of a near-surface temperature inversion, with formation mechanisms connected to inertial oscillations. During NLLJ, we still have a lower amount of weaker LLJs when the temperature inversion is broken by surface warming, which may account for the LLJs without the inversion presence. A detailed analysis of the vertical structure of the atmosphere for the different LLJ types and regions will be done in the next chapters.

The global mean in the frequency of occurrence of LLJs is 21%. It is important to mention that this is an average over all grid points and the regions closest to the poles have a higher weight. The mean frequencies for LLJs with a simultaneous appearance of an inversion measured by $\Delta\theta_v > 0.001\ Km^{-1}$ from surface until the LLJ core (in the lowest 100 m a.g.l.) occur in 15% (12%) of the profiles. The slight difference in the occurrence frequency of the LLJs with inversion layers at different altitudes can be explained by the neutral to unstable stratification close to ocean surfaces that become more stably stratified with increasing height. Specifically, the frequency of occurrence of LLJs

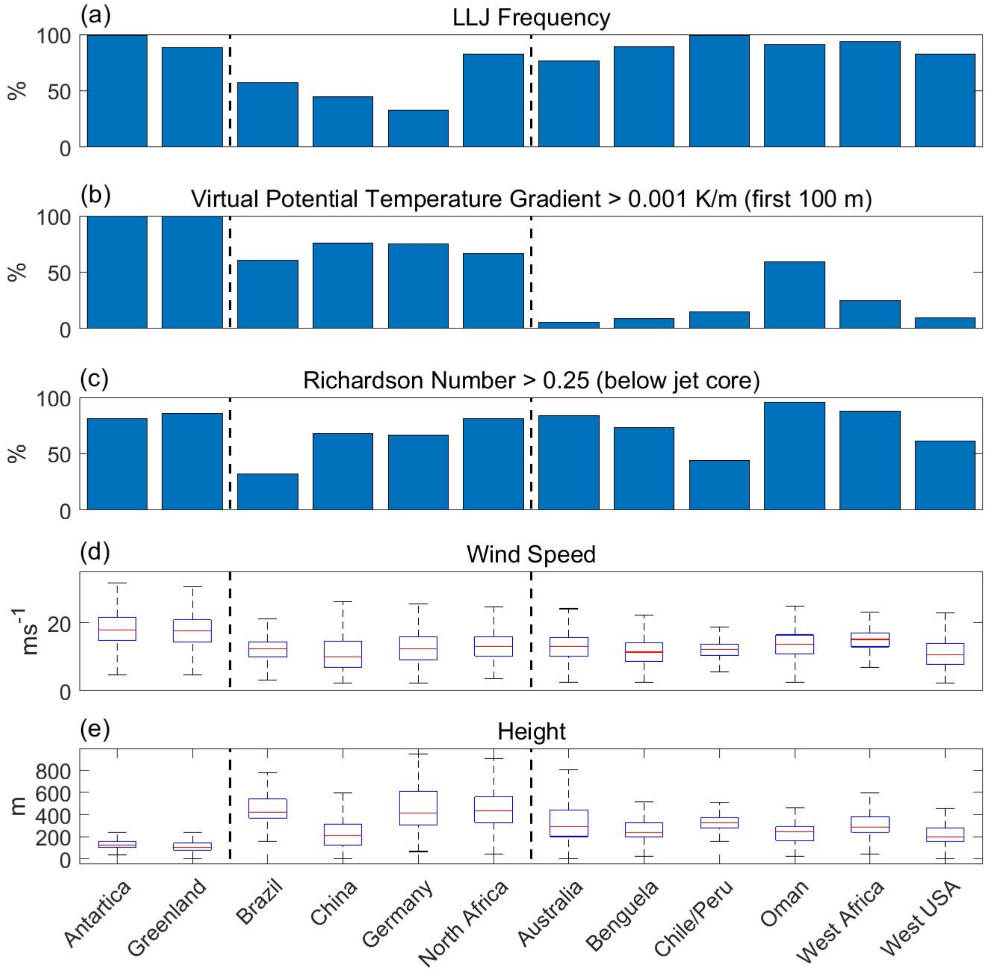

Figure 5. Statistics of different LLJ types at the selected locations. Shown are the (a) LLJ frequency of occurrence in % of all profiles, (b) percentage of LLJs with co-occurring virtual potential temperature gradient of $\Delta\theta_v > 0.001\,\mathrm{Km}^{-1}$ in the lowest 100 m a.g.l., (c) percentage of LLJs with the Richardson Number in the below the LLJ core $Ri > 0.25$, (d) statistics of the wind speed and (e) height of the LLJ cores showing the means (red), quartiles (box), and the 25 and 75 percentiles (whiskers). The vertical dashed lines separate (left to right) PLLJs, LLLJs, and CLLJs. The locations are marked in Figure 1.

averaged over oceans for all LLJ cases, with a stable stratification below the LLJ core and those with a surface temperature inversion in the lowest 100ṁ a.g.l is 15%, 8% and 5%, respectively. On land, the differences associated with a temperature inversion are less apparent, with average frequencies of occurrence of LLJs of 28–32%. On average, the frequency of occurrence of LLJs on land is higher than over the oceans, because many regions over the ocean have very small LLJ frequency of occurrence. This can be seen by the mask made for regions with frequency of occurrence smaller than 15% from Figure 4.

3.2 Global LLJ characteristics

Globally averaged, the mean wind speed of LLJs is about $12\,\mathrm{ms}^{-1}$, with a difference at the order of 10 % ($< 1\,ms^{-1}$) when we compute the average over ocean and land regions separately. The mean height of the LLJ cores differs more between the ocean with 419 m against land with 325 m. The global average of the LLJ core height is 371 m. Accounting for the co-occurrence of a temperature inversion for LLJs has a marginal influence on the globally averaged wind speed and height of the LLJ cores. The average height of LLJs for regions with frequencies of occurrence higher than 15% and a co-occurring temperature inversion, measured by $\Delta\theta_v > 0.001\ Km^{-1}$ underneath the LLJ core, is for instance 387 m.

Figure 4a–b shows the spatial patterns of wind speed and height of the LLJ cores averaged for 1992–2021 with a mask over the regions with frequency of occurence smaller than 15%. The value of 15% was chosen in this study as an objective criterion to analyze the regions with the main LLJ types defined here. The LLJ heights in both Antarctica and Greenland are less than 200 m a.g.l. which is lower compared to most other regions. The wind speed in the core of LLJs in these cold deserts is around 12 ms^{-1} which is stronger compared to most other land regions. Over ocean regions, stronger wind speeds in LLJ cores are seen in the extra-tropical storm tracks of both hemispheres, at around latitudes of 50°. Here the LLJ profiles can be connected with frontal systems associated with extra-tropical cyclones. Interestingly, the height of LLJ cores increases over oceans from the poles towards the equator, consistent with the deeper boundary layer over warmer tropical waters relative to cooler sea-surface temperatures towards the poles.

Seasonal differences in the LLJ intensity show a remarkably consistent hemispheric asymmetry, with typically stronger (weaker) LLJs across most of the summer (winter) hemisphere compared to the annual mean (Figure 4c–f). The asymmetry in the LLJ strength is most pronounced in the extra-tropics than in the tropics consistent with the stronger seasonal variation in near-surface temperatures. Typically higher summertime boundary layers over land in the extra-tropics also lead to regionally higher LLJ cores relative to the annual mean, e.g., for many mid-latitude regions in the northern hemisphere and over Australia during the summer seasons. An interesting opposite behavior of the described seasonality of the regional LLJ characteristics in the extra-tropics is seen along the coast of Oman. Here, the wind speed and height of the LLJ cores are higher (lower) during the winter (summer) months compared to the annual mean, due to its different driving mechanism: the Indian Monsoon (Ranjha et al., 2015).

3.3 LLJ Regions

We analyze LLJ dynamics in more detail for the three different regions inspired by existing classifications from the literature (see Methods Section for details), namely nonpolar land low-level jets (LLLJs), coastal low-level jets (CLLJs) and polar low-level jets (PLLJs). Examples of averaged wind profiles for the year 2018 are found in Figure S1 from all locations marked in Figure 1. PLLJs were the strongest and lowest LLJs amongst the locations assessed here. In Antarctica, LLJs can have core wind speeds exceeding 20 ms^{-1} at heights well below 200 m a.g.l.. The PLLJs are, therefore, much lower than LLJs formed by reduced dynamical friction in hot deserts. The LLLJs locations presented the highest cores compared to all LLJ locations assessed, e.g., the Bodélé Depression in Chad, North Africa, has high NLLJ cores around 500 m a.g.l. in the mean for 2018.

We systematically assessed the regional LLJ differences by statistical analyses over the entire 30-year period with Figure 5, including atmospheric stability metrics, height and speed of the LLJ cores as well as the frequency of occurrence of the LLJs. Again, we can see the lower heights and higher wind speeds of PLLJs, while the highest LLJs are found at the LLLJ locations. CLLJs and LLLJs have similar wind speed characteristics. Most LLLJs coincide with stable stratification directly below the LLJ core, which allows for the balance of shear-induced mixing of momentum by the LLJ. This can be seen by the high simultaneity of LLJs and Richardson Numbers larger than 0.25 from surface until the LLJ core. The Brazilian site is an exception with less than 50% of the

LLJs having Richardson numbers exceeding 0.25. It implies that the LLJs here are typically less stable compared to the other locations, which implies some downward mixing of momentum. This aspect is further assessed in the following.

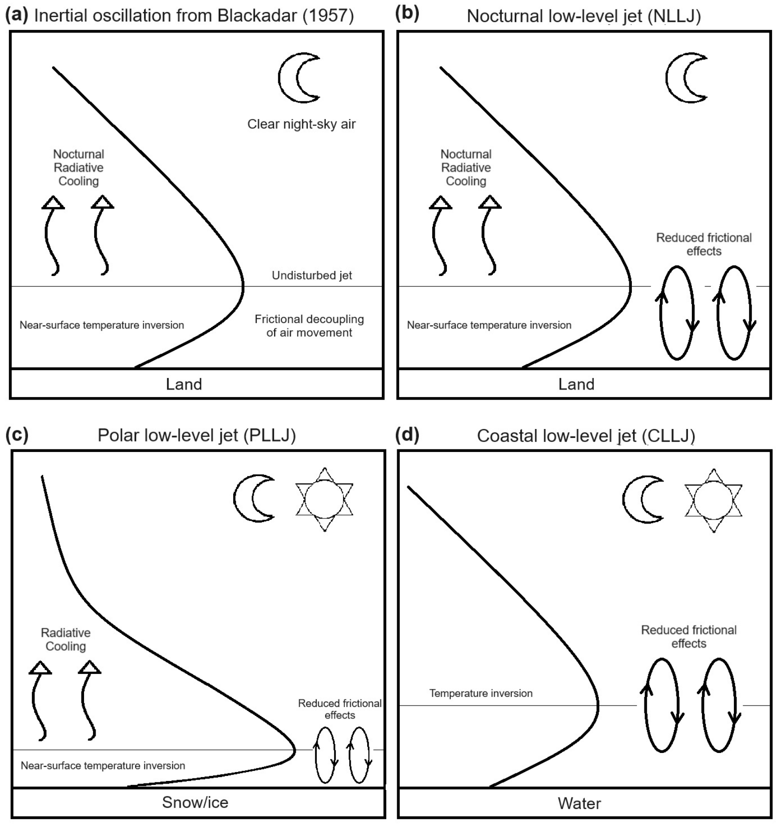

Figure 6. Schematic diagram of different LLJ types. Depicted are the conditions for the theory of an inertial oscillation (Blackadar, 1957) and the LLJ types analyzed in this study.

3.3.1 Non-polar land low-level jets (LLLJ)

In general, LLLJ regions present high frequency of NLLJs, which are formed by a mechanism similar to a inertial oscillation and usually occur during the night, when radiative cooling allows the formation of a near-surface temperature inversion. These mechanisms are schematically depicted in Figure 6a–b following the idealized theory of an inertial oscillation from (Blackadar, 1957) and accounting for non-stationary effects that are common in reality. The average frequency of occurrence over LLLJ areas is about 20%, with 75% of them coinciding with a near-surface temperature inversion. From the picked LLLJ locations (Figure 5), more than 50% of the LLLJ profiles coincide with a near-surface temperature inversion, measured by a mean of $\Delta\theta_v > 0.001\ Km^{-1}$ over the lowest 100 m a.g.l.. Similarly, a stable stratification underneath the most LLLJ locations allows a relatively stable development of LLJs, as measured by Ri > 0.25.

To better understand the development of NLLJs, Figure 7a–b shows a case study for an NLLJ in North Africa with a wind speed profile that is closest to the mean NLLJ profile for 2018. We see the transition from a well-mixed daytime boundary layer to the evening formation of a near-surface inversion. It implies increasing static stability after sunset (19 LST) initially seen as an increase in θ_v with height close to the surface. This

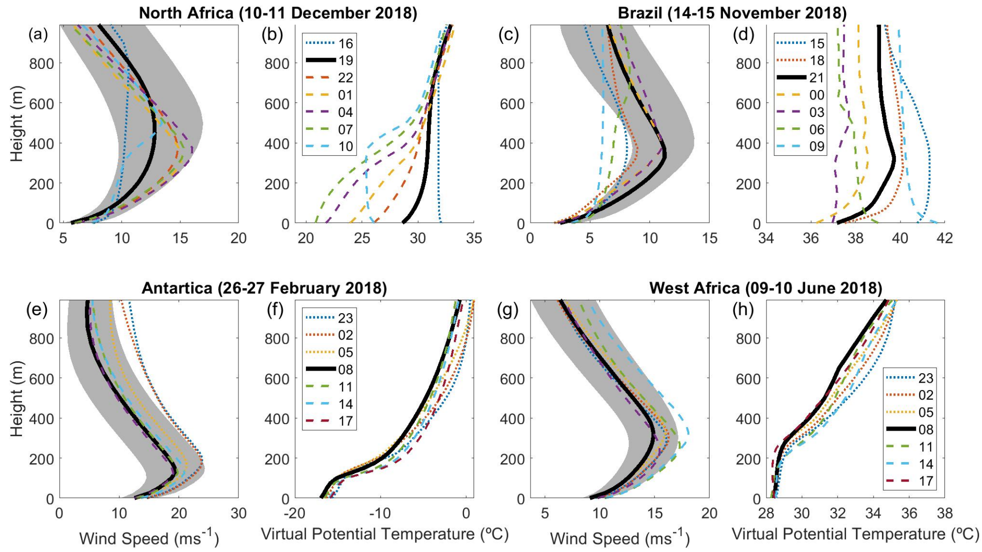

Figure 7. Case studies for the development of different LLJ types representative of their respective mean at the same location. Shown are the vertical profiles of (left) the wind speed and (right) the virtual potential temperature for the LLJ location and time stated in the title. The solid black lines are the wind profile of the selected LLJ that is most similar to the average for the LLJs at the same location in 2018. Shading marks the area of $\pm 1\sigma$, one standard deviation. Colored lines are the profiles for different hours before and after the selected LLJ to illustrate the development.

development continues by further surface cooling, deepening of the inversion layer up to 600 m a.g.l. in the course of the night. Simultaneously an NLLJ develops with the characteristic nocturnal acceleration of the air motion several hundred meters above the surface with a maximum at 04 LST and a subsequent slight deceleration associated with the turning of the wind field driven by the Coriolis force. The mid-morning breakdown of the NLLJ is associated with morning heating leading to a well-mixed boundary layer at 10 LST. At that time, the momentum of the NLLJ has been transferred to the surface and the core now appears about 100 m higher than at night.

The development of NLLJs at the Brazilian location can behave differently causing the lowest number of stable LLJs (compare Figure 5). Figure 7c–d shows the case study for a NLLJ in Brazil that is close to the 2018 mean. The wind speed profile of the NLLJ has characteristics similar to North Africa. However, in Brazil the inversion and hence the stability during the NLLJ was much weaker directly underneath the NLLJ and shallower until midnight compared to North Africa. The inversion decayed already during the night, specifically a well-mixed boundary layer is seen at 03 LST interrupting the nocturnal acceleration of the air motion. The momentum is subsequently transfered towards the surface causing the disappearance of the NLLJ already at 06 LST, much earlier than in North Africa.

In both case studies the wind speed in the core of the NLLJ is sub-geostrophic throughout the lifetime and there is no ideal change in the wind direction over time as one would expect from the theory of (Blackadar, 1957) (not shown). Deviations from the theory are to be expected since the assumption of stationarity is not fulfilled. Some cases, however, can show supergeostrophy. We see, for instance, for the NLLJ case study for Germany, a clear circular cyclonic change in the wind direction in the course of the night leading to a supergeostrophic wind speed in the NLLJ core, e.g., at 23 LST and 01 LST

(Figure S2). Supergeostrophy is expected from the theory but it is predicted to be a much smoother and gradual development, indicating that also in this case study non-stationary effects influenced the development of the NLLJ.

3.3.2 Polar low-level jets (PLLJ)

PLLJs are common throughout the year and mostly co-occur with a temperature inversion (Figure 5), namely in 90% of the cases in Antarctica and Greenland. The average frequency of occurrence of PLLJ over Antartica and Greenland is very high, about 59%; with some locations having values above 90%. This is broadly consistent with previous studies (e.g. Tuononen et al. (2015); Heinemann and Zentek (2021)). The development of PLLJs is similar to inertial oscillations that one expected due to near-surface inversion formed by little irradiance in polar nights causing low surface temperatures throughout the day for several months (Figure 6c). The very high frequency of LLJs coinciding with a near-surface temperature inversion (99%) at PLLJ regions suggest other different driving mechanism than NLLJs, since they also happen during day time. PLLJs can then be further favored by the cold surface, complex topography and baroclinicity (Tuononen et al., 2015).

Figure 7e–f shows a case study for Antarctica. It shows a snapshot of a long-lived PLLJ with a core at around 100 m with wind speeds of more than 20 $\mathrm{m\,s^{-1}}$. It occurs during stably stratified conditions that show only little variation over time with a particularly strong inversion around the LLJ core. Similar conditions can also be seen in Greenland (not shown). The case studies at both locations also showed a circular change of the wind direction over time, with a clockwise (anticlockwise) turning in Greenland (Antarctica) due to the Coriolis force. The selected case shown here for Antarctica also reached supergeostrophic wind speeds in the LLJ core, but this is not always the case, as suggested by the subgeostrophic PLLJ in a case assessed over Greenland (not shown).

Most continental LLJs, thus PLLJs and NLLJs have wind directions depending on the regional weather patterns causing differently oriented geostrophic wind vectors (Figure S3). It is interesting that they have a clearly prevailing direction per location. North African NLLJs, for instance, primarily have northeasterly directions (Figure S4), consistent with earlier findings based on another reanalysis (Fiedler et al., 2013). The largest spread in LLJ directions is seen for the location in Germany, consistent with different weather patterns driving LLJs there (E. W. Luiz & Fiedler, 2022).

3.3.3 Coastal low-level jets (CLLJ)

Most CLLJs form offshore off the west coast of continents. On average, the frequency of occurrence over the coast (19%) is bit higher than the frequency of occurrence over all ocean (15%). Differently from LLLJ regions, we can see some hotspots with values close to 90% for the CLLJ regions. These LLJs develop under different conditions than NLLJs and PLLJs (Figure 6d). CLLJs are rarely associated with a near surface temperature inversion. They occur most often during neutral to unstable atmospheric conditions in the mean over the lowest 100 m a.g.l.. The case study for West Africa shows that the boundary layer is rather neutral stratified close to the surface and becomes stably stratified around the CLLJ core (Figure 7g–h). Above the LLJ core, θ_v particularly strongly increased with height; an indicative of a stable stratification. Amongst CLLJ locations, Oman has most frequently a near-surface inversion, but this is still about 50% of the cases; less frequent than for PLLJs and most LLLJs (Figure 5b).

Depending on their location, CLLJs might undergo a strong seasonal cycle. The Benguela CLLJ, for example, can occur throughout the year, with differences in its mean frequency and the location of the maximum. Such differences depend primarily on the zonal pressure gradient near the surface (Lima et al., 2019). Differently, the seasonal cycle of CLLJ in Australia is strong, with a maximum in the frequency of occurrence during austral summer. The Oman CLLJ is unique by its location, synoptic forcing and its link to South Asia Monsoon (Ranjha et al., 2015). Hence it behaves differently throughout the year, with a maximum frequency of occurrence during July and August. The wind directions of CLLJs are typically parallel to the coastlines and usually towards the equator (S3 and S4). Again, Oman is the exception due to it's different dynamical forcing.

3.4 Past changes of LLJs

We assess to what extent LLJs might have changed during the past decades by computing linear trends (Figure 8a). The global averaged frequency of occurrence trend is of 0.02 %/year. There are regionally positive trends in the annually averaged frequency of occurrence of LLJs in the Arctic and eastern equatorial regions of the Atlantic and Pacific. The location with the largest positive trend is seen in the southern part of the Caribbean Sea. The positive trends in the Arctic and also in southern Greenland and western USA were especially strong during boreal winter. Amongst the selected locations for case studies, Chile/Peru had also an increase in the LLJ frequency of occurrence over time that is statistically significant at the 95% level of significance. Negative trends in the frequency of occurrence of LLJs are seen in the southern Indian Ocean, and to the southwest of the regions with positive trends in the Atlantic and Pacific. There is also a strong negative trend in the Barents Sea, which is most pronounced during boreal winter. Also, Northeast of the Oman LLJ region, a strong negative trend was seen during boreal summer, but is not seen in the annual mean. Amongst the locations for case studies, only Chile/Peru presented a positive trend.

Trends in the LLJ core wind speed (Figure 8b) are typically negative (positive) North (South) of 20 degrees North, with a global average of $0.02\,\mathrm{ms^{-1}year^{-1}}$. Most positive trends are seen over Antarctica, central and northeast Africa, and offshore of the western coasts of Africa. Negative trends were detected over central and eastern Europe, northern India, and the northern Pacific. Amongst the locations for case studies, Antarctica, Chile/Peru, North Africa, and West Africa had positive trends in the LLJ wind speed, whereas Germany had a negative trend.

4 Discussion

Some regions have seen higher frequency and intensity of LLJs over the past 30 years. Over the Amazon region, for example, the mean frequency of occurrence is relatively low, but our results indicate an increase in their frequency and intensity. These trends can imply changes in the precipitation in the Southern Amazonia and the La Plata River Basin. For instance, the amount of atmospheric moisture transported by the South American LLJ is comparable to the Amazon River (Arraut et al., 2012). This may increase the climate change impacts related to changes in land use (particularly deforestation) due to its influence on the water cycle (Zemp et al., 2014).

LLJs frequently form in desert areas such as Northern Africa (Fiedler et al., 2013). The NLLJs in Northern Africa play an important role in emitting mineral dust into the atmosphere (Schepanski et al., 2009; Heinold et al., 2013; Knippertz & Todd, 2012), which are known for several different impacts in the Earth system (Prospero et al., 2002; Washington et al., 2003). In some parts of North Africa, specifically in the Sahel, our results suggest a decreasing frequency of occurrence but little change elsewhere. The intensity of NLLJs, however, has increased over comparably larger regions in eastern parts of North Africa, including the Bodélé Depression in Chad which has been named as the dustiest place on Earth. These trends might have led to a change in regional dust storm frequency and intensity, e.g., a tendency to more intense dust storms associated with NLLJs in the Bodélé Depression and beyond.

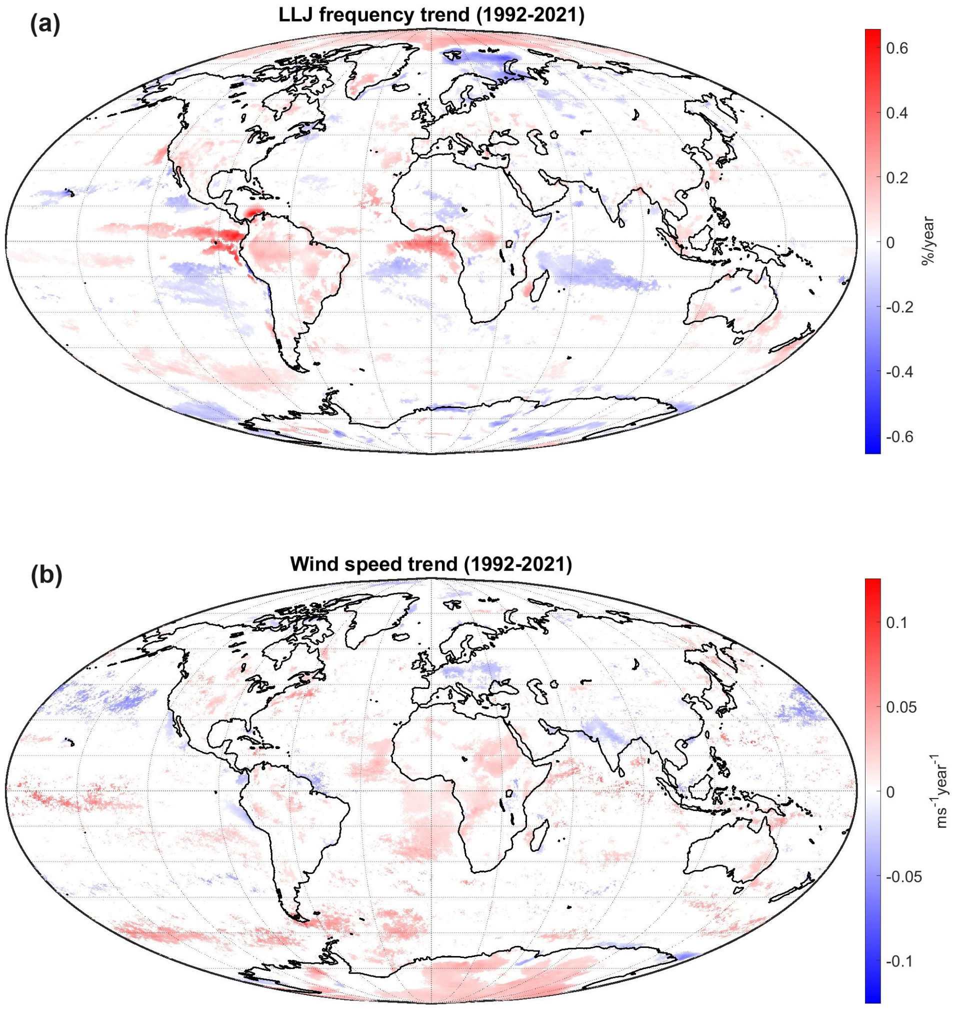

Figure 8. Past trends for LLJs for 1992–2021. Shown are the statistically significant linear trends in (a) the frequency of occurrence of LLJs and (b) the wind speed in the LLJ core. The results are based on ERA5 and for a 95% level of significance using the Mann Kendal test.

Changes in LLJs over the ocean can have implications for the transport of moisture, known to play a role in the hydrological cycle in several regions of the world, e.g., for the Asian monsoon systems. In particular, the Gulf of Bengal and the Indian Ocean function as primary reservoirs of moisture for the India Monsoon LLJ, the Southeast Asia Monsoon LLJ, and the China Monsoon LLJ (Algarra et al., 2019). We found no significant changes in the frequency of occurrence of the India Monsoon LLJ. However, in offshore regions along the coast of Oman and Somalia, we can see an increase in the LLJ intensity, while Northern India experiences a negative trend in the mean LLJ wind speed. These changes may have repercussions on the moisture advection potentially affecting precipitation formation downwind during the Indian summer monsoon.

We can see large areas with positive trends in wind speed at the LLJ core, and also at the fixed level of 100 m (not shown). Close to the surface (2–10 m), previously reported trends in wind speed are negative in different parts of the world (McVicar et al., 2012). The authors point to a global decrease in the wind speed near the surface, based on the results from different studies. The results discussed here concern the past changes of LLJs.

Future trends may not necessarily be the same. For example, Semedo et al. (2016) assessed changes in CLLJs, through experiments with the CMIP5 model EC-Earth for future scenarios. The model projected the largest regional increase in the frequency of occurrence, intensity, and height of LLJs for the Iberian Peninsula and the Oman CLLJs. CLLJ regions show in their study negative trends in the LLJ core wind speed, e.g., in West USA and West Africa. Different from the future development, we detected positive trends in the frequency of occurrence of CLLJ for the past that were regionally seen elsewhere, e.g., in Chile/Peru and West Africa.

LLJs also have impacts on wind power production, e.g., offshore wind power due to the high frequency of occurrence of CLLJs. Locations with more frequent and more intense CLLJs can be strongly affected since wind speed at the rotor layer can be strongly connected to the LLJ intensities. However, negative impacts on the wind turbines shall be also taken into consideration due to the higher shear connected to LLJs (E. W. Luiz & Fiedler, 2022). In addition, long LLJ events can also decrease wind variability (Kamath, 2010; Wimhurst & Greene, 2019), having a positive impact on the grid stability. Increased future LLJ frequency could therefore reduce the occurrence of ramp events in offshore areas (CLLJs) as well as over land (NLLJs).

5 Conclusion

A global climatology of low-level jets (LLJs) based on ERA5 was compiled with a focus on different driving mechanisms. The analysis encompasses the years 1992–2021 using the latest ECMWF reanalysis. Given the improvements in ERA5 compared to its predecessors for LLJ analysis (Lima et al., 2022), particularly the higher spatial and temporal resolution, improved data assimilation schemes, and an increased amount of assimilated observations, this study was able to analyze regional circulation features and characteristics of the associated LLJs.

The global mean frequency of occurrence was of 21%, with averages of 32% and 15% over land and ocean. The results were also presented over three specific regions with some differences on the main LLJ formation mechanism, as follow: non-polar land (LLLJ), polar (PLLJ) and coastal LLJs (CLLJ). The following findings were found:

- Over LLLJ areas, the most common LLJ type follows NLLJ formation mechanism, which is based by the classical theory of inertial oscillation over land. Interestingly, NLLJs are not dominating the LLJ formation from a global perspective, with mean occurrence frequencies of 20% over LLLJ regions. Some exceptions over the world can be metioned, e.g. the Bodélé Depression which stands out as a desert NLLJ hotspot globally.
- Over PLLJ areas, NLLJ can be also very frequent specially due to the prolonged stable and shallow boundary layer in polar winter, making the PLLJs the lowest and strongest LLJ. However, due to their extremely high frequencies, getting to values higher than 90%, also during day time, they can be further favored by other factors e.g. cold polar surfaces and katabatic winds over the ice shelf (Jakobson et al., 2013; Heinemann et al., 2021).
- CLLJs have different characteristics compared to NLLJs and PLLJs. There is no surface temperature inversion co-occurring with CLLJs but an elevated inversion layer around the core of the CLLJ that maintains their stability. Despite similar frequency of occurrence to LLLJ regions (19%), CLLJ present hotspots with values around 90%, specially on the west coast of the continents. The favorable conditions for the CLLJ formation are the presence of an elevated temperature inversion, e.g., due to the subsidence of air in the trade wind regions over cold waters from coastal upwelling and/or the advection of hot desert air over the relatively cool marine boundary layer offshore of the coast.

Our trend analysis indicates past changes in both the frequency and intensity of regional LLJs, including major sources for dust aerosols, polar ice, and moisture transport. It is currently unclear how these trends will continue with global warming and what the implications are, e.g., for climate feedbacks and weather extremes. Given the known relevance of LLJs under the current climate conditions, future studies will investigate long-term trends for LLJs and the associated implications in a warming world.

Open Research

The ERA5 dataset is available on the Copernicus Climate Change Service Information website (https://cds.climate.copernicus.eu). The Radiosondes data can be obtained from the department of Atmospheric Science of the University of Wyoming

(https://weather.uwyo.edu/upperair/sounding.html).

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JGR: Atmospheres

Supporting Information for

Global climatology of low-level-jets: occurrence, characteristics, and meteorological drivers

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Contents of this file

Introduction

The manuscript presents a global climatology of low-level jets (LLJ) using the ERA5 reanalysis. The supporting information presents four Figures, which are not necessary for the complete comprehension of the manuscript, but are interesting for a deeper and more specific understanding of the LLJ characteristics.

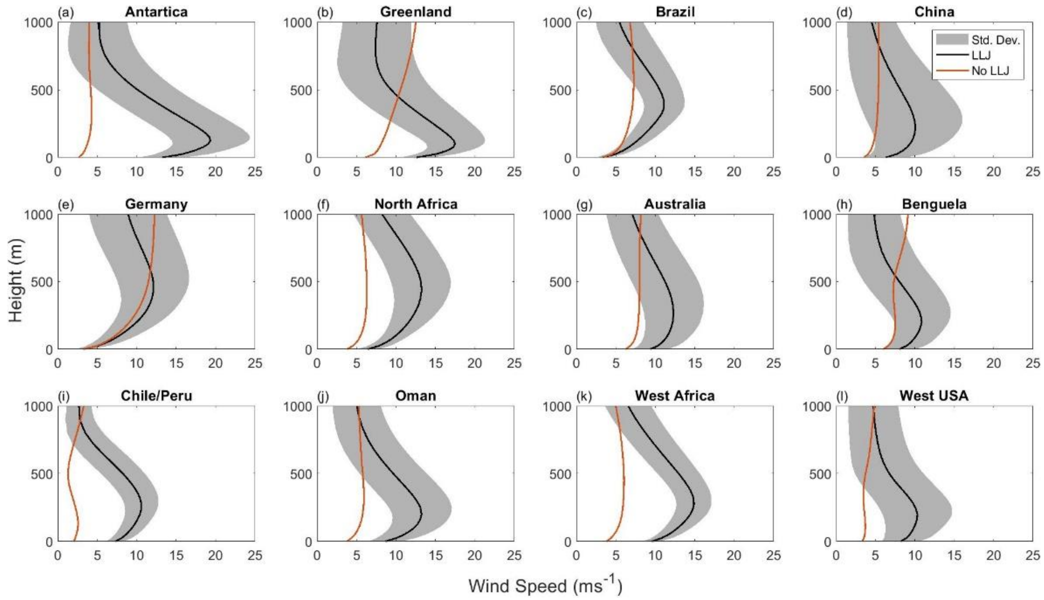

Figure S1. Examples of wind speed profiles for the 3 months with the highest LLJ frequency of occurrence in 2018. Shown are the averaged LLJ profiles (black) ± standard deviation (gray shading) and the mean profiles excluding LLJs (red). The results are based on ERA5 at the locations marked in Figure 1.

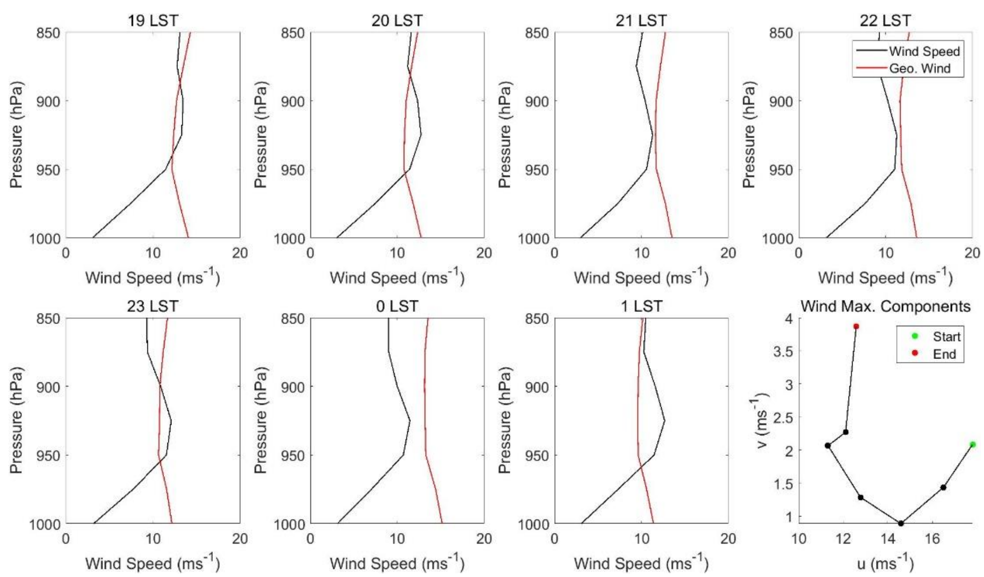

Figure S2. Case study representative of a NLLJ in Germany starting on 03 December 2018. Shown are the (black) the profiles of the wind speed and (red) the geostrophic wind speed to assess the occurrence of supergeostrophy. The hourly horizontal wind components in zonal (u) and meridional direction (v) from 19 local time are shown in the last plot to assess the expected turning of the wind field.

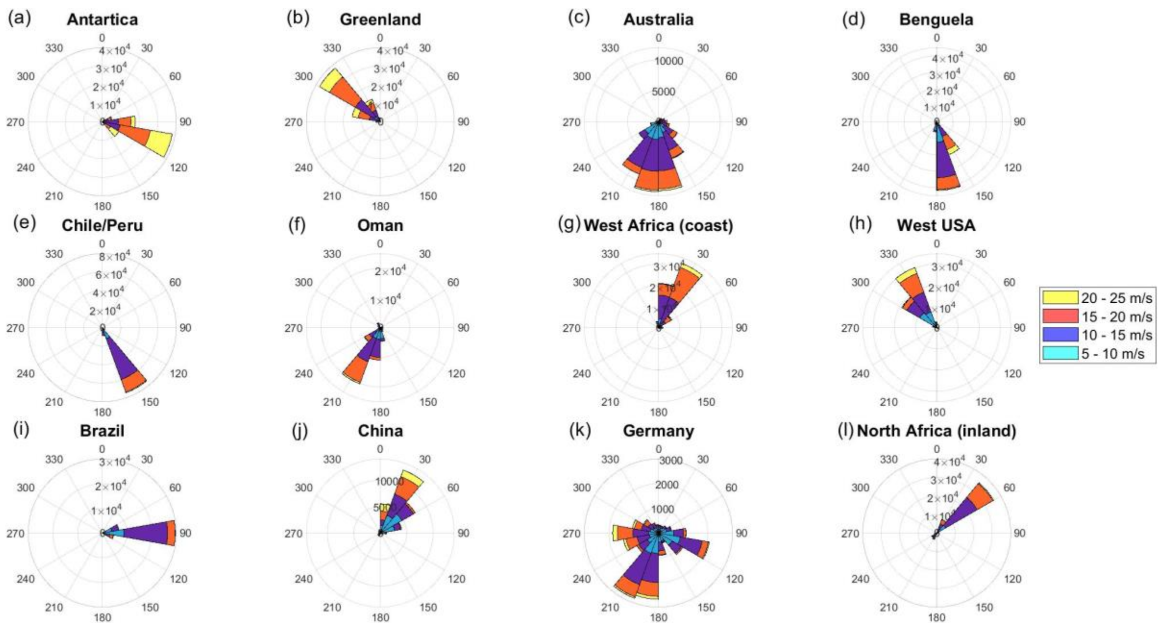

Figure S3. Wind roses for the LLJ cores at the selected locations. Shown are the total number of LLJs per wind direction with color-coded wind speeds. The results are based on ERA5 for 1992-2021 at the locations marked in Figure 1.

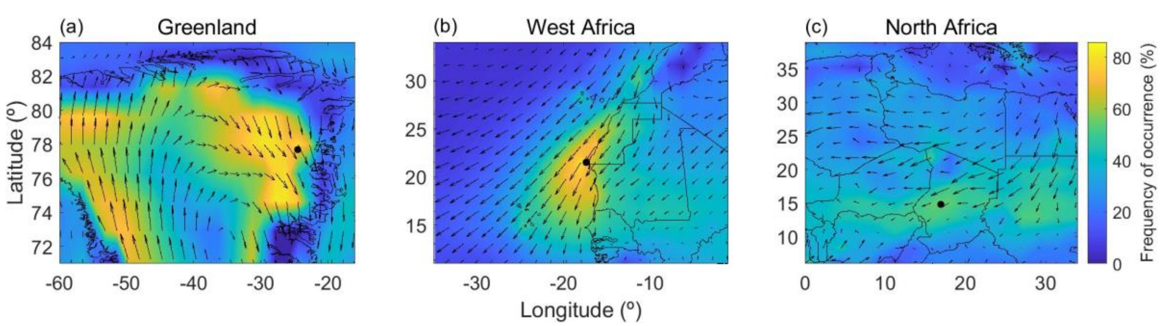

Figure S4. Zoom-in for spatial patterns of the frequency of occurrence along with the prevailing wind direction for one of each LLJ type assessed. Shown are the results for (a) the PLLJ in Greenland, (b) the CLLJ in West Africa, and (c) the NLLJ in North Africa. The black dots mark the location for the composite analysis of the LLJ types.