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Shallow and deep low-wind events in Europe: an ERA5-based event dataset (1979–2024)

Lihong Zhou[1], Igor Esau[1]

[1]Department of Physics and Technology, The Arctic University of Norway, Tromsø, 9010, Norway

Correspondence to: Lihong Zhou (lihong.zhou@uit.no)

Abstract. Persistent low-wind events (LWEs), often referred to as wind droughts, pose a growing challenge to power systems with high shares of wind energy. Existing assessments typically identify LWEs using wind speed at a single height, implicitly treating wind droughts as vertically homogeneous. However, weak-wind conditions can exhibit different vertical structures within the atmospheric boundary layer, leading to different wind conditions at turbine height. We present an event-based dataset of European LWEs derived from hourly ERA5 reanalysis for 1979–2024. The dataset introduces a two-height classification based on 10 and 100 m wind speeds. Events lasting at least 48 h are classified as shallow LWEs when wind speed is below 3 m s^{-1} at 10 m but above this threshold at 100 m, and as deep LWEs when wind speed remains below the threshold at both heights. Corresponding shallow-LWE-like and deep-LWE-like events are also identified for durations shorter than 48 h. The principal novelty of the dataset is that it adds a previously neglected vertical dimension to wind-drought climatology by distinguishing between weak-wind conditions confined near the surface and those that extend to turbine height. The physical plausibility of the classification is supported by distinct spatial and seasonal distributions and contrasting boundary-layer characteristics. Shallow LWEs are associated with stronger 10–100 m wind contrasts and more stable surface conditions, whereas deep LWEs represent more vertically coherent weak-wind states. The dataset contains event timing, duration, location, and classification, providing a resource for investigating European wind-drought climatology, boundary-layer controls, and land–sea contrasts. It also supports separate assessment of near-surface and turbine-height low-wind exposure in future renewable-energy systems. The dataset is available at https://doi.org/10.5281/zenodo.20748499 (Zhou and Esau, 2026).

1 Introduction

The rapid expansion of wind power in Europe has made the reliability of electricity systems increasingly sensitive to weather variability (Staffell and Pfenninger, 2018).While short-term fluctuations in wind speed can be balanced by fast-response storage technologies such as batteries, multi-day periods of weak winds, often referred to as low-wind events (LWEs) or "wind droughts", pose a more fundamental challenge (Mockert et al., 2023). These persistent events can exhaust storage capacity and trigger severe system stress. An example is the 11-day 2021 UK "wind drought", where output plummeted to just 11% of rated capacity, forcing a heavy reliance on fossil-fuel back-up to meet heating and electricity demands (Potisomporn et al., 2024).

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Such persistent low wind is expected to become a key driver of supply risk in a future energy system dominated by renewable sources and reduced synchronous generation (Veers et al., 2019).

LWEs are typically identified using thresholds applied to wind speed or wind power output, either through capacity factors or wind-speed-based metrics, in both meteorological and energy-system studies (e.g., Leahy and McKeogh, 2013; Qu et al., 2025; Rougès et al., 2025). Despite differences in implementation, these approaches share an implicit assumption: that low wind at a given level is representative of a vertically coherent weak-flow state relevant for wind-energy production. In other words, LWEs are generally treated as only one single class of atmospheric phenomenon.

However, this assumption is not always physically justified. Wind turbines operate within the atmospheric boundary layer (ABL), where vertical wind profiles are shaped by turbulent mixing and atmospheric stability. Weak winds, on the one hand, can be confined to a stably stratified surface layer in which turbulent mixing is suppressed, and the flow aloft remains relatively strong. On the other hand, weak winds may extend throughout the turbine-relevant layer, reflecting a vertically coherent low-momentum environment. These two situations are dynamically distinct, yet indistinguishable under existing definitions of LWEs.

This ambiguity is not merely conceptual. From a physical perspective, it obscures the role of boundary-layer processes such as stability, turbulent mixing, and vertical momentum exchange. From an energy perspective, it can lead to misinterpretation of wind-resource variability, since surface-confined weak-wind conditions and vertically extensive weak-flow regimes imply fundamentally different impacts on wind-power generation. Near-surface wind speed (10 m), widely available in observations and reanalysis products, does not uniquely determine wind conditions at turbine height, especially under stable stratification where vertical decoupling can occur (Foken 2022; Stull, 1988; Zilitinkevich and Esau, 2005). Treating LWEs as a single phenomenon therefore risks merging dynamically distinct events into a single category, potentially biasing both climatological analyses and assessments of energy-system risk.

These considerations indicate that a reusable LWE dataset for wind-energy and climate applications should retain information on the vertical structure of weak-wind conditions within the ABL. In this study, we therefore develop a two-height, boundary-layer-aware classification framework of European LWEs based on the relationship between near-surface and turbine-height winds (Fig. 1). Shallow LWEs are defined as events in which weak winds are confined to the near-surface layer, whereas deep LWEs are defined as events in which weak winds remain below the threshold at both heights. This classification distinguishes near-surface-confined weak-wind conditions from events that also affect turbine-height winds.

The temporal scale of LWEs is also important for both atmospheric interpretation and energy applications. We focus on persistent events lasting at least 48 hours in order to separate sustained weak-wind episodes from shorter fluctuations that may

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arise from the regular diurnal cycle of the ABL, especially over land where stable nocturnal and convective daytime regimes alternate (Holtslag et al., 2013; Liu and Liang, 2010). This persistence criterion is also consistent with energy-system studies, where multi-day wind deficits pose different challenges from short-term wind variability (Grams et al., 2017; Staffell and Pfenninger, 2018). Episodes with similar two-height wind structures but shorter durations are retained as shallow-LWE-like and deep-LWE-like events to support sensitivity analyses and comparisons between persistent and shorter weak-wind states.

Using hourly ERA5 reanalysis data for 1979–2024, we apply this classification across Europe to generate an event-based dataset of shallow and deep LWEs. In the following sections, we describe the detection procedure, dataset structure, event characteristics; and we demonstrate the physical plausibility and potential reuse of the dataset through analyses of spatial occurrence, seasonality, persistence, and boundary-layer diagnostics.

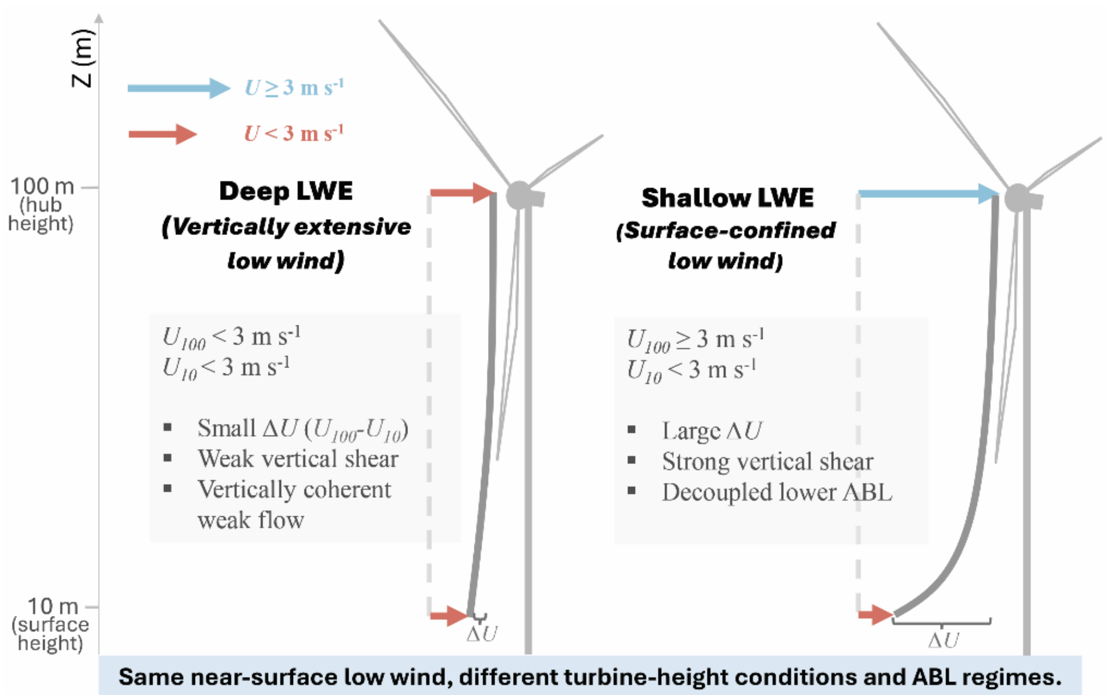

Figure 1: Conceptual schematic of the classification for the shallow and deep low-wind event (LWE).

2 Theoretical backgrounds

This section establishes the physical basis for the proposed classification. We first review how LWEs have been defined in previous studies and identify the single-level assumption common to most definitions. We then use boundary-layer theory to show why low winds at one height may correspond to distinct vertical structures. Finally, we explain why persistence beyond the diurnal cycle is required to distinguish dynamically sustained LWEs from transient boundary-layer variability.

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2.1 How low-wind events are defined in existing studies

LWEs often referred to as "wind droughts", have been studied in both meteorological and energy-system contexts. Depending on the scope of the study, different labels are used to describe such events. Wind-focused studies commonly use terms such as low wind speed events, or low wind power events or wind droughts (e.g., Kay et al., 2023; Ohlendorf and Schill, 2020; Patlakas et al., 2017), whereas multi-energy studies often adopt broader terms such as "Dunkelflaute", energy shortfalls, or compound solar-wind droughts (e.g., Kittel and Schill, 2024; Mockert et al., 2023; Richardson et al., 2023). Despite the differences in wording, the common aim is to identify periods during which wind conditions are too weak to sustain power generation over extended durations.

Existing identification approaches can be broadly grouped into capacity-factor-based and wind-speed-based metrics. Capacity-factor-based approaches connect directly to power-system impacts but depend on turbine specifications and spatial aggregation (Gao et al., 2025). Wind-speed-based metrics avoid some of these dependencies by working directly with meteorological variables, for example using fixed thresholds, percentiles thresholds or wind power density (Kay et al., 2023; Leahy and McKeogh, 2013; van der Wiel et al., 2019). Table 1 summarizes existing approaches for identifying wind droughts.

For the purposes of the present study, however, the key common feature is that most existing definitions diagnose low-wind conditions from either a single vertical level or an aggregated production metric. As a result, the vertical structure of weak winds within the ABL remains implicit. This is a potentially important omission, because weak winds near the surface do not necessarily imply weak winds at turbine height. The present study therefore asks whether persistent LWEs should be interpreted as a single event class, or instead as distinct boundary-layer weak-wind regimes with different physical and practical implications.

Table 1: Existing approaches to identifying wind droughts and the information retained by each approach.

Definition	Representative examples	What it captures	What information is not retained?
Fixed threshold	The cut-in speed for wind turbines (Leahy and McKeogh 2013)	Easy to interpret and compare across studies	Vertical structure of weak winds
Percentile	20th percentile of daily 10 m wind (Kay et al. 2023)	Accounts for regional wind climatology	Turbine-height conditions
Capacity factor	Capacity factor duration (Qu et al. 2025)	Closely linked to wind-energy production	Atmospheric drivers and vertical structure
Aggregated capacity factor	Aggregated capacity factor (Ohlendorf and Schill 2020)	Reflects system-scale wind availability	Regional meteorological heterogeneity
Joint wind–solar	Joint power density (Wang et al. 2025) Joint capacity factor (Mockert et al. 2023)	Captures compound renewable deficits	Wind-specific processes
Renewable shortfall	Low renewable production or high shortfall over fixed windows (van der Wiel et al. 2019)	Directly linked to system impacts	Atmospheric mechanisms
This study	Two-height LWE classification (10 m and 100 m)	Persistence and vertical extent of weak winds	Does not directly quantify system impacts

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2.2 Physical basis for distinguishing shallow and deep LWEs

The ABL, within which wind turbines operate, is directly influenced by surface forcing and governs the vertical distribution of wind speed. The vertical wind profile in the ABL is controlled by turbulent mixing, which regulates the exchange of momentum between the surface and the flow aloft. The intensity and structure of this turbulence depend strongly on atmospheric stability.

According to the dominant turbulence-generating mechanism, the ABL is typically classified into convective (unstable), neutral, and stable regimes (Albornoz et al., 2022). Under convective conditions, buoyancy-driven turbulence promotes strong vertical mixing, resulting in relatively uniform mean speeds with height (Esau and Zilitinkevich, 2006). Under neutral conditions, turbulence is shear-driven, maintaining moderate vertical coupling. In contrast, under stable conditions, turbulence is suppressed by negative sensible heat flux, leading to weak vertical mixing, strong wind shear, and, in many cases, decoupling between the surface layer and the flow aloft (Zilitinkevich and Esau, 2005). This decoupling has important consequences for wind profiles: while near-surface winds can become very weak or even calm, winds aloft accelerate, sometimes forming a low-level jet near the top of the stable layer (Hallgren et al., 2022). Consequently, the wind conditions experienced by a turbine at e.g., 100 m can be dynamically independent from those observed at the 10 m level. This matters because 10 m winds are widely available in observations and reanalysis products, whereas modern wind-energy impacts are determined by the flow across the rotor layer. For wind-energy applications, a surface-confined low-wind event and a turbine-height low-wind event imply very different production risks.

In wind-energy applications, hub-height wind speeds are often estimated from near-surface measurements using logarithmic or power-law profiles based on Monin-Obukhov similarity theory. These formulations assume vertically homogeneous and continuously turbulent flow, conditions that are approximately satisfied in convective or neutral regimes. However, under stable conditions, turbulence becomes intermittent and spatially heterogeneous, leading to significant deviations from these idealized profiles (Foken, 2006; Foken, 2022; Zilitinkevich, 1989; Zilitinkevich and Esau, 2005). Low wind situation at the surface may correspond either to a shallow, stably stratified layer with residual flow aloft, or to a deep weak-wind regime extending throughout the entire boundary layer. These two situations reflect fundamentally different dynamical states of the ABL. Consequently, near-surface wind speed does not uniquely determine wind conditions at turbine height.

This physical distinction implies that LWEs cannot be adequately characterized using a single-level definition. Instead, a classification that explicitly accounts for vertical structure naturally emerges from boundary-layer theory. In this study, we therefore distinguish between shallow LWEs, where weak winds are confined to the near-surface layer, often associated with stable stratification and suppressed vertical mixing, and deep LWEs, where weak winds extend throughout the boundary layer,

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consistent with a vertically coherent low-momentum state. This classification is thus not arbitrary but follows directly from the dynamical behavior of the ABL.

2.3 Why should persistent LWEs be defined beyond the diurnal cycle?

In addition to their vertical structure, the temporal scale of low-wind events is crucial for both physical interpretation and energy-system relevance. In this study, we define LWEs using a minimum duration of 48 hours, corresponding to events lasting at least two consecutive days. This choice is motivated by both engineering considerations and boundary-layer dynamics.

From an energy-system perspective, the temporal scale of wind variability determines the type of mitigation strategy required. Short-term fluctuations (seconds to hours) can typically be balanced by fast-response technologies such as batteries, whereas multi-day deficits require fundamentally different solutions, including large-scale storage, geographical balancing, or backup generation (Blanco et al., 2018; Fekri et al., 2025). Persistent low-wind events have therefore been identified as a major challenge for renewable-dominated systems, as they can exceed the capacity of short-term storage and may occur over large spatial scales, thereby constraining the effectiveness of geographical balancing through interconnection (Grams et al., 2017; Staffell and Pfenninger, 2018).

From a dynamical perspective, the distinction between shallow and deep LWEs becomes meaningful primarily for persistent boundary-layer states rather than for transient hourly fluctuations. Over land, the ABL typically follows a pronounced diurnal cycle, transitioning from a shallow stable boundary layer at night to a deeper convective boundary layer during daytime (Holtslag et al., 2013; Liu and Liang, 2010). Even in the absence of any sustained large-scale weak-flow anomaly, this daily cycle can produce substantial but short-lived changes in near-surface wind speed, vertical shear and boundary-layer depth (Stull, 1988). If LWEs were defined on purely hourly or sub-diurnal time scales, many detected cases would therefore reflect ordinary day-night variability rather than physically persistent weak-wind regimes (e.g. the shallow-like events in Fig. 2e).

This distinction is consistent with the conceptual separation between short-lived (or nocturnal) stable boundary layers and long-lived stable boundary layers. Zilitinkevich et al. (2007) showed that stable boundary layers can be separated into nocturnal stable layers associated with the regular diurnal cycle, and long-lived stable layers that evolve under stronger stratification of the free atmosphere above. The former are transient and locally forced, whereas the latter are dynamically sustained states that can persist beyond a single night. For the present study, this distinction is important because long-lived stable boundary layers are much more relevant to multi-day renewable-energy shortfalls than ordinary nocturnal cooling episodes; it ensures that the shallow-deep separation reflects persistent ABL weak-wind structure rather than transient surface-layer variability.

The 48-h threshold therefore serves two purposes: it filters out ordinary diurnal variability, and it selects events long enough to be relevant for energy-system balancing. Combined with the vertical classification introduced above, this persistence

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criterion allows for a physically consistent identification of low-wind regimes that are both dynamically meaningful and relevant for wind-energy applications.

3 Data

3.1 Definition and classifications of hourly LWE dataset

Motivated by wind-power supply shortfalls, our definition of LWE requires persistent low-wind lasting for at least 48 consecutive hours. To characterize the vertical structure of low-wind conditions, we classify LWEs using wind speeds at both 10 m and 100 m, taking U_{ci} as the threshold to identify events separately at each ERA5 grid cell. We distinguish (i) deep LWEs, for which $U_{10} < U_{ci}$ and U100 < U_{ci} throughout the event, and (ii) shallow LWEs, for which $U_{10} < U_{ci}$ and $U_{100} \geq U_{ci}$. This two-level definition enables explicit identification of potential vertical decoupling between near-surface and turbine-level winds.

We use wind speed rather than capacity factor as the primary metric because it directly links meteorological conditions to turbine operation and facilitates physical interpretation. Reported cut-in speeds typically range from 3–4 m s^{-1} (Leahy and McKeogh, 2013; Patlakas et al., 2017; van der Wiel et al., 2019); following Ohlendorf and Schill (2020), we adopted U_{ci} = 3 m s-1 for Europe. After detection, two consecutive events of the same type are merged if the non-event gap between them is ≤ 6 hours, consistent with the approach of Qu et al. (2025). We also conducted sensitivity analysis with U_{ci} = 3.5 and 4 m s-1. The results are shown in Appendix.

Following the identification steps described above, we constructed an hourly gridded LWE classification dataset for the study domain over the full study period. For each grid cell (0.25°×0.25°, inherited ERA5 grid size) and each hourly timestamp, we assign an integer flag in {0, 1, 2, 3, 4, 5} indicating one of six wind-condition class; the definitions of all flags are summarized in Table 2. In this study, our main analysis focuses on LWEs with duration ≥ 48 h (flags 4–5). For completeness, the classification also includes shorter low-wind periods (flags 2–3) and hub-height-only low-wind conditions (flag 1). We distinguish between shallow LWEs (flag 4), which satisfy the full duration criterion, and shallow-LWE-like events (flag 2), which exhibit the same vertical wind structure as shallow LWEs but do not reach the 48-h persistence threshold. We apply the same procedure to deep LWEs, with flag 5 denoting deep LWEs and flag 3 denoting deep-LWE-like events.

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Table 2: Definition of LWE flags, event types, and classification criteria.

Flag	Event type	Criteria
0	No LWEs conditions	$U_{10} \geq 3$ m s^{-1} and $U_{100} \geq 3$ m s^{-1}
1	Hub-height-only low wind	$U_{10} \geq 3$ m s^{-1} and $U_{100} < 3$ m s^{-1}
2	Shallow-LWE-like events (short)	$U_{10} < 3$ m s^{-1}, $U_{100} \geq 3$ m s^{-1}, duration < 48 h
3	Deep-LWE-like events (short)	$U_{10} < 3$ m s^{-1}, $U_{100} < 3$ m s^{-1}, duration < 48 h
4	Shallow LWEs	$U_{10} < 3$ m s^{-1}, $U_{100} \geq 3$ m s^{-1}, duration ≥ 48 h
5	Deep LWEs	$U_{10} < 3$ m s^{-1}, $U_{100} < 3$ m s^{-1}, duration ≥ 48 h

3.2 ERA5 reanalysis

All analyses are based on the ERA5 reanalysis (Bell et al., 2021; Hersbach et al., 2020; Hersbach et al., 2023), obtained from the Copernicus Climate Data Store. ERA5 was selected for its relatively high spatial and temporal resolution, and its demonstrated skill in representing near-surface and turbine-height wind over Europe (Fan et al., 2021; Ramon et al., 2019). The study period spans 1979-01-01 to 2024-12-31, and the study domain covers Europe (30–75°N, 25°W–40°E). Fields are analysed on the native ERA5 grid (0.25°×0.25°).

Near-surface (10 m) and hub-height (100 m) wind speeds were computed from the ERA5 u- and v-components at the corresponding levels (hourly single-level product) as $U = \sqrt{u^2 + v^2}$ .Grid cells were classified as land or sea using the ERA5 land-sea mask, a static field ranging from 0 to 1 that represents the land fraction in each grid cell. Following the ECMWF documentation, grid cells with values > 0.5 were classified as land, whereas grid cells with values ≤ 0.5 were treated as water (ocean or inland water; the two can be further separated using the lake-cover field if needed, which is not considered in this study).

Boundary layer height (BLH), surface sensible heat flux (SSHF) and mean sea level pressure (SLP) were obtained from the ERA5 hourly single-level product. The surface sensible heat flux is provided as accumulated surface energy per unit area (J m^{-2}) over the output interval with a downward-positive sign convention. We converted the sensible heat flux to hourly mean fluxes (W m^{-2}) by dividing by 3600 and multiplied by minus one to adopt an upward-positive convention throughout this study.

4 Results

The new classification of LWEs reveals that European LWE climatology is not spatially uniform but organized into regions dominated by different weak-wind regimes (Fig. 2a). Deep LWEs dominate most ocean areas and southern Europe, in which only ~10% of LWEs are shallow, whereas shallow LWEs become increasingly important over northern continental Europe (with ~80% of the LWEs being shallow LWEs). Central Europe forms a transition belt in which both regimes occur frequently. This implies that persistent low-wind conditions over Europe cannot be interpreted as a single class of events.

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The site-level examples confirm that the regional contrasts are not merely cartographic features. The two offshore wind-farm grid cells (Hornsea and Hollandse Kust Zuid) experience only deep LWEs (Fig. 2b–2c), whereas the northern inland site Markbygden experiences shallow LWEs almost every year (Fig. 2d). The example time series further illustrates that shallow and deep LWEs can occur within the same month under clearly different vertical wind structures (Fig. 2e), demonstrating that the classification is not an abstract climatological construct but captures physically distinct event types at individual locations.

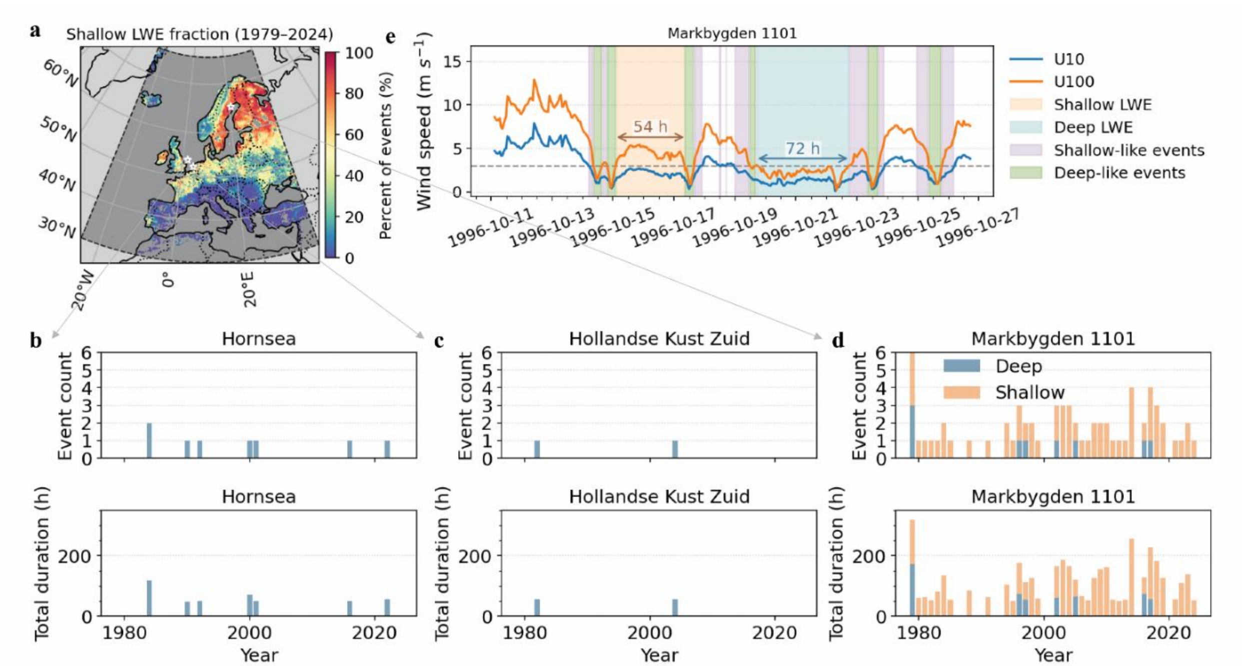

Figure 2: Spatial distribution and site-level characteristics of shallow and deep low-wind events (LWEs). (a) Fraction of shallow LWEs relative to all LWEs (shallow and deep) in each ERA5 grid cell across Europe for the period 1979–2024. Light grey indicates areas outside the study domain (no data), and dark grey marks 0% (no shallow LWE). Higher fractions indicate a larger contribution of shallow LWEs anda smaller contribution of deep LWEs.

(b–d) Event counts (top) and total duration (bottom) of shallow and deep LWEs at three wind farm locations: Hornsea (offshore wind farm), Hollandse Kust Zuid (offshore wind farm), and Markbygden 1101 (onshore wind farm). These sites illustrate contrasting regimes, with coastal sites showing no shallow LWE events, and the northern inland site exhibiting more frequent shallow LWEs.

(e) Example time series of 10 m (U10) and 100 m (U100) wind speeds at Markbygden 1101, illustrating the classification of shallow and deep LWEs, as well as shallow-like and deep-like events. Shaded areas indicate identified events, and arrows highlight example durations of shallow (e.g. 54 h) and deep (e.g. 72 h) LWEs.

The second key result we found is that duration alone is unable to distinguish between the two weak-wind regimes. Across most of Europe, shallow and deep LWEs have similar median durations, typically around 55–60 h, despite their strongly different vertical structures (Fig. 3a–3b). Although deep LWEs tend to exhibit a somewhat longer upper tail, the substantial (80%) overlap between the two duration distributions implies that events with similar persistence may arise from very different

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ABL dynamics (Fig. 3c). Consequently, persistence alone can group together vertically coupled weak-flow events and near-surface decoupled events with very different turbine-height wind conditions.

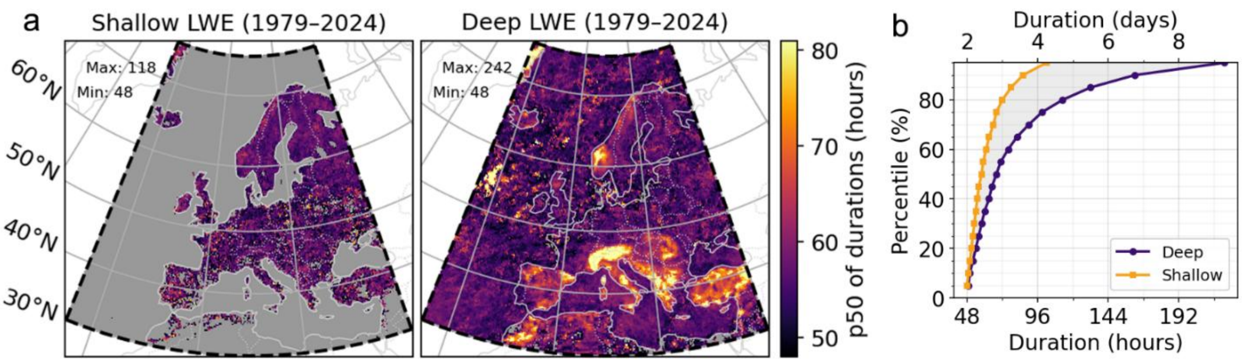

Figure 3: Distribution of LWE durations. (a) Spatial distribution of the median (p50) duration (hours) of shallow (left) and deep (right) LWEs over 1979-2024. Grey areas indicate grid cells where the corresponding LWE type is not detected. (b) Percentile-duration curves for shallow and deep LWEs, showing event duration (hours) as a function of percentile from the 5th to the 95th percentile in steps of 5%.

The Seasonal behaviors provide evidence that shallow and deep LWEs are distinct physical regimes rather than simple variants of the same event type. Shallow LWEs are consistently concentrated in the cold season and remain almost exclusively a terrestrial phenomenon, consistent with their characterization as stable, vertically decoupled boundary-layer states. Deep LWEs, by contrast, exhibit marked land-sea asymmetry and latitudinal contrasts; its seasonality depends strongly on both surface type and geographic location. Over the ocean, deep LWEs are a warm-season phenomenon, peaking from May to August north of 45°N and from July to November south of 45°N. Over land, the seasonal signal is more heterogeneous: south of 45°N, deep LWEs are clearly concentrated in the cold season, whereas north of 45°N, they occur across a broader portion of the year with only weak seasonal modulation. Thus, unlike the relatively uniform cold-season dominance of shallow LWEs, deep LWEs reflect distinct land and marine weak-flow regimes that lack a singular European seasonal pattern.

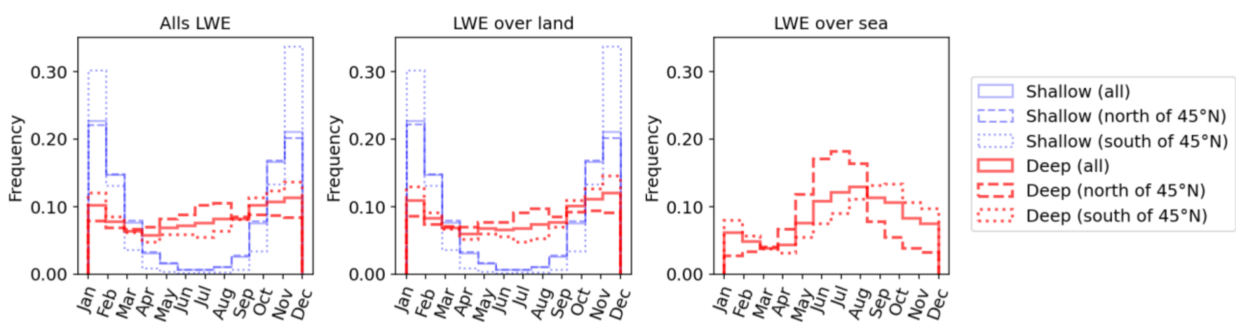

Figure 4: Seasonal distribution of shallow and deep low-wind events (LWEs). Monthly relative frequency of shallow and deep LWEs for all events (left panel), LWEs over land (middle panel), and LWEs over sea (right panel). Events at 45°N are included in the ≥ 45°N category. Note: shallow LWEs over sea are rare and thus omitted from the right panel.

The clearest evidence that shallow and deep LWEs represent dynamically distinct ABL regimes is provided by their contrasting distributions of SSHF, BLH and vertical wind shear (Fig. 5). In contrast, event-median SLP exhibits substantial overlap between the two regimes, suggesting that large-scale pressure conditions, at least as represented by SLP alone, are insufficient to distinguish the two regimes.

Shallow LWEs are clearly shifted towards more negative SSHF, consistent with stronger stable stratification driven by surface forcing and reduced turbulent exchange. Deep LWEs are distributed closer to zero and thus exhibit a weaker stable signature. It occurs under a broader range of surface forcing, including some stable atmospheric states cases (SSHF < 0). But deep LWEs are not restricted to neutral or convective conditions, as a substantial fraction still occurs under negative SSHF, implying that vertically coupled weak-flow states can also arise in relatively stable boundary layers.

BLH distributions also differ, but less trivially. Deep LWEs are strongly concentrated at very low BLH, especially below 100 m, indicating that many deep events occur in unusually shallow boundary layers in which weak flow extends through most of the layer. Shallow LWEs, by contrast, occur across a broader range of BLH values, consistent with near-surface suppression under more varied boundary-layer depths. Among the four variables, vertical wind shear provides by far the clearest separation between regimes. Deep LWEs are tightly concentrated at small ΔU, whereas shallow LWEs cluster at much larger ΔU with only limited overlap. This indicates that the proposed classification is not merely definitional: in the ERA5 climatology, deep LWEs are overwhelmingly realized as vertically coupled weak-flow states, while shallow LWEs are realized as decoupled states with strong near-surface-to-hub-height shear.

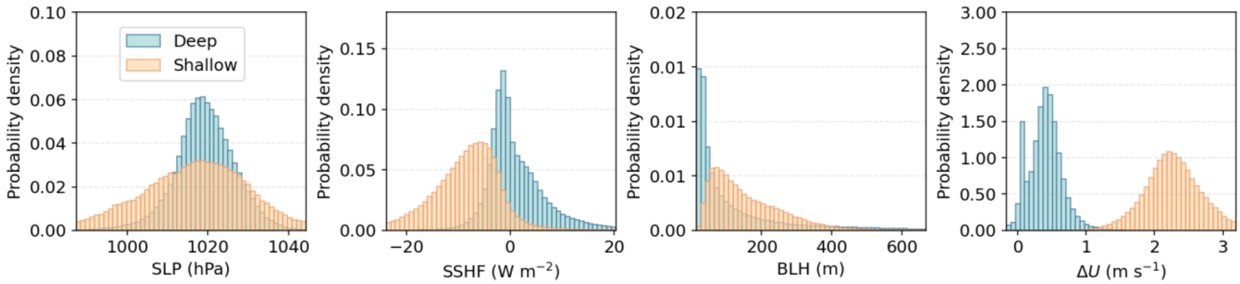

Figure 5: Distribution of key atmospheric variables for shallow and deep low-wind events (LWEs). Probability density functions of event-median values of sea-level pressure (SLP), surface sensible heat flux (SSHF), boundary-layer height (BLH), and vertical wind shear (ΔU) for shallow and deep LWEs.

5 Discussion

5.1 The two physically distinct ABL weak-wind regimes

The central scientific advance of this study lies in showing that commonly used LWEs metrics may conflate physically distinct ABL weak-wind regimes into a single statistical category. We demonstrate that persistent European low-wind events can arise

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from fundamentally different boundary-layer dynamics, motivating a vertically resolved and regime-aware interpretation of wind droughts. Persistent LWEs reflect at least two dynamically distinct ABL weak-wind regimes: a shallow regime associated with stable, weakly mixed and vertically decoupled flow, and a deep regime, characterized by more vertically coherent weak-flow conditions.

This distinction is supported by consistent differences in vertical wind shear, surface sensible heat flux, seasonality, and land-sea occurrence. Together, these features indicate that shallow-deep separation reflects a physically motivated separation of weak-wind that are otherwise conflated within single-level statistical definitions.

A key implication is that persistence alone is insufficient to distinguish between weak-wind events arising from fundamentally different ABL dynamics. Although deep LWEs exhibit a somewhat heavier upper-duration tail, the two regimes overlap substantially in duration across much of Europe. As a result, events with similar lifetimes may correspond to fundamentally different ABL states, either vertically coherent weak-flow conditions (deep LWEs) or stably stratified, vertically decoupled regimes (shallow LWEs).

This finding is particularly relevant because persistence is widely used in existing low-wind and wind-drought studies (e.g., Leahy and McKeogh, 2013; Ohlendorf and Schill, 2020; Qu et al., 2025). Duration-based or single-level metrics therefore risk conflating events with different dynamical origins, vertical structures, and implications for wind-energy applications.

The geographical and seasonal contrasts identified here are best interpreted as manifestations of different ABL regimes. Shallow LWEs occur predominantly over land and in the cold season, consistent with stable stratification, weak mixing, and enhanced near-surface-to-hub-height decoupling. Deep LWEs, by contrast, dominate marine regions and exhibit clear land-sea asymmetries and latitudinal differences in seasonality. The European climatology of persistent LWEs should therefore be interpreted as the combined expression of multiple ABL weak-wind regimes rather than as a single spatially coherent phenomenon.

The perspective refines previous low-wind studies, which predominantly focused on winter events due to their synergy with low solar generation and resulting energy shortfalls (Kay et al., 2023; Mockert et al., 2023). While our findings confirm the prevalence of persistent LWEs over land during winter, they also reveal a high frequency of deep LWEs in marine regions during summer and autumn. This indicates that a winter-centric approach may overlook the oceanic weak-flow regimes, an increasingly vital consideration as offshore wind capacity expands.

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5.2 Implications for future modelling

A case study by Li et al. (2021) provides independent validation for our framework. Their WRF-based analysis of a coastal "Dunkelflaute" event supported by multi-source observations, mirrors our deep-LWE regime, showing prolonged duration, weak vertical shear, and positive sensible heat flux within a shallow ABL.

This agreement suggests that the deep LWE class diagnosed from ERA5 corresponds to a dynamically coherent weak-flow regime that is also identifiable in mesoscale models. At the same time, Li et al. (2021) reported substantial challenges in representing boundary-layer evolution, residual-layer structure, mixed-layer growth, and turbine-layer wind speeds. This indicates that the predictability of deep LWEs is not solely a synoptic-scale problem: even when large-scale weak-flow conditions are captured, accurate prediction of turbine-height winds depends critically on the representation of boundary-layer mixing and entrainment processes.

The relative scarcity of process-based modeling studies on persistent low-wind events, compared to the extensive literature on their climatology and energy-system impacts, likely reflects both the technical difficulty of simulating weak-flow boundary layers (Shaw et al., 2022; Stull, 1988) and the lack of a clear dynamical framework. The shallow-deep classification proposed here provides a basis for addressing this gap by defining physically distinct targets for high-resolution modeling and forecast evaluation. It also offers a new perspective for model evaluation, as biases in low-wind statistics may be linked to deficiencies in boundary-layer coupling, turbulence parameterizations, or the representation of stable conditions.

While the circulation dependence of LWEs is beyond our current scope, prior studies link persistent low wind to anticyclonic and blocking like conditions (e.g., Richardson et al., 2023). Our results suggest that this relationship warrants revaluation through a regime-aware lens. Metrics that do not distinguish between shallow and deep LWEs may conflate weak-wind events with different boundary-layer dynamics and potentially different links to large-scale circulation forcing.

6 Code and data availability

The ERA5 hourly reanalysis data used in this study are available from the Copernicus Climate Data Store (Hersbach et al., 2023). The European low-wind-event dataset (1979–2024), including event catalogues, gridded classifications, metadata documentation, and the source code used to generate the dataset, is publicly available at the following repository: https://doi.org/10.5281/zenodo.20748499 (Zhou and Esau, 2026).

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7 Conclusions

We present an event-based dataset of European low-wind events (LWEs) derived from hourly ERA5 reanalysis for 1979–2024. The dataset extends conventional single-height and duration-based descriptions of wind droughts by jointly considering wind speeds at 10 and 100 m. Persistent events lasting at least 48 h are classified as shallow LWEs when low-wind conditions (< 3 m s^{-1}) occur at 10 m but not at 100 m, and as deep LWEs when the prescribed low-wind threshold is met at both heights. Shorter episodes with the same two-height structures are retained as shallow-LWE-like and deep-LWE-like events. The resulting data product therefore adds information on the vertical extent of weak-wind conditions and distinguishes near-surface low winds from events that also reach turbine height.

The climatological and meteorological characteristics of the dataset support the physical interpretability of this classification. Shallow LWEs occur predominantly over land and during the cold season and are associated with stronger 10–100 m wind contrasts, more negative surface sensible heat fluxes, and conditions consistent with reduced near-surface coupling. Deep LWEs represent more vertically coherent weak-wind states, occur over both land and sea, and overwhelmingly dominate the offshore LWE population. The two classes have substantially overlapped duration and sea-level-pressure distributions. Their separation therefore contains information that is not reproduced by event persistence or pressure-based diagnostics alone.

The dataset is intended as a reusable resource for research across climate science, meteorology, geography, and wind-energy applications. It can support analyses of, e.g., LWE climatology and its variability under climate change, regional and land–sea contrasts, and the representation of persistent weak-wind conditions in weather and climate models. For wind-energy studies, the classification provides a physically informed basis for separating near-surface low winds from meteorological events that also affect 100 m wind conditions. The dataset itself does not provide turbine-specific power production or grid-risk estimates, which additionally depend on turbine characteristics, installed capacity, and other energy-system factors.

The dataset inherits limitations from ERA5, including its spatial resolution, the representation of complex terrain and coastal environments, and uncertainties in near-surface and boundary-layer variables under strongly stable conditions. In addition, the use of 10 and 100 m winds provides a two-height representation rather than a complete vertical profile of the atmospheric boundary layer. These limitations should be considered when applying the dataset to local wind farms or individual turbine technologies. Nevertheless, the dataset establishes a consistent European reference for investigating the vertical structure of multi-day weak-wind events. The underlying two-height classification is not specific to Europe and provides a transferable framework for distinguishing near-surface-confined from vertically extensive low-wind conditions in other regions. We therefore encourage researchers to apply and evaluate the approach beyond Europe using regionally appropriate low-wind thresholds, turbine-relevant heights, and atmospheric datasets. Such applications would enable comparisons of shallow and deep low-wind regimes across different climates, geographical settings, and wind-energy systems.

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Appendix A: Sensitivity to wind speed thresholds

To assess the robustness of our results to the choice of cut-in threshold (U_{ci}), we repeated the LWE detection and classification using U_{ci} of 3.5 and 4.0 m s^{-1}, keeping all other methodological parameters (minimum duration, merging criterion, vertical classification) unchanged. The large-scale spatial distribution of LWEs remains consistent across all thresholds: shallow events predominate over Northern Europe, while deep events are more prevalent over southern Europe and in complex terrain area (Fig. A1). Increasing the threshold primarily enhances the shallow fraction along a mid-latitude belt from Western to Eastern Europe. This occurs because, in these regions, near-surface winds and turbine-height winds frequently fall within the 3–4 m s^{-1} range; when the threshold is raised, the places with low surface wind but still relatively strong turbine-height winds are newly classified as shallow LWEs.

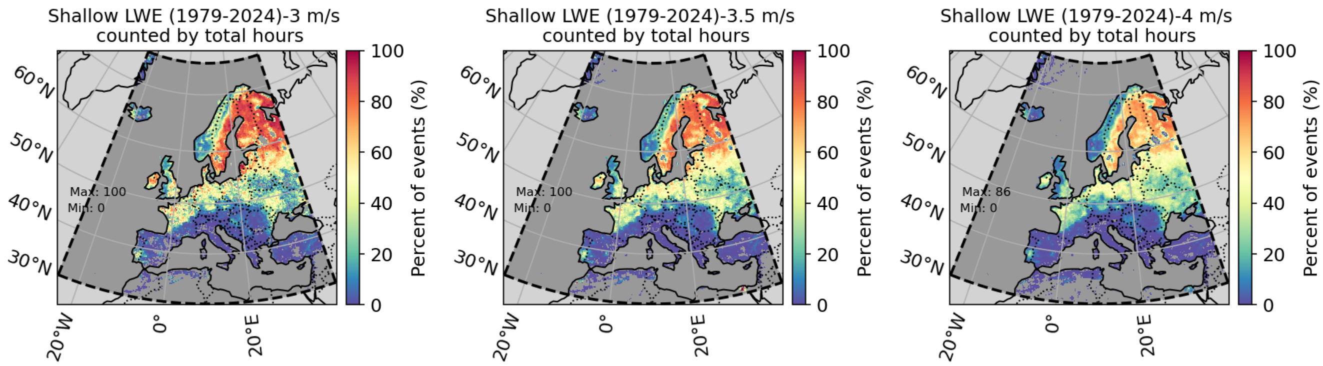

Figure A1: Fraction of shallow low-wind events (LWE) relative to all LWE (shallow and deep) in each ERA5 grid cell across Europe, with three panels corresponding to thresholds of 3.0, 3.5 and 4.0 m s^{-1} (from left to right). Light grey indicates areas outside the study domain (no data); dark grey marks 0% (no shallow LWE). Higher fractions mean a larger share of shallow LWE and, a smaller share of deep LWE in that grid cell.

While the dominance of shallow LWEs in northern Europe is persistent, their relative fraction decreases slightly at higher thresholds. This is due to a reclassification effect: raising U_{ci} creates new deep events and reclassifies some previously shallow events (where $U_{10} < 3.0$ m s^{-1} and $3.0 \leq U_{100} < 4.0$ m s^{-1}) as deep. Consequently, at $U_{ci} = 4.0$ m s^{-1}, no grid cell reaches a 100 % shallow LWEs fraction. These results confirm that the large-scale geographical division between shallow- and deep-dominated regimes is robust, the exact shallow-LWE share in mid-latitude transition zone is more sensitive to the specific cut-in threshold.

Coefficient-of-variation (CV) maps reveal that both shallow and deep LWE counts are subject to substantial relative changes when U_{ci} varies between 3.0 and 4.0 m s^{-1} (Fig. A2). High CV values for deep LWEs are concentrated over parts of northern and central Europe, whereas for shallow LWEs, they peak along the mid-latitude belt, identifying these transition regions as the most sensitive to threshold choice.

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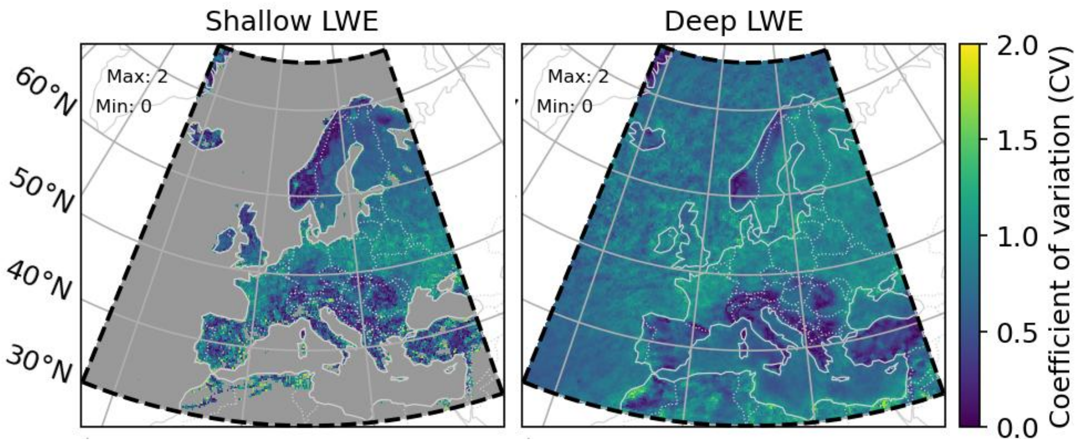

Figure A2: Sensitivity of LWE event counts to cut-in threshold. Coefficient of variation maps of shallow (left) and deep (right) LWE event counts, computed across three cut-in thresholds (3.0, 3.5, and 4.0 m s^{-1}). The value is calculated for each grid cell based on the variability in event counts across thresholds.

Scatter plots in Fig. A3 further show that event counts for all threshold pairs lie predominantly above the 1:1 line, confirming that higher cut-in speeds consistently increase the number of detected events. For deep LWEs, the data form a narrow band with exceptionally high correlations ($r \approx 0.93$–0.98), suggesting that threshold changes act as a spatially uniform scaling factor and do not alter the identified regional hotspots. In contrast, shallow LWEs exhibit significantly larger scatter and weaker correlations ($r \approx 0.60$ between 3.0 and 4.0 m s^{-1}). This indicates a more heterogeneous response, where the diagnosed pattern of shallow-LWE hotspots is more dependent on the chosen threshold than its deep counterpart.

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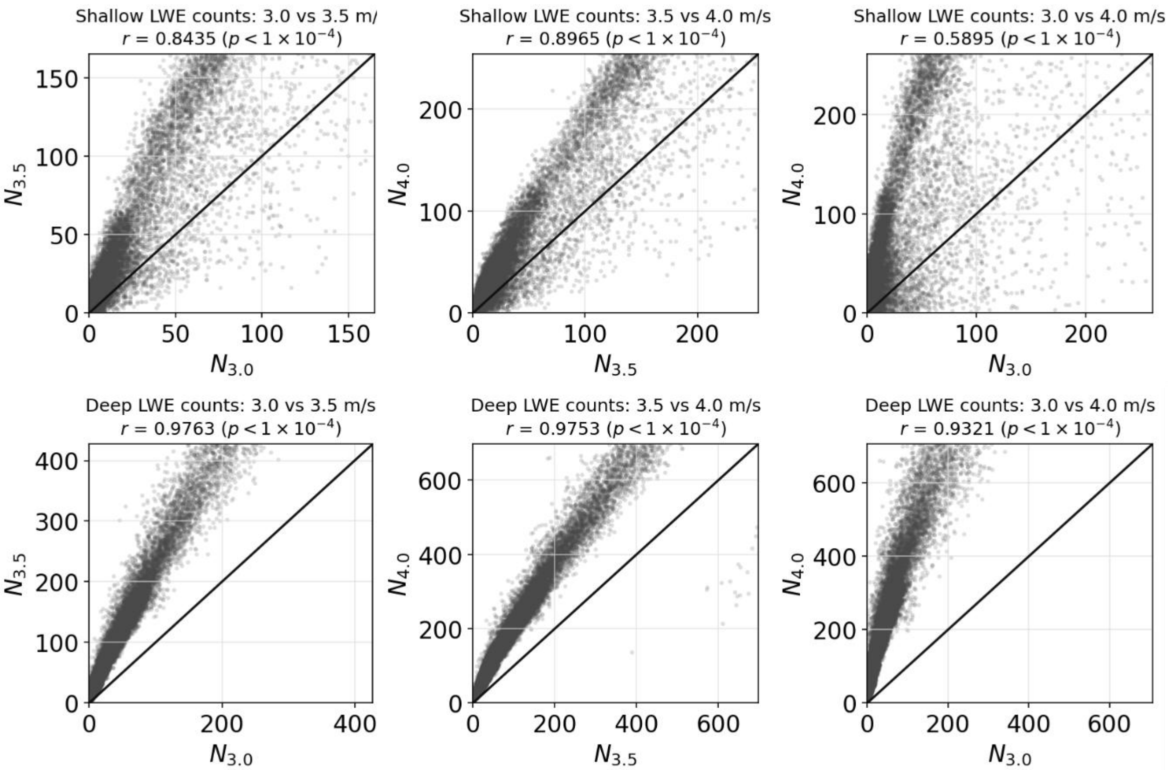

Figure A3: Consistency of LWE event counts across different cut-in wind speed thresholds. Scatter plots of LWE event counts for three cut-in thresholds (3.0, 3.5 and 4.0 m s^{-1}). The top row shows shallow LWEs and the bottom row deep LWEs. Each dot represents one grid cell, and the x- and y-axes indicate the number of LWEs identified using the thresholds specified on each axis. To emphasise the bulk of the distribution, axes are truncated at the 90th percentile of the counts, and only data within this range are shown. Correlation coefficients (*r*) are given in each panel. Results are qualitatively similar when using the 95th percentile (not shown).

Appendix B: Uncertainty from complex terrain

The performance of ERA5 in complex terrain highlights a broader challenge in interpreting LWEs across varying spatial scales. ERA5 is known to underestimate the variability and magnitude of 100 m winds in mountainous regions, largely due to the smoothing of orography within the model (Contreras et al., 2026). This limitation represents more than a data bias; it fundamentally alters the physical interpretation of LWEs in heterogeneous terrain.

Specifically, sub-grid-scale flows can decouple grid-cell-averaged winds from actual turbine-level conditions. For instance, local valley winds may intermittently exceed turbine cut-in speeds even when large-scale conditions indicate weak near-surface winds. Such localized flow effectively fragmenting what appears as a persistent large-scale LWE into shorter, discontinuous intervals (Henkies et al., 2025). Consequently, LWEs identified at the reanalysis grid scale do not necessarily correspond to persistent low wind conditions at individual wind turbines in complex terrain.

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This scale mismatch is driven by the interaction between large-scale atmospheric forcing and locally topographically induced circulations. Under such conditions, mesoscale pressure gradients are small, and local flows often dominate, thereby increasing the spatial heterogeneity of wind at turbine heights. As a result, the representativeness of grid-based LWE classifications is inherently lower in mountainous regions than over flat terrain.

To address this inherent limitation without explicitly resolving these sub-grid processes, we provide a practical framework. Following the European Environment Agency (EEA, 2008) and Kapos et al. (2000), we developed a mountain region mask on the ERA5 grid (Fig. B1). This auxiliary dataset allows users to either exclude mountainous regions when high-precision local wind estimates are critical or reinterpret LWEs in these regions as indicators of large-scale weak-flow conditions rather than direct proxies for local power output. Where necessary, this classification can be further refined using terrain complexity metrics, such as the standard deviation of elevation (Borowski et al., 2025).

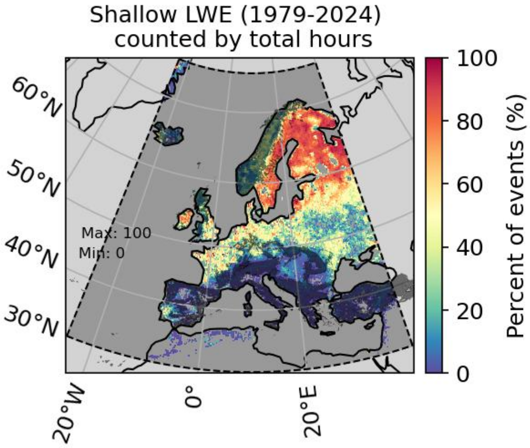

Figure B1: Same as Fig. 1a, but with the mountain-area mask applied; mountain regions are shown in light grey.

Author contributions

LH prepared the data, conducted the analysis and investigation, produced the visualizations, and wrote the manuscript. IE proposed the physical concept and interpretation of the results, supervised the study, administered the project, acquired funding and resources, and contributed to the writing through review and editing. LH and IE jointly developed the conceptual and methodological framework of the study.

Competing interests

The authors declare that they have no conflict of interest.

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