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Association between sleep and meteorology in late-onset depression patients

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Abstract

Objective To explore the sleep characteristics in different seasons and whether meteorology are related to sleep quality in LOD patients.

Methods A total of 241 LDO patients from Anhui Mental Health Center (2019–2023) were recruited. Meteorological data from the U.S. National Centers for Environmental Information (https://www.ncei.noaa.gov/maps/daily/). Difference analysis, correlation analysis, multiple linear regression models and restricted cubic splines to evaluate the relationship between season, meteorology and sleep quality among LOD patients.

Results Compared with winter and spring, LOD patients have higher sleep efficiency and shorter awakening time in summer and autumn ($p < 0.05$). Higher precipitation was associated with improved sleep efficiency (β = 0.193, 95% CI [0.044, 0.685], $p = 0.026$), and associated with decreased awakening time (β =—0.194, 95% CI [-3.712, -0.252], $p = 0.025$). Higher sunshine intensity was related to increased rapid eye movement (REM) sleep duration (β = 0.27, 95% CI [0.024, 0.151], $p = 0.007$) and REM% (β = 0.26, 95% CI [0.005, 0.036], $p = 0.010$). Sunshine intensity exhibited an inverted U-shaped relationship with awakening time (inflection points at 160.8 Wh/m^2, $p = 0.031$, p-nonlinear = 0.008) and exhibited U-shaped relationship with sleep efficiency (inflection points at 166.9 Wh/m^2, $p = 0.081$, p-nonlinear = 0.029). Temperature exhibited U-shaped relationship with sleep efficiency (inflection points at 20.3 °C, $p = 0.044$, p-nonlinear = 0.030), total sleep time (inflection points at 20.7 °C, $p = 0.006$, p-nonlinear = 0.008) and stage 2 of non-rapid eye movement (N2) duration (inflection points at 18.5 °C, $p < 0.001$, p-nonlinear < 0.001). Specific humidity exhibited U-shaped relationship with sleep efficiency (inflection points at 11.9 g/kg, $p = 0.123$, p-nonlinear = 0.042) and N2 duration (inflection points at 11.7 g/kg, $p = 0.028$, p-nonlinear = 0.008), and exhibited inverted U-shaped relationship with stage 1 of non-rapid eye movement (N1) duration (inflection points at 10 g/kg, $p = 0.007$, p-nonlinear = 0.020).

Conclusion This study demonstrates that sleep quality is poorest in LOD patients under moderate sunshine intensity, temperature, and humidity conditions, whereas extreme conditions enhance sleep efficiency and N2 duration while reducing awakening time.

Keywords Depression, Late Onset Disorders, Sleep, Meteorology, Season

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Introduction

Late-onset depression (LOD) is a major psychiatric disorder prevalent among the elderly [1] and is characterized by its initial onset after 50 years of age [2]. Compared with early-onset depression (EOD), LOD patients with sleep disturbances being particularly prevalent and severe [3]. LOD patients with sleep disturbances are harder to manage and have worse outcome [4–8]. Thus, LOD patients with sleep disorders draw much attention and urgently need effective treatment to enhance sleep quality and aid recovery.

The interplay between depression and sleep disorder is bidirectional and complex [9]. Underlying mechanisms circadian rhythm alterations, neurohormonal fluctuations (e.g., melatonin), and neuroinflammatory processes [10]. These mechanisms are more apparent in older adults due to age-related central nervous system (CNS) changes, such as: reduced phase and amplitude of circadian rhythms, changes in clock genes, damage and desynchronisation of the suprachiasmatic nucleus (SCN) and peripheral oscillators, Hypothalamic–pituitary–adrenal (HPA) axis overactivation and endocrine changes [11]. Human genetic studies link clock gene polymorphisms to diurnal mood variability and depressive recurrence [12]. Moreover, clock gene polymorphisms have also been associated with sleep and insomnia in depression patients [13], as well as playing a role in the efficacy of antidepressant treatment [14]. These findings highlight the potential of circadian rhythm modulation as a strategic intervention to improve depressive symptoms and promote recovery in LOD patients.

Meteorological parameters can exacerbate these neurochemical and circadian disruptions, worsening depression and sleep disorders [15]. As a socio-demographic and psychological vulnerable group, LOD patients are more difficult to cope with extreme weather conditions and exhibit changes in mood and sleep [16]. Seasonal variations, driven by latitude-dependent solar radiation (temperature, day/night length, sunshine intensity), affect mood and behavior: subtropical studies link autumn/winter depression spikes to reduced light, weather shifts, and circadian adjustment [17], Sleep quality also varies seasonally—winter/spring extend REM sleep duration and shorten latency compared to summer/autumn [18]. Numerous studies corroborate the strong association between human sleep patterns and temperature [19]. Regional studies across North/Central Asia and Alaska have linked sleep disturbances to seasonal extremes in light and temperature [20]. Daily light synchronizes these endogenous circadian rhythms with exogenous 24-h light and dark cycles, which alters body temperature [21] and melatonin [22]. Research in Iceland on older adults demonstrated significant predictions of total sleep time, mid-sleep, and wake time based on daylight hours [23]. A study on adolescents revealed that snowfall correlates with extended sleep durations [24]. Ravi Gupta et al. found that the low-pressure environment in high-altitude areas can lead to decreased sleep quality, frequent awakenings, and altered sleep structure [25].

Despite the recognized influence of weather on sleep, evidence in late-onset depression (LOD) remains lacking. Hence, we collected the clinical data and polysomnography (PSG) data of LOD patients hospitalized in Anhui Mental Health Center from 2019 to 2023, and obtain the meteorological data on the day of sleep monitoring. We hypothesized that the sleep of LOD patients would be associated with meteorological parameters and seasonal variation. This study aims to: (1) Characterize seasonal distributions of LOD patients and compare seasonal sleep differences; (2) Identify unfavorable meteorological conditions by analyzing meteorology-sleep relationships; (3) clarify the seasonal and meteorological conditions that should be considered when designing intervention measures to improve sleep in LOD patients.

Methods

Participants

One thousand five hundred fourteen LOD patients' general and clinical data (admission date, sleep monitoring date, sex, age, age of first onset, diagnosis, use of sedative-hypnotic drugs, and comorbidities) were collected from Anhui Mental Health Center (2019–2023). No personally identifiable information (e.g., names, hospital IDs, phone numbers) was collected. Inclusion criteria were as follows (1) diagnosis of "depressive episode" or "recurrent depressive disorder" according to International Statistical Classification of Diseases and Related Health Problems (ICD-10); (2) First onset age $\geq$50 years old; (3) Hamilton Depression Scale 17 (HAMD-17) total score $\geq$17; (4) polysomnography performed during hospitalisation; (5) Medication regimen has not been changed in the last two weeks. Exclusion criteria; (1) severe somatic diseases; (2) history of other mental disorder, dependence and abuse of psychoactive substances and drugs; (3) suffered from central nervous system infections, cerebrovascular accidents, hydrocephalus, B-cell tumors and other nervous system diseases during hospitalization; (4) acute or unstable medical problems. All procedures complied with relevant regulations and were approved by the Clinical Research Ethics Committee of Hefei Fourth People's Hospital (Ethics ID: HFSY-IRB-YJ-KYXM-KXM).

A total of 241 LOD patients were finally recruited. They were divided into four seasonal groups based on the Northern Hemisphere Meteorological Seasonal Division method: spring is from March to May, summer is from June to August, autumn is from September to November,

and winter is from December to February. The sampling procedure is shown in Fig. 1. Data were recorded using Epidata3.1 software.

Polysomnography (PSG) data

PSG monitoring was performed using equipment from Bio-logic Systems Corp, NATUS Group, USA (device number: 580G2cGss). Monitoring occurred in a dedicated sleep room, covering the entire night's sleep. Patients maintained habitual sleep schedules. EEG electrodes were positioned per international 10–20 system standards (central, frontal, occipital regions; contralateral mastoid references). Trained technicians analyzed polysomnographic data using American Academy of Sleep Medicine criteria (AASM, 2012) [26], quantifying: time in bed (TIB), total sleep time (TST), sleep efficiency (SE) and sleep latency (SL), rapid eye movement (REM) sleep duration and REM%, Non-rapid eye movement (NREM) sleep duration and NREM%, Phases of NREM: N1, N2, N3 duration and N1%, N2%, N3%.

Meteorological data

Hefei (31°49′14″ N, 117°13′38″ E) exhibits a humid subtropical monsoon climate with four distinct seasons. Daily meteorological data(2019–2023) from the National Environmental Information Center (NCEI) of

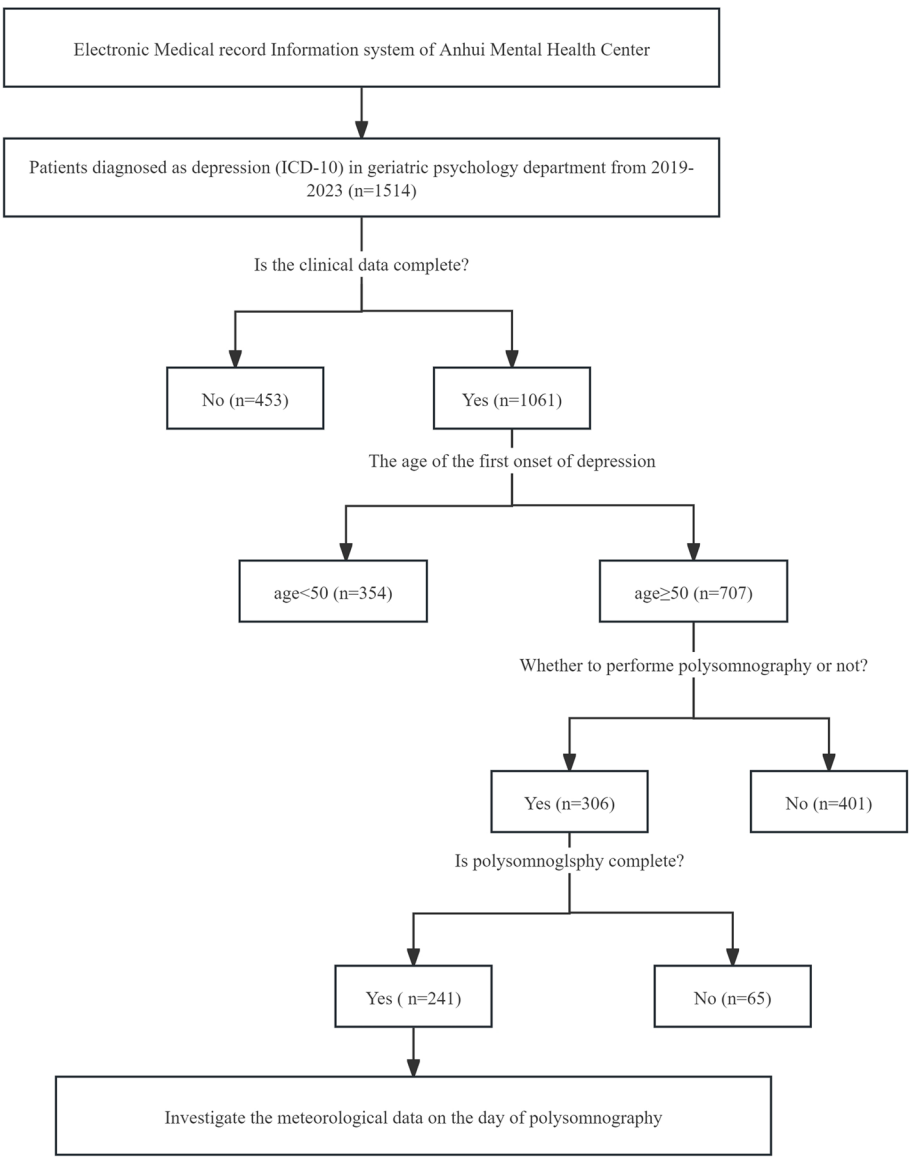

Fig. 1 Flowchart of the sampling process

the National Oceanic and Atmospheric Administration (NOAA) at https://www.ncei.noaa.gov/maps/daily/. The data include sunshine intensity (Wh/m^2), frost point (℃), temperature (℃), specific humidity (g/kg), relative humidity (%), precipitation (mm/day), wind speed (m/s) and surface pressure (kPa).

Statistical analyzes

Sample size calculations: Based on the relevant literature on the seasonal differences in past sleep patterns [27], with the awakening time as the main outcome, the mean awakening time of the groups in spring, summer, autumn, and winter are 131.8, 95.0, 144.7, and 91.4 respectively, and the standard deviations are 40.2, 27.6, 76.5, and 24.4 respectively. By setting $\alpha = 0.05$ and power $(1-\beta) = 0.9$, the calculated minimum sample size required is 164 cases. In this study, a total of 243 cases were finally included, which meets the requirements of the test.

Continuous variables are presented as mean ± standard (Mean ± SD) if normally distributed, or median (interquartile range, IQR) otherwise. Categorical variables are reported as counts (percentages). Group differences in categorical data were analyzed using Chi-Squared (χ^2) tests, with Fisher's exact test applied for cells having expected counts < 5. Seasonal variations in sleep parameters were assessed via ANOVA followed by Bonferroni-corrected post hoc tests. Multiple linear regression models evaluated associations between meteorological parameters (independent variables) and sleep metrics (dependent variables), structured as: model 1 was unadjusted, model 2 adjusted age, sex and disease duration, and model 3 was further adjusted for hospitalization frequency, sedative-hypnotic use, psychotic symptoms, disease severity, and comorbidities (hypertension, diabetes, stroke history). Nonlinear relationships were explored using restricted cubic splines (RCS), adjusting for all covariates in Model 3. Variables with variance inflation factors (VIF) > 5 were excluded to multicollinearity. All analyses were performed in SPSS (v25.0; IBM) and R (v4.4.0), with two-tailed p-values < 0.05 considered statistically significant.

Results

General and clinical information of LOD patients

A total of 241 LOD patients were recruited, with seasonal distributions as follows: spring ($n = 66$, 27.39%), summer ($n = 77$, 31.95%), autumn ($n = 56$, 23.23%), and winter ($n = 42$, 17.43%). Table 1 shows the distribution of their general and clinical information in four seasonal groups, with no significant inter-seasonal differences observed.

Seasonal differences in sleep among LOD patients

The ANOVA test revealed significant seasonal variations in sleep parameters among LOD patients ($p < 0.05$). Notably, Compared to winter, sleep efficiency was significantly higher in autumn and awakening time was significantly longer in summer. Compared to summer, N1 duration was significantly longer in autumn and N1% was significantly higher in spring. Please consult Fig. 2 for a detailed presentation of the data.

Multiple linear regression models: the linear relationship between sleep and meteorology

Multiple linear regression models revealed: Sleep efficiency improved with higher precipitation ($\beta = 0.193$, 95% CI [0.044, 0.685], $p = 0.026$); Awakening time increased with lower precipitation ($\beta = -0.194$, 95% CI [−3.712, −0.252], $p = 0.025$); REM duration ($\beta = 0.27$, 95% CI [0.024, 0.151], $p = 0.007$) and REM% ($\beta = 0.26$, 95% CI [0.005, 0.036], $p = 0.010$) increased with higher sunshine intensity. These findings were consistent across all model adjustments ($p < 0.05$) and are detailed in Tables 2 and 3.

Restricted cubic splines: the nonlinear relationship between sleep and meteorology

Sunshine intensity exhibited an inverted U-shaped relationship with awakening time (inflection points at 160.8 Wh/m^2, $p = 0.031$, p-nonlinear $= 0.008$) and exhibited U-shaped relationship with sleep efficiency (inflection points at 166.9 Wh/m^2, $p = 0.081$, p-nonlinear $= 0.029$). Temperature exhibited U-shaped relationship with sleep efficiency (inflection points at 20.3 °C, $p = 0.044$, p-nonlinear $= 0.030$), total sleep time (inflection points at 20.7 °C, $p = 0.006$, p-nonlinear $= 0.008$) and stage 2 of non-rapid eye movement (N2) duration (inflection points at 18.5 °C, $p < 0.001$, p-nonlinear < 0.001). Specific humidity exhibited U-shaped relationship with sleep efficiency (inflection points at 11.9 g/kg, $p = 0.123$, p-nonlinear $= 0.042$) and N2 duration (inflection points at 11.7 g/kg, $p = 0.028$, p-nonlinear $= 0.008$), and exhibited inverted U-shaped relationship with stage 1 of non-rapid eye movement (N1) duration (inflection points at 10 g/kg, $p = 0.007$, p-nonlinear $= 0.020$) Figs. 3, 4 and 5.

Discussion

This investigation marks the first to examine the relationship between meteorology and sleep quality in LOD patients within a subtropical climate. Higher sleep efficiency, shorter awakening time, and reduced N1 sleep duration/N1% were observed in summer and autumn compared to other seasons. Sunshine intensity exhibited positive linear correlations with REM duration and REM%. While precipitation exhibited positive linear

Table 1 Chi-Squared Test for general and clinical information in four seasons on hospitalized late-onset depression(LOD) patients during 2019–2023 (n, %)

Clinical variables		Total N (%)	Seasonal group				Chi-squared test	
			Spring 66 (27.4%)	Summer 77 (32.0%)	Autumn 56 (23.2%)	Winter 42 (17.4%)	X^2	*p*
Age	50–60	38 (15.8)	14 (21.2)	15 (19.5)	5 (8.9)	4 (9.5)	7.472	0.588
	61–70	105 (43.6)	26 (39.4)	31 (40.3)	28 (50.0)	20 (47.6)		
	71–80	90 (37.3)	25 (37.9)	28 (35.4)	20 (35.7)	17 (40.5)		
	> 80	8 (3.3)	1 (1.5)	3 (3.9)	3 (5.4)	1 (2.4)		
Gender	male	88 (36.5)	26 (39.4)	25 (32.5)	23 (41.1)	14 (33.3)	1.465	0.690
	female	153 (63.5)	40 (60.6)	52 (67.5))	33 (58.9))	28 (66.7)		
Diagnose	severe	165 (68.5)	43 (65.2)	52 (67.5)	41 (73,2)	29 (69.0)	0.958	0.811
	non-severe	76 (31.5)	23 (34.8)	25 (32.5)	15 (26.8)	13 (31.0)		
Presence of psychiatric symptoms	yes	17 (7.1)	5 (7.6)	6 (7.8)	1 (1.8)	5 (11.9)	3.969	0.265
	no	224 (92.9)	61 (92.4)	71 (92.2)	55 (98.2)	37 (88.1)		
Combined hypertension	yes	111 (46.1)	27 (40.9)	32 (41.6)	29 (51.8)	23 (54.8)	3.352	0.340
	no	130 (53.9)	39 (59.1)	45 (58.4)	27 (48.2)	19 (45.2)		
Combined diabetes	yes	32 (13.3)	6 (9.1)	10 (13.0)	8 (14.3)	8 (19.0)	2.274	0.518
	no	209 (86.7)	60 (90.9)	67 (87.0)	48 (85.7)	34 (81.0)		
Combined stroke	yes	7 (10.6)	7 (9.1)	5 (8.9)	3 (7.1)	22 (9.1)	0.376	0.945
	no	59 (89.4)	70 (90.9)	51 (91.1)	39 (92.9)	219 (90.9)		
Sedative-hypnotic drug	Not sedative-hypnotic drug	35 (14.5)	9 (13.6)	13 (16.9)	6 (10.7)	7 (16.7)	7.055	0.631
	Short-acting benzodiazepines	77 (32.0)	22 (33.3)	25 (32.5)	22 (39.3)	8 (19.0)		
	Long-acting benzodiazepines	90 (37.3)	24 (36.4)	29 (37.7)	17 (30.4)	20 (47.6)		
	Non-benzodiazepines	39 (16.2)	11 (16.7)	10 (13.0)	11 (19.6)	7 (16.7)		

correlations with sleep efficiency, elevated precipitation was associated with increased humidity, and nonlinear analysis revealed a significant inflection point at 11.9 g/kg specific humidity, beyond which sleep efficiency progressively improved. The poorest sleep efficiency (65.7–67.8%) occurred under moderate conditions: sunshine (166.9 Wh/m^2), temperature (20.3 ℃), specific humidity (11.9 g/kg). Extreme climatic conditions (high heat-humidity/low temperature) were associated with prolonged total sleep time and N2 duration, alongside reduced N1 duration.

The study revealed that sleep disturbances in LOD patients vary significantly with seasonal changes. Existing studies have also found seasonal differences in sleep among people of all ages [24, 27–29]. Our research found that sleep efficiency was the lowest and awakening time was longest in winter, aligning with broader epidemiological data that suggest higher insomnia rates in colder, darker months [30]. The least amount of light sleep stages (N1, N1%) occurred during summer, facilitating quicker transitions into deeper sleep stages. These findings demonstrates that sleep quality in LOD patients is superior in summer and autumn, differing from conclusions in general elderly populations where "summer sleep is prone to disruption [28]." This discrepancy may stem from two factors: First, population heterogeneity, as the depressive symptoms of LOD patients create a unique pathological context—reduced depressive episodes in summer weaken emotional interference with sleep [31]; Second, seasons as 90-day time units involve complex interactions of multiple meteorological factors (temperature, sunshine intensity, humidity, precipitation), which may obscure subtle associations between specific meteorological parameters and sleep architecture. Through further analysis of linear and nonlinear relationships between sleep and meteorological variables, we found that LOD patients exhibit the poorest sleep quality under moderate conditions: sunshine intensity (160.8–166.9 Wh/m^2), temperature (18.5–20.7 °C), and specific humidity (10–11.9 g/kg). This challenges the conventional understanding from general population studies that "moderate environmental conditions

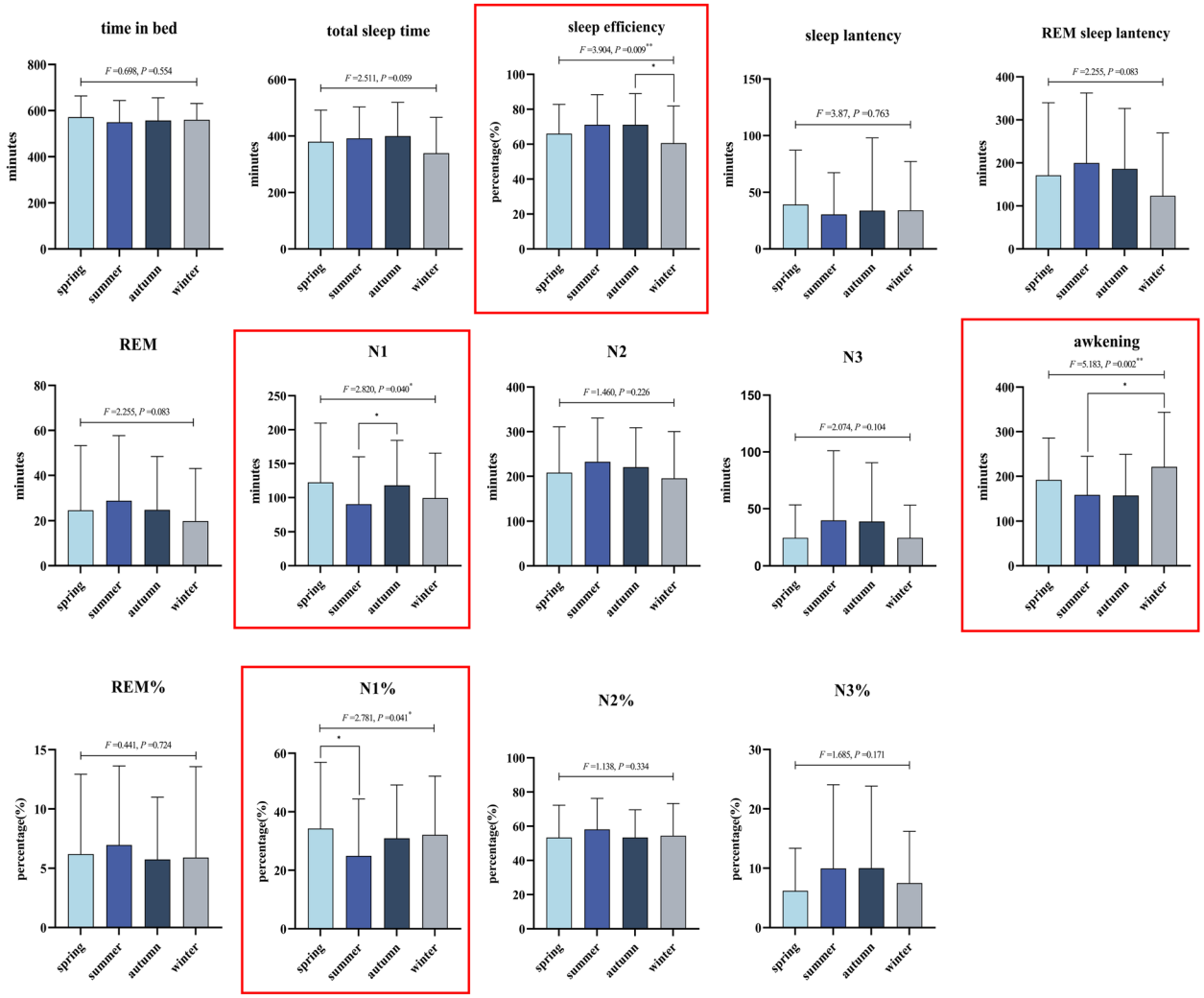

Fig. 2 Difference of sleep parameters of LOD patients in four seasonal groups. There were significant differences in SE, N1, N1% and awakening among the four seasonal groups, in which the sleep efficiency in autumn was significantly higher than that in winter, N1 duration in autumn was significantly longer than that in summer, N1% in spring was significantly higher than that in summer., and awakening time in winter was significantly longer than that in summer. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

are most conducive to sleep [32, 33]", highlighting the unique environmental-sleep regulatory mechanisms in LOD patients. Due to the absence of biological samples in this study, we cannot directly explain the neurobiological mechanisms. However, based on existing theories, we have made the following speculations. This study has also motivated us to further explore the biological mechanisms underlying this unique sleep-meteorological relationship in the future.

Sunshine intensity is positively correlated with REM sleep, as sunshine promotes REM sleep through serotonin synthesis [34] and melatonin regulation [35] (indirect effects) as well as acetylcholine release [36] (directly initiating and maintaining REM sleep). However, the explanatory power of the linear model is limited ($R^2 = 0.357$), and further restricted cubic spline (RCS) analysis shows that sunshine intensity exhibits a U-shaped relationship with sleep efficiency and an inverted U-shaped relationship with awakening time in LOD patients. At moderate light levels (160.8–166.9 Wh/m^2), sleep efficiency is lowest and awakening time is longest. This nonlinear regulatory pattern is population-specific: healthy individuals maintain a stable sleep–wake cycle by using light to regulate circadian clock-related gene expression via the retina-hypothalamic pathway [37]. In contrast, LOD patients exhibit reduced melanopsin expression and limbic system dysfunction [38]—melanopsin is critical for light-mediated circadian regulation, and its reduction

Table 2 Relationship between sleep efficiency, awakening and meteorological parameters in LOD patients (2019–2023)

	Model 1		Model 2		Model 3	
	β (95% CI)	*p*	β (95% CI)	*p*-value	β (95% CI)	*p*
Sleep efficiency						
Sunshine intensity	0.141 (−0.012, 0.075)	0.158	0.148 (−0.011, 0.076)	0.139	0.160 (−0.009, 0.08)	0.118
Frost point	−1.296 (−5.174, 0.073)	0.057	−1.212 (−5.025, 0.257)	0.077	−1.158 (−5.001, 0.444)	0.100
Temperature	0.98 (−0.51, 4.392)	0.120	0.883 (−0.7, 4.198)	0.161	0.818 (−0.886, 4.127)	0.204
Specific humidity	0.448 (−0.438, 3.097)	0.140	0.449 (−0.429, 3.096)	0.137	0.427 (−0.526, 3.064)	0.165
Relative humidity	0.383 (−0.079, 1.212)	0.085	0.368 (−0.105, 1.193)	0.100	0.365 (−0.128, 1.208)	0.113
Precipitation	0.193 (0.044, 0.685)	0.026	0.206 (0.068, 0.712)	0.018	0.181 (0.01, 0.674)	0.043
Wind speed	0.065 (−1.029, 3.005)	0.336	0.067 (−1.006, 3.051)	0.322	0.078 (−0.914, 3.277)	0.268
Surface pressure	0.212 (−2.767, 10.794)	0.245	0.209 (−2.799, 10.716)	0.250	0.168 (−3.779, 10.119)	0.370
F	2.040		2.026		0.668	
R^2	0.257		0.300		0.334	
ΔR^2	0.055		0.090		0.112	
Awakening						
Sunshine intensity	−0.159 (−0.426, 0.045)	0.112	−0.164 (−0.431, 0.038)	0.099	−0.173 (−0.447, 0.031)	0.088
Frost point	1.158 (−1.825, 26.518)	0.087	1.077 (−2.754, 25.727)	0.113	1.004 (−3.972, 25.377)	0.152
Temperature	−0.967 (−23.623, 2.855)	0.124	−0.871 (−22.557, 3.85)	0.164	−0.81 (−22.208, 4.815)	0.206
Specific humidity	−0.346 (−15.115, 3.983)	0.252	−0.348 (−15.105, 3.9)	0.247	−0.314 (−14.726, 4.625)	0.305
Relative humidity	−0.36 (−6.371, 0.602)	0.104	−0.346 (−6.271, 0.727)	0.120	−0.328 (−6.235, 0.969)	0.151
Precipitation	−0.194 (−3.712, −0.252)	0.025	−0.206 (−3.842, −0.372)	0.018	−0.192 (−3.751, −0.174)	0.032
Wind speed	−0.202 (−57.337, 15.915)	0.266	−0.103 (−19.418, 2.451)	0.128	−0.17 (−54.866, 20.047)	0.361
Surface pressure	−0.099 (−19.049, 2.745)	0.142	−0.197 (−56.66, 16.201)	0.275	−0.118 (−20.955, 1.632)	0.093
F	2.244		2.297		1.600	
R^2	0.072		0.100		0.056	
ΔR^2	0.040		0.1221		0.045	

Model 1: unadjusted; Model 2: adjusted age, sex and disease duration; Model 3: further adjusted for hospitalization frequency, sedative-hypnotic use, psychotic symptoms, disease severity, and comorbidities (hypertension, diabetes, stroke history)

impairs the normal physiological response to light [39], while limbic system dysfunction disrupts emotional and physiological regulation of environmental factors [38], compromising circadian sensitivity to moderate sunlight. Speculating mechanically, low-intensity light (< 160.8 Wh/m^2) can reduce the inhibition of melatonin secretion may help improve sleep quality and mood by regulating circadian rhythms [40]. High-intensity exposure (> 166.9 Wh/m^2) activates the suprachiasmatic nucleus (SCN) to regulate Per/Cry gene expression [41], enhance serotonin synthesis [42], and significantly improve sleep efficiency.

Consistent with the findings on sunshine intensity, this study reveals nonlinear relationships between temperature, humidity and LOD patients' sleep, showing that: under extreme low temperature (< 18.5 °C) or low specific humidity (< 11.9 g/kg), patients exhibit higher sleep efficiency and longer N2 duration; moderate temperature and humidity (20 °C, 11.9 g/kg) lead to the lowest sleep efficiency, shortest N2, and longest N1; when temperature continues to rise beyond this threshold, sleep efficiency and N2 duration increase again with higher temperature and humidity. Sleep progresses from shallow to deep, with N1 as the initial shallow sleep phase—reduced N1 duration indicates a faster transition to deeper sleep stages. The N2 is a critical sleep phase, and its stability significantly contributes to overall sleep quality [43].

Due to declined thermoregulatory function [44] and age-related respiratory mucosal atrophy [45] in LOD patients, they are less sensitive to stimuli from moderate temperature and humidity, and are unable to induce the body to make appropriate adjustments to maintain stable sleep. Extreme temperatures (cold or hot) and humidity (dry or damp) provide clear stimuli to LOD patients. According to the available literature, low temperature may prolong the N2 duration of LOD patients by enhancing sleep spindle activity [46], low humidity may trigger a slight respiratory irritation, which may prompt a rapid transition of N1 phase into the N2 phase through a neural reflex mechanism. High temperature accelerates core body temperature decline, a key trigger for initiating and maintaining sleep, thereby promoting N2 duration, total

Table 3 Relationship between REM, REM% and meteorological parameters in LOD patients (2019–2023)

	Model 1		Model 2		Model 3	
	β (95% CI)	*p*	β (95% CI)	*p*	β (95% CI)	*p*
REM						
Sunshine intensity	0.27 (0.024, 0.151)	0.007	0.263 (0.022, 0.148)	0.009	0.288 (0.029, 0.157)	0.005
Frost point	−0.794 (−6.094, 1.526)	0.239	−0.577 (−5.508, 2.189)	0.396	−0.441 (−5.21, 2.676)	0.527
Temperature	0.548 (−1.972, 5.146)	0.381	0.437 (−2.303, 4.833)	0.486	0.278 (−2.827, 4.434)	0.663
Specific humidity	0.403 (−0.816, 4.318)	0.180	0.349 (−1.051, 4.085)	0.246	0.325 (−1.188, 4.011)	0.286
Relative humidity	0.375 (−0.127, 1.747)	0.090	0.303 (−0.29, 1.601)	0.173	0.256 (−0.414, 1.521)	0.261
Precipitation	0.091 (−0.214, 0.716)	0.289	0.075 (−0.262, 0.675)	0.386	0.055 (−0.328, 0.633)	0.532
Wind speed	0.088 (−0.988, 4.871)	0.193	0.105 (−0.629, 5.281)	0.122	0.101 (−0.791, 5.278)	0.147
Surface pressure	0.219 (−3.803, 15.889)	0.228	0.245 (−3.069, 16.62)	0.176	0.203 (−4.452, 15.677)	0.273
F	2.423		1.528		0.997	
R^2	0.278		0.309		0.357	
ΔR^2	0.077		0.096		0.127	
REM%						
Sunshine intensity	0.26 (0.005, 0.036)	0.010	0.251 (0.004, 0.035)	0.013	0.276 (0.006, 0.038)	0.008
Frost point	−0.672 (−1.41, 0.465)	0.322	−0.517 (−1.314, 0.587)	0.452	−0.431 (−1.281, 0.675)	0.542
Temperature	0.433 (−0.569, 1.182)	0.491	0.363 (−0.624, 1.138)	0.566	0.287 (−0.697, 1.104)	0.657
Specific humidity	0.359 (−0.251, 1.012)	0.236	0.316 (−0.299, 0.969)	0.299	0.288 (−0.34, 0.95)	0.352
Relative humidity	0.342 (−0.05, 0.411)	0.124	0.288 (−0.081, 0.386)	0.200	0.259 (−0.103, 0.377)	0.263
Precipitation	0.062 (−0.073, 0.156)	0.475	0.045 (−0.086, 0.146)	0.608	0.052 (−0.084, 0.155)	0.559
Wind speed	0.159 (−1.35, 3.495)	0.384	0.07 (−0.348, 1.111)	0.304	0.059 (−0.432, 1.074)	0.402
Surface pressure	0.055 (−0.423, 1.019)	0.417	0.179 (−1.223, 3.639)	0.329	0.179 (−1.291, 3.703)	0.342
F	2.016		0.981		0.731	
R^2	0.065		0.077		0.101	
ΔR^2	0.033		0.033		0.023	

Model 1: unadjusted; Model 2: adjusted age, sex and disease duration; Model 3: further adjusted for hospitalization frequency, sedative-hypnotic use, psychotic symptoms, disease severity, and comorbidities (hypertension, diabetes, stroke history)

sleep time and sleep efficiency (e.g., activation of the ventrolateral preoptic nucleus [VLPO] in the hypothalamus) [47]. High humidity improves respiratory function by maintaining mucosal moisture [48], which may improve sleep quality. Wen-Te Liu et al. also found that temperature and humidity are closely related to sleep, such as increased humidity correlates with decreased N1 and increased N2 [49]. However, because the lack of neurobiological samples, we cannot clarify the underlying mechanisms. Further experiments on neurobiological samples are needed to understand the relationship between sleep and meteorological changes in LOD patients.

It is important to note that while seasonal variation, sunshine intensity, temperature, and humidity were significantly correlated, no associations were found between other meteorological parameters (wind speed, surface pressure, frost point) and sleep. Wind speed may not be directly related to sleep, but wind may affect thermal comfort [50], and its effect may be masked by the predominantly relationship between temperature/humidity and sleep. The indicated surface pressure variation in the atmosphere at the same altitude during our study period is small, basically around 100 kPa, may be one of the reasons for its negative results. Moreover, potentially reduced sensitivity of LOD patients to subtle atmospheric changes. These hypotheses warrant further experimental validation.

This study characterizes the peculiar relationship between sleep and meteorology in LOD patients, but had limitations: 1) retrospective cross-sectional PSG data could not infer causality; 2) lack of biomarkers would limit neuroendocrine pathway analysis; 3) NOAA data and single-center design limit the insight and generalizability of microclimates. Future multicenter longitudinal studies should include repeated seasonal measurements, dynamic biomarker collection, and localized weather monitoring. However, this work is first and foremost to systematically characterize weather-sensitive sleep in LOD patients, providing a basis for studying mechanisms and developing individualized environmental strategies.

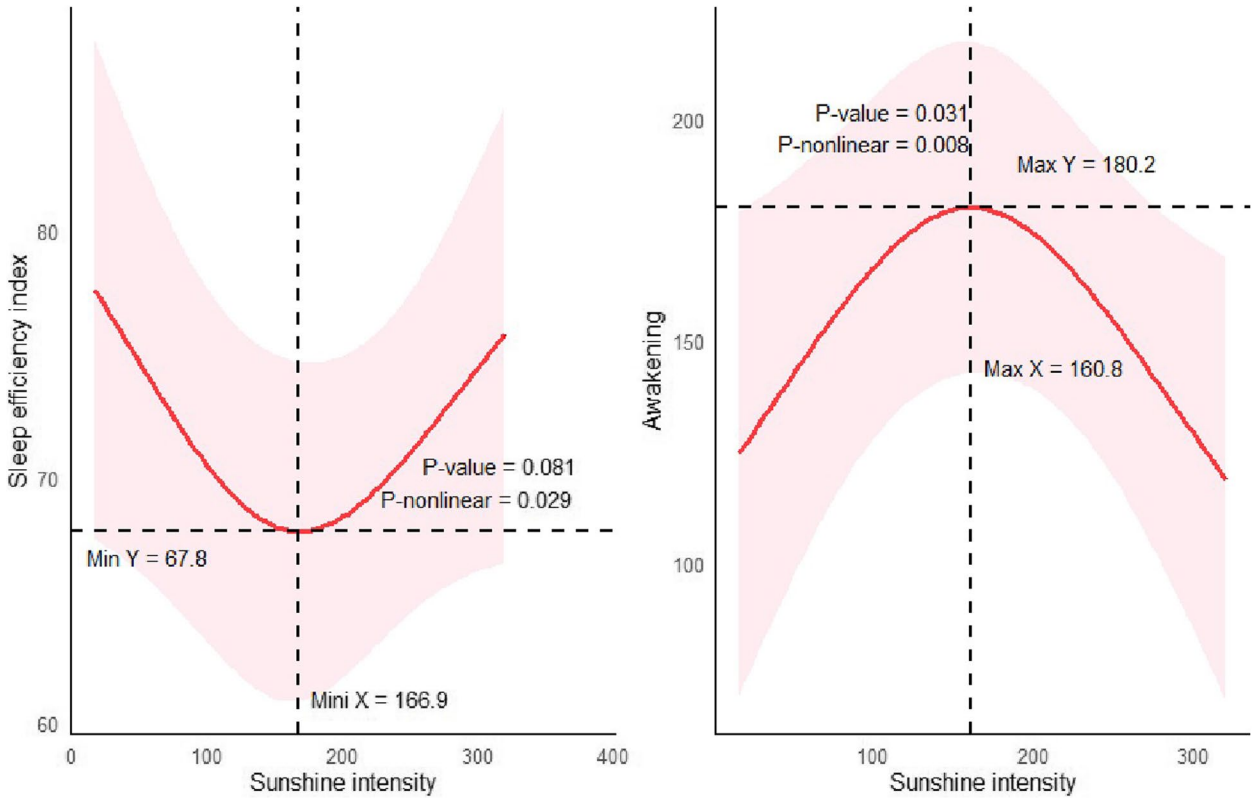

Fig. 3 Schematic diagram of restricted cubic spline (RCS) analysis results of sunshine intensity and PSG parameters. The Y-axis represents PSG parameters, the X-axis is sunshine intensity. Shaded areas indicate 95% confidence intervals. Sunshine intensity and awakening time exhibited an inverted U-shaped relationship (*p*-value = 0.031, *p*-nonlinear = 0.008). Sunshine intensity and sleep efficiency demonstrated U-shaped relationship (*p*-value = 0.081, *p*-nonlinear = 0.029)

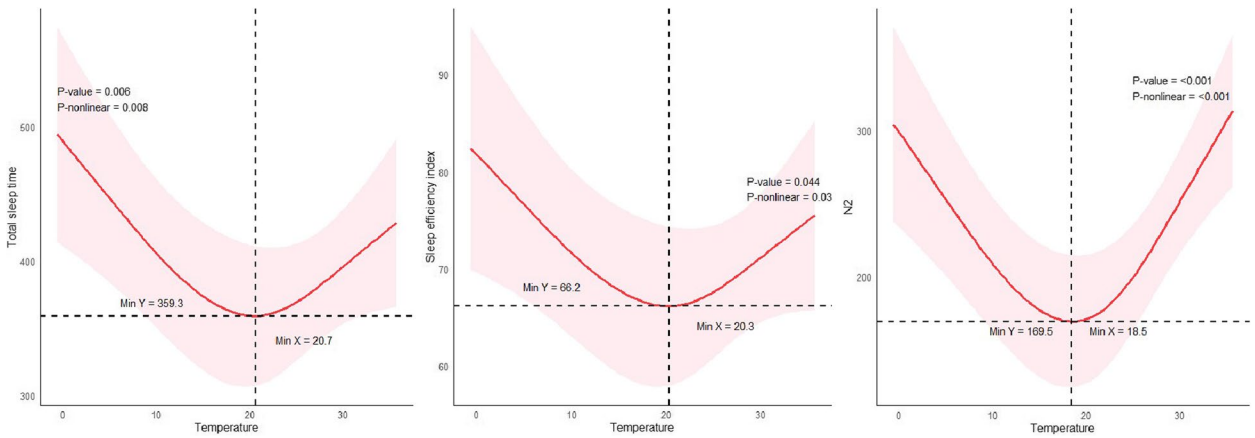

Fig. 4 Schematic diagram of restricted cubic spline (RCS) analysis results of temperature and PSG parameters. The Y-axis represents PSG parameters, the X-axis is temperature. Shaded areas indicate 95% confidence intervals. Temperature exhibited U-shaped relationships with three sleep parameters: sleep efficiency (*p*-value = 0.044, *p*-nonlinear = 0.030), total sleep time (*p*-value = 0.006, *p*-nonlinear = 0.008), and N2 duration(*p*-value < 0.001, *p*-nonlinear < 0.001)

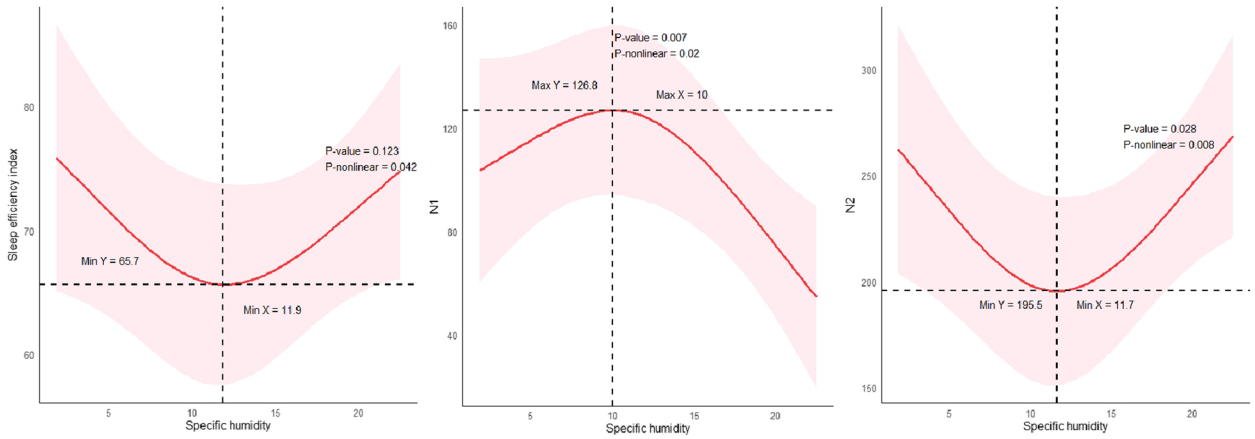

Fig. 5 Schematic diagram of restricted cubic spline (RCS) analysis results of specific humidity and PSG parameters**.** The Y-axis represents PSG parameters, the X-axis is specific humidity. Shaded areas indicate 95% confidence intervals. Specific humidity exhibited U-shaped relationships with two sleep parameters: sleep efficiency (*p*-value = 0.123, p-nonlinear = 0.042), total sleep time (*p*-value = 0.028, p-nonlinear = 0.008). Specific humidity and N1 duration demonstrated an inverted U-shaped relationship (*p*-value = 0.007, *p*-nonlinear = 0.020)

Conclusion

In conclusion, this study identifies nonlinear associations between meteorological variables (sunlight, temperature, humidity) and sleep quality in LOD patients, showing that extreme environmental conditions (high/low temperature/humidity) enhance sleep efficiency, N2 duration and decrease awakening time, whereas moderate conditions disrupt sleep architecture, contrasting with norms in the general population. These findings underscore the unique environmental vulnerability of LOD patients and challenge the paradigm of "neutral environments as optimal for sleep," providing a scientific basis for developing climate-tailored interventions to improve sleep health in this vulnerable population.

Abbreviations

LOD	Late-onset depression
EOD	Early-onset depression
PSG	Polysomnography
SWS	Slow wave sleep
REM	Rapid eye movement
SCN	Suprachiasmatic nucleus
HPA	Hypothalamic–pituitary–adrenal
TIB	Time in bed
TST	Total sleep time
SE	Sleep efficiency
SL	Sleep latency
REMSL	Rapid eye movement sleep latency
NREM	Non-rapid eye movement

Supplementary Information

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Supplementary Material 1.

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In the preparation of this paper, the author uses Chat Generative Pre-trained Transformer 4o (ChatGPT 4o) to check grammar and spelling errors and improve sentence structure. The date of using ChatGPT 4o is December 18, 2024. After using ChatGPT 4o, the author reviews and edits the content as needed and takes full responsibility for the content of the publication. The author gratefully acknowledge the National Environmental Information Center (NCEI) of the National Oceanic and Atmospheric Administration (NOAA) for the meteorological data provided, and thank Jiao-jiao Li, Le-tian Yang from Anhui Medical University for they help register clinical datas. In addition, we would like to thank patients, parents, caregivers and their attending physicians.

Clinical trial number

Not applicable.

Authors' contributions

Conceptualization: Xiao-ming Kong. Methodology: Yan Sun, Hao Geng. Validation: all authors. Formal analysis: Yu Guo, Zi-fan Zhu, Si-wen Lv. Investigation: all authors. Data curation: Xin-yu Gao, Yin-song Lu. Project administration: Lou-feng Zhang. Resources: Xiao-ming Kong. Supervision: Peng-yu Xie. Writing—original draft: Yu Guo. Writing—review & editing: all authors.

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Data availability

The sources of meteorological data in this study: https://www.ncei.noaa.gov/maps/daily/. The data sets of general data, clinical information and sleep data of the subjects in this paper are owned by the Department of Geriatric Psychology of Anhui Mental Health Center and contain personal information, but are available from the corresponding authors on reasonable request.

Declarations

Ethics approval and consent to participate
All experiments were performed in accordance with the declaration of Helsinki and institutional guidelines and have been approved by the Clinical Research Ethics Review Committee of the fourth people's Hospital of Hefei (2023.10.27, reference number of the ethical approval: HFSY-IRB-YJ-KYXM-KXM (2023–070-001). Informed consent was obtained from all individual participants included in the study. Authors ensure that patient confidentiality is in no way breached.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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