Journal of Sleep Research

RESEARCH ARTICLE OPEN ACCESS

Weather-Associated Variations of Device-Detected Severe Sleep Apnea in Cardiac Pacemaker Patients

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Received: 16 December 2024 | **Revised:** 19 January 2025 | **Accepted:** 7 February 2025

Funding: The authors received no specific funding for this work.

Keywords: ambient temperature | continuous monitoring | environmental exposome | humidity | transthoracic impedance sensor

ABSTRACT

Using continuous thoracic impedance measurements, sleep apnea can be long-time monitored via an electronic device sensor. In the ACaSA trial, 233 patients implanted with a cardiac pacemaker (MicroPort CRM, Clamart, France) were prospectively observed between March 2022 and July 2024. For each night of follow-up, the burden of device-detected sleep apnea (DDSA) was measured via transthoracic impedance, defined by a respiratory disturbance index (RDI) ≥ 20 events per sleeping hour. Local meteorological data including maximum ambient diurnal temperature, humidity, precipitation and air pressure change were extracted from the national weather system and linked to the individual patient's place of residence. The association between these weather conditions and RDI in the following night was estimated using a generalised linear mixed effects model. Overall, 74,031 patient-nights of 210 individuals (median age 75.7 years [IQR 69.9–81.3], 77 [36.7%] female) with a median follow up of 593 nights (IQR 348–755) were analysed. In a multivariate regression analysis, ambient maximum diurnal temperature was independently associated with presence of DDSA. Following days with a maximum of 30°C, the odds of experiencing severe DDSA increased by 1.34 (95% CI: 1.17–1.54, $p < 0.001$) compared to days with only 10°C. Higher relative humidity increased the odds for suffering from severe DDSA as well (OR 1.19 [1.07–1.33] in 90% relative humidity vs. 65% humidity; $p = 0.007$). These associations of ambient maximum diurnal temperature and relative humidity with severe DDSA the following night need further investigations, in particular in view of upcoming global climate changes.

1 | Introduction

Sleep apnea (SA) is a common health issue, impairing sleep quality while increasing the risk of cardiovascular conditions such as arterial hypertension, myocardial infarction, arrhythmias and stroke (Wipper et al. 2024). SA is also associated with a significant increased risk of dementia, in particular Alzheimer's disease (Bubu et al. 2020; Ibrahim et al. 2024). SA affects about 10%

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of men and 3% of women aged 50 to 70 years with its prevalence showing a rising trend in recent years (Peppard et al. 2013). The incidence of SA is particularly high among pacemaker patients, with up to 31% suffering from severe SA (Marti-Almor et al. 2020).

Many patients with severe SA remain undiagnosed, and the underlying mechanisms linking SA to adverse cardiovascular outcomes are not fully understood. Timely diagnosis and long-term monitoring of SA are limited to complex and resource-intensive methods, such as polygraphy (PG) or polysomnography (PSG), restricting opportunities to study SA in large populations over extended periods of time. Notably, a single measurement may result in a large target inaccuracy, as SA has a significant night-to-night variability (Stöberl et al. 2017). Modern pacemakers offer such continuous long-term monitoring of SA. Automated detection of SA using an impedance sensor in Microport pacemakers has shown a good agreement with PSG (Defaye et al. 2014) and PG (Champ-Rigot et al. 2023) to detect severe SA.

Current climate change, with its associated rise in global temperatures and the frequency of extreme weather events, may contribute to the increasing incidence of SA by influencing the environmental exposome. While direct evidence linking weather and SA incidence is currently sparse, weather has been associated with an increased incidence of other diseases. For example, a recent meta-analysis reported a 2.1% increase in mortality for each 1°C rise in temperature, driven primarily by coronary heart disease and stroke (Liu et al. 2022; He et al. 2024). Ischemic strokes have also been linked to elevated nocturnal temperatures in southern Germany (Sisodiya et al. 2024). Considering the established association between SA and both stroke and Alzheimer's disease, these connections underscore the importance of prevention, timely identification, and treatment of SA to protect brain health (Bassetti et al. 2022; Ruszkiewicz et al. 2019). Large-scale, long-term monitoring will be essential to better understand potential links between weather patterns and SA.

The ongoing ACaSA (Pacemaker Based Long-term Sleep Apnea Monitoring) trial (NCT05127720) is a prospective cohort study in pacemaker patients (focusing on device-based measurement of nocturnal SA, daily physical activity and atrial fibrillation burden as well as on co-morbidities), with a planned follow-up of up to two decades. The primary combined outcome parameter is time to first occurrence of death, myocardial infarction or stroke. The principal aim of the study is to better understand the complex interplay between SA, a sedentary lifestyle or cardiac arrhythmias with clinically relevant endpoints. This sub-study investigates the impact of the environmental exposome, analysing device-based measurements with local weather data in an elderly patient cohort.

2 | Methods

2.1 | Study Data

This study analysed data from observational ACaSA cohort study (NCT05127720), which prospectively enrolled patients implanted with a Microport BOREA DR or TEO DR pacemaker. Pacemaker settings were programmed at investigators discretion respecting clinical indications and individual patient requirements. Between December 2021 and July 2024, ACaSA recruited 233 participants after informed consent. Recruitment is currently on-going. All participants received telemedical monitoring of their pacemaker system using the SMARTVIEW technology, in the vast majority of cases remotely transmitting data to the study center on a weekly basis. Data were collected prospectively via remote follow up until the end of the observation period, death or withdrawal of consent.

2.2 | Study Cohort

All participants recruited in ACaSA study were eligible for inclusion in the analysis. Since weather patterns are highly seasonal, we only included data from 1 March 2022, at which point >10 patients had started actively contributing data. To further get a representative sample per patient across a range of temperatures, participants with a follow up <90 days were excluded. Finally, to rule out any influence of surgery on the results, the first 4 weeks after pacemaker implantation were excluded from analysis. Follow-up for this study continued until July 2024.

2.3 | Analyses of Severe DDSA

A respiratory disturbance index (RDI) was measured from midnight to 5 o'clock in the morning in all patients (irrespective of sleeping habits) using thoracic impedance monitoring. RDI was stratified to <20 and ≥ 20 apnea or hypopnea events per sleeping hour. The SA algorithm in Microport pacemakers counts an apnea event in the absence of a significant respiratory cycle for >10 s or a hypopnea event upon a sustained (>10 s) reduction of the respiratory amplitude by at least 50% compared to the mean minute ventilation of preceding validated respiratory cycles. The RDI correlates with the apnea-hypopnea index (AHI) measured by PSG, the gold standard for diagnosing SA: a cut-off value of ≥ 20 events per sleeping hour was shown to have a sensitivity of 88.9% and a specificity of 84.6% in detecting severe SA defined by an AHI >30 events per hour in PSG (Defaye et al. 2014). Measurements were labelled as invalid by the pacemaker software and not included in the analysis if there were more than 400 unstable or noisy signals per hour (due to movements while sleeping or active periods of the patients).

2.4 | Climate Data

Daily climate data were generated from the Integrated Nowcasting through Comprehensive Analysis (INCA) (GeoSphere Austria 2024) which provides hourly, gridded data for Austria at a 1×1 km resolution. INCA combines various data sources including data from weather stations. Western Austria's complex topography features heterogenous climatological conditions. To achieve the most representative location, each patient was allocated to the grid cell with the highest population density in their municipality of residence (Lehner et al. 2024). We considered

a range of weather parameters, which were often highly correlated (such as maximum and minimum daily temperature). Considering correlation and ease of interpretation, we included the following parameters in our analysis: maximum temperature, average relative humidity, total precipitation and maximum 3-h air pressure change. Ambient maximum diurnal temperature is the maximum of daily hourly values, representative for the air temperature at 2 m above ground. Relative humidity was calculated as the average hourly value of each day. Precipitation was summed up the entire day and categorised as ≤10 and >10 mm. Air pressure change was defined as the greatest absolute 3-h difference in Pa during 24 h.

2.5 | Statistics

Categorical variables were summarised as numbers and percentages. Continuous variables were summarised as mean +/− standard deviation if normally distributed, or as median (interquartile range [IQR]) otherwise. The temporal course of weather data was shown graphically and geographical variation was calculated. Correlations between different weather variables were calculated and, in the case of a strong correlation, taken into account in the subsequent analysis. Associations between weather conditions and SA were estimated using a generalised linear mixed effects model. In order to account for repeated daily measurements of the same participants, a random intercept per participant was included. Natural cubic splines were considered for all continuous weather parameters. Knots and degrees of freedom were chosen based on visual inspection, giving preference to parsimonious models. Seasonal differences not explained by weather conditions were fitted using indicators for each calendar month. In subgroup analyses, we fit additional models with interactions with age (<75 and ≥75 years), sex, and altitude (<800 vs. ≥800 m above sea level [masl]). Statistically significant differences between sugroups were tested via likelihood ratio tests. All analyses were performed with R software, version 4.2.3 (R Foundation for Statistical Computing Vienna, Austria).

3 | Results

Out of 233 patients enrolled in the ACaSA study, 210 were included in the analyses. Patients were excluded due to a follow-up of <90 days (19 patients) and no valid measurements of RDI (4 patients), as shown in Figure 1. Overall, 72.6% of recorded nights were labelled as valid by the pacemaker algorithm and therefore included in the analysis. Median age was 75.7 years (IQR 69.9–81.3), 77 (36.7%) were female. Median follow-up per patient was 593 days (IQR 348–755) and a total of 74,031 patient nights were analysed. Baseline characteristics of included patients as well of analysed subgroups are shown in Table 1.

3.1 | Climate Characteristics

Figure 2 shows the locations of patients' residences in the western part of Austria (Tyrol, Vorarlberg). Dot sizes correlate with the number of study patients from each location, while dot colours represent altitude. As patients lived at elevations between 500 and 1500 masl, and temperature is strongly correlated with elevation, they experienced a broad range of climatic conditions. The climate is representative of mid-latitudes with usually January being the coldest and July being the warmest month with an approximate difference of 20° between the 2 months. The lowest maximum diurnal temperature recorded was −10.6°C, while the warmest day reached 37.7°C. The mean maximum diurnal temperature for all patients during the observation period was 16.9°C (±2.0°C). Due to the—from a climate perspective—relatively short study period, extreme ambient maximum diurnal temperatures above 30°C were sparse. However, locations above 1500 masl extend the temperature range on the colder side, particularly below 0°C. Weighted local maximum diurnal temperatures for the study cohort are shown in Figure 2B. In the study period, the highest temperatures occurred from mid-July to early September, while the coldest episodes were between mid-December and early February. Weighted relative humidity, shown in Figure 2C, varies from an average of around 65% in April to 85% in December. This is also a typical seasonal

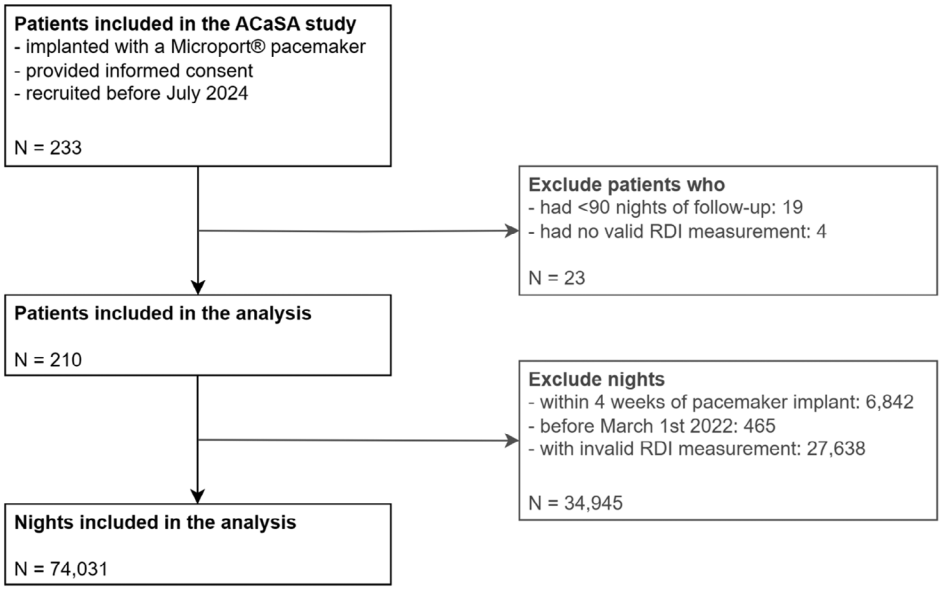


FIGURE 1 | Flow chart of selected patients and nights.

TABLE 1 | Baseline characteristics of the total cohort and by age, sex and altitude.

	Total cohort	Sex		Altitude		Age	
	Total ($n=210$)	Male ($n=133$)	Female ($n=77$)	≥800 masl ($n=72$)	<800 masl ($n=138$)	<75 years ($n=100$)	≥75 years ($n=110$)
Age, years, median (IQR)	75.7 (69.9–81.3)	75.7 (70.2–81.8)	75.9 (69.0–80.7)	77.1 (70.97–82.02)	74.95 (69.15–80.49)	69.1 (63.2–73.2)	80.9 (78.0–83.1)
Male, *n* (%)	133 (63.3)			47 (65.3)	86 (62.3)	63 (63.0)	70 (63.6)
Body mass index, kg/m^2, median (IQR)	25.8 (22.9–28.3)	26.2 (24–28.4)	23.7 (21.2–25.0)	26.2 (23.64–28.81)	25.48 (22.45–27.74)	26.2 (23.5–27.9)	25.3 (22.7–28.4)
Paroxysmal AF, *n* (%)	64 (30.5)	40 (30.1)	24 (31.2)	16 (22.2)	48 (34.8)	31 (31.0)	33 (30.0)
Persistent AF, *n* (%)	11 (5.2)	7 (5.3)	4 (5.2)	2 (2.8)	9 (6.5)	6 (6.0)	5 (4.5)
Pacing indication: SSS, *n* (%)	106 (50.5)	65 (48.9)	41 (53.2)	33 (45.8)	73 (52.9)	49 (49.0)	57 (51.8)
Pacing indication AVB, *n* (%)	86 (41.0)	54 (40.6)	32 (41.6)	29 (40.3)	57 (41.3)	42 (42.0)	44 (40.0)
Pacing indication Bradyarrhythmia, *n* (%)	15 (7.1)	12 (9)	3 (3.9)	7 (9.7)	8 (5.8)	7 (7.0)	8 (7.3)
History of heart failure, *n* (%)	21 (10.0)	11 (8.3)	10 (13)	7 (9.7)	14 (10.1)	9 (9.0)	12 (10.9)
Previous MI, *n* (%)	21 (10.0)	16 (12)	5 (6.5)	6 (8.3)	15 (10.9)	11 (11.0)	10 (9.1)
Diabetes, *n* (%)	41 (19.5)	32 (24.1)	9 (11.7)	13 (18.1)	28 (20.3)	18 (18.0)	23 (20.9)
Previous stroke, *n* (%)	19 (9.0)	14 (10.5)	5 (6.5)	9 (12.5)	10 (7.2)	9 (9.0)	10 (9.1)
Coronary artery disease, *n* (%)	77 (36.7)	58 (43.6)	19 (24.7)	35 (48.6)	42 (30.4)	29 (29.0)	48 (43.6)
LVEF, %, median (IQR)	57.2 (53.2–62.9)	56.5 (53.1–63)	57.6 (53.3–62.8)	56.0 (53.4–62.2)	58.0 (53.1–63.25)	56.0 (53.5–62.1)	58.4 (52.8–63.3)
NOAC, *n* (%)	84 (40.0)	55 (41.4)	29 (37.7)	25 (34.7)	59 (42.8)	39 (39.0)	45 (40.9)
VKA, *n* (%)	8 (3.8)	4 (3)	4 (5.2)	2 (2.8)	6 (4.3)	7 (7.0)	1 (0.9)
BB, *n* (%)	61 (29.0)	33 (24.8)	28 (36.4)	17 (23.6)	44 (31.9)	33 (33.0)	28 (25.5)
Amiodarone, *n* (%)	8 (3.8)	5 (3.8)	3 (3.9)	2 (2.8)	6 (4.3)	4 (4.0)	4 (3.6)
Flecainide, *n* (%)	4 (1.9)	3 (2.3)	1 (1.3)	3 (4.2)	1 (0.7)	3 (3.0)	1 (0.9)
Digitalis, *n* (%)	5 (2.4)	4 (3)	1 (1.3)	1 (1.4)	4 (2.9)	4 (4.0)	1 (0.9)
Statin, *n* (%)	125 (59.5)	81 (60.9)	44 (57.1)	45 (62.5)	80 (57.9)	53 (53.0)	72 (65.5)

(Continues)

TABLE 1 | (Continued)

	Total cohort	Sex		Altitude		Age	
	Total ($n=210$)	Male ($n=133$)	Female ($n=77$)	≥ 800 masl ($n=72$)	< 800 masl ($n=138$)	< 75 years ($n=100$)	≥ 75 years ($n=110$)
CCB, *n* (%)	47 (22.4)	31 (23.3)	16 (20.8)	18 (25.0)	29 (21.0)	18 (18.0)	29 (26.4)
Aspirin, *n* (%)	67 (31.9)	49 (36.8)	18 (23.4)	29 (40.3)	38 (27.5)	25 (25.0)	42 (38.2)
Clopidogrel, *n* (%)	19 (9.0)	17 (12.8)	2 (2.6)	9 (12.5)	10 (7.2)	6 (6.0)	13 (11.8)

behaviour for Central Europe. As relative humidity is lowest in spring and summer, maximum diurnal temperature and average daily relative humidity have opposite seasonal patterns. It should be noted that the described climate characteristics refer only to the study period, which is not representative of long-term climate conditions.

3.2 | SA Monitoring

On average, patients experienced severe device-detected sleep apnea (DDSA) defined as an RDI ≥ 20 per sleeping hour in 33.8% (IQR 3.8%–62.3%) of nights. At least one night of severe DDSA was seen in 190 (90.5%) patients. Severe DDSA was more common in older patients (36.0% of nights in patients aged ≥ 75 years compared to 27.3% in patients aged < 75 years; aOR [95% CI]: 1.33 [1.07–1.64]; $p=0.009$). Males experienced DDSA in 32.0% of nights, while females experienced DDSA in 7.5% of nights (aOR: 0.18; 95%-CI: 0.09–0.39; $p<0.001$). The altitude of the patient's place of residence was a strong risk factor for the occurrence of severe DDSA (aOR: 4.06, 95%-CI: (1.89–8.75); $p<0.001$ for ≥ 800 masl).

3.3 | DDSA and Maximum Diurnal Temperature

The odds of severe DDSA increased with maximum diurnal temperature (Figure 3A). After warm days with 30°C, patients were 1.34-times (95%-CI 1.17–1.64; $p<0.001$) as likely to have severe DDSA than on days with 10°C. The odds of severe DDSA particularly increased above a temperature of 20°C–25°C, with no or little difference at lower temperatures. Subgroup analysis showed a more pronounced effect in patients below the age of 75 years ($p=0.041$) and in women ($p=0.006$; Figure 3B,C). In an univariable analysis not adjusted for other weather factors, there was an even larger effect with an OR of 1.48 (95%-CI 1.23–1.58, $p<0.001$).

3.4 | DDSA and Relative Humidity

The odds of severe DDSA also increased with higher relative humidity (Figure 4A). Compared to days with 65% relative humidity, patients were 1.19-times (95% CI 1.07–1.33; $p=0.007$) as likely to experience severe DDSA after a day with 95% relative humidity. As with temperature, associations were numerically more pronounced in patients below the age of 75 years ($p=0.058$) or in women ($p=0.112$; Figure 3B,C). Univariable analysis did not show a significant effect of relative humidity.

3.5 | DDSA and Other Covariates

Neither change in air pressure nor precipitation were associated with odds of experiencing severe DDSA (Table 2).

4 | Discussion

This study presents new insights into how weather factors affect severe DDSA. These findings suggest that day-to-day

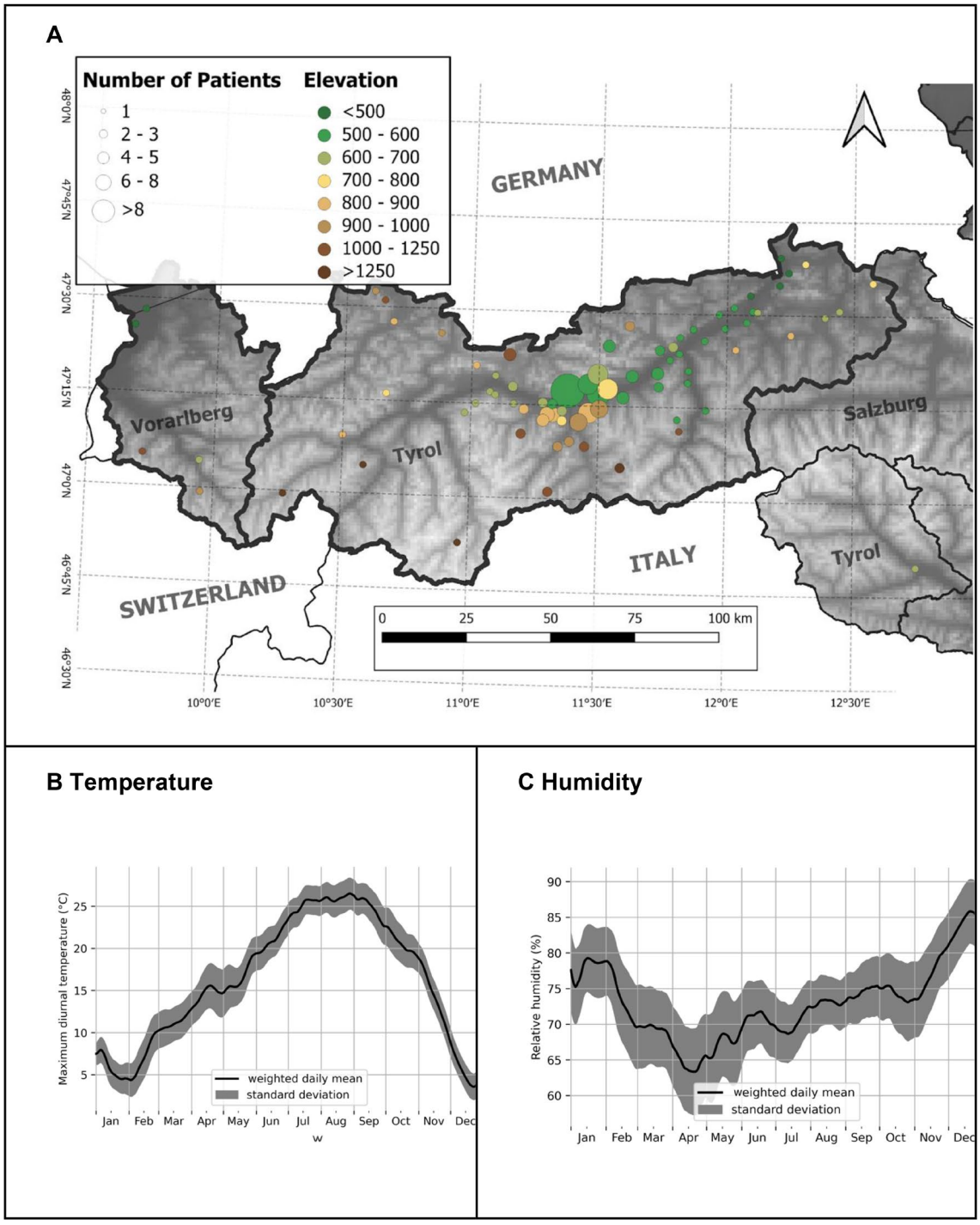


FIGURE 2 | Residence of study patients and baseline weather data. (A) Locations of patients shown with the circles. The colours of the circles represent the elevation of the patient's home municipality in meters above sea level. The size of the circles shows the number of patients living in the municipality. About 67 patients live in the city of Innsbruck. (B) Mean maximum diurnal temperature calculated as average over a 28-day period. The thick line represents the mean of all for all study patients, the shaded area the standard deviation showing the spread of values between the patients. (C) Average relative humidity calculated as average over a 28-day period. The thick line represents the mean of all for all study patients, the shaded area the standard deviation showing the spread of values between the patients.

variations in ambient diurnal maximum temperature and relative humidity influence the instantaneous rate of SA events in the following night. Given the associations between SA and non-communicable diseases, these results highlight how climate and environmental conditions may impact public health, especially in vulnerable populations.

New temperature records have been reported worldwide, with 2023 being the warmest year ever recorded at 1.45°C (±0.12°C) above pre-industrial levels (World Meteorological Organization (WMO) 2024), making climate change the greatest challenge facing humanity in the 21st century. Beside extreme weather events such as heat waves, which will likely occur more frequently in

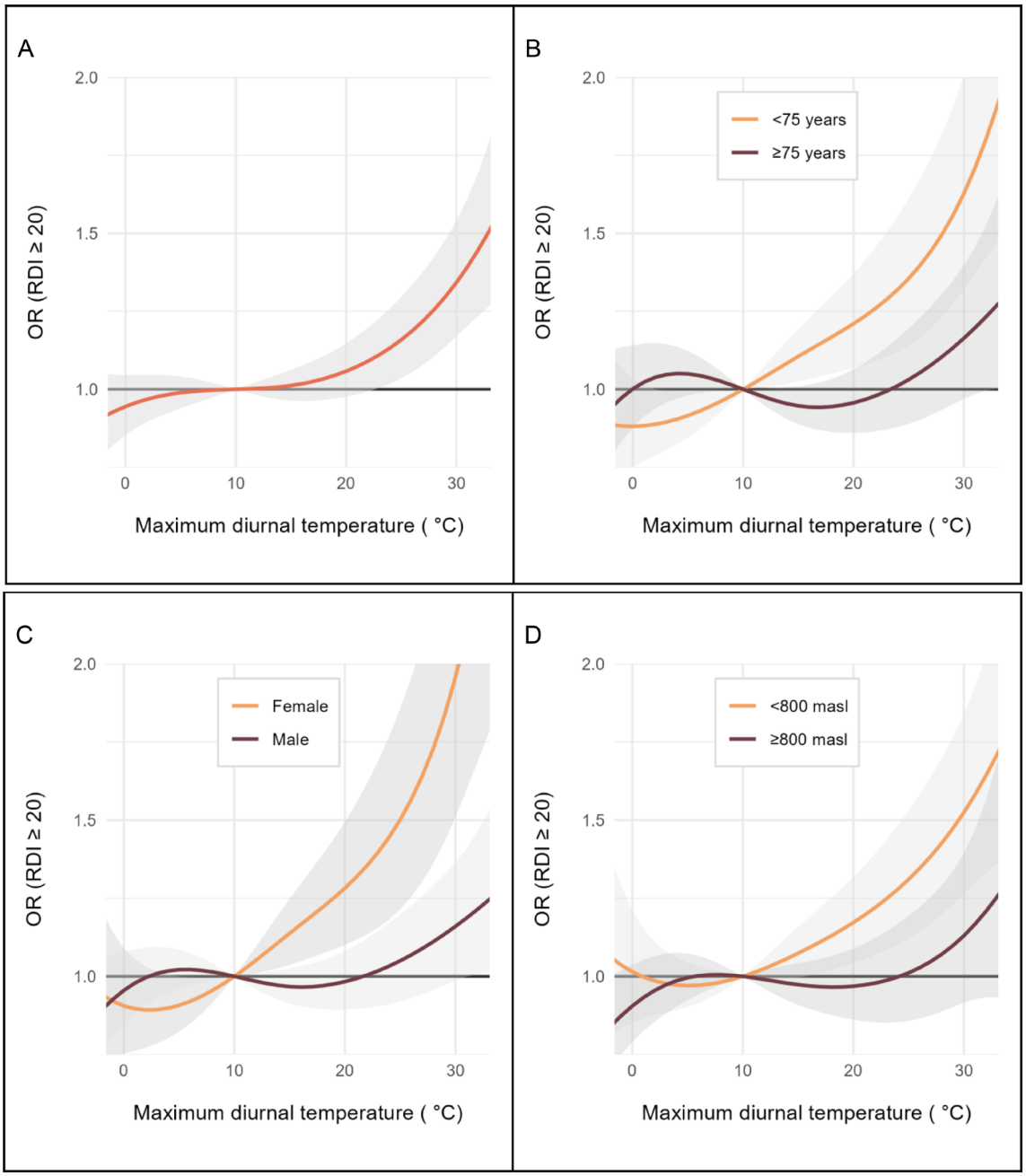


FIGURE 3 | Association between maximum diurnal temperature (°C) and odds of severe DDSA (RDI ≥ 20/h) in the following night in (A) the overall DDSA cohort, (B) subgroups of < 75 and ≥ 75 years of age, (C) male and female patients, (D) patients living ≥ 800 and < 800 m above sea level.

the upcoming years (Bell et al. 2024), changing climate may have a significant impact on human health. Rising incidences of SA might be in part caused by the changing environmental exposome.

The current evidence of SA and ambient temperature is scarce. A large-scale Chinese study analysing 6.2 million nights across more than 50,000 individuals using smartwatch-based monitoring reported findings that are broadly consistent with the herein presented analysis (Li et al. 2024). Although smartwatch-based detection is less sensitive to breathing pauses compared to direct measurement methods and average follow up period was only 120 days per participant, the extensive sample size of this study lends weight to its overall trends, which align with our observations regarding the relationship between temperature increases and severe SA burden. However, notable differences emerged in subgroup analyses: the Chinese study indicated that men and older patients showed a stronger reaction to rising temperatures. It is important to note that the study populations differ significantly between these analyses, as the Chinese study involved younger and generally healthier individuals, in contrast to our population of older patients with pacemakers.

Another study conducted in Spain on pacemaker patients using the same algorithm to detect SA observed an increase in RDI values during the summer months, although individual-level analysis was not performed (Roldán Sevilla et al. 2023). All these findings support the concept of a seasonal trend in severe

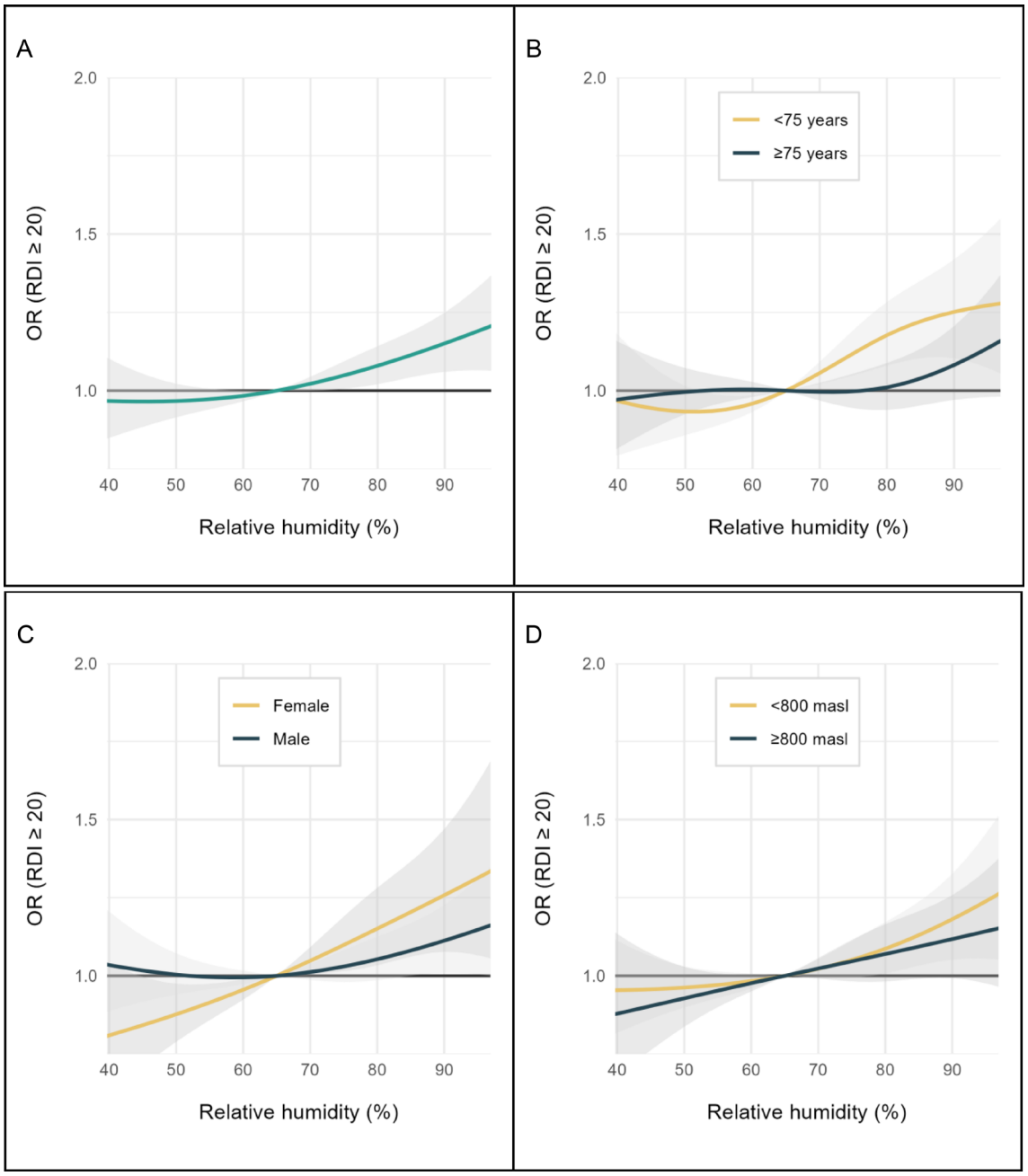


FIGURE 4 | Association between relative humidity (%) and odds of severe DDSA (RDI ≥ 20/h) in the following night in (A) the overall DDSA cohort, (B) subgroups of < 75 and ≥ 75 years of age, (C) male and female patients, (D) patients living ≥ 800 and < 800 m above sea level.

DDSA. Potential mechanisms underlying these associations include heat-induced dehydration, increased blood viscosity and changes in vascular function, all of which can contribute to heightened cardiovascular strain and, in turn, increased susceptibility to apnea episodes. However, the precise pathophysiological pathways remain to be fully elucidated and merit further investigation.

The strong effect of living altitude on severe DDSA observed in this study must be interpreted with caution, and selection bias may play a role. In Tyrol and Vorarlberg, higher living altitudes are predominantly found in tributary valleys, which tend to be more remote and rural. This is associated with different socio-economic conditions and lifestyle habits and, due to the increased geographical distance to pacemaker centers, with a greater barrier to medical care. This is partially reflected in the baseline characteristics, with patients from higher altitudes being older and exhibiting significant differences in underlying diseases, indicating a trend toward higher morbidity in this group (Table 1). It remains unclear whether this alone explains the significantly higher prevalence at higher altitudes or if additional physiological factors also contribute.

Interestingly, the study identified gender-specific effects, with women under 75 showing a greater propensity for severe DDSA under warmer conditions. This observation aligns with existing evidence suggesting that women may be more susceptible to environmental exposures (Liu et al. 2022, 2017). A recent study

TABLE 2 | Univariable and multivariable associations of demography and daily weather conditions with nightly DDSA.

	Univariable		Multivariable	
	OR (95%-CI)	***p***	**aOR (95%-CI)**	***p***
Age (per 5 years)	1.39 (1.11–1.74)	0.004	1.33 (1.07–1.64)	0.009
Sex		< 0.001		< 0.001
Male	1		1	
Female	0.17 (0.08–0.38)		0.18 (0.09–0.39)	
Height (masl)		< 0.001		< 0.001
< 800	1		1	
≥ 800	4.66 (2.07–10.5)		4.06 (1.89–8.75)	
Temperature (°C)*		< 0.001		< 0.001
0	0.85 (0.78–0.92)		0.94 (0.85–1.04)	
10	1		1	
20	1.17 (1.12–1.23)		1.06 (0.98–1.15)	
30	1.48 (1.23–1.58)		1.34 (1.17–1.54)	
Relative humidity (%)*		0.775		0.007
50	1.00 (0.95–1.04)		0.97 (0.97–1.02)	
65	1		1	
80	0.99 (0.94–1.03)		1.08 (1.02–1.14)	
95	0.96 (0.88–1.04)		1.19 (1.07–1.33)	
Air pressure change (per 1000 Pa)	1.19 (1.00–1.42)	0.057	1.11 (0.90–1.37)	0.323
Precipitation (mm/day)		< 0.001		0.197
< 10	1		1	
≥ 10	1.13 (1.06–1.21)		1.05 (0.98–1.13)	

*Point estimates and 95%-CIs derived from a natural cubic spline. Joint *p* for all knots were calculated with a likelihood ratio test.

has shown that women exposed to high temperatures during sleep may face a greater risk of stroke (He et al. 2024).

Elevated relative humidity was associated with a higher DDSA burden across all patient groups. High humidity may increase respiratory workload and cardiovascular strain, suggesting that this factor may play a critical role in modulating sleep-disordered breathing. These findings underline the need for additional research into the role of humidity in respiratory and cardiovascular health, which could ultimately inform risk mitigation strategies for individuals vulnerable to SA.

This study presents both unique strengths and notable limitations: the ACaSA protocol provides a longitudinal night-to-night monitoring of SA over years, allowing for detailed variability analysis in response to environmental conditions. Data granularity significantly increased with individualised weather data stratified to the exact region of each home address, even if it was not possible to track patients' exact locations at the time of each single DDSA measurement. Given the older age of the cohort, it is assumed that most patients remained close to their primary residences. Even in the general population, people stay at home for a significant proportion of time, especially at night (Eurostat 2021). One rather minor limitation is that the study did not account for whether patients had air conditioning or ventilation in their homes. In Austria, less than 10% of households have air conditioning, with an even lower rate expected in the alpine regions of Western Austria (Statistik Austria 2024). Measuring respiratory cycles through transthoracic impedance, pacemaker-derived SA monitoring cannot distinguish whether the events are of obstructive, central aetiology or a combination of both. Probably the most relevant limitation is the still unmet need for further validation and refinement of pacemaker-derived SA detection and quantification.

5 | Conclusion

In summary, this study provides new evidence that environmental factors, particularly temperature and humidity, may significantly affect the burden of SA in pacemaker patients. There is a higher probability of nights with severe DDSA after higher daytime ambient temperatures and in higher relative humidity, in particular in females below 75 years of age. Given projected climate changes, these findings could have important implications for the management of SA and related health risks. Future

research is needed to further clarify the mechanisms underlying these associations and to develop potential prevention strategies to protect vulnerable populations from climate-related health risks.

Author Contributions

Valentin Bilgeri: conceptualization, investigation, writing – original draft, project administration, data curation, resources, methodology, validation, writing – review and editing. **Philipp Spitaler:** conceptualization, investigation, writing – original draft, writing – review and editing, validation, methodology, project administration, data curation, resources. **Patrick Rockenschaub:** conceptualization, investigation, writing – original draft, methodology, validation, visualization, writing – review and editing, formal analysis, software. **Fabian Lehner:** conceptualization, writing – original draft, writing – review and editing, visualization, methodology, data curation, software. **Bernhard Erich Pfeifer:** resources, funding acquisition, software. **Peter Willeit:** writing – review and editing, supervision, methodology, visualization, formal analysis. **Fabian Barbieri:** funding acquisition, writing – review and editing. **Ambra Stefani:** writing – review and editing, methodology. **Birgit Högl:** methodology, writing – review and editing. **Herbert Formayer:** conceptualization, writing – original draft, writing – review and editing, methodology, data curation, visualization, software. **Axel Bauer:** supervision, resources, methodology, writing – review and editing. **Wolfgang Dichtl:** conceptualization, investigation, funding acquisition, writing – original draft, writing – review and editing, validation, methodology, supervision, resources, project administration.

Acknowledgements

We thank Agne Adukauskaite, Wilhelm Grander and Simone Gasser for their support during patient recruitment. Open Access funding provided by Medizinische Universitat Innsbruck/KEMÖ. [Correction added on 15 May 2025, after first online publication: KEMÖ-DEAL funding statement has been added.]

Ethics Statement

The ACaSA study has been approved by the ethics committee of the Medical University Innsbruck (EK Nr: 1322/2020).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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