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RESEARCH ARTICLE

The impacts of ambient relative humidity and temperature on supine position-related obstructive sleep apnea in adults

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Abstract

Obstructive sleep apnea (OSA) is associated with seasonal variations. The objective of this study was to examine associations of ambient relative humidity (RH) and temperature on sleep parameters. We conducted a cross-sectional study by retrospectively recruiting 5204 adults from a sleep center in Taipei, Taiwan. Associations of 1-night polysomnography with ambient RH and temperature in 1-day, 7-day, 1-month, 6-month, and 1-year averages were examined using linear regression models and a mediation analysis. RH increase was associated with snoring index decrease and apnea/hypopnea index (AHI) increase. Temperature increase was associated with decreases in sleep efficiency and the AHI, and increases in the wake time after sleep onset and snoring index. RH increase was inversely associated with non-rapid eye movement (NREM) sleep stage I (N1), III (N3), and rapid eye movement (REM) sleep, but positively associated with the NREM sleep stage II (N2) stage. Temperature increase was associated with N1, N2, and N3 sleep. An increase in RH was associated with an increase in the arousal index and a decrease in the < 95% arterial oxygen saturation (SaO_2) among total, REM, and NREM sleep, whereas a temperature increase was associated with a decrease in the arousal index and an increase in < 95% SaO_2 among total, REM, and NREM sleep. An increase in RH was associated with increases in the time spent in a supine posture and the supine AHI. An increase in temperature was associated with decreases in the supine posture, supine AHI, and non-supine AHI. The N3 sleep stage was an important mediator in increasing the supine AHI with a long-term increase in RH. But the N1 and N2 sleep stages mediated a decrease in the supine AHI with an increase in RH. In conclusion, ambient RH and temperature were associated with alterations in sleep parameters in adults, which were mediated by the sleep cycle. An understanding of outdoor environments has important implications for diagnostic classifications in the supine dominance of OSA in adults.

Keywords Apnea/hypopnea index · Climate · Rapid eye movement · Oxygen saturation · Sleep-related breathing disorder

Wen-Te Liu and Yuan-Hung Wang contributed equally to this study.

Background

Climate and living environment are considered determining factors in adverse effects on human health, including respiratory mobility and mortality (Gerardi & Kellerman 2014). Obstructive sleep apnea (OSA), for example, is recognized to be a winter disease, which is associated with seasonal changes (Cassol et al. 2012; Ingram et al. 2015). The effects of seasonal variations on biologic and environmental aspects causing OSA led to the hypothesis that climate, through humidity and temperature, affects the severity of sleep apnea in a seasonal fashion. However, most epidemiological evidence was gathered in indoor environments over a short term during sleep (Lappharat et al. 2018). Effects of the outdoor ambient climate on sleep remain unclear.

OSA, a prevalent disorder, is characterized by sleep fragmentation, frequent arousal, and hypoxemia during sleep. The apnea/hypopnea index (AHI) is a clinical index to evaluate OSA severity, which also shows differences in severity between rapid eye movement (REM) and non-rapid eye

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movement (NREM) sleep (Alzoubaidi and Mokhlesi 2016, Liu et al. 2011). Sleep apnea during REM sleep often occurs due to upper airway anatomical structure characteristics and pharyngeal muscle responses (Dempsey et al. 2010). Half of OSA subjects have higher AHI values in NREM than REM (Koo and Nam 2016, Siddiqui et al. 2006), which may be associated with non-anatomical traits. Although OSA is believed to be a seasonal disease, associations of seasonal patterns, such as changes in humidity and temperature, with OSA during REM and NREM sleep, are still poorly understood.

Supine OSA is the dominant phenotype of the OSA syndrome. The prevalence of supine OSA in a general population ranged 20 ~ 60% (Dieltjens et al. 2014), which mainly occurs in people who are younger and those with a lower body-mass index (BMI) and less-severe OSA. The definition of supine OSA is commonly referenced to Cartwright and colleagues (Cartwright 1984), which is a supine AHI of greater than or equal to twice as high as the non-supine AHI. For patients with supine OSA, breathing abnormalities mainly occur in the supine posture. Clinically, classification of the total AHI into supine AHI and non-supine AHI is important for further treatment strategies. However, the roles of climatic factors, such as ambient humidity and temperature, on supine OSA have yet to be fully elucidated.

The significance and novelty of this study are that we investigated associations of ambient relative humidity (RH) and temperature with sleep parameters in adults. We conducted a cross-sectional study by retrospectively recruiting 5204 adults from a sleep center in Taipei, Taiwan. Associations of 1-night polysomnography (PSG) with ambient RH and temperature in 1-day, 7-day, 1-month, 6-month, and 1-year averages were examined using linear regression models and a mediation analysis.

Methods

Ethic

This study was approved by the Taipei Medical University-Joint Institution Review Board in Taipei, Taiwan (TMU-JIRB no. N201910048). The methods were carried out in accordance with the approved protocol.

Study population

We conducted a cross-sectional study to retrospectively recruit subjects in a sleep center of a hospital (New Taipei City, Taiwan) between January 2015 and April 2019. The inclusion criteria were subjects who had completed 1-night PSG and were aged 20 ~ 80 years. The exclusion criteria were subjects currently using continuous positive airway pressure (CPAP), those who had undergone a uvulopalatopharyngoplasty, tonsillectomy, or adenoidectomy, were pregnant, had a fever, regularly consumed alcohol, or had pulmonary disease with oxygen therapy, kidney disease on hemodialysis, or an unstable disease. Basic information was collected, including age, gender, BMI (kg/m^2), neck circumference (cm), and waist circumference (cm).

Ambient RH and temperature

Estimates of individual-level exposure to ambient RH and temperature were performed, and this process was described previously (Chen et al. 2020). Ambient RH and temperature data were collected from 71 Taiwan Environmental Protection Administration air quality monitoring stations to develop the prediction model. One-day, 7-day, 1-month, 6-month, and 1-year averages of continuous surfaces of RH and temperature were rendered using an ordinary kriging interpolation combined with a spherical semivariogram model, and these were included in the temporality model development. Daily RH and temperature values were then aggregated into average concentrations for model development.

Sleep parameters

One-night sleep parameters were recorded using a digital PSG system (Embla N7000, Medcare, Reykjavik, Iceland) followed by analysis with Somnologica (Medcare). Also, sleep parameters were re-evaluated by a sleep technician according to American Academy of Sleep Medicine (AASM) criteria (Ruehland et al. 2009). Clinical characteristics of sleep parameters we obtained included sleep efficiency (%), wake time after sleep onset (WASO), snoring index (events/h), the AHI (events/h), percentage of total sleep time (TST) in NREM sleep stage I (N1; %), percentage of TST in NREM sleep stage II (N2; %), percentage of TST in NREM sleep stage III (N3; %), percentage of TST in the REM sleep stage (REM; %), arousal index (events/h), REM arousal index (events/h), NREM arousal index (events/h), < 95% arterial oxygen saturation (SaO$_2$; %), < 95% SaO$_2$ in REM (%), < 95% SaO$_2$ in NREM (%), percentage of TST in time spent in a supine posture (%), supine AHI (events/h), and non-supine AHI (events/h). The definition of hypopnea was nasal airflow decreasing 30 ~ 89% for at least 10 s with arousal or at least 3% oxygen desaturation. The definition of apnea was oral airflow reduced by more than 90% for at least 10 s with or without arousal or desaturation. The AHI was the number of hypopnea plus apnea events divided by the TST (events/h). Sleep efficiency was defined as the TST divided by the time in bed and multiplied by 100%. WASO was defined as the duration of wake time after sleep onset. The arousal index was defined as the total number of arousal events during sleep.

Statistical analyses

All data of ambient RH and temperature and PSG parameters were treated as continuous variables. To minimize the influence of severe outliers and to better achieve a normal distribution of residuals for the PSG parameters, we replaced the extreme low and high values outside the 1 and 99 percentiles, respectively, using a winsorization approach (Tsai et al. 2012). A normality test was conducted to examine if the data were normally distributed. A linear regression analysis was conducted to examine associations of RH and temperature averages (1 day, 7 days, 1 month, 6 months, and 1 year) with sleep parameters. Covariates for the models were adjusted for age, sex, and the BMI. A mediation analysis was conducted with PROCESS to examine the mediating effects of the sleep cycle between RH and the supine AHI. Data were analyzed using SPSS vers. 26 (SPSS, Chicago, IL, USA). Statistical significance was accepted at $p < 0.05$.

Results

Characteristics of study subjects

There were 5204 subjects recruited in this study; their baseline demographic characteristics are summarized in Table 1. The mean age of subjects was 49.5 years, and more than 70% of study subjects were male. Their mean BMI, neck circumference, and waist circumference were 27.1 kg/m^2, 38.5 cm, and 92.1 cm, respectively. The sleep efficiency, WASO, snoring index, and AHI were 76.4%, 62.4 min, 227.2 events/h, and 31.2 events/h, respectively. The sleep cycle was 14.1% for N1, 70.7% for N2, 3.1% for N3, and 12.1% for REM. The arousal index and arousal index in REM and NREM were 22.9, 23.9, and 27.7 events/h, respectively. The < 95% SaO_2, < 95% SaO_2 in REM, and < 95% SaO_2 in NREM were 35.5%, 4.6%, and 30.9%, respectively. The time spent in the supine posture, supine AHI, and non-supine AHI were 67.7%, 36.9 events/h, and 36.9 events/h, respectively. The 1-day, 7-day, 1-month, 6-month, and 1-year RH averages were between 75.8 and 76.3% (Table 2). The temperature averages for 1 day, 7 days, 1 month, 6 months, and 1 year were between 22.9 and 23.9 °C.

Associations of RH and temperature with sleep parameters

Associations of RH and temperature with sleep parameters are shown in Fig. 1. We observed that an increase in the

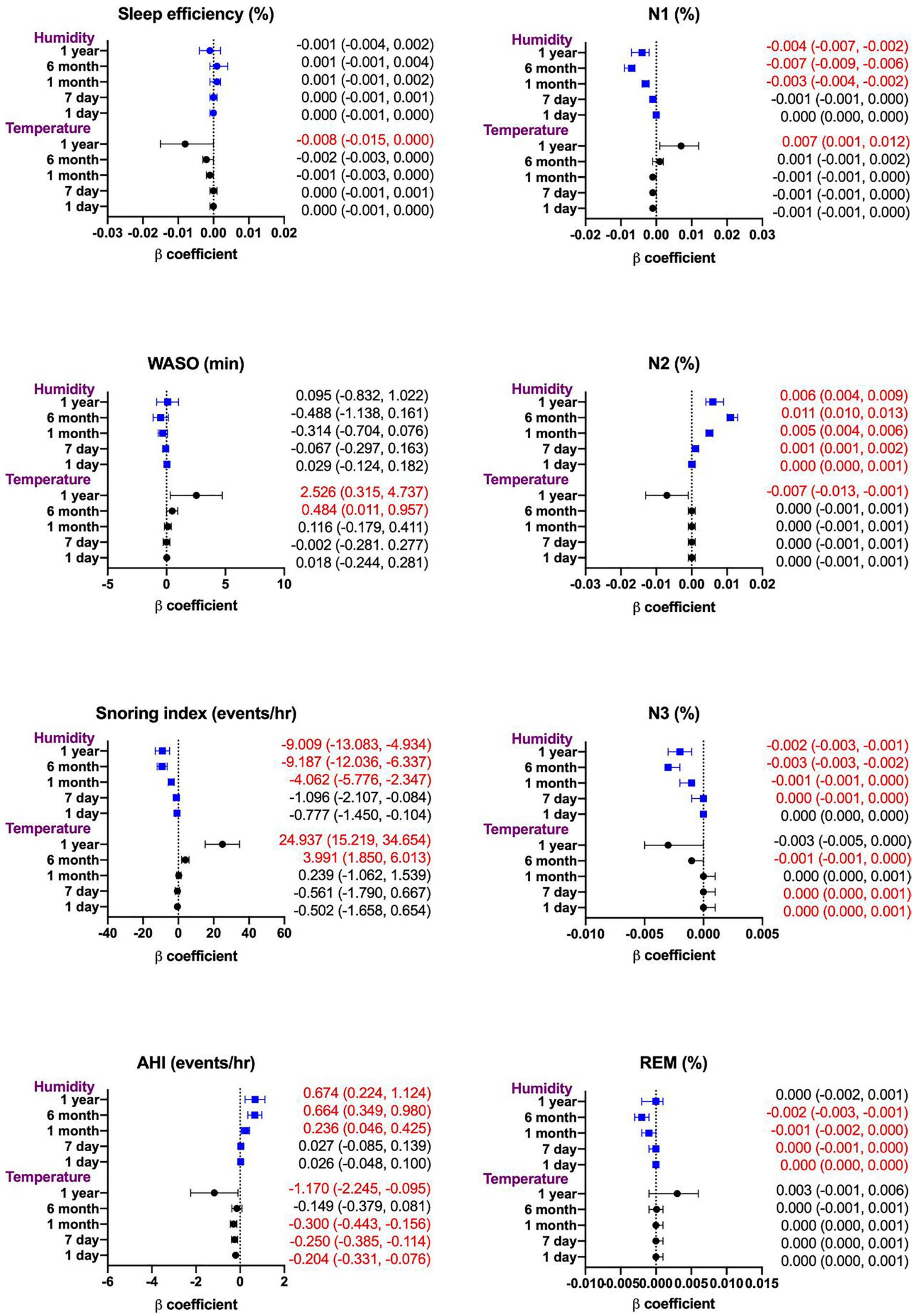
Table 1 Basic characteristics and sleep measures in adult subjects

Characteristics	Mean ± SD
N	5204
Age (years)	49.5 ± 13.5
Male (%)	3650 (70.1)
Body-mass index (kg/m^2)	27.1 ± 5.0
Neck circumference (cm)	38.5 ± 9.0
Waist circumference (cm)	92.1 ± 17.8
Sleep efficiency (%)	76.4 ± 16.5
WASO (min)	62.4 ± 50.0
Snoring index (events/h)	227.2 ± 221.4
AHI (events/h)	31.2 ± 27.5
Sleep cycle of total sleep time	
N1 (%)	14.1 ± 11.8
N2 (%)	70.7 ± 12.6
N3 (%)	3.1 ± 6.6
Rapid eye movement (REM) (%)	12.1 ± 7.2
Arousal index (events/h)	22.9 ± 15.8
REM arousal index (events/h)	23. 9 ± 12.2
NREM arousal index (events/h)	27.7 ± 19.9
< 95% SaO_2 (%)	35.5 ± 50.6
< 95% SaO_2 in REM (%)	4.6 ± 7.9
< 95% SaO_2 in NREM (%)	30.9 ± 44.9
Time spent in a supine posture (%)	67.7 ± 28.6
Supine AHI (events/h)	36.9 ± 30.2
Non-supine AHI (events/h)	26.4 ± 43.4

SD, standard deviation; *WASO*, wake time after sleep onset; *AHI*, apnea/hypopnea index; *NREM*, non-rapid eye movement; *SaO_2*, arterial oxygen saturation

Table 2 Ambient relative humidity and temperatures for 1-day, 7-day, 1-month, 6-month, and 1-year averages for adult subjects ($N = 5204$)

Ambient parameters	Mean (minimum ~ maximum)
Relative humidity (%)	
1 day	75.8 (46.2 ~ 98.8)
7 day	75.9 (56.6 ~ 95.4)
1 month	75.9 (66.9 ~ 93.9)
6 month	75.9 (69.6 ~ 87.9)
1 year	76.3 (72.4 ~ 88.3)
Temperature (°C)	
1 day	23.9 (4.8 ~ 32.6)
7 day	23.9 (10.1 ~ 31.9)
1 month	23.8 (13.9 ~ 31.0)
6 month	23.3 (17.7 ~ 28.7)
1 year	22.9 (20.4 ~ 24.3)


Sleep efficiency (%)
Humidity
1 year
6 month
1 month
7 day
1 day
Temperature
1 year
6 month
1 month
7 day
1 day
-0.001 (-0.004, 0.002)
0.001 (-0.001, 0.004)
0.001 (-0.001, 0.002)
0.000 (-0.001, 0.001)
0.000 (-0.001, 0.000)
-0.008 (-0.015, 0.000)
-0.002 (-0.003, 0.000)
-0.001 (-0.003, 0.000)
0.000 (-0.001, 0.001)
0.000 (-0.001, 0.000)
-0.03 -0.02 -0.01 0.00 0.01 0.02
β coefficient
N1 (%)
-0.004 (-0.007, -0.002)
-0.007 (-0.009, -0.006)
-0.003 (-0.004, -0.002)
-0.001 (-0.001, 0.000)
0.000 (0.000, 0.000)
0.007 (0.001, 0.012)
0.001 (-0.001, 0.002)
-0.001 (-0.001, 0.000)
-0.001 (-0.001, 0.000)
-0.001 (-0.001, 0.000)
-0.02 -0.01 0.00 0.01 0.02 0.03
β coefficient
WASO (min)
0.095 (-0.832, 1.022)
-0.488 (-1.138, 0.161)
-0.314 (-0.704, 0.076)
-0.067 (-0.297, 0.163)
0.029 (-0.124, 0.182)
2.526 (0.315, 4.737)
0.484 (0.011, 0.957)
0.116 (-0.179, 0.411)
-0.002 (-0.281. 0.277)
0.018 (-0.244, 0.281)
-5 0 5 10
β coefficient
N2 (%)
0.006 (0.004, 0.009)
0.011 (0.010, 0.013)
0.005 (0.004, 0.006)
0.001 (0.001, 0.002)
0.000 (0.000, 0.001)
-0.007 (-0.013, -0.001)
0.000 (-0.001, 0.001)
0.000 (-0.001, 0.001)
0.000 (-0.001, 0.001)
0.000 (-0.001, 0.001)
-0.03 -0.02 -0.01 0.00 0.01 0.02
β coefficient
Snoring index (events/hr)
-9.009 (-13.083, -4.934)
-9.187 (-12.036, -6.337)
-4.062 (-5.776, -2.347)
-1.096 (-2.107, -0.084)
-0.777 (-1.450, -0.104)
24.937 (15.219, 34.654)
3.991 (1.850, 6.013)
0.239 (-1.062, 1.539)
-0.561 (-1.790, 0.667)
-0.502 (-1.658, 0.654)
-40 -20 0 20 40 60
β coefficient
N3 (%)
-0.002 (-0.003, -0.001)
-0.003 (-0.003, -0.002)
-0.001 (-0.001, 0.000)
0.000 (-0.001, 0.000)
0.000 (0.000, 0.000)
-0.003 (-0.005, 0.000)
-0.001 (-0.001, 0.000)
0.000 (0.000, 0.001)
0.000 (0.000, 0.001)
0.000 (0.000, 0.001)
-0.010 -0.005 0.000 0.005
β coefficient
AHI (events/hr)
0.674 (0.224, 1.124)
0.664 (0.349, 0.980)
0.236 (0.046, 0.425)
0.027 (-0.085, 0.139)
0.026 (-0.048, 0.100)
-1.170 (-2.245, -0.095)
-0.149 (-0.379, 0.081)
-0.300 (-0.443, -0.156)
-0.250 (-0.385, -0.114)
-0.204 (-0.331, -0.076)
-6 -4 -2 0 2
β coefficient
REM (%)
0.000 (-0.002, 0.001)
-0.002 (-0.003, -0.001)
-0.001 (-0.002, 0.000)
0.000 (-0.001, 0.000)
0.000 (0.000, 0.000)
0.003 (-0.001, 0.006)
0.000 (-0.001, 0.001)
0.000 (0.000, 0.001)
0.000 (0.000, 0.001)
0.000 (0.000, 0.001)
-0.010 -0.005 0.000 0.005 0.010 0.015
β coefficient

◂**Fig. 1** Associations of ambient relative humidity and temperature in 1-day, 7-day, 1-month, 6-month, and 1-year averages with sleep efficiency, wake time after sleep onset (WASO), snoring index, apnea/hypopnea index (AHI), and sleep cycle. Data are presented as regression coefficients (*β*) and 95% confident intervals (CIs). Red indicates statistical significance at $p < 0.05$

1-year temperature average was associated with a decrease in the sleep efficiency, whereas increases in the 6-month and 1-year temperature averages were associated with an increase in the WASO. Increases in the 1-month, 6-month, and 1-year RH averages were associated with a decrease in the snoring index. But increases in the 6-month and 1-year temperature averages were associated with an increase in the snoring index. We observed that increases in the 1-month, 6-month, and 1-year RH averages were associated with an increase in the AHI, but a temperature increase was associated with a decrease in the AHI (expect for at 6 months). An increase in RH was associated with decreases in the percentages of N1, N3, and REM sleep, but it was associated with an increase in the percentage of N2 sleep. An increase in temperature was associated with increases in the percentages of N1, N2, and N3 sleep.

We next examined associations of RH and temperature with sleep parameters in REM and NREM sleep as well as in the supine posture (Fig. 2). We observed that an increase in RH was associated with increases in the arousal index, REM arousal index, and NREM arousal index, whereas a temperature increase was associated with decreases in the arousal index, REM arousal index, and NREM arousal index. Notably, a RH increase was associated with decreases in < 95% SaO_2, < 95% SaO_2 in REM, and < 95% SaO_2 in NREM in time-dependent manners. An increase in temperature was associated with increases in < 95% SaO_2, < 95% SaO_2 in REM, and < 95% SaO_2 in NREM, but these were mainly observed with 1-year exposure. An increase in RH was associated with increases in time spent in the supine posture and the supine AHI, but not in the non-supine AHI. We observed that a short-term increase in temperature was associated with decreases in supine posture, the supine AHI, and non-supine AHI.

Mediation effects of the sleep cycle between RH and the supine AHI

The mediating effects of the sleep cycle between RH and the supine AHI were examined as shown in Fig. 3. We observed indirect (mediated) effects of 6-month and 1-year RH averages with the N1, N2, and N3 stages of the sleep cycle (path a), and the N1, N2, and N3 stages of the sleep cycle were statistically associated with the supine AHI (path b). The direct effects of 6-month and 1-year RH averages on the supine AHI (path c’) after controlling for the indirect (mediated) effects was statistically significant. The total effect (mediated and direct) of 6-month and 1-year RH averages on the supine AHI (path c) was statistically significant with higher regression coefficients (β) compared to the direct effect of path c’.

Discussion

OSA is considered a winter disease, which is associated with seasonal variations. Recently, most studies related to sleep measured indoor temperatures and humidity levels. However, there are still many people who spend most of their time outdoors and semi-indoor environments. To study the roles of ambient humidity and temperature in sleep in a subtropical area, adult subjects who had undergone 1-night PSG measurements in a sleep center in Taipei, Taiwan were recruited. Also, to investigate the time-dependent effects of humidity and temperature on sleep, their previous ambient relative humidity and temperature exposures at 1 day, 7 days, 1 month, 6 months, and 1 year before admission were estimated. The average humidity ranged 75.8 ~ 76.3% and average temperature ranged 22.9 ~ 23.9 °C, which are relatively higher than in non-subtropical areas. The effects of relatively high humidity and temperature levels on sleep were further explored in our study.

Long-term variations in ambient temperature were associated with a decrease in sleep efficiency and an increase in the WASO in adults. These observations suggest that a long-term increase in ambient temperature may disrupt sleep quality. A previous report showed that subjects had better sleep efficiency in a cold environment (16 °C) (Valham et al. 2012). Higher ambient temperatures may reduce sleep efficiency with more awake time during sleep. Additionally, a study conducted by an Internet search on snoring and apnea in the USA and Australia indicated seasonal effects on snoring during colder months (Ingram et al. 2015). We further found that humidity and temperature had distinct effects on the snoring index and AHI. A higher humidity was associated with a lower snoring index and a higher AHI, whereas a higher temperature was associated with a higher snoring index and a lower AHI. One study indicated that humidity was associated with a decrease in the AHI (Cassol et al. 2012), which was inconsistent with our findings. Several studies examined associations of temperature with the AHI with controversial results. One experimental study showed that a room temperature of 24 °C was associated with a lower AHI than that of 16 °C (Valham et al. 2012). A study in Brazil observed that a lower temperature was associated with a higher AHI (Buckley et al. 2014). However, a study form the European Sleep Apnoea Database (ESADA) cohort showed that the AHI increased at higher temperatures (Staats et al. 2021). Collectively, the inverse directions of associations in those studies suggest that relationships of

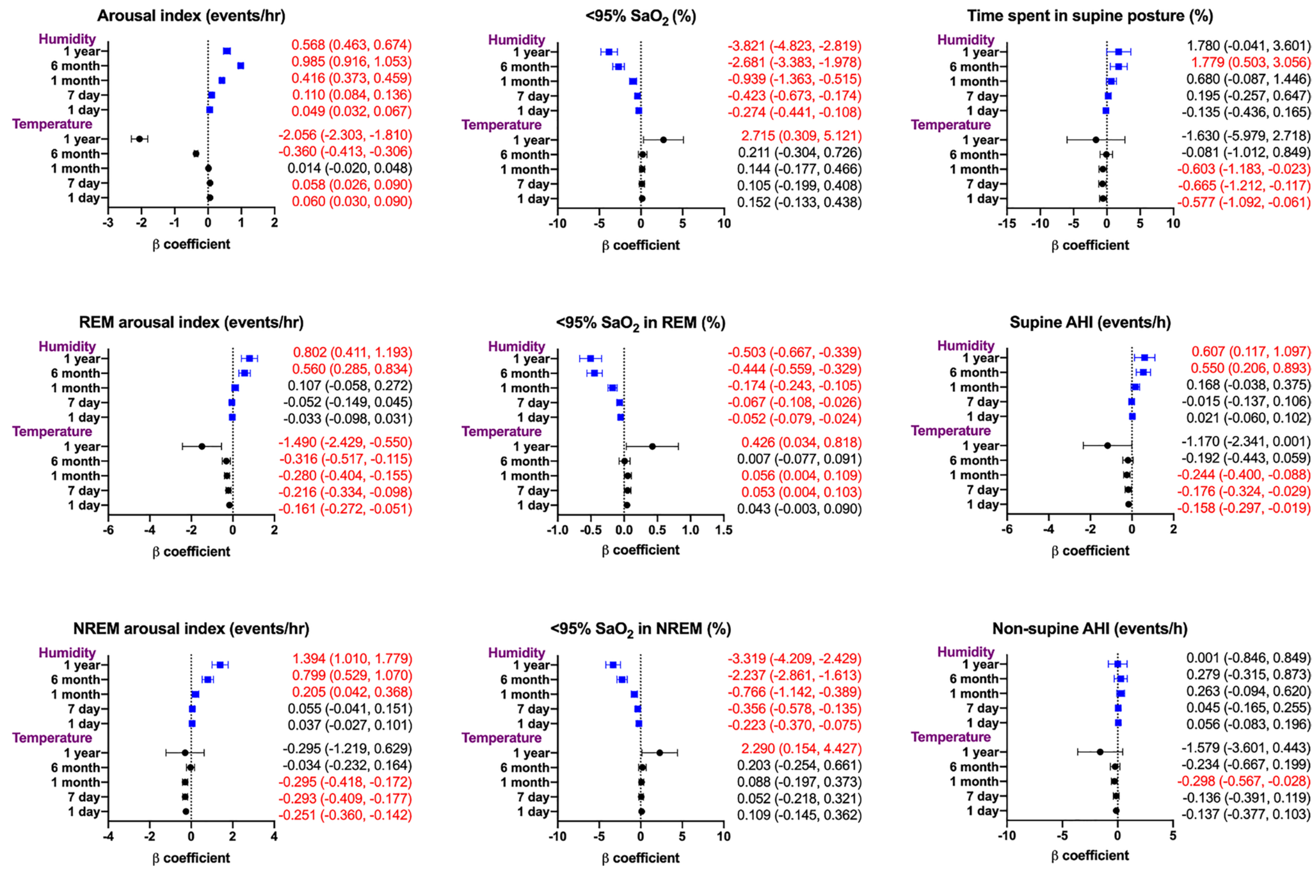


Fig. 2 Associations of ambient relative humidity and temperature in 1-day, 7-day, 1-month, 6-month, and 1-year averages with the arousal index in total, rapid eye movement (REM), and non-REM (NREM) sleep, < 95% oxygen saturation (SaO_2) in total, REM, and NREM sleep, time spent in a supine posture, supine apnea/hypopnea index (AHI), and non-supine AHI. Data are presented as regression coefficients (β) and 95% confident intervals (CIs). Red indicates statistical significance at $p < 0.05$

humidity and temperature with snoring and the AHI might not be linear.

We found that an increase in the ambient temperature was associated with disruption of sleep quality in terms of the sleep efficiency and WASO. Therefore, we assumed that the reduction in sleep quality may be associated with alterations in the sleep cycle. Indeed, we found that humidity and temperature, especially humidity, were associated with alterations in sleep stages in adults. A study that recruited 10 healthy male subjects under different environmental conditions for sleep measurements (Okamoto-Mizuno et al. 2004) found that wakefulness was significantly increased and REM decreased at 32 °C compared to at 26 °C. Subjects exposed to 35 °C with 75% humidity had significant lower N3 and REM stages compared to those exposed to 35 °C with 50% humidity and 29 °C with 50% humidity (Okamoto-Mizuno et al. 1999). Temperature-related alterations in sleep stages may result from a general disruption of sleep processes rather than being specifically related to the status of the thermoregulatory system during REM sleep (Harding et al. 2019). However, in the present study, we found that humidity and temperature were related to alterations in sleep stages, leading to lighter sleep. This was especially true for long-term exposure to high humidity in adults.

Next, we examined the associations of humidity and temperature with the arousal index and < 95% SaO_2 in total, REM, and NREM sleep. An increase in humidity was associated with higher arousal index values in total, REM, and NREM sleep, whereas an increase in temperature was mainly associated with a lower arousal index. An increase in arousal can lead to hypoxemia. Indeed, we found that humidity and temperature had inverse associations with < 95% SaO_2 in total, REM, and NREM sleep rather than with arousal, particularly for humidity which showed a time-dependent effect on < 95% SaO_2. The results suggested that an increase in humidity was associated with oxygen desaturation and higher arousal. Furthermore, an increase in temperature was associated with increased oxygen saturation and lower arousal. Another study indicated that the oxygen desaturation index (ODI) increased and minimum oxygen saturation decreased with higher temperatures (Staats et al. 2021). Together, our results add further epidemiological

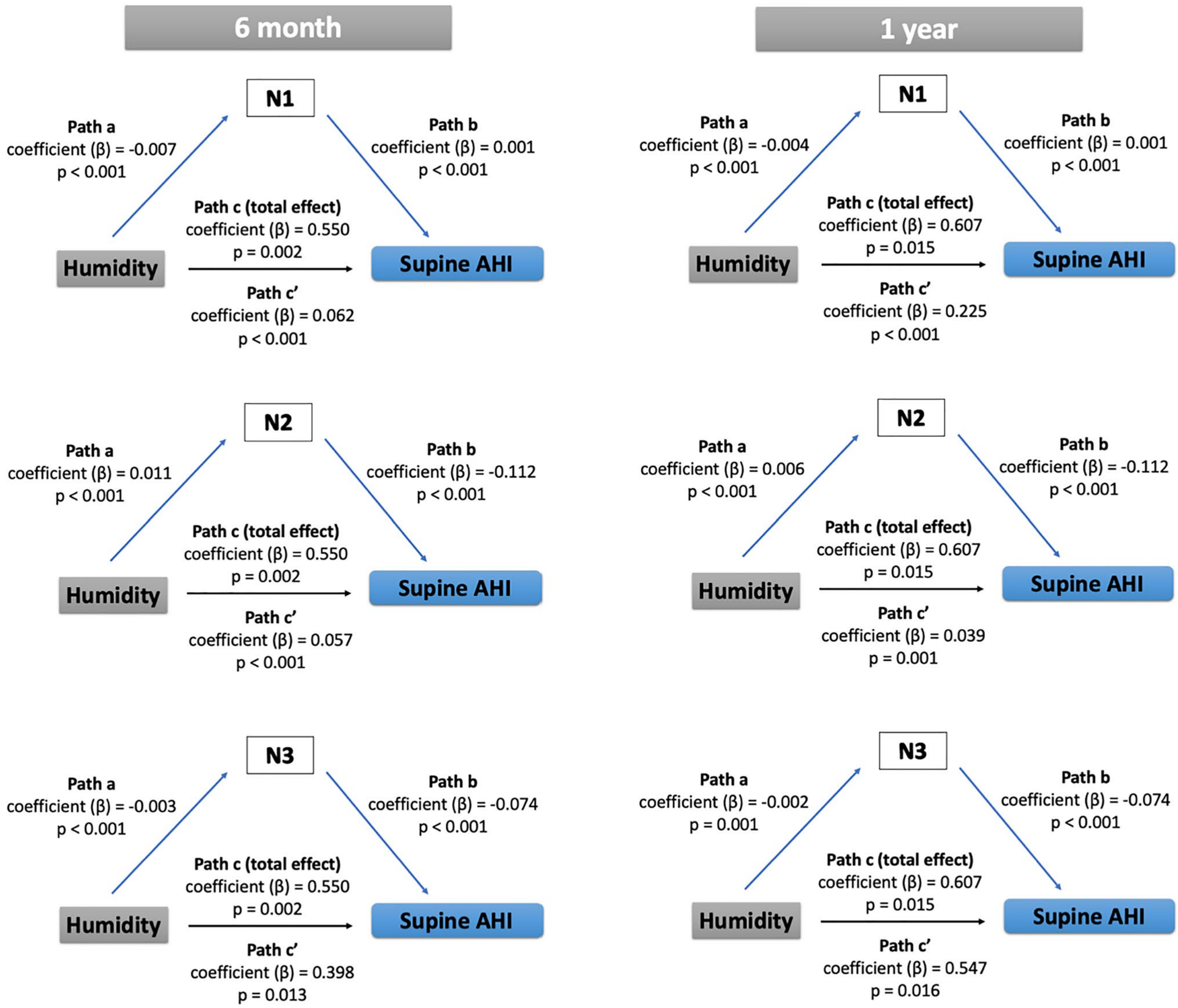


Fig. 3 Mediation analysis of the sleep cycle (N1, N2, and N3) of 6-month and 1-year average relative humidity with the supine apnea/hypopnea index (AHI). Depicted is the path diagram (including regression coefficients and *p* values) of the mediation analysis demonstrating that the N1, N2, and N3 stages mediated the effects of relative humidity on the supine AHI. All four requirements for a mediation effect were satisfied: path a, path b, and path c were significant

evidence that humidity is a more important determinant in oxygen desaturation as well as arousal than is temperature.

We observed that humidity and temperature were mainly associated with time spent in a supine posture as well as the supine AHI. OSA is characterized by repetitive upper airway collapse or upper airway narrowing during sleep. This leads to hypoxemia and arousal from sleep as observed in our findings about humidity and temperature in adults. Clinical evidence shows that supine-related OSA is caused by changes in the airway geometry and an inability of the airway dilator muscles to adequately compensate, leading to airway collapse. This causes hypoxemia and arousal during sleep. Also, a high-humidity and -temperature environment could change upper airway secretions, changing surface tension forces in the upper airway. Our previous study also showed that environmental factors, such as air pollution, are able to change the body composition during sleep (Tung et al. 2021). Together, these might be associated with the severity of supine AHI. Notably, subjects with supine OSA often have relatively lower OSA severity (a lower AHI) (Dieltjens et al. 2014). Thus, patients with supine OSA or a lower supine AHI may be sensitive to changes in ambient humidity and temperature.

The sleep stage dependence of OSA was previously studied, and approximately half of patients with OSA were REM dominant (Haba-Rubio et al. 2005; Liu et al. 2011). We further examined the mediating effects of the sleep cycle between humidity and the supine AHI in study subjects. The results suggested that the N3 stage is important in increasing the supine AHI with long-term humidity increases (6 months and 1 year). But decreased supine AHI values in the N1 and N2 stages were mediated by an increase in humidity. Another report indicated that OSA patients had higher AHI values in REM sleep and the supine posture (Eiseman et al. 2012). The reason for supine-related worsening of OSA severity may be a result of gravity-driven collapse of the tongue and pharyngeal soft tissues, leading to occlusion of the airway (Eckert and Malhotra 2008, Subramani et al. 2017). Severe respiratory pauses occur in REM sleep by virtue of the event duration and oxygen desaturation (Eiseman et al. 2012; Rissanen et al. 2021). Furthermore, an increased OSA severity in REM sleep is likely related to the accompanying atonia resulting in more-prominent airway collapse as well as greater oxygen desaturation (Owens and Malhotra 2010). Together, the sleep cycle may be an important determinant in regulating the humidity-associated supine AHI in adults.

There are some limitations to our study. Data on comorbidities were not collected in this study, which should be included in future work. Other co-factors (i.e., alcohol consumption, smoking, noise exposure, and physical activities) should also be considered. Previous reports indicated that chronic liver disease (Plotogea et al. 2021) and metabolic syndrome (Ghitea et al. 2021) are associated with OSA, which should be considered in future works. Indoor humidity and temperature should be included in future work.

Conclusions

We investigated associations of relative humidity and temperature with sleep parameters in adults. Our results provide further evidence that an increase in relative humidity can contribute to increasing risk of supine position related-OSA in adults. Also, ambient relative humidity was associated with supine position-related OSA which was mediated by the sleep cycle. It is important to understand that outdoor environments have important implications for diagnostic classifications in supine-dominance of OSA in adults.

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Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Li-Te Chang, Chih-Da Wu, Dean Wu, Cheng-Yu Tsai, Chen-Chen Lo, Kang Lo, Kian Fan Chung, Ta-Yuan Chang, Kai-Jen Chuang, Yueh-Lun Lee, and Hsiao-Chi Chuang. The first draft of the manuscript was written by Wen-Te Liu, Yuan-Hung Wang, and Hsiao-Chi Chuang, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate This study was approved by the Ethics Committee of the Taipei Medical University-Joint Institutional Review Board (TMU-JIRB no. N201910048; Taipei, Taiwan). All patients received written information and provided informed consent.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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