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The influence of specific weather types on stroke occurrence: an analysis of 23,000 patients from Augsburg, Germany

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ABSTRACT

For the first time, the relationships between large-scale weather types and local stroke events in the urban area of Augsburg, Germany are analyzed. Over 23,000 stroke cases (2006 – 2020) were standardized to account for long-term trends and seasonality. Using ERA5 reanalysis data, a composite analysis identified stroke-related atmospheric variables, while seasonal weather types were classified via the neural network algorithm of self-organizing maps. Cyclonic westerlies during the cold season, which transport warm air masses from the Atlantic Ocean to Germany, were a major risk factor for ischemic stroke, while colder easterly conditions reduced stroke incidence. In the warm season, both anticyclonic conditions and westerly/northerly air advection, leading to slightly warmer or distinctly colder temperatures, were linked to increased ischemic stroke risk. Additionally, hemorrhagic strokes in the cold season were triggered by weather conditions contrary to those associated with ischemic strokes and transitory ischemic attacks.

Introduction

Worldwide, stroke is the second most common cause of death and causes estimated global costs over 891 billion USD (Feigin et al. 2022). During 2019, there were more than 13 million reported stroke incidents and over 80 million individuals were affected by stroke at least once in their lifetime (World Health Organization 2020). Stroke incidence has shown a mild increase in the European Union during the past decades; thus, prevalence has increased as well, due to an increase in the number of residents of older age. Nevertheless, due to advancements in acute stroke therapy and secondary prophylaxis, disability-adjusted life years and deaths have declined and are expected to do so in future (Wafa et al. 2020). In addition to established risk factors, including hypertension, smoking, obesity, and diabetes mellitus, the effect of weather elements on stroke risk has gained attention (McArthur et al. 2010; Cao et al. 2016; Ertl et al. 2019; He et al. 2024; Zhu et al. 2024).

We assume that not only individual weather elements, such as temperature (Amiri et al. 2021) or air pressure (Guan et al. 2019) and humidity (Rakers et al. 2016) are important for stroke risk, but rather their interaction. Studies have revealed that changes in meteorological elements are particularly relevant to stroke risk (Kyobutungi et al. 2005; Lian et al. 2015;

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Rakers et al. 2016; Lavados et al. 2018). The concept of weather-type classifications (WTCs) (Huth et al. 2008) provides a suitable integrative framework for investigating these interactions and changes.

Although this methodology is commonly employed in synoptic climatology for various target variables (Wang and Zhang 2020; Adams et al. 2021; Ibebuchi 2021), it has not yet been applied to strokes. The study conducted by Ertl et al. (2019), which explored particular air masses defined by local meteorological conditions, comes closest to this topic. The main focus of our study is on large-scale weather types (WTs), which rely on spatial distributions of meteorological parameters such as air pressure, temperature, wind, and relative humidity (RH). These WTs characterize the dynamical features of the atmospheric circulation and the resulting weather conditions. Our objective is to investigate whether particular WTs have an impact on the occurrence of strokes in a local area and whether these WTs share specific synoptic characteristics.

Materials and methods

Stroke data

A dataset comprising approximately 23,000 stroke cases recorded between January 2006 and August 2020 (study period) was made available by the University Centre for Health Sciences at the University Hospital Augsburg (UNIKA-T). The Department of Neurology and Clinical Neurophysiology at the University Hospital Augsburg conducted a retrospective analysis, which formed the basis of this dataset. For each stroke patient, the dataset includes, among others, the date of admission, International Classification of Diseases (ICD-10) code, age, sex, and stroke number (i.e. the total number of strokes this patient has already suffered), and the modified Rankin Scale (mRS), a disability scale ranging from 0 to 6, where larger values denote more severe disabilities caused by the stroke (Wilson et al. 2005). For patients who were hospitalized several times under the same case ID, all but the first hospitalization was removed from the data set. Additionally, 218 duplicated stroke cases were removed. Three types of strokes have been identified: ischemic (ICD-10: I63), hemorrhagic (ICD-10: I60, I61, I62), and transient ischemic attack (TIA; ICD-10: G45). In our dataset, ischemic strokes are the most prevalent, with a count of 15,082, while TIAs and hemorrhagic strokes have counts of 5,028 and 1,332, respectively. The average daily hospitalizations during the study period were 2.82 (ischemic), 1.08 (TIA), and 0.25 (hemorrhagic).

The daily cases of ischemic strokes and TIAs were standardized using the STL (Seasonal Decomposition of Time Series by Loess) method (Cleveland et al. 1990) to account for long-term trends and seasonal cycles, here annual (365.25 days) and weekly (7 days). The STL method aims to break down a time series y into a trend T, seasonal components S_P with period P, and the remaining residual component R. The following additive decomposition of y can be derived:

$$y = T + S_7 + S_{365.25} + R.$$

As a result, we obtain daily stroke cases that are STL-standardized and expressed as residuals R(referred to as STL-DSC). These residuals express daily deviations from an expected value and can thus be negative. Due to a limited sample size, hemorrhagic strokes were excluded from this standardization process. Descriptive statistics of the STL-DSC for ischemic strokes and TIAs are presented in Table 1. For hemorrhagic strokes, the descriptive statistics of the absolute stroke hospitalizations are shown.

The study protocol was approved by the local institutional review board (No. 2016–5, 19 July 2016) and has, therefore, been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. Given the retrospective design of this study, the need to obtain informed consent was waived.

Table 1. Descriptive statistics for STL-standardized (ischemic, TIA) and non-standardized (hemorrhagic) daily stroke cases.

Type of Stroke	Min	1st Qu.	Median	Mean	3rd Qu.	Max.	SD
Ischemic	−4.17	−1.01	−0.11	0.00	0.91	7.22	1.43
TIA	−2.22	−0.63	−0.10	0.00	0.53	3.85	0.88
Hemorrhagic	0	0.00	0.00	0.25	0.00	3	0.50

For ischemic strokes and TIAs, the statistics are based on the STL-DSC, for hemorrhagic strokes, the absolute daily stroke hospitalizations are considered.

Reanalysis data

The basic input data for the WTCs are extracted from ERA5 reanalysis datasets. We retrieved gridded ERA5 reanalysis datasets of the following climate variables on single levels (Hersbach et al. 2023): mean seal-level pressure (MSLP) [hPa], 2m temperature (2mTemp) [$^{\circ}C$], u- and v-components of the near-surface (10m) wind speed (u10m-wind and v10m-wind, respectively) [ms^{-1}], and total cloud cover (TCC). In addition, we retrieved geopotential heights at the 500hPa level (GPH500) [m^2s^{-2}] and the RH at the 1,000hPa level (RH1000) [%] from the ERA5 dataset on pressure levels (Hersbach et al. 2023). The data was obtained upon a regular latitude–longitude grid of 0.25 degrees and projected onto a coarser grid of 1.00 degrees. The data covered a European spatial domain with boundary coordinates of 35°N–75°E and 40°W–60°E. All reanalysis data was provided with a daily frequency of values at 12:00 UTC and within the time period from 1 January to 31 December 2020 (data period). To eliminate any possible influence of climate change, the 2mTemp and RH1000 datasets were adjusted for the linear trend over the data period. Circulation-related variables (MSLP, GPH500, u10m-wind, v10m-wind, and TCC) were spatially standardized, while seasonally driven variables (2mTemp and RH1000) were temporally standardized.

Local meteorological data

Daily measurements of meteorological variables, such as daily mean temperature (TMK), were acquired from the Augsburg-Mühlhausen weather station of the German Weather Service (DWD – Deutscher Wetterdienst) and downloaded from the Climate Data Center (CDC) of the DWD (DWD Climate Data Center 2024).

Composite analysis

A composite analysis (CA) was conducted to initially evaluate the relationships between strokes and weather elements, and to establish the weights of the potentially stroke-related input variables for subsequent WTCs. CA is a straightforward and effective approach to illustrate atmospheric conditions linked to specific environmental variables of interest (Yarnal 1993) and has been employed in several climatological applications (Boschat et al. 2016; Freychet et al. 2017; Sfîcă et al. 2021). Initially, all days within the study period were categorized as days with high stroke cases (T_{high}), moderate stroke cases (T_{mod}) or low stroke cases (T_{low}). This categorization was based on the STL-DSC for ischemic strokes and TIAs. T_{high} included the 10th decile, T_{low} the 1st decile, and T_{mod} the remaining deciles. For hemorrhagic strokes, T_{low} included all days with zero stroke cases, T_{mod} all days with one stroke case, and T_{high} all remaining days. Secondly, for each of these three categories of days, the gridded means of the meteorological data were calculated over the data period. Beforehand, the time series was smoothed by weighted four-day ($k = 4$) running means. Thereby, the highest weight (0.4) was assigned to the day of hospital admission, while the preceding days received a lower weight (0.3, 0.2, and 0.1). For each meteorological variable, these averages were then compared to the long-term averages for the data period, and anomalies were calculated according to this climatology. Afterward, a Mann–Whitney test (U-test) was performed to test the statistical significance of each grid point's anomaly. We conducted the CA separately for each meteorological variable, stroke subtype, stroke mRS grade, and season, namely the warm season (April 1st to September 30) and the cold season (October 1st to March 31st).

Weather type classifications

Based on the results of the CA, seasonal WTCs were computed using the cost733class software (Philipp et al. 2010, 2014). In general, a WTC $C(T, N, A, D_K, P_K)$ is dependent on a time period T, the number of WTs N, a classification algorithm A, K input datasets $D_1, \ldots, D_K$, each characterized by a setting of parameters P_i $(i = 1, \ldots, K)$ (like for standardization or weighting). $C(T, N, A, D_K, P_K)$ consists of a set of centroids $X_C = \{X_1, \ldots, X_N\}$ (WTs) and a catalog $W_C(X, T)$, which is a list that assigns one of the centroids from X_C to each discrete time interval in T. Twelve WTs were identified using self-organizing maps (SOMs) (Sheridan and Lee 2011; Kohonen 2013). The SOM technique employs a neural network algorithm to identify and display the distribution function of a multidimensional dataset (Sheridan and Lee 2011). Initially, random WTs are iteratively modified to increase their resemblance to the respective most similar daily input pattern. The algorithm proceeds until an optimum is reached where the most similar input fields are commonly assigned to one of the WTs. In the context of the cost733class software, the SOM is single-dimensional where nodes are solely linked to their neighbouring nodes on the left and right sides (Philipp et al. 2014). In addition to the ERA5 reanalysis input datasets mentioned above, we opted for an environment-to-circulation approach (Yarnal 1993) and also incorporated the STL-DSC for ischemic strokes and TIAs as input data for the WTCs. Input data for hemorrhagic strokes consisted of daily non-standardised stroke-related hospital admissions. However, the stroke-weights were set as low as 0.05 to prevent distortion of the essential dynamic features of WTs and to guarantee their synoptic interpretability. Observation sequences of four consecutive days for each meteorological variable were created to account for the impact of weather changes. A total of six WTCs, denoted as C_1 to C_6, were established. C_1, C_2, C_3 denote the classifications for the cold season, whereas C_4, C_5, C_6 denote the classifications for the warm season, each for ischemic strokes (C_1, C_4), hemorrhagic strokes (C_2, C_5) and TIAs (C_3, C_6). The individual relative weights of the input variables were determined by evaluating the composite results, namely the spatial patterns of anomaly significance levels for days with high and low stroke incidence. Highly statistically significant patterns received greater weights than those with lower statistical significance. MSLP as the main characterizing variable of the synoptic near-surface flow received a weighting of 1.00 in all cases. Table 2 displays the resulting weights for all six WTCs.

Relating weather types to strokes

A one-sample Poisson rate test (Ostle and Malone 1988) was applied to identify weather types X_j that are associated with significantly more stroke hospitalizations. For each weather type X_j, the null

Table 2. Relative weights of the input variables for the six WTCs.

Variable	C_1	C_2	C_3	C_4	C_5	C_6
MSLP	1.00	1.00	1.00	1.00	1.00	1.00
GP500	0.80	0.80	0.60	0.20	0.90	0.70
u10m-wind	0.80	0.90	0.50	0.20	0.40	0.80
v10m-wind	0.60	0.70	0.50	0.20	0.60	0.70
2mTemp	0.40	0.30	0.40	0.50	0.50	0.60
RH1000	0.50	0.20	0.20	0.70	0.40	0.70
TCC	0.20	0.10	0.10	0.20	0.90	0.20
Strokes	0.05	0.05	0.05	0.05	0.05	0.05

C_1, C_2, C_3 denote the classifications for the cold season, whereas C_4, C_5, C_6 denote the classifications for the warm season, each for ischemic strokes (C_1, C_4), hemorrhagic strokes (C_2, C_5), and TIAs (C_3, C_6).

hypothesis $H_0(X_j)$ states that there is no significant effect of weather type X_j on the number of stroke-related hospitalizations (stroke load) during the presence of this weather type. The aim is to reject the null hypothesis and therefore to identify weather types X_S that are associated with such a high load of strokes that it cannot simply be attributed to the relative frequency $F(X_S)$ of X_S. As stroke cases are evidently independent random events that occur with a certain rate, it was assumed that the stroke load $\sum S_{obs}(X_j)$ per weather type X_j follows a Poisson-distribution with rate $\lambda(X_j)$. Under the null hypothesis $\lambda(X_j)$ equals a modelled Poisson rate $\mu(X_j)$, with $\mu(X_J) := \mu_1(X_j) + \mu_2(X_j)$. Here, $\mu_1(X_j)$ is the Poisson rate of the sum of the STL standardized stroke cases weighted by $F(X_j)$, whereas $\mu_2(X_j)$ is the Poisson rate of the sum of the seasonal components and the trend of $S_{obs}(X_j)$. The alternative hypothesis essentially states that $\lambda(X_j) > \mu(X_j)$. Since hemorrhagic stroke cases were not STL-standardized due to limited sample size, μ_1 was calculated based on the actual non-standardized sum of hemorrhagic stroke cases (weighted by the relative frequency of weather types) and hence μ_2 was 0. The null hypothesis was rejected if $p < 0.05$, where p is the associated p-value of the one-sample Poisson rate test. Weather types with significantly lower stroke loads were identified for $1 - p < 0.05$.

Results

Presentation of results – separately for the cold and warm seasons – focuses on ischemic strokes. Results for other stroke subtypes are only mentioned where appropriate.

Cold season

During the cold season, there is a clear link between the most investigated atmospheric variables and strokes. Figure 1 presents associations between MSLP anomaly fields and ischemic stroke incidence from CA.

Figure 1 shows that a negative MSLP anomaly over and to the west of the British Isles is strongly correlated with high ischemic stroke incidence levels ($\alpha < 0.01$). Days with low ischemic stroke incidence, on the other hand, exhibit positive MSLP anomalies covering Scandinavia, Central Europe, and Eastern Europe ($\alpha < 0.10$). This suggests a weakening of the mid-latitude westerly

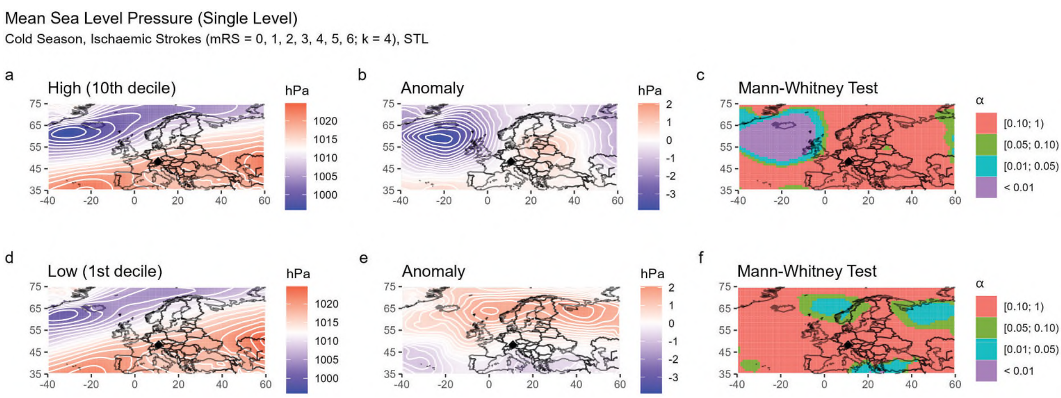

Figure 1. Composite analysis: spatial MSLP patterns in the cold season for days with high (10th decile) and low (1st decile) ischemic stroke incidence based on the STL-DSC and considering all mRS grades. The climatological reference period was 2000–2020. The figure consists of a 2 × 3 matrix of MSLP maps. The rows represent high and low stroke incidence; the columns show the MSLP pattern for days with high and low stroke incidence the difference between these MSLP fields and the long-term mean (2000–2020) for the season in question and the results of a grid-wise Mann–Whitney test (U-test) for different significance levels.

flow and more anticyclonic conditions across Europe. Similar anomalies were also detected for GP500 (not shown). These findings are consistent with respective results from the WTC, as depicted in Figure 2, which displays the significant (according to the one-sample Poisson rate test) MSLP, 2mTemp, and u10m-wind centroids for C_1. All 12 MSLP centroids from C_1 are displayed in Figure S1. It is apparent that WTs ten/one, are linked to an increase/decrease in ischemic stroke incidence. MSLP patterns (Figure 2a) of these types show a distinct cyclonic westerly flow situation (WT ten) and a well-established high-pressure system (WT one) governing weather conditions over Central Europe. In addition to and connected to the MSLP-related characteristics of high/low ischemic stroke incidence, striking specific features become also evident for 2mTemp and zonal wind components, from CA (not shown) as well as WTC. Thereby, high/low ischemic stroke incidence appears to be connected with warm/cold anomalies over Europe (Figure 2b).

These findings – based on the analysis of large-scale reanalysis temperature data – are supported by respective analysis of local air temperature values. Split-violin plots in Figure 3 clearly show that the lowest TMK values in Augsburg occurred during the presence of WT one, while WT ten shows remarkably higher TMK values (only exceeded by WT six). However, although significantly increased/reduced ischemic stroke incidences have been detected for WTs ten/one, Figure 3 generally indicates rather small differences between distributions of STL-DSC per WT. The briefly explained connections between MSLP and air temperature patterns and high/low stroke incidence

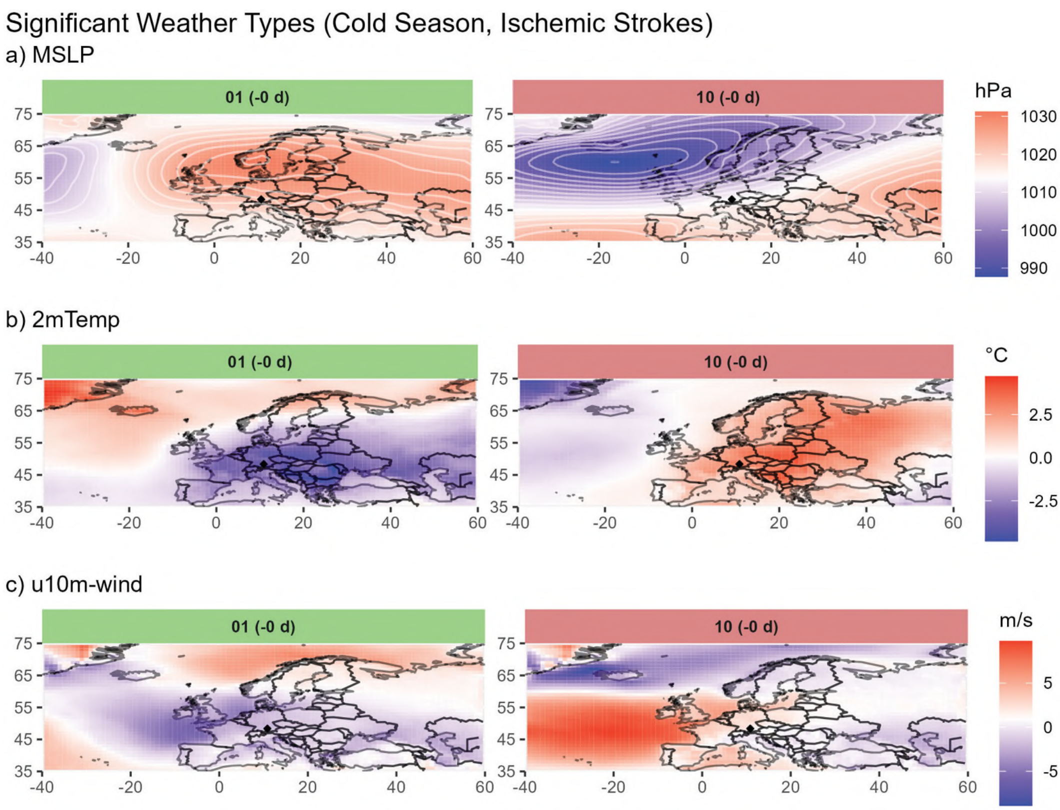

Figure 2. Statistically significant MSLP (a), 2mTemp (b), and u10m-wind (c) centroids for the cold season and ischemic strokes (C_1) and the day of hospitalization (-0 d) as determined by WTC. MSLP centroids are displayed in absolute values, whereas 2mTemp und u10m-wind centroids show spatial patterns of anomalies. Positive u10m-wind anomalies indicate enhanced flow from west to east and vice versa. The color of the panel indicates higher (red) or lower (green) local stroke incidence in the city of Augsburg, Germany (black dot). For the exact *p*-values refer to Figure S1.

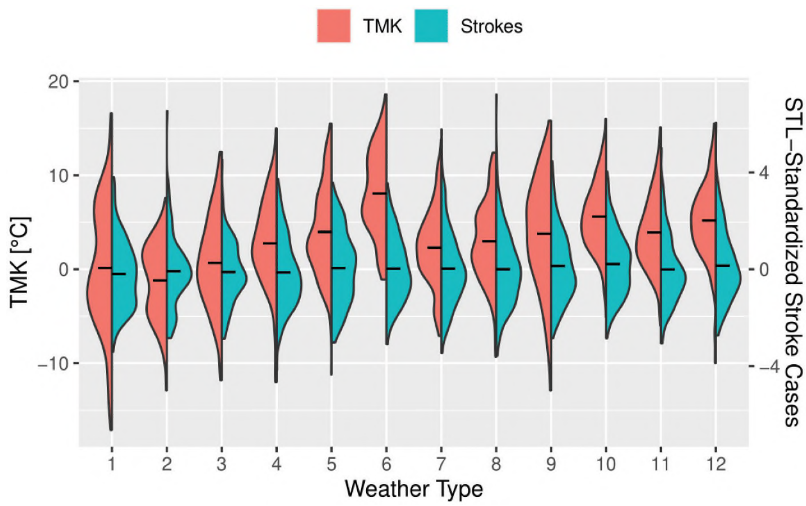

Figure 3. Split-violin plots for the twelve WTs for the cold season and ischemic strokes (C_1). The left side of the violins shows the distribution of TMK values per WT, whereas the right side displays the distribution of STL-standardized ischemic stroke cases. The small black lines within the violins indicates the mean value of the respective parameter.

are confirmed by significant associations that have been discerned between ischemic stroke incidence and the u10m-wind component in the cold season from both, CA (not shown) and WTC (Figure 2c). From that, it is evident that high ischemic stroke incidence is associated with enhanced near surface westerlies, whereas low ischemic stroke incidence is coupled with enhanced advection from the east.

Weather situations associated with ischemic strokes/TIAs and hemorrhagic strokes differed significantly, especially concerning their MSLP characteristics. Whereas the negative MSLP anomaly west of the British Isles was associated with more ischemic strokes, a positive anomaly of comparable magnitude could be related to a higher incidence of hemorrhagic strokes (Figure S2). This was also reflected in the stroke-related WTs. Westerly WTs were associated with higher numbers of ischemic strokes (Figure 2) and TIAs (Figure S3), but lower numbers of hemorrhagic strokes (Figure S2).

Warm season

Results from both, CA and WTC were more ambiguous in the warm season. Regarding the associations between MSLP and ischemic strokes, CA did not yield any significant MSLP anomalies for either high or low ischemic and hemorrhagic stroke incidence. However, for 2mTemp, we found that low ischemic as well as high and moderate hemorrhagic stroke incidences were associated with cooler temperatures across Europe ($\alpha < 0.05$). For TIAs, we only found significant associations with lower 2Temp anomalies for low severe (mRS $\geq$ 4) stroke incidence ($\alpha < 0.01$).

However, WTC – utilizing the combined variables – did yield multiple WTs with particularly high or low ischemic stroke incidence at different levels of significance. The most significant MSLP and 2mTemp centroids are displayed in Figure 4a,b, respectively. All twelve MSLP centroids from C_4 are displayed in Figure S4. WTs four and twelve are related to increased ischemic stroke incidence but feature partly different atmospheric characteristics. WT four is accompanied by predominantly anticyclonic conditions and westerly air advection leading to slight warm anomalies in Central Europe. WT twelve on the other hand implies a more northerly advection and cyclonic conditions inducing distinct negative temperature anomalies over Central Europe. WTs eight and ten represent atmospheric conditions connected to reduced ischemic stroke incidence. The former

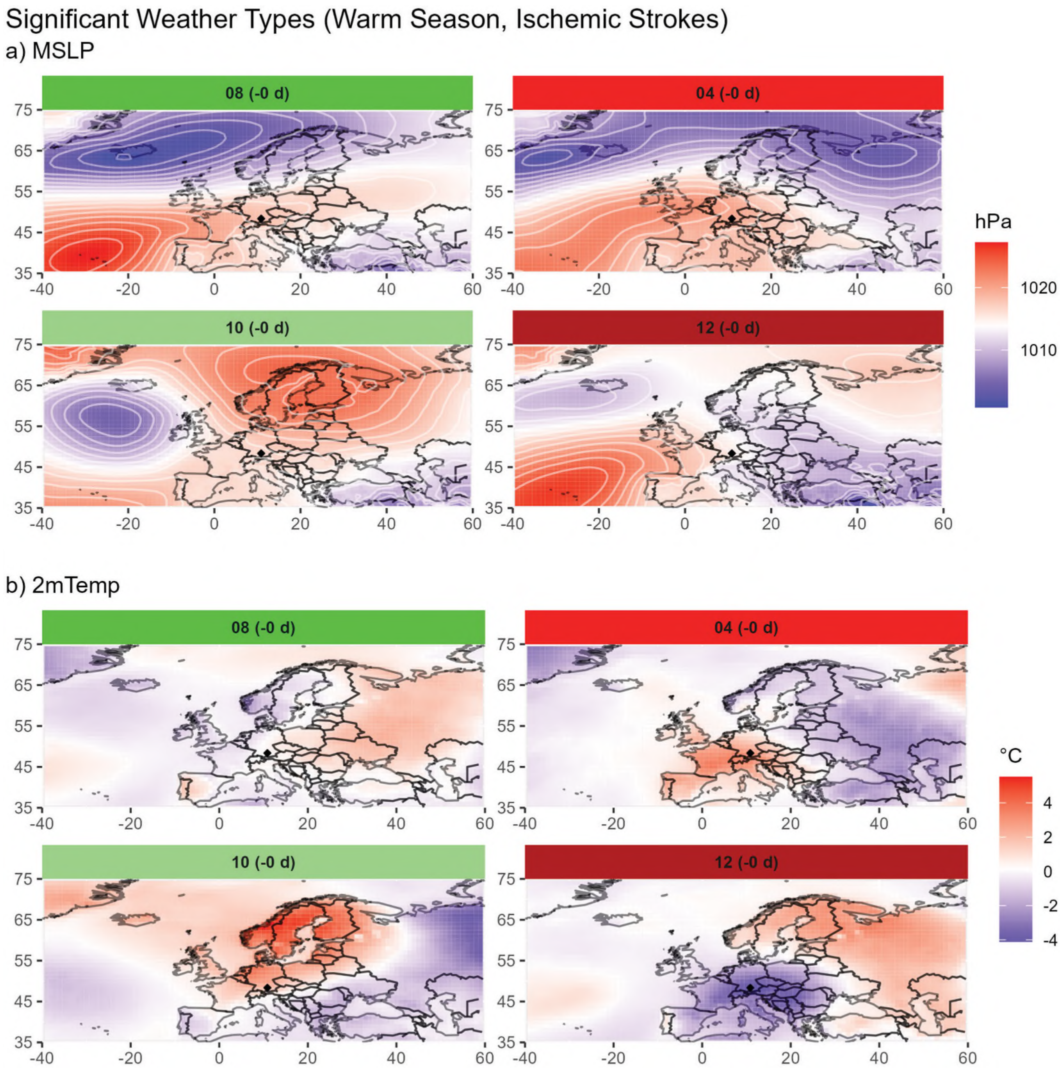

Figure 4. Statistically significant MSLP (a) and 2mTemp (b) centroids for the warm season and ischemic strokes (C_4) and the day of hospitalization (-0 d) as determined by WTC. MSLP centroids are displayed in absolute values, whereas 2mTemp centroids show spatial patterns of anomalies. The color of the panel indicates higher (red) or lower (green) local stroke incidence in the city of Augsburg, Germany (black dot). Darker shading of this color indicates higher statistical significance, i.e., $p < 0.05$ for WT ten, $p < 0.01$ for WTs four and eight, $p < 0.001$ for WT twelve. For the exact p-values refer to Figure S4.

WT again represents a – compared to the preceding types intensified – westerly circulation leading to around normal temperature conditions in Central Europe, whereas the latter WT is dominated by an anticyclone over the Baltic, leading to anticyclonic and distinctly warm conditions in Central Europe.

For hemorrhagic stroke incidence, CA showed that high hemorrhagic stroke incidence is associated with cooler temperatures in Germany and Northern Europe (not shown). This is confirmed by the results of the WTC that yields two 2mTemp centroids showing negative temperature anomalies in central and northern Europe, respectively, that are associated with higher hemorrhagic stroke incidence (Figure S5). WTC for TIAs was again well in line with the respective results for ischemic strokes as cyclonic atmospheric conditions were identified as a risk factor for TIAs, whereas under anticyclonic easterly warm conditions fewer TIAs occurred (Figure S6).

Discussion

In this large retrospective stroke study with approximately 23, 000 cases, several striking associations of weather conditions and stroke incidence could be elaborated applying the method of WTC for the first time in this context. Cold season cyclonic westerly weather was associated with a higher risk for ischemic strokes, and to a lesser degree, for TIAs, yet not for hemorrhagic strokes, where those weather conditions were associated with a lower risk of hemorrhagic strokes. On the other hand, stable weather in the cold season was a protective factor for ischemic strokes and TIAs. These findings were consistent with the temperature and wind conditions induced by the large-scale WTs with a considerable agreement of the CA and WTC. In the cold season, westerly weather patterns bring relatively warm air masses from the Atlantic Ocean to Europe. This is the reason why, for example, high/low ischemic/hemorrhagic stroke incidence is associated with positive/negative temperature anomalies during the cold season. Similarly, low ischemic stroke incidence in the cold season was associated with stable weather conditions over Central Europe. These stable weather conditions go in line with easterly cold air advection from Russia to Central Europe. Thus, our approach improves the understanding of the underlying synoptic mechanisms in the relationship between weather and strokes by focusing on the interplay of different meteorological variables rather than considering each variable separately.

Our analysis revealed that increased temperatures during the colder months led to a higher risk for ischemic stroke. A pathophysiologic explanation might be the ”unexpected” increase of temperature during weather deterioration leading to an imbalance of sympathetic and parasympathetic influences, potentially triggering cerebral infarction (Morimoto 2015).

Apart from these climatological aspects, increased cold season stroke incidence might also be associated with secondary variables, including changes in activity, ambient temperature, daylight, or sun exposure. Other direct causes may include higher levels of serum lipids, blood glucose, fibrinogen (McArthur et al. 2010), and the higher incidence of atrial fibrillation during the cold season (Younis et al. 2020). Correspondingly, temperature increases have been associated with lower risks of macroangiopathic and cardioembolic stroke. On the other hand, a sudden decrease in temperature 5 days prior to the event was shown to increase the risk for embolic stroke, especially in those with many stroke risk factors (Ertl et al. 2019). One possible cause for the greater influence of ambient factors on cardioembolic and macroangiopathic stroke incidences, compared to microangiopathic stroke, might be that the latter is a chronic inflammatory process of the microcirculation (Ertl et al. 2019).

During the warm season, cooler temperatures were found to be a risk factor for hemorrhagic stroke, but a protective factor for ischemic stroke. One possible explanation for the higher incidence of (hemorrhagic) strokes in colder temperatures is the higher level of vasoconstriction to ensure stable temperatures to the inner organs. This further leads to a higher vascular resistance, ultimately resulting in elevated blood pressure, the most important risk factor for stroke. This seasonal effect, mediated by ambient temperature, on blood pressure and thereby indirectly on incidence of intracerebral hemorrhage, has already been shown in multiple studies (Fares 2013). Lower temperatures increase clotting factors including fibrinogen and proconvertin, hematocrit, as well as serum lipids, all of which amplify the likelihood of stroke (McArthur et al. 2010; Tamasauskiene et al. 2017). The association between atmospheric pressure and stroke lacks an explained physiological mechanism and it can only be hypothesized that alterations in atmospheric pressure may cause variations in pressure along the walls of blood vessels, which could increase the risk of ruptures and bleeding complications (McArthur et al. 2010).

We recognize that there are several limitations to this study. The analysis is associated with the immanent restrictions of a retrospective design. On the other hand, the high number of stroke cases and the long time period are outstanding advantages of the present study. There is still a large research gap on the associations between non-temperature variables and stroke, and seasonal studies are even scarcer. Moreover, weather not only influences physical health but also human behaviour like physical activity (McArthur et al. 2010). Despite being grounded in quantitative analyses, our synoptic-climatological approach incorporates several subjective decisions. Initially, categories of days representing high, moderate, or low stroke morbidity have been defined based on deciles of standardized stroke data (for ischemic stroke and TIA) and actual daily stroke cases (for hemorrhagic stroke). Further subjective interventions relate to the WTC, namely the selection of the classification algorithm, the selection and preprocessing of the input variables, the number of WTs, the relative weighting of the input datasets, and the division into warm and cold season samples.

In conclusion, our study is unique in its focus on weather patterns rather than single factors such as temperature or air pressure and provides new insights into the complex relationships between weather patterns and stroke incidence. Our findings suggest that weather patterns can have a significant impact on stroke incidence, particularly in the cold season, and that WTC is a useful tool for identifying WTs associated with higher or lower stroke incidence. These findings have important implications for public health and suggest that measures could be taken to mitigate the impact of WTs on stroke incidence, particularly in vulnerable populations. However, further research is needed to confirm these findings and to develop effective interventions to reduce the impact of weather patterns on stroke incidence. Large scale spatial patterns of MSLP anomalies cannot only be described by atmospheric weather types, but may also related to teleconnection indices. Well-known teleconnections governing MSLP anomalies over Central and Northern Europe are the North Atlantic Oscillation, the East Atlantic/West Russia pattern, the Scandinavian pattern, or even the El Niño-Southern Oscillation. Recent studies have found associations between those teleconnections and stroke risk (Vencloviene et al. 2021; Vaičiulis et al. 2022). Taking into account a further aspect in the complex interaction between atmospheric conditions and stroke our approach could be extended by incorporating air pollution variables for which several studies have shown significant effects on strokes (Miller et al. 2007; Lee et al. 2018). One main advantage of the presented WTC approach is its flexibility. The approach could easily be extended through the incorporation of teleconnection indices or air pollution indicators as input data sets for the WTCs. Furthermore, the here presented findings have potential to enhance epidemiological models by including WTs as predictor variables in addition to other large-scale atmospheric patterns.

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