Boletín de la Asociación de Geógrafos Españoles N.º 75 - 2017, págs. 673-679
I.S.S.N.: 0212-9426

CLASSIFICATION OF TYPES OF WEATHER AND THEIR INFLUENCE ON THE CONCENTRATIONS OF NITROGEN DIOXIDE, PARTICULATE MATERIAL (PM_{10}) AND OZONE IN THE CITY OF MADRID (SPAIN)

María Rosa Cañada Torrecilla
Department of Geography. Autonomous University of Madrid
rosa.canada@uam.es

I. INTRODUCTION

Urban areas are complex places where we can find interaction between, on the one hand, meteorological and environmental variables and, on the other hand, the heat island effect and the variety of sources of emission of contamination. Therefore, it is important to carry out synoptic weather analysis, as it allows us to summarize a series of weather conditions in a catalogue that contains a small number of weather types that are ultimately responsible for the concentration or immission of the contaminants found in cities and, consequently, the air quality in these urban areas.

There are many methods to carry out the classification of weather conditions in different categories. The classification proposed in this article is an objective one whose aim is to establish some weather types that are the result of the combination of a series of jointly treated meteorological variables, behind which we can find specific traffic patterns and geographical factors. After this synoptic characterization, we will assess the concentration of atmospheric contaminants in the different weather types established.

II. DATA AND METHODS

The meteorological information used comes from the synoptic station in the Barajas area of Madrid which supplied daily surface meteorological data at 1 p.m. and geopotential height information at a level of 850 hPa at 12 pm every day. The variables used for the surface were: pressure, two temperature variables (maximum and minimum), direction and speed of the wind, converted into a vector-scalar South-North meridian (v) and a West-East zonal one (u) through sine-cosine transformation, relative humidity and cloud cover. The variables of height correspond to the height at which the 850 hPa are found, the temperature at that height, the dew point and the direction and speed of the wind, converted into a vector-scalar, using the same procedure as with the surface data. The period of observation was from the 1st of January 2010 to the 31st of December 2015.

The data on contamination were taken daily from the quality network used by Madrid City Council and the variable used was the daily average of NO_2, O_3 and PM_{10} over the same time period.

The delimitation of the weather types was made using Factorial Analysis techniques (the Principal Component Analysis method (PCA) and grouping techniques (cluster analysis). An agglomerative hierarchical method was applied, specifically Ward's method, as it is much more effective at delimiting weather types. Knowledge of the climate of the area was very important in the choice of the final number of weather types established. They were then submitted to measurement contrast testing in order to see whether or not the differences between them were significant from a statistical point of view.

After making the classification of the average of the twelve meteorological variables in each weather type, we checked the predominant traffic patterns on the days classified based on the analysis of the maps of pressure, height and surface. Then we related the weather types and the levels of immission registered in the air quality stations located in the city of Madrid in order to establish the causes and mechanisms that contribute to better or worse air quality and, where necessary, encourage the adoption of the measures necessary to solve or limit the negative effects of this contamination.

III. ANALYSIS OF RESULTS AND DISCUSSION

The final result were nine different weather types. In order to identify them based on their meteorological variables, we calculated the average and the dispersion measurements for each one of the weather variables that made up all of the cases in a single group.

Type 1 corresponds to masses of maritime polar air, channeled through an anticyclone located in the Atlantic, to the North of the Azores, or through a depression to the West of the British Isles, with South-East surface winds with a speed of 5.29 m/s (a light breeze according to the Beaufort Scale) and high North-West winds with a greater speed, 8.02 m/s (fresh winds). In the Iberian Peninsula, there is a prevalence of high pressures, although they are not very high. There was an average maximum daytime temperature of 13.2ºC and average minimums of 4.5ºC. This weather type is present in every month of the year except in summer, and is most frequent in the months of January and February.

Type 2 groups together the days with maritime polar air masses that reach very low latitudes through a great Atlantic channel, which heats up and sends towards the Iberian Peninsula humid South-East surface winds, 2.64 m/s (gentle breeze) and stronger ones, 6.36 m/s (moderate breeze) in the higher layers of the atmosphere. Over the Spanish Plateau, there are high pressures with temperatures of 13.6ºC (average maximums) and 5.2ºC (average minimums), a humidity content of 68% and cloud cover of 7 oktas. This weather type is dominant mainly in the months of January and December, although November also has a high frequency.

Type 3 corresponds to days with maritime tropical air masses with South-East surface and high winds, with a speed of 1.58 m/s (gentle breeze) and 3,4 m/s (light breeze) respectively, channeled through a depression located over the Iberian Peninsula. There is some instability, high temperatures, with average maximums of 17.6ºC and average minimums of 8.6ºC; at 850 hPa, an average of 7ºC is reached. The weather type is the dominant one mainly in spring and autumn.

Group 4 is characterized by North-West surface winds (5.6 m/s) and high North-East winds (7.1 m/s) (a moderate breeze on the Beaufort Scale). The air mass comes from the inland Europe and is a polar continental air mass that penetrates through a channel with a NE-SW axis and is channeled through a depression located in the Ligurian Sea. The temperatures are low, with the highs reaching an average of 10.6ºC and the lows 2.6ºC. The relative humidity is 51%. This weather type is most frequent in the months of February and November.

Type 5 shows the configuration of an anticyclone that spreads out from the Atlantic to Central Europe, sending North-East winds, 3.50 m/s when they are surface winds (light breeze) and 6.27 m/s when they are high winds (moderate breeze). The cloud cover is low, as is the relative humidity that reaches an average of 30%. Some days, thermal inversions may take place in this weather type. In fact, the average temperature at 850 hPa (7.7ºC) is higher than the average minimum surface temperature (6.6ºC). This may happen in any month of the year, although it is most frequent in March. The air mass is dry, and will be cold in the winter months and warmer during the equinoxes and summer months.

The weather type corresponding to Group 6 is the typical anticyclonic winter weather, with the anticyclone concentrated on the Iberian Peninsula and a high back. The air mass which is of maritime tropical origin gradually becomes colder inside the Iberian Peninsula until it turns into a cold and dry air mass. This is a weather type with broad daytime temperature variations and frequent frost. It has the lowest minimum temperatures of all the weather types, with a minimum temperature of -0.41ºC and frequent thermal inversions, and the average temperature at 850 hPa is 6.3ºC. South-West surface winds (0.83 m/s) and North-West high winds (1.21 m/s). It is most frequent in the months of December, January and February.

The anticyclonic weather type corresponds to Group 7. The isobaric form is similar to that of Group 6, but with warmer air masses. The maximum temperature reaches an average of 23.3ºC and a minimum of 7.1ºC. There are South-West winds both on the surface (0.95 m/s) and in the highest layers of the atmosphere (0.97 m/s). The air is very dry and there are few clouds (1.8 oktas). It is more common in spring and autumn.

Type 8 is a weather type with an average maximum temperature of 23.8ºC and a minimum of 12.5ºC, which is a consequence of the maritime tropical air masses that arrive in this region and come from an Atlantic channel which on the surface corresponds to low pressure. The Spanish Plateau is located in an area with high pressures or relative low pressures. The South-West winds reach speeds of 4.73 m/s on the surface (light breeze) and 5.97 m/s at 850 hPa (moderate breeze). The humidity reaches 42% and the cloud cover is 5.4 oktas. This weather type is representative of the months of October and September, on the one hand, and April and May on the other hand.

Type 9 includes the weather types linked to the summer months. The anticyclone from the Azores increases in latitude and is located over the archipelago of the same name, and channels maritime tropical air masses towards our region. This barometric situation alternates with other situations characterized by low thermal pressures over the Spanish Plateau, with very warm and dry air masses which come from the North of Africa. The maximum temperatures are very high, with averages of 32.3ºC, South-West winds (2.85 m/s and 2.73 m/s for surface and high winds respectively). There is little relative humidity (22%) and not much cloud (2 oktas on average).

For each weather type, defined by values of the meteorological variables, we calculated the average and the statistics of variability for the concentrations of contamination due to NO_2, PM_{10} and O_3 on the days included in this type, and for all of the measuring stations in the city of Madrid.

Contamination due to NO_2

The weather type that causes the highest contamination due to nitrogen dioxide is Type 6. It corresponds to an anticyclonic winter weather type, with a centre of very powerful high pressures over the interior of the Iberian Peninsula. There are sub-zero temperatures on the surface due to the cooling of the air when it enters into contact with the cold surface, due to the strong night-time irradiation, which is assisted by clear skies and significant thermal inversions, which impede upward movement by the air and facilitate the stagnation of contaminants.

In general, traffic stations register the highest levels of NO_2 contamination and the lowest levels are found in suburban stations, in the case of all weather types, as nitrogen dioxide is a contaminant that is indicative of transportation activities, especially road traffic.

The station that shows the highest figure is located in Plaza Fernández Ladreda with more than 80 $\mu g/m^3$, followed by Villaverde, Barrio del Pilar, Cuatro Caminos, Escuelas Aguirre, Ramón y Cajal, Plaza Castilla, Carmen and Plaza España, with values below 80 and over 70 $\mu g/m^3$. On the contrary, El Pardo and Juan Carlos I do not reach 40 $\mu g/m^3$.

Types 7 and 2 are also associated with high levels of NO_2 contamination, although they are lower than those of Type 6. They are anticyclonic weather types, with higher temperatures. In Type 7, the stations with contamination show similar behaviour to that of Type 6, and the greatest concentrations of NO_2 are found in Fernández Ladreda (68.9 $\mu g/m^3$) and in Escuelas Aguirre (60.14. $\mu g/m^3$) and the lowest ones in El Pardo (21.4 $\mu g/m^3$), Juan Carlos I (27.01 $\mu g/m^3$), Casa de Campo (31 $\mu g/m^3$) and Retiro (36.5 $\mu g/m^3$). In the rest of the stations, the figures fluctuate over 40 $\mu g/m^3$ and below 60 $\mu g/m^3$. In Type 2, the stations behave in a similar way, but with values which are a little lower than in Type 7, and the amounts vary from 60 $\mu g/m^3$ to 21.19 $\mu g/m^3$.

The weather types with the lowest concentrations of NO_2 are 1 and 8. Both cases correspond to weather types with not very high pressures and with wind, which facilitates the dispersion of contamination. In the first one, the NO_2 levels vary from a minimum of 12.3 $\mu g/m^3$ in El Pardo and Casa de Campo, and a maximum of 45 $\mu g/m^3$ in Plaza de Castilla. In Type 8, the concentration of NO_2 fluctuates between 15.2 $\mu g/m^3$ in El Pardo and 43.75 $\mu g/m^3$ in Fernández Ladreda.

Contamination due to Ozone (O_3)

Weather Type 9 produces the highest levels of ozone immission in the atmosphere. It is a type of summer anticyclonic weather, linked to tropical maritime and tropical continental air masses which are warm and dry. The isobaric configuration that causes this weather type is either a high back or a Saharan ridge concentrated on its axis around 5º West with a predominance of generalized high pressures. With these meteorological conditions, it is difficult for contaminants to be dispersed.

With this weather type, the stations with the highest daily levels of contamination due to ozone concentration (higher than 70 $\mu g/m^3$) are: Tres Olivos, Casa de Campo, El Pardo and Juan Carlos I, all of which are located in metropolitan or suburban areas. On the contrary, Plaza Fernández Ladreda, Escuelas Aguirre and Villaverde, which are located in areas with heavy traffic, have the lowest figures for this weather type, with values above 52 $\mu g/m^3$. This model of spatial distribution of ozone is the opposite to that found in the case of nitrogen dioxide. The reason is to be found in the processes of formation and destruction of ozone.

High levels of ozone are associated with Types 5 and 8, which are both anticyclonic, with average maximum daytime temperatures of 20.8ºC and 23.8ºC respectively. The same behaviour can be observed at stations in central and outlying areas. In Type 5, the figures range from minimums of 44 and 47 $\mu g/m^3$ and maximums of between 60 and 64.8$\mu g/m^3$, and in Category 8, the lowest values fluctuate between 37.2 and 43.8 $\mu g/m^3$ and the highest ones are between 55.7 and 57.9 $\mu g/m^3$.

The weather type that leads to the lowest concentrations of ozone is Type 6, which is precisely the one that causes the greatest quantities of NO_2 immission. It is a central winter weather type, characterized by temperatures which are lower than for other weather types.

Contamination due to airborne particles (PM_{10})

Of the twelve air quality stations that form part of the network organized by Madrid City Council and measure airborne particles below 10 μm (PM_{10}), in nine of them the weather type that leads to the highest levels of immission is Type 9. In one station (Cuatro Caminos), there is some match between Types 9 and 6, and in two stations (Méndez Álvaro and Plaza Castilla) it is Type 6 that is higher than Type 9 in terms of the levels of contamination due to particles. Both weather types are anticyclonic, and one is a winter type and the other is a central winter type. Type 9 is characteristic of summer, when the Iberian Peninsula is invaded by tropical continental air masses from Africa, which are mainly responsible for the presence of airborne dust in the atmosphere. The station that has the worst situation is Escuelas Aguirre with an average daily concentration of 32.89 $\mu g/m^3$, in which along with the particles that have a natural origin we have to add those that are caused by road traffic. The one with the lowest figures is Casa de Campo with 24.39 $\mu g/m^3$, located in a suburban area, with less presence of traffic, but where Saharan airborne dust arrives naturally.

In Type 6, the strong atmospheric stability and the thermal inversion impede the dispersion of contaminants, thus favouring an abundance of airborne particles, which come from the combustion processes which include road traffic and the immission of nitrogen dioxide, which is also high during these days. The spatial distribution of the PM_{10} contamination follows the same pattern as in Type 9, over 28 $\mu g/m^3$, is found in the stations at Escuelas Aguirre, Mendez Álvaro and Cuatro Caminos, and the rest are above 20 $\mu g/m^3$, except for Casa de Campo which has 19.32 $\mu g/m^3$.

Therefore, there are two favourable seasons of the year when the immission of particles is significant: winter, when the main sources of emission are combustion, encouraged by the low dispersion capacity of the atmosphere at this time of year, and summer, when the main source of emission is Saharan dust.

Los weather types that cause the lowest concentration of particles are 1 and 4. The contamination values with these situations are very low and, as always, the highest figures are registered at the traffic stations (Escuelas Aguirre, 15.15 $\mu g/m^3$ or Plaza Castilla, 15.55 $\mu g/m^3$) rather than the suburban or metropolitan stations (Casa de Campo 7.9 $\mu g/m^3$).

IV. CONCLUSIONS

Multivariate analysis techniques were applied, specifically factorial and cluster analysis, in the classification and identification of the weather types in the Barajas area of Madrid based on knowledge of the climate of the region. The twelve meteorological variables used were reduced to four components or factors that explain 83% of the total variance. The temperature with positive values and the humidity with negative values are strongly correlated to the first component. The surface pressure and the geopotential height at 850hPa contribute to the second component with negative figures compared to the temperature of the dew point at 850 hPa y and the cloud cover which have positive figures. Factors 3 and 4 refer to the meridian and zonal components of the wind respectively.

After calculating the factorial points for all of the days for the four components, we then grouped together the days with an agglomerative hierarchical method, Ward's method. The result was nine different clusters or weather types. For each one, we calculated its frequency throughout the year, the average characteristics and the variation measures of the meteorological variables used in its definition. Significant statistical differences were found to exist between the different groups based on those variables. Statistic F shows a level of significance which was lower than 0.05. The multiple comparisons made with the Dunnet T3 reinforced the statistical significance of the differences between groups, although some pairs of variables did not show any significant differences. Specifically, the height at which the 850 hPa are reached is the one which discriminates the best and the one which does so the worst is the cloud cover.

For each weather type, we computed the average and the measurements of dispersion for the concentrations of contamination due to NO_2, O_3 and PM_{10} for all of the measuring stations in the city of Madrid.

The results indicate that weather Type 6, anticyclonic winter weather, linked to cold and dry air masses, with frequent thermal inversions, is what causes the maximum levels of NO_2 immissions. The traffic stations register the highest figures and suburban stations have the lowest values. Plaza Fernández Ladreda, with more than 80 $\mu g/m^3$, has the worst situation, closely followed by Villaverde, Barrio del Pilar, Cuatro Caminos, Escuelas Aguirre, Ramón y Cajal, Plaza Castilla, Carmen and Plaza España, with values below 80 $\mu g/m^3$ and above 70 $\mu g/m^3$. On the contrary, El Pardo and Juan Carlos I do not reach 40 $\mu g/m^3$.

This same weather type is what contributes to the high levels of PM_{10} immission, caused by very heavy traffic along with great atmospheric stability. All of the stations have daily averages which are lower than 50 $\mu g/m^3$, but higher than 20 $\mu g/m^3$ except Casa de Campo (19,32 $\mu g/m^3$). On the other hand, this weather type is what produces lower concentrations of ozone.

The lowest concentrations of NO_2 occur with the anticyclonic Types 1 and 5. In Type 1, the values range from 12.3 $\mu g/m^3$ in El Pardo and Casa de Campo and 45 $\mu g/m^3$ in Plaza de Castilla. In Type 5, they range from 15.1 $\mu g/m^3$ in El Pardo and 56.9 $\mu g/m^3$ in Plaza Fernández Ladreda. Furthermore, this last weather type causes high concentrations of ozone.

The anticyclonic summer weather type (Type 9), characterized by great stability, linked to warm maritime tropical air masses and tropical continental ones, with high temperatures, few clouds and high insolation, is the one that produces the highest levels of ozone immission in the atmosphere. The suburban stations at Tres Olivos, Casa de Campo, El Pardo and Juan Carlos I have the highest daily figures, which are higher than 70 $\mu g/m^3$. On the other hand, Plaza Fernández Ladreda, Escuelas Aguirre and Villaverde, which are located in areas with heavy traffic, have the lowest figures, but still have values over 52 $\mu g/m^3$. This model of spatial distribution of ozone is the opposite of the nitrogen dioxide model. The reason is to be found in the processes of formation and destruction of ozone.

Moreover, when Type 9 is linked to the arrival in the Iberian Peninsula of tropical continental air masses from Africa (Saharan air), which are responsible for the presence of airborne dust in the atmosphere, it causes high levels of PM_{10} immission. With this weather type, although all of the stations are below the daily limit established by current legislation which is 50 $\mu g/m^3$, all of them fail to comply with the annual limit set by the World Health Organization at 20 $\mu g/m^3$. The station with the worst situation is the one at Escuelas Aguirre, which has an average daily concentration of 32.89 $\mu g/m^3$ and in which, along with the particles that have a natural origin, has to be added to those caused by road traffic. The one with the lowest figures is the one at Casa de Campo with 24.39 $\mu g/m^3$, which is located in a suburban area and has less traffic, but where airborne dust arrives naturally.

Weather Type 1, which is anticyclonic and is associated with maritime polar air masses with a predominance of Westerly winds, along with Type 4, linked to continental polar air masses from Europe (North-East), are what cause the lower concentration of PM_{10} contamination due to the atmospheric ventilation that they typically perform. The figures range from 15.15 $\mu g/m^3$ at Escuelas Aguirre and 15.55 $\mu g/m^3$ at Plaza Castilla (traffic stations) and 7.9 $\mu g/m^3$ at Casa de Campo (a metropolitan station).

The results found confirm the importance of weather types in the air quality of cities. The levels of air pollution are controlled by determined atmospheric conditions in such a way that they could be used to predict periods of high contamination in the area studied and create warning systems for those people who are more sensitive to the arrival of air masses which can be proven to be associated with high levels of immission of contaminants.