# Application of meteorological classification methods for present and future air quality projections.

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## 1. Purpose of the visit

As the Belgian representative in the Management Committee of COST 733, I have a good overview of the Belgian scientific interest in weather types classifications. At this moment, COST 733 is finishing its second year of the Action, and the objectives of the first Work Package ("existing methods and applications") have been fulfilled (COST733 – MoU). Thereby, a questionnaire prepared by Dr. Zbigniew Ustrnul and Dr. Radan Huth has been sent to all interested "classification methods scientist" in Europe. In the returns, almost 70 methods were reported. An initial analysis was undertaken to remove those methods which were clearly not appropriate for use in COST733. These included methods which were too local in scale or based on local correlations with highly specific quantities, thus being unable to define synoptic-scale types. Other methods were rejected by having too few types (therefore having too little informational value) or being based only on mid-tropospheric variables (therefore yielding types with too little surface structure), or having too many types and sub-types (therefore having too little focus and relevance). Where several WTCs were based on essentially the same generic method (e.g. Jenkinson-Collison), only a single, representative method was selected. As a result, 19 WTCs remain for the further investigation.

In the next (present) fase, three new working groups started their specific tasks. As vice-president of Working Group 4 ("Testing methods for various applications"), our goals are e.g. the selection of dedicated applications (using results from WG1), collection/development of application software, performance of the selected applications using available weather type data, comparison of the application results with results of former methods and the final assessment of the results and uncertainties. All members of Working Group 4 have different backgrounds (climatological, chemistry, forecasting…) so that various kinds of applications can be tested. Keeping my own PhD – research in mind, this STSM will strengthen my skills in mesoscale meteorological phenomena and their relation to air pollution dispersion. Not only I want to work on new classification methods applicable for all kinds of regions and various spatial and temporal scales. I also aim at more practical applications involving the feedbacks between emissions/air pollution and circulation patterns, thereby relating air pollution dispersion changes to future climatic changes and the occurrence of intermediate and extreme events. Weather types are a broad concept, with lots of possibilities and applications, and it is my objective to concretize these ideas concerning the relationships between emissions, climate change and air pollution at the European scale in my PhD.

Before the research topics described above can be tackled, it is important to understand the physics and dynamics of meteorology and chemistry. Only then I will fully understand and be able to cope with the methods behind all circulation type classifications. After following two additional courses at the University of Louvain-La-Neuve with Dr. Berger, Dr. Schayes and Dr. Fichefet on dynamics and physics of meteorology and PBL meteorology, I want to apply and extend this knowledge working with meteorological mesoscale model(s) and (a) emission / dispersion model(s). Because of the fact that our Regional and Physical Geography Research Group is, until today, mainly focused on soil conservation, erosion and land use modeling and meteorological modeling, especially in regards to precipitation and cloud microphysics, a stay at the Wageningen University and Research Center for Meteorology and Air Quality would strengthen my skills in the domain of air quality and the physical concepts of boundary layer meteorology. Not only it would enhance the existing networks between the different institutes, as a young scientist, I would also benefit from this cooperation. I could learn about new techniques and methods, gain more in-depth theoretical knowledge and learn about emission and meteorological measurement techniques in the field. Frequent and profound discussions about this and related topics will be an advantage for all involved scientists, not to mention the scientific experience I will gain for myself.

I think the opportunity offered by the COST-programme is of great importance to me and I am therefore very motivated to use this opportunity at the Wageningen University and Research Center for Meteorology and Air Quality for my further scientific development. The Meteorology and Air Quality Section at the Wageningen University has large experience on research and on education on the influence of atmospheric physics on air quality. The main emphasis is placed on how phenomena such as vertical turbulent transport, radiation and clouds can affect the distribution and evolution of air pollutants. Therefore, the Wageningen Research Center is the perfect location to perform this STSM, as well for my personal scientific background, as for the goals of the COST733 action.

## 2. Description of the datasets

a. ECMWF-data

In order to classify the synoptic patterns with the Jenkinson-Collison classification method (see 3.Methods), the ECMWF - ERA40 SLP dataset was selected on a 2.5°x2.5° grid, for the larger European Atlantic Region (27.5°W-30°E, 75°N-15°N), in first instance centered above Belgium, afterwards with its central point over the Netherlands (Figure 1). The 6 hourly SLP values are averaged over a 24 hourly period resulting in daily mean sea level pressure fields for the year 2001.

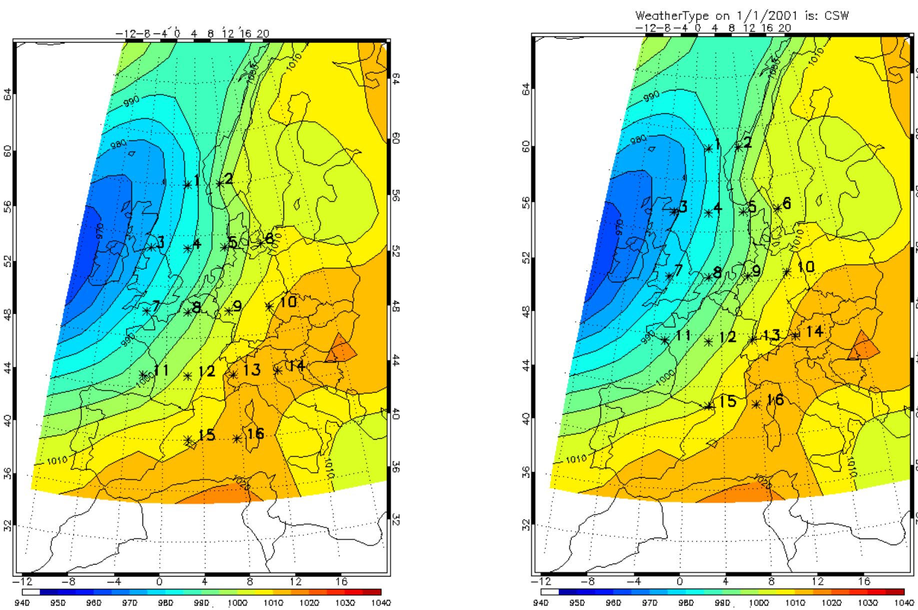



Figure 1: Location of the Jenkinson-Collison grid centred on Belgium (left panel) and on The Netherlands (right panel). Mean sea level pressure data is used for the $1^{st}$ of January 2001.

Furthermore, other meteorological variables are obtained from the ER40-ECWMF reanalysis database. This include the following parameters, on a 2.5x2.5° grid, for 12UTC only:

- 10 meter U,V wind component [$ms^{-1}$] (165, 166)
- Boundary layer height [m] (159)
- Low, medium, high cloud cover [0-1] (186, 187, 188, 164)
- Surface sensible heat flux [$Wm^{-2}$] (146)
- Total column water vapour [$kgm^{-2}$](137)

From the whole area, the data is selected for the ECMWF grid cell covering the Brussels measurement station (50°N, 5°W). The data is summarized in Table 1.

Table 1: Summary of meteorological and air quality parameters used in this study, 2001, 12UTC values, for the Brussels measurement station.

| Variable | | Minimum | Maximum | Comments |
|---|---|---|---|---|
| Total column water vapour [$kgm^{-2}$] | | 2.67 | 39.66 | |
| Boundary layer height [m] | | 12.93 | 2356.6 | |
| Cloud Covers [0-1] | | 0 | 1 | |
| Air Temperature [K] | | 265.17 | 297.36 | |
| Wind Speed [$m\ s^{-1}$] | | 0.62 | 18.25 | |
| Surface sensible heat flux [$Wm^{-2}$] | | 64.8 | 217 | |
| Ozone [$\mu gm^{-3}$] | max 8h average | 2 | 144.1 | 44 days without values |
| | daily maximum | 2 | 169 | 6 days without values |
| Pm10 [$\mu gm^{-3}$] | | 0 | 183 | 3 days without values |

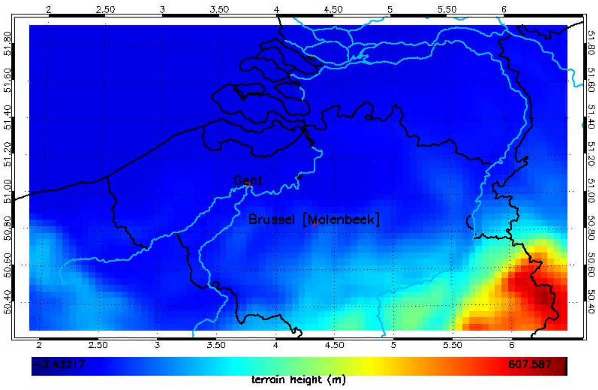
Hereby, the sensible heat fluxes are the averaged values over a 6h period, ranging from 12h to 18h UTC. This has to be kept in mind when correlating the sensible heat fluxes with concentrations of $PM_{10}$ and $O_3$. From the U-V wind component, wind speed and direction are calculated (Beljaars, 1995).

b. Meteorological point measurements

In order to be able to correlate $PM_{10}$ and $O_3$ concentrations on a more local scale, meteorological point measurements are obtained from the meteorological measurement tower in Cabauw. This station is partly operated by the KNMI and is located in a rural area (http://www.knmi.nl/~bosveld/). These meteorological measurements will be used in the remainder of this STSM, which is scheduled as future planned work (see section 6.).

c. Air quality data

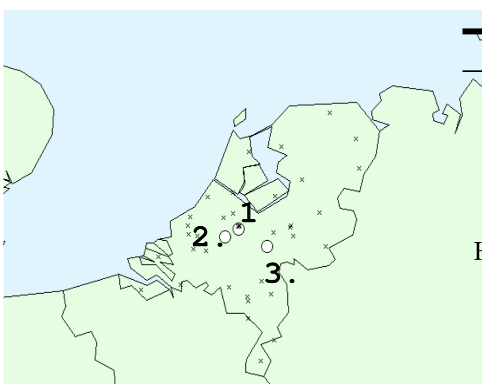
Based on the AIRBASE (http://air-climate.eionet.europa.eu/databases/EuroAirnet/) network, two locations are selected (Figure 2 and Table 2): Brussels (41R001) with traffic type emissions and Gent (44R701), a station with background emissions. For both stations, $PM_{10}$ values include daily means, while $O_3$ measurements are done hourly. In a first phase, only the Brussels station will be used for this correlation with the circulation types and specific parameters.




| | Brussels (Molenbeek) | Gent |
|---|---|---|
| **Code** | 41R001 | 44R701 |
| **Type** | Traffic | Background station |
| **Lat** | 50°51'01" | 51°03'33" |
| **Lon** | 4°20'06' | 03°43'50" |
| **PM10** | Daily mean | Daily mean |
| **O3** | Hourly | Hourly |

Table 2 & Figure 1: Location and characteristics of the (traffic) station of Brussels and (background) Gent, provided by the AIRBASE dataset. Background of figure 11 presents the altitude levels in Belgium.

Furthermore, three locations are selected in the Netherlands (Figure 3 and Table 3): Cabauw/Zijdeweg (620) with rural background emissions for ozone, Utrecht/Erzeijstraat (639) with ozone and $PM_{10}$ urban traffic emissions and Wageningen – Binnenhaven (724) with $PM_{10}$ rural background emissions. For all stations, $PM_{10}$ and $O_3$ measurements are done hourly. In a first phase, only the Wageningen-Binnenhaven and the Cabauw (background) measurements will be used for this correlation with the circulation types and specific parameters. As mentioned before, this work in progress will be done in the home institute (see section 6.).




| | **1.Utrecht** | **3.Wageningen** | **2.Cabauw** |
|---|---|---|---|
| Code | 639 | 724 | 620 |
| Lat/lon | 52.06°N<br>5.12°E | 51.97°N<br>5.64°E | 51°95N<br>4°90E |
| Height (asl) | - | - | 0.7 |
| Type | Urban<br>Traffic | Rural<br>Background | Rural<br>Background |

Table 3 & Figure 3: Location and characteristics of the measurement stations of Utrecht (1), Cabauw (2) and Wageningen (3), provided by the AIRBASE dataset.

## 3. Methods & Models

b. Jenkinson-Collison Classification scheme

The Jenkinson-Collison circulation type for a given day is described using the locations of the high and low pressure centers that determine the direction of the geostrophic flow. It uses coarsely gridded pressure data on a 16-point moveable grid, and is therefore easily applicable in any area with available data (Dessouky and Jenkinson, 1977; Jones *et al*., 1993, Demuzere *et al*, 2007). This method allows 27 different classification weather types to be defined. These types are characterized through the use of a set of indices associated to the direction and vorticity of geostrophic flow. The indices used were the following: southerly flow (SF), westerly flow (WF), total flow (F), southerly shear vorticity (ZS), westerly shear vorticity (ZW) and total shear vorticity (Z). These indices were computed using sea level pressure (SLP) values obtained for the 16 grid points. The weather types are defined by comparing values of FF and Z:

- Direction of flow is given by $\tan^{-1}$ (W/S), 180° being added if W is positive. The appropriate wind direction is computed using an eight-point compass, allowing 45° per sector.
- If $|Z|<FF$, flow is essentially straight and considered to be of a pure directional type (eight different possibilities according to the compass directions).
- If $|Z|>2FF$, the pattern is considered to be of a pure cyclonic type if $Z>0$, or of a pure anticyclonic type if $Z<0$.
- If $FF<|Z|<2FF$, flow is considered to be of a hybrid type and is therefore characterized by both direction and circulation (16 different types).

Threshold values of Z and FF are used to define whether a day is allocated as unclassified or not. Values of Z and FF don't show any clustering or grouping, which is in line with the findings of Goodess (2000). Therefore, the implementation of another more useful cut-off point for the central European region is not appropriate and hence of value of 6 was retained (Jones *et al*., 1993).

This results in 26 +1 different weather types. Because of the fact that a typing scheme is constructed to result in circulation types each with a characteristic synoptic pattern and surface flow and because the aim of this paper is to investigate if Jenkinson-Collison weather types are able to explain present and future air quality thresholds, the 27 types are classified according to their directional characteristics, which results in 8 directional types (e.g. N(d) = N, CN, AN) 2 pure vorticity types A and C and the unclassified U type, so 11 types in total (Demuzere *et al.,* 2007).

For the whole of 2001, the frequencies of all 27 types, with a grid center above Belgium and The Netherlands are shown in respectively figure 4a and figure 4c. As the hybrid types are very low in frequency and to simplify future correlation analysis between types and concentrations of air polluters, the types are clustered by their direction, as mentioned above (figure 4b and figure 4d for Belgium and The Netherlands respectively).

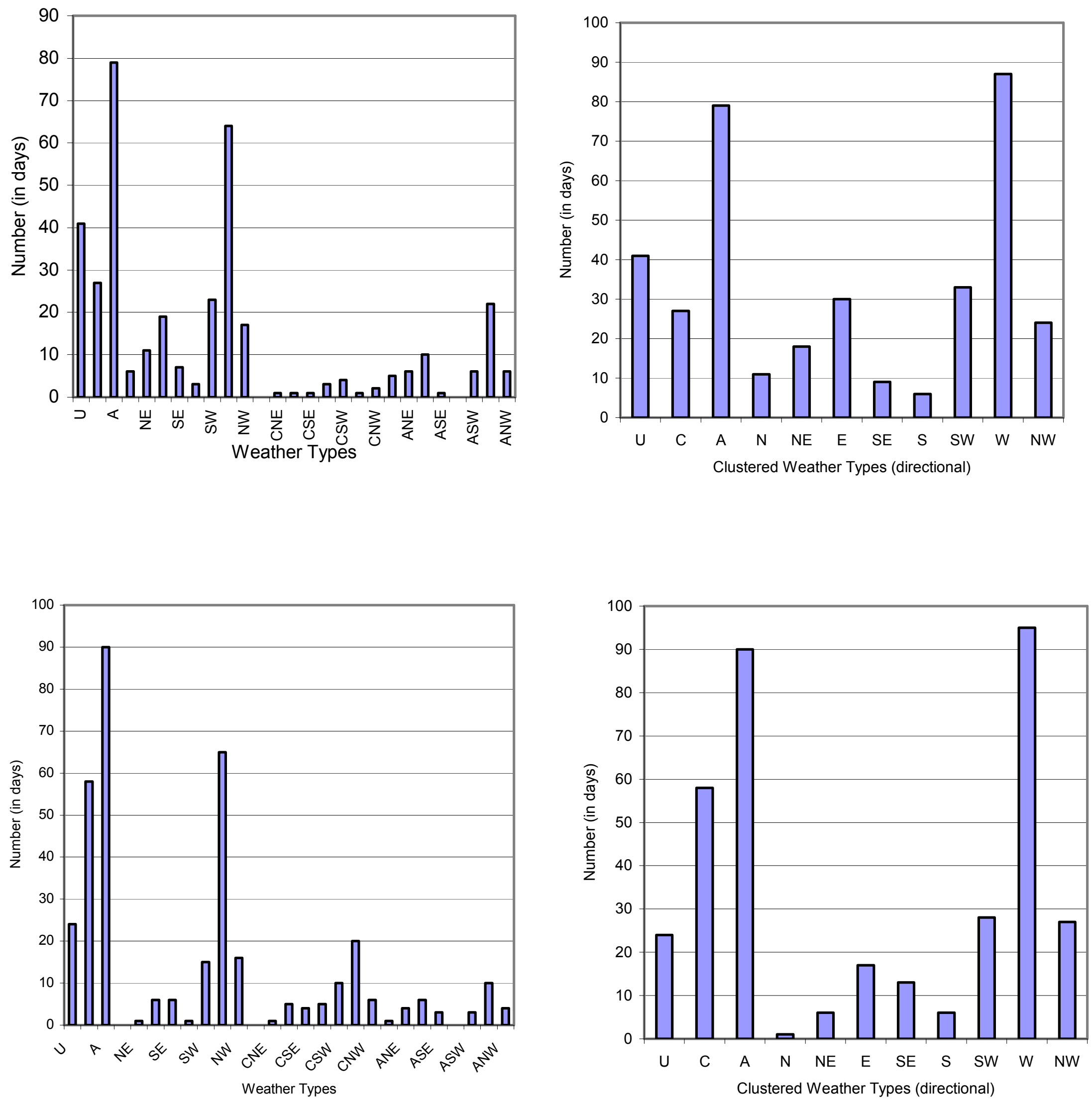



Figure 4a, b, c and d: Frequencies of Jenkinson-Collison weather types for all types for Belgium and The Netherlands (a: upper left panel, c: lower left panel) and clustered based on their direction for Belgium and The Netherlands (b: upper right panel, d: lower right panel), for 2001.

b. Mixed- layer model

In a clear convective boundary layer, warm rising air from the surface organizes itself into thermal plumes of eddies, and reach the top of the boundary layer. In that way, air from surface to the top of the boundary layer is mixed, and as a result, quantities of heat and moisture within the boundary layer don't change with height, and the vertical gradient of these quantities doesn't change with time. Moreover, warm dry air from the free troposphere (FT) is also introduced into the boundary layer. This processes is called entrainment, and the amount of mixing is for a great deal governed by the temperature inversion gradient and the temperature lapse rate in the FT.

This structure results in a boundary layer with a few segments. Closest the surface is the surface layer, above the well-mixed layer, topped of by the inversion layer the free troposphere.

The inversion layer is represented as a sharp discontinuity between the well-mixed boundary layer (bulk layer) and the above troposphere. It therefore represents the difference between the value of the under and above situated quantities. This approach is called the zero-order jump approach, which is also introduced into the mixed-layer model. In this way, the growth of the boundary layer is characterized by 1) the entrainment flux, which brings air with properties of the free troposphere, 2) the buoyancy, which regulates thermal plumes and eddies over substantial areas and 3) the subsidence (which has a negative value on the boundary layer growth (e.g. high-pressure conditions)).

Therefore, a rather simple conceptual (mixed-layer) model will be used to reproduce the diurnal cycle of, in first instance, $CO_2$. The model reproduces very well the boundary layer growth and the main thermodynamic characteristics. In addition, we have implemented a simple chemical mechanism (10 species and reactions) to study the effect of boundary layer on the $CO_2$ chemistry. In addition, and due to its simplicity, it will allow us to do quite a lot of sensitivity analysis. By using meteorological/ atmospheric chemistry data, the use of this model will also allow us insight in how boundary layer dynamics can influence atmospheric dynamics, and to what degree this should be incorporated into the classification method. Finally, some test cases will be selected to evaluate our findings (De Arellano *et al.*, 2004).

## 4. Results and evaluation

a. Sensitivity of the mixed layer model

First of all, a sensitivity test has been done on the growth of the boundary layer depending on various values of gamma – temperature lapse rate ($\gamma$) and delta theta – the temperature inversion ($\Delta\theta$). The results are shown in figure 5.

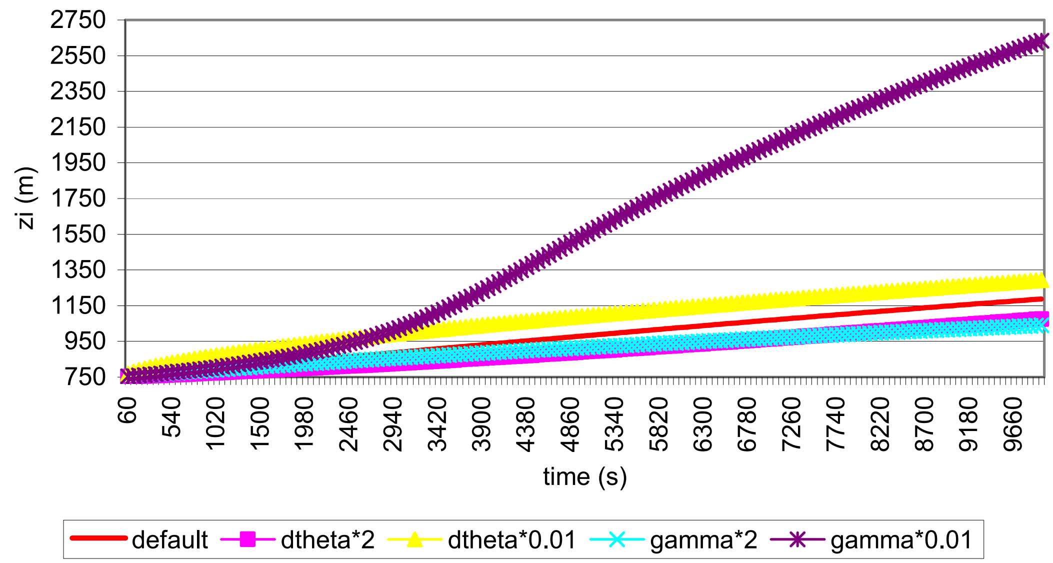



Figure 5: The sensitivity of the boundary layer growth (zi) with the mixed model (run for 10000s) for various values of gamma – temperature lapse rate ($\gamma$) and delta theta – the temperature inversion jump ($\Delta\theta$).

From figure 5, one can see that the growth of the boundary layer height is more sensitive to a decrease in the temperature lapse rate than a decrease in the temperature inversion jump. The former results in a growth to 2600m (+1250m compared to default case), whereas the latter has an increase of 150m compared to the default run (with $\gamma$ = 0.003 K/m and $\Delta\theta$ = 0.45 K).

Based on these results, we select 2 cases, which we will use in our further studies to test the sensitivity of the boundary layer dynamics to chemistry. In one case, a dynamic system is constructed, with a low value for gamma, in the other case a quasi-static boundary layer is selected (with a high value for gamma).

1) dynamic case, with $\gamma$ = 0.0003 K/m
2) quasi-static case, with $\gamma$ = 0.006 K/m

All the other parameters in the mixed-layer model are kept constant, as mentioned in De Arellano *et al.* (2004).

Since we now have a framework of our sensitivity studies, the chemistry (in first instance $CO_2$) can be tested. The diurnal cycle of $CO_2$ governed partly by the surface (source at night, and a sink during daytime, where $CO_2$ is taken up by vegetation/surface cover). In this respect, the dynamics of $CO_2$ at the surface are well known. The surface scratches $CO_2$ away from the surface, whereas this decreasing quantity of $CO_2$ progresses vertically upwards, with a lowering of the total $CO_2$ in the entire boundary layer. This is also positively influenced by the dilution of $CO_2$, due to the boundary height growth itself. But on the other hand, one also has to consider what happens at the top of the boundary layer height. Depending on the boundary layer growth in se and the entrainment fluxes of $CO_2$ from the free troposphere, the concentrations in the boundary layer are influenced as well.

First, some modeled parameters for the 2 default cases as mentioned above are compared (not shown). In case of a quasi-static boundary layer (case 2), the entrainment flux is constantly low, with a decrease of $CO_2$ concentration in the atmosphere due to photosynthesis and boundary layer growth. Furthermore, the $CO_2$ concentration jump at inversion is slowly moving to a positive value after 5 hours, whereby an already low value of the entrainment $CO_2$ flux is changing to a negative sign, which means an outflow of $CO_2$ into the free troposphere. For the dynamic case on the other hand, the entrainment $CO_2$ flux is high positive in the beginning of the boundary layer development. This is due to the fact that the entrainment $CO_2$ velocity is related to the entrainment velocity (and in that way entrainment flux (w'θ')e or we [m/s] which is in its part influenced by the temperature jump at inversion. With in increasing boundary layer height, $\Delta\theta$ is decreasing, while the entrainment flux is increasing. This means that more air from the boundary layer enters the free troposphere. After a period of time, $\Delta\theta$ starts to increase again due to a higher (increasing) temperature in the boundary layer itself, so that also a ceiling is reached for the entrainment flux, which will decrease again at a rate of the growth of $\Delta\theta$. This is also what happens for the scalar of $CO_2$. From the moment the $CO_2$ concentration jump at inversion is stabilizing (towards 0 ppm), the positive entrainment $CO_2$ flux peak declines and stabilizes around 0 ppm m/s. During the peak of positive entrainment $CO_2$ flux, the mean concentration of $CO_2$ in the boundary layer is lower than for the quasi-static state, because of a higher outflow of $CO_2$ to the free troposphere.

In order to test the influence of the $CO_2$ cycle in the boundary layer on the boundary evolution itself, we run the model for different values of the $CO_2$ surface flux $(w'\ CO_2')_s$ and the $CO_2$ inversion jump ($\Delta CO_2$) (table 4).

Table 4: Sensitivity setup values for of the $CO_2$ surface flux $(w'\ CO_2')_s$ and the $CO_2$ inversion jump ($\Delta CO_2$) in the mixed-layer model.

| | **-100%** | **-80%** | **-60%** | **-40%** | **-20%** | **Def.** | **+20%** | **+40%** | **+60%** | **+80%** | **+100%** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **w' $CO_2$'** | 0 | -0.072 | -0.144 | -0.216 | -0.288 | -0.36 | -0.432 | -0.504 | -0.576 | -0.648 | -0.72 |
| **$\Delta CO_2$** | 0 | -6 | -12 | -18 | -24 | -30 | -36 | -42 | -48 | -54 | -60 |

### *4.A.1 Case 1: Dynamic boundary layer growth*

From this first sensitivity study with a fast growing boundary layer, we can conclude that the smaller (negative value) the concentration at inversion jump ($\Delta\theta$), the smaller the mean concentration in the boundary layer (here 332 ppm). This means that in an early stage of the boundary layer growth, the large positive entrainment flux (for the $\Delta\theta$ +100% run) will transport air from the boundary layer into the free troposphere and will dilute the boundary layer. After the entrainment flux peak, all factors are stabilizing and from now on, concentration changes in the boundary layer can be due to other processes such as photosynthesis at the surface.

Furthermore, when the surface flux is highest negative (run with $(w' CO_2')_s$ +100%), the entrainment flux is the highest compared to all other runs. Thereby, the concentration in the boundary layer is the lowest and the concentration at the inversion jump the highest. Of course, when the initial surface flux is going towards zero, differences in concentration of $CO_2$ in the boundary layer and the more clear free troposphere will be lower, which results in a smaller concentration $CO_2$ difference at the inversion layer jump and a smaller entrainment velocity putting $CO_2$ in the free troposphere. Thereby, the mean concentration of $CO_2$ in the boundary layer will be higher. So again in this case, the entrainment velocity is responsible for a lower concentration of $CO_2$ in the boundary layer.

Hereby we can also conclude that changing the scalars doesn't influence a change of boundary layer dynamics. The boundary layer growth and entrainment flux both stay constant through time.

Another difference between both $CO_2$ concentration jump at inversion and the $CO_2$ surface flux sensitivities are the quantities of the parameters. Thereby, we can conclude that a 0 $CO_2$ concentration jump (compared to the smallest negative $CO_2$ surface flux) has:

- A larger influence on the $CO_2$ entrainment flux values (respectively 6.5 and 4 ppm $ms^{-1}$)
- Which also affects the $CO_2$ mean concentration in the boundary layer, with respectively 330 and 360 ppm)

Next to that, the range of parameter ($CO_2$ mean concentration, $CO_2$ entrainment flux, $CO_2$ concentration jump at inversion) is larger influenced by the sensitivity to the $CO_2$ concentration jump at inversion, than the $CO_2$ surface flux.

### *4.A.2 Case 2: Quasi-static boundary layer growth*

From this sensitivity study, we can conclude that the mean $CO_2$ concentration of in the boundary layer is more sensitive to a change in the $CO_2$ concentration at the inversion jump, with lower values for $\Delta\theta$ + 100% than the flux + 100%. Thereby, the $CO_2$ entrainment flux is less influenced by the surface flux changes. This confirms the fact that the mean concentration in the initial phase of the simulation is influenced by this flux, while afterwards, the $CO_2$ concentration at the inversion jump will play a more important role.

b. Correlation between meteorological variables and air quality parameters

Now that some of the principles and dynamics of the boundary layer have been investigated using concentrations of $CO_2$, a next phase will focus on the combination of weather types, boundary layer dynamics and concentrations of $PM_{10}$ and $O_3$. In order to capture the spatial and temporal variability in as well the datasets as the environmental issues, the following two main streams are followed; one using the lower resolution ECMWF-ERA40 data, the other one using meteorological point measurements (see 6. future work). In the former, ECMWF-ERA40 meteorological grid data is used combined with air quality data from point measurements from Airbase for the Brussels measurement station.

Based on the multiple linear regression technique, a regression line is fitted between all selected meteorological variables and $PM_{10}$ and $O_3$ measurements (figure 6, 7, 8), whereby also correlation factors are calculated (Table 5).

Table 5: Correlation factors between the meteorological variables and the 8h maximum $O_3$ average, daily maximum hourly $O_3$ value and daily mean concentration of $PM_{10}$, this for the whole year of 2001, summer (JJA) and winter (DJF) 2001.

| | **8h maximum $O_3$** | | | **daily max. hourly $O_3$** | | | **$PM_{10}$** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **ALL** | **DJF** | **JJA** | **ALL** | **DJF** | **JJA** | **ALL** | **DJF** | **JJA** |
| Boundary layer height | **-0.43** | -0.05 | **-0.36** | **-0.46** | -0.11 | **-0.38** | 0.05 | -0.11 | -0.01 |
| Air Temperature | **0.54** | **-0.31** | **0.62** | **0.52** | **-0.24** | **0.58** | -0.02 | **0.23** | 0.12 |
| Total column water vapour | **0.45** | -0.02 | **0.2** | **0.42** | 0.08 | **0.17** | -0.11 | -0.06 | -0.2 |
| Surface sensible heat flux | **0.36** | **-0.21** | **0.31** | **0.36** | -0.08 | **0.28** | 0.06 | **0.25** | 0.04 |
| Low cloud cover | **-0.4** | **0.007** | **-0.33** | **-0.42** | -0.04 | **-0.31** | 0.07 | 0.13 | -0.08 |
| Medium cloud cover | -0.12 | **0.36** | **-0.15** | **-0.15** | **0.31** | **-0.19** | **-0.17** | **-0.31** | **-0.24** |
| High cloud cover | **-0.16** | **0.2** | **-0.2** | -0.03 | **0.23** | **-0.24** | **-0.16** | **-0.23** | **-0.19** |
| Wind direction | -0.08 | -0.1 | -0.02 | -0.06 | -0.04 | -0.05 | 0.08 | 0.03 | **-0.21** |
| Wind speed | **-0.26** | **0.21** | **-0.22** | **-0.26** | 0.11 | **-0.25** | -0.07 | **-0.34** | -0.3 |
| Vorticity Z (JC-scheme) | 0.11 | **0.45** | -0.07 | 0.13 | **0.42** | -0.06 | **-0.17** | **-0.23** | 0.1 |
| JC – Weather Types (clus) | -0.1 | **0.51** | **-0.3** | **-0.08** | **0.48** | **-0.29** | **-0.36** | **-0.47** | **-0.44** |

Based on the contingency table (using df=363), a correlation coefficient of higher (lower) than 0.148 (–0.148) is significant on a 99% significance level (bold values in table 5). In this case, almost all meteorological variables are correlating significant for ozone for all year and DJF and JJA separately. Therefore, a higher level of correlation is arbitrarily introduced (0.3 – red values). Based on this, the situation for maximum 8 hourly average concentrations and maximum hourly daily concentration is quite obvious. In general (for all days), air temperature has the strongest positive connection to ozone. Next to that, also sensible heat flux and column water vapor play an important positive role. Boundary layer height and low cloud cover are negatively significant, the latter especially in the summer period. In winter periods (for ozone), a strong positive correlation with vorticity and Jenkinson-Collison clustered weather types, together with a negative correlation with air temperature appears. This situation could point out inversion conditions in winter, characterized by a low and stable boundary layer.

The relations between $PM_{10}$ and meteorological variables are not so clear. Only in winter, there is a small negative correlation with wind speed (-0.34) and medium cloud cover (-0.31). Next to that, $PM_{10}$ and correlates strongly (>0.3) with Jenkinson-Collison clustered weather types. As at has been shown that persistence of circulation patterns is important in various applications, e.g. heat waves occurrences in Europe (Kysely, J., 2002, 2007), also the relation between the persistency of weather types and $PM_{10}$ and $O_3$ concentrations is investigated. Hereby, there is no clear evidence of strong correlation, neither for all days of 2001 nor for the DJF and JJA season (not shown in Table 5).

In general, we can conclude that for this 2001 period, high concentrations of $PM_{10}$ can difficulty be understood by the above-considered meteorological variables, but nevertheless, concentrations seem to correlate positively with the clustered Jenkinson-Collison weather types. For high $O_3$ concentrations, the situation is more complex, with a more pronounced positive correlation with 2m air temperature, total column water vapor and sensible heat flux, and negatively correlated with boundary layer height and low cloud cover. In summer months (JJA), the positive (negative) correlations with air temperature (boundary layer height and low cloud cover) are still valid. In contrary, in DJF, none of the above-mentioned relations is valid, but there is a negative correlation with air temperature and a strong positive correlation with vorticity and the clustered Jenkinson-Collison weather types.

Thereby it seems to be difficult to set up a clear set of meteorological-based indices, which can be used to represent high concentrations of $PM_{10}$ and $O_3$ concentrations.

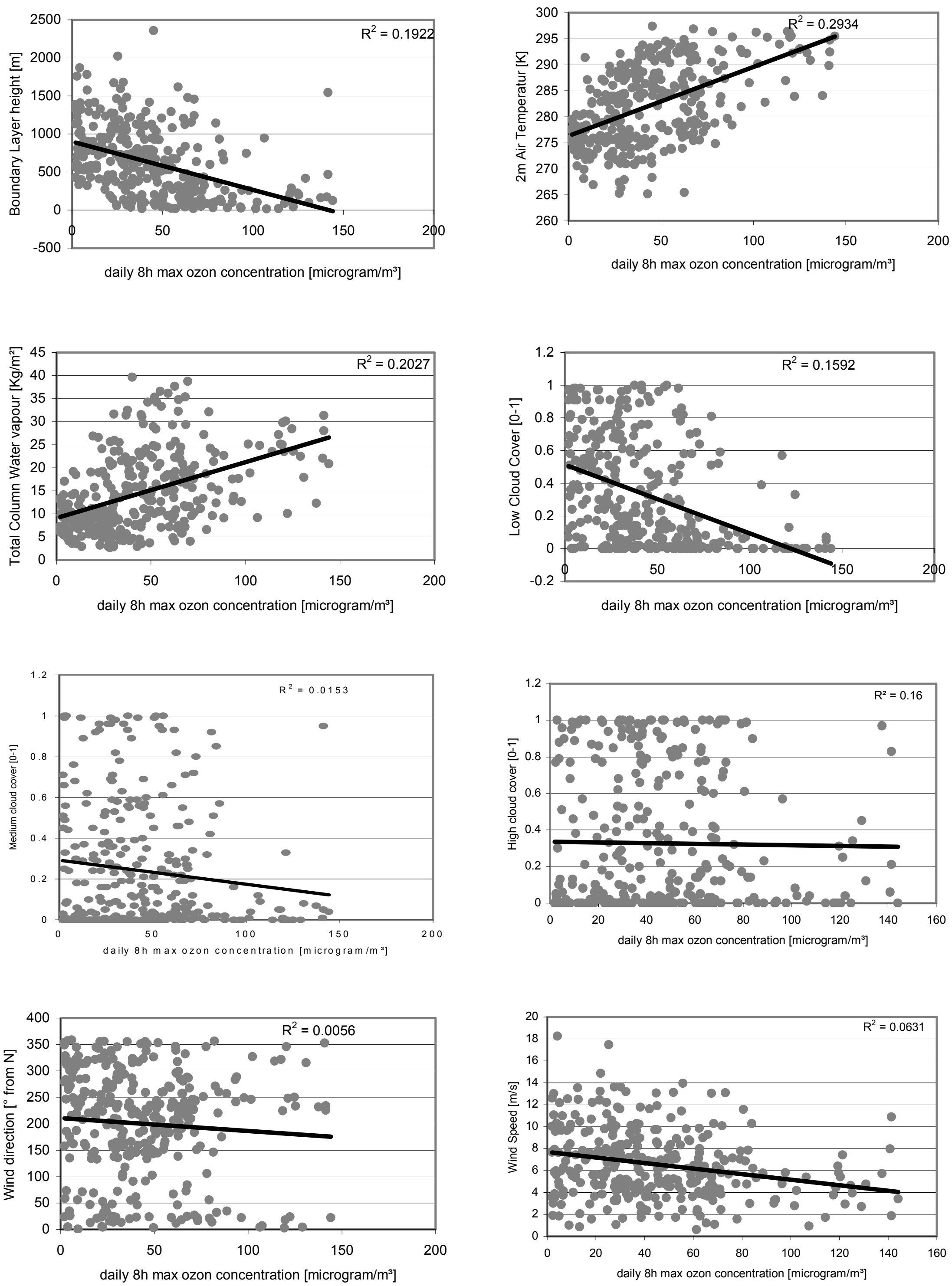



Figure 6: Linear regression plots between the meteorological variables (blh, p2t, tcwv, low, middle and high cloud cover and wind direction and speed) and the maximum daily 8 hour average concentration of $O_3$ for 2001.

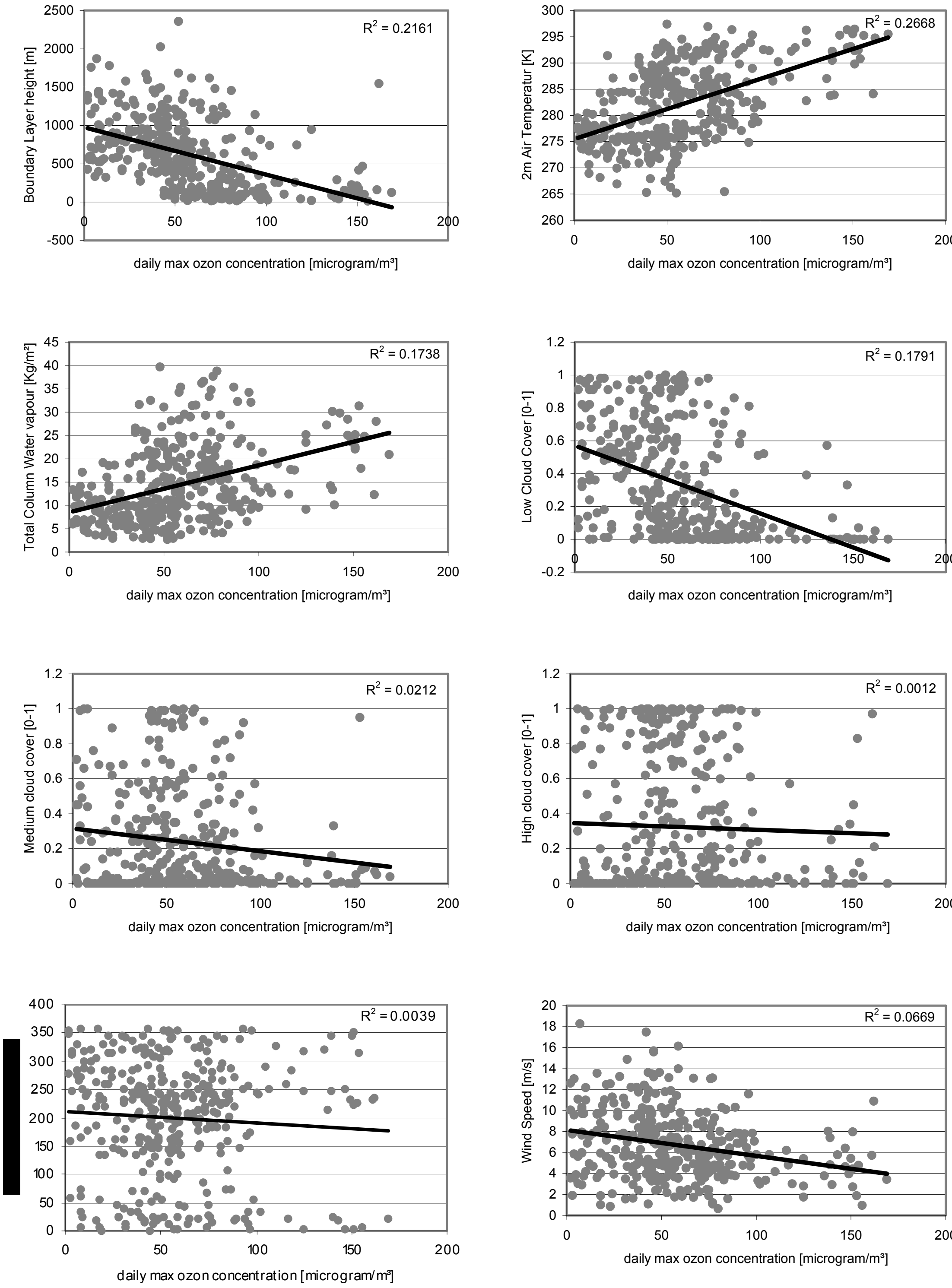



Figure 7: Same as Figure 14, but for the maximum hourly concentration of $O_3$ per day for 2001.

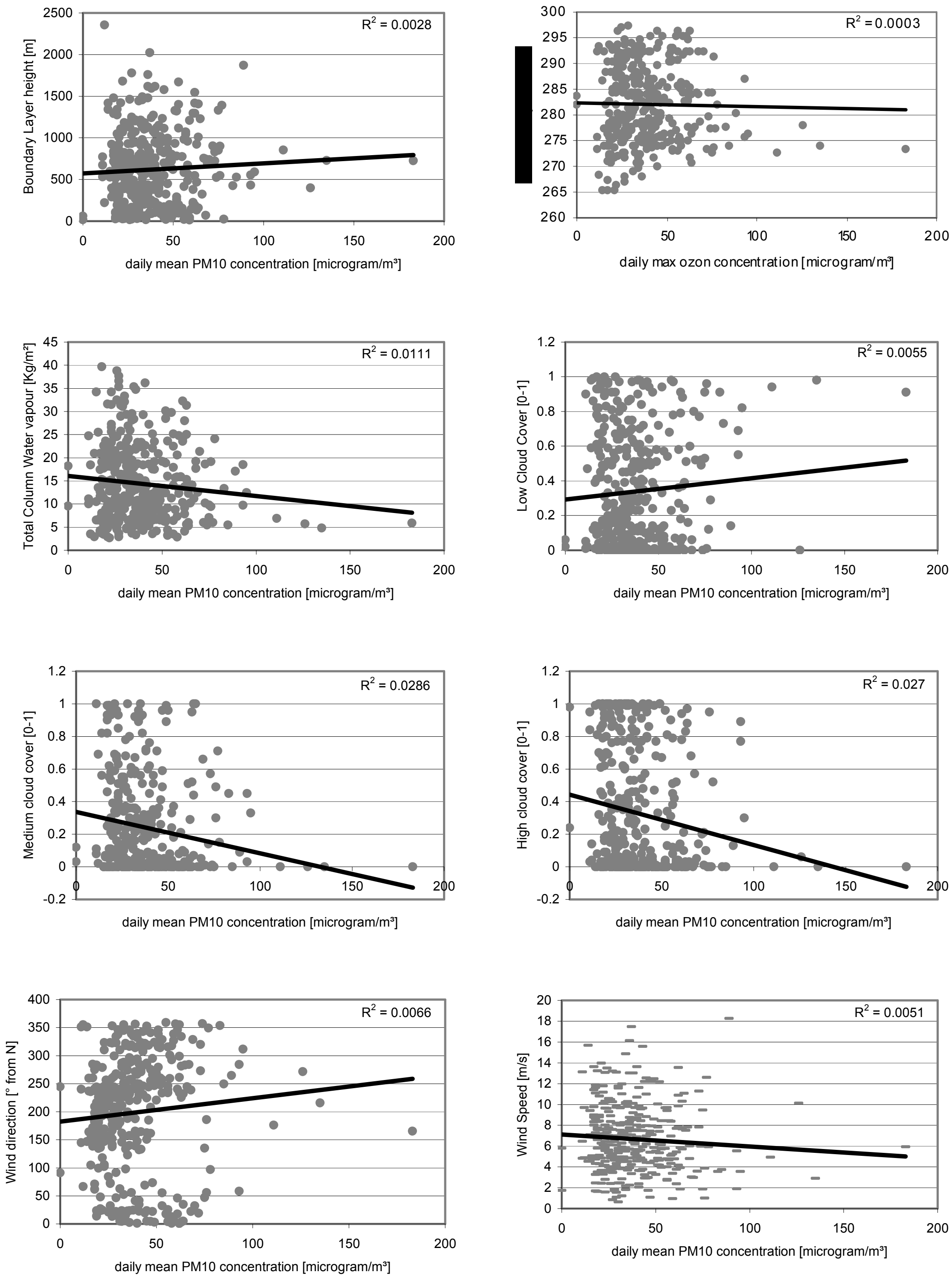



Figure 8: Same as Figure 14, but for the mean daily PM10 concentration for 2001.

c. Link between circulation patterns, meteorological variables and air pollution measurements.

In the previous section b, correlations between meteorological values and $PM_{10}$ and $O_3$ concentrations are determined. Now, in order to link these results to the daily circulation patterns, all variables are combined into one plot (Figure 9 & 10).

From figure 9 and the maximum hourly daily values it is clear that not a single day in 2001 is exceeding the hourly limit of 180 µg/m³, following the European Guidelines for air pollution (1999/30/EG). Next to that, only few days are exceeding the 120 µg/m³, for which most of the days are classified as an “unclassified” circulation pattern. Thereby it is hard to interpret this dataset, although this result includes a first remark. The occurrence of higher ozone concentrations in unclassified days would mean that higher ozone concentrations occur more frequently when there is no clear pressure gradient or when geostrophic flow is reduced to a minimum and thereby not recognized by the Jenkinson-Collison weather type scheme. One solution could be to extend the dataset over a longer period, or to find a solution for the unclassified days in the Jenkinson-Collison weather-typing scheme.

Furthermore, 2 days of concentrations > 120 µg/m³ occur in SW-types, combined a low boundary layer height, high air temperatures and moderate low, medium and high cloud cover and wind speeds.

Figure 10 presents $PM_{10}$ concentrations against the meteorological variables and weather types. In general, we can state that high concentrations occur especially in anticyclonic (A) types and south and southeast directional weather types (S and SE). The unclear correlations between the $PM_{10}$ concentrations and meteorological variables are also represented in figure 10, whereby in one cluster of weather types it is quasi impossible to get a clear link with the meteorological variable value.

Therefore, as mentioned in the introduction and goals of this report, we will focus on 4 clusters of weather types, representing respectively high and low concentrations of $PM_{10}$ concentrations. Thereby we select the two opposed zonal circulations (E and W), and both pure cyclonic types (A and C) (Table 6).

Table 6: Number of days of 2001 grouped by 2 pure cyclonic types C and A, and 2 clustered zonal types E and W, respective to their mean daily concentration of $PM_{10}$.

| | **C** | **A** | **E** | **W** |
|---|---|---|---|---|
| < 40 µg/m³ | 20 | 34 | 4 | 82 |
| 40 >< 50 µg/m³ | 1 | 24 | 9 | 5 |
| > 50 µg/m³ | 6 | 21 | 17 | 0 |

In total 227 days of 2001 are covered by this selection. Knowing the poor relations between concentrations of $PM_{10}$ and the meteorological variables (Table 4), and based on the above-mentioned results and the simple mixed layer model, we will try to understand and simulate the principle boundary layer processes, in order to explain the variability in concentrations of $PM_{10}$ for a certain weather type cluster (section 5.6). Part of this will be done at the home institute (see section 6.).

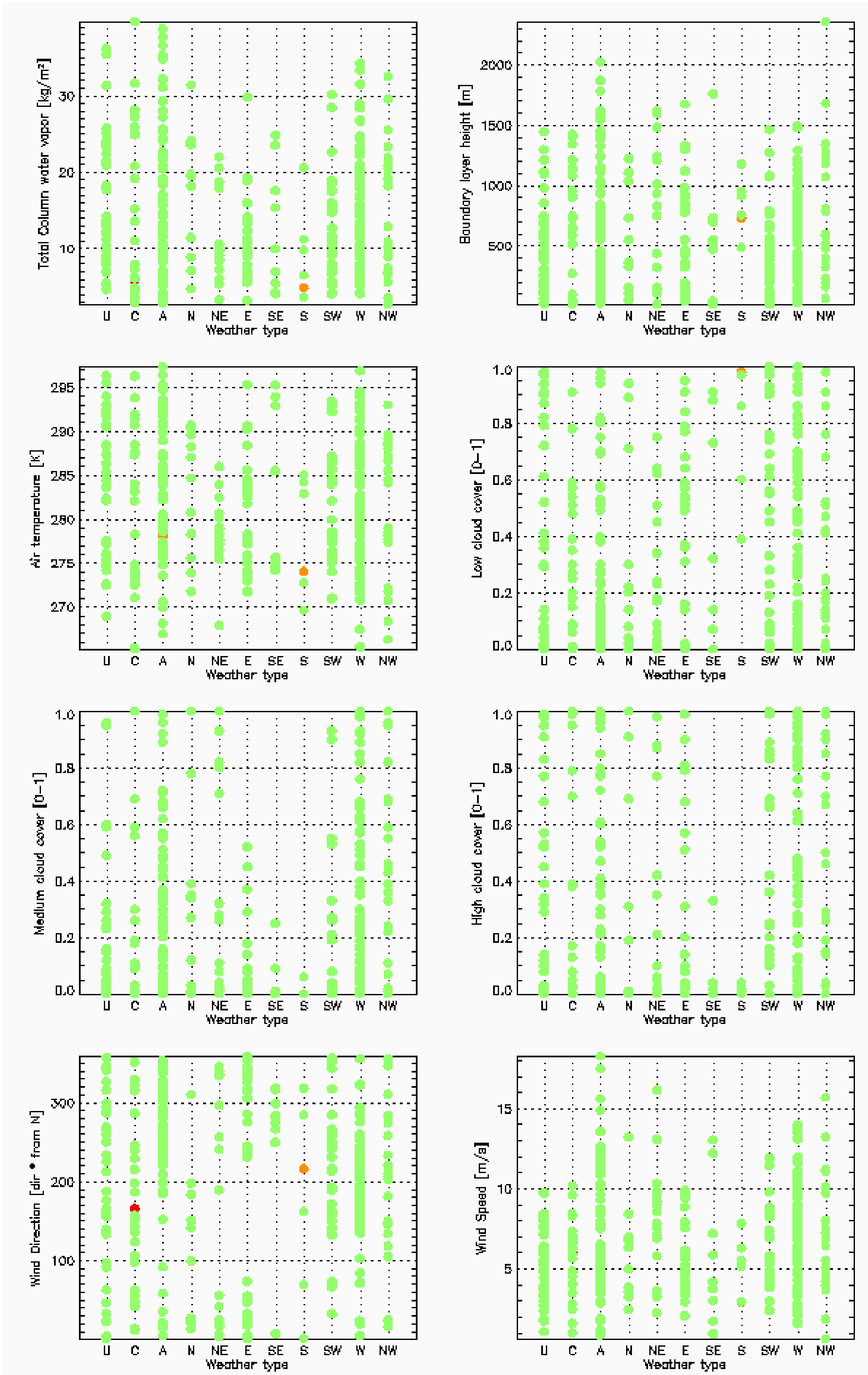



Figure 9: Links between clustered Jenkinson-Collison types, wind speed and maximum 8h daily mean ozone concentration (green < 120 µg/m³, orange < 180 µg/m³, red > 180 µg/m³.

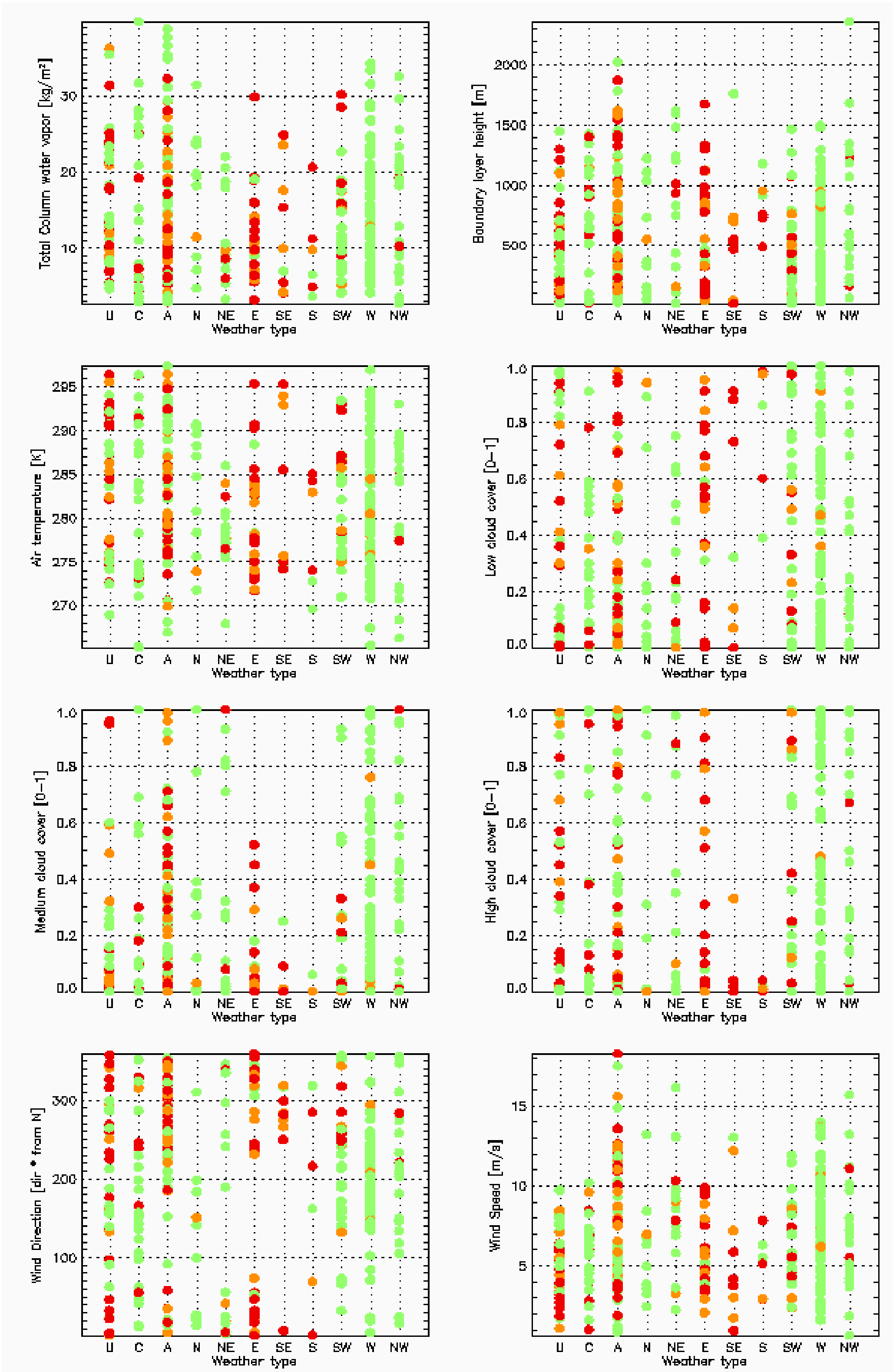



Figure 10: Links between clustered Jenkinson-Collison types, the meteorological variables and daily mean $PM_{10}$ concentration (green < 40 µg/m³, orange < 50 µg/m³, red > 50 µg/m³).

d. Intra-cluster meteorological variability

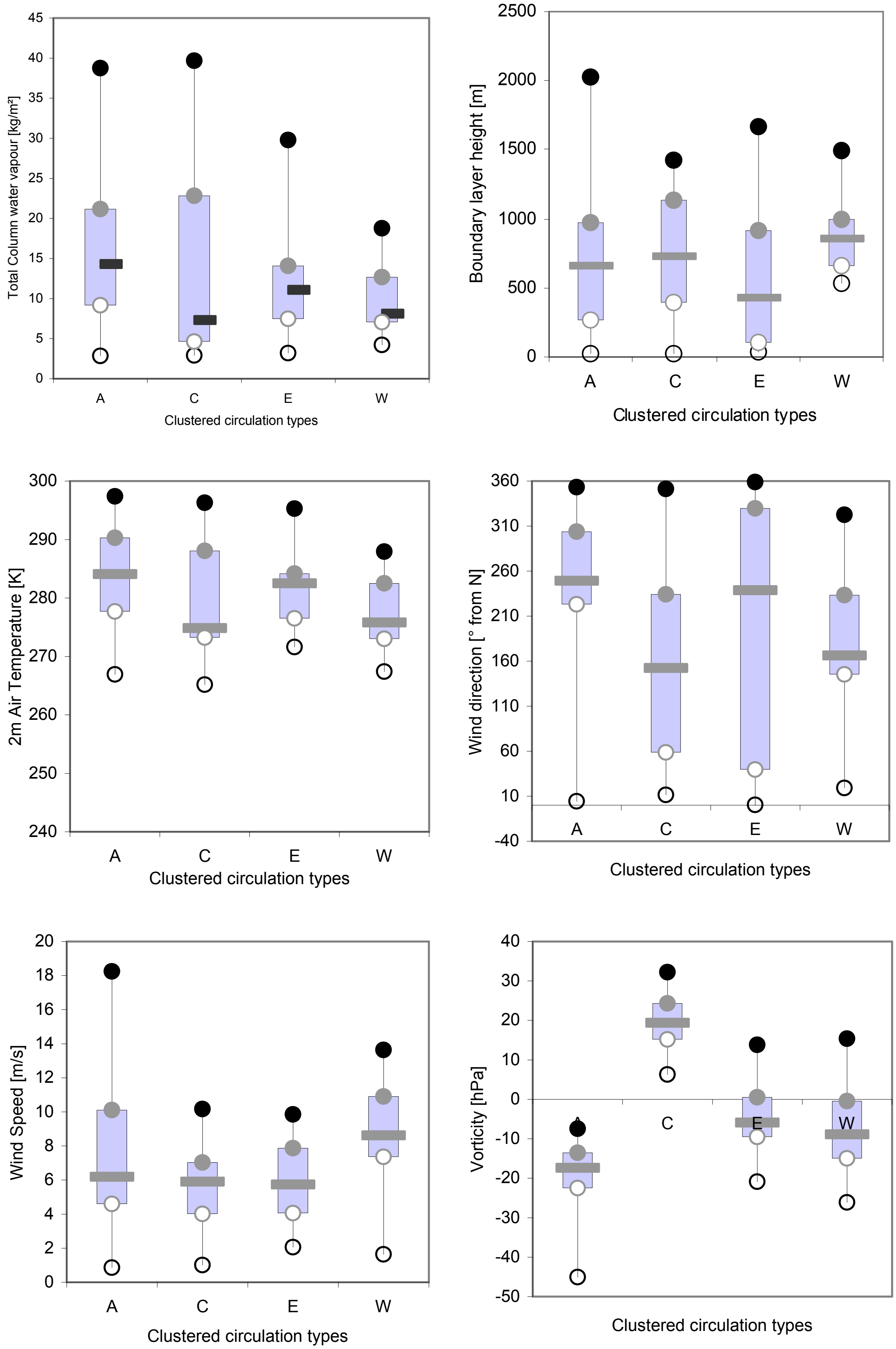
In order to get more insight into the intra-cluster variability, box plots for all meteorological and air quality variables are plotted (Figure 11).

For $O_3$ concentrations, highest peak values are reached in cluster A and E, while highest median values are reserved for A and C. Maximum values exceeding the European Guidelines of Air Quality only occur in the A and E cluster. Next to that, the W cluster shows overall low $O_3$ concentrations, with a maximum value of 51 µg/m³. For $PM_{10}$ concentrations, the differences are more pronounced. With respect to the European Guidelines for Air Quality concerning $PM_{10}$, more than 50% of the days in the E cluster are exceeding the limit of $[PM_{10}] > 50$ µg/m³, although, the limited number of days of 35 a year is not exceeded (=9$^{th}$ percentile). C and W clusters are characterized by a lower median concentration around 30 µg/m³, while the clustered anticyclonic days have a median daily mean of 40 µg/m³, with a maximum up to 126 µg/m³.

Although above-mentioned research (see 5.b, 5.c) showed that there are no clear relations between high $O_3$/$PM_{10}$ concentrations and the meteorological variables, it is interesting to see if there is a clear difference in variability of the meteorological variables within each cluster.

Based on Figure 11, the following conclusions can be drawn:

- **Total column water vapor**: A and E have slightly higher concentrations of water vapour in the air column compared to C and W, although maximum values are retained in the C cluster.
- **Boundary layer height**: Highest median boundary layers are located in the C and W cluster, although highest maximum values are in A and E. The variance in the W cluster is small, while the days in E cluster are most characterized by low boundary layers.
- **Air temperature**: A and E clustered days are described by higher mean air temperatures, while the general distribution in all clusters is similar.
- **Wind direction**: not mentioned in detail, because wind direction is already taken into account by clustering the days with the Jenkinson-Collison classification method.
- **Wind Speed**: Except for a higher median wind speed in the W cluster, wind speeds are similar distributed around a median of 6m/s for all other clusters.
- **Vorticity**: Same remark as for wind direction.



Total Column water vapour [kg/m²]
45
40
35
30
25
20
15
10
5
0
A
C
E
W
Clustered circulation types
Boundary layer height [m]
2500
2000
1500
1000
500
0
A
C
E
W
Clustered circulation types
2m Air Temperature [K]
300
290
280
270
260
250
240
A
C
E
W
Clustered circulation types
Wind direction [° from N]
360
310
260
210
160
110
60
10
-40
A
C
E
W
Clustered circulation types
Wind Speed [m/s]
20
18
16
14
12
10
8
6
4
2
0
A
C
E
W
Clustered circulation types
Vorticity [hPa]
40
30
20
10
0
-10
-20
-30
-40
-50
A
C
E
W
Clustered circulation types

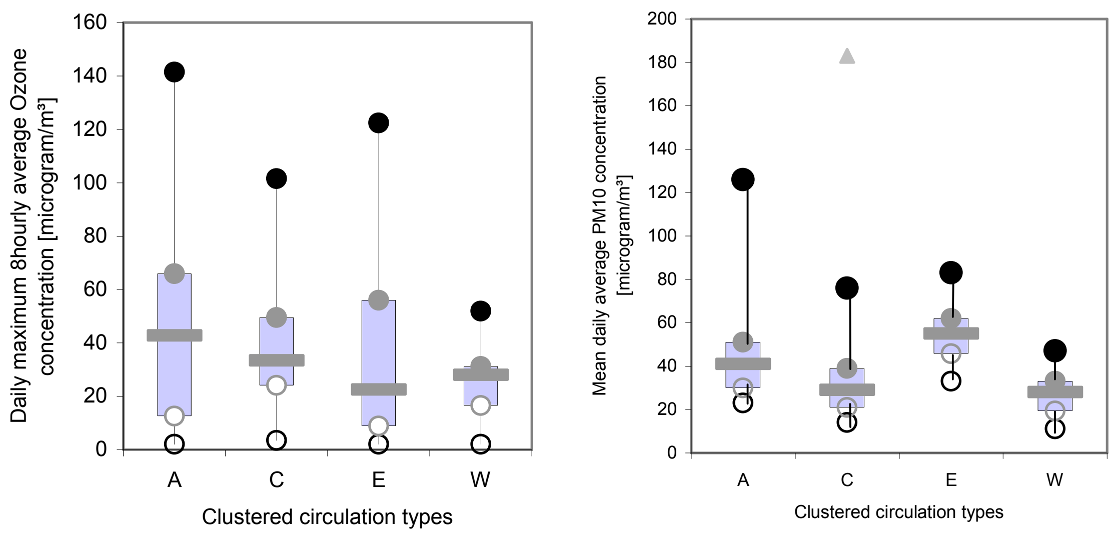



Figure 11: Box plots of all meteorological variables and air quality parameters. Filled black circles denote the maximum, filled grey the 75$^{th}$ percentile, grey line the median, open grey the 25$^{th}$ percentile and open black the minimum. Outliers are denoted with a filled grey triangle.

As a last step, the correlation coefficients between the meteorological variables and the 8h maximum $O_3$ average, daily maximum hourly $O_3$ value and daily mean concentration of $PM_{10}$ are calculated (as in table 5), but than within the above-mentioned selected clusters (table 7). As the number of fields within one cluster is small, the minimum correlation value on a 99% significance level is 0.5, 0.29, 0.48 and 0.29, respectively for the A, C, E and W cluster.

From table 7, we can draw the following conclusions. The maximum 8h mean average ozone concentration has a strong positive correlation with air temperature and negative with boundary layer height for all clusters (except E for the latter). Also, for the 2 zonal clusters, low cloud cover plays an important negative role. For the maximum daily hourly value, correlations are less strong than the 8h average values, but still significant positive correlated with air temperature and water vapor, and negative with boundary layer height, low and medium cloud cover and vorticity for the A cluster. Negative correlations are also strong but less significant for the other clusters, except for W.

For PM10 there is a significant negative correlation with air temperature and water vapor for A. For W, there is a significant negative correlation with low cloud cover and vorticity. For the other clusters, there are no clear within cluster meteorological-air quality correlations.

In general, we can state that almost for all clusters and for ozone, air temperature and water vapor are positively correlated, and boundary layer height and low cloud cover negatively. For PM10, there are some negative correlations with air temperature, water vapor and low cloud cover (especially for A), as mentioned in the conclusions for table 5.

Table 7: Correlation factors between the meteorological variables and the 8h maximum $O_3$ average, daily maximum hourly $O_3$ value and daily mean concentration of $PM_{10}$, for each of the selected Jenkinson-Collison weather types A, C, E and W.

| | **8h maximum $O_3$** | | | | **daily max. hourly $O_3$** | | | | **$PM_{10}$** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **C** | **E** | **W** | **A** | **C** | **E** | **W** | **A** | **C** | E | W |
| Boundary layer height | **-0.40** | **-0.50** | **-0.45** | **-0.38** | **-0.40** | **-0.47** | **-0.47** | **-0.47** | 0.16 | 0.02 | 0.02 | 0.02 |
| Air Temperature | **0.60** | **0.51** | **0.67** | **0.35** | **0.55** | -0.23 | -0.23 | -0.23 | **-0.34** | 0.01 | 0.01 | 0.01 |
| Total column water vapour | **0.50** | **0.40** | **0.43** | **0.35** | **0.46** | **0.31** | **0.31** | **0.31** | **-0.31** | -0.08 | -0.08 | -0.08 |
| Low cloud cover | **-0.32** | **-0.34** | **-0.64** | **-0.36** | **-0.31** | **-0.36** | **-0.36** | **-0.36** | 0.25 | **-0.31** | **-0.31** | **-0.31** |
| Medium cloud cover | **-0.32** | **-0.30** | -0.14 | 0.05 | **-0.30** | -0.23 | -0.23 | -0.23 | 0.05 | 0.02 | 0.02 | 0.02 |
| High cloud cover | 0.02 | -0.16 | **-0.31** | 0.18 | 0.04 | -0.12 | -0.12 | -0.12 | -0.02 | 0.14 | 0.14 | 0.14 |
| Wind direction | -0.21 | -0.02 | -0.06 | 0.11 | -0.20 | -0.01 | -0.01 | -0.01 | 0.09 | 0.01 | 0.01 | 0.01 |
| Wind speed | -0.26 | **-0.46** | **-0.37** | -0.11 | -0.25 | **-0.33** | **-0.33** | **-0.33** | 0.19 | -0.07 | -0.07 | -0.07 |
| Vorticity Z (JC-scheme) | **-0.40** | -0.15 | 0.26 | 0.22 | **-0.40** | -0.15 | -0.15 | -0.15 | 0.16 | **-0.45** | **-0.45** | **-0.45** |

## 5. Conclusions

Hereby, we can conclude that the Jenkinson-Collison clustering method is able to group days with high and low $PM_{10}$ concentrations into different clusters based on vorticity and strength of geostrophic flow. Thereby it seems that advection is already playing an important role in episodes with high $PM_{10}$ concentrations. For low/high ozone concentrations this pattern is not so distinct. For the selected 2001 period in this study, a large deal of the high ozone concentrations days is classified as “unclassified” days.

That high ozone concentrations in se are appearing frequently in unclassified days is a drawback of using this classification method for ozone air quality predictions. Therefore, in a future working strategy, it could be useful to select a longer period, or to adjust the Jenkinson Collison algorithms in order to prevent the number of days with low-pressure gradients as unclassified. Another option could be to lower the $O_3$ threshold values (instead of 120 and 180), to see more clear correlations with meteorological parameters and to understand physical processes playing a role in these high concentration episodes.

Furthermore, it has been shown that within each selected Jenkinson-Collison directional cluster, the variability of the meteorological variables is high, and together with the correlation factors from section 4.b and 4.d, we can state that for $PM_{10}$ air quality predictions purposes, there is no simple way in combining the Jenkinson-Collison method with other meteorological variables. For $O_3$ concentrations this could be different, but therefore, as mentioned above, an episode with higher concentrations (which are not classified as “unclassified”) should be investigated.

## 6. Future planned work

The further progress of this STSM (at the home institute) consists of finding a first basis of correlation between detailed measurements from the Cabauw measurement tower and air quality variables. Thereby, a period with stable weather and circulation patterns will be selected, in order to investigate correlation factors between weather variables and concentrations of ozone and pm10. This result will afterwards be projected onto the classification method and the obtained clusters, in order to see whether this classification method is able to solve and predict high concentration episodes of ozone and PM10. Again, in order to get insight into the physical conditions playing a role, some cases will be selected and will be run with the simple mixed-layer model.

This research will be done in cooperation with Jordi Vila (UR Wageningen) and Fred Bosveld (KNMI, Cabauw measurement tower).

## 7. Confirmation by the host institute of the successful execution of the mission

Matthias Demuzere has spent two months (May – June 2007) doing research at the Meteorology and Air Quality Group at the Wageningen University. He has been working on the sensitivity of boundary layer dynamics on air quality. In particular, the influence of boundary layer growth to the air pollutant concentrations. He has been very actively involved in the subject and he has obtained results that can be very useful to continue his PhD research. During our last discussion, he has defined a research strategy based on meteorological and atmospheric chemistry observations to determine the validity of his cluster analysis on the air pollution problematic.

## 8. Comments - Acknowledgements

First of all, I would like to thank the COST733 chair Dr. Ole Einar Tveito and the whole Management Committee for the chance they give me to collaborate with the University and meteorological and air quality research center of Wageningen. Of course I would like to acknowledge Dr. Jordi Vila, who supervised me during this research and gave some constructive comments and information about boundary layer processes, available datasets and some more technical details on the mixed-layer model.

I hope that these findings will help in the search for a harmonized general numerical method for assessing, comparing and classifying typical weather situation in Europe. I do believe that these results will help further studies on how (and which) classification methods could be used in air quality modeling and predictions, and give further insight on the meteorological variables that should be taken into account for these kind of environmental studies. Of course this research is limited to one type of classification, but these results can give perspective to future comparative and application studies.

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